CODA / GO-WEST Cruise Report, R/V Sikuliaq, Nov 2019

Final version: 2 Dec 2019

Cruise # SKQ2019-23S

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1. OVERVIEW

The R/V Sikuliaq conducted a joint cruise supporting both the CODA (Coastal Ocean Dynamics in the Arctic) and GO-WEST (Arctic cod) projects in Nov 2019. The CODA goals were to observe the interactions of sea ice with winds and waves along the coast of northern Alaska. CODA is a University of Washington project funded by the National Science Foundation, and more information on CODA is at: http://www.apl.uw.edu/coda . The GO-WEST goals were to investigate Arctic cod and other ice-associated fauna beneath the autumn sea ice cover. GO-WEST is a project funded by the Arctic Research Icebreaker Consortium (ARICE), the Bureau of Ocean and Energy Management (BOEM), the German Helmholtz Association and the University of Alaska Fairbanks, and more information on GO-WEST is at: https://arice.eu/call-results/2018#go-west-rv-sikuliak-beaufort-sea. The cruise also conducted mooring operations for the ONR acoustics program (Univ. of Delaware project).

The cruise spanned 7 – 27 November, 2019, operating from Nome, AK. The actual end of the cruise was 1 December, 2019, in Dutch Harbor, AK. The cruise report is organized as narrative of the activities spanning both projects. The projects traded days based on wind, wave, and ice forecasts, in an effort to minimize transit distances and partition the time based on the funding of 17 days for CODA, 8 days for GO-WEST, and 3 days for ONR mooring operations.

All activities were recorded in an online Event Logger running on a local server onboard the ship, with ship positions and UTC timestamps embedded. This has been exported as a csv file and is available with the other data. Station numbers were assigned spanning both projects, such that any collection of activities was assigned a single station number. A log of visual ice observations was maintained separately, using the ASSIST protocols. This is also available as a csv file.

Table 1.1 gives an overview of the activities, and Figure 1.1 shows the whole cruise track. Sections follow with details for each station(s), then a cruise data summary concludes the report.

Table 1.1: *Cruise dates, activities, and stations.*

Date (2019)	Activity	Station #
6 Nov	Mobilize in Nome, AK	
7 Nov	Depart, transit north	
8 Nov	Transit North	
9 Nov	Deploy mooring line and sampling at Icy Cape (CODA Site 1)	001-004
10 Nov	Recover/redeploy U Delaware / ONR acoustics mooring	005
11 Nov	GOWEST Fishing in open water	006
12 Nov	Moorings, Stations, and SWIFTs at Jones Islands (CODA Site 2)	007-014
13 Nov	Moorings, Stations at Flaxman Island (CODA Site 3)	015-019
14 Nov	GOWEST fishing at the eastern shelfbreak	020
15 Nov	GOWEST fishing in the eastern basin and the mid-slope	021-022
16 Nov	Stations and redeploy at Jones Is (CODA Site 2)	022-028
17 Nov	GOWEST fishing at the mid shelf break (with full ice station)	029
18 Nov	GOWEST fishing in the mid basin (and transits West)	030-031
19 Nov	GOWEST fishing at the western basin (and transits West)	032-034
20 Nov	GOWEST fishing at the western shelf (and transits South)	035
21 Nov	SWIFT buoys and stations at Icy Cape (CODA S1)	036…
22 Nov	SWIFT buoys and stations at Icy Cape (CODA S1)	…
23 Nov	SWIFT buoys and stations at Icy Cape (CODA S1)	…133
24 Nov	Turnaround moorings at Icy Cape (CODA S1)	134-140
25 Nov	Transit south*	
26 Nov	Transit south	
27 Nov	Personnel transfer in Nome	
28 Nov	Transit south	
29 Nov	Transit south, with pause for SWIFT buoy testing in open water	
30 Nov	Transit south, with pause for SWIFT buoy testing in open water	
1 Dec	Arrive Dutch, begin demob	

* The return transit began early to account for an adverse weather forecast. This amounts to two days of lost science operations from the CODA project.

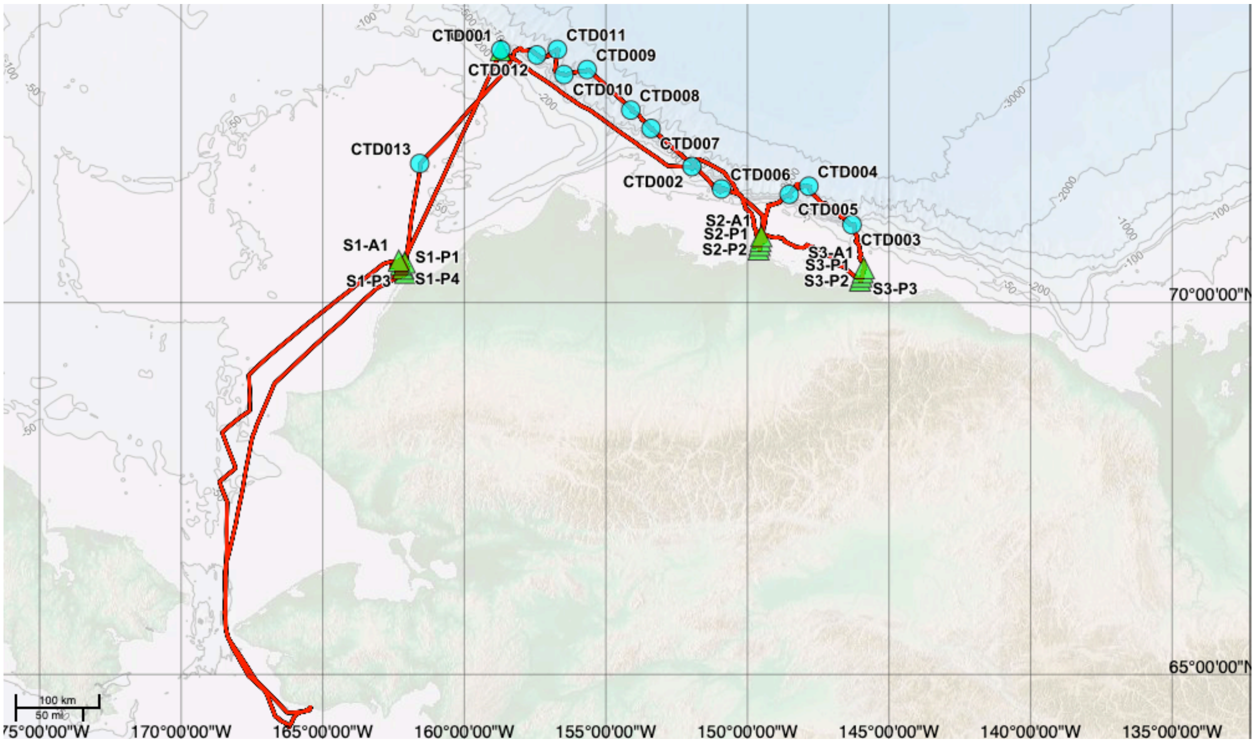

Figure 1.1: *Cruise track, with CODA mooring locations (green triangles) and ship's CTD stations (cyan circles).*

2. CRUISE NARRATIVE

9 Nov 2019, Stations 001-004: CODA S1 mooring deployments at Icy Cape

The first set of stations were conducted at Icy Cape. No sea ice was present and the winds were moderate. The GO-WEST project used the ring net to obtain a zooplankton sample for physiological experiments (respirometer).

A "sea spider" seafloor tripod was deployed at S1-A1, with a Nortek Signature500 AD2CP to measure directional waves, sea ice draft and speed, and current profiles. Moorings with seafloor pressure recorders and temperature chains were deployed at S1-P1, P2, P3. Mooring deployments went as planned and were within 5 m of intended positions.

Triplicate casts of CTD+Tu and LISST profiles were collected at each location, as well as triplicate Shipek bottom grabs. Water-column turbidity values were generally low (<50 NTU), and decreased seaward. The seabed composition was was generally sandy, with intermittent mud clumps on the seabed surface.

Casts originally used a small winch mounted on the starboard quarter, but this was determined to have insufficient reach beyond the vessel.

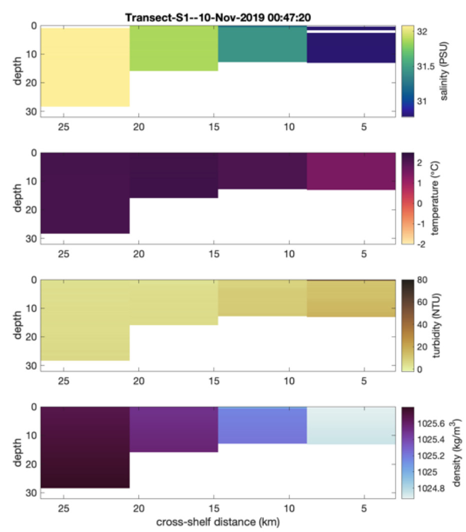

Figure 2.1: *Underway CTD transect from first visit to S1 on 9 Nov 2019.*

10 Nov 2019, Station 005: ONR mooring work
The ONR acoustics mooring was recovered exactly at the given position, after collecting a calibration profile with the ship's CTD. Water samples were taken at multiple depths for analyzing nutrients, chlorophyll, algal toxins (harmful algal blooms, HAB), trophic biomarkers and environmental DNA for the GO-WEST project. All CTD components appeared intact and in good condition. The ring net was deployed to sample zooplankton for respirometry. The new mooring was rigged and deployed at the same position later that day. After an anchor-last deployment, the mooring location was surveyed by obtaining ranges to the acoustic release at 4 different quadrants.

<u>11 Nov 2019, Station 006:</u> GO-WEST open water testing

A first trial run with the full sequence of events planned for each fishing station was conducted in open water along the slope just east of Barrow Canyon outside the ice. This sampling event served as a trial run for both deploying the SUIT off *R/V Sikuliaq* and determining the work flow for sample processing. The net caught one Arctic cod in open water on its first deployment. The full sequence of planned sampling events at GO-WEST fishing stations was executed, consisting of a ship's CTD cast with water sampling, a Calvet Net sample, calibration of the SUIT CTD, SUIT fishing, and midwater fishing (Methot Net). The Methot net was fished obliquely from the surface to 200 m to determine the composition of backscatter in the upper 200 m, which was characterized by moderate backscatter at lower frequencies in the upper 100 m (likely reflecting juvenile fish) and multiple layers of relatively strong backscatter near 100 m, likely reflecting zooplankton (Fig. 2.2). Fishing was followed by an exploratory transit into the leading edge of the offshore sea ice, traveling overnight to the CODA S2 site.

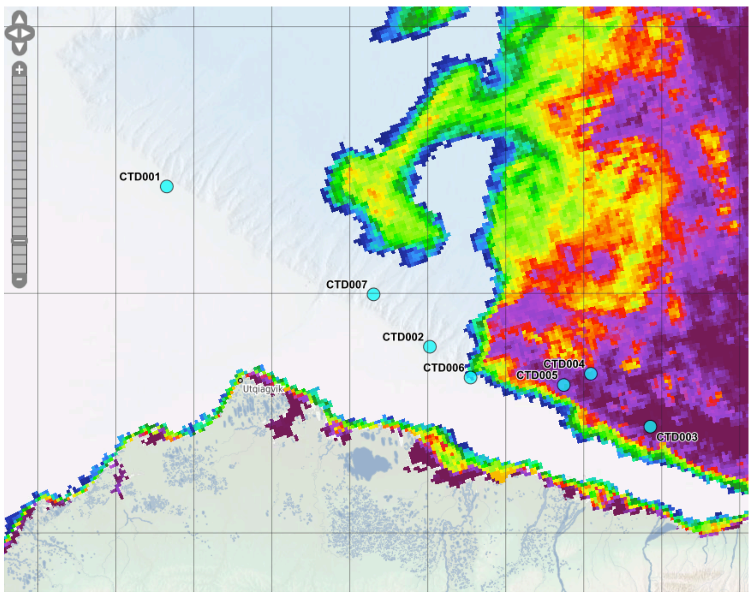

Figure 2.2: *Ice conditions during Station 006 (CTD 002).*

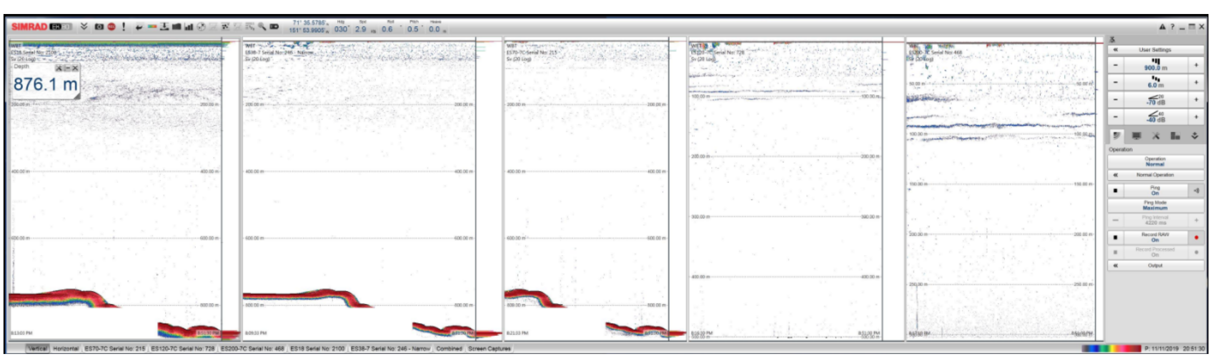

Figure 2.3: *Acoustic backscatter at station 006 at 18, 38, 760, 120, and 200 kHz (from left to right), where an oblique Methot trawl sample was obtained from the surface to 200 m.*

<u>12 Nov 2019, Stations 007-014:</u> CODA S2 mooring recoveries /deployment at Jones Islands

Stations near Jones Island were conducted in a moderate sea state (onshore wind and waves), with freezing spray. Only a small fetch of open water remained between the shorefast ice and the pack ice to the north. Pancake ice was forming at the most inshore station (mooring site S2-P1).

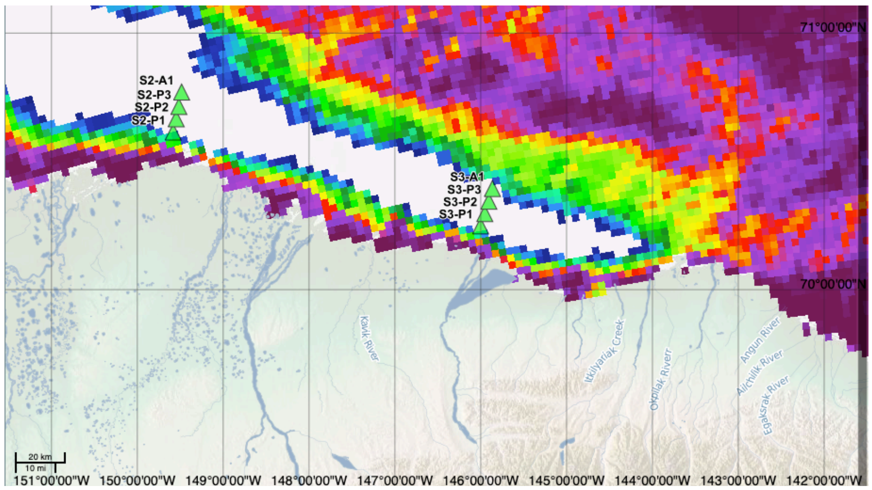

Figure 2.4: *ice concentrations during stations at CODA S2 on 12 November 2019.*

Mooring work included the deployment of another "sea spider" seafloor tripod at S2-A1, with a Nortek Signature500 AD2CP. Then, bottom-pressure moorings previous deployed in August 2019 were recovered. S2-P1 was recovered with release floats in small pancake ice, with 100% data return. S2-P2 was recovered with release floats in open water, but RBR bottom pressure did not record. Turbidity and temperature sensors at S2-P2 did record. S2-P3 was recovered by dragging with grappling hook (release fired, but floats did not surface) in open water, with 100% data return. Processed data showing the significant wave heights recorded by these instruments from August to November 2019 is shown below. There is a remarkable wave event and generally a lot of wave activity in October (at a time for which this area would normally be very quiescent because of both lack of fetch in the basin and shorefast ice). There is a notable difference in wave height between the two stations at the beginning of November, which should be explored for shorefast ice influence.

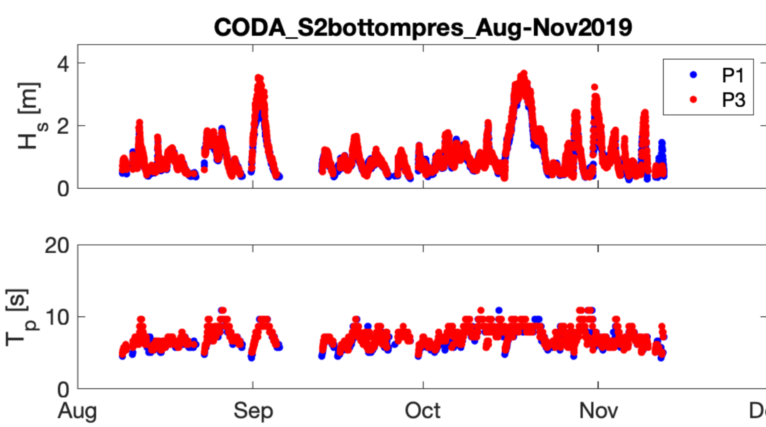

Figure 2.5: Wave statistics from processing bottom pressure records at CODA S2-P1 and S2-P2.

Four SWIFT buoys were briefly deployed during stations 007 to 014. All experienced heavy icing on masts/antenna, such that telemetry failed after a few hours and buoys had to be recovered. SWIFT 15 had a prototype heater on the Iridium antenna, which worked well to maintain telemetry for over 6 hours in heavy freezing spray, though it drew the battery down substantially. SWIFT 19 had a minimal payload and only recorded waves. SWIFT 24 did not record primary GPS, but the secondary GPS worked and has been applied to the data, which includes a standalone turbidity sensor. SWIFT 25 did not record as a result of CF card error. The SWIFTs show fresher, colder water and smaller waves near the coast (where pancake ice was forming), relative to offshore.

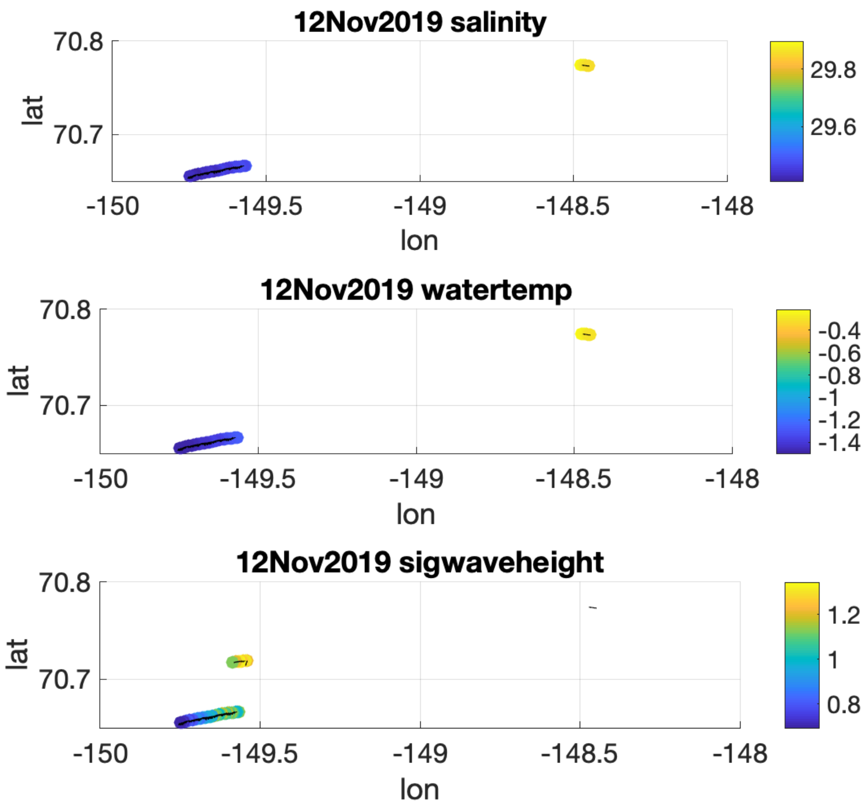

Figure 2.6: *Salinity, temperature, and wave heights measured by SWIFTs at CODA S2.*

Triplicate casts of CTD+Tu and LISST profiles were collected at each location, as well as triplicate Shipek bottom grabs. The seabed composition was a mix of sand and mud.
Casts switched to using the under-wire winch on the crane exclusively.

<u>13 Nov 2019, Stations 015-019:</u> CODA S3 mooring recovery / deployment at Flaxman Island

Stations near Flaxman Island were conducted in complete ice cover, which was a remarkable change from the previous day (see figures 2.5 and 2.7). The ice was mostly consolidated pancake at all stations, and some areas had enough structure for large cracks to form. The first live-stream outreach event was conducted during these stations.

The bottom pressure recorder mooring at S3-P1 was recovered with difficulty in full ice cover, with 100% data return. The wave results are similar to the S2 line results and are not reproduced here. S3-P1 was redeployed later in the day. The bottom pressure recorder mooring at S3-P2 was not recovered—the acoustic release communicated, but did not confirm release; grappling was unsuccessful. No attempt was made to recover S3-P3, because of failing daylight and complete ice cover; the mooring was left for the October 2020 cruise. Another "sea spider" tripod with a Signature500 was deployed at S3-A1 in heavy ice cover (30-40 cm).

Triplicate casts of CTD+Tu and LISST profiles were collected at each location, as well as triplicate Shipek bottom grabs. The seabed composition was a mostly mud.

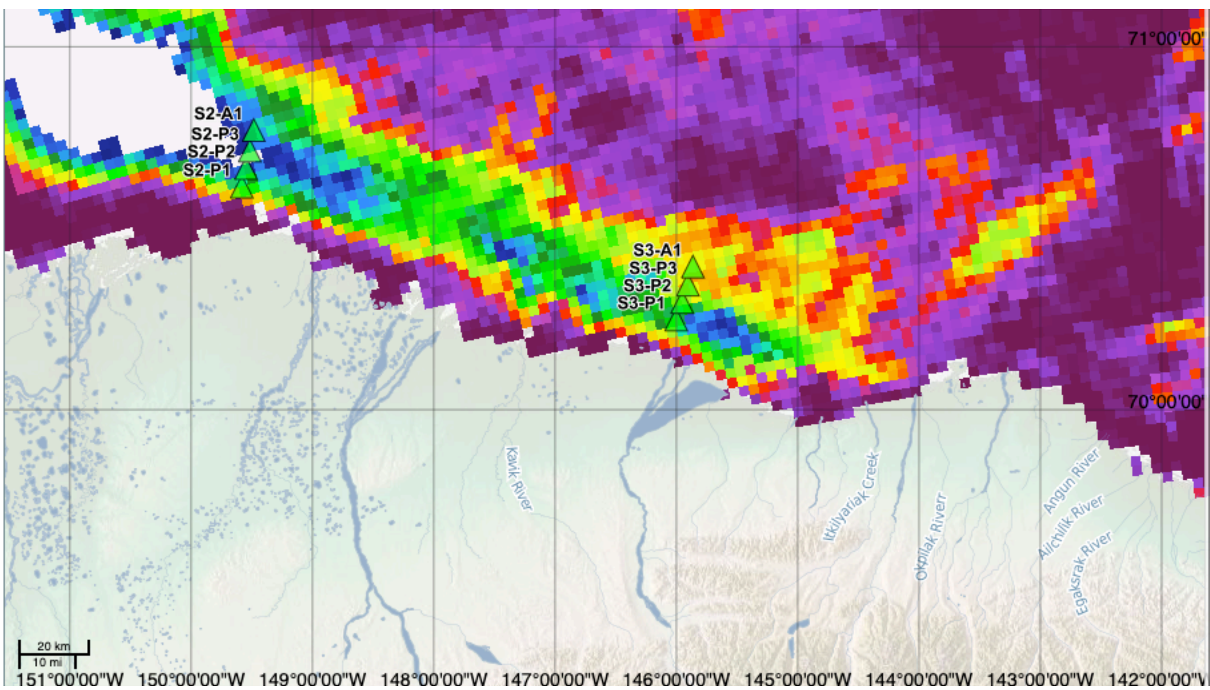

Figure 2.7*: Ice concentrations during stations at CODA S3 on 13 November 2019.*

14 Nov 2019, Station 020: GO-WEST fishing at western shelf break

The full sampling protocol was executed at station 020 along the outer shelf in approximately 165 m of water and in near 100% ice cover, mostly consisting of young grey ice floes up to 30cm thick with some moderate ridges. The SUIT was deployed for the first time in ice. Deployment was challenging due to limited open water and rapid freezing. As a result, the two nets mounted to the SUIT collected a large amount of ice that was melted using the ship's fire hose. The fish net of the SUIT caught 9 young Arctic cod.

The SUIT haul was followed by a midwater trawl in a semi-open lead using the Methot net after clearing ice with the ship's thrusters in the deployment and haul-out areas. Unfortunately, the net possibly caught some ice during deployment, behaving somewhat erratically during the tow in spite of consistent speed of the ship and wire. During haul-back, the net started rising to the surface very rapidly with approximately 130 m of wire out (30 m in 30 seconds, see Figure). As soon as it surfaced, the net caught a large amount of ice, leading to a spike in wire tension at ~11,000 lbs. The ship came to a stop immediately and retrieved the net, but the frame was damaged beyond repair, with moderate damage to the net.

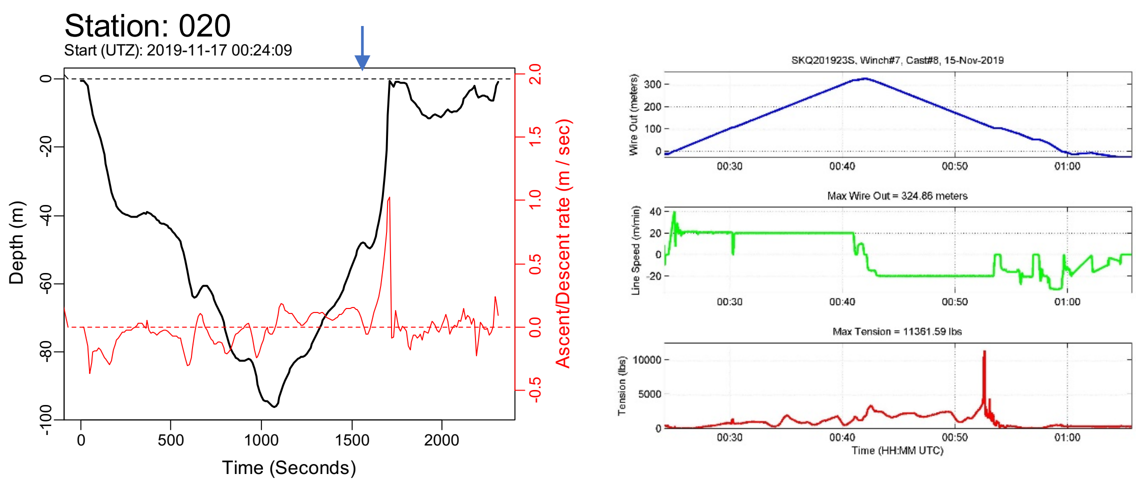

***Figure 2.8**: Depth profile of the Methot net from deployment through retrieval and ascent/descent rate (left) and winch data including tension, line speed and wire out for Method haul at station 020. Note spike in ascent rate approximately 1700 sec into the tow. The blue arrow indicates the sudden spike in wire tension recorded in the winch record.*

15 Nov 2019, Station 021-022: GO-WEST fishing at western basin (deep site)

After transiting overnight to the deep basin, we sampled two fishing stations at approximately 2400 m over the lower slope (station 021) and 1300 m in the mid-slope region (station 022). The full range of gears was employed at station 021, including a ring net to collect zooplankton for respirometry. Ice conditions at the station were dominated by young grey ice approximately 20-30 cm thick. The first SUIT deployment had to be aborted because the net did not shear properly when it entered brash ice along the edge. The second, successful SUIT haul over the outer slope resulted in a catch of 31 Arctic cod, the largest catch of Arctic cod in the SUIT to date. The SUIT haul was followed by midwater fishing with the IKMT in a mostly open lead. Following fishing, we occupied an ice station using the man basket to collect four ice cores for collecting trophic biomarker and harmful algae samples.

After transiting to the mid-slope station (022), we repeated the standard sequence of deployments without the ring net and without midwater trawling, because open water to deploy the IKMT was not available. The SUIT haul resulted in the catch of another 7 Arctic cod. After the second fishing station we transited to CODA site S2 overnight.

<u>16 Nov 2019, Stations 022-028:</u> CODA S2 mooring redeployments at Jones Islands

Stations near Jones Islands were repeated in complete ice cover (contrast the open water at these stations 4 days earlier, Fig. 2.5). Bottom pressure recorder S2-P3 was redeployed through 10 cm nilas ice, with small open water breaks. Bottom pressure recorder S2-P2 was redeployed through 15 cm consolidated pancake ice. Bottom pressure recorder S2-P1 through 16 cm ice, which was heavily loaded with sediment (top layer). This ice was notably stronger; it stopped the ship.

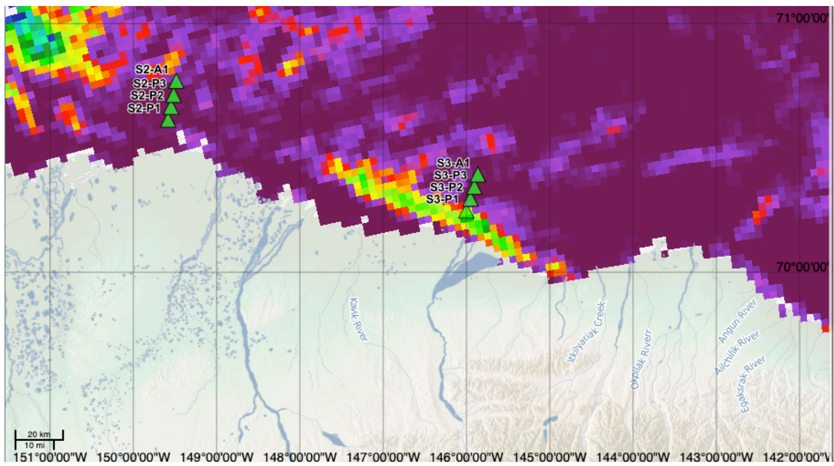

***Figure 2.9**: Ice concentration during the revisit to S2 on 16 November 2019.*

CTD+Tu casts and bottom grabs were conducted at all five stations. Ice cores were taken (via man-basket ice station) at S2-A1 and S2-P2. Two offshore stations were added to the S2 line (new sites: S2-A2 and S2-A3). The ice at the most onshore station was visibly laden with sediment at the surface, relative to other ice. A large sample was collected to melt and filter for sediments. The figure shows a cross-shore section of the hydrography.

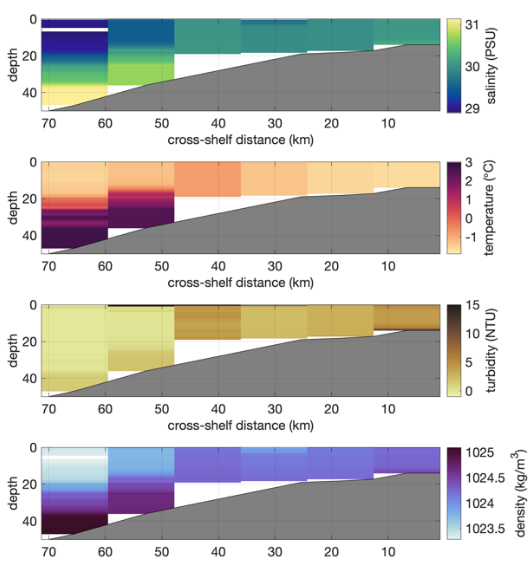

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***Figure 2.10:** Cross-section hydrographic section during the second visit to S2 line on 16 Nov.*

17 Nov 2019, Station 029: GOWEST fishing and ice station

After a night-time transit we started with an early morning GO-WEST fishing station (029) near the shelfbreak (~200 m). The area was dominated by young ice floes of approximately 15-25 cm thickness with some recently open leads that had some nilas and some open areas that were actively freezing while we were on station. Following the CTD and zooplankton sampling, but prior to deploying the SUIT, we set up a large ice station on the portside of the ship with a gangway to a 20-40 cm thick floe. Over about 4.5 hours, the RAMSES hyperspectral sensor was deployed under the ice with an L-arm and a total of 10 ice cores were taken and sectioned on the ice in preparation for melting and filtering. The material on the filters will be used to calibrate the hyperspectral light sensor (RAMSES) mounted on the SUIT (total chlorophyll), take samples for biomarkers, and test for HABs. We experienced significant drift to the west-southwest into shallower water while on station. After the ice station was completed, the SUIT was deployed in the same area under a similar ice floe.

18 Nov 2019, Stations, 030-031: GOWEST fishing in the mid shelf

We sampled two GO-WEST fishing stations in the mid-shelf region at about 1500 m (Station 030) and 1900 m (Station 031). Both areas were dominated by thinner young grey ice (10-20cm) with significant amounts of nilas between floes. The ice was thinning notably as we proceed westward along the slope. We obtained four additional ice cores using a man basket to collect organic matter for measuring biomarkers, and testing for harmful algae. After completing the ice station, we cleared a small area (‘runway’) for deploying the SUIT, but the first deployment was unsuccessful as the SUIT did not dive under the ice and was pulled along the ice edge in brash ice. We likely did not have enough wire out when entering the ice because of the short approach to the ice edge. For the second attempt we entered an open lead that was actively spreading and deployed the net while traveling along the main axis of the lead before conducting a sharp starboard turn into the ice floe. At station 030, the greatest number of Arctic cod of the entire expedition was caught, totaling 37 fish. Station 31, further down the slope, yielded 17 Arctic cod.

19 Nov 2019, Stations, 032-034: GOWEST fishing at deep stations

We continue transiting towards the west, keeping a minimum distance of 70 miles from Utqiagvik as requested by the community. After an overnight transit we start fishing at a deep station on the lower slope in ~ 2550 m of water (032), followed by a station in the mid-slope region (033, ~1550 m) and a final station 034 at ~ 2000 m. All three stations were characterized by very young, grey ice approximately 10-15 cm thick with 10-20% nilas between the thicker floes. All stations required some clearing of ice prior to deployment using the ship and the ship’s thrusters, although some small pockets of open water were present. Most deployments were successful with a relatively short ‘runway’, but one aborted SUIT haul at station 034 could be attributed to the lack of a clearly worked out deployment and communications plan (scientist on bridge to winch) and a very short 'runway'. We caught 6 Arctic cod at station 032, 2 at station 033, and 19 at station 34.

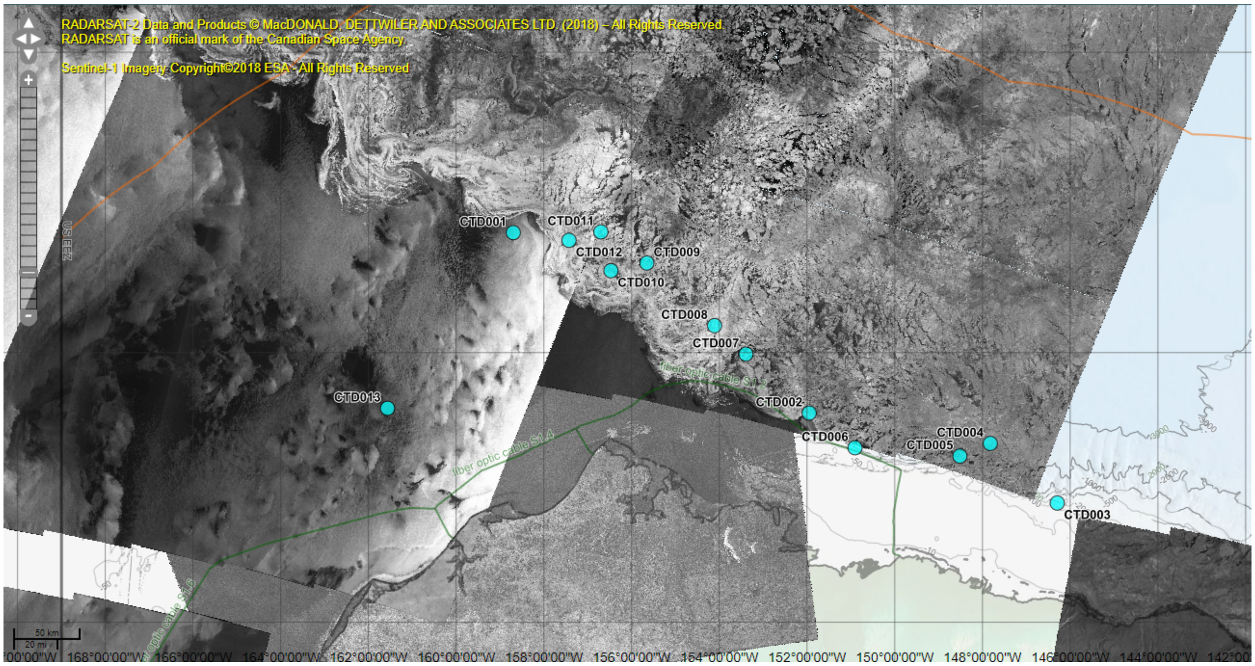

Figure 2.11: *GO-WEST sampling stations (CTD locations) sampled between Nov 10 and Nov 20, 2019, with ESA Sentinel-1 images taken 2019/11/19 around 17:00 to 18:00 UTC, and earlier Radarsat images (background). Stations 032-034 correspond to CTD009, CTD010 and CTD011.*

<u>20 Nov 2019, Station 035</u>: GOWEST fishing at shelfbreak

Final day of fishing for the GO-WEST project. The ice is getting still thinner as we transit overnight towards the shelf break. We stop at approximately 1000 m depth over the mid-shelf region in a pool with some open water and frazil ice with an adjacent ice floe about 10-15 cm thick. The open pool of water makes for a relatively easy deployment. This concludes the fishing portion of the cruise, except for opportunistic ring net deployments to collect zooplankton for respirometry experiments. Station 035 yielded 19 Arctic cod in the SUIT.

21-23 Nov 2019, Stations 035-133: CODA S1 event sampling

Drifting SWIFT buoys, moorings, and stations sampled a three-day wave event at Icy Cape. The ship arrived on site as the waves were building, reaching a maximum of 3 m significant wave height during the first day, and later settling to a sustained 2 m height. Winds and waves were from the northeast, and later the north. Substantial pancake ice was observed near the coast, at mooring location S1-P1 (water depth 13 m, distance offshore 5 km). The pancake ice at this location reduced throughout the event, becoming mostly grease and frazil ice by the second day, and entirely open water by the end of the third day. The other mooring locations farther offshore remained ice-free throughout the event.

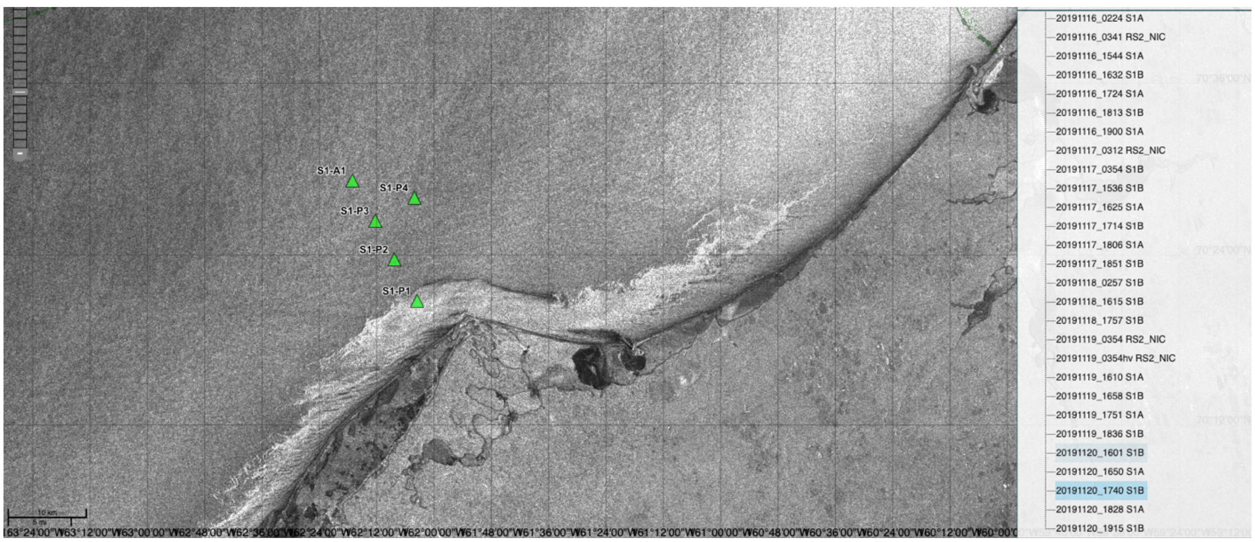

***Figure 2.12**: Sentinel-1 radar image showing ice near the shore at Icy Cape at the begin of the wave event. Mooring locations are in bright green.*

In addition to the three bottom-moorings deployed along the CODA S1 line in the beginning of the cruise, a fourth mooring was deployed temporarily during the wave event. This mooring had both a SWIFT at the surface, as well as bottom pressure and turbidity. The mooring provides an Eulerian (fixed reference frame) time series of the event, while the repeating deployments of other SWIFTs provide a Lagrangian (drifting reference frame) mapping of the event.

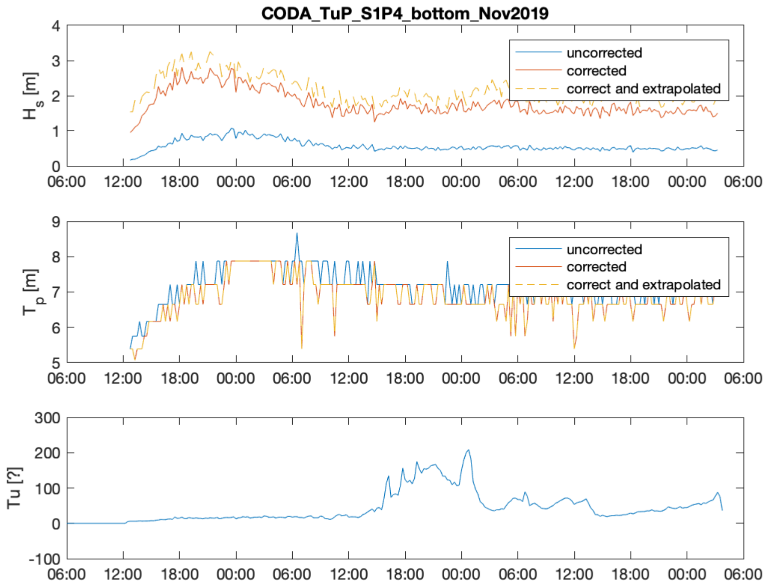

Figure 2.13: *Moored time series of wave parameters and turbidity at location S1-P4 during wave event 21-24 Nov 2019.*

The pancake and frazil ice near the coast caused attenuation of the waves, as expected. The overall pattern was a nearly two-fold reduction in wave height, which is four-fold in energy. As expected from prior work in deep water, the attenuation was strongest at higher frequencies (i.e., the short waves are preferentially damped). This pattern evolved throughout the event, as the ice became less substantial and eventually was gone altogether.

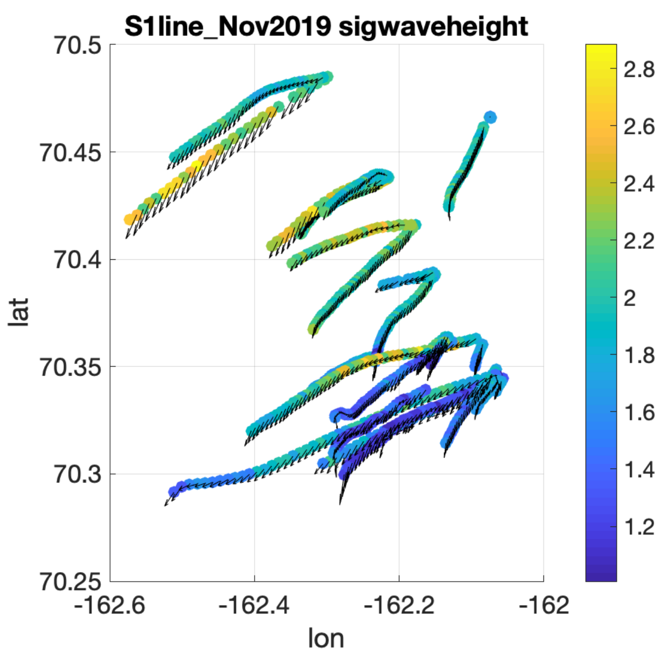

Figure 2.14: *Drifting SWIFT measurements of significant wave height [m] during the wave event at Icy Cape. Releases generally started at mooring locations, then drifted west-southwest. The coast in the bottom right corner.*

Further analysis of the wave attenuation by frequency will combine the observed wave energy spectra with classification of ice types using images collected onboard the SWIFTs and onboard the ship. This will use ice codes previously established for wave attenuation in pancake ice. A preliminary analysis using ice codes from timelapses made from the images recorded by the SWIFTs already shows a strong change in the energy at higher frequencies when ice is present.

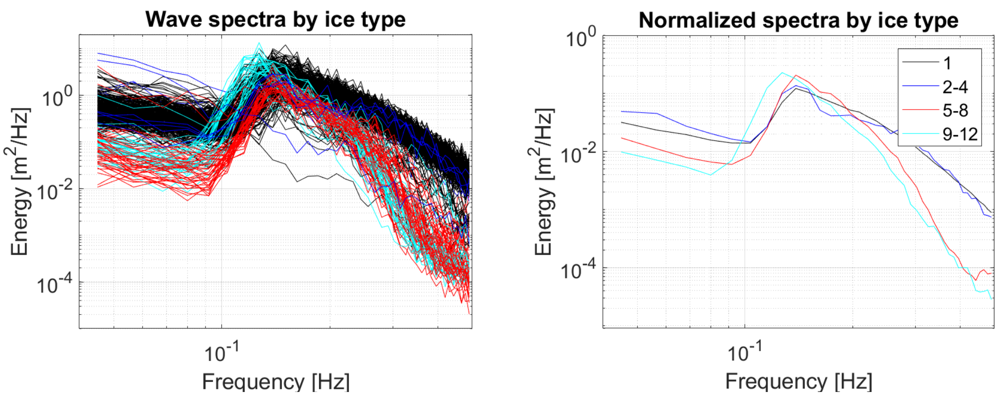

Figure 2.15: *Wave energy versus frequency for SWIFT buoys in open water and ice; (left) all spectra from SWIFTs 11-19, (right) the spectra averaged by ice type and normalized by total energy. The colors stand for: black, open water (ice code 1); blue, frazil ice (ice codes 2-4); red, small-to-medium sized pancakes (ice codes 5-8); cyan, substantial pancakes (ice codes 9-12). Spectra for undetermined ice type are not included.*

The reduction of ice observed throughout the event is likely the result of ocean heat transported and mixed into the nearshore zone. Both the surface temperatures from the SWIFTs and the depth profiles from the "underway" CTD show warm water (+ 1 deg C) offshore, relative to water at the freezing point (-1.8 deg C) near the coast. The onshore wind and waves likely transported some of this warm water towards the coast throughout the event, via processes such as Stokes drift. It may also be that the alongshore component of the northeast winds was sufficient to cause upwelling of the warm sub-surface waters offshore. Both mechanisms will be assessed in an analysis of the ice evolution. The air temperatures were cold (around -10 deg C) throughout the experiment, so the surface heat fluxes were likely always negative (heat loss from the ocean) and any melting of sea ice would therefore be the result of ocean heat. It is also possible that ice advected away from Icy Cape, rather than melting in place. This should be assessed in the drifting reference frame of the SWIFT buoys.

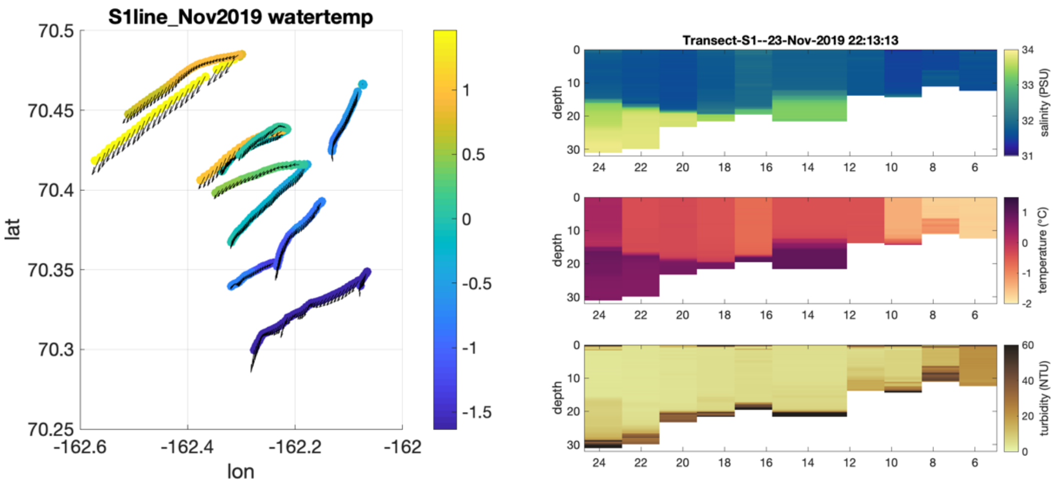

Figure 2.16*: Drifting SWIFT surface temperatures (left) and underway profiles of salinity, temperature, and turbidity versus cross-shore distance (right) at Icy Cape.*

The event at Icy Cape can be described by an evolution in time, with a dependence on cross-shore location, as shown in the following figure. The waves peak during the first portion of the event, as does the nearshore ice concentration and the associated cross-shore gradient. Likewise, the event begins with a strong cross-shore gradient in temperature that fades throughout the event.

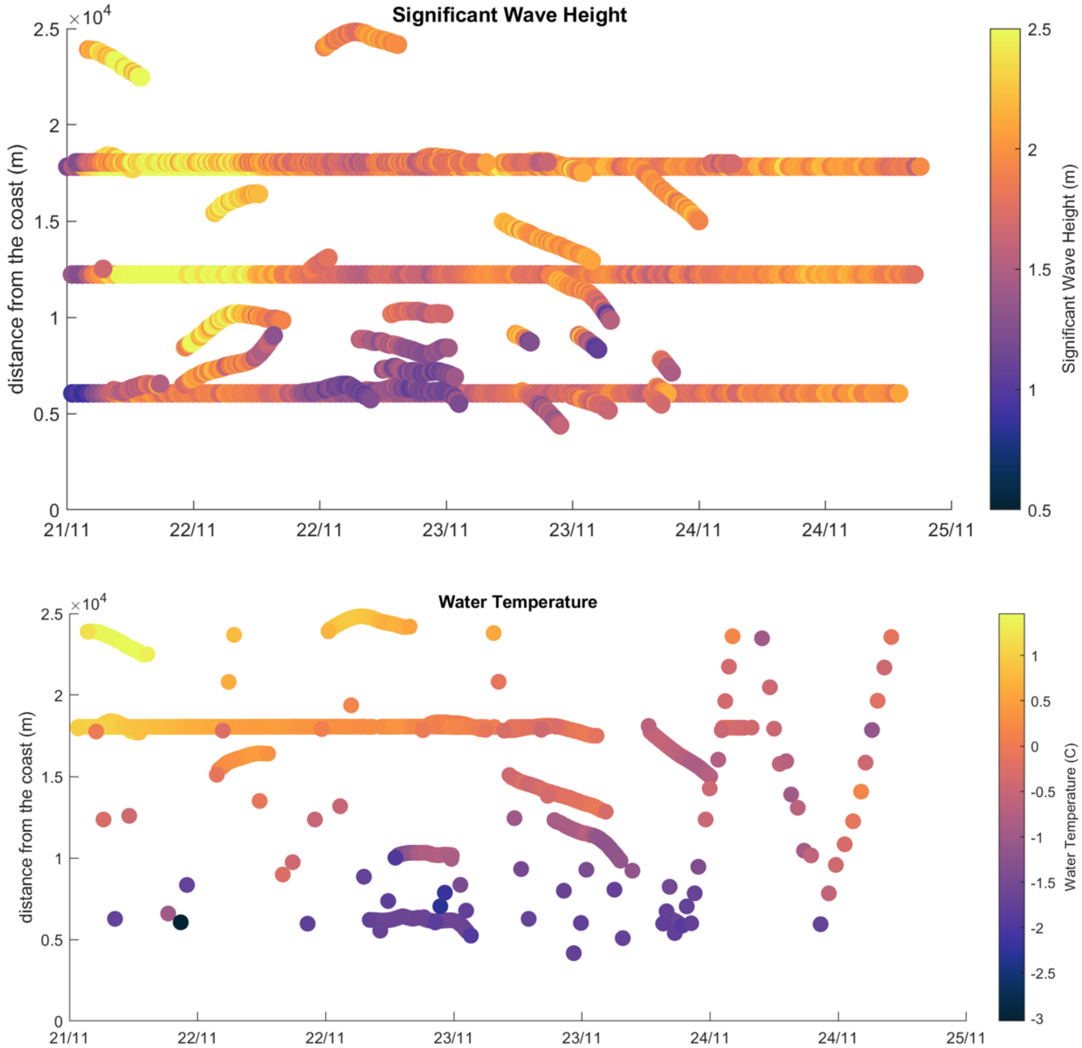

Figure 2.17: *Cross-shore distribution of wave heights (top panel) and sea surface temperatures (lower panel) as a function of time from 21 to 25 November. Wave heights are from drifting SWIFT buoys and bottom pressure moorings. Temperatures are from SWIFT buoys and the top bin of the underway CTD.*

24 Nov 2019, Stations 134-140: CODA S1 mooring turnarounds

As the wave event at Icy Cape finished, the temporary mooring (S1-P4) was recovered, and the other moorings (S1-P1,P2,P3,A1) were recovered and redeployed. All of the recoveries went smoothly. Processed wave results from the bottom pressure 'P' moorings show a strong wave event (Hs ~ 4 m) earlier in November, as well as the progression of the event just sampled with SWIFTs and the ship. The mooring results show a consistent regional gradient, in which there are larger waves farther offshore. This is most likely a result of wave refraction across the shoals and changes in the fetch. Note that the moorings do not provide much information on the high-frequency waves, because the bottom pressure recordings do not capture the short waves at the surface.

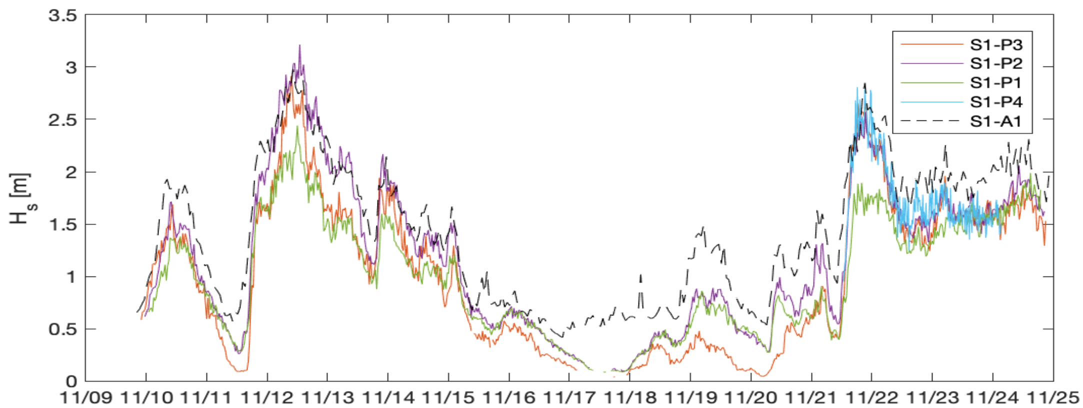

***Figure 2.18**: Wave results at S1 moorings throughout November 2019. The wave event sampled with SWIFTs and the ship is the final three days of the record.*

The Nortek Signature500 AD2CP at S1-A1 shows similar wave signals as the 'P' moorings. The current profiles measured by this instrument show strong synoptic variations that appear related to large scale pressure gradients of the Bering Strait inflow and atmospheric forcing. When water levels are elevated, flow is to the northeast. When water levels are depressed, flow is to the southwest. These synoptic pressure signals are consistent with observations at all of the 'P' moorings. The currents are almost depth-uniform, with minimal vertical shear. This suggests that SWIFT surface drift velocities might be used as a proxy measure of current profiles during the wave event sampling.

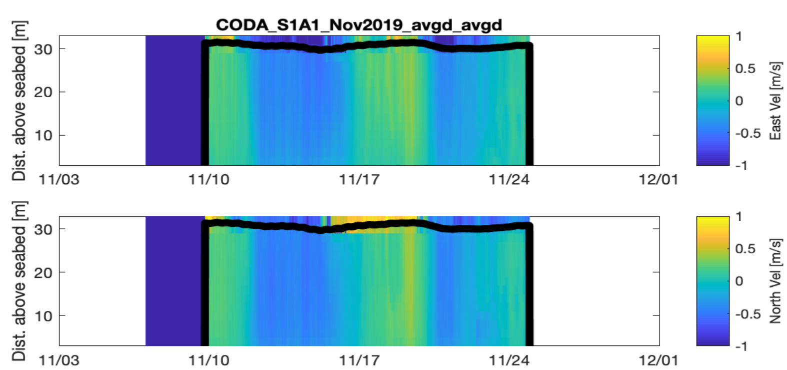

***Figure 2.19**: Current profiles (colors) and bottom pressure (black line) observed by the Nortek Signature500 at S1-A1.*

The moored temperature signals at Icy Cape show signals consistent with both the surface temperature evolution and with the intrusion of warm, salty water near the bottom at the outer moorings (as also shown by the underway CTD). There is no direct evidence that the intrusion made it to the shallower sites, but it may be that the increase in temperatures nearshore (at S1-P1) is the result of this intrusion mixing shoreward. Alternatively, warm surface waters may have advected shoreward.

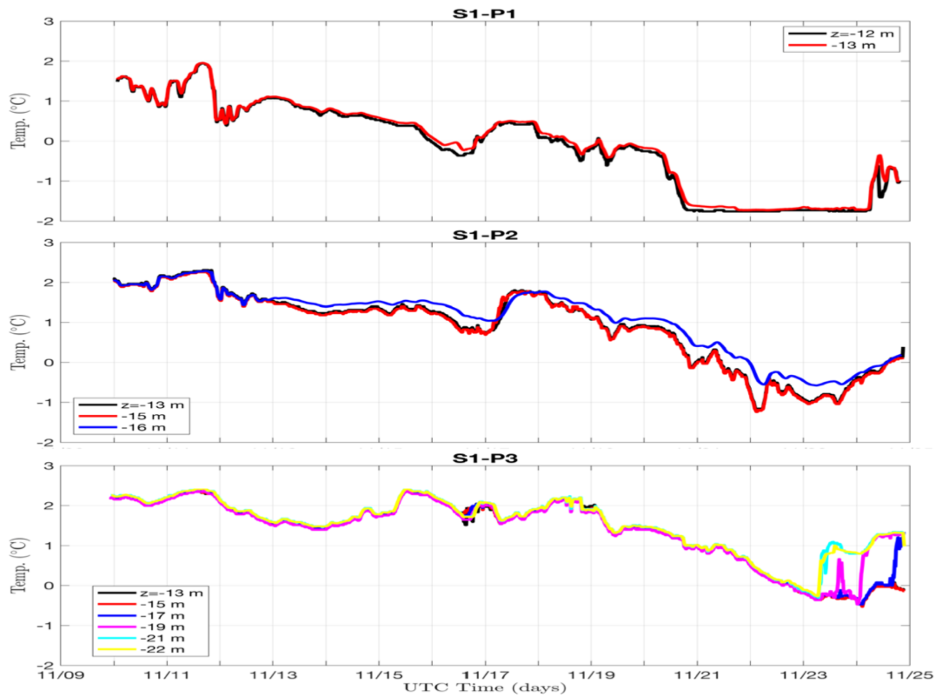

Figure 2.20: *Temperature versus time at the Icy Cape moorings. Depths in the legend are measured from the surface.*

A zoom in on the Signature500 data at S1-A1 shows that the currents changed from southwest to northeast at the end of the event, after the ice mostly melted near the shore and simultaneous with the bottom-water intrusion. (Note that currents are described as direction towards, whereas wind and waves are described as direction from.)

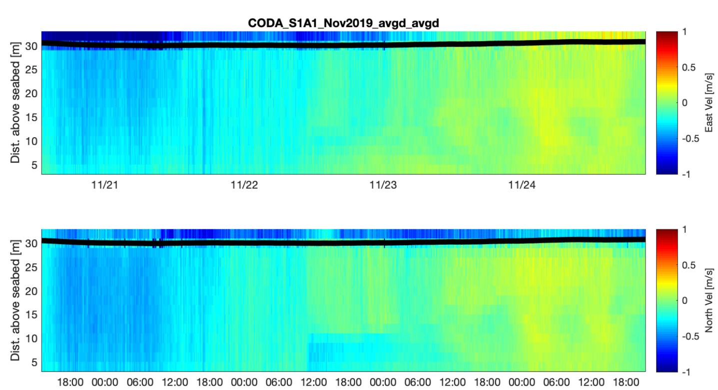

Figure 2.21: *Zoom-in on the current profiles at S1-A1 during the Icy Cape wave event for 21 to 24 Nov 2019.*

Section 3: RESULTS & SYNTHESIS

Underway data summary

The ship's underway data collected continuously throughout the cruise, expect for clogging of the flow-through seawater measurements during ice transits.

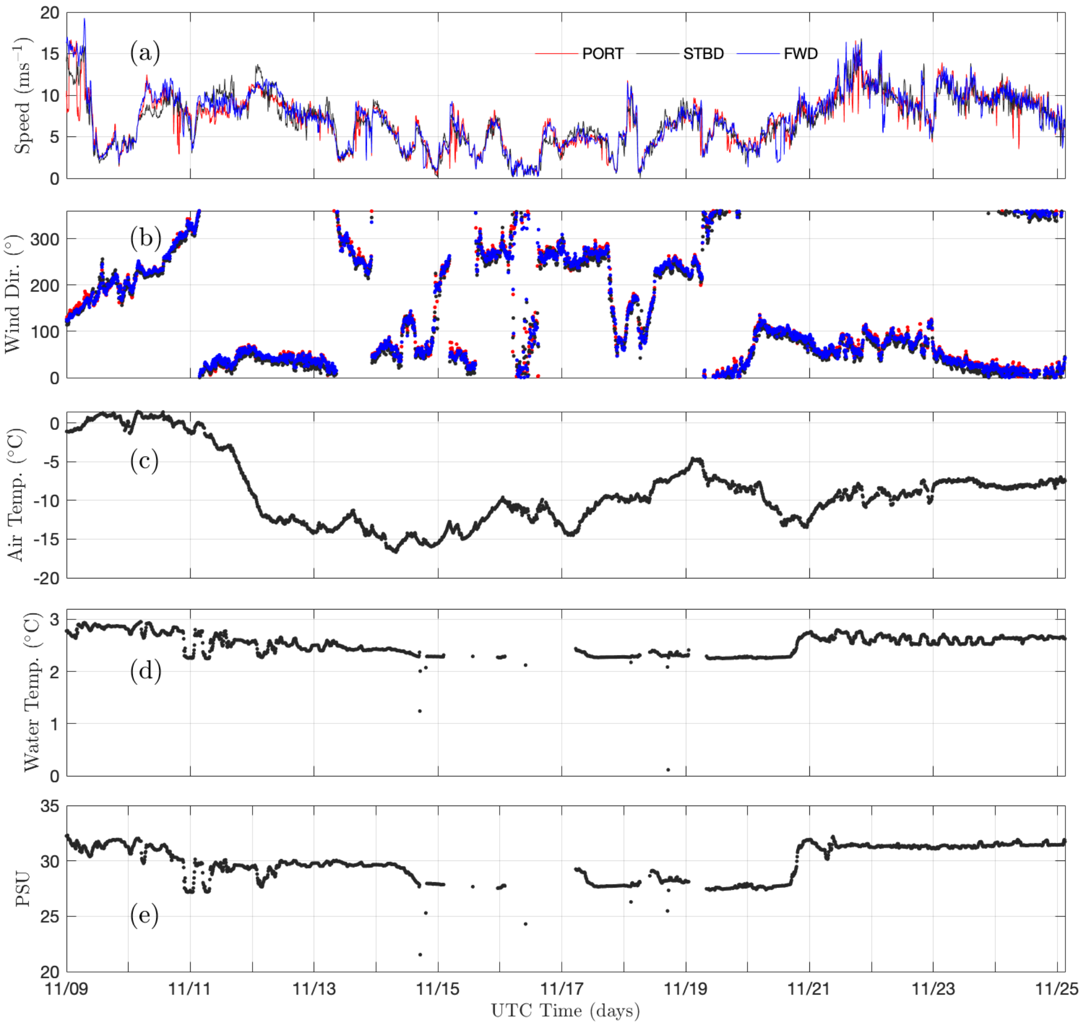

Figure 3.1*: Underway measurements of wind speed, wind direction, air temperature, water temperature, and salinity during the operational portion of the cruise (i.e., Icy Cape to Icy Cape). The water temperatures and salinity have gaps when the seawater pump becomes clogged with sea ice.*

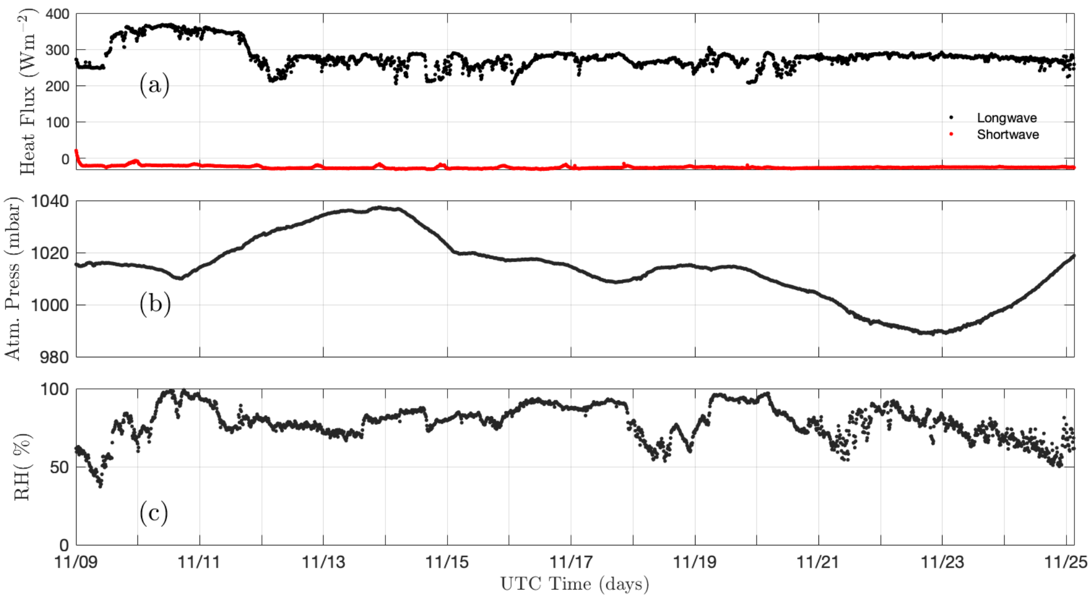

Figure 3.2*: Underway measurements of downwelling longwave and shortwave radiation, barometric pressure, and relative humidity during the operational portion of the cruise (i.e., Icy Cape to Icy Cape).*

Ice observations

The science party conducted hourly ice observations throughout the cruise, following the ASSIST/ASPECT protocols. This resulted in a csv file (available separately). A remarkable amount of pancake ice was observed, relative to previous work in the Western Arctic. This is of course related to the increasing prevalence of waves.

The estimated ice thickness has a correlation with both the air temperatures (which is a strong control on the flux of heat and thus the formation of ice) and with the skin temperature of the ice, as measured by the ship's forward-looking radiometer. Further analysis may connect a total estimated net heat flux with the ice observations, and with climatology of autumn ice formation. This would include satellite products.

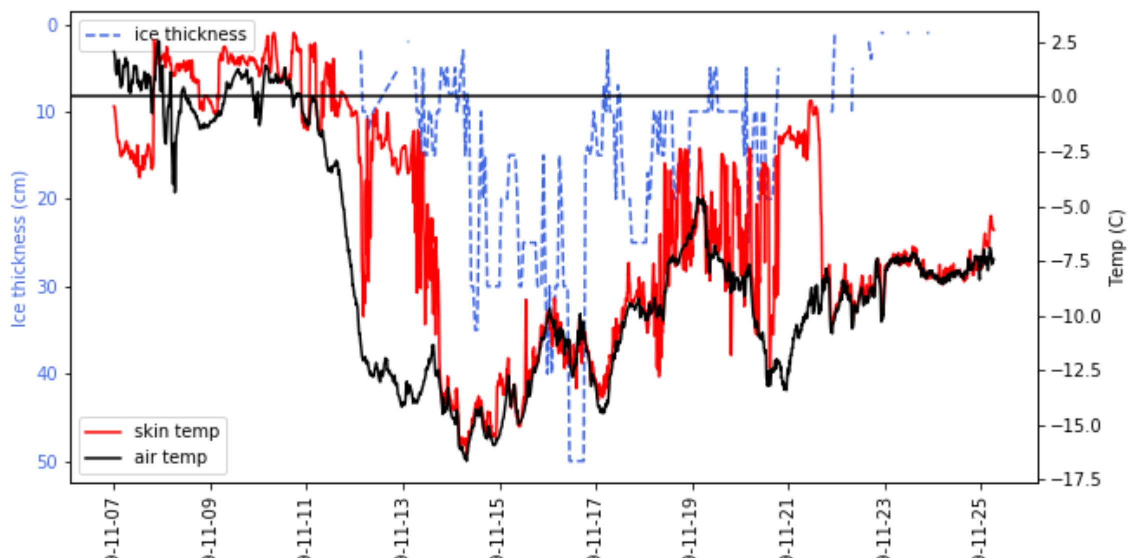

Figure 3.3*: Full time series of estimated ice thickness, air temperatures, and skin temperatures.*

CODA results and plans for analysis

Several themes emerge from the CODA observations, all related to the overall effects of an increasing wave climate and an expanding open water season along the Arctic coast. The first two topics might be suitable for an overview paper in a less technical journal, the later topics are more appropriate for technical journal submissions.

1) The CODA mooring observations show a tremendous amount of wave activity in October, which is much later in the season than baseline wave climatology would suggest. This is an increase in the total exposure of the coast line, which might be analyzed in an equilibrium shoreline framework. This analysis might include updated climatology from long-term wave measurements in the Beaufort Gyre Observing System. This analysis might also explore the differences in waves measured at Jones Island sites S2-P1 and S2-P3, which are likely related to newly formed sea ice.
2) The underway ice observations show a prevalence of pancake ice. This should be related to the increasing wave climate, and could be assessed as shift in the dominant ice formation process in the western Arctic. Incorporating the observed heat fluxes along the cruise track could identify times/regions in which ice formation was likely fastest.
3) The wave event at Icy Cape shows strong spectral attenuation of waves in pancake ice. Using the coded SWIFT and shipboard images, the attenuation coefficients might be segregated into different ice types. This would be useful for tuning numerical wave models, and for testing viscoelastic parameterizations for wave attenuation in sea ice. The overall domain is small (~20 km), and the ice-covered portion even smaller (~5 km) so the wind input can likely be ignored in this calculation.
4) The evolution of the sea ice during the Icy Cape event may be addressed using heat and salt budgets to determine what caused the disappearance of sea ice at the end of the event. Possible explanations are advection of the sea ice out of the domain, or an influx of heat from offshore (including possibly as bottom-water intrusion). This analysis might be linked to the wave analysis (above) in a single publication, particularly if the wave dynamics have any control on the heat budget.
5) Mooring and underway CTD stations show strong turbidity signals at the seabed that are correlated with wave forcing. Analysis may show evolution of the seabed and sediment transport throughout the Icy Cape event, perhaps in contrast to longer measurements at the other sites (including a turbidity spike in October at S2-P2).

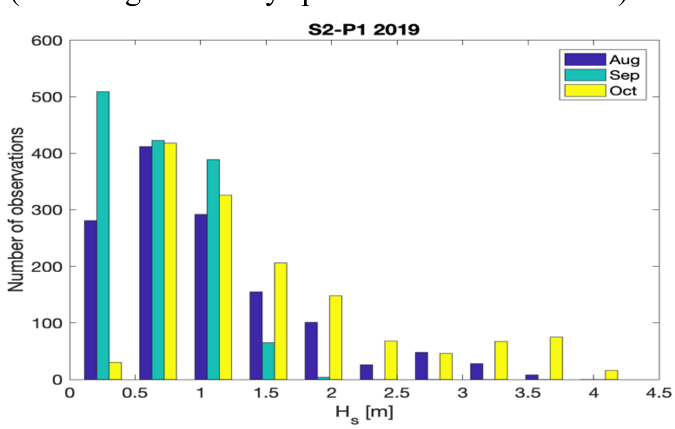

Figure 3.4: *Histogram of wave heights observed at S2-P1, showing higher occurrence of large waves in October.*

Wildlife Observations

Methods

The United States Fish and Wildlife Service (USFWS) conducted marine bird surveys for the entire duration of the cruise whenever conditions were suitable. Surveys were conducted using U.S. Fish and Wildlife Service protocols. Observations were made from the port side of the bridge during daylight hours while the ship was underway. The observer scanned the water ahead of the ship using hand-held 10x binoculars if necessary for identification and recorded all birds and mammals within a 300 m, 90° arc from the bow to the beam. We used strip transect methodology and four distance bins extending from the vessel: 0-50 m, 51-100 m, 101-200 m, and 201-300 m and recorded the animal's behavior (flying, on water, foraging). Rare birds, large flocks, and mammals beyond 300 m or on the starboard side (off-transect) were also recorded but will not be included in density calculations. Birds on the water, or actively foraging were counted continuously. Flying birds were recorded during quick 'Scans' of the transect window, with scan intervals based on ship speed (typically every 65 seconds). Observations were entered directly into a GPS-integrated laptop computer using the program DLOG3 (A.G. Ford Consultants, Portland, OR). Location data was also recorded automatically at 20 sec intervals, providing continuous records on weather, Beaufort Sea State, ice coverage, glare conditions, fog conditions, and overall observation conditions.

Preliminary Results

We completed 53 transects over 43.85 hours and observed 404 individual birds of 11 different species. Northern fulmar was the most abundant bird overall. This species was mainly observed in the Bering Sea but one individual was observed in the northern Chukchi at 72.7913 N 158.5944 W. Black guillemot was the most abundant bird species observed in ice-dominated habitats and the fourth most abundant bird species overall. Perhaps the most interesting bird observations were of short-tailed shearwaters on two different occasions flying over pack ice farther than two kilometers from open water. Analyses of data for density estimates and addition to the pelagic seabird database is pending.

Table 3.1: Marine birds recorded on transect (<300 m) 7 Nov-26 Nov

Common Name	Scientific Name	Count
Common eider	*Somateria mollissima*	1
Unidentified eider	*Somateria spp.*	1
Unidentified duck	*Anatinae (gen, sp)*	1
Black Guillemot	*Cepphus grylle*	20
Unidentified murrelet	*Brachyramphus spp.*	4
Unidentified alcid	*Alcid spp.*	3
Ivory gull	*Pagophila eburnea*	4
Black-legged Kittiwake	*Rissa tridactyla*	30
Glaucous gull	*Larus hyperboreus*	47
Unidentified gull	*Laridae spp.*	8
Pacific loon	*Gavia pacifica*	1
Northern fulmar	*Fulmarus glacialis*	104
Unidentified dark shearwater	*Ardenna spp.*	3

Pelagic cormorant	*Phalacrocorax pelagicus*	1
Total		228

Table 3.2: Marine birds recorded off transect (>300 m) 7 Nov-26 Nov

Common Name	Scientific Name	Count
Unidentified eider	*Somateria spp.*	74
Unidentified duck	*Anatinae (gen, sp)*	4
Black Guillemot	*Cepphus grylle*	32
Thick-billed murre	*Uria lomvia*	1
Kittlitz's murrelet	*Brachyramphus brevirostris*	1
Unidentified murrelet	*Brachyramphus spp.*	2
Ivory gull	*Pagophila eburnea*	17
Black-legged Kittiwake	*Rissa tridactyla*	9
Glaucous gull	*Larus hyperboreus*	14
Unidentified gull	*Laridae spp.*	7
Northern fulmar	*Fulmarus glacialis*	2
Short-tailed shearwater	*Ardenna tenuirostri*	5
Unidentified dark shearwater	*Ardenna spp.*	6
Pelagic cormorant	*Phalacrocorax pelagicus*	2
Total		176

Table 3.3: Marine mammals recorded both on and off transect 7 Nov-26 Nov

Common Name	Scientific Name	Count
Ringed Seal	Pusa hispida	41
Unidentified Seal	Phocidae spp.	4
Polar Bear	Ursus maritimus	3
Unidentified Pinniped	Pinnipedia spp.	1
Total		49

GO-WEST results

The overall goal of the Go-West expedition was to test the hypothesis that entrainment of young Arctic cod into the sea-ice habitat in the Chukchi and Beaufort seas during autumn is significant, and hence sea-ice association is an important survival strategy for Arctic cod. We sampled Arctic cod and its prey in the ice-water interface layer along with high resolution profiles of sea-ice and surface water properties with a Surface and Under-Ice Trawl (SUIT). We recorded backscatter of fish and zooplankton in the water column with the Sikuliaq's EK80 echosounder, and sampled pelagic communities with two midwater trawls (Methot trawl and IKMT) and vertical zooplankton nets (CalVET and ring net). In addition, we performed respiration measurements on potential zooplankton prey species of Arctic cod.

A conductivity-temperature—depth probe equipped with a rosette water sampler (CTD) sampled vertical profiles of temperature, salinity and fluorescence and was used to collect water samples for the analysis for chlorophyll a concentration, nutrient concentrations, trophic biomarkers and harmful algae (HAB).

During four ice stations, we sampled the sea ice for the same parameters (except nutrients), and performed hyperspectral light measurements needed to derive ice algae biomass from hyperspectral profiles obtained from a sensor mounted on the SUIT (Fig. 3.5). Three stations (021, 030 and 035) were performed by two scientists deployed on the ice with the ship's man basket, allowing for the collection of several ice cores within less than 1 hour. A longer ice station (6 hours) was occupied at station 029, allowing for both ice-core sampling and spectral measurements at 2 different sites. The sea ice at all 4 ice stations was young and between 15 and 43 cm thick, with a thin (0-6 cm) snow cover.

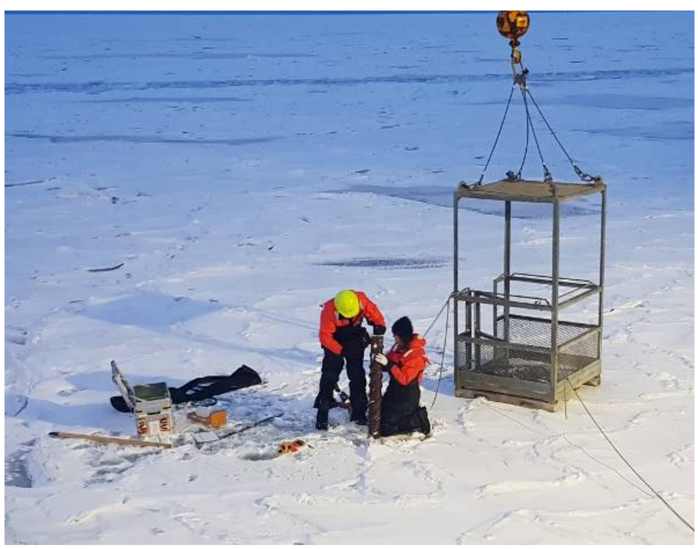

Figure 3.5. *Go-West participants R. ten Boer and S. Maes performing a short-time ice station with the Sikuliaq's man basket.*

Altogether, we completed 11 SUIT stations (1 in open water, 10 under ice), 4 ice stations and 3 midwater trawls (Fig. 3.6). All SUIT deployments were successful, expanding Sikuliaq's capability of advanced scientific operations in ice-covered waters. Arctic cod were caught at all SUIT stations, totalling 153 fish (Fig. 3.7). Otherwise, the catch composition of the SUIT was dominated by the sea angel *Clione limacine* and the ice amphipods (*Onisimus* spp., *Gammarus wilkitzkii*; Fig. 3.8). Most fish appeared to be first-year juveniles between 6 and 8 cm in size, pending age determinations. Fish abundance increased with increasing ocean depth, sea-ice draft (Fig. 3.9), and abundance of the ice amphipod Onisimus spp.. The mesozooplankton community in the upper 50 m was dominated by the copepod Metridia longa. Respiration experiments indicated that Metridia and, surprisingly, *Calanus glacialis* from shelf stations were in an active metabolic state.

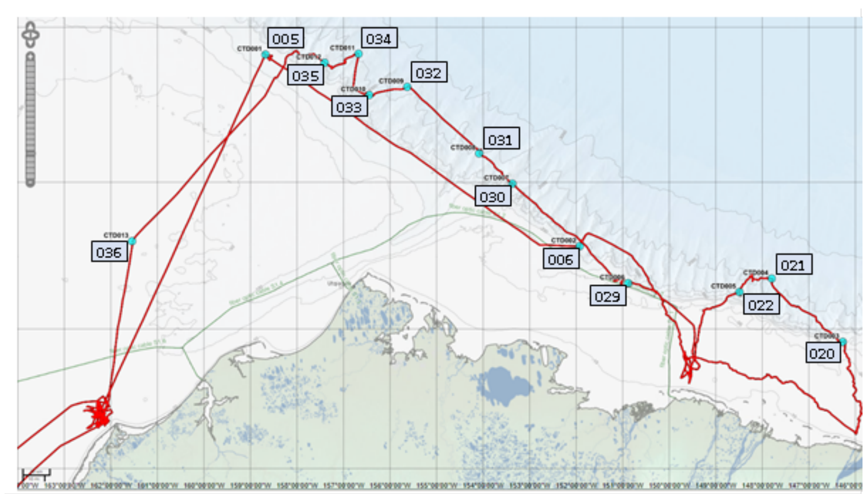

Fig. 3.6. *Working area and track chart of R/V Sikuliaq, Cruise SKQ201923S with fishing stations and ship CTD station numbers indicated.*

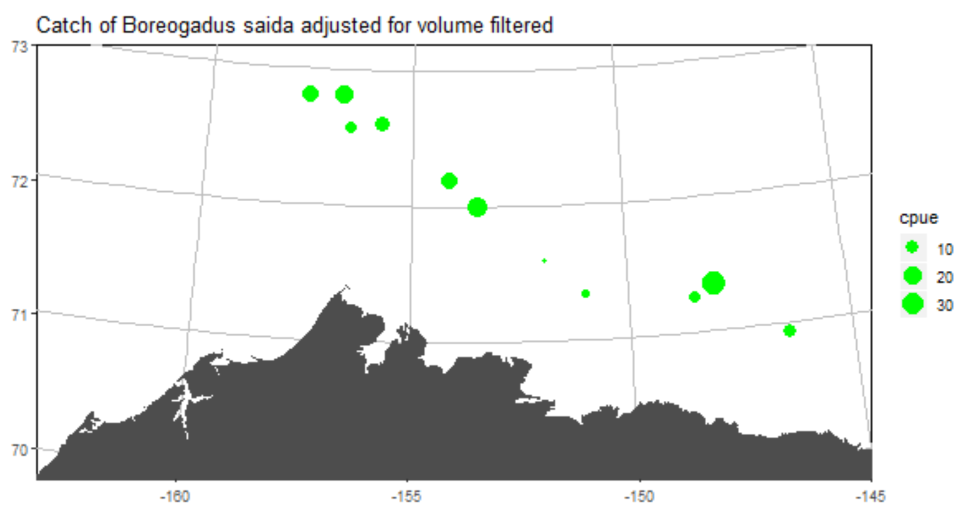

***Figure 3.7**: Catch-per-unit-effort (CPUE in numbers per average volume filtered) of Arctic cod (*Boreogradus saida*) at 11 SUIT fishing locations occupied during the cruise.*

Chlorophyll a concentrations were low (< 0.5 mg m-3) in the water column. Conversely, visual inspection of ice core filters indicated that ice algal biomass had already begun to accumulate in the autumn sea ice. The trophic relationships between ice algae, zooplankton and sea-ice fauna and Arctic cod will be analyzed in detail based on hundreds of biological samples, including diet and trophic biomarker samples. Investigations of otolith microchemistry and population genetics studies on each sampled fish will help elucidate their origins and migration patterns. Preliminary results of this expedition support our hypothesis that juvenile Arctic cod associate with sea ice in autumn and show that prey is available to sustain them at the onset of winter.

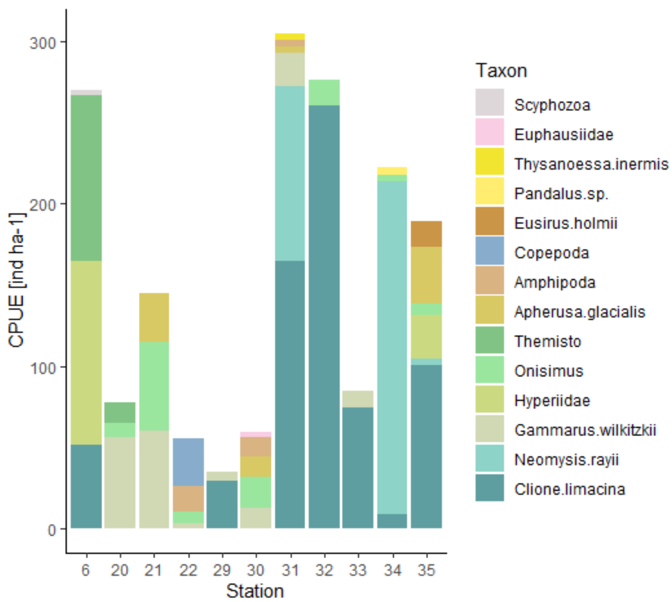

***Figure 3.8**. Catch per unit effort (CPUE) of macrozooplankton species caught with SUIT at each station*

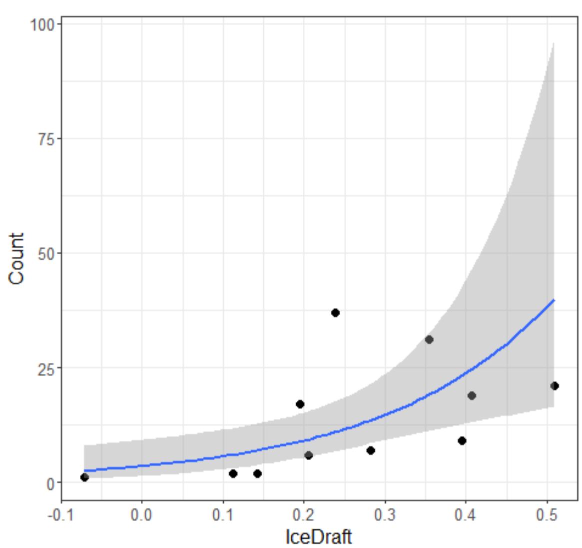

***Figure 3.9.** Relationship between catch numbers of Boreogadus saida and ice draft. Negative binomial regression fit (blue lines with 95% confidence bands), suggests a significant increase in catch numbers with increasing ice thickness (R^2=0.40, p=0.0013). The regression model scales catch numbers by sampling effort (surface area sampled by SUIT).*

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4. ADDITIONAL INFORMATION

Table 4.1: Cumulative list of all science activities during the cruise.

Science Gear	Yesterday	Overall
Mooring Deployment	0	15
Mooring Recovery	0	9
LISST	0	121
CHUMP (underwire) CTD	0	123
NISKI	0	32
Ring Net (group of 3)	0	1
Ring Net (single dip)	0	12
Calvet Net	0	11
Shipek Core	0	169
SUIT	0	14
IKMT	0	3
SWIFT deployment	0	33
SWIFT recovery	0	33
Sikuliaq CTD	0	13
Hand CTD	0	10
Ice Station	0	6

Table 4.2: Science Party

Name and institution	Project	Role
Jim Thomson (UW)	CODA	Chief Sci.
Nirnimesh Kumar (UW)	CODA	PI
Lucia Hosekova (UW)	CODA	postdoc
Alex de Klerk (UW)	CODA	Technician
John Guillote	CODA	photographer
Becca Guillote	CODA	writer
Mika Malila (UW)	CODA	Grad student
Lettie Roach (UW)	CODA	postdoc
Emily Eidam (UNC)	CODA	PI
John Malito (UNC)	CODA	Grad student
Rob Mills (JASCO)	CANAPE	Technician
Hauke Flores (AWI)	GO-WEST	PI
Franz Mueter (UAF)	GO-WEST	PI
Alexei Pinchuk (UAF)	GO-WEST	PI
Apasiri Klasmeier (AWI)	GO-WEST	Grad student
Michiel van Dorsson	GO-WEST	Technician
Sarah Maes (KUL)	GO-WEST	PhD student
Ron ten Boer (WMR)	GO-WEST	Grad student
Nadezhda Zakjharova (?)	GO-WEST	Grad student
Jared Weems (UAF)	GO-WEST	Technician
Lorena Edenfield (BOEM)	BOEM	Technician
Kristina Kunz (AWI)	GO-WEST	Researcher
Brendan Higgins (USFWS)	USFWS	Seabird Obs
Ethan Roth (UAF)	SKQ	SKQ mar tech
Bern McKiernan (UAF)	SKQ	SKQ mar tech
Steve Roberts (UAF)	SKQ	SKQ mar tech

Figure: Science party. Photo by John Guillote.

Glossary:

AD2CP: Acoustic Doppler Current Profiler (2nd generation)

CODA: Coastal Ocean Dynamics in the Arctic (project name)

CTD: Conductivity, Temperature, Depth sensor

GO-WEST: Sea-ice association of polar cod and its prey in the western Arctic Ocean (project name)

IKMT: IK Mid-water Trawl

LISST: Laser In Situ Sizing Transmissometer

Niskin: a sea water collection bottle (triggered at depth)

SUIT: Surface Under Ice Trawl

SWIFT: Surface Wave Instrument Float with Tracking

Acknowledgements:

The captain, crew, and marine technicians onboard R/V Sikuliaq worked tirelessly to support the science. Their efforts underpin everything achieved during this research cruise.

The National Ice Center (NIC) provided essential ice charting products daily, which were used both for safe navigation and for targeting science measurements. These products will continue to be valuable during the analysis phase.

The CODA participants were funded by the National Science Foundation office of Polar Programs and Ocean Sciences (Award ID 1818485 to Dr. Thomson of U. Washington, and Award ID 1913195 to Dr. Eidam from U. North Carolina). Additional support for coastal modeling and forecasting was provided by the Office of Naval Research program on Global and Arctic prediction (Award to E. Rogers at the Naval Research Lab).

The GO-WEST participants were funded by the Arctic Research Icebreaker Consortium (ARICE), with addition support from the US Bureau of Ocean Energy Management (BOEM).

The U. Delaware mooring was supported by the Office of Naval Research program in Ocean Acoustics.

The U. of Miami undertook the collection of ice and wave radar data throughout the cruise.