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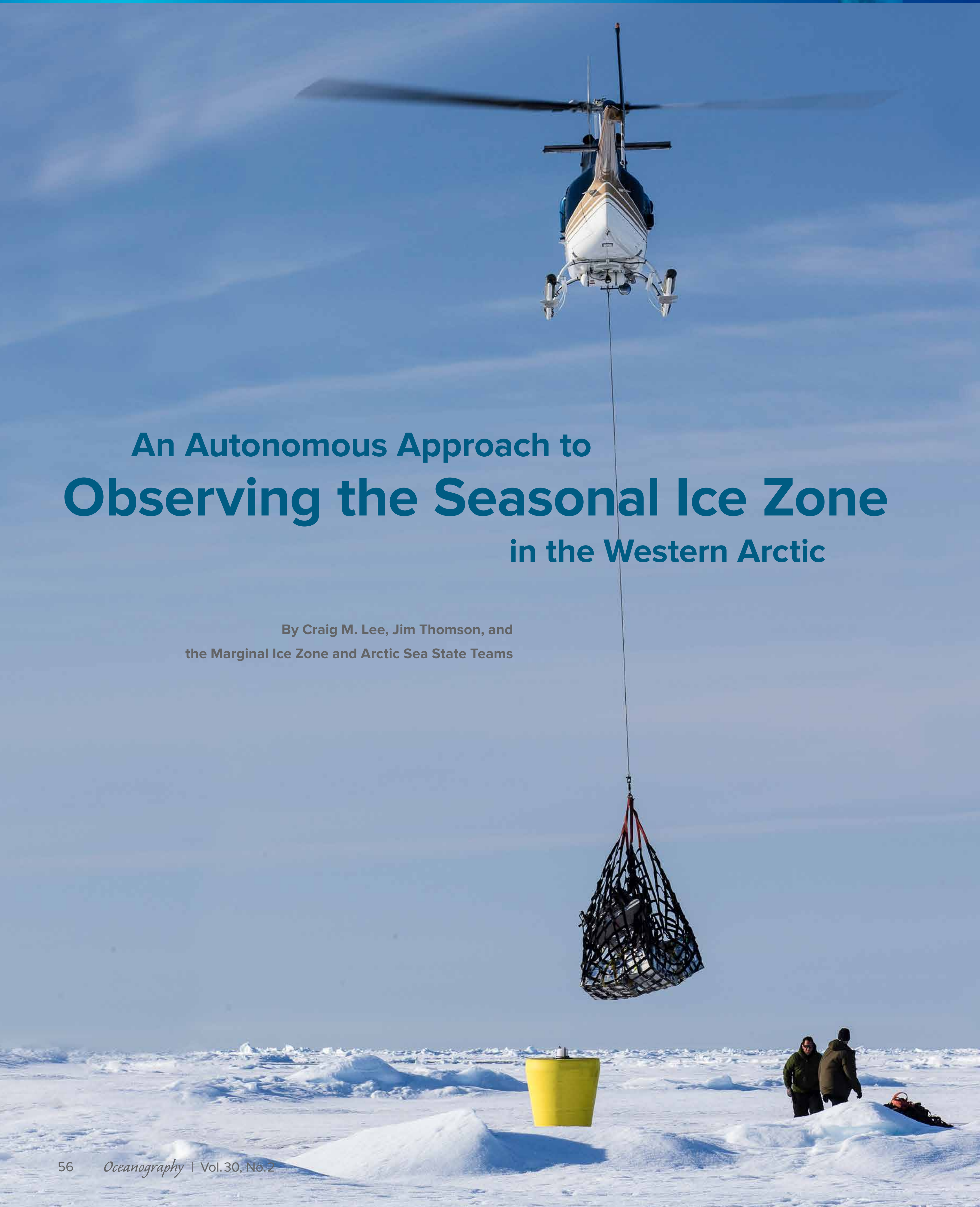
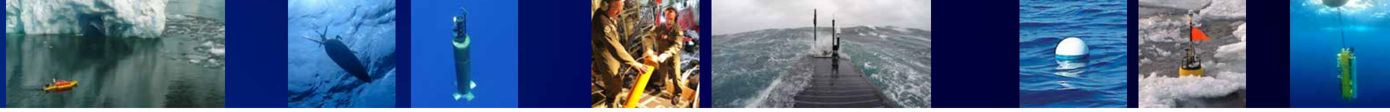


An Autonomous Approach to Observing the Seasonal Ice Zone in the Western Arctic

By Craig M. Lee, Jim Thomson, and
the Marginal Ice Zone and Arctic Sea State Teams



ABSTRACT. The Marginal Ice Zone and Arctic Sea State programs examined the processes that govern evolution of the rapidly changing seasonal ice zone in the Beaufort Sea. Autonomous platforms operating from the ice and within the water column collected measurements across the atmosphere-ice-ocean system and provided the persistence to sample continuously through the springtime retreat and autumn advance of sea ice. Autonomous platforms also allowed operational modalities that reduced the field programs' logistical requirements. Observations indicate that thermodynamics, especially the radiative balances of the ice-albedo feedback, govern the seasonal cycle of sea ice, with the role of surface waves confined to specific events. Continuous sampling from winter into autumn also reveals the imprint of winter ice conditions and fracturing on summertime floe size distribution. These programs demonstrate effective use of integrated systems of autonomous platforms for persistent, multiscale Arctic observing. Networks of autonomous systems are well suited to capturing the vast scales of variability inherent in the Arctic system.

INTRODUCTION

Dramatic changes in summertime Arctic sea ice motivated two process studies that relied on recent advances in autonomous observing to collect atmosphere, ice, and ocean measurements across the necessary span of temporal and spatial scales. The Arctic is warming at over twice the rate observed at lower latitudes (Overland et al., 2016), with pronounced impacts on the timing and extent of sea ice. Arctic Ocean sea ice follows a seasonal cycle dictated by incoming solar radiation, with sea ice advancing southward in autumn, as insolation drops with the approaching Arctic night, and retreating northward in spring as insolation increases. This seasonality has changed in recent decades, with a trend toward greater ice retreat each summer and a smaller, but significant, trend of decreasing wintertime maximum sea ice extent. The timing of these extrema has also shifted (Perovich et al., 2016). Summertime minimum Arctic sea ice extent has been in decline for nearly 40 years (Perovich et al., 2012), which, along with a reduction in thickness, has led to an overall decrease in sea ice volume (e.g., Kwok and Rothrock, 2009; Schweiger et al., 2011). The most dramatic sea ice decline has occurred in the Beaufort Sea and the Canada Basin (Figure 1a; Shimada et al., 2006), resulting in the loss of thick, multiyear ice (e.g., Maslanik et al., 2007) and the northward retreat of the summertime ice edge from the shelf into the deep basin.

Climate models have successfully captured the overall trend in summertime sea ice extent; however, they under-predict the observed rate of decline (Figure 1c; Jeffries et al., 2013). Observed summertime minimum sea ice extent varies significantly year to year, but the underlying rapid decline is just within the one standard deviation bound of predictions generated by an ensemble of climate models. This suggests that simulations may fail to properly represent the processes and feedbacks that govern sea ice evolution.

Limited understanding of the processes that govern sea ice evolution in the marginal ice zone (MIZ) may contribute to the inability of models to reproduce the steep decline in sea ice. Summertime opening of the Beaufort and Chukchi Seas has amplified the extent and influence of the seasonal MIZ, the region of fractional ice cover that forms the transition between open water and pack ice (Figure 1a). The MIZ is a region of complex atmosphere-ice-ocean dynamics that varies with sea ice properties and distance from the ice edge (Figure 2; e.g., Morison et al., 1987). Additionally, the northward retreat of sea ice exposes an increasing expanse of open water south of the ice edge, eventually providing sufficient fetch for the generation of long-period, large-amplitude waves (e.g., Thomson and Rogers, 2014). Such waves are capable of propagating north and penetrating into the pack to effect mechanical breakup of floes, greatly accelerating melt. Accurate characterization of MIZ processes becomes increasingly important as the Beaufort MIZ gains prominence.

In addition to the increasing areal extent of open water, the duration of the open water season is also increasing. This is particularly notable in the autumn; the freeze-up in much of the Beaufort and Chukchi Sea region is now one full month delayed from historic timing (Thomson et al., 2016). This delay provides more opportunity for the ocean to receive heat directly from solar radiation, as well as more opportunity for autumn storms to mix that heat far below the canonical depths of the near-surface temperature maximum (Jackson et al., 2010). The delay in ice formation thus feeds back to affect the type of ice that is formed and the persistence of that ice into the next seasonal cycle. For example, increasing surface wave activity is more likely to produce pancake ice, which until recently was rarely observed in the Arctic (Thomson et al., 2017). The formation of pancake ice can actually accelerate the autumn ice advance, but the ability to forecast this process is extremely limited.

Rapid changes in sea ice can have profound impacts on human subsistence and commercial activities. Arctic ecosystems responding to changing sea ice affect the timing and availability of subsistence hunting. Declining sea ice has also generated increased interest in activities such as transpolar shipping, resource extraction, and tourism, with implications for safety and national security. Coastal communities suffer from accelerated erosion as sea ice retreats northward, leaving shorelines exposed to increased summertime wave activity. Improved sea ice predictions are needed to inform planning and formulate responses to these challenging developments.

Recent advances in autonomous platforms are providing new perspectives on the processes that govern Arctic sea ice evolution because they capture spatial and temporal scales that previously had been challenging to sample. Robotic instruments that operate from the sea ice and in the water column have demonstrated persistent sampling over many months while resolving scales of kilometers and hours. Relative to conventional sampling (Figure 3), autonomous observations can span seasonal cycles with much greater temporal coverage.

Motivated by an overall need to improve predictability in the western Arctic on both operational and climate time scales, the US Office of Naval Research (ONR) supported two large, integrated observational programs focused on the Beaufort Sea. In 2014, the Marginal Ice Zone (http://apl.uw.edu/miz) program employed a large array of autonomous platforms to study the seasonal ice retreat. In 2015, the Sea State (http://apl.uw.edu/arcticseastate) program used a research vessel and autonomous platforms to study the seasonal ice advance. Although conducted in different years, taken together the two programs provide a novel picture of the processes that govern sea ice evolution during the highly dynamic period that spans melt-out to freeze-up. Alongside their scientific objectives, these programs also focused on advancing methodologies for autonomous observing, developing and demonstrating new approaches for conducting sustained observations in ice-covered environments. Here, we report on the approaches and early combined findings of both programs.

AUTONOMOUS PLATFORMS AND EXPERIMENT DESIGN

The dynamics associated with summertime sea ice retreat and autumn advance pose significant observational challenges. Coincident measurements of the atmosphere, sea ice, and ocean must resolve a broad range of spatial and temporal scales to document how the balance of processes evolves in response to changing surface forcing, ice cover, and upper-ocean stratification. During the transition periods, rapid shifts in sea ice extent and properties demand mobile approaches that are capable of tracking the ice edge as it moves. Continuous measurements that span months to years are needed to illuminate the feedbacks that unfold at longer time scales, such as the sequestration of summertime solar heating and its influence on the timing and spatial variability of freeze-up (Timmermans et al., 2014). Previous and ongoing Arctic research programs, such as the Beaufort Gyre Observing System (e.g., Proshuntinsky et al., 2009a, 2009b) and the International Arctic Buoy Programme (http://iabp.apl.washington.edu), have demonstrated the value of autonomous sampling in this complex region.

The seasonal distribution of ice thickness measurements in the western Arctic reflects the challenges of making measurements in this difficult environment (Figure 3). The two largest concentrations of measurements center on late summer, when maximal open water offers the best access for ships, and spring, when the ice pack and operating conditions allow researchers to access the ice

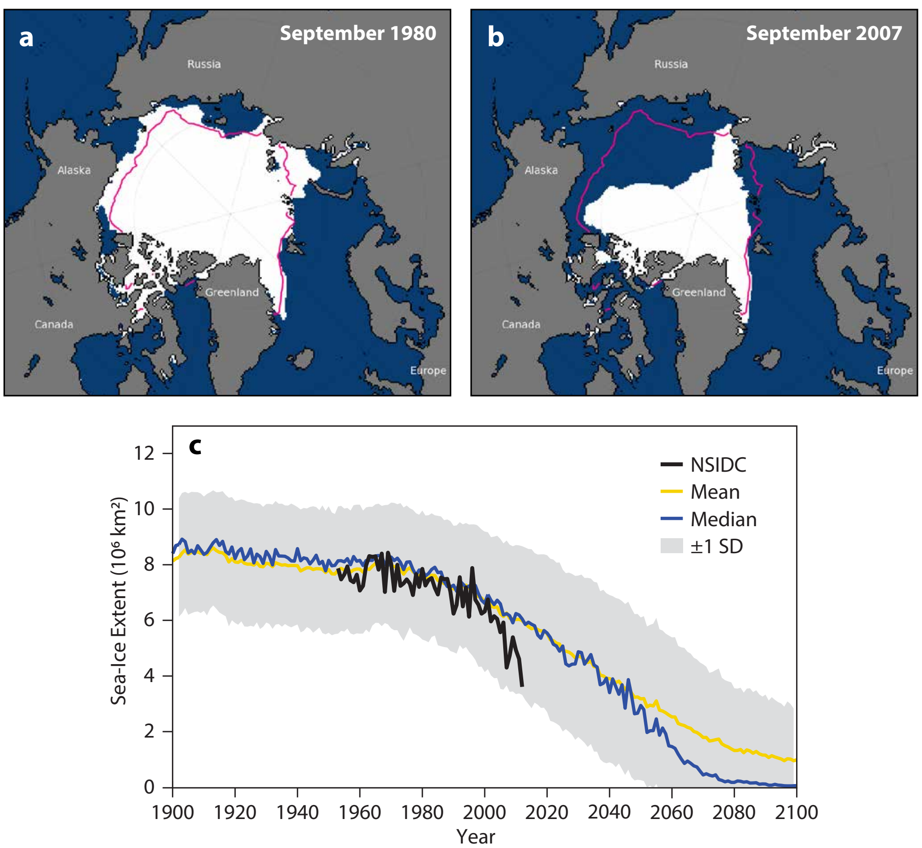


FIGURE 1. September sea ice cover in 1980 (a) and in 2007 (b). The red outline shows the difference in ice coverage, which is most notable in the western Arctic. *Credit: NSIDC* (c) Time series of the sea ice area at the September minimum each year. The black line is a satellite data product from the US National Snow and Ice Data Center. The yellow and blue lines mark the mean and median of September sea ice minimum predictions from an ensemble of climate models, with gray shading marking the one standard deviation bounds. *From Jeffries et al. (2013)*

using aircraft. During the transition periods, which embody the most dramatic changes, observations have been fewer due to the challenges associated with collecting measurements when both aircraft and ships struggle to provide access. Near-complete ice cover and inhospitable operating conditions have limited wintertime data collection to only a handful of observations.

The presence of sea ice presents challenges beyond those associated with logistics. Modern autonomous platforms rely on satellite services for geolocation (GPS) and telemetry (Iridium). Instruments mounted on the sea ice utilize these services, but those that operate independently of the ice, such as floats and gliders, must rely on arrays of acoustic beacons for geolocation, and they can communicate only irregularly through leads and other ice-free areas. The transition periods (melt-out and freeze-up) present challenges to instruments that rely on ice for a platform, making continuous operation in the seasonal ice zone difficult. Significant effort has been invested to engineer platforms capable of surviving these transitions. Lastly, the hazards of ice rafting, severe weather, extreme cold, and wildlife can take a toll on untended sensors mounted on the sea ice.

Marginal Ice Zone and Sea State program science objectives required continuous, high-resolution observations of the atmosphere, sea ice, and upper ocean that spanned the two sparsely sampled transition periods. To meet this challenge, both programs integrated the assets, interests, and expertise of large international teams of investigators and drew upon autonomous approaches. Such broad collaboration reflects both the scope of the science and the need for a multifaceted observational approach.

Observational Approach and Experiment Design

The Marginal Ice Zone and Sea State programs adopted measurement strategies that capitalize on the persistence, mobility, and lightweight logistics provided by autonomous platforms. Used in concert, ice-based platforms along with mobile instruments operating independently of the ice can collect collocated time series of the atmosphere, ice, and ocean with an expansive spatial footprint, resolving scales of kilometers and hours. Robotic instruments possess the endurance to sustain continuous sampling that extends from before the start of melt-out to the period of freeze-up and ice advance. This sustained, highly resolved four-dimensional sampling captures a region of the spatial-temporal spectrum that previously had been difficult to access, but is required to quantify the multiscale processes and feedbacks governing sea ice.

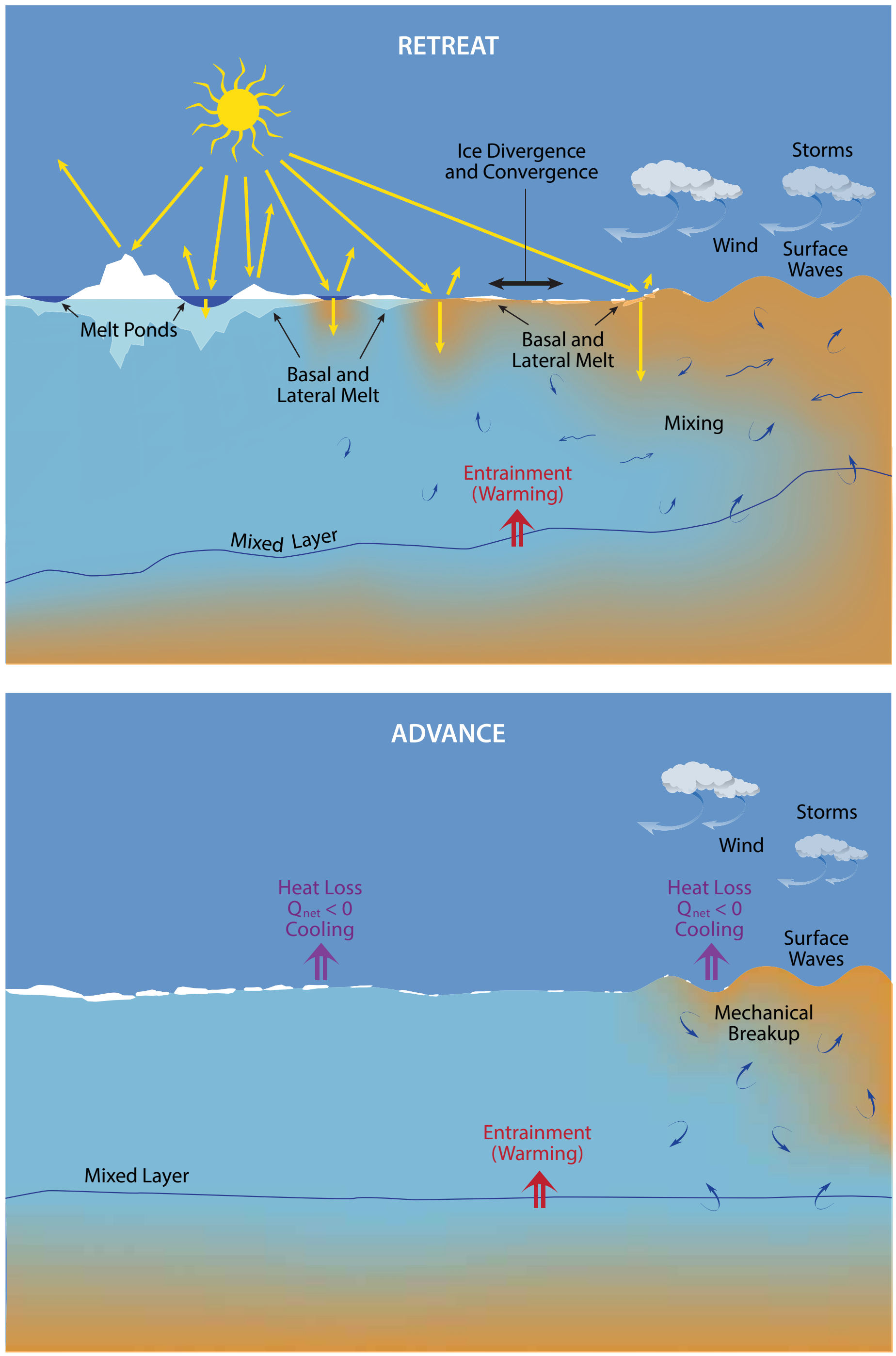


FIGURE 2. Atmosphere, ice, and upper-ocean processes governing (a) summertime sea ice retreat and (b) autumn sea ice advance. *Image credit: Kim Reading, Applied Physics Lab, University of Washington*

The intrinsic nature of ice-based platforms places sampling strategies into a Lagrangian framework: an ice-based instrument drifts with its host floe, thus providing an excellent reference frame for documenting its evolution. For observing ocean variability, this framework resembles sampling from a slow-moving ship. Spatial sampling of the upper ocean around the drifting assets is thus required to fully resolve the processes that govern interactions between the upper ocean and the sea ice. On a larger scale, the ability to deploy many autonomous instruments, along with gliders, autonomous surface and underwater vehicles, and ships that provide mobility, allowed sampling to maintain focus on the rapidly translating MIZ—the transition region between open water and pack ice thought to have the greatest dynamic variability.

MIZ experimental design exploited operational modalities provided by autonomous platforms to overcome the logistical constraints imposed by sea ice. Expansive ice cover at the start of the sampling program made ship-based sampling problematic, but favored aircraft operations. Fixed-wing and rotary aircraft can land on the springtime ice to deliver personnel and equipment, providing the opportunity for widespread deployments of numerous, lightweight ice-based robotic instruments. The MIZ program thus adopted an approach that relied primarily on autonomous platforms deployed by aircraft. This strategy allowed autonomous platforms to begin sampling in spring, well before the start of melt, and operate continuously through the autumn freeze-up.

In contrast, the Sea State program focused on the period of advancing sea ice, and thus began sampling around the time of maximum open water extent. This allowed broad access for ship-based sampling, but limited the utility of ice-based instruments. Sea State thus adopted an observing strategy centered on a heavily instrumented research vessel, with autonomous assets used to expand the footprint of shipboard operations and to provide measurements (e.g., ice draft) that could not be made from the ship.

With a ship as the central asset during the Sea State experiment, it was possible to target specific events and conditions in real time. R/V *Sikuliaq* operated with a rolling three-day plan, updated daily in response to weather forecasts and satellite remote sensing. The team aboard developed plans to deploy and maintain arrays of autonomous platforms to sample each weather event, and then adapted the plans as the event unfolded. As a result, the autonomous deployments during Sea State were generally much shorter than those in the MIZ experiment. The focus in Sea State was more specifically on using autonomy for dense spatial coverage, rather than for temporal endurance.

Components of an Integrated Atmosphere-Ice-Ocean Observing System

The Marginal Ice Zone and Sea State programs employed observational systems (Figure 4) composed of autonomous platforms, ships, and moorings selected for their complementary capabilities. Multiple platforms operating in concert were typically required to span the range of variables (atmosphere, ice, ocean) and scales required to resolve target processes. All platforms except moorings featured two-way telemetry, allowing them to upload their data and download new commands. This setup mitigated risk by ensuring data return regardless of the fate of the platforms, and allowed the science teams to adjust sampling plans in response to observed variability.

ICE-BASED DRIFTING AUTONOMOUS PLATFORMS

Autonomous instruments were deployed on sea ice, and thus sampled in a drifting reference frame that allowed their measurements to document the evolution of the host floes. Systems of complementary ice-based platforms currently provide the only approach capable of collecting contemporaneous, collocated measurements of the atmosphere, sea ice, and upper ocean. Ice-based platforms that depend entirely on ice for flotation do not survive melt-out, while others, such as Ice-Tethered Profilers, that have been engineered to survive melt-out and freeze-up can span these transitions, albeit with increased risk. During the MIZ and Sea State programs, these systems were deployed in regions of relatively solid ice cover.

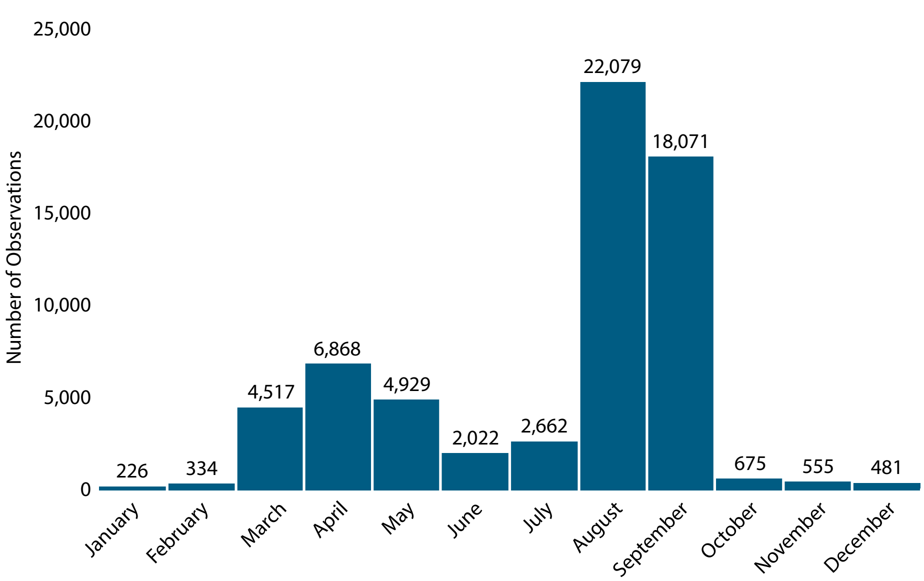


FIGURE 3. Number of sea ice thickness measurements, by month, in the western Arctic. These include on-ice (~in situ) sea ice thickness measurements taken by augers, cores, and surface electromagnetic radiation compiled from field experiments conducted from the 1890s (*Fram*) through 2011. *Source: Benjamin Holt, NASA/JPLCaltech*

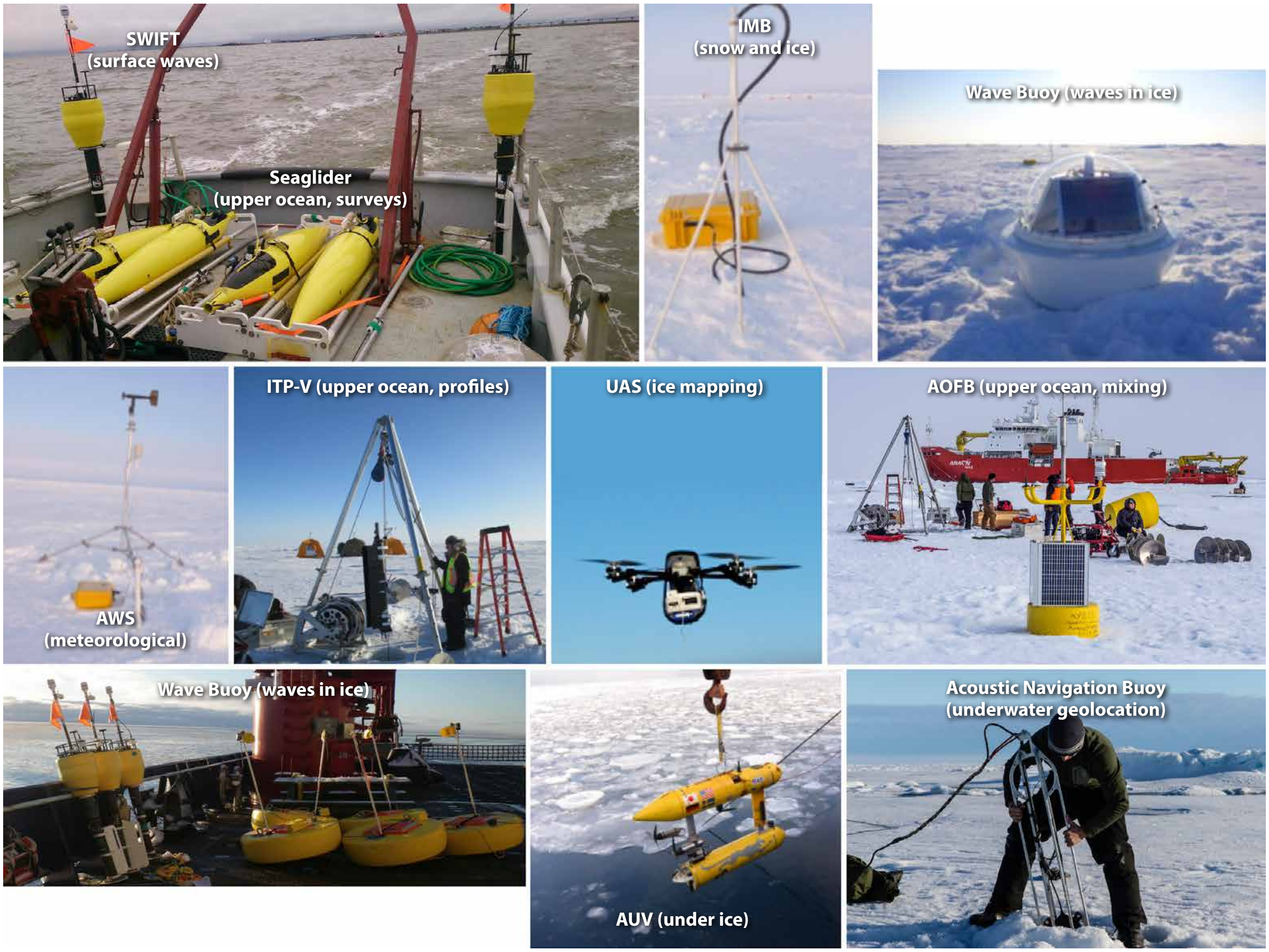


FIGURE 4. Autonomous platforms used in the field programs. SWIFT = Surface Wave Instrument Float with Tracking drifter. IMB = Ice Mass Balance Buoy. AWS = Autonomous Weather Station. ITP-V = Ice-Tethered Profiler with Velocity. UAS = Unmanned Aerial System. AOFB = Autonomous Ocean Flux Buoy. AUV = Autonomous Underwater Vehicle.

Ice Mass Balance Buoys (IMBs; Jackson et al., 2013) measured profiles of temperature and thermal response at finely spaced vertical intervals through the air, snow, ice, and upper water column. Thermal characteristics were interpreted to identify the interfaces between air, snow, ice, and water, and to quantify surface and basal sea ice melt rates (Polashenski et al., 2011).

Wave Buoys (Doble et al., 2017) installed on the ice used accelerometers and tiltmeters to measure spectral surface wave properties. These instruments quantified surface wave activity that penetrated into ice-covered waters.

Ice-Tethered Profilers (ITPs; Krishfield et al., 2008) provided high spatial (1 m) and temporal resolution profiles of temperature, salinity, and velocity (Cole et al., 2015) from near the ice-ocean interface to 250 m depth (at three-hour intervals) and 750 m depth (once per day), and direct estimates of the turbulent vertical fluxes of heat, salt, and momentum within the ocean mixed layer (Cole et al., 2015).

Autonomous Ocean Flux Buoys (AOFBs) measured profiles of mixed layer currents; vertical turbulent fluxes of heat, salt, and momentum near the top of the ocean mixed layer; shortwave radiative fluxes; and air-ice momentum transfer (using a three-dimensional sonic aneomometer) at 2 m above the ice, temperature from the ice surface to 4.5 m depth (using a thermistor string), and surface waves (Gallaher et al., 2017).

Automated Weather Stations (AWSs) composed of commercial, off-the-shelf instruments measured wind velocity, humidity, air temperature, surface pressure, solar radiation, and floe rotation. Untended atmospheric measurements are extremely difficult to sustain in the Arctic, and data return from these stations was limited.

Acoustic Navigation Buoys provided geolocation for autonomous platforms operating beneath the ice. A network of 900 Hz, broadband sound sources employed highly accurate clocks to broadcast on a fixed schedule, with each element transmitting six times per day (Freitag et al., 2015). Autonomous platforms calculated range from each source based on travel time and source location, which was transmitted as part of the signal. Position was then estimated through multilateration from multiple receptions.

OCEAN-BASED DRIFTING AUTONOMOUS PLATFORMS

Surface-drifting platforms targeted open water and the MIZ, collecting complementary measurements in the regimes that were challenging for ice-based instrumentation.

Surface Wave Instrument Float with Tracking (SWIFT) Drifters (Thomson, 2012) characterized surface waves and turbulence in both open water and partial ice cover. SWIFTs measured wind speed, wave height, wave directional spectra, air temperature, sea surface temperature, surface currents, and dissipation by turbulence while drifting at the sea surface.

MOBILE AUTONOMOUS PLATFORMS

Mobile platforms were directed to follow the shifting ice edge to characterize spatial variability around other drifting elements of the system.

Seagliders (Eriksen et al., 2001) are long-endurance, buoyancy-driven underwater vehicles that profile between the surface (or ice-ocean interface) and 1,000 m depth while moving at a horizontal speed of ~0.25 m s^{-1}. Gliders collected profiles of temperature, salinity, dissolved oxygen, chlorophyll fluorescence, optical backscatter, and spectral downwelling irradiance. The mobility provided by gliders was used to collect high-resolution sections from open water, through the MIZ, and into the pack, spanning the different regimes and providing spatial context for drifting assets.

Jaguar Autonomous Underwater Vehicle (Woods Hole Oceanographic Institution, Deep Submergence Lab) was used to conduct under-ice surveys, complementing observations collected by the ship. Measurements included ice draft as well as upper-ocean properties. The resulting ice draft maps are merged with aerial surveys to create maps and distributions of ice thickness.

Autonomous Surface Vehicles (Wave Gliders; e.g., Lenain and Melville, 2014) maintained a persistent presence in the open water immediately south of the MIZ, collecting meteorological and near-surface measurements just south of the ice edge.

Unmanned Aerial Systems (UAS) such as the quad-rotor (DJI Phantom 3, a commercial, off-the-shelf system) and fixed wing systems were flown to map ice and surface conditions near the ship and autonomous in situ arrays during the Sea State campaign. Video and still images collected during each flight were post-processed for georectification and estimation of three-dimensional digital elevation models using structure-from-motion techniques.

MOORINGS

The Marginal Ice Zone program augmented existing surface moorings, deployed as elements of other programs, to obtain extended time series of surface wave properties at sites in the Beaufort Sea.

SHIPS

During Sea State, a shipboard suite of instruments on R/V *Sikuliaq* that was designed to survey the air-ice-ocean system included an underway CTD sensor towed from the stern, a meteorological flux package mounted on the bow, and a Sea Ice Measurement System (SIMS) deployed on a boom over the side.

REMOTE SENSING

Both programs included extensive collection of synthetic aperture radar (3 m to 50 m resolution) and National Technical Means (visible, 1 m resolution) sea ice imagery targeted on the in situ assets (http://www.apl.washington.edu/miz). Time series of open water fraction and floe size distribution, critical for interpreting the in situ observations, were derived from the collection of images. Real-time remotely sensed sea ice extent was also used for operational decision-making for ships and mobile autonomous platforms. The Sea State program also employed local remote sensing, including shipboard radar, video, and LiDAR, as well as video from UAS.

SITUATIONAL AWARENESS AND DECISION-MAKING

Real-time situational awareness was required to target satellite image acquisitions on drifting ice-based assets and mobile vehicles during the Marginal Ice Zone program, and to inform ship-based surveys conducted during the Sea State program. During the MIZ program, real-time platform position data were used to model drift and predict instrument positions at the time of proposed image collections. A dedicated targeting team then used these predictions to keep remote-sensing collections centered on MIZ instruments. This facilitated acquisition of time series of images that document sea ice evolution around MIZ program assets. The Sea State program relied on rapid processing and curation (to optimize use of R/V *Sikuliaq*'s limited Internet bandwidth) of satellite imagery and weather forecasts to inform observational strategies. A dedicated shore-based team ensured timely delivery of useful products to the seagoing effort.

Putting it All Together— The MIZ and Sea State Programs

MIZ

The MIZ sampling strategy featured a large array of ice-based instruments, including acoustic navigation sources to support autonomous platforms working under the ice (Figure 5). Aircraft were used to deploy the array in early spring 2014 along a 300 km-long line extending northward in the eastern Beaufort Sea. The array was designed to quantify ice and snow thickness, surface wave properties within the MIZ, sea ice deformation, upper-ocean water properties, currents and turbulence, and meteorological variables as a function of distance from the ice edge. A 300 km-long span was chosen to ensure continuous measurements from the MIZ northward throughout the melt season, accounting for the expected westward drift, deformation, and melt-out (and resulting instrument loss) from the south. The actual drift involved considerably more rotation than had been predicted from modeling and analyses of historical drift data, with the ice-based array into an east-west orientation as it swept westward through the Beaufort Sea (Figure 6).

Drifting and mobile platforms sampled within the matrix of the ice-based array. A small boat (R/V *Ukpik*) operating out of Prudhoe Bay was used to deploy drifting and mobile assets (SWIFTs, Seagliders, and Wave Gliders) as soon as open water developed along the coast. SWIFTS and Wave Gliders sampled the open water and the MIZ, while Seagliders occupied sections that spanned open water, the MIZ, and pack ice, providing spatial context to bind measurements from the other assets.

The MIZ program also included late summer sampling from the Korean Polar Research Institute (KOPRI) Ice Breaking Research Vessel (IBRV) *Araon*. *Araon* extended the northward reach of the array by deploying a cluster of ice-based platforms at 78°N and conducted intensive sampling of sea ice, melt ponds, and biological and biogeochemical variability from a brief, collaborative, KOPRI-MIZ program ice camp staged from the ship.

Due to its focus on small, robotic platforms, the MIZ program was able to operate with a relatively light logistical footprint. An array of over 60 ice-based instruments was deployed over the course of a single week using a pair of Twin Otter fixed-wing aircraft and a Bell 412 helicopter operating out of Sachs Harbour, Canada. Overnight stays on the ice involved minimal personnel supported by light, mountaineering-style camps, minimizing the equipment and fuel required to execute the deployments. Ship operations were limited to a deployment cruise conducted from a small boat (R/V *Ukpik*), autumn recovery of Seagliders and SWIFTs from a short cruise aboard R/V *Norseman 2*, and instrument deployments and measurements far to the north conducted in collaboration with KOPRI aboard IBRV *Araon*.

SEA STATE

The Sea State field program consisted of a 42-day expedition on R/V *Sikuliaq* in the autumn of 2015. Figure 7 shows the ship track and satellite images of the ice conditions as the autumn progressed. Although the approach was more traditional (based on a ship), arrays of autonomous platforms were central to the work, both as a way to achieve greater spatial coverage and as a way to avoid the influence of the ship in the measurements.

A central science theme for the Sea State expedition was the interaction of surface waves and ice; this signal is intrinsically spatial, and thus distributed arrays of autonomous platforms provided a distinct advantage over a single vessel in observing this process. A total of seven wave-ice experiments were conducted during the expedition, each including the deployment of up to 16 Wave Buoys and SWIFTs. The ship surveyed both during and in between these wave experiments, using the surface flux system to map the

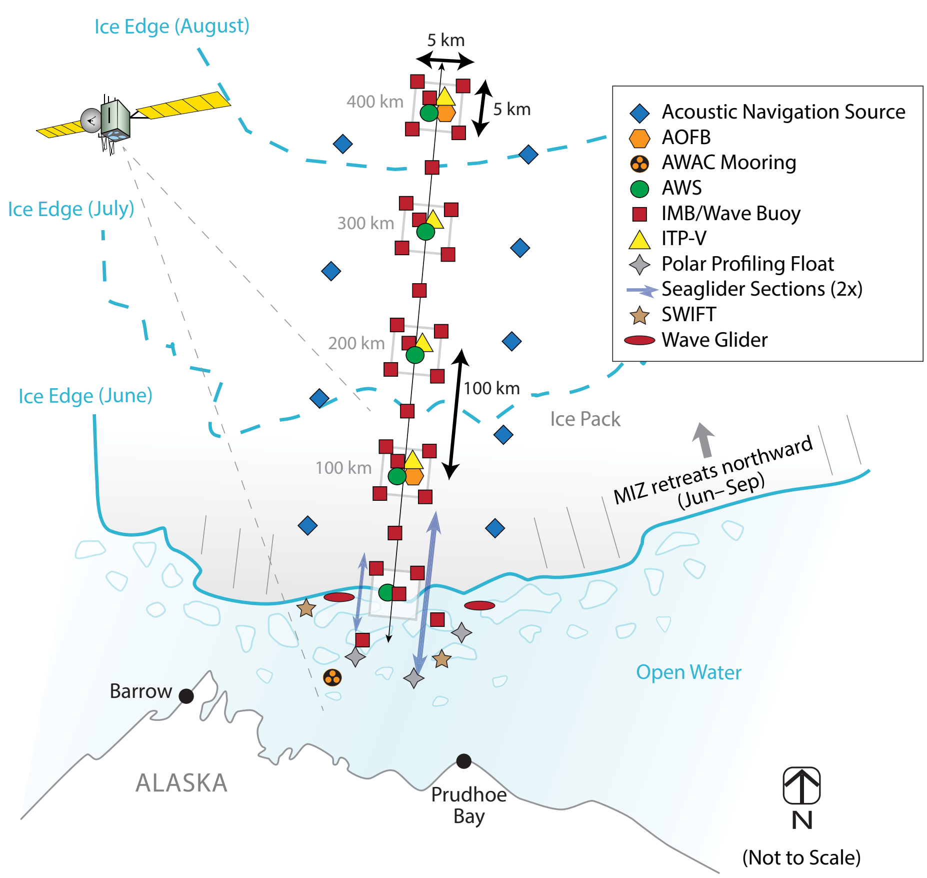


FIGURE 5. Idealized Marginal Ice Zone (MIZ) program observing array configuration. Note the markers indicating various instrument separations (drawing is not to scale). The northernmost cluster (400 km) was deployed by IBRV *Araon*. All other ice-based instruments were deployed using aircraft. Ice-based instruments melt out from the south as the MIZ retreats northward. Blue, double-ended arrows mark glider sections that follow the northward retreat of the sea ice to remain centered on the MIZ. Solid (dashed) light blue lines mark notional positions of the ice edge in June (July and August) relative to the observing array. *From Lee et al. (2012)*

cooling at the surface, and the underway CTD to observe the ocean response. The ship also supported 12 ice stations that collected detailed maps of ice floes from above (with UAS) and from below (with autonomous underwater vehicles), while more conventional thickness samples (hand drills) were collected by personnel on the ice.

A SEASONAL CHRONOLOGY OF ATMOSPHERE-ICE-OCEAN INTERACTIONS

Sea ice is part of a tightly coupled air-ice-ocean system where there are multiple feedbacks and interdependencies. Sea ice mediates exchanges of heat and momentum between atmosphere and ocean that increase as the sea ice retreats. In the MIZ, the large range of sea ice coverage and properties and the strong lateral gradients associated with the transitions lead to large variations in processes that govern these exchanges. In addition, surface waves, incident from open water, propagate into the MIZ.

Preliminary findings from these programs exploit the persistence provided by autonomous sampling to confirm the dominance of thermodynamics and radiative balances in controlling ice evolution, and also point to strong influences of ocean heat and surface waves. The relative importance of these processes appears to shift throughout the seasonal cycle. Thermodynamics are clearly dominant in the quiescent conditions of early spring. Once melting is well underway and the ocean is exposed to direct forcing by the wind, the system becomes much more energetic. Steele et al. (2015) show the importance of chronology in the seasonal ice cycle, and Zhang et al. (2016) report on ice floe size distribution throughout this cycle. Here, we provide a brief overview of the key processes targeted during the field campaigns (Figure 2).

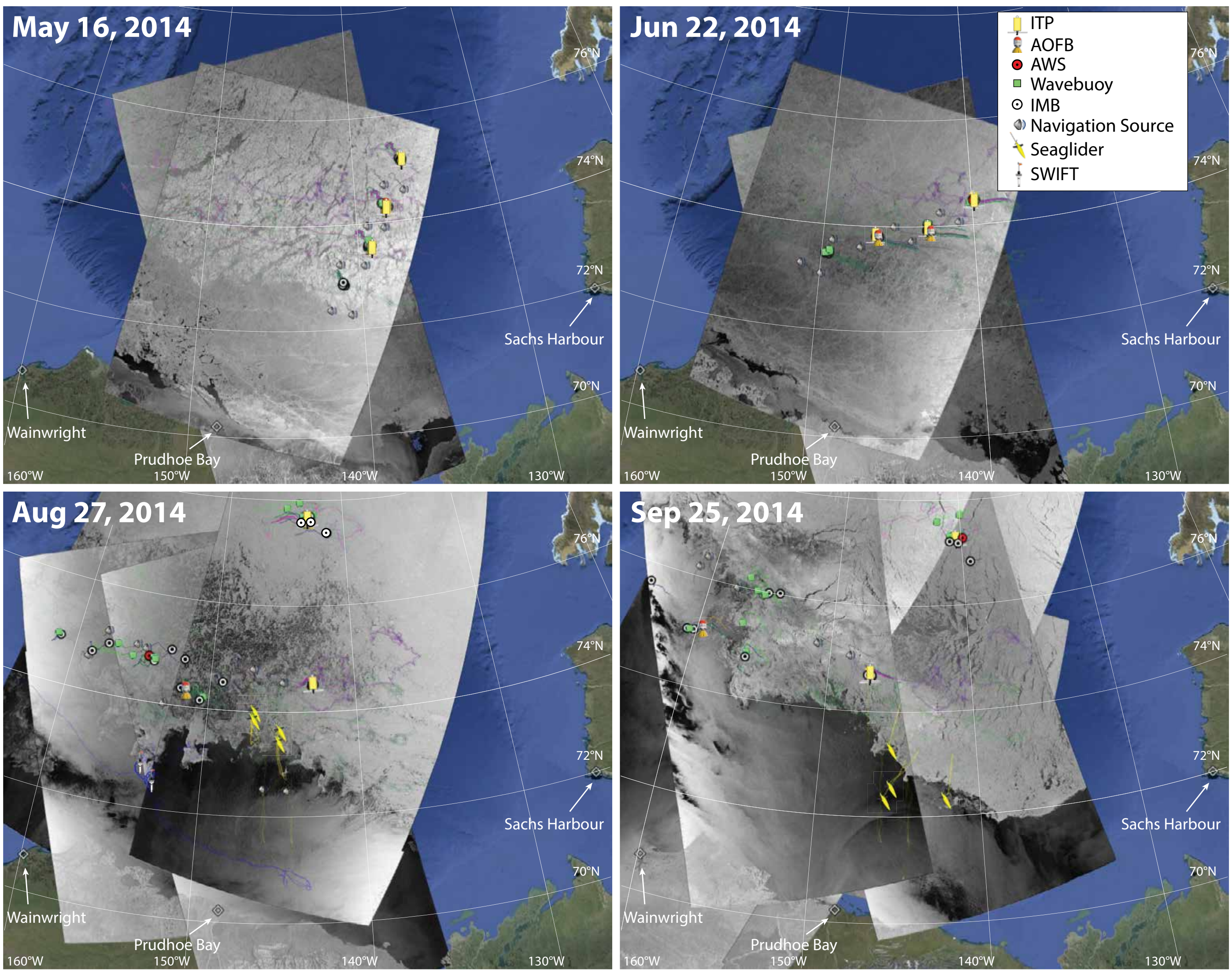


FIGURE 6. Snapshots of the progression of autonomous platform positions and RADARSAT-2 synthetic aperture radar ice images during the MIZ experiment. Light colors denote sea ice, while blacks and dark grays indicate open water. Colored markers indicate instrument positions at the time of the image. The May 16, 2014, image was taken roughly two months after MIZ deployment, before the array accelerated westward. By June 22, ice-based instruments had drifted westward and rotated into an east-west orientation. *RADARSAT-2 Data and Product MacDonald, Dettwiler, and Associates Ltd., All Rights Reserved. Figure credit: Luc Rainville, Applied Physics Lab, University of Washington, and the National Ice Center*

Ice Retreat Processes

Ice cover modulates penetration of solar radiation and isolates the upper ocean from direct wind forcing, but increasing open water within the MIZ and the proximity of large expanses of open water immediately to the south permit more direct connection with the atmosphere. Strong open water swell and surface wave activity attenuate as they enter the MIZ. Likewise, internal waves, submesoscale eddies, and mixing weaken with increasing ice cover. Small-scale wind stress curl associated with ice to open-water transitions and variations in ice roughness may induce intense secondary circulations that drive rapid vertical exchange. Enhanced mixing and vertical exchange can entrain heat stored below the mixed layer, increasing basal melting of sea ice within the MIZ. In ice-covered regions, local radiative solar warming leads to direct ablation of sea ice and some bottom melt from the radiation penetrating weakly into the ice-covered upper ocean. Open water regions within and outside of the MIZ allow increased radiative upper-ocean warming and, through lateral advection, accelerated ice melt. These processes are expected to amplify variance at short spatial and temporal scales across the MIZ.

WINTER CONDITIONING

Persistent observations of the atmosphere-ice-ocean system provided by autonomous platforms, combined with time series of remotely sensed synthetic aperture radar and visible sea ice imagery, allowed Hwang et al. (2017) to document episodic, storm-driven, wintertime sea ice breakup events, and to identify the influence of wintertime sea ice composition and fracturing on floe size distribution in the subsequent summer. Illuminating the connections between winter sea ice conditions and summer evolution required the sustained observations across winter-to-summer transition provided by autonomous platforms.

SURFACE MELT

In spring, increased local insolation drives snow and surface ice melt. Melting causes ponds to form on the surface of the sea ice (Figure 8a), decreasing surface albedo and initiating a strong feedback mechanism where reduced albedo increases absorption of solar radiation, driving more melt and thus further reductions in albedo. Gallaher et al. (2017) use AOFB data to show that the eventual drainage of these melt ponds provides a significant source of buoyant water to maintain strong near-surface stratification. This inhibits vertical mixing and thus helps generate and preserve the near-surface temperature maximum throughout much of the open water season.

BASAL AND LATERAL MELT

As spring progresses, expansion of open water areas and melt pond coverage introduce heat into the upper ocean that is then available to drive basal and lateral melting. Buoyancy from melt pond drainage also helps insulate the sea ice from heat stored below. Increasingly mobile sea ice and regions of open water provide more efficient transfer of momentum from the atmosphere to the upper ocean. This transfer of momentum can lead to generation of near-inertial motions and eddies that can enhance mixing and lateral stirring, competing with the dampening effects of elevated stratification. This represents another positive feedback, where ice melt leads to elevated mixing and more ice melt, modulated by the negative feedback of stabilizing melt water. These processes can bring recently warmed waters into contact with the base of the remaining sea ice, driving basal melting. This basal melting often occurs simultaneously with the ice breaking up

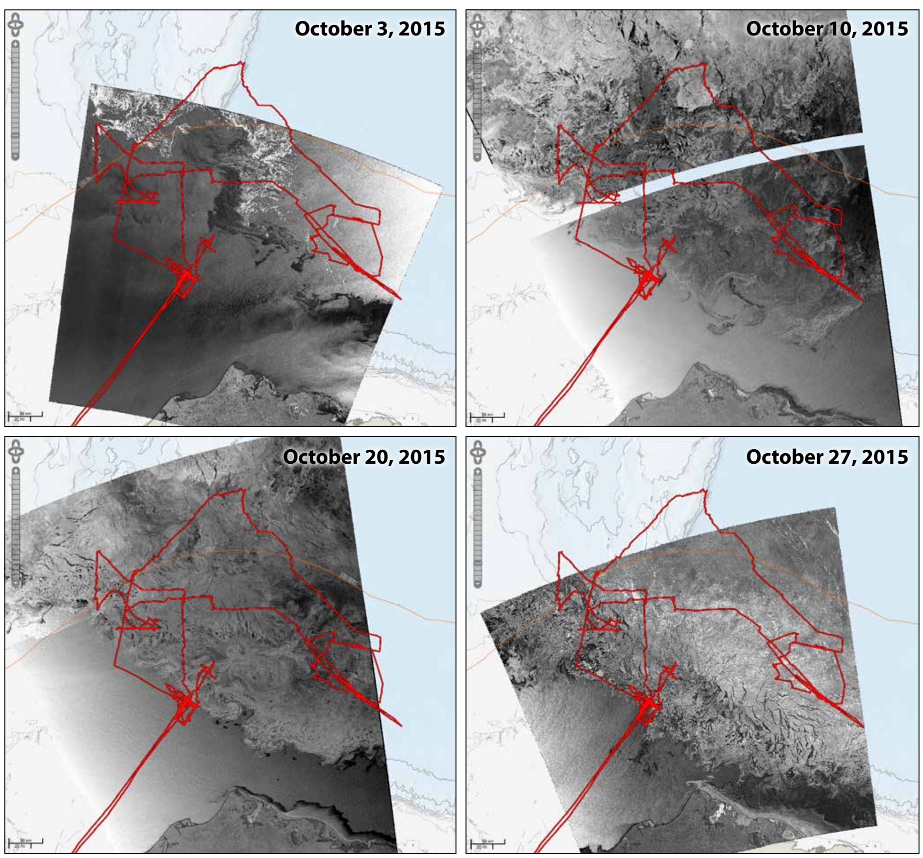


FIGURE 7. Ship track (red) and RADARSAT-2 synthetic aperture radar ice images during the Sea State experiment. The Alaskan coast and Point Barrow are visible in the lower portion of each image. The ice advanced through the experiment. *RADARSAT-2 Data and Product MacDonald, Dettwiler, and Associates Ltd., All Rights Reserved. Figure credit: Steve Roberts, University of Alaska Fairbanks, and the National Ice Center*

to form a marginal ice zone (Figure 8b). Gallaher et al. (2016) use AOFB data to show that ice divergence in the MIZ allows for enhanced ocean-to-ice turbulent heat flux and increased basal melting as the spring season progresses. This MIZ is still thermodynamically driven, modulated by the mechanics of winds and waves moving the sea ice.

WAVES AND STORMS

As spring turns to summer, later stages of ice retreat can be enhanced by storms, which generate waves in open water that propagate into the MIZ. The storms also provide wind stress to drive ocean mixing, which can enhance the basal melting already occurring. Figure 8c shows an example of open water and remnant brash ice (accumulations of floating ice made up of fragments not more than 2 m across) in the MIZ near the northern coast of Alaska in August 2014. This process can be challenging to capture with observing platforms because it is episodic and often localized. Wind and wave processes become more likely to dominate the ice retreat processes as summer progresses because the open water fetch available for wave generation increases (Smith and Thomson, 2016). This is another potential feedback mechanism, because the potential for waves to enhance ice retreat will create more fetch for even larger waves to form. Wang et al. (2016) used remote sensing and autonomous wave buoy data to show that floe size distribution eventually correlates with surface wave conditions as the season progresses.

Ice Advance Processes

The ocean surface heat budget controls ice formation. In the autumn, local insolation diminishes and cold air moves over the ocean. As the surface cools, the upper ocean also cools. There is a known near-surface temperature maximum, which is formed by solar heating over open water areas each summer (Jackson et al., 2010). The near-surface temperature maximum layer can contain sufficient heat to delay ice formation in the autumn, provided there is enough mixing to bring this heat to the surface where the strong cooling is occurring. By late autumn, this heat is either removed (via mixing to the surface) or trapped (via stable stratification).

GREASE AND FRAZIL ICE

As ice crystals form, they float near the ocean surface in a slurry called frazil ice, and are advected by winds and waves (Lange et al., 1989). Zippel and Thomson (2016) use SWIFT data to show strong suppression of turbulence in the presence of grease ice (a very thin layer of frazil crystals clumped together at the sea surface, making it look like an oil slick), which may decouple the surface from the wind and wave forcing (Figure 8d). If the wind and the waves are strong enough, the ice crystals coalesce and begin to form floes. The next stages of ice formation are thus distinct between calm and storm conditions.

NILAS ICE

When heat loss is dramatic and conditions are calm, thin sheets of new ice, termed nilas, can rapidly cover large areas (Figure 8e). This ice type is most prevalent during periods of off-ice wind.

FIGURE 8. Surface images throughout the seasonal ice cycle. (a) Photo of spring melt ponds on the surface of the sea ice taken from an autonomous Wave Buoy during the MIZ 2104 deployment. (b) Photo looking upward from an autonomous underwater vehicle, with the lower hull of a SWIFT buoy visible. (c) Open water and brash ice, with a SWIFT buoy. (d) Grease and frazil ice, with bands of open water. (e) Nilas ice sheets. (f) Pancake ice in waves, with a Wave Buoy in the distance. *Photo Credits: (a) Jeremy Wilkinson and Martin Doble, (b) Ted Maksym, (c) Jim Thomson, (d) Steve Ackley, (e) Jim Thomson, (f) Martin Doble*

Several nilas ice events were observed during the Sea State program, including one when a region approximately 5,000 km^2 was frozen in a single day.

PANCAKE ICE

Waves are responsible for the formation of pancake ice, which occurs when frazil ice is continually agitated by wave orbital motions (Figure 8f). During an October 2015 storm observed on the Sea State cruise, the ice edge retreated, but then rapidly advanced again immediately following the event, because the air temperatures were well below freezing. Rogers et al. (2016) use data from the array of 16 wave buoys and SWIFTs to explore the damping of waves by pancake ice during this storm; the work also presents the state-of-the-art in wave forecasting in the presence of ice. Though the effects of this autumn event were dramatic, as the season continues, the storms have less and less effect, because there is very little open water left to generate surface waves and little direct air-ocean heat exchange.

CONCLUSIONS

The seasonal/marginal ice zone of the western Arctic Ocean is expanding. Key processes coupling the atmosphere, ice, and ocean have been observed in two recent ONR-funded field programs: MIZ (2014) and Sea State (2015). These programs made extensive use of autonomous platforms to investigate the seasonal retreat and advance of sea ice. Relative to a starting hypothesis that surface waves have an increasing role in the seasonal cycle of the western Arctic, we find that this effect is, at present, confined to specific events in late summer and early autumn. Much of the seasonal cycle appears to be controlled by thermodynamics, especially surface radiative balances and the well-known ice-albedo feedback.

Observing the many and coupled processes of sea ice evolution requires persistence, especially for event-driven processes. These programs built on previous deployments of autonomous ice-based observatories to demonstrate that multi-scale Arctic observing can be done effectively and successfully using coordinated autonomous platforms. Ships and aircraft are still required as part of these operations, but they need not be the central platforms for data collection. Distributed networks of autonomous platforms are far better suited to capturing the vast scales of variability present across the Arctic system.

As the Arctic continues to change, observational approaches will be forced to continue to adapt. It may be that springtime ice camps supported by aircraft are no longer viable because of weak ice, or that ice-based autonomous assets melt out long before intended end-of-mission. The answers to these challenges will no doubt be more autonomy, with better synthesis of forecast and satellite products to help make decisions on the best use of assets in near-real time. The next ONR-supported effort, Stratified Ocean Dynamics in the Arctic (SODA, www.apl.washington.edu/soda), will study an entire annual cycle of the region and will continue to advance autonomous capabilities, including sustained under-ice observations with profiling floats and Seagliders throughout the winter.

Data analysis from the MIZ and Sea State programs is ongoing. Journal articles detailing the results are forthcoming in special issues of *Elementa: Science of the Anthropocene* and the *Journal of Geophysical Research – Oceans*, respectively.

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