

# ONR Sea State DRI Cruise Report

## R/V Sikuliaq, Fall 2015 (SKQ201512S)

Revision date: 8 November 2015 (DRAFT)

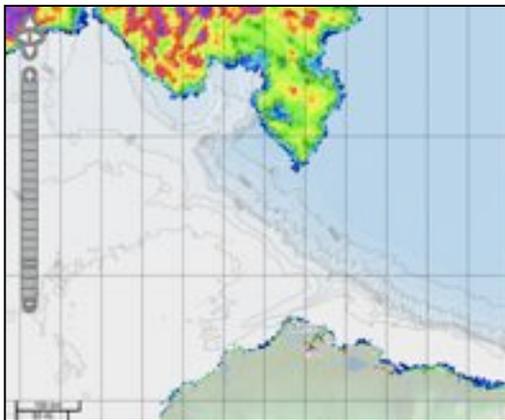
Chief scientist: Jim Thomson



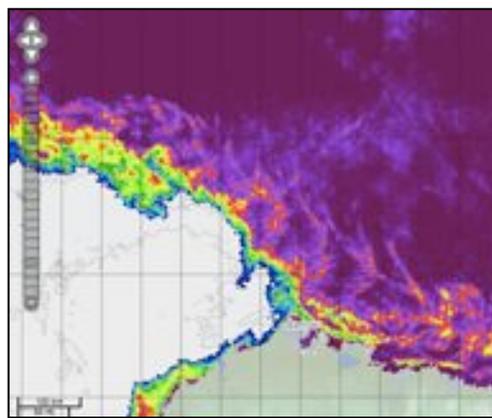
### Overview

The primary observational component of the Sea State Department Research Initiative (DRI) was a research cruise to the western Arctic Ocean in the fall of 2015 (1 Oct to 10 Nov). The goal was to observe the fall ice advance and the interactions with winds and waves. The cruise plan was driven by the detailed objectives laid out in the science plan (published in 2013 as APL technical report #1306). That document and more information are available at the project web page: [http://www.apl.uw.edu/project/project.php?id=arctic\\_sea\\_state](http://www.apl.uw.edu/project/project.php?id=arctic_sea_state). This cruise report is a narrative of the measurements and activities completed during the research cruise, as well as preliminary findings.

Our measurements suggest that waves play an important role in the fall freeze-up of the Beaufort and Chukchi Seas, especially near the ice edge facing the prevailing easterly winds. Pancake ice formation was common, and, in one particular event, extended for almost 100 nm. Our measurements suggest that ocean heat also is important, and that mixing can delay or temporarily reverse the formation of first year ice. Eventually, strong heat loss to the atmosphere becomes the dominant process, especially during off-ice wind events, and large expanses of the ocean freeze rapidly. As intended, we observed a significant advance in ice cover, and we sampled several wave/wind events.



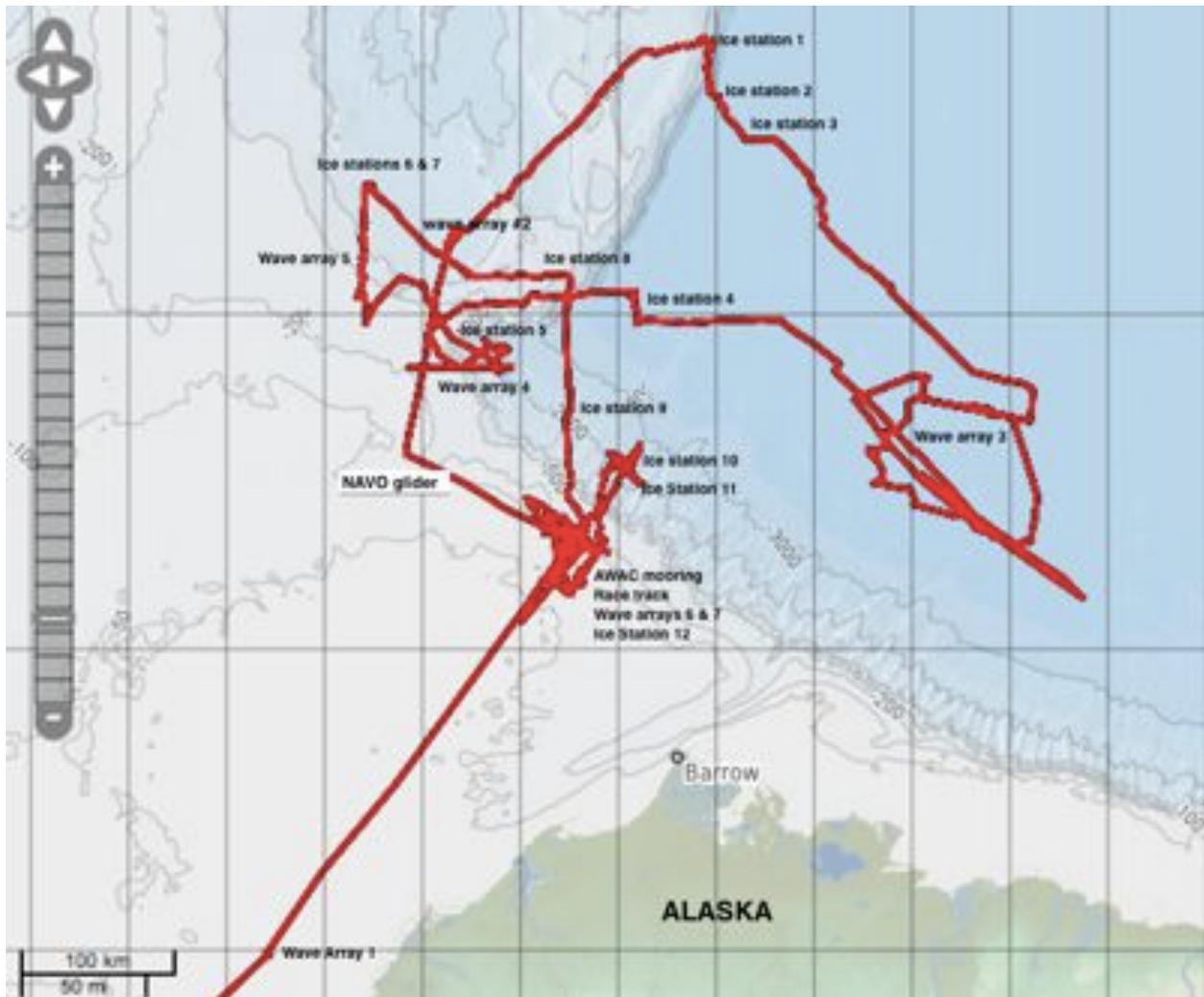
**AMSR2 ice conc. on 1 Oct 2015**



**AMSR2 ice con. on 1 Nov 2015**

## Cruise track

An overview of the cruise track is shown below. The narrative text that follows includes more detailed views of each leg along the track. The track plan was constantly updated throughout the trip according to weather/wave forecasts and ice conditions.



**Cruise track and stations**

## Cruise log summary

A detailed event log, available as a csv file was maintained for all activities onboard the ship, including the time (UTC) and position of each activity. An overview of the daily activities is below. The narrative text that follows groups the activities chronologically.

28 Sep	Staging (Nome), install cameras, LiDAR and flux system
29-Sep	Mobilize (Nome), crane on vans and heavy gear
30-Sep	Mobilize (Nome), depart at 21:00 ADT
1-Oct	Transit
2-Oct	Wave array #1 (open water inter-calibration), transit
3-Oct	Deploy AWAC mooring, UAS tests, NAVO glider recovery
4-Oct	Wave array #2 (ice edge w/ flux stations), ROV testing
5-Oct	SIMS survey north thru nilas ice sheets
6-Oct	Ice station #1 ("Ben"), with NASA UAVSAR overflights
7-Oct	Ice station #1 completed
8-Oct	Ice stations #2 ("potato") & 3 ("cake")
9-Oct	SIMS survey southeast ice edge
10-Oct	Wave array #3 (combined array for pancake ice at southeast ice)
11-Oct	Wave array #3 (combined array for pancake ice at southeast ice)
12-Oct	Wave array #3 (combined array for pancake ice at southeast ice)
13-Oct	Wave array #3 (combined array for pancake ice at southeast ice)
14-Oct	SIMS survey westward into ice
15-Oct	Ice station #4 ("mixed nuts"), NRL flight #1 along E-W transect
16-Oct	Wave array #4, NRL flight #2 completing E-W transect
17-Oct	Wave array #4 & Ice station #5 (Peter's floe)
18-Oct	Wave array #5 & flux line for off-ice winds
19-Oct	Ice station #6 ("Ethan")
20-Oct	Ice station #7, evening SIMS survey eastward
21-Oct	Ice station #8, NRL flight #3 (E-W transect + station)
22-Oct	Ice station #9 ("goldilocks"), evening SIMS survey southward
23-Oct	Wave array #6 (line near AWAC mooring), NRL flight #4
24-Oct	Wave array #6 (line near AWAC mooring), NRL flight #5
25-Oct	Recover AWAC mooring, begin six flux stations and UCTD along a "race track" survey
26-Oct	Race track survey at advancing ice edge, ROV & LiDAR ice survey at point #6
27-Oct	Race track survey at advancing ice edge, ROV & LiDAR ice survey at point #6
28-Oct	Ice station #10 (w/ fluxes)
29-Oct	Ice station #11 (w/fluxes)
30-Oct	Ice station #12 (w/fluxes) at race track point #1
31-Oct	Wave array #7, partial race track survey
1-Nov	Wave array #7, partial race track survey
2-Nov	Race track survey at advancing ice edge, ROV & LiDAR ice survey
3-Nov	Race track survey at advancing ice edge,
4-Nov	Transit with underway CTD until 71 N
5-Nov	Transit
6-Nov	Transit
7-Nov	Transit
8-Nov	Transit
9-Nov	Transit
10-Nov	Arrive Dutch Harbor
11-Nov	Demobilize (Dutch Harbor)
12-Nov	Demobilize (Dutch Harbor)

## Underway measurements

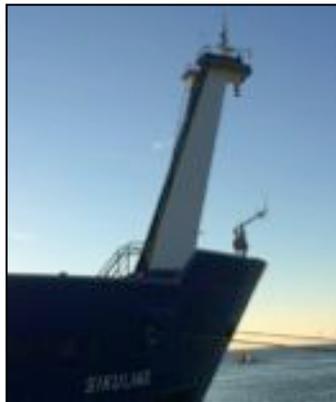
Numerous measurements were made continuously throughout the research cruise:

- 32 days (559 hours) of visual ice observations (ASSIST & ASPeCt protocols)
- 228423 ice camera images
- 467 physical ice samples
- 1520 nm of SIMS (Sea Ice Measurement System) transects
- 4292 casts of the underway CTD (Conductivity, Temperature, Depth)
- 478 hours of flux measurements from the meteorological mast
- 35 days of wave and ice measurements from the ship's Rutter radar (2,325,000 images)
- 169 weather balloon (radiosonde) launches
- 487 hours of covariance flux measurements from two meteorological masts
- 95 high-quality 1-hour turbulent flux stations (table available as .csv and matlab files)
- continuous radiative energy fluxes, surface temperatures, and ceilometer (cloud height)
- continuous scanning LiDAR measurements of waves and ice forward of the bow
- 10 hours of underway (mobile) LiDAR scans of sea ice topography off port beam
- 18 hours of stereo video (3D wave mapping) acquisition

These measurements provide context for the various modules, as well as datasets for synthesis of the overall air-ocean-ice system in autumn.



**Underway CTD**



**Flux measurements at the bow**



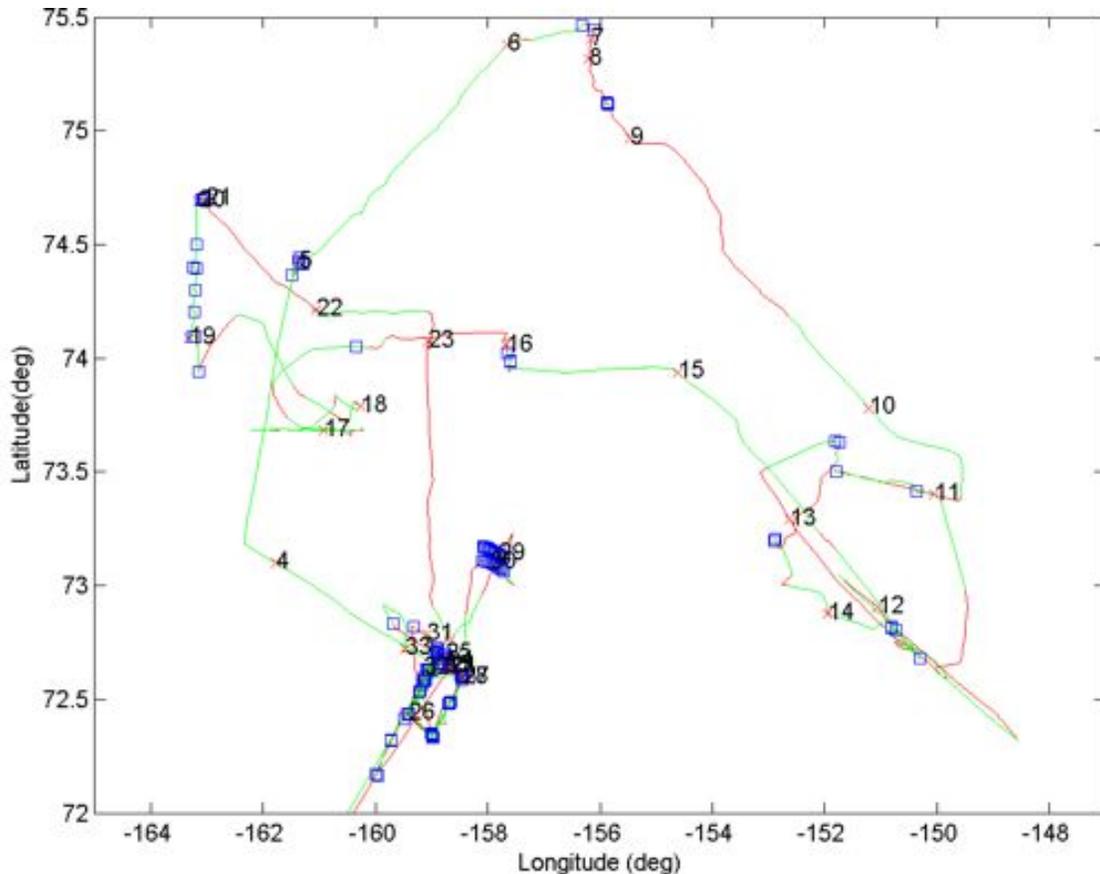
**Weather balloons**



**SIMS (Sea Ice Measurement System)  
suspended from port crane**



**Rutter radar antenna (center)**



**The Sea State track showing 60-min flux stations (blue squares) and times of ship-relative wind direction < 60 degrees (i.e., good underway fluxes) (green). Numbers show the October date at 00 UTC.**

### **SIMS (Sea Ice Measurement System) Sampling (underway)**

Indirect sampling of sea ice thickness through electromagnetic induction sounding (EMI) and ranging techniques was accomplished with the SIMS rig suspended on the aft port crane during most underway transits from Oct 5 – 23. Only in high wind conditions and in open water transits were SIMS operations curtailed. Data were collected at a 1 Hz sampling rate. At a nominal ship speed of 4 knots, this temporal sampling rate corresponds to a spatial sampling interval of 2 m. The SIM system was also instrumented with a FLIR thermal imaging camera that acquired a thermal record of sea ice and sea water temperature at a 1 Hz sampling rate. Preliminary assessment of the thermal record indicates that very thin ice, below the sensitivity threshold of the EM method, may be empirically quantified by its temperature signal.

## **Satellite remote sensing**

Satellite images were provided by the US National Ice Center, DLR in Germany, the Bedford Institute of Oceanography, the Department of Fisheries and Oceans Canada, CSTARS at the University of Miami, and CNR (Consiglio Nazionale per la Ricerca) in Italy. Over 400 images were collected and made available in near-realtime for operational use onboard the ship. The operational use was greatly enhanced by a map server running locally onboard the ship. Screen shots from the map server are included in this report.

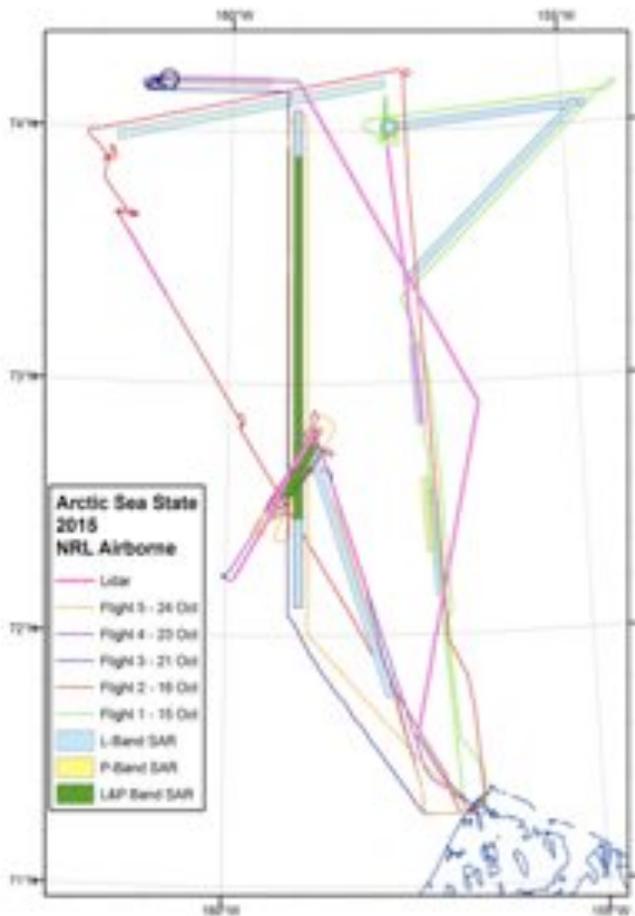
On a daily basis, the satellite remote sensing opportunities were evaluated looking ahead 2-3 days based on the cruise future planning for measurements and locations. If Radarsat-2 planned acquisitions provided by the National Ice Center and the Department of Fisheries and Oceans Canada did not match the cruise plans, a separate request was developed and submitted to NIC who in turn would submit such requests to MDA. On a shorter lag period of 24-36 hours, plans were also developed between U. Victoria and the ship for TerraSAR-X acquisitions. Often these plans were coordinated with CSTARS at the University of Miami for either TerraSAR-X and/or CosmoSkyMed. Acquired and processed data were retrieved by the ship from land-based FTP sites or via email as attachments. Additionally, SAR acquisitions of opportunity were obtained from the Sentinel-1 and ALOS-2 SAR missions. All available processed imagery was displayed on the MapServer to be used for navigation, and assessment and possible replanning of current measurement plans. The ftp site at the University of Victoria is the primary location of acquired remote sensing imagery.



**TerraSAR-X satellite orders**

## Airborne Remote Sensing

In addition to the satellite acquisitions, airborne LiDAR, SAR, and visible images were collected by NRL operating a Twin Otter aircraft (5 missions on 15, 16, 21, 23, 24 Oct) and UAVSAR data were collected by NASA operating a Gulfstream aircraft (1 mission on 6 Oct).



**NRL aerial surveys**

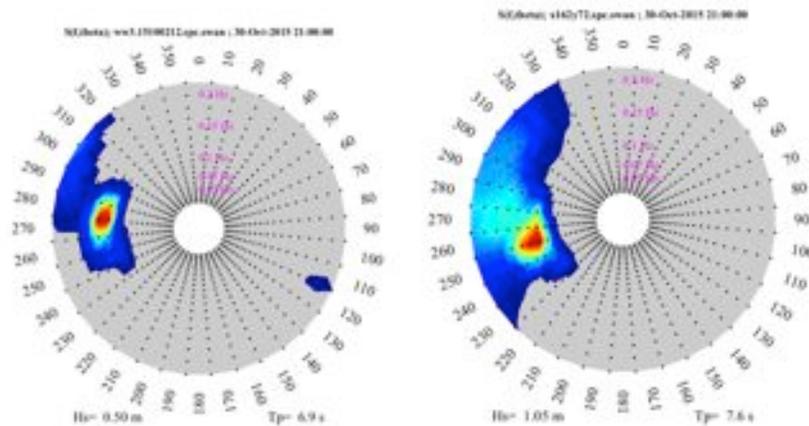


**NASA UAVSAR flight lines**

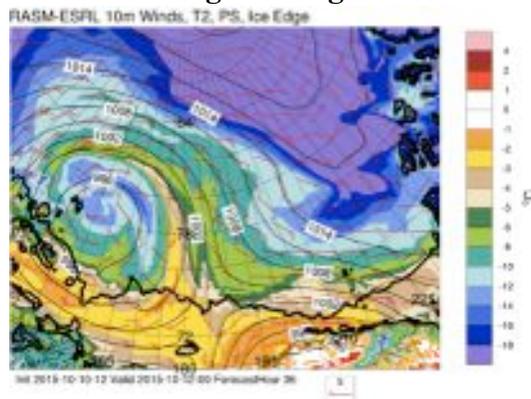
## Wave and Weather Forecasting (daily)

Daily wave and weather forecasts were used to adjust plans throughout the cruise and balance priorities. Wave forecasts were especially useful during design of the wave experiments. The forecasts were briefed at the Plan of the Day (POD) meetings held each evening on the ship. The wave forecasts were based on wave model simulations from three sources. The first was a nested modeling system run from the ship, a development version of the open-source community model, WAVEWATCH III(R). The second wave modeling system used was provided by ECMWF, using the WAM model. The third wave modeling system was another system using WAVEWATCH III run by personnel at NRL-Stennis, using a system that was established for support of the USCGC Healy cruises in the summer of 2015. Weather forecasts were provided by NOAA, using both the standard GFS system and an experimental RASM forecast with higher resolution. ECMWF forecasts were also used, in particular the EPSGRAM output for specific locations. The weather forecasts were essential for identifying periods off active ice formation and for ensuring a balance of data collection during on-ice, off-ice, and along-ice winds.

Well prior to the cruise, automated systems were created to deliver the outputs from the second and third modeling systems, and the ice and wind inputs necessary to run to the ship-based modeling system, to the ftp site administered by the University of Victoria. This proved to be a highly reliable method for aggregation and transfer of data.



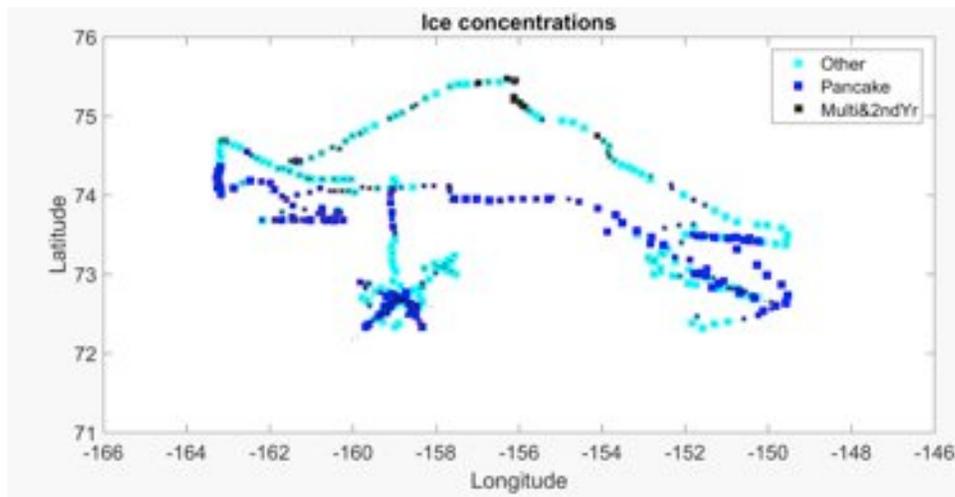
**Two forecasts of directional wave spectrum used in planning Wave Array #7.  
Left: Briefed at Oct 25 POD meeting. Right: Briefed at Oct 30 POD meeting.**



**Surface winds and isobars from NOAA RASM forecast during Wave Experiment #3.**

### **Ice observations (underway)**

Visual ice observations were made every hour from the bridge and logged using the ASSIST protocols. These logs are available as daily csv files, as well as a summary of the entire record. The small scale of the pancakes, ice cakes and brash (meters to submeters) are well below the resolution of satellite radar images. Occasional ground truth from sampling is noted in the record whenever possible. The summary of ice observations along the track shown below therefore offers a new view of the ice edge region only available from near surface observations. The figure shows the observations divided into Pancake ice, Multiyear ice and Other (consisting mostly of Nilas and broken young ice forms into brash and small cakes). A previously unreported finding for this region from this cruise is the widespread occurrence of newly forming pancake ice as shown in the figure throughout the ice edge region observed on the cruise track. These observations will be closely compared with the remote sensing products (satellite and airborne radars and LiDAR) obtained simultaneously over the study area to identify distinct signatures associated with the surface observed ice types. Pancake ice formation, because of its close association with waves, will present a significant challenge to predictive models of the ice edge advance and eventual configuration of the seasonal ice pack. However, pancake ice is characteristic of the “new normal” Arctic ice pack.



**Map of ice type determined from hourly visual observations**



**Examples of visual ice observations**

### **Physical Ice sampling (underway and stations)**

Direct sampling of the ice was carried on throughout the voyage whenever the ship stopped or slowed, and was carried out 24 hours a day. At each stop two samples were taken. Frazil ice was sampled by a frazilometer, a tube closed at one end by fine mesh, which was lowered below the surface and pulled up through the frazil layer so that the volume of frazil collected could be converted into a volume per unit area of sea surface (equivalent to a thickness). Sea water was allowed to drain out of the frazilometer then the sample collected in a plastic bottle. Pancake ice samples were collected by an over-the-side landing net. During the early days of the cruise when the ice consisted of small pancakes embedded in frazil, this brought in representative whole pancakes, but later the cakes sampled were the smaller cakes or fragments of ice broken up by the ship's reamer. In every case efforts were made to obtain samples that were as representative as possible of the visually observed dominant thickness nearby, and sometimes more than one sample was taken with the results collected in different bottles according to thickness.

The samples were analyzed for salinity using a conductivity meter, and most of them were packaged up in small sample bottles for later analysis of O18/16 ratios, which will mainly indicate the fractional meteoric (snow) origin of the ice. It was always found to be the case that when pancake and frazil were collected at the same site, the pancake ice had the lower salinity. This was because the pancakes were growing out of the frazil by the frazil freezing-on, and the cake would start draining salt through newly forming brine drainage channels once the pancake structure was established. Typical salinities were 10-12 PSU for frazil and 7-10 PSU for pancakes. As the autumn progressed the pancake ice grew thicker and became more like a continuous ice cover, with many pancakes rafted and cemented together in groups ("cemented pancakes") and then cemented together further to yield vast ice sheets. New ice was now adding itself at the bottom by the congelation process so that frazil was no longer evident. The later samples therefore tended to be solid pancakes or fragments of pancake. The salinity in the solid pancakes was found to be inversely correlated with thickness, again indicating that in the older thicker pancakes the brine drainage process had been going on for longer. The thickest ice cakes had salinities of 5-6 PSU and thicknesses of 20-25 cm.

In addition to under-way sampling, physical ice samples were taken from the following sources:

- a) Systematic cross-sectioning of a small number of the pancakes that were recovered whole, to study salt distribution through the pancake;
- b) Ice samples from 10 cm sections of ice cores done during ice stations;
- c) Ice samples from refrozen melt pools, again during ice stations, to test whether the pools had thawed through to the ocean before refreezing;
- d) Ice samples from frost flowers. These are delicate crystals which sometimes form on new dark nilas and look like small white flowers strewn over the surface. They grow by a wicking process from the mushy nilas beneath, and they are highly saline, giving frost flower-covered ice a bright return on SAR imagery. Two of the samples taken had salinities of 89 and 92 PSU, about three times that of the Arctic Ocean surface water.
- e) Ice samples from riming of ship structures (rails, antennas)

A total of 467 ice samples were taken and analyzed, comprising 70 frazil, 154 under-way pancake, 24 cross-sectional pancakes, 136 ice core samples, 64 melt pool samples, 11 riming and 6 frost flowers. Representative samples of all ice types recovered were kept in the freezer and the crystal structure examined using thick sections and crossed polaroids.

### **Atmospheric Profile Measurements (underway and stations)**

A variety of atmospheric profile measurements were performed throughout the cruise. Every 6 hours (nominally at 0530, 1130, 1730 and 2330 UT) weather balloons with attached radiosondes were launched. The frequency was increased to every two or three hours during certain periods (usually when crossing the ice edge). These measured pressure (height), temperature, humidity and wind vector. There were two types of balloon measurements: 1. Complete troposphere and 2. “Up/downs”. The former were standard radiosonde observations where the balloon ascended to between 13000 and 16000 meters elevation (well into the stratosphere) before popping. Data were collected during the ascent and sometimes while the sonde descended but usually not all the way back to the surface. For the “up/downs” a leak was induced in the balloon which caused it to rise to about 4000 meters and then descend back down, data were collected throughout the up and down portions of the flight. The up/downs allowed two profiles to be obtained and allowed quantification of small scale horizontal variations. Typical distances between launch and touch down were 3-15 km.



**InstantEye UAS with radiosonde attached below**

During several of the ice camps, a radiosonde was attached to an “Instant Eye” miniature quad-rotor UAS to perform low level measurements of pressure (height), temperature and humidity. By flying upwind and downwind of leads and open water or thin ice regions it was possible to quantify the heat and moisture fluxes coming out of these regions. These also allowed detailed studies of the atmospheric surface layer structure and horizontal and vertical variations that were not possible with the balloon measurements. At ice station #10 similar measurements were performed using a fixed wing UAS.



**Fixed wind UAS with radiosonde on top.**

### **Stereo Video (underway and stations)**

A stereo camera setup on both the port and starboard side were used throughout the cruise to measure waves and ice. Each setup consists of three small Point Grey “flea” cameras, installed at 18° below horizontal on the rail. The two outer cameras have approximately the same field of view, and are used to find the stereo solution. The center camera has a wider field of view, giving the context for the stereo measurement and a view of the horizon for motion correction in post processing. Both setups were calibrated during mobilization in Nome. The port side setup also consists of a Novatel IMU, which can be run concurrently with either camera setup to allow correction for the ship’s motion in post processing. The IMU was also used to give a solution for mobile LiDAR scans.

The primary objective of the stereo camera setup is to measure surface waves via 3D mapping. In particular, we are interested in the motion of ice at a wavy ocean surface, and were able to capture a number of such cases with an in situ wave measurement from a SWIFT wave buoy close by. Such wave measurements are best made while holding station, but the stereo cameras were also used to measure waves and while underway at relatively low speeds. At some ice stations, the stereo cameras captured the surface of the floe, with the intent of calibrating the setup as an alternative method for mapping the surface roughness. As the stereo camera setup is daylight limited, amount of recording was limited later in the cruise.



**Port Side Stereo Cameras and IMU**

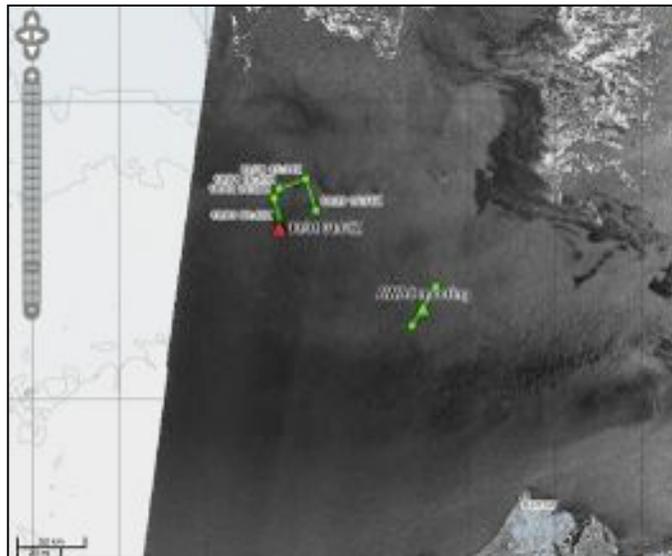


**Starboard Side Stereo Camera Setup**

### **Outbound Transit, Wave Array #1, and AWAC Mooring (1-3 October 2015)**

R/V Sikuliaq departed Nome, AK on the evening of 30 Sept 2015 and headed north towards the Chukchi and Beaufort Seas. We paused during transit on the afternoon of 2 October to briefly deploy wave measurement buoys for inter-calibration (wave array #1). Wave conditions were approximately 1.2 m waves at 5 s from the east-northeast. The results indicate that the buoys agree well when using true heave to calculate the frequency spectra of scalar wave energy. A Datawell Waverider was used for independent verification. The Rutter radar measurements agree with the buoys in terms of peak wave period, peak wave direction, and directional distribution of wave energy. A calibration of significant wave height from the radar is still pending. Buoys and radar indicate the presence of a secondary swell wave system from the south.

A sub-surface mooring with a Nortek Acoustic Wave and Current (AWAC) sensor was deployed on 3 Oct 2015 in open water at 72°38.220'N, 159° 00.674' W in 100 m water depth. Later in the afternoon, a NAVO glider deployed earlier in the season was recovered in open water.



**Mooring and glider locations shown over SAR image from the same day**



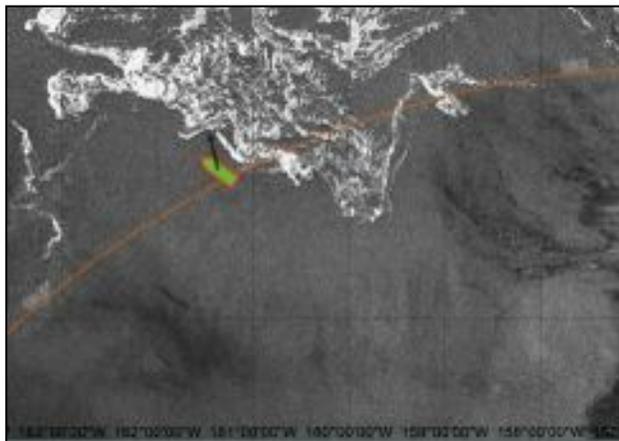
**AWAC mooring**



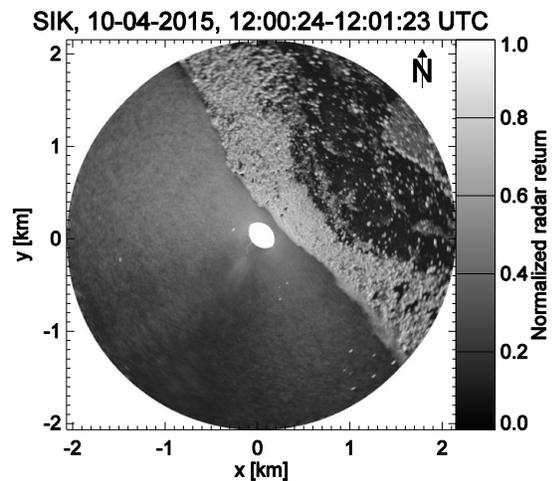
**NAVO glider**

## Wave Array #2 (4 Oct 2015)

We arrived at the ice edge for the first time early in the morning on 4 Oct 2015, when we were just beyond the Chukchi slope. The edge was clearly visible in the Rutter radar. We deployed wave array #2, consisting of three SWIFT buoys crossing from open water into partial ice cover beyond a band of old ice, plus one wave buoy in the ice bands. We held the ship head-to-wind for several flux stations from the meteorological mast. Winds were obliquely off-ice from the northwest to north and generated 0.5 m waves at 3 s from the same direction. A second wave train at 4 s from the west was also detected, but was small. Waves were detected inside the ice band as 10cm wave height and 7 seconds period from the southwest. The Rutter radar was kept running during this and all subsequent stations. The resulting imagery can be used to document relative ice drift. Ballasting and operational readiness tests were conducted for the Woods Hole Oceanographic Institution SeaBED-class autonomous underwater vehicle (AUV) *Jaguar* as well as the Predator remotely-operated vehicle (ROV) system.



**Ice edge and ship position on SAR image**



**Ice edge on Rutter radar**



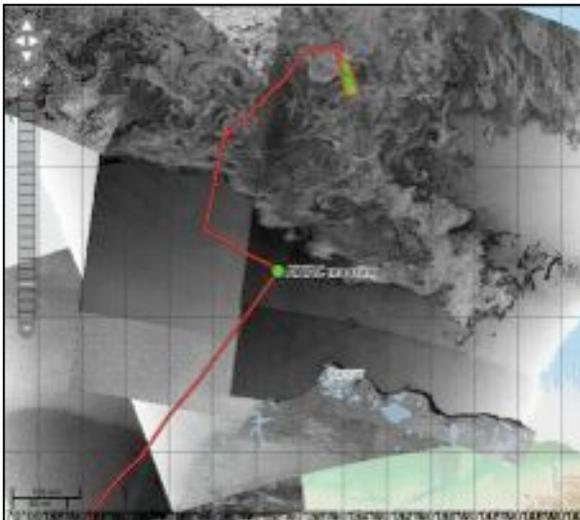
**JAGUAR AUV deployment  
(Guy Williams photo)**



**SWIFT in ice band**

## **SIMS survey and Ice Station #1 (5-7 Oct 2015)**

We transited northward through nilas ice sheets surrounding small thick older floes on 5 Oct, then found a large multi-year floe for Ice Station #1 (“Ben’s floe”) that had been tracked and targeted using the remote sensing imagery early in the morning on 6 Oct 2015. We spent 6 Oct 2015 conducting a large ice station on this floe, including: an AUV multibeam grid survey under the ice with twelve 200 m legs separated by approx. 18 m, UAS surveys and meteorological measurements, LiDAR scans, EMI thickness surveys, drilled ice thickness lines, Magnaprobe snow-depth surveys, and CTD casts. The floe was next to a wide lead, in which two SWIFTs were deployed that immediately froze in place. There was evidence of several refrozen former melt ponds in the big floe. Four locations were core sampled for ice properties and water in the core holes. The floe was at least 100 nm from any ice edge, and there was no sign of wave activity as this station. The NASA airborne UAVSAR sensor collected SAR imagery over this floe and the surrounding area while we were on station. One IMB and one AXIB were deployed at this station. Air temperatures were cold ( $\sim -10$  to  $-8^{\circ}$  C), skies were often clear, and winds were weak and from the north-northeast. The orientation of the lead and ship did not allow on-bow wind component for flux measurements.



**Sikuliaq position and SAR image**



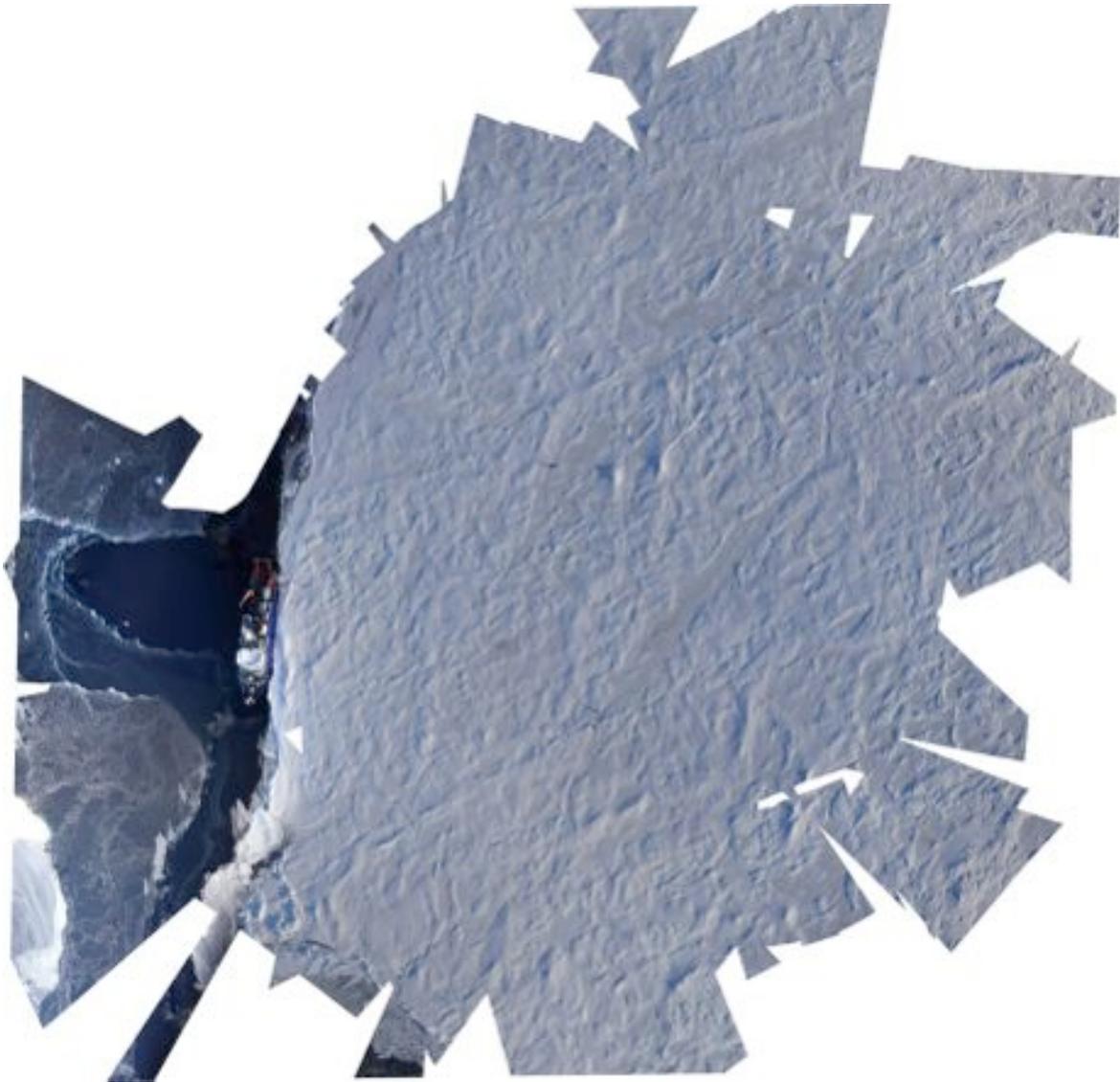
***JAGUAR* AUV recovery  
after approx. 4.5 hr survey under  
ice station #1 (Toshihiro Maki photo)**



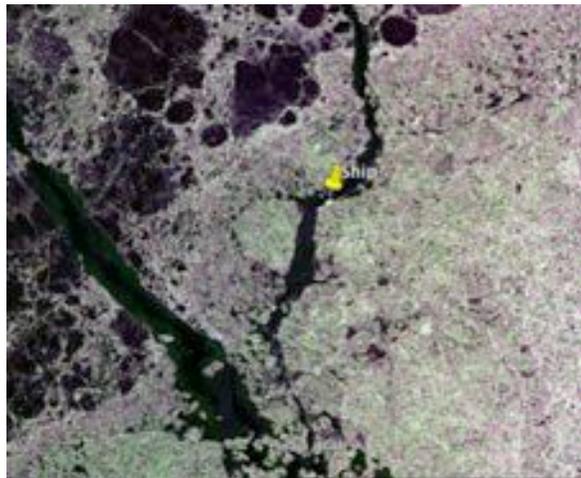
**Ship from LBL & CTD hole**



**AXIB and IMB**



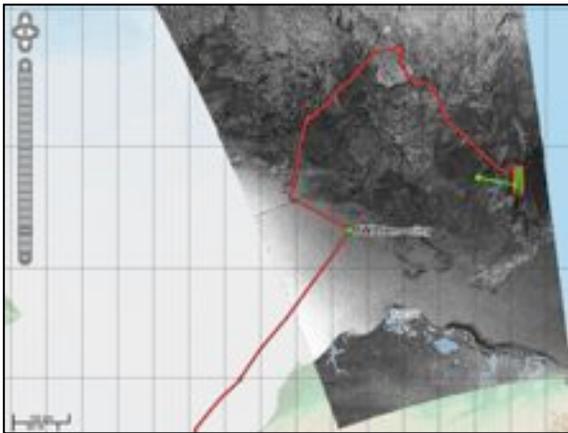
**UAS mosaic of Ice Station #1**



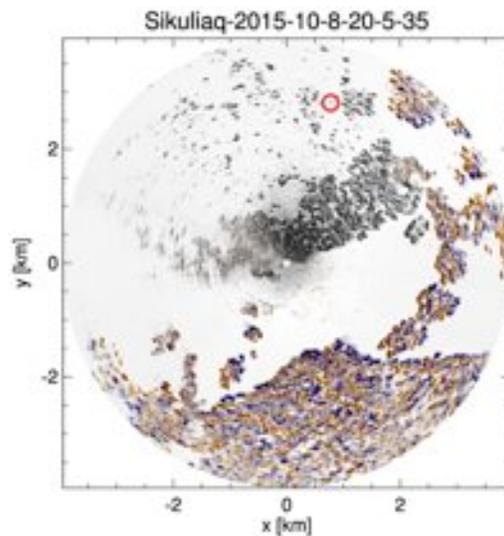
**UAVSAR enlargement showing Sikuliaq at Ice Station #1. Colors provided by different polarizations.**

### Ice Stations #2 and #3, SIMS survey (8-9 Oct 2015)

Ice Station #2 was conducted on 8 Oct at a small (200m major diameter) multi-year floe (named “potato” after its shape) approximately 10 nm southeast of the first station. This was in an area with large leads. UAS photogrammetric surveys and UAS meteorological measurements, LiDAR scans, EMI thickness surveys, snow-depth surveys, flux measurements across a large expanse of nilas, and CTD casts were conducted. An IMB was placed on the floe and a core (272cm) taken adjacent to it. Ice Station #3 followed later that afternoon, and was simply the deployment of an SIMB with a 27cm core on a large pancake(3-5m) about 10 nm southwest of the second ice station. This location is when we first began to see pancake ice (as we approached the ice edge on the Beaufort Sea side). SIMS survey data was collected along the track. As we continued the transit to the southeast on 9 Oct, sheets of nilas ice were most common, but areas of pancake ice were also observed, suggesting wave activity had reached this portion of the domain.



**SIMS survey track and SAR on 8 Oct 2015**



**Rutter radar of Ice Station #2:  
colored areas illustrate relative ice drift  
and a polar bear is at red circle**



**Ice station #2**



**Ice Station #3**



**UAS mosaic of Ice Station #2**



**Fluxes obtained across nilas at Ice Station #2**

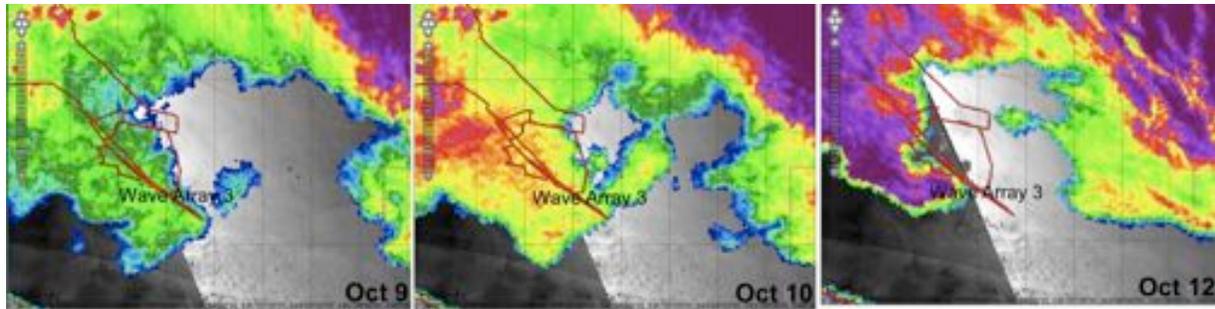
### **Wave Array #3 (10-13 Oct 2015)**

Upon reaching the ice edge on the Beaufort side on 10 Oct, we began deploying SWIFTs, wave buoys, and one NIWA buoy to drift in an array aligned with the forecasted wave directions. Pancake ice was forming rapidly and waves were approximately 1 m from the southeast. A few hours into the deployment, we received new RadarSat2 image and AMSR2 product, and we realized that the fetch for these waves was rapidly decreasing as an embayment of ice filled in. We decided to recover most of the buoys and shift the array to the south, where the full fetch of the Beaufort Sea would be available for this ESE wind event and waves were forecast to reach 4 m significant wave height. We left two SWIFTs and one NIWA buoy in place on the original line, to measure any waves propagating far into the ice.

The second line of buoys spanned 60 nm, from open water to deep within a field of rapidly growing pancakes. This event was part of prevailing easterly winds, with ESE winds of up to 16 m/s. Throughout the event, underway CTD transects were completed across the buoy line, and stereo video of pancake motion in large waves was recorded as daylight allowed. Early in the storm, waves up to 3 m were propagating all the way through the array (i.e., very little attenuation). The expectation was for the pancake ice to eventually freeze in place as the storm progressed. However, the pancakes largely disappeared overnight from 11 Oct to 12 Oct in the immediate vicinity of the buoy array, while the waves reached a maximum 5 m in the middle of the array. Further to the west, the ice concentration increased from this event. The working hypothesis is that near-surface heat flux convergence melted the existing pancake ice cover because of the observed decrease in the magnitude of the heat loss to the atmosphere and an increase in upward mixing of ocean heat stored in the “near surface temperature maximum” observed with the underway CTD casts. The former was likely caused by warm air advection while the observed waves were likely instrumental for the latter. The waves may not have penetrated into the ice farther to the west, so heat loss to the atmosphere dominated and instead enhanced the ice concentration there during this wind event. The buoys were recovered on 13 Oct, in alternating bands of open water and pancake ice over a span of 100 nm. Heavy icing on the buoys caused many buoys to miss Iridium reports of position. The NIWA buoy, which was the farthest from the open water, recorded waves reaching 3.3 m during the peak of the storm, and was recovered in compacted pancake ice with little evidence of melting. The two SWIFTs left behind along the initial line were not recovered.



**Buoy positions and SAR image for 12 Oct**



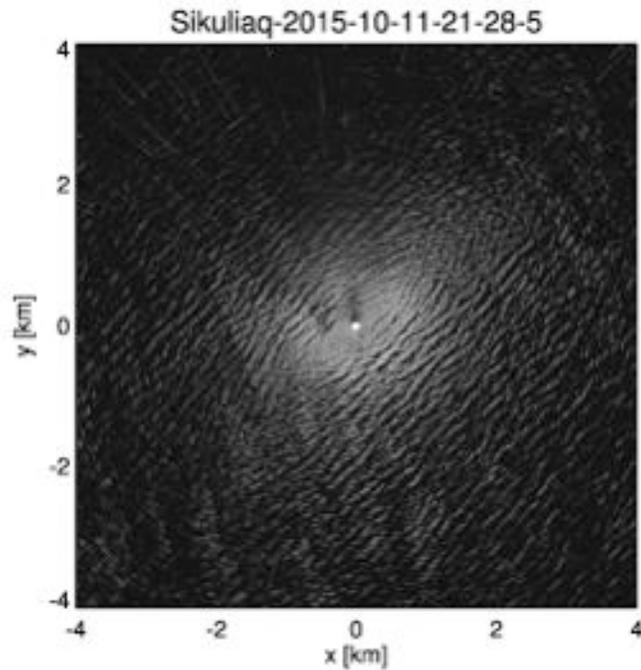
**Progression of AMRS2 ice concentration (color scale) during Wave Array 3**



**WaveBuoy 02: an example of the heavy icing during the deployment**



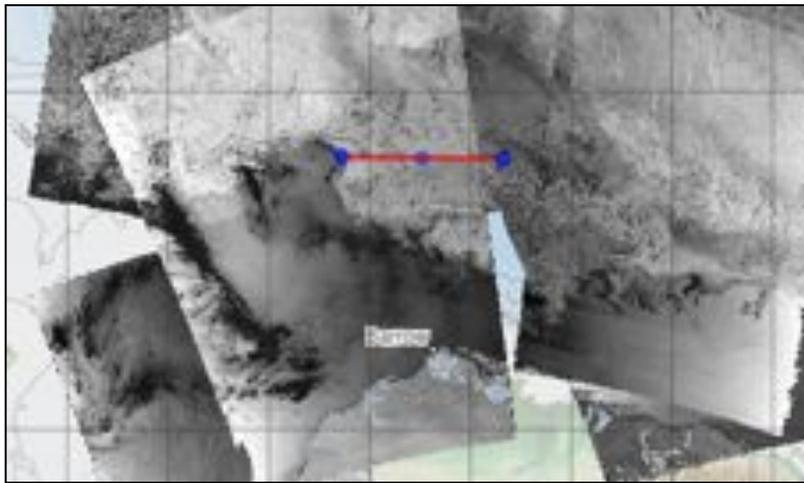
**Big waves amongst the pancakes**



**Rutter radar raw image of wave signal within the pancake ice**

### **SIMS Ice Survey and Ice Station #4 (14-15 Oct 2015)**

A westward ice thickness survey using the shipboard SIMS (Sea Ice Measurement System) was conducted along 74° N from the buoy sites on the Beaufort side to an ice station in the middle of the pack ice. An SVP was deployed en route. Once far (> 100 nm) within the ice, there were no more pancakes or evidence of wave activity. Ice station #4 was an ROV and LiDAR survey of a region filled with bits of old floes and ridges (“mixed nuts”), surrounded by new ice. A quad rotor UAS sampled low level atmospheric profiles of temperature and humidity over ice and open water regions. After the short station, the westward transect continued over to the Chukchi side. NRL airborne remote sensing flight #1 was conducted simultaneously, collecting L-band SAR along the same line. Useful underway flux measurements were obtained along parts of this track, as were a few flux stations.



**SIMS survey line overlaid on SAR images for 14-15 Oct 2015**



**SVP deployed on a large pancake**

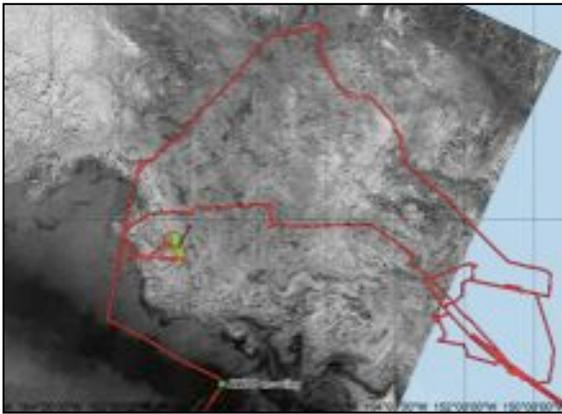


**Ice Station #4 (“mixed nuts”)**

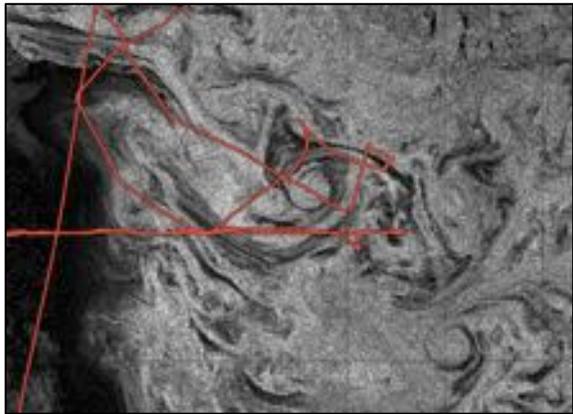
### **Wave Array #4 and Ice Station #5 (16-17 Oct 2015)**

Upon reaching the ice edge on the Chukchi side, we found a diffuse ice edge with small pancakes. The incident waves were 0.3 m at 6 s from the southwest, and we deployed a line of buoys perpendicular to the ice edge. The ice was advancing rapidly, and the buoy farthest out was in grease ice. NRL airborne remote sensing flight #2 was conducted, finishing the L-band SAR line from the day before and collecting LiDAR over the small pancakes near the ship. On the 17th, small eddies were apparent in the region, detected by loose pancake ice being traced by underlying eddy current patterns. CTD collections were also obtained through one or more of the eddies.

While deploying the line of buoys, we encountered a medium sized piece of multi-year ice that was heaving gently amongst the pancakes. We deployed wave buoys on and around this on 16 Oct, and surveyed the floe as Ice Station #5 (“Peter’s floe”) the following day. We conducted an ROV mission, thickness drilling, coring of refrozen melt ponds and a hummock, and LiDAR scans. In the meantime, some of the buoys became frozen in when the waves decreased, while others drifted northwest towards more open water.



**SAR image for 16 Oct**



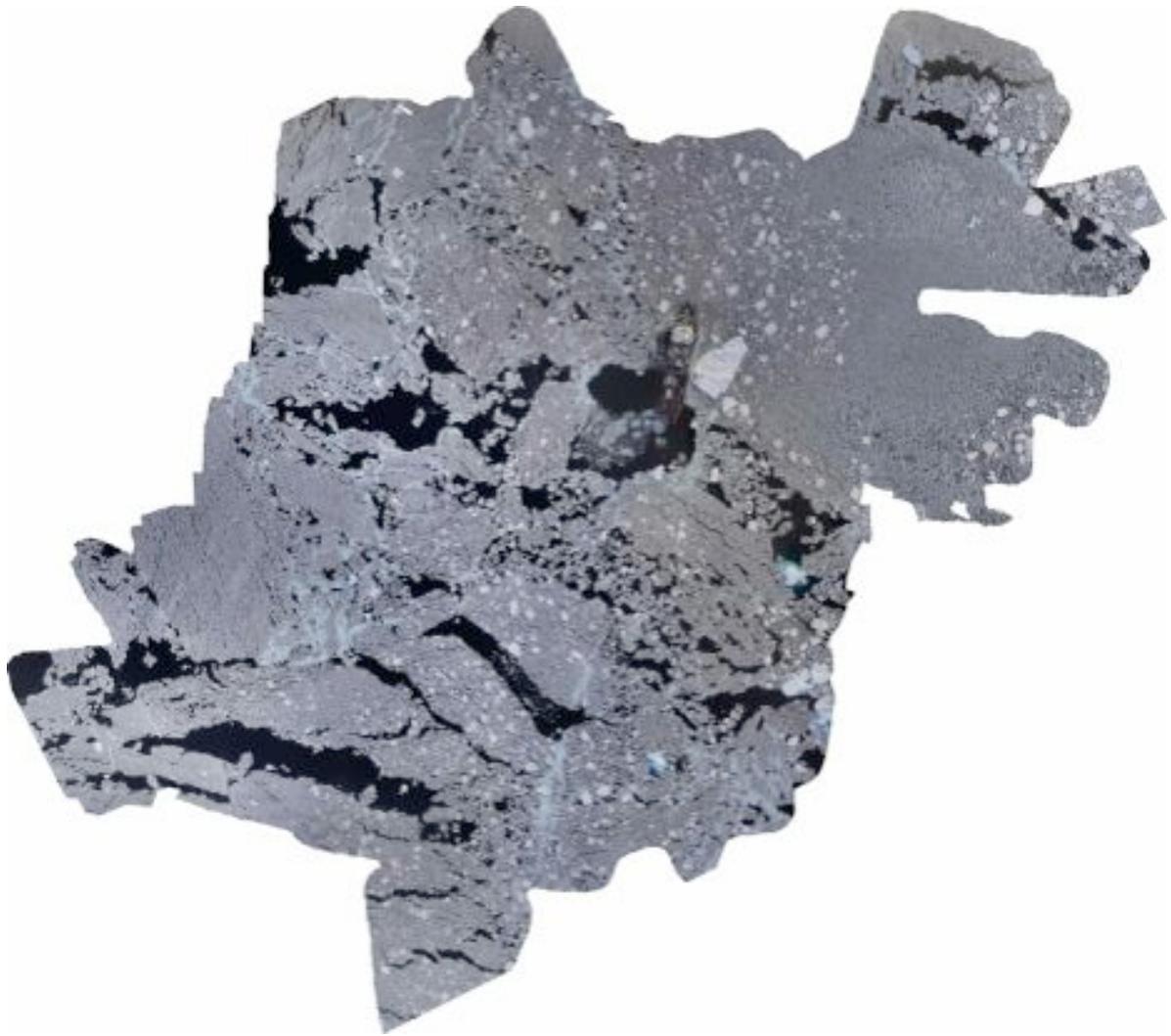
**SAR image for 17 Oct**



**Pancake Ice at wave array 4**



**Ice Station #5 (“Peter’s floe”)**

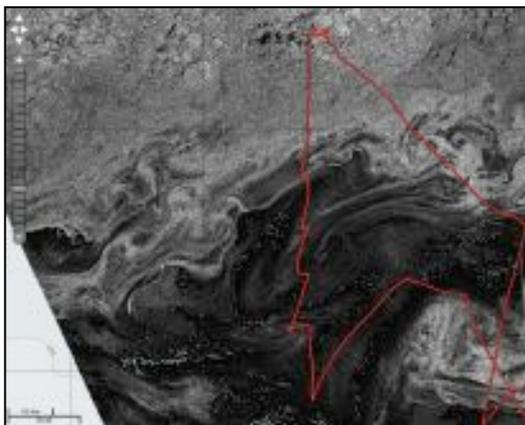


**UAS mosaic of Ice Station #5**

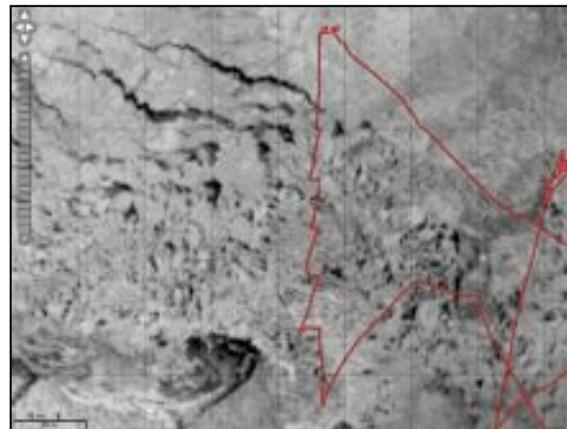
### Northward flux line and Wave Array #5 (18 Oct 2015)

After recovering the buoys from the third pancake line early in the morning on 18 Oct, we stopped northwards on hourly flux stations (ship head-to-wind) through an embayment of open water that was experiencing off-ice winds and rapid cooling. Stereo video of ice at the ocean surface was recorded at two of the flux stations. Underway fluxes were also obtained. At the second flux station location, a narrow sharply-defined band of pancakes was encountered, which under the action of very short waves were causing reflection and scattering at the band edges. To investigate this effect, one SWIFT and two wave buoys were deployed to each side of, and inside, the band (wave array #5). There were very small (<10 cm) local wind waves from the northwest and a hint of the remnant swell at 6 s from the southwest. The array was in place for just over two hours, then was recovered.

A distinct ice-edge cold front was encountered near the southern end of the flux line. Winds were off-ice from the north at  $7\text{-}10\text{ m s}^{-1}$ , with low-level, cold-air outflow from the ice interior causing significant heat loss to the atmosphere. This entire embayment was later observed, via satellite, to freeze up within a day of our measurements.



**Flux line and SAR image on 18 Oct**



**Flux line and SAR image on 19 Oct**

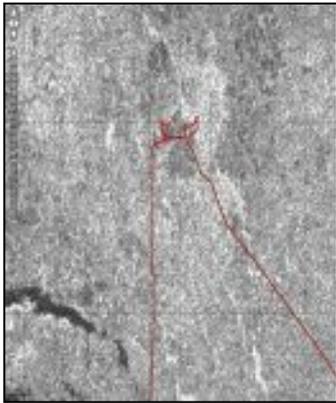


**Pancake ice on 18 Oct**

### **Ice Stations #6 and #7 (19-20 Oct 2015)**

Ice Station #6 (“Barney rubble”) was conducted on 19 Oct in a rubble field of ice between a few large expanses of very flat young ice sheets. Although the satellite images suggested that ice would be substantial in the north-central part of the Chukchi, it proved to be slushy and marginal for on-ice work. An AUV multibeam grid survey under the ice with twelve 300 m legs separated by approx. 18 m. A LiDAR survey was also conducted and CTD casts were taken. The ice was sufficiently flat and smooth to suggest no wave activity.

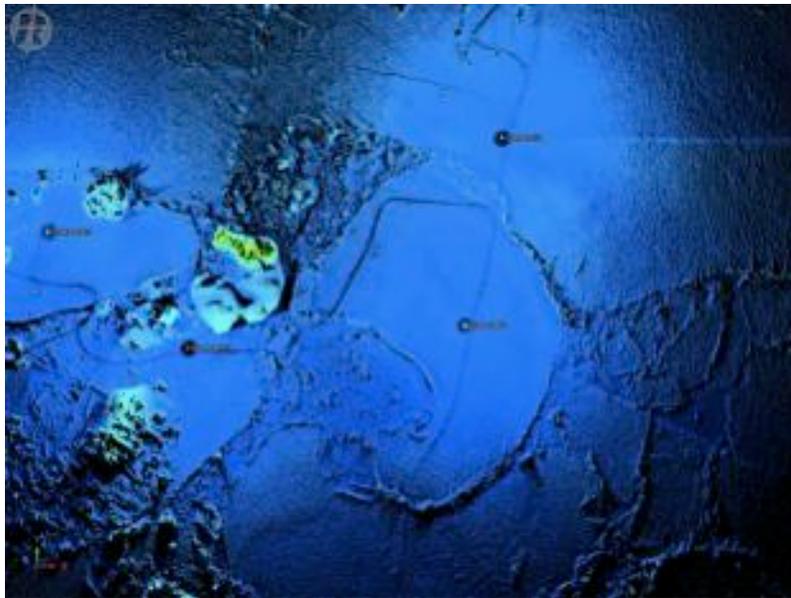
Ice Station #7 (“Seal Bear”; after a Polar bear stalking a seal hole nearby) was conducted nearby on 20 Oct, at a rubble field next to a large lead. An AUV multibeam grid survey under the ice with ten 250 m legs separated by approx. 17 m. UAS, and LiDAR surveys also were conducted, along with coring and CTD casts. A quad rotor-UAV performed atmospheric profiles up and downwind of an open water region behind the ship to quantify “lead” heat fluxes. A few flux stations were obtained in weak northeasterly winds.



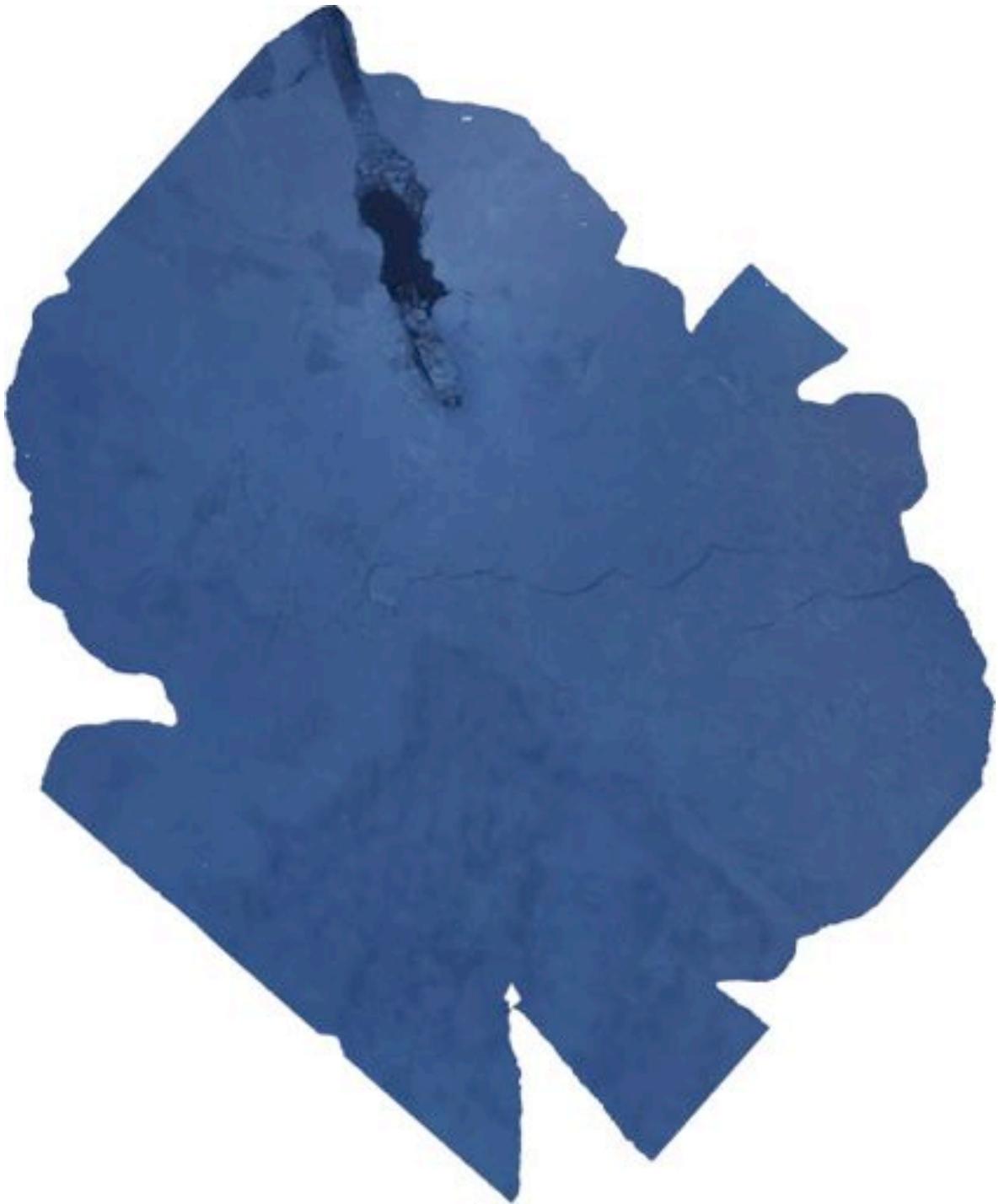
**Ship track and SAR**



**AUV launch at Ice Station #6**



**LiDAR topographic map of Ice Station #6**



**UAS mosaic of Ice Station #6**

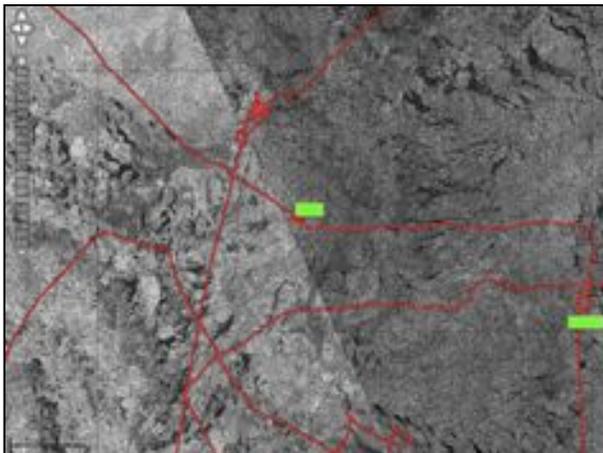


**UAS mosaic of Ice Station #7**

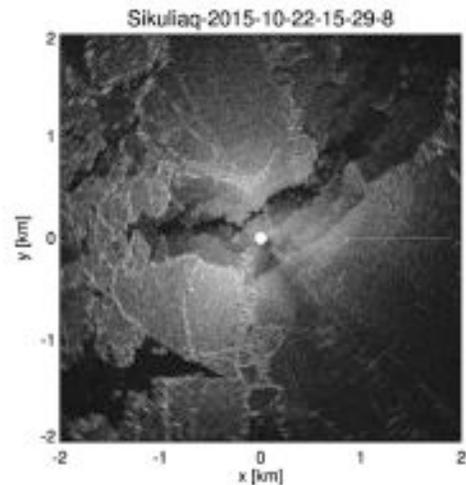
### Ice Stations #8 and #9 (21-22 Oct 2015)

Ice Station #8 was conducted on 21 Oct after transiting eastward back into the middle of the pack. This station used a medium floe for the AUV baseline, and focused on a field of new rafting ice. An AUV multibeam grid survey was conducted under the ice with eleven 180 m legs separated by approx. 10 m. UAS and LiDAR surveys, as well as UAS atmospheric profiles, also were conducted, along with coring and CTD casts. NRL airborne remote sensing flight #3 was conducted, repeating the L-band SAR survey along  $74^{\circ}$  N, collecting LiDAR over the station, and finally an L-band SAR southward along  $159^{\circ}$  W. The Rutter radar provided high-resolution sea ice images here, and over the full duration of the cruise. The images were used heavily both for navigation and identifying areas of interest for ice stations.

Ice Station #9 (“goldilocks” not too thick, not too thin) was conducted on 22 Oct after transiting southwards from the previous station. This station used a small second-year floe to deploy an Ocean Heat Buoy. The southward transit coming into and leaving from this station ran along  $159^{\circ}$  W, mimicking the NRL flight #3 survey.



Ship track and SAR image



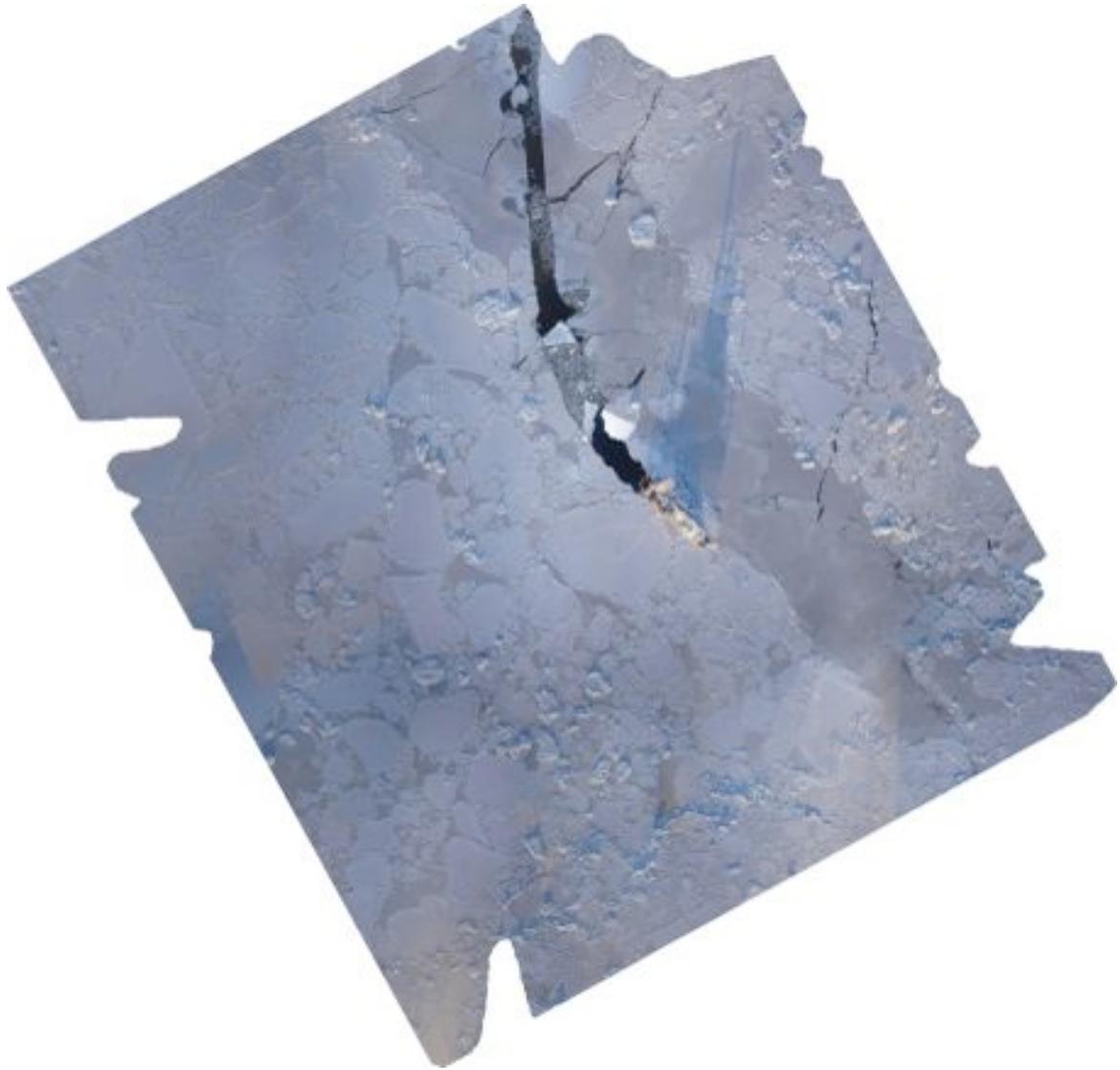
Rutter radar image at Ice Station 9



Ice Station #8



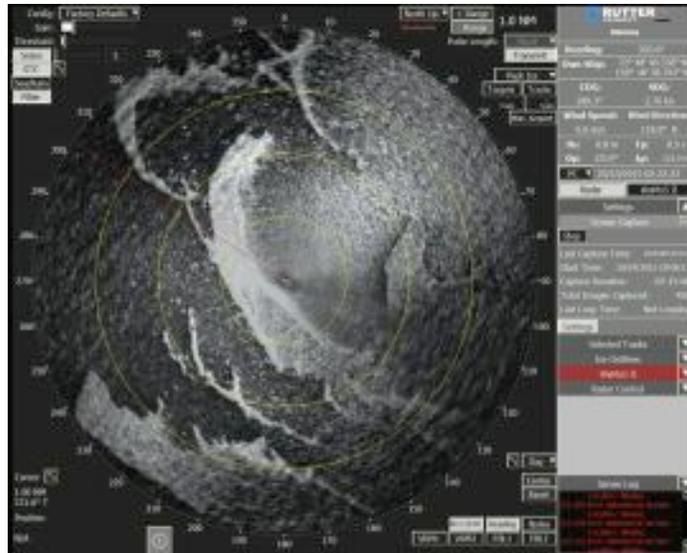
Ice Station #9



**UAS mosaic of Ice Station #8**

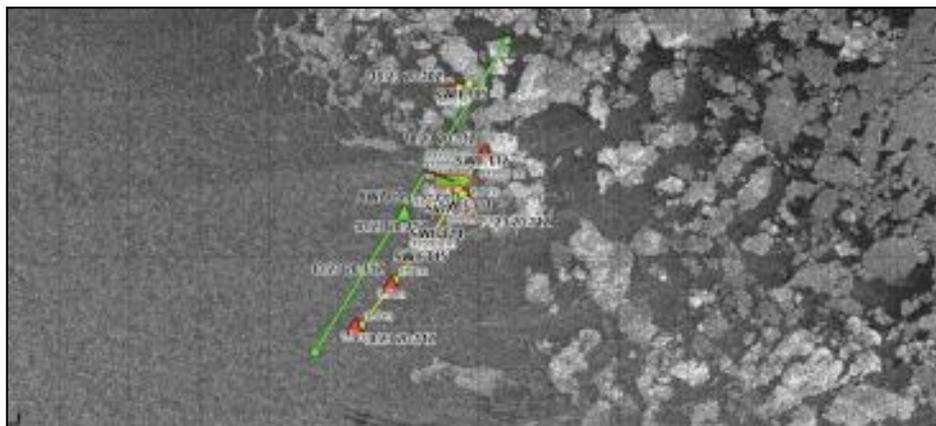
### Wave Array #6 (23-24 Oct 2015)

We arrived at the southern ice edge, near the AWAC mooring site, on the morning of 23 Oct and began deploying wave array #6 as a line of buoys extending from 20km penetration out to open water. Bands of pancakes were forming. Waves were 0.5 m at 7 s from the southeast and 0.5 m at 4 s from the east-southeast. Drift patterns suggested strong eddies at the shelf-break, and the buoys were alternately drifting in and out of bands of ice. The Rutter radar produced wave results throughout. It was also used to monitor the relative position between buoys and ice. Buoys were recovered on 24 Oct.



**A typical band of pancake ice during this deployment, observed on the Rutter radar**

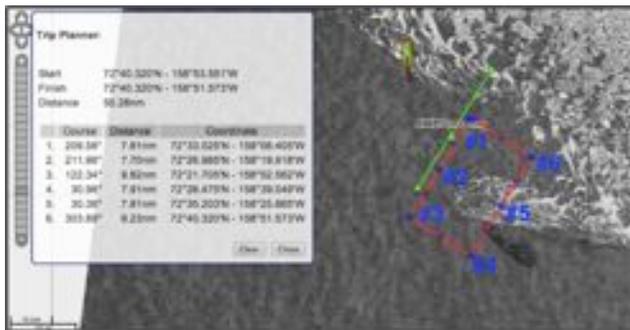
NRL airborne remote sensing flight #4 was conducted on 23 Oct, with LiDAR and SAR lines crossing the ice edge. NRL airborne remote sensing flight #5 was conducted on 25 Oct, with select repeated lines at the ice edge, and a repeated SAR line up 159° W. Several flux stations were obtained in 9-12 m s<sup>-1</sup> winds blowing obliquely off ice from the ESE.



**Ship and buoy positions over SAR image for 23 Oct**

## Flux “Race Track” and AWAC mooring recovery (25-27 Oct 2015)

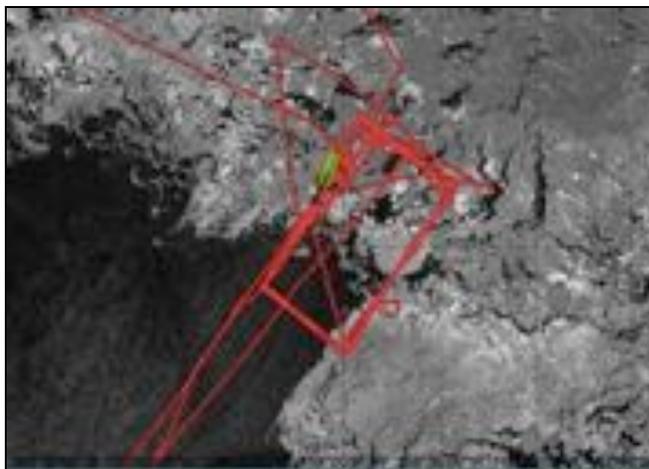
The AWAC mooring was recovered on the morning of 25 Oct, and then a race track pattern was established to measure the fluxes and ocean structure of the advancing ice edge during a forecasted cooling event with weak off-ice winds from NW through NE. The race track had six stations, each separated by 8 nm, running in a counter-clockwise sequence. The western leg of the race track included the AWAC location. The stations were held for 1 hour each and the underway CTD was cast continuously during the transits between stations. Stereo video was recorded at flux stations when daylight and wave conditions allowed. Two SWIFTs were redeployed in open water and eventually froze in place as pancakes formed around them and joined together (see buoy video timelapse). Ice advanced rapidly across the race track, which changed from mostly open water to mostly ice cover in 48 hours. Some of this change was clearly due to advection of existing ice, but many areas experienced new freezing during this time. ROV and LiDAR surveys of the ice were conducted on 26 and 27 Oct at point #6 in the race track. While doing the race track, we left our marks on a large floe “cookie” 10 km across, as later captured by the TSX image on Oct. 29



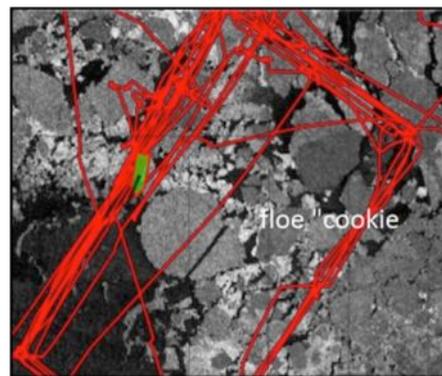
**Race track, AWAC, and SAR image on 25 Oct**



**ROV at Race Track point #6 on 26 Oct**



**SAR image on 27 Oct**



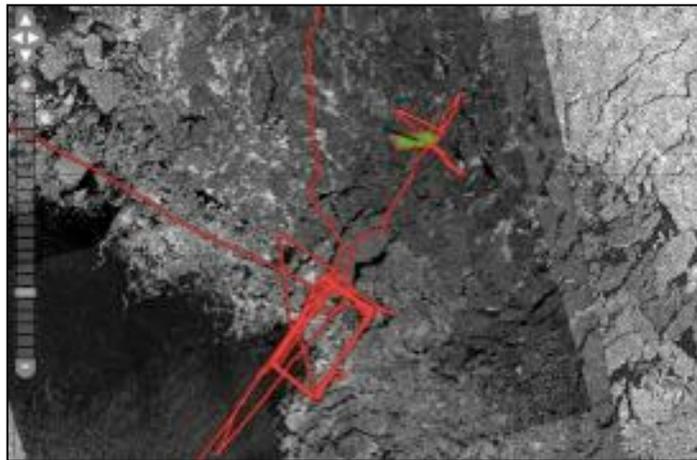
**SAR image on 29 Oct**

### **Ice Stations #10, 11, and 12 (28-30 Oct 2015)**

We transited back into the ice pack approximately 40 nm overnight and selected a broken ridge for Ice Station #10 on the morning of 28 Oct. An AUV multibeam grid survey under the ice with fourteen 300 m legs separated by approx. 15 m was conducted, along with CTD casts, a UAS survey, and drilling/coring. Atmospheric profiles were obtained with both fixed wind and quad rotor UAS. The ship was exactly head-to-wind to maximize the quality of the flux measurements from the met mast in weak ( $4\text{-}5\text{ m s}^{-1}$ ) easterly winds. A LiDAR survey was conducted from the ship after the station was complete, by circling around the AUV survey domain.

We shifted approximately 10 nm overnight and selected another broken ridge for Ice Station #11 on the morning of 29 Oct. An AUV multibeam grid survey under the ice with eight 200 m legs separated by approx. 15 m was conducted, along with CTD casts, a UAS survey, and thickness drilling. The ship was exactly head-to-wind to maximize the quality of the flux measurements from the met mast. The coldest air of the cruise ( $\sim -21^\circ\text{C}$ ) was encountered at this station. A LiDAR survey was conducted from the ship after the station was complete, by circling around the AUV survey domain.

Overnight we transited back to point #6 of the race track (NE corner), then ran the line up to point #1 (NW corner) while tow-yo casting the underway CTD. Upon reaching point #1 in the morning on 30 Oct, we set up for Ice Station #12 on a finger-raftered floe. We conducted a total of four ROV surveys, with repositioning and a LiDAR scan between the first and second surveys. Finally, an SVP buoy was deployed.



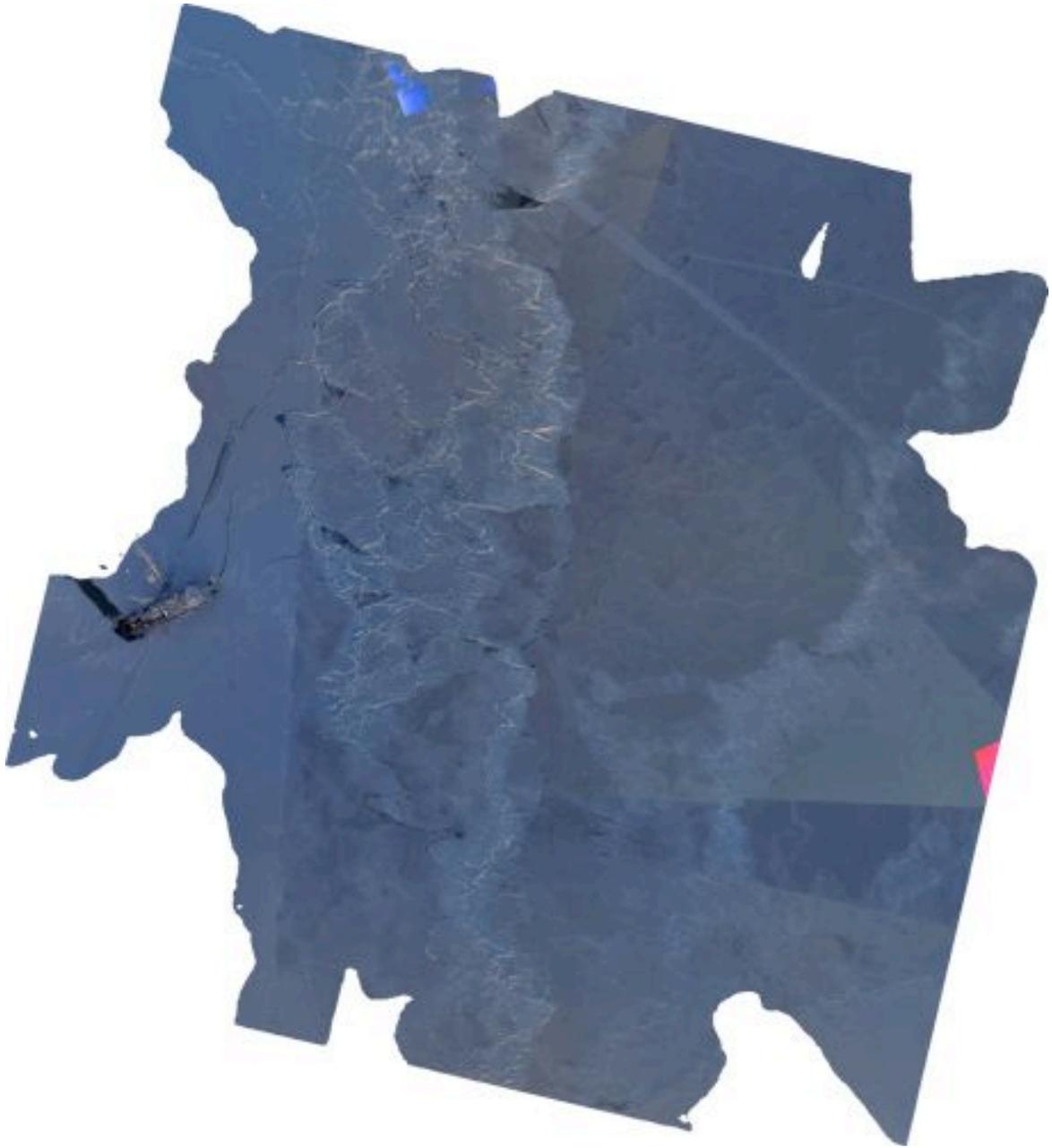
**Ship track and SAR image**



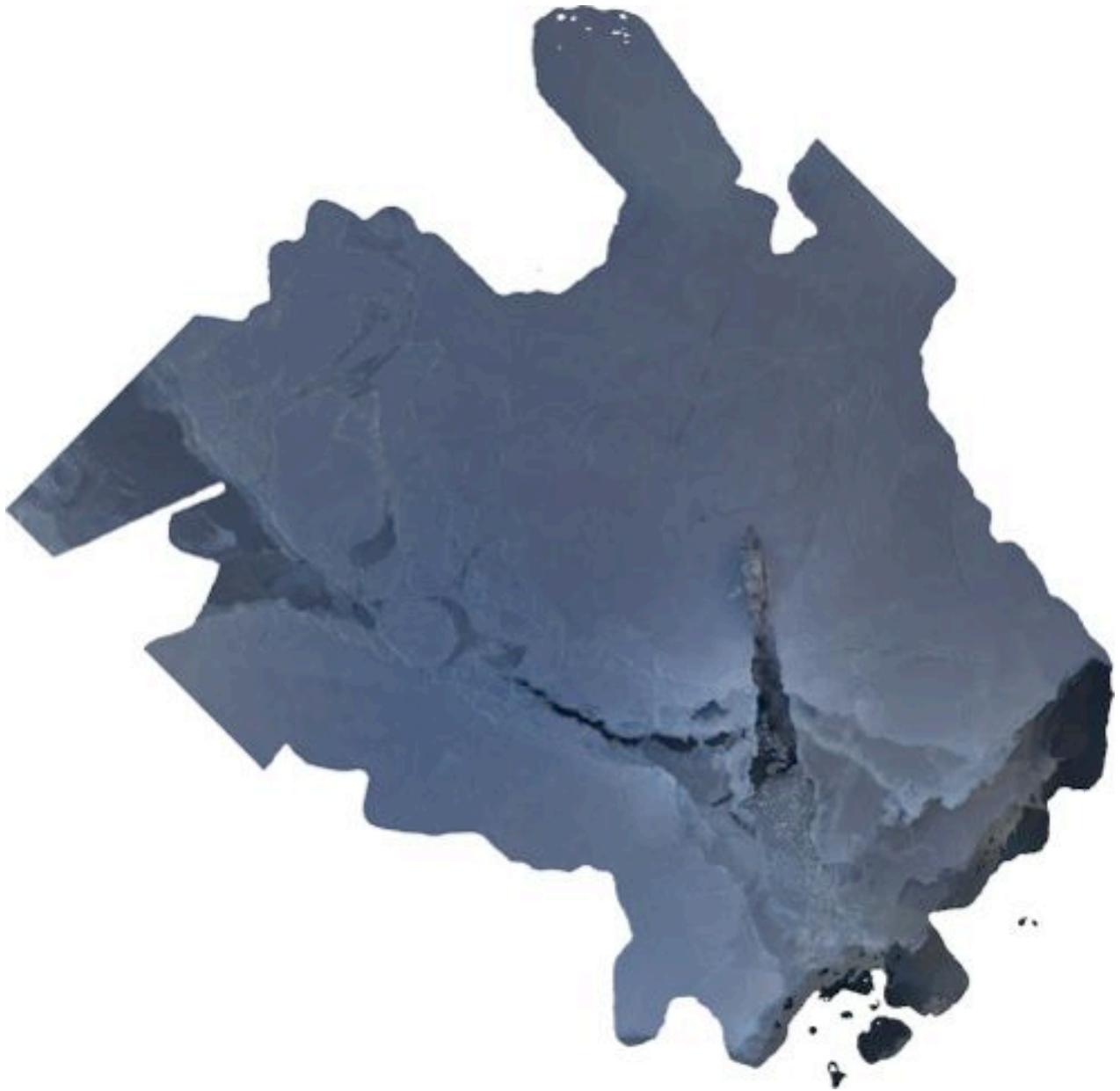
**Ridge at Ice Station 11**



**Finger rafts at Ice Station 12**



**UAS mosaic of Ice Station #10**

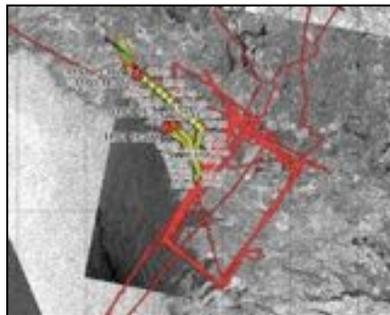


**UAS mosaic of Ice Station #11**

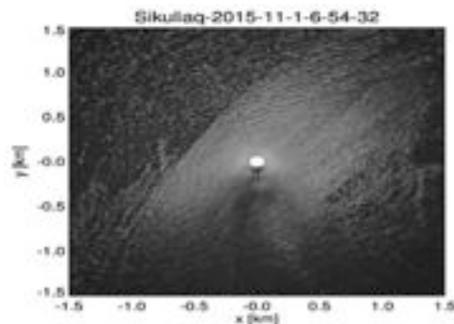
## Wave Array #7 (31 Oct – 1 Nov 2015)

We ran the western side of the race track with flux stations (#1, #2, #3) and underway CTD during the night, arriving at the end of the line in the morning. This line had been mostly sheet ice during the previous race track laps just a few days prior, but was now broken by waves into small cakes and brash ice. Presumably, this was caused by the western swell arriving at the ice edge (0.6 m at 7 s from W and another system from SW). We intended to deploy buoys to measure these waves at the edge around point #3, based on recent SAR images, but the ice retreated almost 10 miles overnight and we deployed at the new ice edge in the vicinity of point #2 instead. We deployed a tight array of 5 wave buoys, 4 SWIFTs, and 1 NIWA buoy for the morning inside the pancakes, at an internal boundary which marked a transition from pancakes to larger cemented floe-sized ice elements of 20 m and more in diameter, then ran a stereo camera and flux station nearby. The tight array was designed to measure scattering, reflection and spectral broadening at a transition to large cakes whose diameters were a substantial fraction of a wavelength, with the hypothesis of scattering as the dominant mechanism of local wave-ice interaction. In the afternoon, we moved two SWIFT buoys out to open water for a larger-scale attenuation measurement. In the evening, we moved one wave buoy further inside the ice. We then resumed the flux stations and upper leg (#1-2-3) of the racetrack. The Rutter radar was collecting data throughout the experiment. It detected waves in a variety of conditions ranging from new sheet ice, pancake ice, and brash ice, to open water.

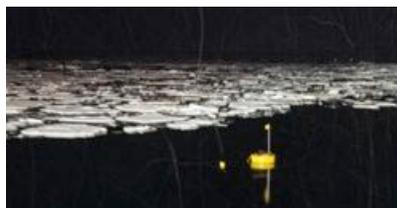
The ice retreated farther during the early morning of 1 Nov, to about halfway between race track points #1 and #2. Active breaking of sheets was observed while transecting out #1-2-3 and back on #3-2-1. The westerly swell died and the southwesterly swell built to 1.7 m at 4.5 s (from the buoys on the edge). In the morning, we left point #1 to recover buoys that had drifted to the northwest. A few of the buoys were recovered from open water, the rest were in loose-cake ice. Moderate SSE winds transitioned into weak and variable as a shallow low-pressure system moved over the array, bringing substantial warm-air advection.



**Positions and SAR on 31 Oct**



**Ice edge from Rutter radar**



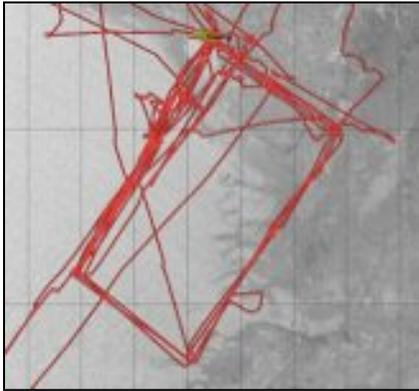
**WaveBuoy in cake and brash ice**



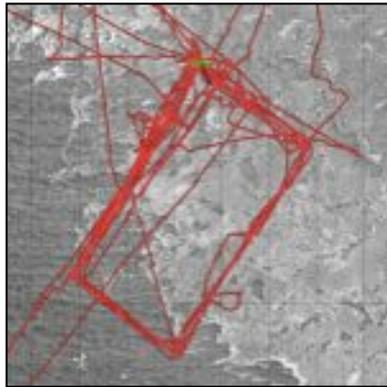
**NIWA buoy**

### **Race track with flux stations (2-3 Nov 2015)**

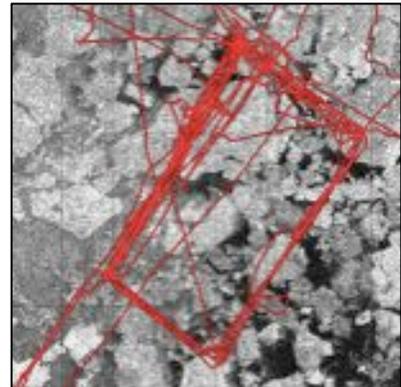
After buoy recoveries on Nov 2, we began a full race track (#1-6) in a clockwise direction. We added short SWIFT deployments during each of the first three flux stations (#6,5,4 for 1 hour each). Strong winds from the east (15 m/s) advected cold air over the racetrack and produced a steep wind sea in patches of open water. On 3 Nov, the ice was drifting fast (0.6 m/s) to the west and substantial first-year ice was moving through the region. In the evening, during the last TSX satellite acquisition, large floes and large leads were both common, with up to 1 m breaking seas in the open areas.



**SAR on 2 Nov**



**SAR on 3 Nov**



**SAR on 5 Nov**



**Mixed ice conditions at Racetrack Point 2 flux station on 2 Nov**

## **Transit and wrap up**

We began our transit south to Dutch Harbor in the evening on 3 Nov. We continued to conduct flux stations until 50 km from the ice edge, and we continued underway CTD casting until 71° N (late afternoon on 4 Nov).

The Sea State DRI team is funded by the Office of Naval Research for two more years to analyze and synthesize the data collected during this effort. Results will be presented in a special issue of an academic journal and at academic conferences. Results will be used to improve forecasts of ice and waves in the Arctic region.



### **Sea State DRI Science Team for R/V Sikuliaq 2015 (left to right):**

Ethan Roth (ship's tech), Mike Hoshlyk (Captain), Martin Doble, Bjorn Lund, Byron Blomquist, Erick Rogers, Jeff Anderson, Ola Persson, Maddie Smith, Jim Thomson, Alex de Klerk, Peter Guest, Toshi Maki, Alison Kohout, Robin Clancy, Peter Wadhams, Guy Williams, Hayley Shen, Ted Maksym, Sharon Stammerjohn, Steve Ackley, Ben Holt, Blake Weissling, Bern McKiernan (ship's tech).

Not Pictured: Bob Ziegenhals, Steve Roberts (ship's tech).

## **Acknowledgements**

**Ship's Crew:** Mike Hoshlyk (Captain), Bob Anderson, John Hamill, Elliot Salyer, John French, Rob Worrada, Chris Gabaldo, Arthur Gould, Marian Tudoran, Terry Anderson, Randy Flannigan, Richard Null, Kevin Reinhardt, Patrick Bedard, Michael Henderson, Jonathan Pierce, Marcel Beaudin, Matt Tocchini, Susan Swartz, Ann Parcels Kurek, Ethan Roth, Bern McKiernan, and Steve Roberts, Doug Baird, and Steve Hartz.

**Shore team (satellite remote sensing and forecasting):** Johannes Gemmrich (chair), Adam Inch, Hui Shen, Will Perrie, Susan Lehner, Rudolf Ressel, Egbert Schwartz, Birgit Schaettler, Staci Langston, Hans Graber, Flavio Parmiggiani, Tripp Collins, David Hebert, Jim Dykes, Pam Posey, Rick Allard, Jean Bidlot, Amy Solomon, Janet Intrieri, Thomas Holden, Micki Ream and the analysts at the National Ice Center.

**NRL aircraft team:** John Brozena, Joan Gardner, David Ball, Richard Webb, Robert Liang

**ONR program managers:** Dr. Martin Jeffries and Dr. Scott Harper