ArcticMix

R/V Sikuliaq
Final Cruise Report

November 2015

1 Overview

The overall goal of this project is to understand the the processes controlling the distribution of heat and salt in the Beaufort sea, and in particular the role of turbulent mixing in setting those distributions. Accurate measurements and ultimately predictions of turbulent salt and heat fluxes in the upper Arctic Ocean are essential to make sense of a changing climate. The Beaufort Gyre (BG) is historically home to some of the oldest and thickest ice in the Arctic, but is now remarkably ice free in summer (*Carmack et al.*, 2015). Large areas of ocean are now exposed to direct wind forcing. Turbulence directly forced by surface wind stress is confined to a shallow mixed layer. However, wind stress also generates near-inertial internal waves (NIW) that can propagate downwards into stratified water and break hundreds of meters or more below the surface (*Dosser et al.*, 2014; *Martini et al.*, 2014). Here we gathered some of the first systematic measurements of turbulent mixing due to near-inertial waves in a variety of different wind conditions and proximity to remnant pack ice through several microstructure time series.

At the same time, the Beaufort is extremely horizontally inhomogeneous; any understanding of basin-wide heat budgets is incomplete without assessment of the complex interplay between vertical mixing and lateral advection of pockets of much warmer and cooler waters. We investigated the lateral variability using a combination of 1) long sections with our towed body, SWIMS; 2) smaller scale process surveys assessing the contributions of warm water from the Mackenzie river outflow and eddies shed off Point Barrow; and 3) sub-mesoscale surveys looking at upper ocean heat distribution near the ice edge with high-frequency ADCPs and a thermistor bow-chain.

One of the unexpected features of the Beaufort this year was the presence of a substantial amount of multi-year ice at relatively southern latitudes (an example is shown in Figure 4). This expanse of ice was separated from the retreating main ice pack, which moved much further north. Over the duration of our trip the ice melted appreciably, but did not melt entirely, befitting the multi-meter thicknesses observed. The presence of this ice pack presented unexpected challenges and opportunities, requiring some changes to our original plans. Downsides were few, mostly involving circuitous travel routes. On the positive side, we had the opportunity for a variety of innovative sampling of turbulent heat fluxes, internal waves, and lateral interleaving very close to and even within the ice pack.

By all measures, this was a very successful cruise. We have managed to gather what we think will be a fascinating dataset characterizing many facets of heat and freshwater distribution and turbulence. Our work is by nature an exercise in adaptive sampling, a mode of operation we found dovetailed well with the unpredictable conditions frequently encountered in the Arctic. Below we describe the timeline of different sampling modules, instruments used, and a smattering of preliminary scientific results.

We are extremely grateful to the captain and crew of the *R/V Sikuliaq*, who have been outstanding in every respect.

2 Cruise track, time-line and travelogue

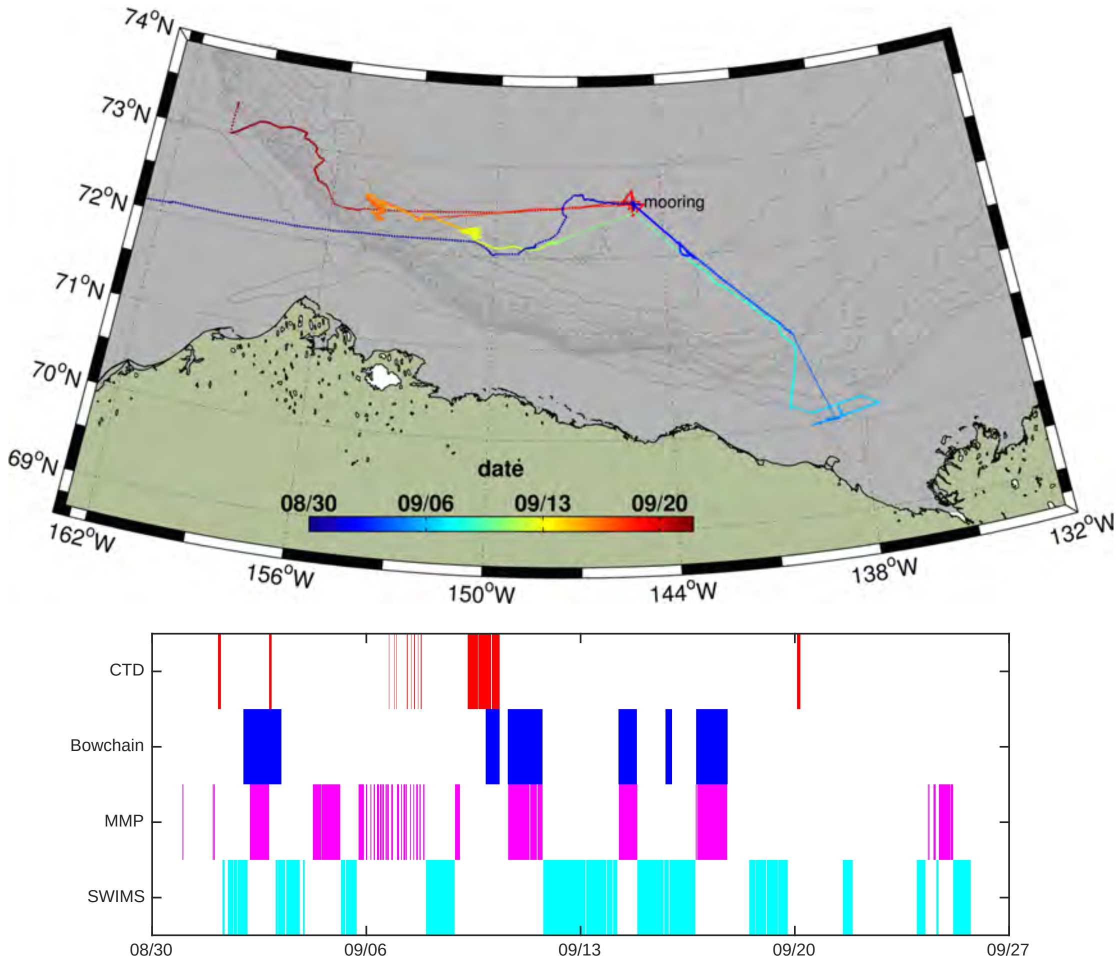

Figure 1: **Top, our cruise track, with date indicated by color. Bottom: timing of measurements conducted.**

Our departure from Nome was slightly unconventional. The majority of the science party arrived in town late on the evening of 23 August, expecting three mobilization days. Instead, we were told that an approaching storm required the Sikuliaq to leave the dock the following afternoon - the dock is quite exposed and apparently not able to accommodate large ships with appreciable weather (an issue likely to plague many future Sikuliaq cruises until additional deep-water ports are available). We got our gear onboard and barely tied down and departed at 1700 24 August. For the next several days we holed up in protected waters near the small town of Teller, and completed our science setup. The people of Teller were very helpful in facilitating additional science and crew personnel transfers (as described in a blog post `https://scripps.ucsd.edu/projects/arcticmix/the-end-of-the-road/`).

We departed 27 August for points north. Our cruise path for the remainder of the trip is shown in Figure 1. On 31 August we arrived at the new mooring location at 72 35.646N, 145 01.002W (moved from the originally planned spot to accommodate ice coverage) and successfully deployed the mooring.

Our next goal was to undertake a long transit with our SWIMS towed body, in the hopes of getting a good first look at large-scale patterns in water masses, turbulent fluxes, and sloping shear layers indicative of internal waves (Sec. 5.2). In order to have this line encompass the transition from deep water to shallow water we decided on a heading towards the Canadian coast (using the clearance we acquired at the last minute); such a line was not possible in America waters due to deference of the 50nm-from-the-coast 'no fly zone' requested by the Alaska Eskimo Whaling Commission in pre-cruise discussions. Once at the coastal end of this line, we decided to spend a few days in the Mackenzie canyon region, investigating 1) heat and freshwater fluxes from the Mackenzie and 2) enhanced upwelling and mixing of warm Atlantic water within the canyon (Sec. 5.10). On 08 September we begin SWIMS measurements on a reciprocal line (offset slightly to add to the multi-beam database) back to the deep central Beaufort. Upon our approach to the mooring location we had temporary technical difficulties; as a result decided to conduct a 24-hour CTD/LADCP station 6nm from the mooring, with the hope that we would document degree of coherence of a variety of features observed at both locations (internal waves, doubly diffusive staircases, water masses) over that separation scale (Sec. 5.8)

At that point we got word of an approaching storm, our best chance to observe the resultant upper ocean turbulence, generation of near-inertial internal waves, and associated mixing. We decided to conduct these measurements near the edge of the conveniently-nearby remnant multi-year ice pack, to asses the influence of ice on wind forcing and water mass mixing. These measurements are thus complementary to the simultaneous measurements on our mooring, which at that time was 50 miles from the ice edge, representative of the ocean's response to a storm in open water conditions. During our time near the ice edge, we alternated between SWIMS towed body surveys and microstructure time series, in increments of the local inertial period, all with our bow-chain deployed (Sec.5.4). We also had the unexpected opportunity to deploy the Sikuliaq's work-boat for transiting deeper into the fractured ice pack, through leeds too small for the Sikuliaq. We manufactured an additional thermistor bow-chain for the work-boat and hand-profiled a small CTD (Sec. 5.5).

Upon departure from the ice edge 16 September we fortuitously came upon a dramatic intra-thermocline eddy, and dedicated some time to map it out and make detailed microstructure observations though it. Similar eddies were observed in several of our other sections, bringing extremely warm Chukchi water into the central Beaufort (Sec. 5.7).

On 19 September we recovered the mooring and started heading for home, allowing time for several additional measurements on the way, starting with SWIMS section from deep water up the slope to the Chukchi, to compare and contrast to the similar continental slope measurements made earlier in Canadian Waters (Sec 5.2).

On 22 September we conducted emergency recovery of a Navy glider that was transiting for the ice edge too rapidly for comfort. Kudos to Sikuliaq crew for a smooth recovery despite having none of the associated recovery gear.

We devoted about 40 hours from 1600L 9/23 to 1000 9/25 of contingency time on our way home to surveys of Bering Strait (Figure 18), where 0.8-1 Sv of water enters the Arctic from the Pacific. Investigating the mixing and possibility of hydraulic control of the flow, we occupied three cross-channel lines on the UW side of Bering Strait, two with SWIMS and one with MMP (Sec 5.11).

3 Instrumentation and Field Methods

The primary science-party-supplied instruments for this project are depicted in Figure 2 and described in the sub-sections below.

Modular Microstructure Profiler

MMP (Figure 2a) 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}, an order of magnitude lower than many commercially available profilers. Shear-based microstructures also provide a crucial 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 minutes. A sample cast is plotted in Figure 17.

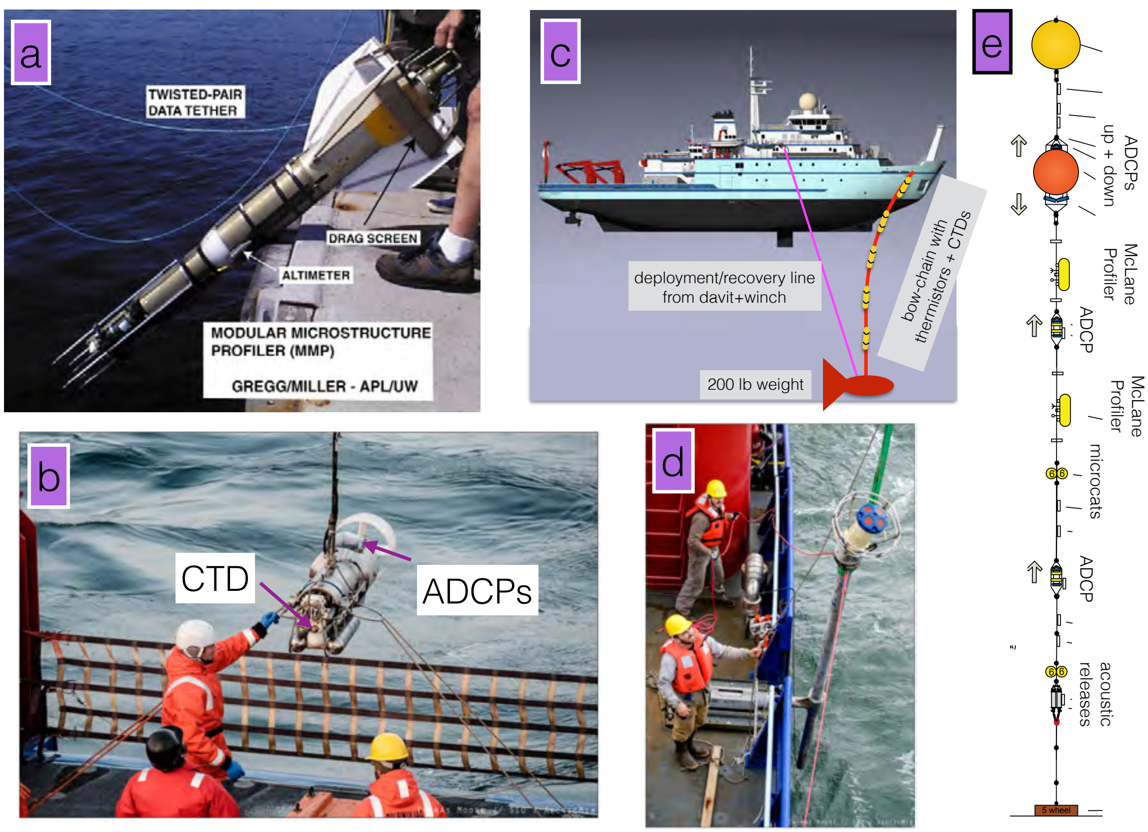

Figure 2: (a) Modular Microstructure Profiler (MMP), with shear probes for directly measuring the turbulent dissipation rate. (b) Shallow water integrated mapping system (SWIMS), a towed body with CTD and ADCPs, (c) the bow chain, (d) additional ADCP mounted on a pole, (e) mooring diagram.

SWIMS

Towed behind a ship, SWIMS (Figure 2b) is winched up and down from the surface giving tight sawtooths to about 500-600 m maximum depth depending on tow speed, which can range from 0-6 knots. It carries up and downlooking ADCP's, two pumped CTD's, optical backscatter, and a temperature microstructure package (χ-ometer). We had substantial problems with our new Dynacon winch including a failed level wind sensor and proximity switch, but solved them and after about 9/6 were profiling reliably. The newly renovated SWIMS has a thicker cable (0.32" O.D. as opposed to 0.25") than the old system, and so we cannot profile as deep at the same tow speeds owning to wire drag as previously. We would often do sections at 5 knots profiling to 150-200 m, having the ship slow down for periodic deeper casts. We also gained a lot of confidence at towing SWIMS through significant first-year and multiyear ice on the Sikuliaq.

Bow Chain

To measure undisturbed near-surface density and turbulence and to capture finescale horizontal gradients of near surface features, we deployed a 20-meter chain of temperature, conductivity and pressure sensors from near the Sikuliaq's bow. A 200 pound weight was hung on a separate line, deployed from a davit on the 02 starboard deck. Deployment and recovery were conducted by hoisting the weight up or down with a nearby (ship-provided) winch; the bow chain itself could be easily clipped in or out of the setup, while both the weight and line attached near the bow remained in place the entire cruise. The system performed well at speeds of up to 3 knots. (Figure 2c)

Mooring

To obtain time series anchoring our spatial surveys, a subsurface mooring was deployed on 9/1/15 and recovered on 9/19/2015 (Figure 2e). It included two McLane profilers (MP) programmed to sample continuously (giving hourly profiles from 40-1000 and 1000-2000 dbar, respectively), and ADCPs at 40, 1000, and 2000 m. All instruments worked as expected except the battery died early for a deep ADCP, the shallow MP stopped profiling after 9 days owing to a broken shaft pin coupling the drive shaft to the drive motor, and the deep profiler's velocity sensor which gave empty files for the second half of the deployment.

ADCPs

To supplement sonars permanently installed in the ship hull (only one of which, the 75kHz was operational during this cruise), two additional science party instruments were utilized during this experiment. A 300-kHZ RDI ADCP was installed in an open well in the centerboard. And a 1200 kHz ADCP was deployed on an over-boarded pole, to capture velocity and shear very near the surface (Figure 2d). All sonar measurements were significantly challenged to get good data; this is by far the weakest part of the Sikulaiq's capacity for physical oceanography, at least in present form. An ongoing discussion is underway with Jules Hummon at UH (who maintains software for the ship-based sonars), and we will just mention a few salient points here:

Low Scatterers: The Arctic is known to have very few plankton scatters, which makes velocity measurement through acoustic means always difficult. In our specific case, the consequence was that data

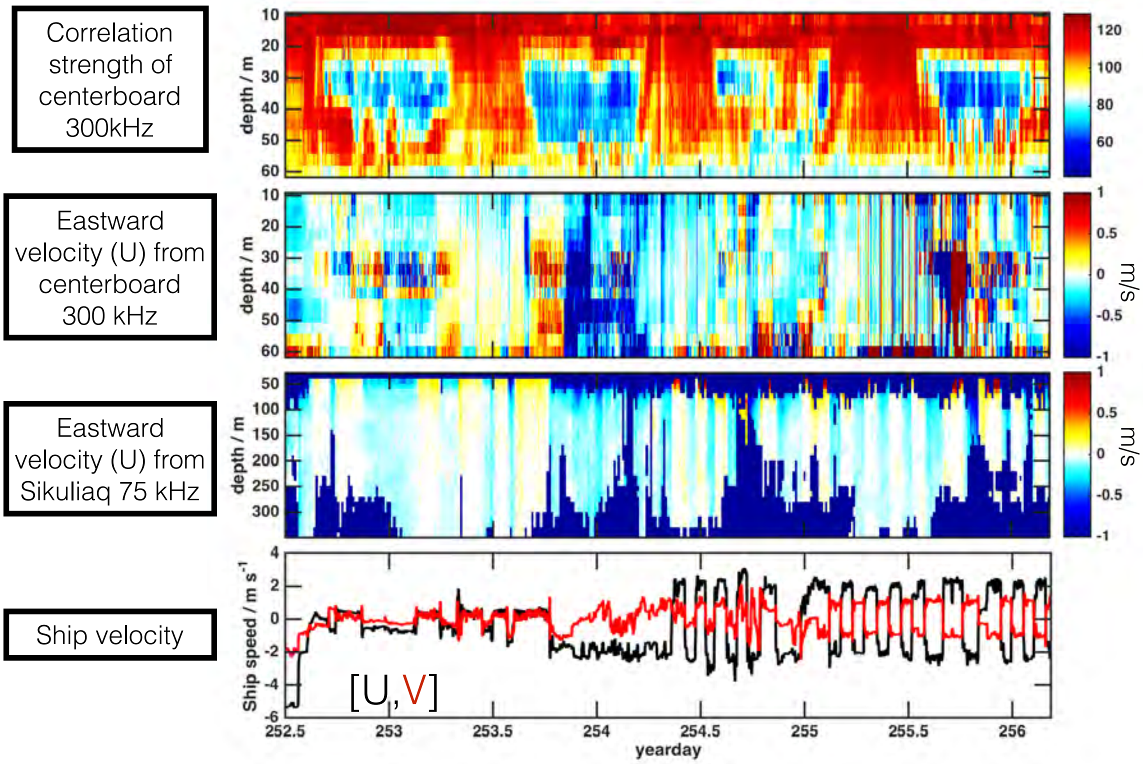

Figure 3: Diagnostics of hull-mounted Acoustic Doppler Current Profilers (ADCPs). Top: correlation strength (a measure of scattering strength required for good data) from the 300 kHz instrument we mounted in a spare well in the Sikuliaq's centerboard; there is a diurnal cycle to low correlation that we attribute to migrating zooplankton. Second: eastward velocity from that same instrument; Patches of 'very suspicious' data are visible where correlation is low, this data is thrown out in later stages of processing. Third: eastward velocity from the Sikuliaq's 75 kHz ADCP; a banding pattern is visible at all depths that correlates with the ship velocity (bottom panel) suggesting this motion has not been correctly removed. Note that the second and third panels cover different depth ranges.

quality became extremely sensitive to diurnal plankton migrations. During night-time when migrating zooplankton were closer to the surface, there were sufficient scatterers for reasonable quality data; for example the 300 kHz instrument we installed in the centerboard reliably measured to 90 meters or so below the surface. However, during day-time, in the open ocean Beaufort basin, once zooplankton migrated downwards there were insufficient scatters in the 30-60 meter range for accurate velocity measurements (Fig. 3). This was unfortunate, as turbulent heat flux dynamics were particularly interesting in this depth range. For future work, it is not entirely clear how this problem can be addressed; design of new sonar instruments with different power parameters might be one way forward, as suggested by the engineers in our science party (who built the "HDSS" sonars on Revelle), subject of course to all appropriate environmental constraints.

Sikuliaq's 75 kHz: In addition to the scattering issues, the 75 kHz instrument permanently mounted in the Sikuliaq hull appeared to be having other significant problems. For example, the third panel of Figure 3 shows eastward velocity from this instrument, processed with the standard onboard UHDAS routines. There is often no good data in the top 60 meters. And at all depths there is still a clear signature of ship velocity (plotted in the lowest panel of this figure for reference). Closer inspection (not shown) indicates that the erroneous ship velocity signal is depth-dependent, which means that there is a subtle problem with the instrument in return strength as a function of depth. Dr. Hummon speculates that acoustic reverberations in the well itself or ship hull may be producing these problems, and suggests she could work with the Sikuliaq to trouble-shoot and ideally fix the problem; a suggestion we heartily endorse.

Throughflow thermosalinograph system and shipboard CTD

The Sikuliaq's thermosalinograph (TSG) through-flow system was very useful. In particular, inclusion of that data in the ship-board map server proved essential for our adaptive sampling. Figure 5 shows the full range of sea-surface temperature observed during our trip, as measured by the TSG.

We conducted 23 total full-depth CTDs, in several groups. The first two profiles (1-2) were individual casts taken nearby and shortly after the mooring deployment. The second set of casts (3-11) were taken near the Mackenzie river outflow area and the nearby continental slope. The third group (12-23) were a 24-hour time series again close to the mooring location. Profiles with numbers 24-29 exist as data, but are not depth profiles, they are 'hanging ADCP' test of the LADCP unit, hung near the surface at fixed depth. The final cast (30) was again near the mooring immediately following mooring recovery. During the final cast, we collected bottle samples at depths of (3348, 3255, 3073, 2869, 2544, 1938, 1427, 922, 420, 133) meters for laboratory salinity analysis post-cruise (Sec. 5.8)

Table 1: **Shipboard CTD operations**

CTD cast name	Deploy. Pos.	Yearday	Max Profile Depth
1	72.5876 N; 144.9984 E	243.1772	3442 m
2	72.1478 N; 143.4390 E	244.8383	3176 m
3-11	70.1426-70.5587 N; 138.5824-140.1091E	248.6055-249.7900	784 m
12-23	72.4946 N; 144.9668 E	251.3317-252.2831	3376 m
30	72.5941 N; 145.0169 E	262.0955	3449 m

Satellite Imagery and the Map Server

The Sikuliaq 'map server' is a truly phenomenal service, one which we are unclear how we will do without on future cruises. The server is a locally hosted web-site with continually updated overlay images available of various ice concentration products, satellite images, modeled SST, satellite microwave data, our own real-time along-track data, and more. Examples are shown in Figures 4 and 18. The crew was very open to inclusion of additional products onto the server by science party request. Radarsat 2 images are part of the normal support Sikuliaq support. We additionally were fortunate and grateful to have additional imagery support from Hans Graber's CSTARS group in Miami. We thank Staci Langsdon and Raymond Turner for their assistance.

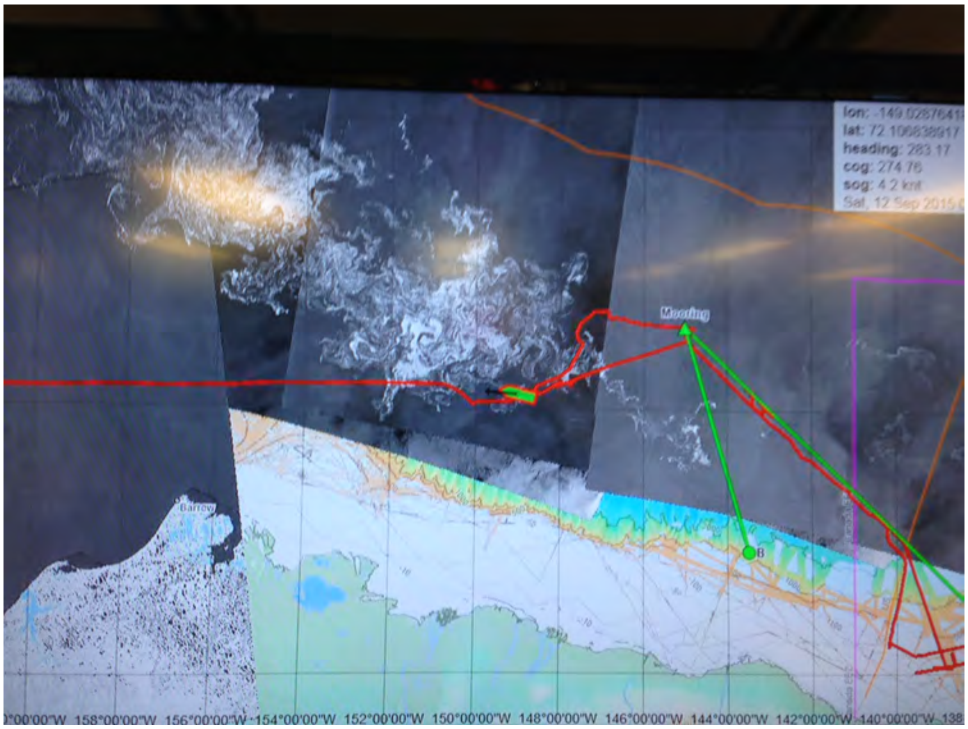

Figure 4: **Example of real-time output from the Sikuliaq map server, with science planned waypoints indicated. The presence and dynamic look of remnant multi-year ice late in the summer is clearly visible.**

While we were operating in areas of marginal ice concentration, the map server was indispensable for cruise track planning. And more generally the map server was an extremely helpful and efficient way to peruse all relevant data when making complicated adaptive sampling decisions. Res-tech Steve Roberts is to be commended for writing the original map server software and continually updating it in such a responsive manner.

Other shipboard services

Being on board the Sikiliaq is like being welcomed into a family; several of the crew mentioned that they left other positions to join this ship because they wanted to be part of consciously creating a new culture, and it shows. The primary question driving the actions and attitude of the crew and marine technicians is "How can we help?" More than on any other ship we've been on, science is first, and they made it happen for us on a number of occasions, from simply lending an extra hand in the hold on deck to allowing us to use the engineers' machine shop to supporting our sometimes unusual requests with whatever tools and brainstorming ability they could muster.

Several individuals deserve special mention: Adam Seamans for his calm, steady and braggadocio-free skippering, Mike Stewart for his warmth, kindness, excellent ship driving and knowledge of the ice; Ethan Roth and Bern McKiernan for their continual support of our operations and Mark for his truly over-the-top cooking. This is the first cruise we've been on wherein hors d'oeuvres and fresh baked cookies were regularly served in the lab in the afternoon, and even on an engine room tour.

4 Educational Activities

We brought six graduate students with us (Table 2) who were involved in all facets of our experimental design, data collection, instrument prep, analysis and interpretation. During the cruise we had daily "science moments" in which one person would present to the group. These were nightly meetings that everyone was expected to attend, and except for people on watch on deck, almost everyone did every day. Each student was given a homework assignment before the cruise, to research and present a thorough report on some facet of Beaufort circulation or dynamics that was relevant to our experiment; they each gave 30-40 minute seminars during the first week of the cruise. They became very engaged in the data analysis (which was extremely helpful for our adaptive planning purposes), and enthusiastically populated the lab with the results of their efforts. During our work-boat survey (Sec. 5.5), for which we made excursions in small batches, students were given the ability to design their own mini-experiments and seemed to enjoy the opportunity. We expect the cruise results will form the bulk of a PhD thesis for one student (Effie Fine), comprise thesis chapters for two others (Marion Alberty and Greg Wagner) and entrain the three others as substantial co-authors on several papers at least. Effie Fine will be presenting the beginnings of her thesis analysis at both the FAMOS meeting in November 2015 and the Ocean Sciences meeting in February 2016.

5 Science Results

5.1 Basin-wide context: surface properties and meteorological forcing

Figure 5 shows an overview of surface temperature and salinity along our cruise track. On both our transit out and back we crossed very sharp boundaries separating the comparatively warm, salty water of the Chukchi with the much cooler fresher central Beaufort surface water. During some of our work in the central Beaufort we made measurements very near the remnant multi-year ice pack, which was surrounded by a 'puddle' of cooler slightly fresher water. Finally, we spent time near the Mackenzie river out-flow; though we only sampled a dilute form of the river water itself (HYCOM model results suggest the main plume was hugging the coast much closer to shore at this time), the surface water is clearly warmer; the Mackenzie is in fact known to be a significant source of heat input to the central Beaufort. We conducted smaller-scale process studies in each of these areas, which are described in more detail below.

Despite the persistent cloud cover for much of the first half of the cruise and the relatively low angle of the sun, shortwave radiation was the largest of the surface heat budget terms and had a cruise-integrated value that was about 5 times that of the other terms. This observation, however, hides the importance of the downward or downwelling longwave (IR) radiation term, which for much of the cruise largely offset the upward black-body radiation of the ocean surface to result in a small total longwave radiation term (red line in figure 6). At times, the downward longwave flux was *larger* than the up-going, causing it to be a small warming term to the upper-ocean heat budget. Due to small air-sea temperature differences,

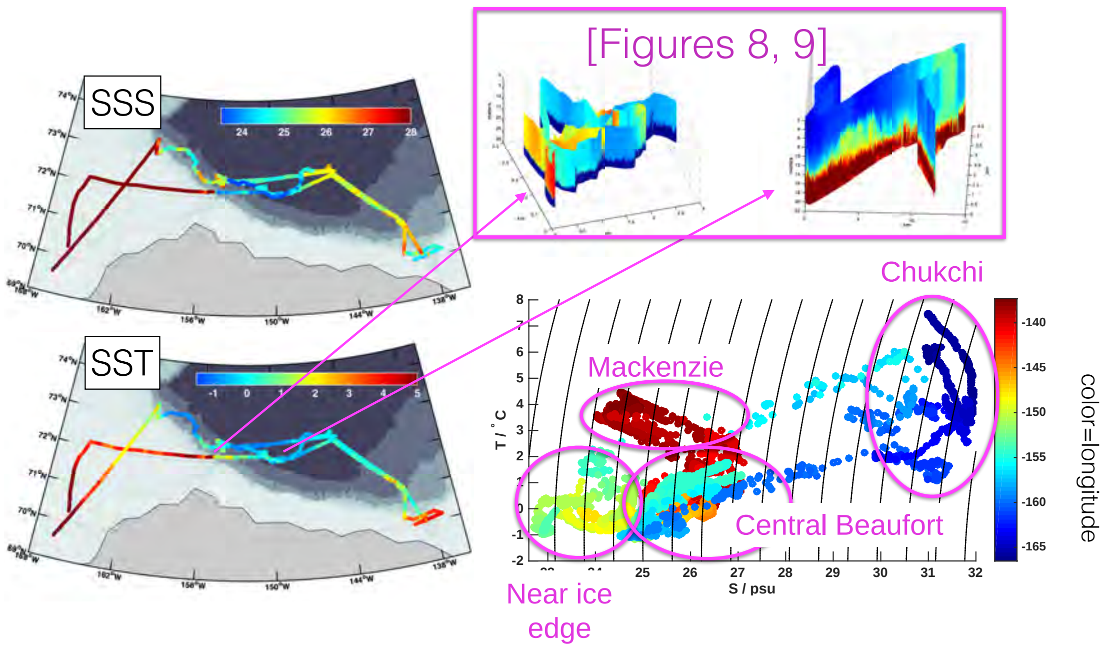

Figure 5: **Overview of surface temperature and salinity properties. Left panels are SSS and SST as measured by the Sikuliaq's TSG instrument. Lower right is a T-S plot of the same data, identifying particular characteristic water masses. Upper right insets are examples of high-resolution bow-chain surveys at a couple locations, which are shown in more detail in Figures 8 and 9**.

high relative humidity, and light to moderate winds, sensible and latent heat fluxes were small at roughly 20-30 W/m^2. Around the 14th and 15th of September, the shorter days (less net shortwave) combined with relatively clear skies (reducing downwelling longwave), and colder, dryer air (larger sensible and latent fluxes) the net warming trend reversed to a cooling trend that persisted until the end of the cruise. Time-integrated surface heat flux from August 30 to September 21st totaled 4×10^4 kJ/m^2, which in the absence of other mixed layer budget terms and neglecting shortwave radiation penetrating below the mixed layer, would have warmed a 10 meter deep mixed layer by 1.0 deg. C.

5.2 Sub-surface structure overview

Complementing the plan-view SST and SSS images in Figure 5, data from our towed body, SWIMS, gives the sub-surface view of evolving temperature and salinity. Figure 7 shows the rich structure especially evident in the top 100 meters of the water column. There is a very fresh surface layer of typically 10-20 meters depth that is separated from the ocean below by a very sharp halocline, $\sim$ 3-4 psu (lower right in Fig. 7). Temperature is nearly a passive tracer in this surface layer. Sometimes temperature decreases with increases depth, frequently there is a sub-surface temperature maximum near and just below the base of the surface fresh layer. Below the surface layer salinity still dominates stratification, with a complex interleaving structure visible in temperature. These temperature filaments are signatures of advection and subduction of warmer water masses, often from near-surface coastal or Chukchi waters.

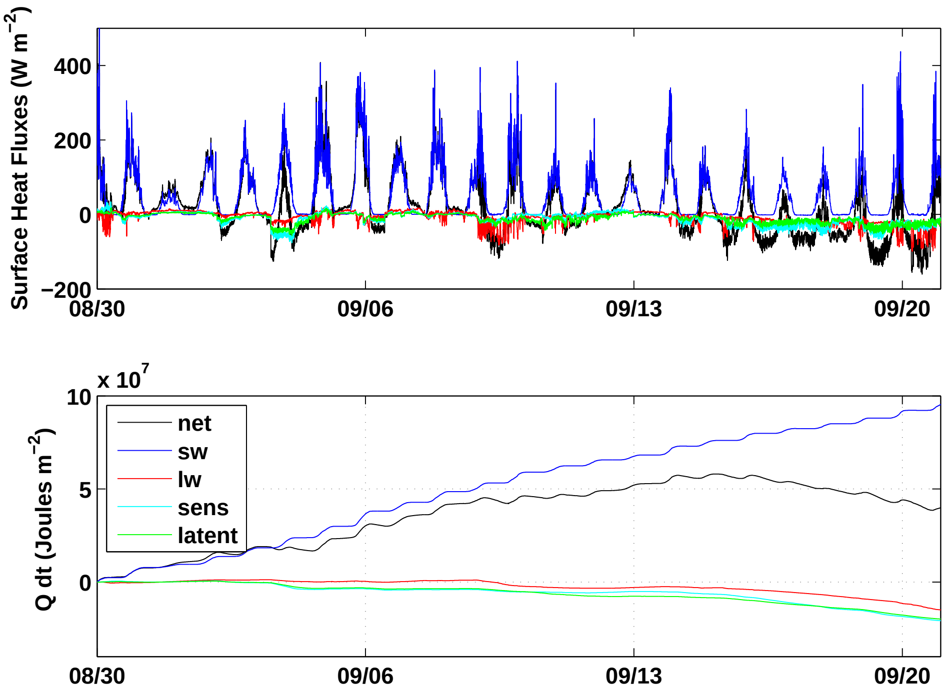

Figure 6: **Top panel: surface heat flux terms over the duration of the cruise. Total (black), shortwave (blue), logwave (red), sensible (cyan) and latent (green). Lower panel: Time-integrated heat flux for net (black) and individual surface heat flux terms over the duration of the cruise. In the absence of other budget terms (e.g. entrainment, lateral advection) the cumulative net flux would result in a warming of a 10 m mixed layer by 1.0 $\circ$ C over the 23 days.**

Turbulent mixing of any of these sub-surface water filaments can bring heat upwards towards the surface; our analysis will focus on quantifying these heat flux rates and understanding the driving dynamics. The remaining sub-sections below look in more detail at particular features observed at various locations.

5.3 Model comparison: HYCOM

Figure 7 also highlights the incredible interpretive value of regional models. We have been informally working with Joe Metzger and colleagues at NRL, who run a real-time data assimilating HYCOM model specifically focused on the Beaufort. Initial comparisons show that the energetic mesoscale swirling of temperature and salinity within the model agrees well with many of the patterns observed in our along-track data. However, the model does not as well reproduce the small-scale sub-mesoscale structures, or vertical structure of heat distribution beneath the surface. The discrepancies likely arise due to choices of sub-grid-scale parameterizations of turbulent mixing processes; analysis of such processes and eventually development of revised parameterizations is one of our main goals for the remainder of this project and beyond. We are looking forward to continuing a conversation with NRL colleagues on this topic.

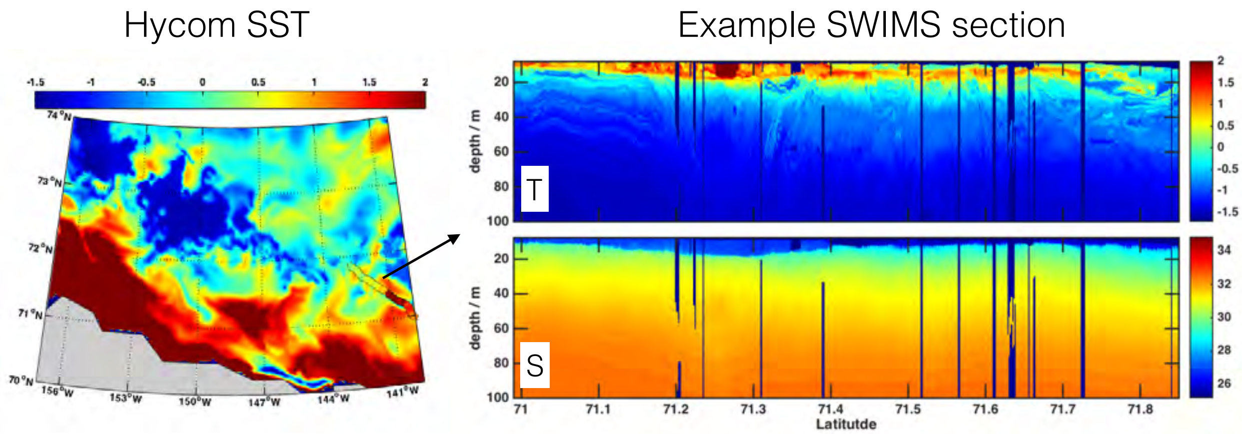

Figure 7: **Left: sea-surface temperature from a hycom regional simulation at the time of our measurements, data graciously provided by Joe Metzger and colleagues at NRL). SST data from the Sikuliaq's through flow system is plotted on top, for one particular section, outlined in grey. Right: an example SWIMS section of temperature and salinity sub-surface for this section. The date and time of the HYCOM now-cast plotted on the left is the average time of this particular SWIMS section.Though SWIMS data was taken down to 400 m, only the top 100 meters are plotted here.**

5.4 Upper ocean surveys: two examples

The upper 20-30 meters of the Beaufort is a turbulent and complex environment. Two examples are shown here. Figure 8 shows a commonly observed situation, in which cooler, fresher water overlies warmer saltier water. Surveys with the bow chain and repeated microstructure casts show a complex stratification within the surface layer; sometimes it is relatively uniform in composition, sometimes quite stratified. A T-S plot (Fig. 8, upper right) has points color coded by depth below the surface; the multi-colored 'fingering' nature of this plot, that the same T-S properties appear at different depths, suggests that a complex interplay between vertical mixing and lateral re-stratification is setting observed properties. Two example microstructure profiles from this survey are shown in black and magenta lines, in the central panels of the figure. The strength of turbulence (third panel) and associated turbulent heat fluxes (fourth panel) respond very sensitively to this stratification, which is variable on small horizontal scales. Note here that because temperature increases with increasing depth, **the heat flux here is upwards**, towards the ice. We should stress that these are instantaneous heat flux values and are higher than the averages, though the average heat flux values described below (Fig. 11) are still quite dramatic!

A second example (Fig. 9) shows a contrasting case. Here we are surveying in an area where a filament of warmer surface water from the Chukchi has been advected seawards by mesoscale eddies (context in Figure 5). Here the same T-S vertical/lateral interleaving is visible in the surface layer. And again, turbulence response sensitively to the stratification within that layer, which is variable on lateral scales of a kilometer or less. However in this situation the heat flux is **downwards**. Also worth noting here, the bow chain survey on the left, taken over only 6 hours, crossed over itself several times, but each time advection of small-scale lateral gradients had changed the water properties dramatically; any surveys or time series in this region will be subject to similar advective change. We anticipate further

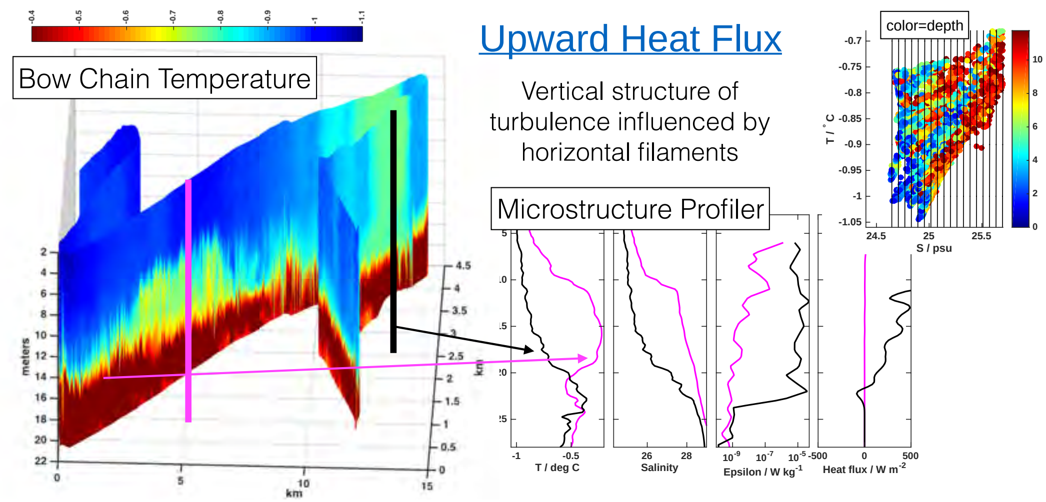

Figure 8: An example survey of upper ocean processes, during a typical situation in which cool fresh surface water lay above warmer saltier water below. Left: temperature as measured from the bow chain. Middle: example profiles from the microstructure profiler, MMP, of temperature, salinity, turbulent dissipation rate (ϵ), and associated turbulent heat fluxes. The locations of these two profiles are indicated with black and magenta lines in the bow chain figure on the left. Upper right: temperature-vs-salinity plot, from MMP, for this survey, from the upper 12 meters. Points are color coded by water depth.

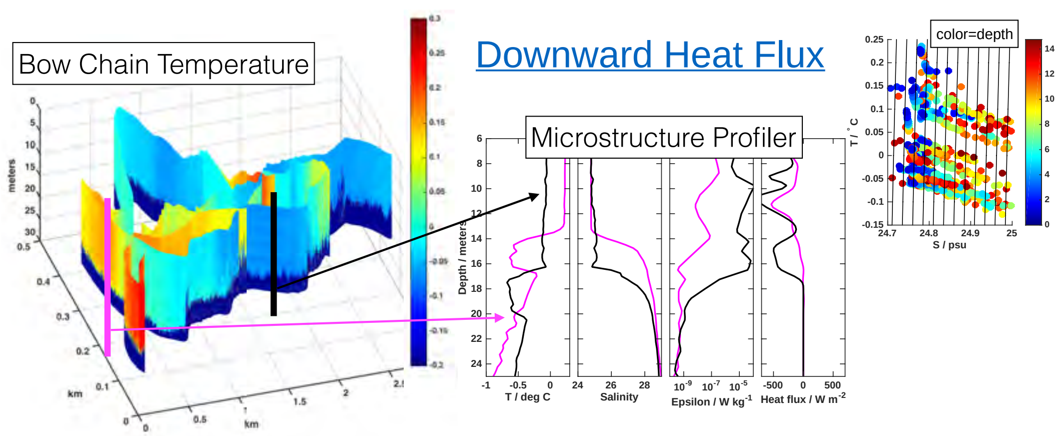

Figure 9: Same as Figure 8, except from a different survey in which warmer saliter water had advected in at the surface, so the sense of both temperature gradient and turbulent heat fluxes was now reversed, with turbulent fluxing heat downwards (instead of upwards in Fig. 8).

analyses of these and other examples will help us significantly contribute to community understanding of the heat budget of the upper ocean, and dynamic processes therein.

5.5 Work boat surveys into the ice pack

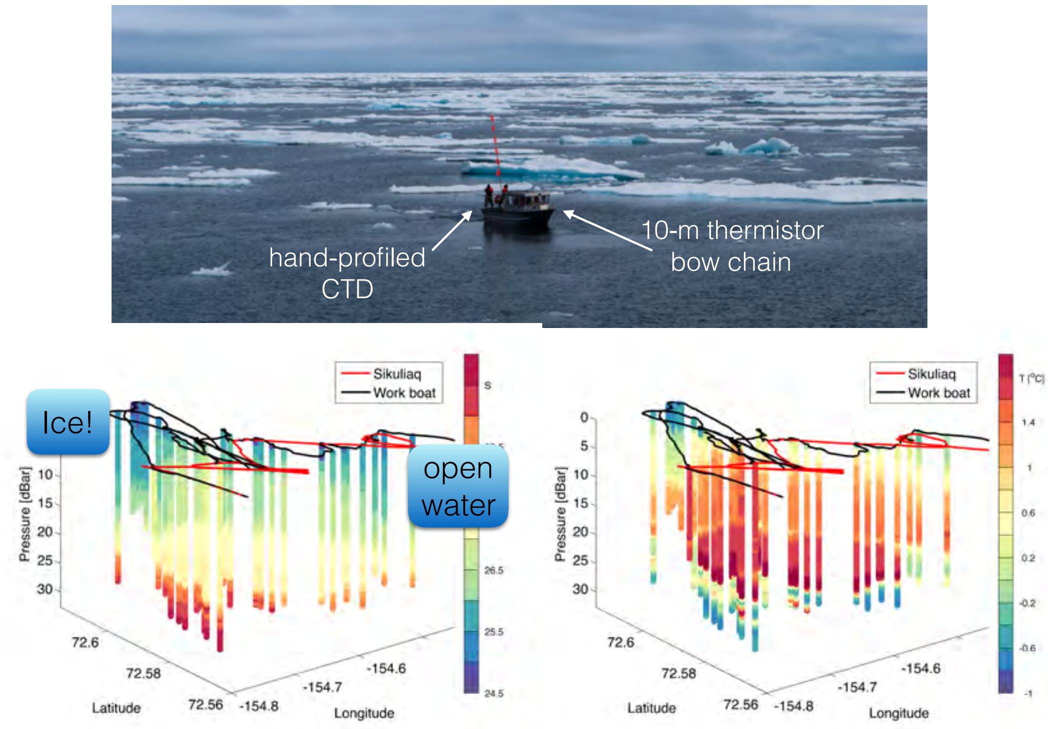

Figure 10: Work boat surveys near the edge of the melting multi-year ice pack. The Sikuliaq's work boat (above) was outfitted with a 10-meter line of thermistors attached to the bow, and an RBR Concerto CTD was periodically profiled by hand to 30 meters depth. Lower panels show the CTD profiles of salinity (left) and temperature (right); with the simultaneous cruise tracks of the Sikuliaq and work boat shown in red and black respectively. The rough gradient between more open water and denser icebergs is indicated.

On 15 September we had the opportunity to conduct a series of small boat surveys near the edge of the remnant multi-year ice pack (Fig. 10). The Sikuliaq's work boat was outfitted with a bow-chain of thermistors 10 meters in length with a weight at the bottom, and we brought along a RBR 'Concerto' CTD that we periodically profiled by hand down to 30 meters below the surface. The goals were two-fold: first, to make measurements very close to the ice, in small leeds and between icebergs in a way that was not contaminated by the ship wake or displacements, and second, to conduct simultaneous parallel measurements from two platforms (the Sikuliaq itself and the work boat), to help detangle the complex dynamics of small-scale, rapidly evolving near-surface waves, instabilities and associated turbulence. The data in the lower panels of Figure 10 gives a first hint at the results. At the furtherest excursion points of the work boat when we had traveled the furthest into the increasingly dense ice pack (upper left parts of these lower two figures) the surface water becomes noticeably fresher and colder, consistent with actively melting multi-year ice. We are looking forward to further analysis this data, as well as the work boat bow chain and simultaneous Sikuliaq SWIMS data, to further understand how this ice melt is stirred and mixed into the ambient Beaufort waters.

5.6 Average upper ocean heat fluxes

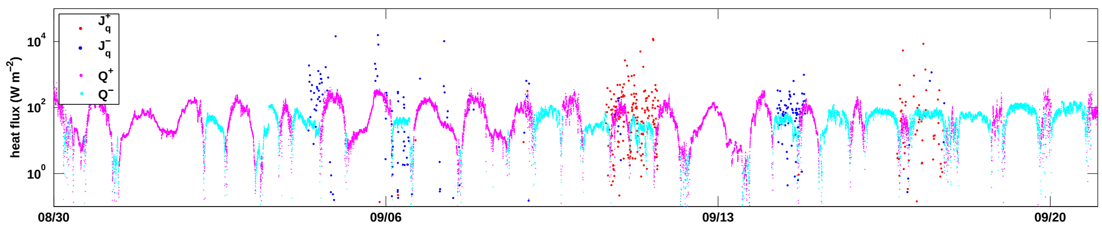

Figure 11: **Time series plot of vertical turbulent heat fluxes, J_q, at the base of the mixed layer as measured by MMP (redupwards, bluedownwards) along with positive (magenta) and negative (cyan) surface heat fluxes, Q. Fluxes are plotted on a log-scale (with the absolute value of the negative fluxes plotted) as turbulent heat fluxes, like ϵ, are logarithmically distributed.**

Moving beyond the specific examples shown above, certical heat fluxes at the mixed layer base estimated from the MMP turbulence measurements were **on average** exceptionally large in comparison to most surface terms, owing to both the shallow depth of the mixed layer and large temperature gradients. Due to the small value of the coefficient of thermal expansion (alpha) at cold Arctic temperatures, stratification is predominantly determined by salinity. Because of this, temperature gradients at the mixed layer base can be both *positive*, with warmer water over colder as is the case in most of the Worlds oceans, or *negative* with colder water directly above warmer water. With the temperature gradients at the mixed layer base governing the sign of the vertical turbulent heat fluxes there, we observed both large upward (positive) and downward (negative) heat fluxes. Preliminary results show mean values for the times of microstructure sampling of 700 W/m^2 for positive fluxes and -400 W/m^2 for negative fluxes (Figure 11). If these fluxes were just integrated *over one day*, they would change the temperature of a 10 m deep mixed layer by 1.5 and 0.85 ° respectively. Such near-surface fluxes play an important role in the seasonal heat budget, setting the timing and strength of fall freeze-up (*Timmermans*, 2015). Preliminary analysis (not shown) suggests the turbulence throughout this surface layer is often related to near-inertial shear; detangling the relationship between near-surface inertial shear, wind forcing, and vertically propagating near-inertial internal waves will be a primary goal over the next year..

5.7 Warm core intra-thermocline eddies

Below the surface layer, warm water often enters the Beaufort in the form of dramatic intra-thermocline eddies. We had the opportunity to carefully sample one such eddy 16-17 September (Fig. 12). The SWIMS instrument was used to explore the shape and extent of the eddy. This survey was followed by an MMP section across the core of the eddy. The eddy was located between 72.3 to 72.5 N, and from 154.5 to 154.1 W, northwest of the mouth of Barrow Canyon. It was characterized by a temperature maximum around 50 m depth, which reached 6 C, a significant departure from background temperatures around 0 C. The eddy was observed to move northwest with a velocity around 3 cm/s. Microstructure measurements show elevated turbulent mixing rates both above and below the core of the eddy. Mixing

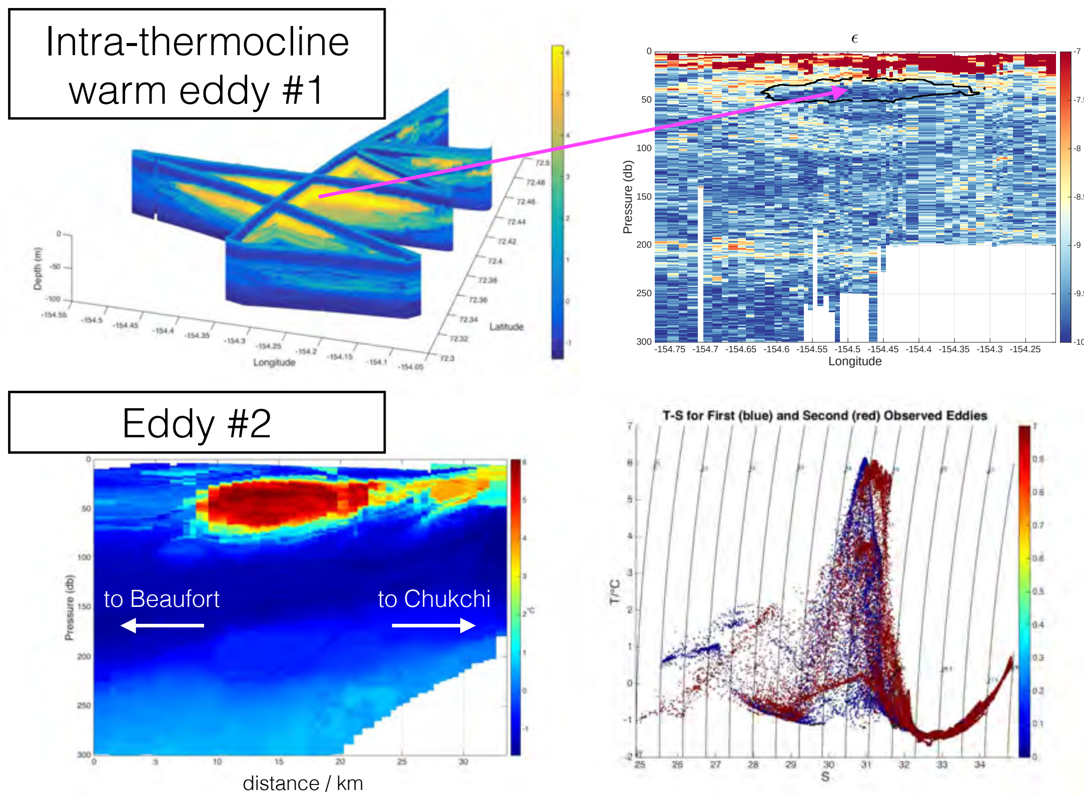

Figure 12: Two example intrathermocline eddies. Upper left is temperature of one eddy sampled with multiple passes of the SWIMS instrument. Upper right shows turbulent dissipation rate (ϵ) from one pass through the same eddy with MMPT. A second eddy (lower left) was sampled with SWIMS only during a section from the deep Beaufort up onto the Chukchi shelf. The lower right panel shows T-S properties for both eddies, the similarity suggests that the water being transported within each eddy is from a similar source.

in these regions is especially significant due to the sharp thermal gradients surrounding the eddy. The eddy core itself is quiescent. Also visible in this figure are the strong mixing in the surface mixed layer, and elevated mixing at 200 m associated with the top of the Atlantic layer.

A second warm core was observed while towing SWIMS up the continental slope on 9/21/15 at 73 N 160 W. This core was also centered around 50 m depth, and also reached temperatures of 6 C. A T-S diagram reveals that both cores are made up of water with similar temperature and salinity characteristics, likely indicating a common origin. The Alaskan Coastal water is a likely source for both of these observed eddies.

5.8 CTD time series

In addition to a few isolated casts, we conducted one 24-hour full-depth CTD time series. Average temperature and salinity profiles show the clear presence of Atlantic warm water at $\sim$ 300 meters depth, dominance of salinity stratification, and a well mixed near-bottom layer. (Fig. 13, left). Time series of isopycnal displacement and velocity (not shown) show indications of near-inertial motions at a variety of depths. (Downward propagating near-inertial motions suggestively following storm passage are visible in the mooring data, Figure 14).

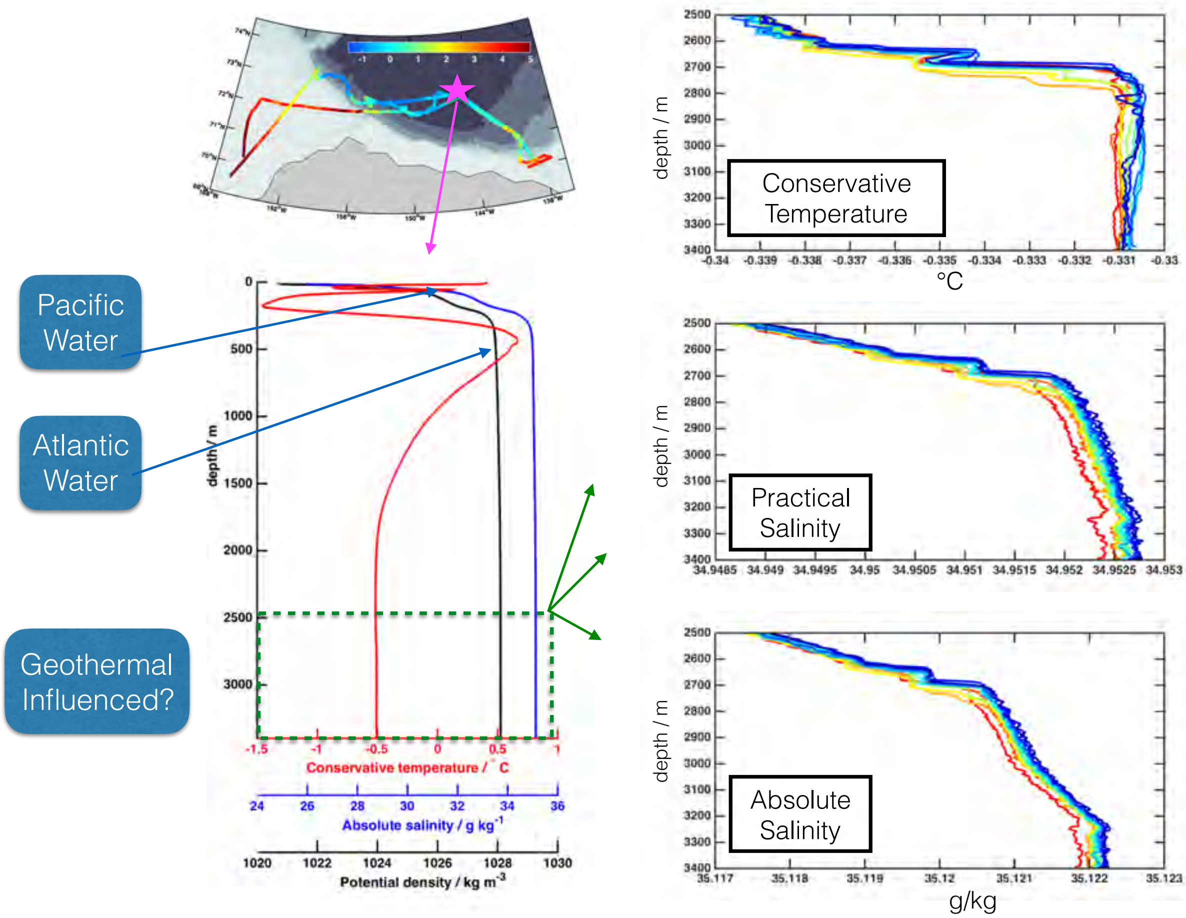

Figure 13: A few plots from a mid-basin 24-hour CTD time series. Location indicated with a magenta star in the upper left. Lower left: average profiles of conservative temperature, absolute salinity, and potential density. Right panels are an expanded view of the bottom 900 meters, showing conservative temperature (referenced to 3000 me water depth), practical and absolute salinity. Profiles are color coded by time, increasing from red to blue.

We grew somewhat intrigued with the bottom portion of the water column (Fig. 13, right panels). Capping this lowest layer are sharp staircases (*Timmermans et al.*, 2003). Over the 24 hours of these measurements the staircases exhibit both vertical heaving and significant changes in structure that are likely associated with lateral advection of what must be gradients in staircase compositor over fairly small horizontal scales. Previous work has raised the possibility the very deepest layer is controlled by geothermal heating, on the order of 50 Wm^{-2} (*Carmack et al.*, 2012) Conservative temperature is reasonably homogenous in depth, but also indicates changes in time that are likely to do lateral advection. Back of the envelope turbulence scaling for a geothermal heat flux of that magnitude argues for more energetic fluctuations in temperature than are observed here, and with a differing vertical structure.

Salinity tells a confusing story. Practical salinity increases moderately with depth within this layer, suggesting it is not actively convecting. Explanations of why this observation is seemingly at odds with Carmaks' result include 1) deep water pouring down the sides of the basin, perhaps residually from deep water formation events the previous winter, 2) salinity probe drift, 3) intermittency in geothermal heating, 4) mixing from above by thermobaricity and/or cabbeling generated by internal wave displacements of the temperature step capping the deep layer.

Absolute salinity (`http://www.teos-10.org/`), which differs from practical salinity by attempting to correct for the presence of non-ionized elements with a world-wide look-up table, is even more strongly stratified within this layer. Which of these is the 'correct' salinity has non-negligible consequences for interpretation of the origin and evolution of these deepest Arctic waters. We have begun a conversation with some of the scientists who developed the new TEOS salinity function to see if our data might help better calibrate that database for the Arctic. The bottle samples we collected on the final CTD cast were specifically for this purpose.

5.9 Mooring observations of near-inertial shear and doubly diffusive staircases

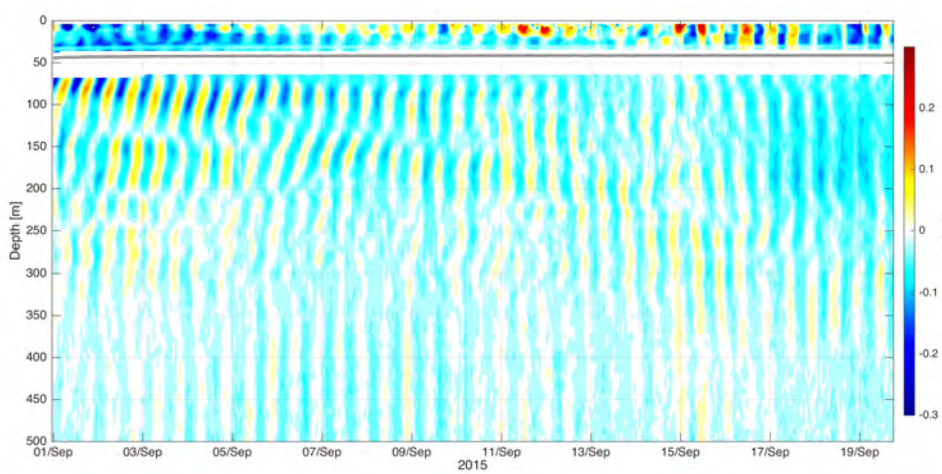

Figure 14: Velocity from the upper 300 KHz and 75KHz on the mooring. Near inertial internal waves are evident as both upward and downward packets of lines of advancing phase.

Mooring velocity data (Figure 14) show clear near-inertial motions, that are enhanced after both storms (the first just prior to the deployment and the second near 9/8). At the beginning of the record there is a clear case of upward phase propagation, indicative of downward energy propagation, consistent with wind-generated near-inertial internal waves propagating downwards from the surface. Later in the record the phase lines are nearly vertical, consistent with very low mode waves. It is important to note that at this latitude, the inertial frequency is very close to the semi-diurnal tidal frequency; whether these later motions are generated by winds, tides, or something else is as yet unclear.

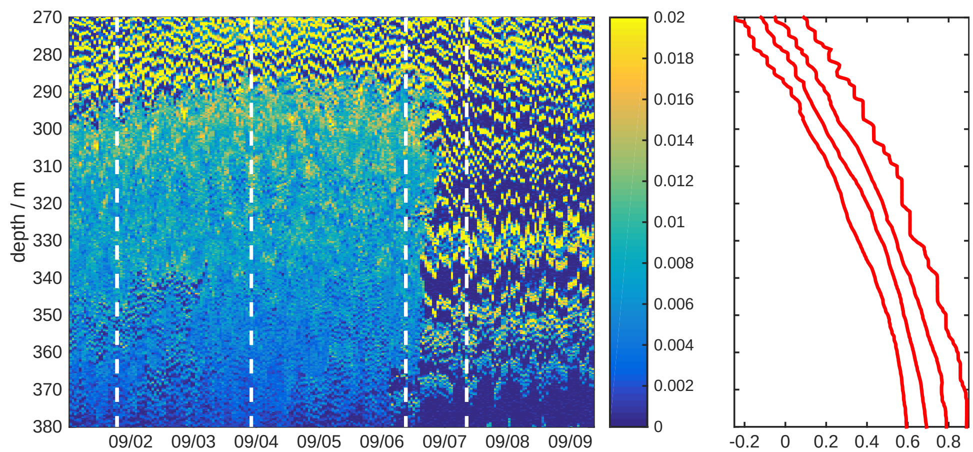

Figure 15: (Left) temperature gradient from the upper MP and (right) profiles at the times indicated at left showing the sudden appearance of staircases.

Doubly diffusive staircases are a well known feature of the central Beaufort, generally found above the Atlantic water, where cooler fresh water overlies warmer saltier water (*Timmermans et al.*, 2008). Previous observations under ice have suggested such staircases can be coherent for vast distances in space. Here, in open water, we observe them to be surprisingly fickle. For example, during the first part of the McLane moored data, a plot of vertical temperature gradient (Fig. 15) initially shows coherent stair-case features (stripes in the plot) between 270 and 290 meters, with a smoother temperature gradient below. However, around 7 September strip-y staircases abruptly fill the entire plotted depth range. Examples profiles on the right correspond to the white dotted lines on the left; the first three are smooth between 300-380 meters, the fourth shows staircases throughout this depth range. It is unclear as of yet whether they have formed in place so rapidly, or advected in. SWIMS data at this depth range (not shown) also show staircases to be very episodic, with spatial coherence scales of only kilometers. A full analysis of doubly diffusive staircases from all observations is underway.

5.10 Mackenzie Canyon

From year days 246.2598 to 249.5506 a combination of SWIMS surveys, MMP stations and CTD profiles were taken across the Mackenzie Canyon area and the continental slope to the east of the canyon. The focus of the Mackenzie region surveys were to understand 1) how submarine canyon geometry enhances the upwelling of Atlantic water onto the continental shelf from the Beaufort Sea and 2) what role the influence of the fresh Mackenzie River water and its filaments has on the distribution of fresh, cool water upon entrance into the Beaufort Sea and continental shelf. Mackenzie canyon is an ideal location to study these mechanisms as the tidal velocities within this canyon are weak, and mean flow and submesoscale-type interactions are not dominated by the tides.

The survey consisted of two cross-canyon transects and one cross-slope transect east of the canyon. For the southern canyon transect (*CanyonS*, Fig. 16), the observations began with continuous MMP

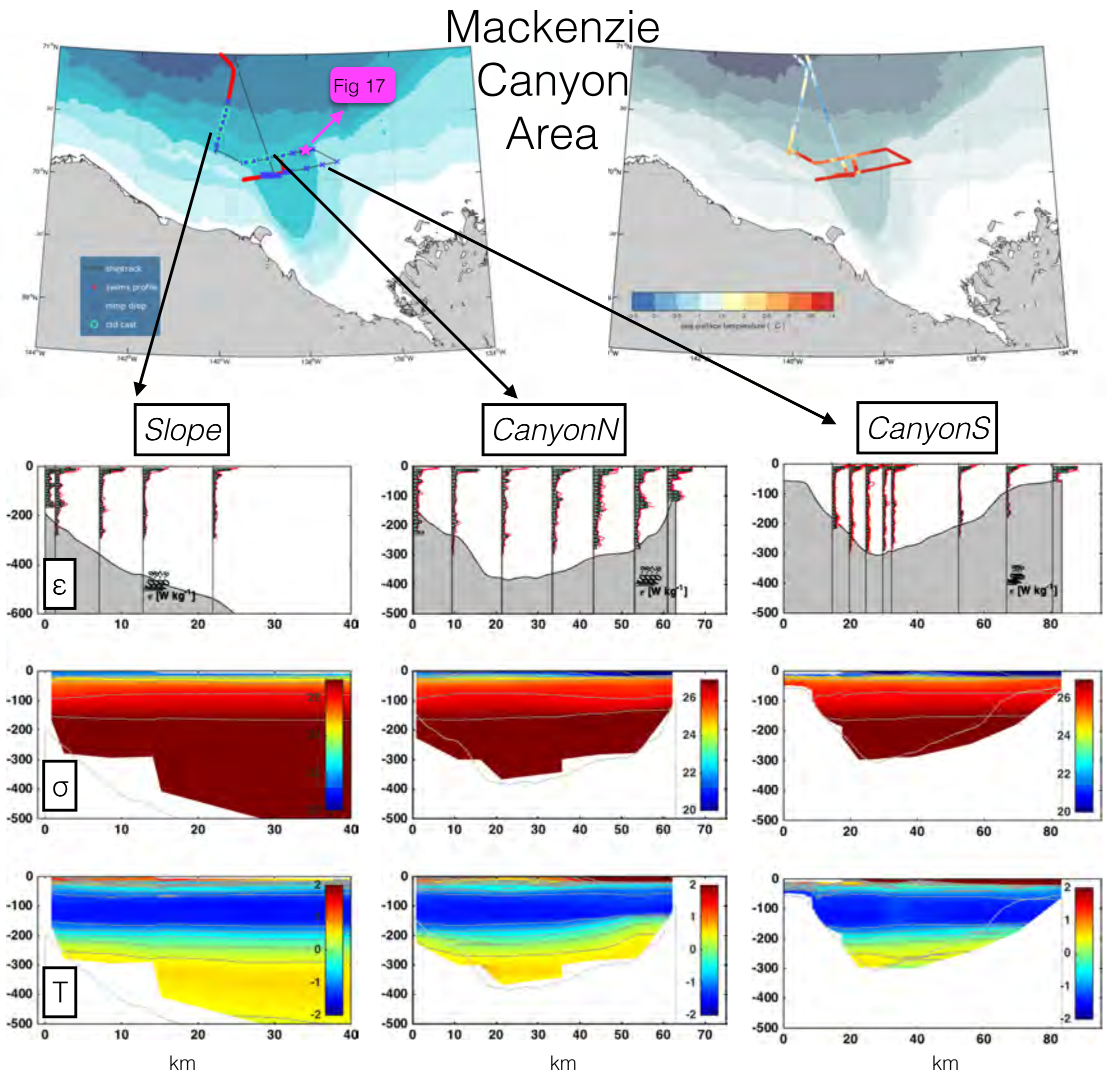

Figure 16: Top: plan view images of cruise track in Mackenzie River delta, with color indicating type of sampling (upper left) and SST (upper right). Lower panels are SWIMS towed body and MMP (microstructure) sections going on-to-off-slope (left), across the northern part of the canyon (middle) and a parallel cross-canyon line to the south (right). Each of these are subdivided into profiles of turbulent dissipation (top), density (middle) and temperature (bottom).

profiles from the middle of the canyon towards the western edge of the canyon. This was followed by a SWIMS survey covering the middle to western edge of the canyon, followed by MMP profiling stations from the center to the eastern edge of the canyon. The second northern transect (*CanyonN*, consisted of 7-MMP profiling stations with additional CTD profiles when the depth of the canyon exceeded 300m, the maximum MMP profiling depth. Finally, 7-cross slope stations were occupied in a cross-slope transect

(*Slope*) with MMP and CTD where slope depths exceeded 300m.

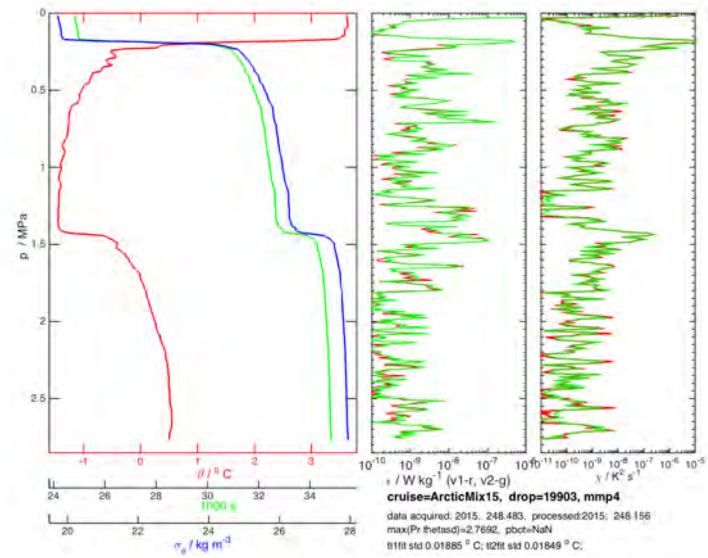

Figure 17: A sample microstructure profile taken in MacKenzie submarine canyon. (Left) temperature, salinity and potential density; (middle) ϵ from the two shear probes; (right) χ from temperature microstructure. ϵ is noticeably elevated at the base of the warm river-influenced surface layer and atop the Atlantic water (150 meters = 1.5 MPa); note that χ determined from temperature microstructure has an extremely complicated relationship with ϵ owing to the dominance of density by salinity and the highly layered temperature structure.

CanyonS and *CanyonN* transects show increased dissipation on the eastern side of the canyon, with the highest dissipation rates along the northern transect. In combination with increased dissipation there, isopycnals and isotherms are uplifted along the eastern canyon rim. The uplifted isopycnals on the eastern side of the canyon indicate that water from deeper depths (with signatures of Atlantic water) are upwelled onto the shelf. Compared to the *Slope* (the cross-slope survey east of the canyon), the canyon is more effective at upwelling deep water from the Beaufort Sea onto the shelf and slope. The enhanced dissipation is likely associated with the increased flow along the eastern edge of the canyon. An example microstructure profile that illustrates these phenomena is shown in Figure 17.

5.11 Bering Strait

Bering Strait is home to 0.8-1 Sv of water flowing into the Arctic from the Pacific, and supplies a large fraction of the fresh water into the Arctic. It has been occupied a large number of times by moorings and 1-nm-spaced CTD stations *Woodgate et al.* (2012, 2015), which suggest strong lateral and vertical stratification due to the presence in the east of the Alaska Coastal Current (ACC). Satellite images (Figure 18) show strong cross-stream structure and vortex shedding.

To measure the lateral and vertical structure and the associated mixing in the Bering Strait at high resolution, we used about 36 hours of contingency time on the way home and sampled them with SWIMS and MMP. We did three cross-stream lines and then a small-scale survey of vortices shed from a small

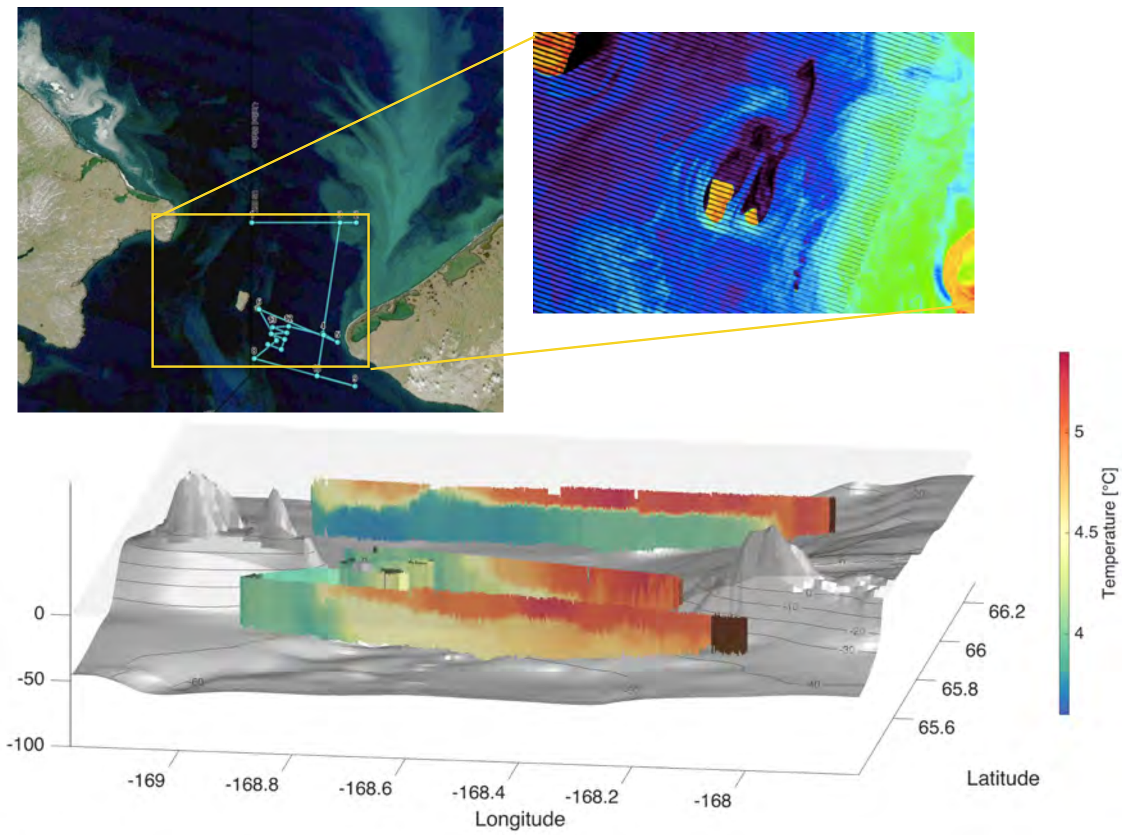

Figure 18: **Top: remote sensing images of the Bering Strait: (left) July 8 2010 MODIS ocean color image; (right) July 18 2013 Landsat microwave brightness temperature image. The image on the top left is from the Sikulaq's map server, and shows way-point for the SWIMS survey. Lower: temperature from the three main lines of the SWIMS survey.**

island just south of Bering Strait (Fig. 18). Temperature observations reveal a warm current banked again the eastern side of the strait, consistent with some past measurements. In shallow (less than 30 m) water on the easter edge, water is well mixed from top to bottom. In the central Bering Strait, the water displayed a two-layer stratification, though there was active turbulence from top to bottom (not shown). For the first two survey lines (northern and middle), the net current was, as expected, towards the north. However, a strong wind sprang up, and by the time of the third section, the ocean was on average flowing towards the south! Such surprising behavior is always welcome, and we look forward to analyzing our measurements to understand how turbulent processes transfer wind momentum from top to bottom during such current reversal events, as well as a more general look at water mass modification rates in this crucial Arctic inflow.

6 Data Sharing

We are currently in the process of processing and quality controlling all the data collected, which we expect will take about a year till data is in final form. Per NSF policy data will be made available within two years, to interested parties. Normal CTD data will be sent to the Rolling Deck to Repository (R2R) program (http://www.rvdata.us) program. Microstructure data will be archived with the new national microstructure database developed with NSF funds as part of the Climate Process Team MacKinnon has been leading (`http://microstructure.ucsd.edu/`).

7 Outreach, communications and media coverage

The ArcticMix voyage had two staff dedicated to outreach related activities, one videographer capturing and editing motion content and one photographer / science writer who created content, managed the voyage blog (`http://arcticmix.ucsd.edu/`), handled social media, and dealt with media management. Our primary goals were to generate media coverage that was accurate, appropriately measured, and included authentic scientific details all while being accessible to the public.

In an effort to build lines of communication with local communities, we sent daily faxes and emails to a variety of communities along the North Slope of Alaska, as suggested by Gay Sheffield in conjunction with the Alaska Eskimo Whaling Commission. These communiques contained descriptions of our operating area, activities, plans, and some science results we thought might be of interest.

Our communication strategy with the wider world involved daily engagement of a curated list of local, national, and international journalists with the proactive planning of media opportunities being one key to securing coverage. All three of the principal investigators dedicated time out of their watch schedules to help review outreach plans and content as well as deal with media interviews. Communication outcomes (with reach estimates* where available) are described as follows:

- Organic content
  - ArcticMix Blog - 2,500 users viewing NSF branded content over 4,700 sessions.
  - Twitter - 58,200 impressions with 5,700 visits to NSF branded profile.
- Selected media coverage
  - **BBC** - "Voyage traces stirred-up Arctic heat" Web: with additional radio coverage via the BBC Worldservice. Reach: Online reach data from BBC is not currently available but the BBC World Service total audience is 210 million and anecdotal evidence suggests our BBC coverage had the largest direct and indirect impact of all ArcticMix media. The BBC coverage was picked up and re-purposed by a large number of outlets including WIRED, Huffington Post, The Weather Channel, and the Telegraph (UK). [http://bbc.com/news/science-environment-34324439]
  - **Mashable** - "Arctic research ship probes frigid depths and 4th-lowest sea ice extent on record" Reach: Over 5.7 million social impressions with 22,000 readers and 1,100 shares [http://mashable.com/2015/09/16/arctic-ice-minimum-research-ship/]
  - **KUAC** - local Alaskan radio coverage - "Researchers Study How Warm, Subsurface Water Affects Accelerated Arctic Sea-ice Melt" [http://fm.kuac.org/post/researchers-study-how-warm-subsurface-water-affects-accelerated-arct
  - Additionally the content created by the ArcticMix team was used by public relations staff at the Scripps Institution of Oceanography, University of Washington, and MIT, leveraging the large audiences of those institutions.

*Estimates of reach are noted where data is available. Interpretation of metrics vary based on platform. Where appropriate a conservative engagement rate of 5% has been used.

Education: We had planned a day of educational activities during the mobilization period with students from a local charter middle school in Nome; our graduate students had brought along demonstration tanks to conduct fluid dynamics experiments with the kids and prepared presentations. However, our surprising early departure sadly forced us to cancel these activities. Our demob period was during a weekend, and a re-schedule hence did not work out for the school during that time. We look forward to conducting such local educational activities on another trip. We did have the opportunity to use the demonstration tank in a few science presentations for the Sikuliaq crew, which appeared to be appreciated.

Video: In addition to a series of short videos showcased on our blog (e.g. `https://scripps.ucsd.edu/projects/arcticmix/video-chasing-storms/`), our videographer, Faith Haney, is planning a documentary length film, as well as brainstorming other avenues of continued involvement in this region.

8 Personnel

Master: Adam Seamans; Resident Technicians: Ethan Roth, Bernard McKiernan, Steve Roberts.

Table 2: Science Party

Who	Role	Institution.
Jennifer MacKinnon	Chief Scientist	Scripps Institution of Oceanography
Matthew Alford	PI	Scripps Institution of Oceanography
John Mickett	PI	University of Washington
Mike Gregg	Scientist	University of Washington
Tom Peacock	Scientist	MIT
Amy Waterhouse	Scientist	Scripps Institution of Oceanography
Gunnar Voet	Scientist	Scripps Institution of Oceanography
Philippe Odier	Scientist	Laboratoire de Physique, Lyon
Marion Alberty	Graduate student	Scripps Institution of Oceanography
Madeline Hamann	Graduate student	Scripps Institution of Oceanography
Elizabeth Fine	Graduate student	Scripps Institution of Oceanography
Olavo Marques	Graduate student	Scripps Institution of Oceanography
Greg Wagner	Graduate student	Scripps Institution of Oceanography
Algot Peterson	Graduate student	University of Bergen
Sam Fletcher	Technician	Scripps Institution of Oceanography
Mike Goldin	Technician	Scripps Institution of Oceanography
Thomas Moore	Outreach	Freelance
Faith Haney	Outreach	Freelance

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Thomas Moore // SIO / ArcticMix


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