



# THE BALANCE OF ICE, WAVES, AND IN THE ARCTIC AUTUMN

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# WINDS

Although summer sea ice loss in the Arctic is well studied, less is known about how ice comes back in autumn. A new program is changing that.

One of the most notable signals of rapid change in the Arctic is the loss of sea ice during summer months [Jeffries *et al.*, 2013; Wang and Overland, 2012]. Not only does the ice cover less area during the summer but also it's growing thinner [e.g., Stroeve and Notz, 2015]. Scientists have focused on studying the mechanisms responsible for summer ice loss, but they've paid less attention to the recovery of the sea ice in the autumn.

Most icebreaker-based research activity in the Arctic concludes by late September each year, resulting in a shortage of data for the autumn months. A new program, Sea State and Boundary Layer Physics of the Emerging Arctic Ocean (see <http://bit.ly/SSBLPEAO>), sponsored by the U.S. Office of Naval Research, has just completed a unique field campaign to investigate the dynamics of the autumn sea ice recovery in the Arctic.

Our expedition on board the newly commissioned R/V *Sikuliaq* collected data on the dynamics of air, sea, and ice from 28 September to 10 November 2015. During this time, the ice edge moved 250 nautical miles southward from the summer ice minimum in the Beaufort and Chukchi seas, reaching the Alaskan coast.

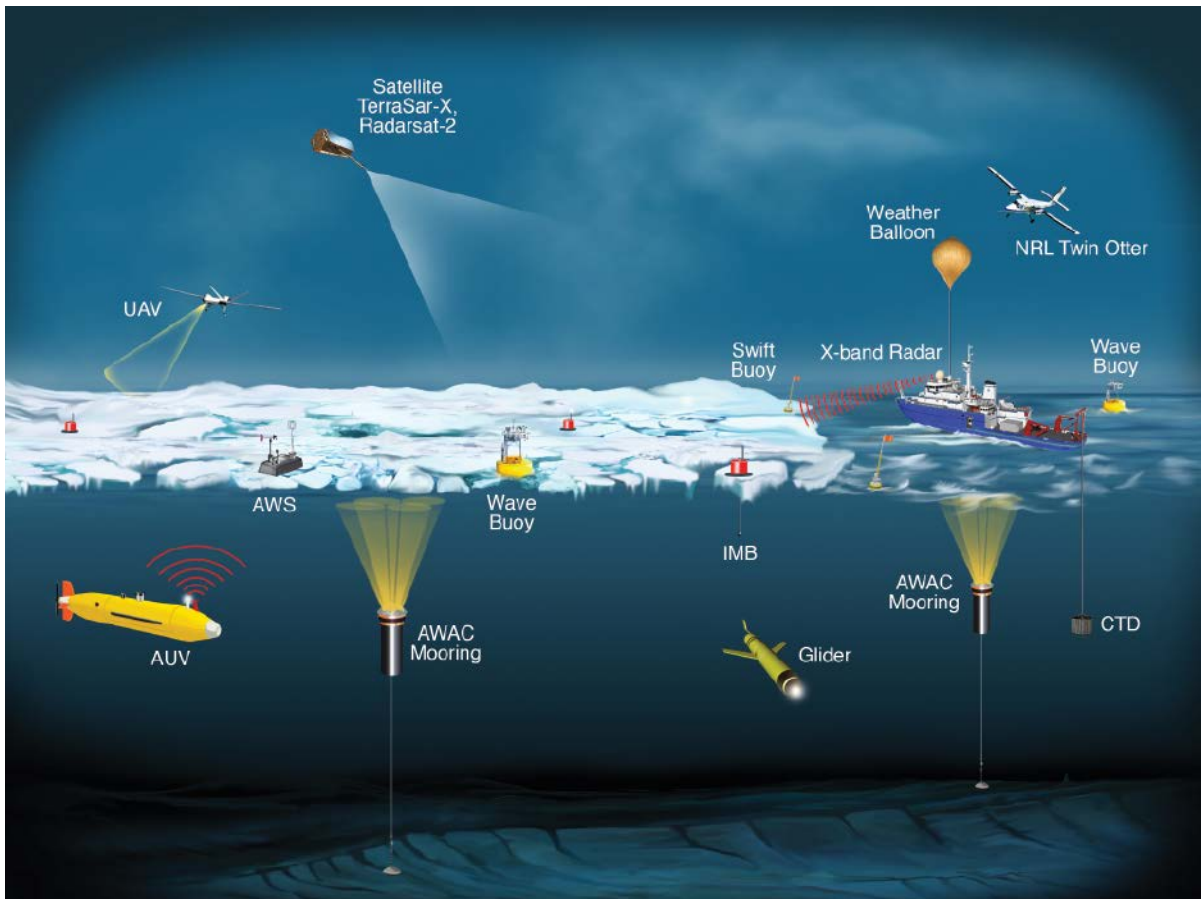
## Making Waves

The field program was designed specifically to understand the effects of an increasingly dynamic sea state (i.e., an increase in surface wave activity) on autumn ice recovery (Figure 1).

The loss of sea ice has not only increased the size of the open sea but also increased the size of the waves themselves, as surface waves have a greater distance

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A Surface Wave Instrument Float with Tracking (SWIFT) buoy measures waves amid pancake ice.



Woods Hole Oceanographic Institution graphics department

Fig. 1. Instrument platforms used in the Sea State and Boundary Layer Physics of the Emerging Arctic Ocean field campaign include unmanned aerial vehicles (UAV), autonomous underwater vehicles (AUV), automatic weather stations (AWS), Acoustic Wave and Current (AWAC) moorings, and underwater gliders. Various instruments are mounted on buoys and weather balloons, and floating instruments measure ice mass balance (IMB) and conductivity-temperature-depth (CTD) data. X band radar and airplanes are used to map the ice and waves around the ship.

over which they can form and grow. To express this in nautical terms, fetch has increased [Thomson and Rogers, 2014].

This effect is most pronounced at the end of September, when sea ice extent is minimum (so fetch is maximum) and wind forcing is generally strong. Over the 6 weeks of the field campaign on board *Sikuliaq*, the simplest observation of all—visual confirmation of pancake ice formation—showed the effect of increased fetch on surface waves (Figure 2).

### Pancake Ice

Pancake ice forms when wave orbital motions (i.e., circular wave movements) disturb collections of ice crystals in the water, collectively called “frazil ice,” as the ice forms. Frazil ice is “slushy”—soft and amorphous—because the water is moving too much to allow a solid sheet of ice to form. Quiet waters can form large, thin, flat sheets of new ice, called nilas, but the mobilized frazil aggregates into small floes that float on the sea surface and collide as each wave passes.

The collisions make floes round so that they resemble pancakes. Because the pancakes are typically 1 meter or less in diameter, they are below the resolution of most

satellite imagery. This means that they are observed only from nearby, from ships or airplanes, or by autonomous platforms with cameras.

Pancake ice is relatively ubiquitous in the Antarctic sea marginal ice zone, but it has rarely been observed in the Beaufort and Chukchi seas. However, it was the dominant newly formed ice type that we encountered during this field campaign. We observed pancake ice with far greater regularity during this field campaign than in recent early autumn cruises in the eastern Beaufort conducted through the Joint Ocean Ice Study/Beaufort Gyre Exploration Project.

Clearly, the presence of pancake ice shows that wind events and the surface waves that come with them are important to the autumn ice recovery in the western Arctic Ocean. Wind and wave actions are perhaps also linked to the known trend of younger, thinner ice throughout the seasonal cycle [e.g., Maslanik *et al.*, 2011].

### Advance, Retreat, Advance

The prevalence of pancake ice has a large-scale effect on the autumn recovery of sea ice in the Beaufort and Chukchi seas. Figure 3 shows three maps of sea ice over 1 month; the daily progression is even more complex. As the wave



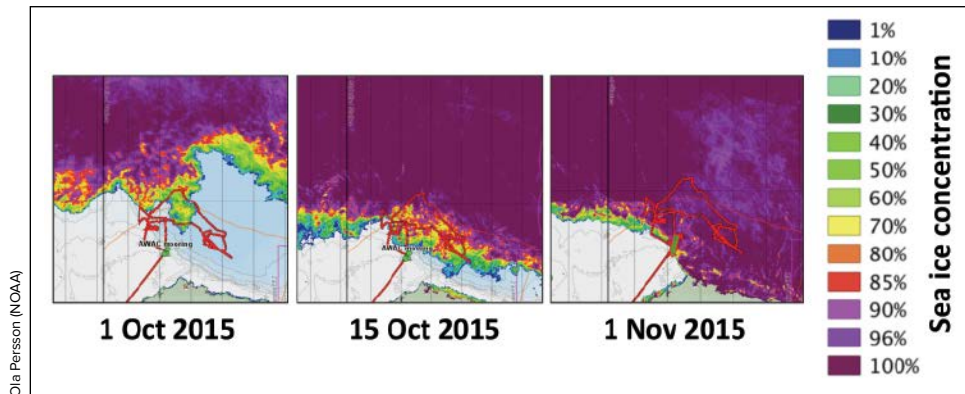


Fig. 3. Ship track (red path) of the R/V Sikuliaq as it traversed the Beaufort and Chukchi seas north of the Alaskan coast (gray landmass at bottom). Bathymetry (blue shading), and satellite-based ice concentrations (colors, representing the percentage of the area covered by ice in each pixel) show the recovery of sea ice during October 2015. These images were captured from the map server on board the R/V Sikuliaq, which was built and maintained by Steve Roberts of the University of Alaska Fairbanks. Ice concentrations, derived from data from the satellite-based Advanced Microwave Scanning Radiometer 2 (AMSR2), are from the University of Bremen.

motion declined (in either time or space), the pancakes often rafted together and formed larger, thicker sea ice floes. The pancakes then consolidated (or “cemented”) into surface sheets that were rougher than nilas sheets; these sheets of pancake ice aggregates presumably survived and became the winter ice pack.

Sometimes the pancakes’ dampening of the wave energy appeared to accelerate this cementing process, which eventually protected the interior pancakes from wave motions and allowed larger floes to form. In some other events, however, strong wind- and wave-driven mixing of ocean heat prevented the ice edge from advancing, and the pancakes melted in place. Thus, the ice edge advanced one week, retreated the next, and eventually advanced again in an irregular pattern driven by regional storm cycles.

### Linked Effects from Air, Ice, and Ocean

The autumn recovery of sea ice is the result of a tightly coupled air-ice-ocean system. This system is described by a surface energy budget, which quantifies the flux of heat at the air-ocean interface. If the sea surface loses heat when its temperature is already near freezing, freezing occurs. Colder air temperatures can enhance ice formation, which we observed on several occasions when winds blew over existing ice and out to open water.

Heat flux from the upper ocean can also counteract or retard ice formation. With larger areas of the Arctic Ocean exposed to the summer Sun, the upper ocean accumulates more heat now than in previous years when it was ice covered for more of the seasonal

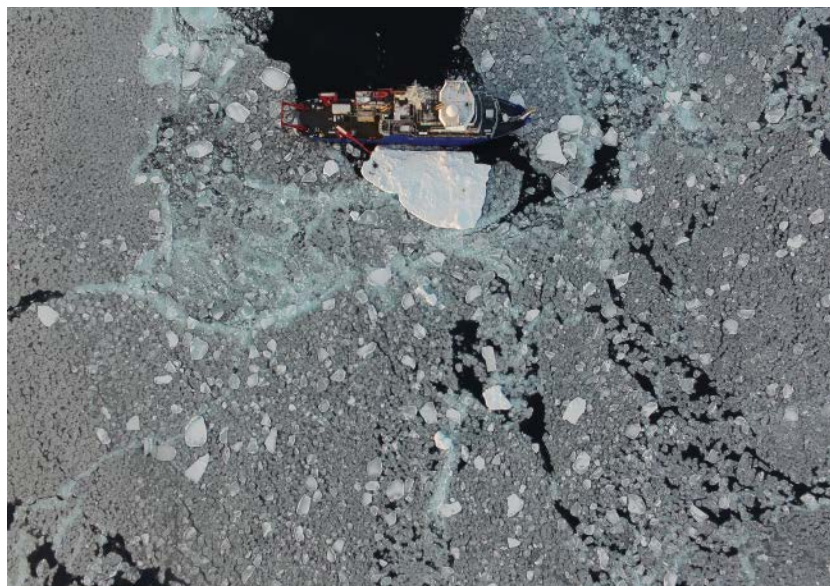
cycle [Perovich *et al.*, 2007]. This heat is often trapped in a near-surface temperature maximum layer [Jackson *et al.*, 2010]. We observed strong winds and waves mixing this layer upward to the surface.

Diagnosing the freezing process and autumn ice recovery thus requires comprehensive air-ice-ocean measurements, including wave and wind forcing and sea ice transport. Observations from our fall 2015

### Planning and Forecasting

The *Sikuliaq* cruise used a dynamic planning strategy that was crucial to adapting to the fast changing region of our study. Every day, the whole onboard science team participated in updating our plans for the next 3 days, with detailed activities for the day to come and less detailed plans for the following 2 days.

The team based these plans on weather forecasts, wave forecasts performed aboard the ship, and ice data from satellite remote sensing telemetered to the ship by the shoreside team members. Our short-term wave forecasts



The R/V Sikuliaq is surrounded by new pancake ice (gray) and remnants of multiyear ice (white) during an “ice station,” when the ship stopped at an ice floe immediately following a wave event on 17 October 2016. This photo was taken using a DGI Phantom unmanned aerial system.

Ola Perisson (NOAA)

Guy Williams (University of Tasmania/ACE CRC) and Ted Maksym (WHOI)



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were accurate in open water but much less so inside the ice cover. The accuracy of the remotely determined ice edge strongly affected the performance of the wave forecast. These forecasts tended to deviate substantially from observations during a strong wind event or rapid ice growth.

### Analysis to Come

We have an enormous set of air, ice, and ocean measurements to analyze, from the ship and from numerous autonomous platforms used during the field campaign. The 2015 autumn ice recovery demonstrated the highly interactive nature of ice, wave, atmospheric, and oceanic processes. The winds and waves modulate this ice recovery, which, in turn, influences interactions between the atmosphere and ocean.

This strongly coupled problem is clearly a massive challenge for the models we use to forecast the ice, waves, ocean, and atmosphere. These interactions cannot be implemented in computational codes before we understand them empirically or, better yet, before the underlying physical principles are understood.

Our task now is to use these data to quantify the sea state and ice formation processes. The end goal is to improve prediction for immediate operational use and for long-term climate scenarios. We intend for the subsequent model improvements to be useful to both the broader research community and the local communities who live along the Arctic coastline and experience climate change firsthand.

Our results will be published in a special issue of *Journal of Geophysical Research: Oceans* that has been approved for 2017.

### Acknowledgments

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