Ice-Capable Seagliders: Extended Under-Ice Operations and Real-Time Acoustic Navigation

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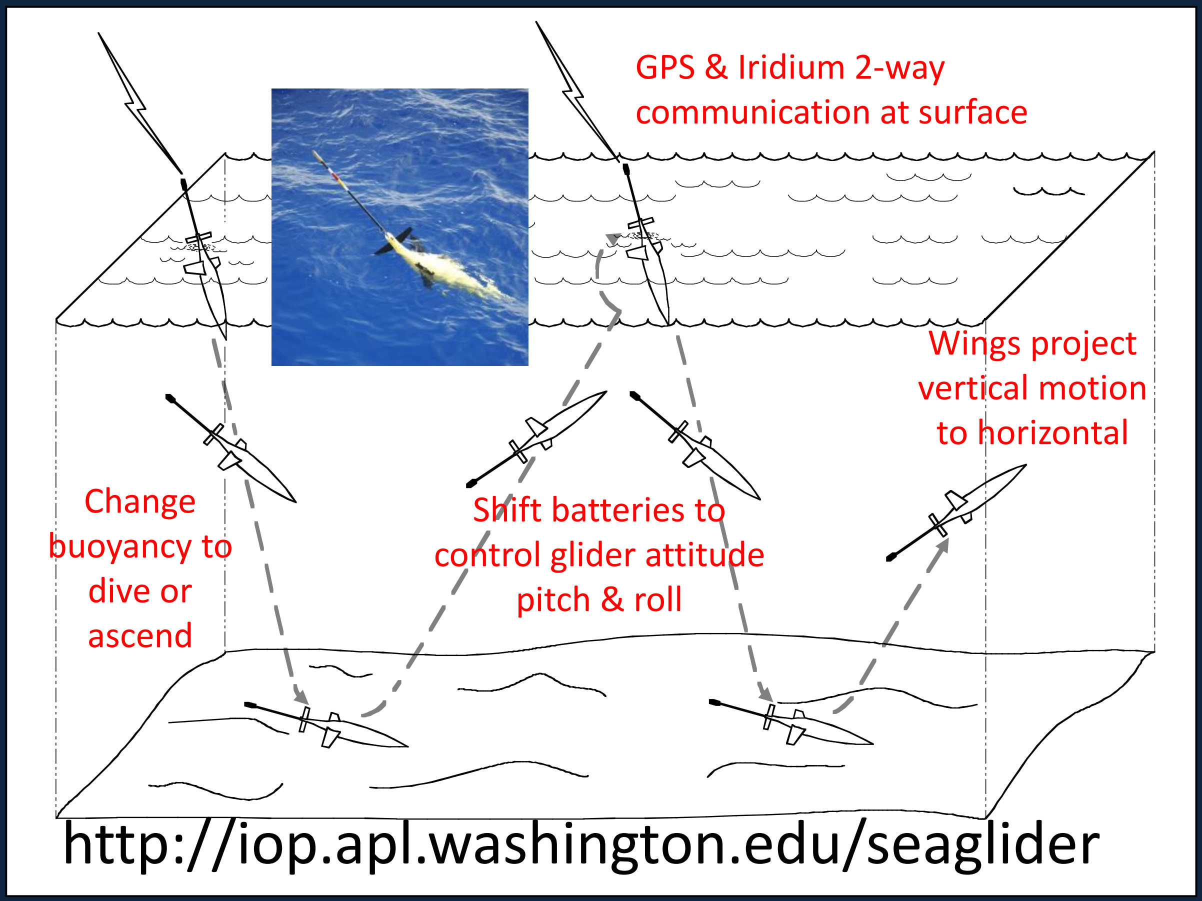
Woods Hole Oceanographic Institution

1. Seagliders
2. Baffin Bay – Davis Strait
3. MIZ Program
4. Perspectives

Long Endurance Autonomous Seagliders



- 50 kg, 2-m length
- Cycle 0-1000 m, ~6 km ~6 hours
- Horizontal velocity ~0.25 m/s (20 km/day)
- Vertical velocity ~0.1 m/s
- Typical deployment 3-5 months, longest to-date ~11 months.
- Endurance depends on ambient stratification, dive depth and desired speed.
- 2-way Iridium comms, data upload, slow remote control
- Temperature, salinity, pressure, current, optics, dissolved oxygen, turbulence, depth-average velocity (inferred).

Missions include: eastern and western boundary currents (Kuroshio), typhoons, quantitative biogeochemistry, fronts, eddies, submesoscale dynamics, subpolar, Arctic and Antarctic

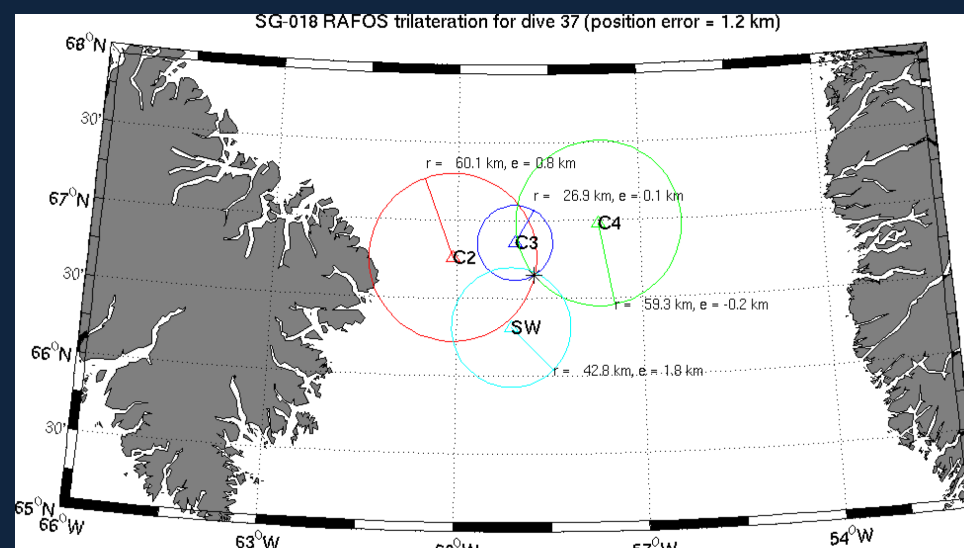
Lee/Gobat

Long-Endurance Seagliders for Ice-Covered Oceans

Lee, Rainville, Gobat (APL-UW)

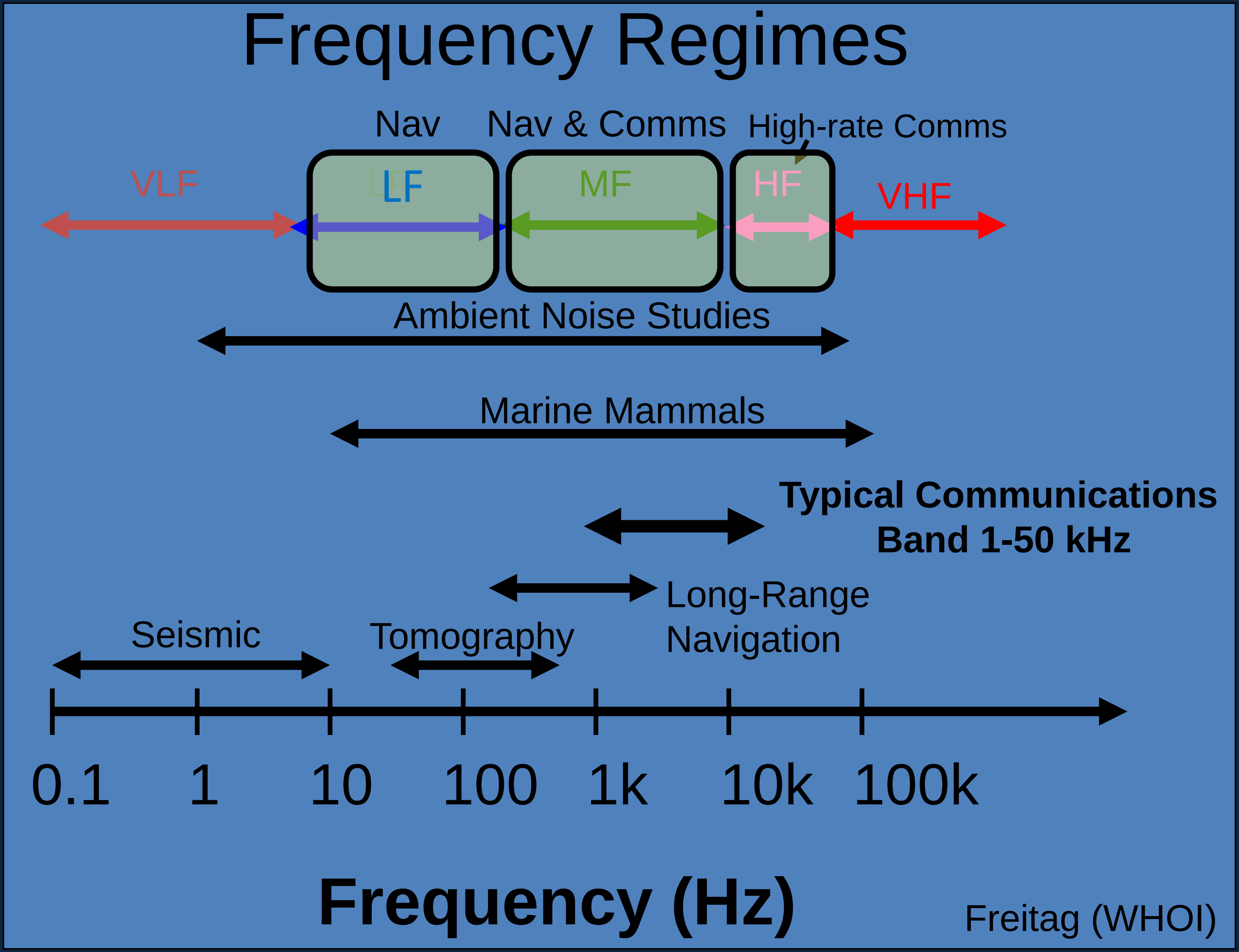
- Enhanced endurance, reliability
- Compass calibration/check procedures for high-latitudes ops
- Real-time acoustic navigation
- Ice detection- ice climatology, temperature, altimeter
- Enhanced autonomy with ‘ice ‘behaviors’
- Routine operations in full ice cover and marginal ice zone
- Acoustic communication for data transfer

- Broad Access
  - Remote regions, full ice cover
  - Ice-ocean interface, marginal ice zone.
  - Persistent sampling- long endurance
- Risk Mitigation
  - Limited exposure to ice-ocean interface.
  - Data return when open water available.
- Highly Adaptable
  - Simple logistics.
  - Real time reprogramming.
  - Flexible sampling.
  - Scalable.



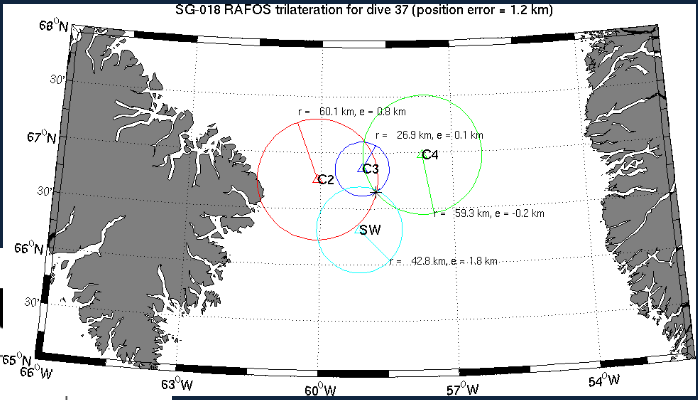
Acoustic Geopositioning & Communication for Autonomous Platforms

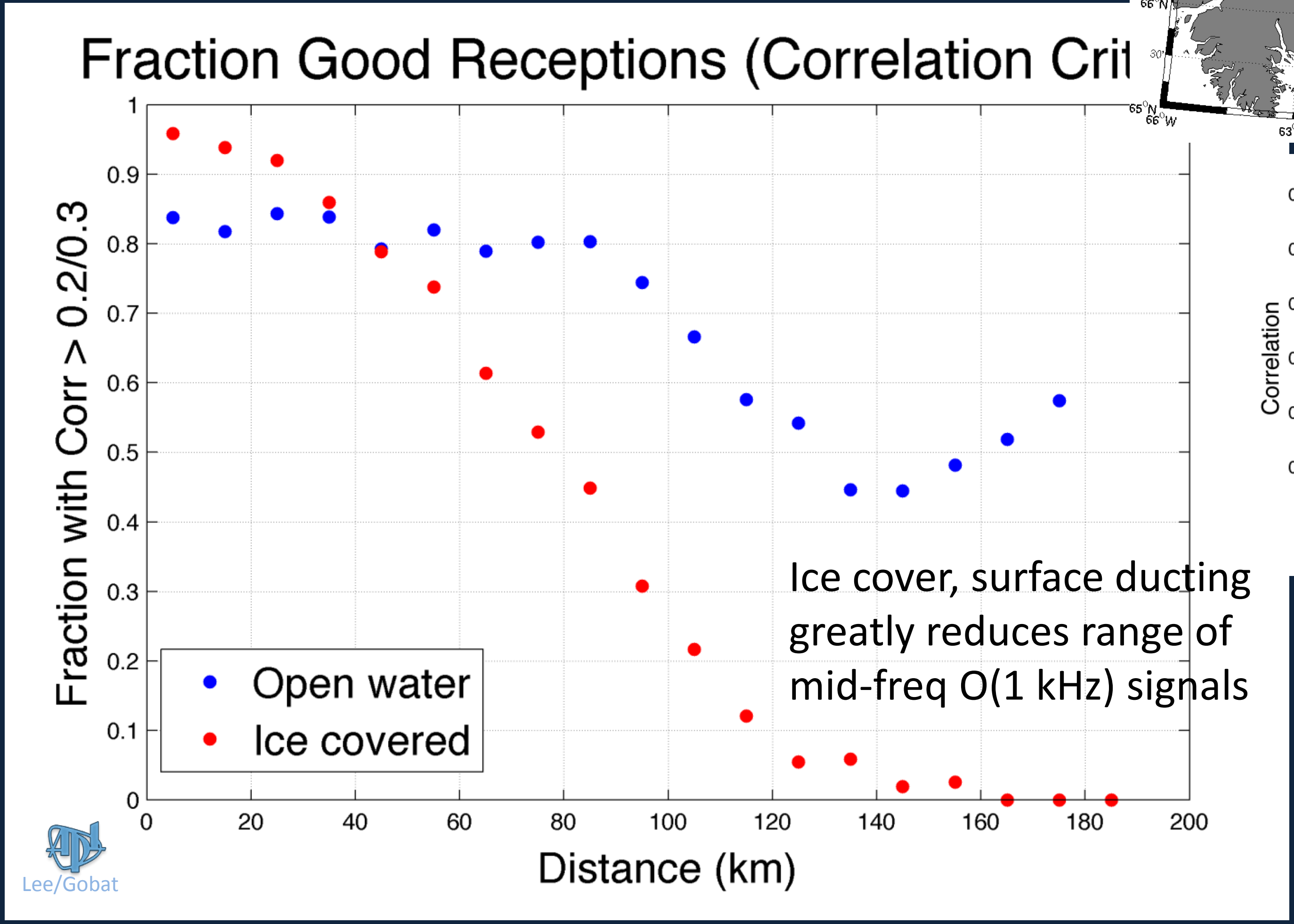
Additional information & community report: http://anchor.apl.washington.edu



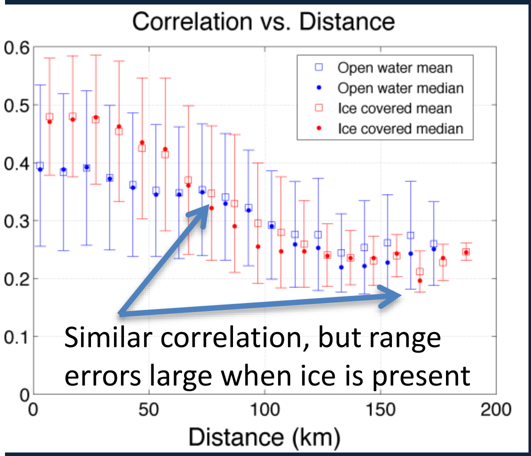
Davis Strait Arctic Gateway: 780 Hz Narrowband Real Time Acoustic Navigation

- Multilaterate from fixed sources (bottom moored)
- Broadcasts on known schedules
- Platforms carry accurate clocks, sync when possible





Ice cover, surface ducting greatly reduces range of mid-freq O(1 kHz) signals

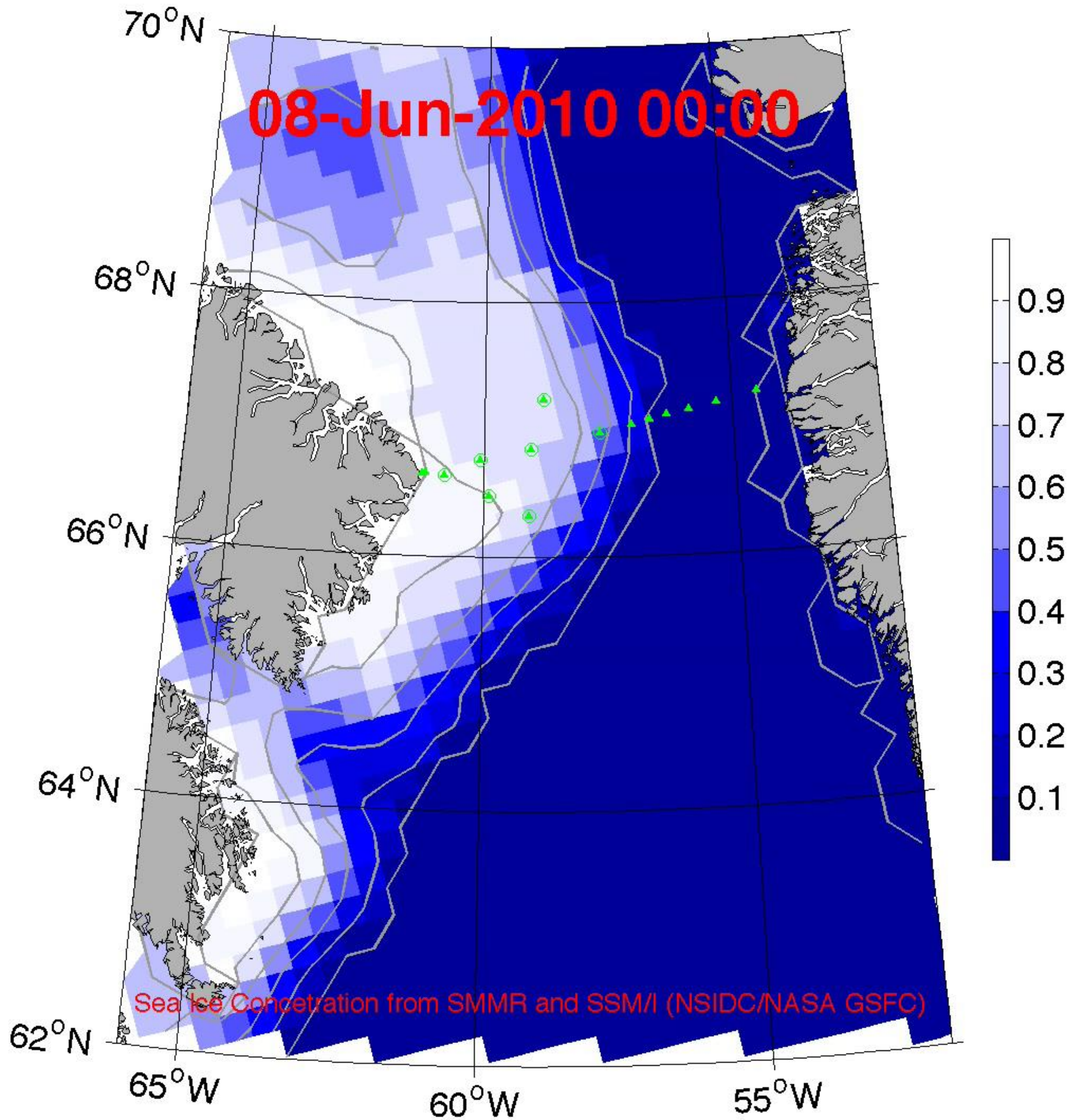


Similar correlation, but range errors large when ice is present

- Higher correlation required for RT fix when ice present.
- Accuracy ~1-2 km.

Year-Round Operations in Davis Strait

Lee, Gobat, Shilling, Huxtable (APL-UW)



SG108, SG183 & SG141
9 Jun 2010 – 17 Jun 2011

Jan-May:	ice-covered
Jun:	transition
Jul-Nov:	ice-free
Dec:	transition

- 34 sections
- 2113 profiles
- 1762 w/ ice autonomy
- 84% correct detection
    - 11% ice-obstacle
    - 42% ice-temperature
    - 47% open water
- 2.5% detect errors
- 13.5% ambiguous
- 52 forced surfacings
    - 23% success

Lee/Gobat

Autonomous Investigation of the MIZ

Craig Lee (APL-UW), Lee Freitag (WHOI), Martin Doble (LOV), Wieslaw Maslowski (NPS), Tim Stanton (NPS), Jim Thomson (APL-UW), Mary-Louise Timmermans (Yale), Jeremy Wilkinson (BAS) and the MIZ Team

Ice Mass Balance Buoys- Wilkinson (BAS), Hwang (SAMS), Maksym (WHOI), Richter-Menge (CRREL)

Wave Buoys- Wadhams (Cambridge), Doble (LOV)

Surface Wave Measurements- Thomson (APL-UW)

Autonomous Ocean Flux Buoys- Stanton, Shaw (NPS)

Autonomous Gliders- Lee, Rainville, Gobat (APL-UW)

Biogechemical Measurements (Perry, U. Maine)

Acoustic Navigation and Wavegliders- Freitag (WHOI)

Profiling Floats- Owens, Jayne (WHOI)

Ice-Tethered Profilers- Toole, Krishfield, Cole, Thwaites (WHOI), Timmermans (Yale)

Remote Sensing- Graber (CSTARS, U. Miami), Hwang (SAMS)

MIZMAS model- Zhang, Schweiger, Steel (APL-UW)

Regional Arctic Climate System Model- Maslowski, Roberts, Cassano, Hughes (NPS)

Arctic Nowcast/Forecast Model- Posey, Allard, Brozena, Gardner (NRL)

Melt Ponds, Biology, Biogeochemistry- Kang, Yang & colleagues (Korean Polar Research Institute)

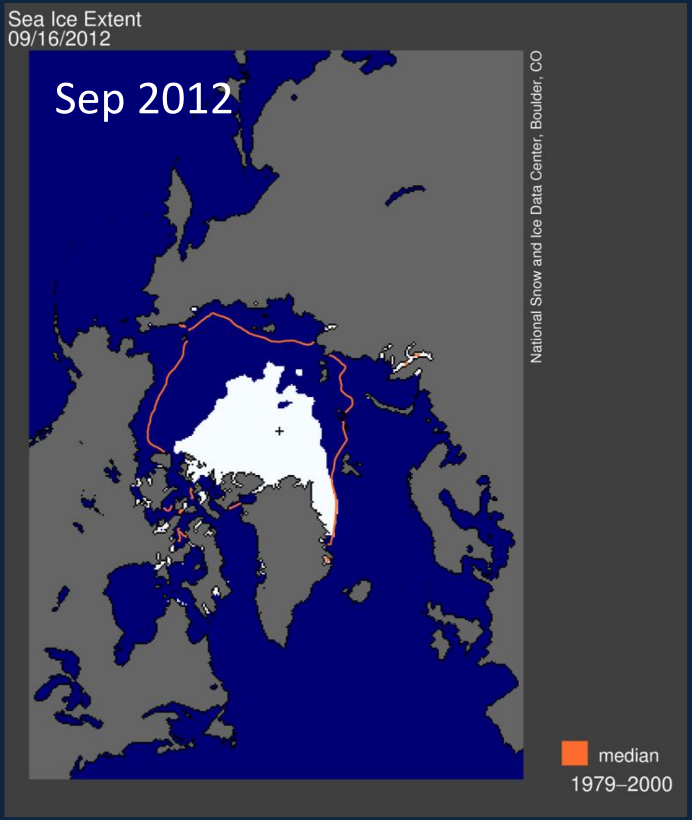
External Collaborations- NRL, NASA, NOAA, ESA

- Tightly integrated program.
- Interdependent elements.
- Exceptional collaboration.
- Strong team effort.

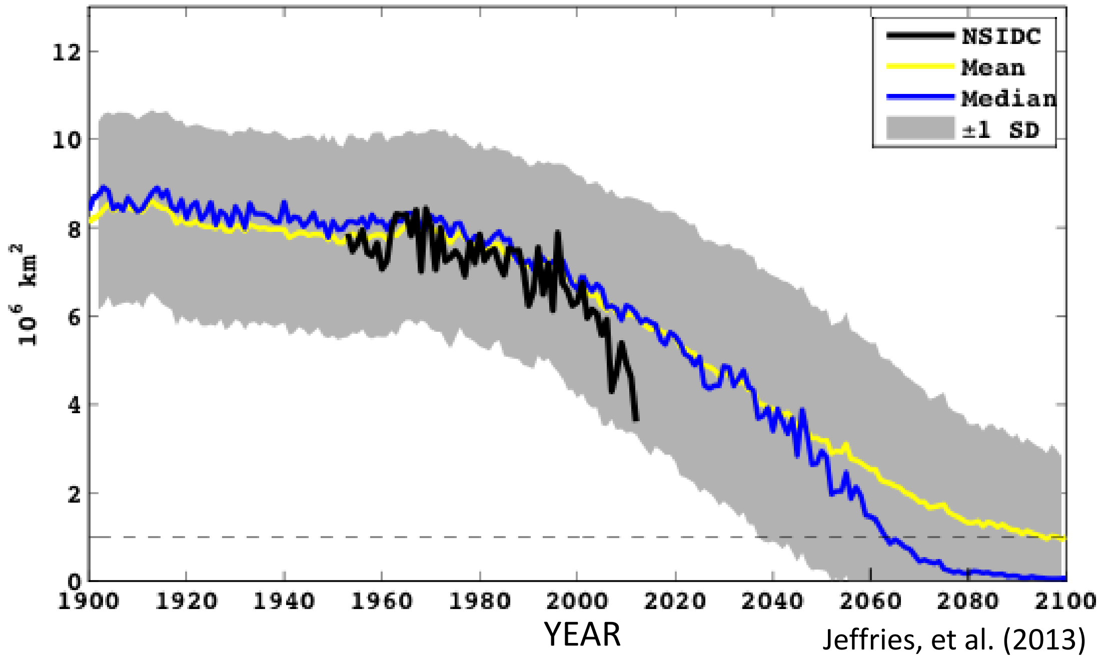
Models Struggle to Reproduce Dramatic Reduction in Summertime Sea Ice Extent

- 50% reduction in summer sea ice extent
  - 7 million km^2 in the 1970s
  - 3.4 million km^2 in 2012
- Wintertime sea ice maximum declining.
- Decline primarily thermodynamic, other processes may increase in importance.

Minimum Sea Ice Extent



Projected Changes in September Arctic Sea Ice Extent



Improve Predictability – Refine Models

- Process-level investigations
- Improve physics, parameterizations
- Continued testing against sustained observations

Refine physics <u>at the ice edge</u> – between pack ice and open water – <u>Marginal Ice Zone</u>

Program Objectives

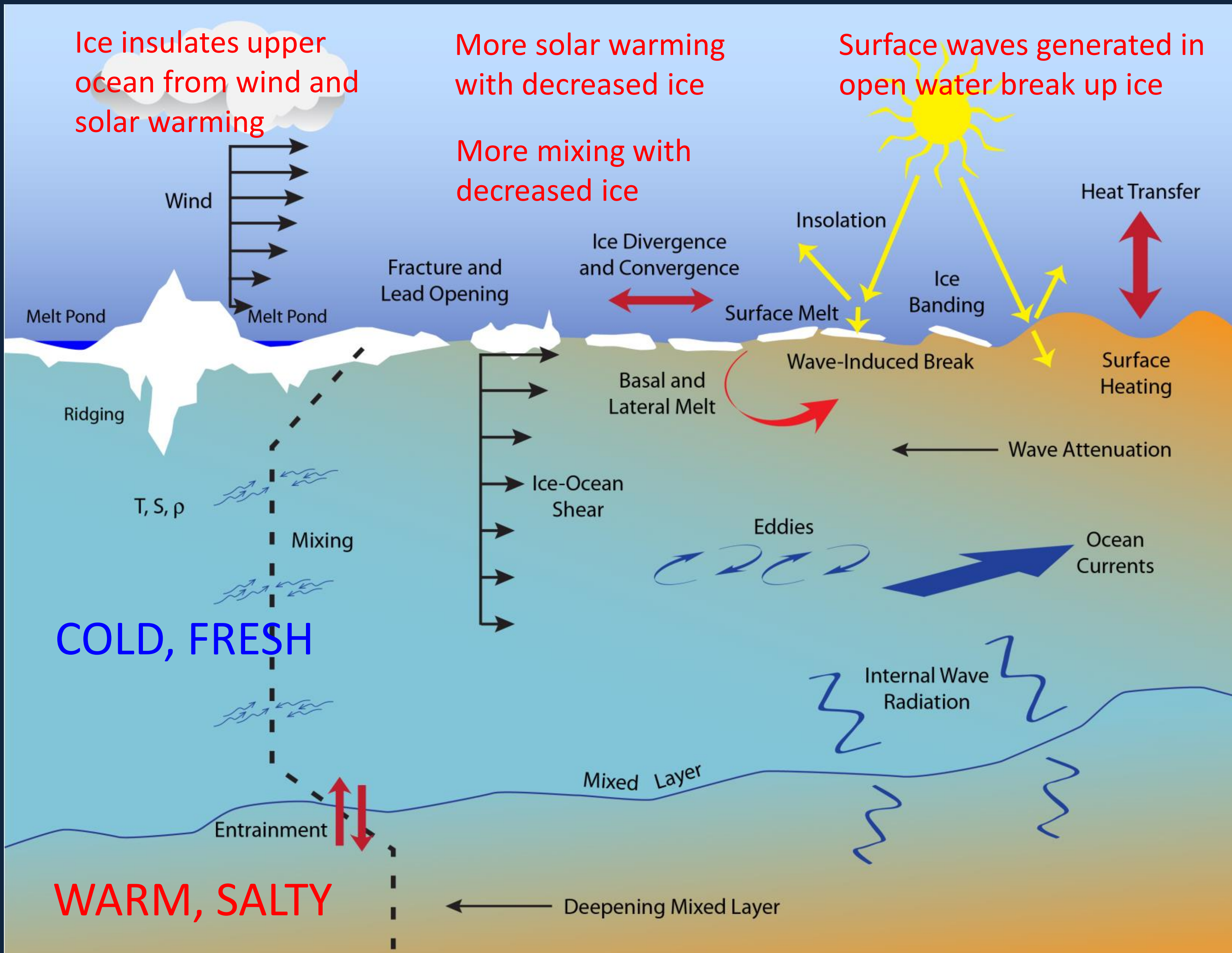
Science

1. Understand the physics that control sea ice breakup and melt in and around the ice edge (Marginal Ice Zone - MIZ).
2. Characterize changes in physics associated with decreasing ice/increasing open water.
3. Explore feedbacks in the ice-ocean-atmosphere system that might increase/decrease the speed of sea ice decline.
4. Collect a benchmark dataset for refining and testing models.

Technical

1. Develop and demonstrate new robotic networks for collecting observations in, under and around sea ice.
2. Improve interpretation of satellite imagery.
3. Improve numerical models to enhance seasonal forecast capability.

Atmosphere-Ice-Ocean Interaction



Challenges

To understand the processes that govern sea ice melt:

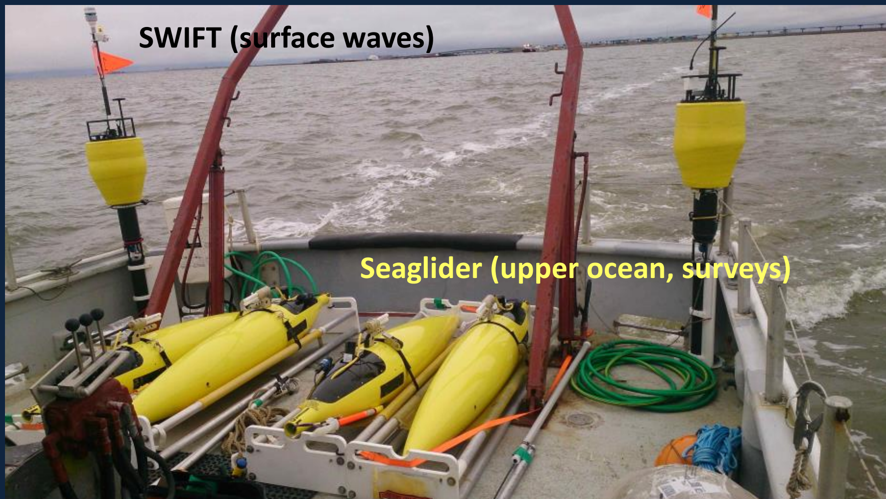
- Ice mass balance.
- Sea ice dynamics (locally and regionally).
- Open water fraction/floe size distribution.
- Surface wave penetration and dissipation.
- Meteorological forcing.
- Upper ocean variability.

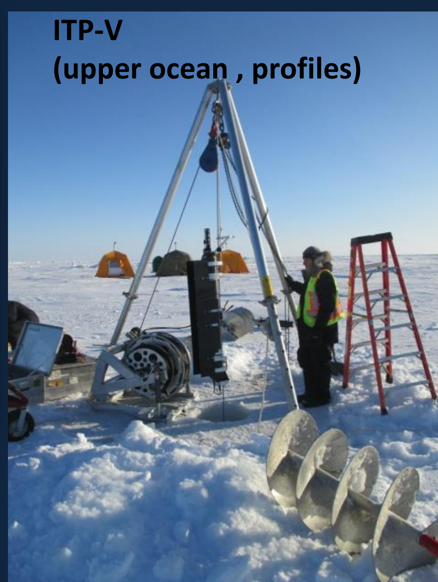
1. Resolution: Resolve temporal evolution and small-scale spatial variability (4-D physics).
2. Persistence: Sample entire melt season (Jun – Sep). Physics change as a function of open water extent.
3. Access: Measurements in full- and partial- ice cover.
4. Scalability: Large number of platforms provide distributed sampling, mitigate risk.

MIZ

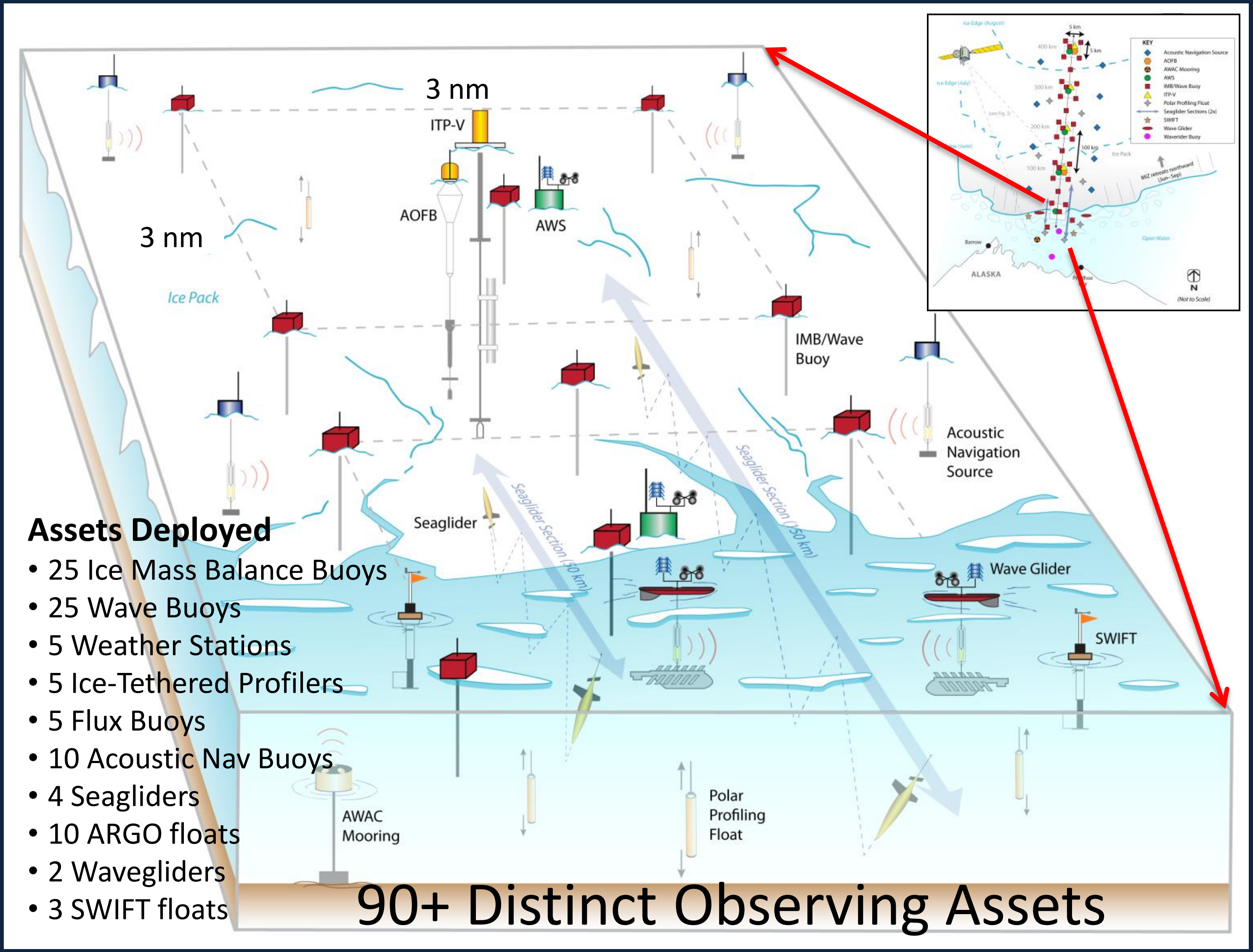
The Revolution in Robotic Observing

ONR
Revolutionary Research . . . Relevant Results





Putting the Pieces Together



Assets Deployed
- 25 Ice Mass Balance Buoys
- 25 Wave Buoys
- 5 Weather Stations
- 5 Ice-Tethered Profilers
- 5 Flux Buoys
- 10 Acoustic Nav Buoys
- 4 Seagliders
- 10 ARGO floats
- 2 Wavegliders
- 3 SWIFT floats

90+ Distinct Observing Assets

Fast and light logistics

Ice-based array deployed by aircraft in April (full ice cover).

Drifters & gliders deployed in July, with first open water.

Array drifts with ice pack

Extensive remote sensing (SAR): open water fraction, floe size distribution

Broadband Acoustic Navigation

Freitag (WHOI), Gobat, Webster, Lee (APL-UW)


Buoys:

- Transmit every 4 hours, fixed times.
- GPS synched.
- 900 Hz carrier.
- ~1 bps data rate.


Receiver on Glider:

- Measures time, computes range.
- Decodes location of buoy.
- Ranges and source locations used to compute real-time position.

Mobile Acoustic Sources

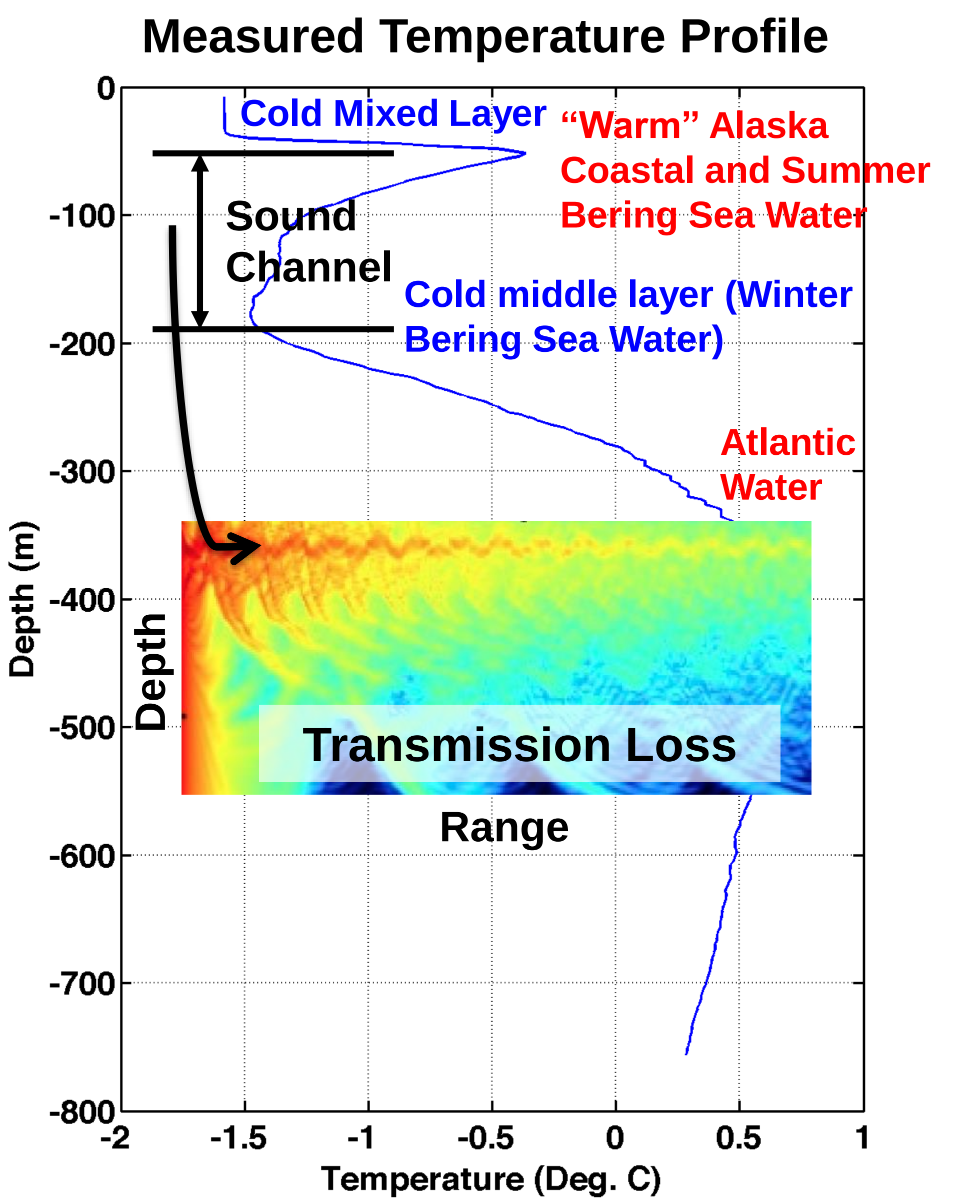
- Ice-based nav sources drift.
- Therefore must transmit source positions to allow real-time geo-location by gliders.
- Data transmission capability also means commands can be sent to glider.
- May also be used in moored (fixed) configurations.

Glider Receiver Hydrophone

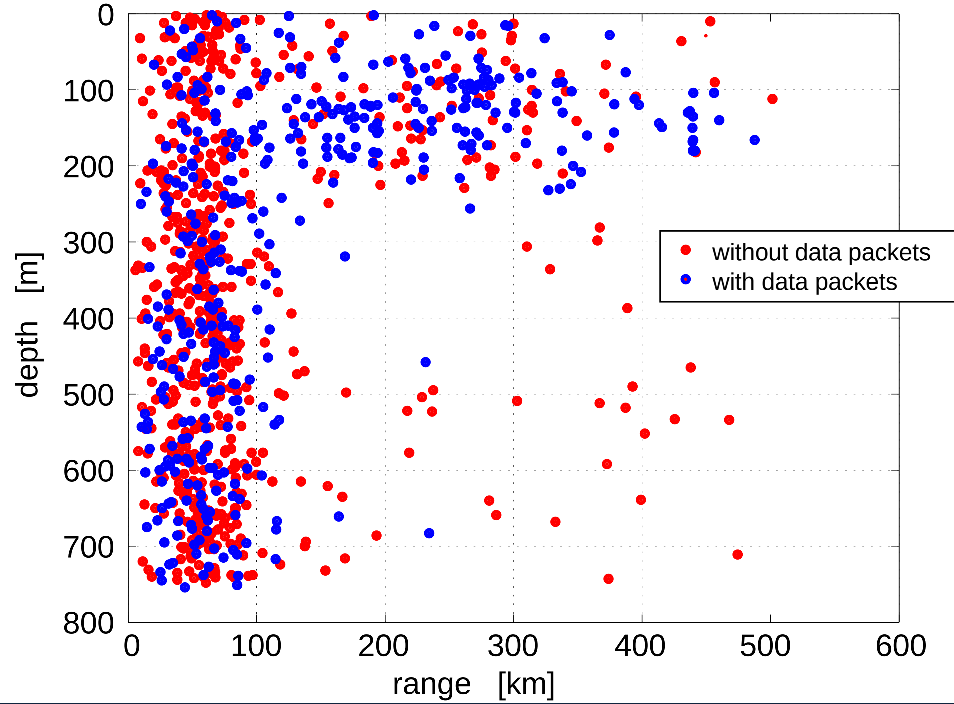
Glider Receiver Board

Beaufort Sound Channel Yields 400+ km Range

Freitag (WHOI), Gobat, Webster, Lee (APL-UW),



Glider Receptions vs. Depth



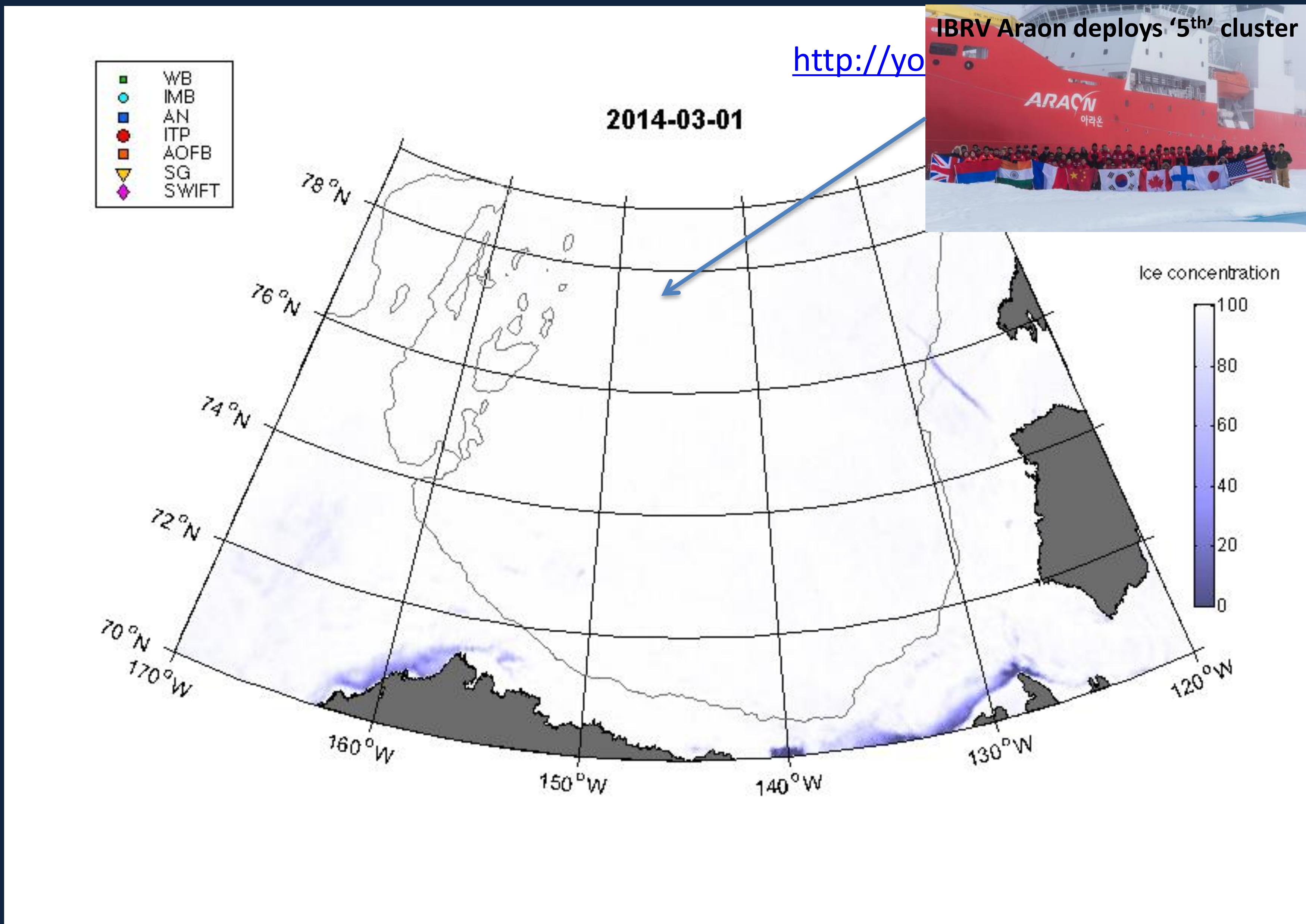
Glider performance:

To 100 km at all depths.

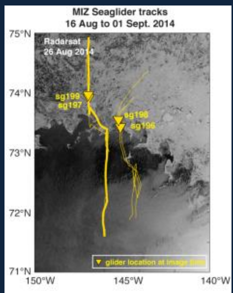
To 400 km when in duct.

MIZ Autonomous Sampling (1 Mar – 20 Oct 2014, 8 months)

http://yo

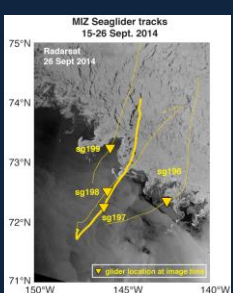


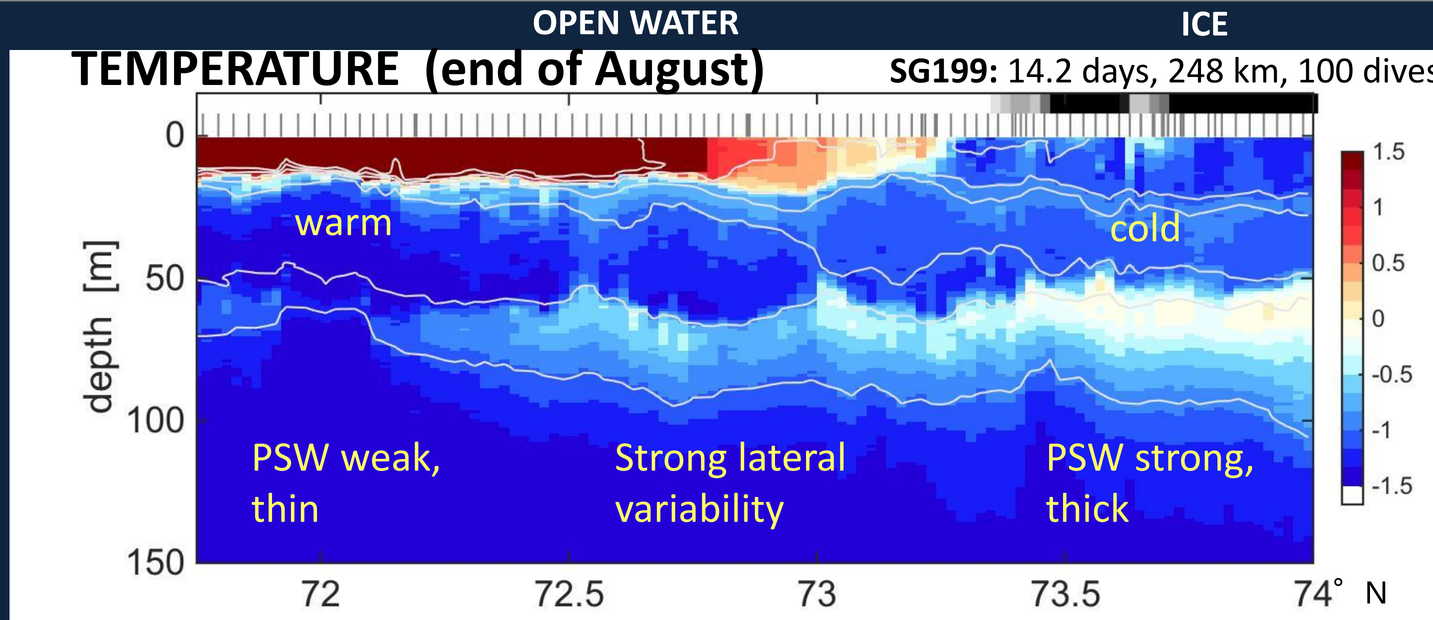
Glider sections across the MIZ

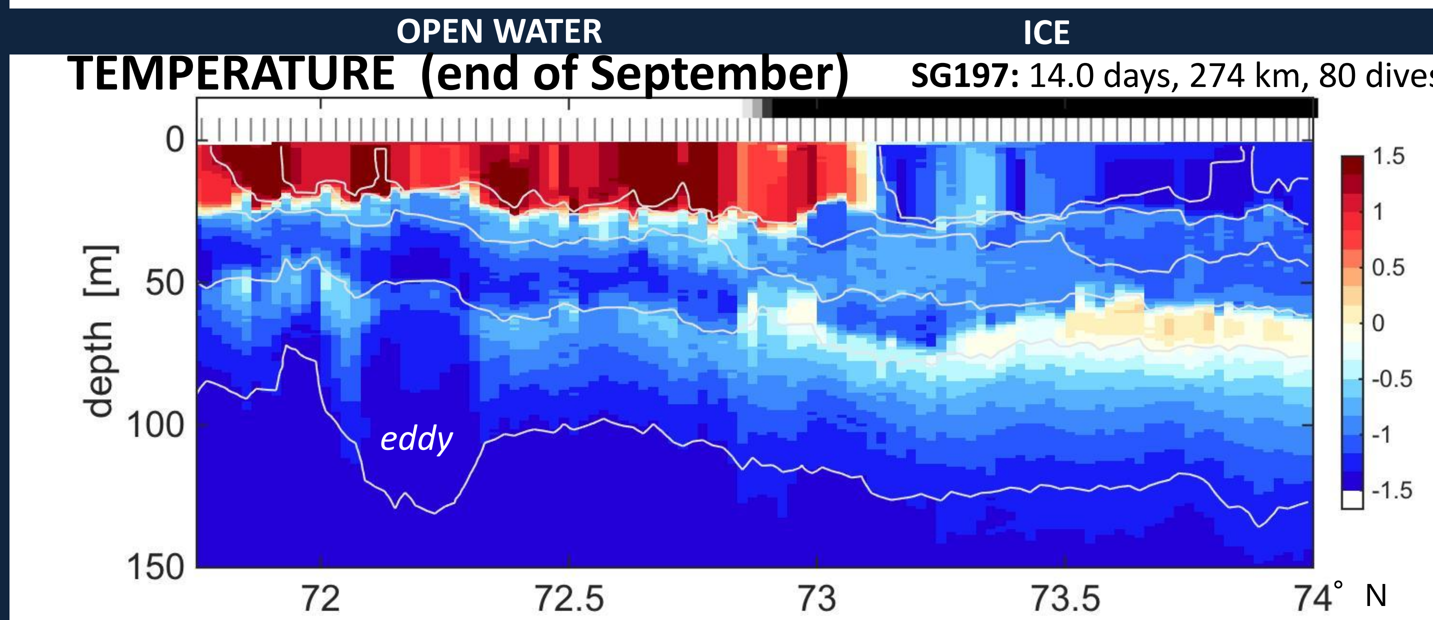


In September…

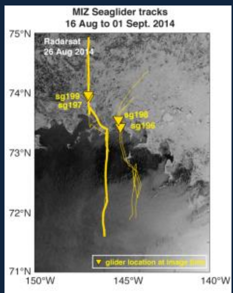
- Deeper mixed layer.
- Strong lateral variability.
- Thickening of PSW layer.







Glider sections across the MIZ

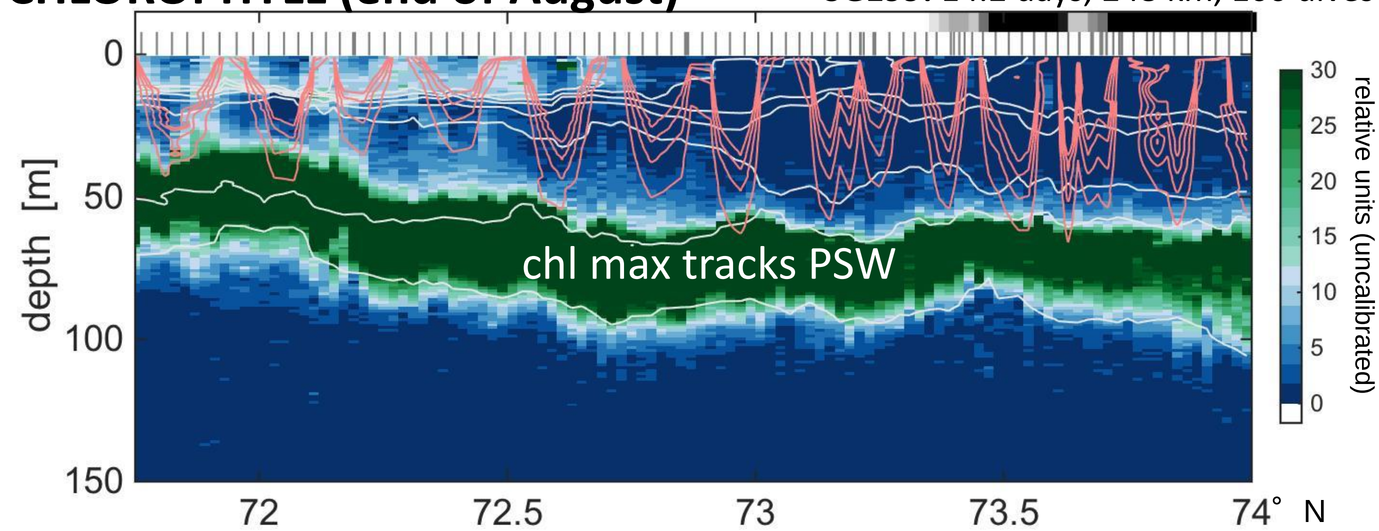


In September…

- Less light.
- Weaker Chl max.
- Large Chl signal in the mixed layer.

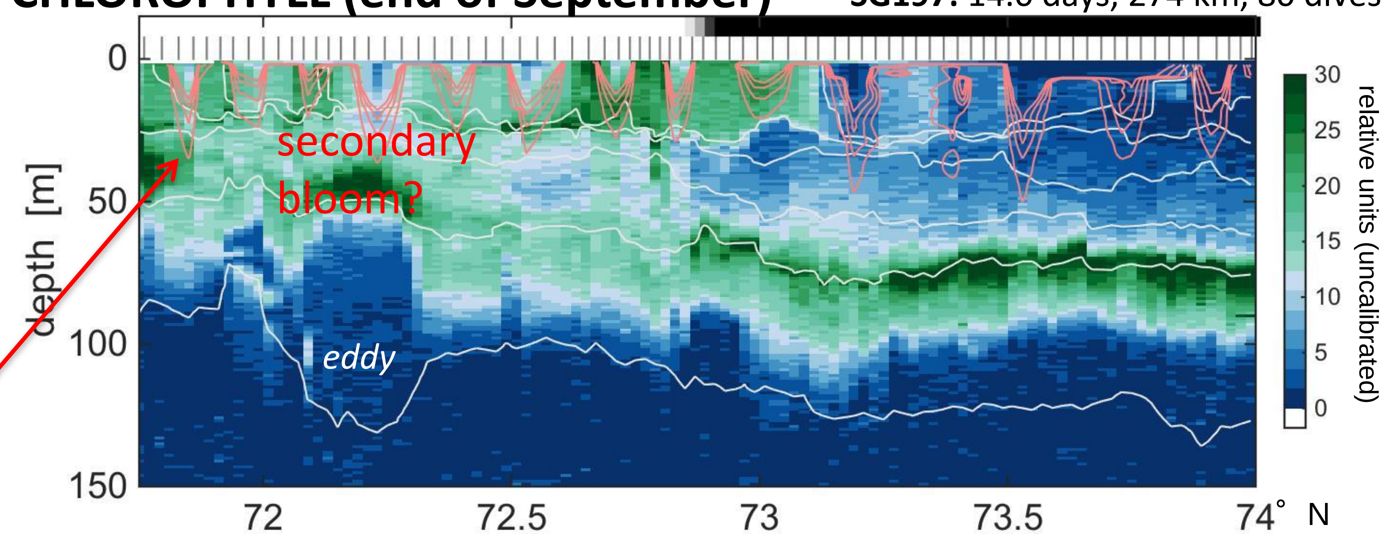
OPEN WATER ICE

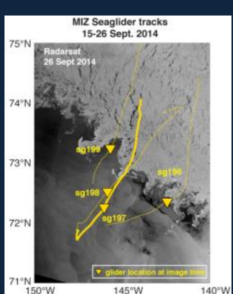
CHLOROPHYLL (end of August) **SG199:** 14.2 days, 248 km, 100 dives



OPEN WATER ICE

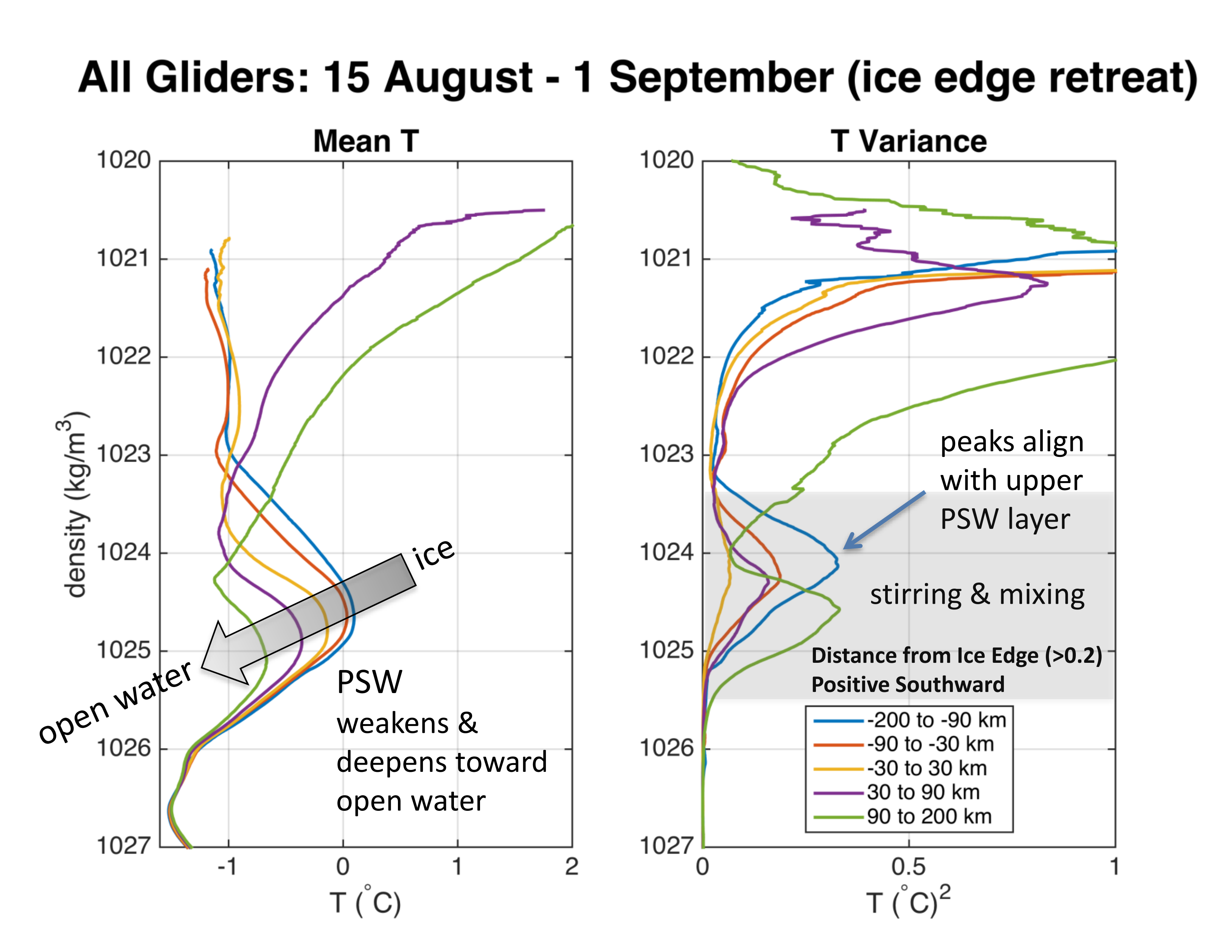
CHLOROPHYLL (end of September) **SG197:** 14.0 days, 274 km, 80 dives





Contours of solar radiation (multispectral downward irradiance)

Mixing and Stirring of the PSW



Results

https://www.elementascience.org/collections/special/special-feature-marginal-ice-zone-processes-in-the-summertime-arctic/

http://www.apl.washington.edu/project/project.php?id=miz

Science

1. In this year, waves do not appear to have played a large role in breakup of the pack- thermodynamics dominate.
2. Surface waves attenuate rapidly upon encountering ice, even in fractional cover.
3. Signatures of lateral mixing and vertical exchange driven by small-scale front and eddies near the ice ‘edge’.
4. Clear contrasts in chlorophyll distribution associated with ice ‘edge’.

Technical

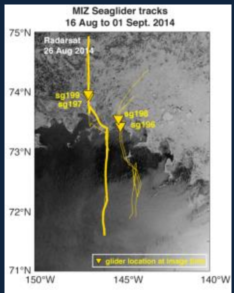
1. Autonomous observing from pack ice, though the MIZ and into open water spanning an entire melt season (March – October 2014).
2. Under-ice glider operations using new, drifting broadband sources.
3. Acoustic receptions at 400+ km due to shallow sound channel associated with Beaufort Sea near-surface temperature maximum.

Some Thoughts on the First 20 Years

- Struggling with scalability- ease of use, reliability, cost, science focus…
- Gliders well-tuned for sustained sampling of regions with strong gradients (mesoscale/submesoscale process studies, fronts, boundary currents).
- Glider and float cost per profile similar ($20k/200 profiles, $100k/1000 profiles)- usage differs. Floats- distributed, Gliders- concentrated.
- Sustained long-term efforts typically reach beyond basic research to serve other needs- operations, local communities…
- Local logistics critical for sustained observing efforts.
- Practical considerations (e.g. EEZ access, hazmat shipping) can play controlling roles.

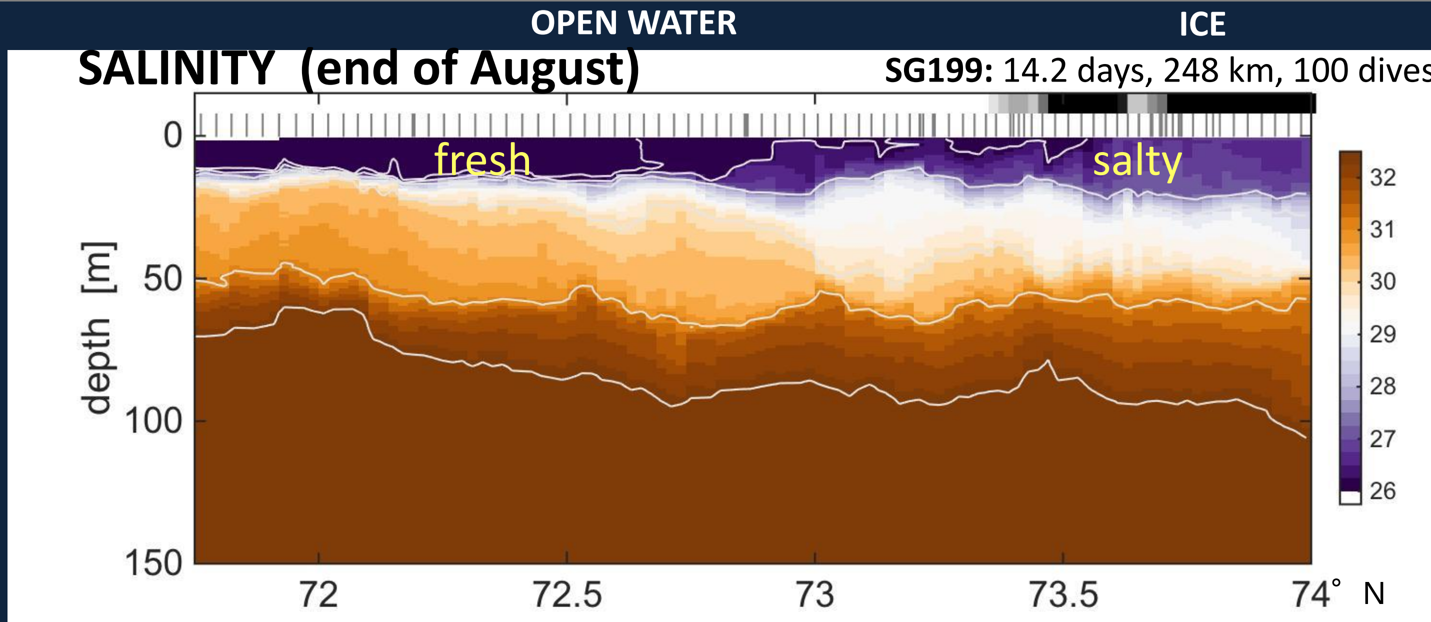
Gliders are one tool in a large toolbox. Creative, multi-platform approaches offer great power. Focus on the science questions and consider the full system.

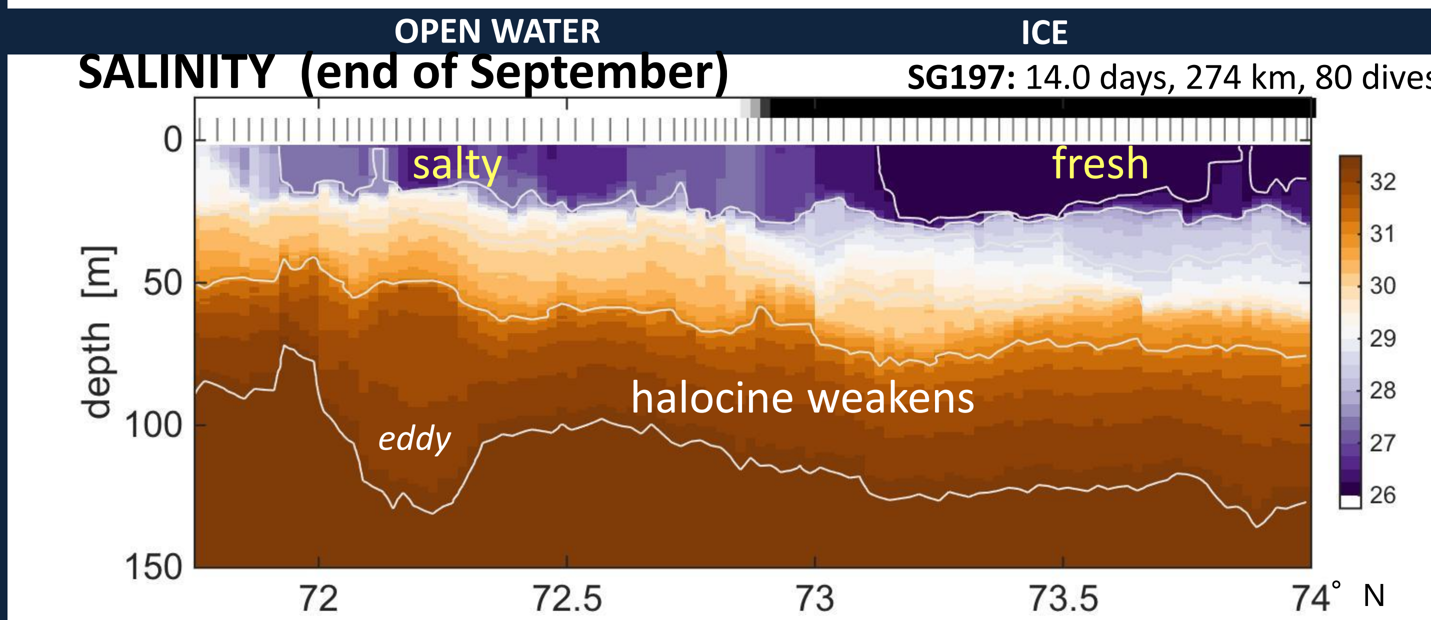
MIZ Glider sections across the MIZ ONR

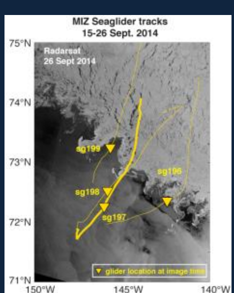


In September…

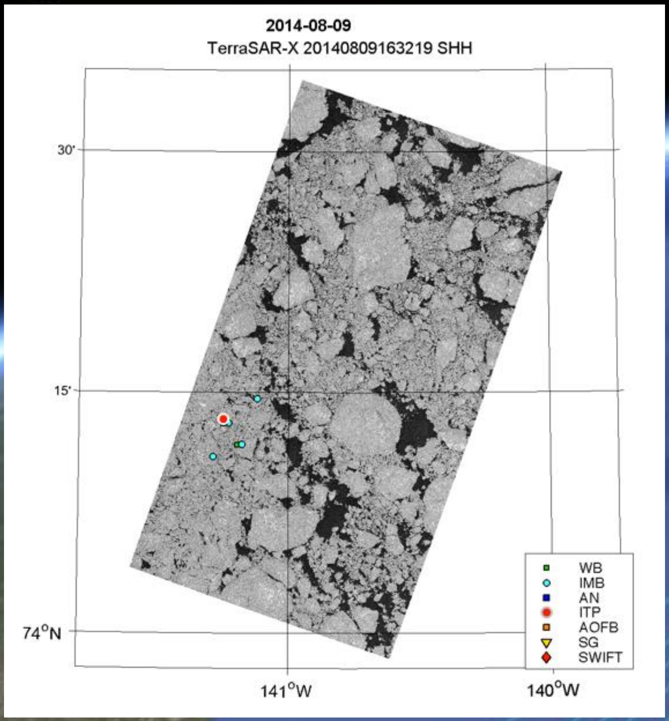
- Relatively cooler, saltier mixed layer in open water.
- Thickening of PSW layer.
- Weaker halocline stratification.







MIZ Remote Sensing



Experiment planning, execution and analysis.

TerraSAR-X (418 images)

Radarsat-2 (69 images)

675 SAR collections (plus 464 additional as needed)

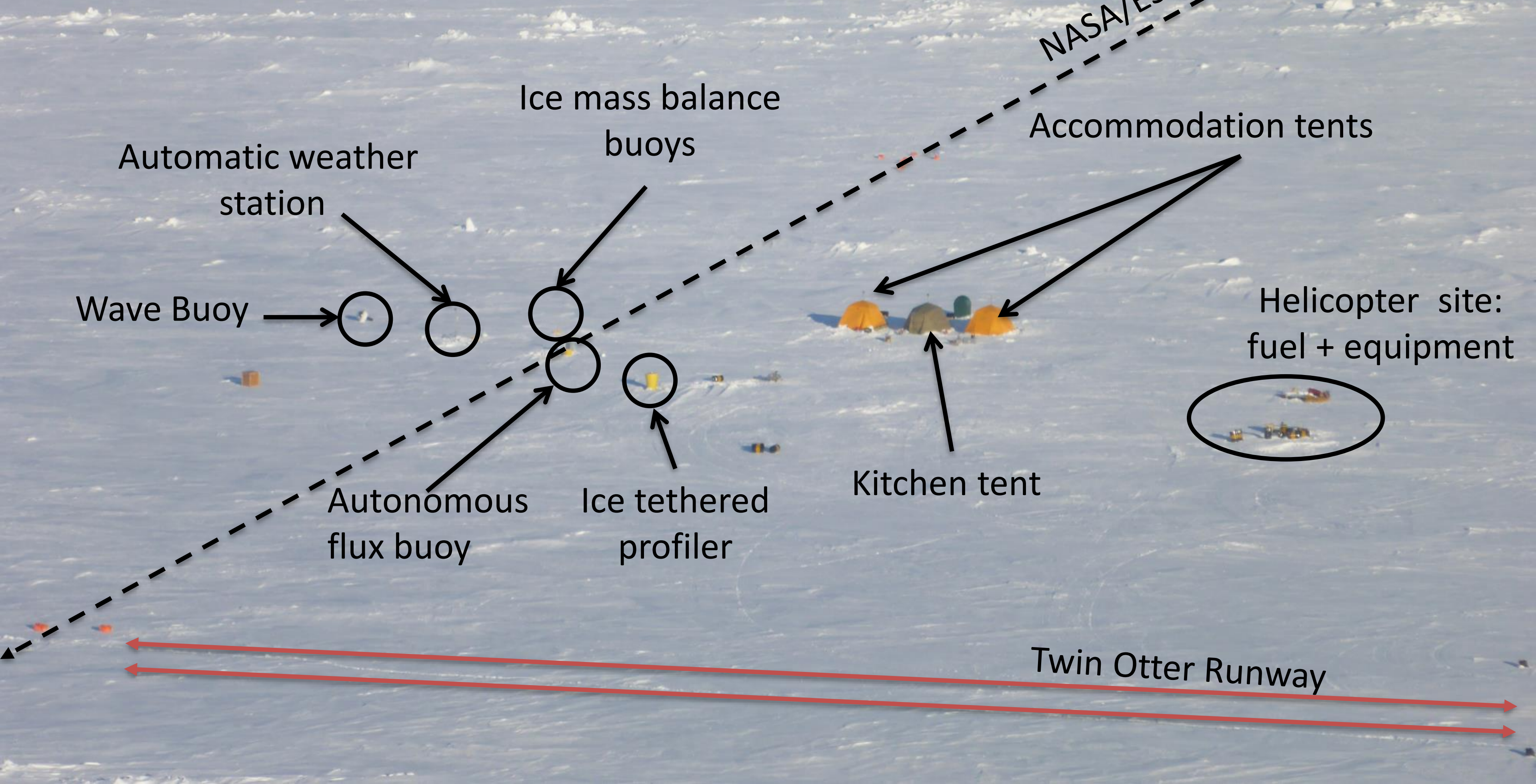
- Dedicated support from National Ice Center, meteorological reports & drift forecasts inform planning & targeting.
- Agile targeting to follow drifting instruments, respond to rapidly-evolving MIZ
- Targeting strategy and protocols developed & tested prior to main program.
- Small targeting team (remote sensing, models, observations) led by Bill Shaw

'Fast & Light' Ice Camp Logistics

- 60+ assets deployed over 300 km km range.
- 2 Twin Otters + 1 Bell 412
- 1 week setup, 1 week ops

Personnel = 6 persons + dog

- 3 x scientists/engineers
- 3 x helicopter personnel



'Fast & Light' Vessel Logistics

R/V Ukpik, July 2014

Deploy:
4 seagliders
3 SWIFT buoys
2 wavegliders

Ice edge measurements
(turbulence wave attenuation)

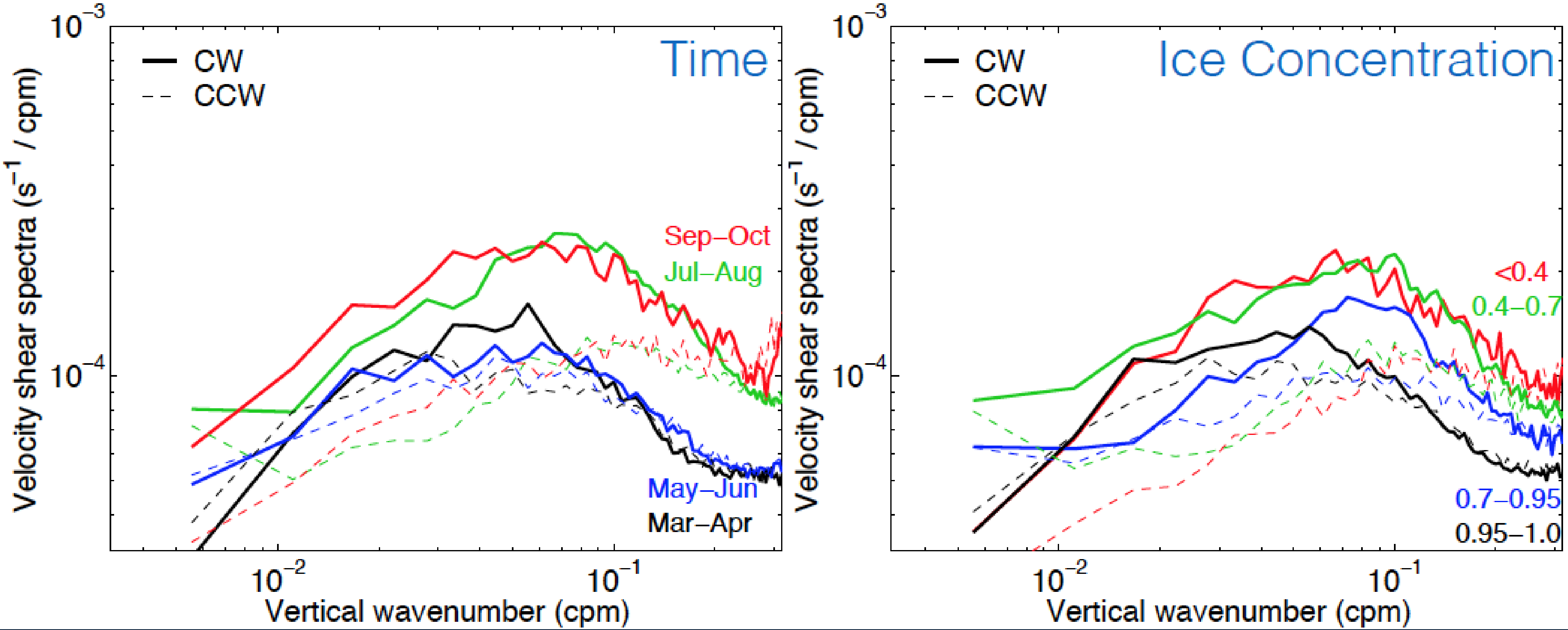
R/V Norseman II, Sept 2014

Recover:
4 seagliders
3 SWIFT buoys
1 wavegliders

Ice edge measurements
(CTD and wave attenuation)

Internal Wave Energy Changes with Ice Cover

Cole, Toole, Timmermans, Krishfield (WHOI)

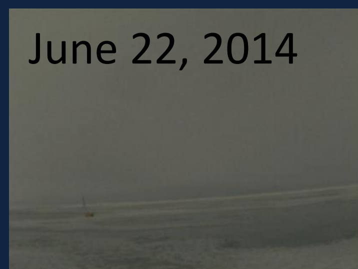


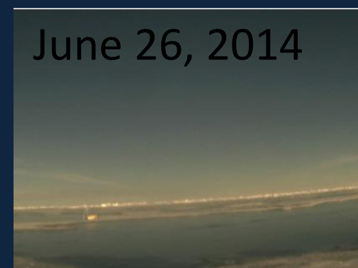
- Ice-Tethered Profilers at C2 and C4
- 70-250 m depth
- IW energy increases from spring into summer
- IW energy appears to increase with increasing open water fraction.

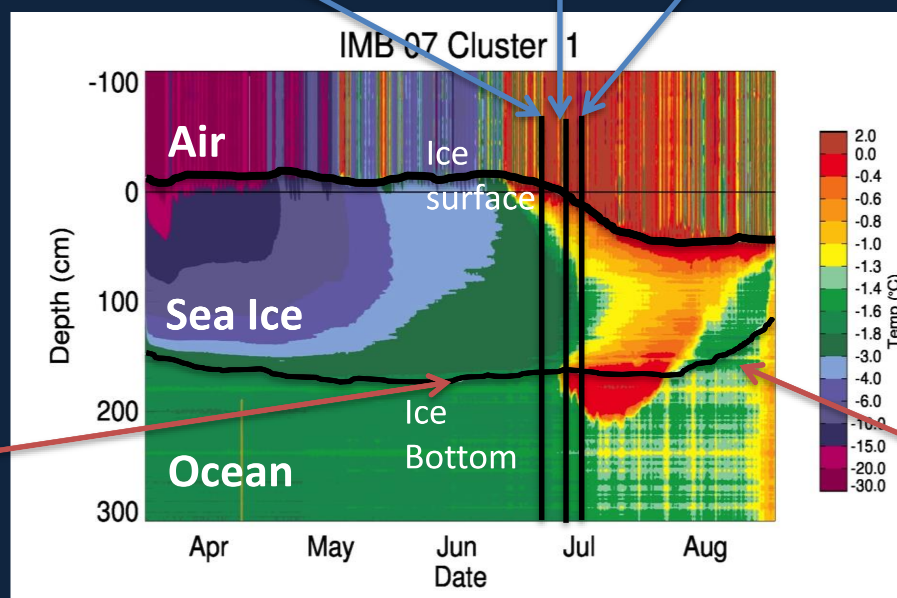
Sea ice mass balance

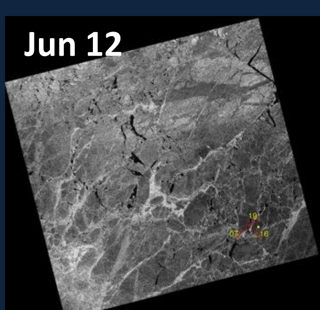
Cannot directly measure ice thickness from space
Need autonomous platforms

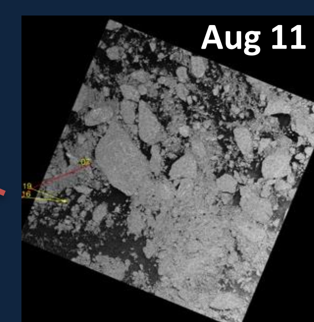
20 x ICE MASS BALANCE BUOYS



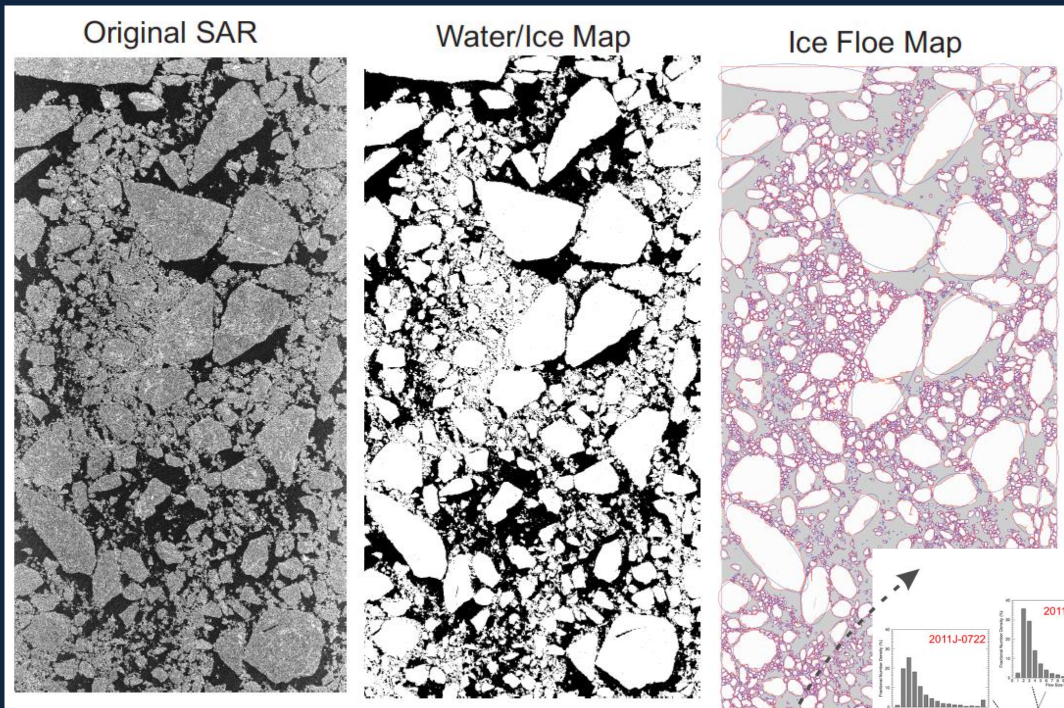






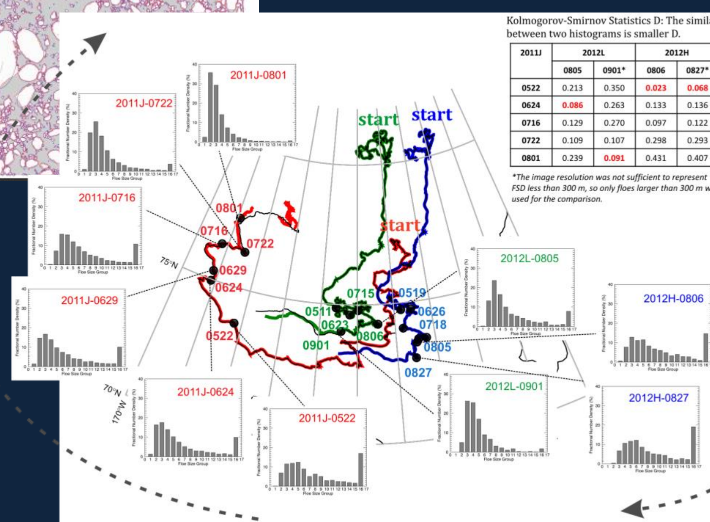


Open water fraction



- Complex algorithms needed to separate floes.
- Not fully automated
- Floe size distribution
- Fraction of open water

Can be applied to both high resolution radar and visible satellite imagery.

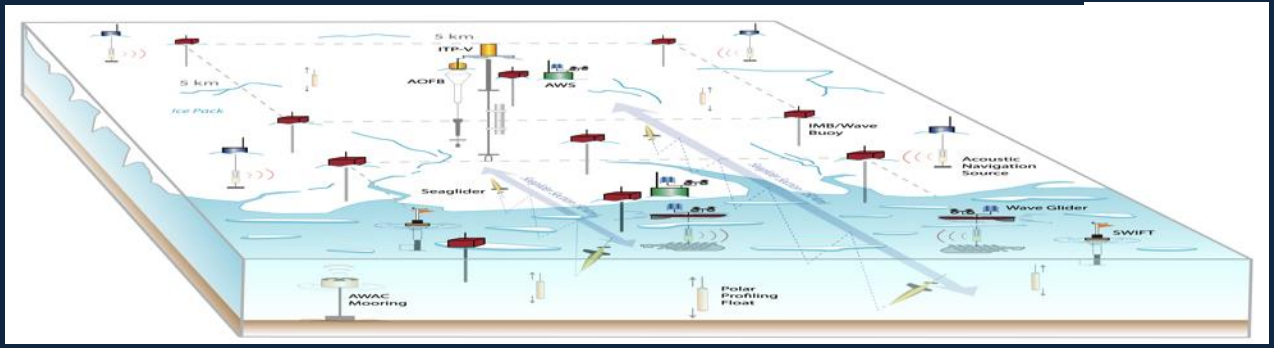


Kolmogorov-Smirnov Statistics D: The similar between two histograms is smaller D.

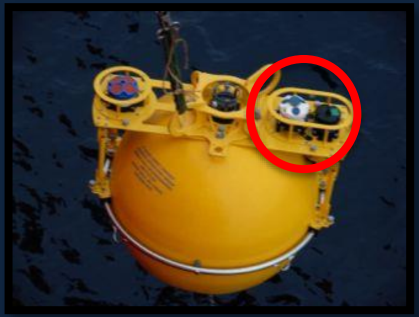
2011J	2012L		2012H	
	0805	0901*	0806	0827*
0522	0.213	0.350	0.023	0.068
0624	0.086	0.263	0.133	0.136
0716	0.129	0.270	0.097	0.122
0722	0.109	0.107	0.298	0.293
0801	0.239	0.091	0.431	0.407

The image resolution was not sufficient to represent FSD less than 300 m, so only floes larger than 300 m was used for the comparison.

Wave measurements



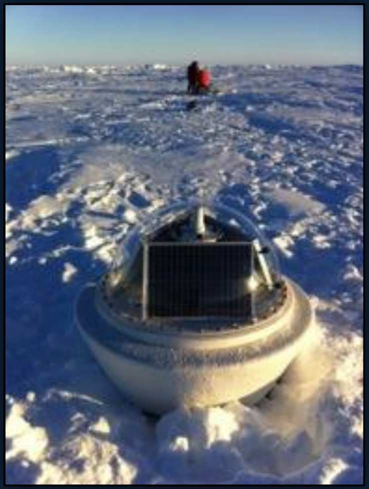
Under the ice



Nortek AWAC
at 50 m sub-surface

WHOI BGEP mooring “A”
75 N, 150 W

On the ice



Wave buoys
(drifting)

In open water (and ice)

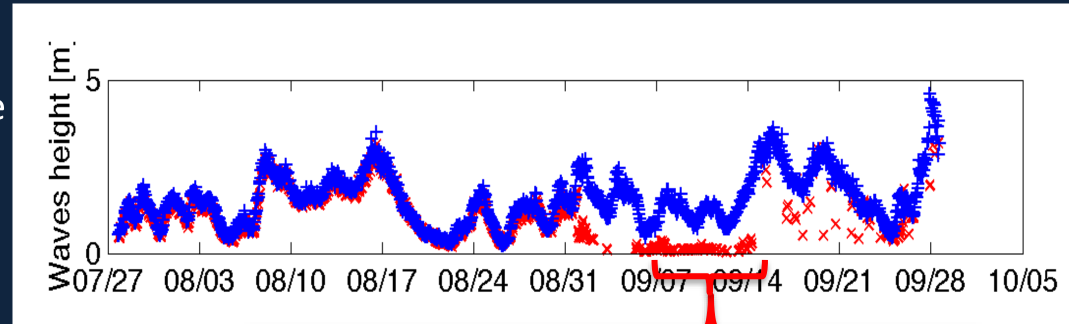
SWIFT buoys
(drifting)

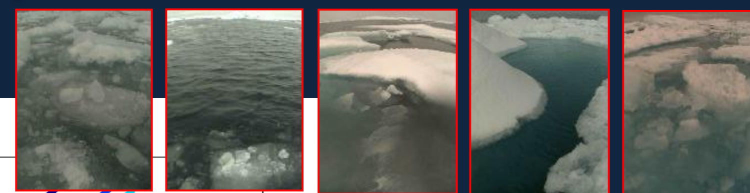
waveglider
(piloted)

Surface Wave Attenuation in Sea Ice

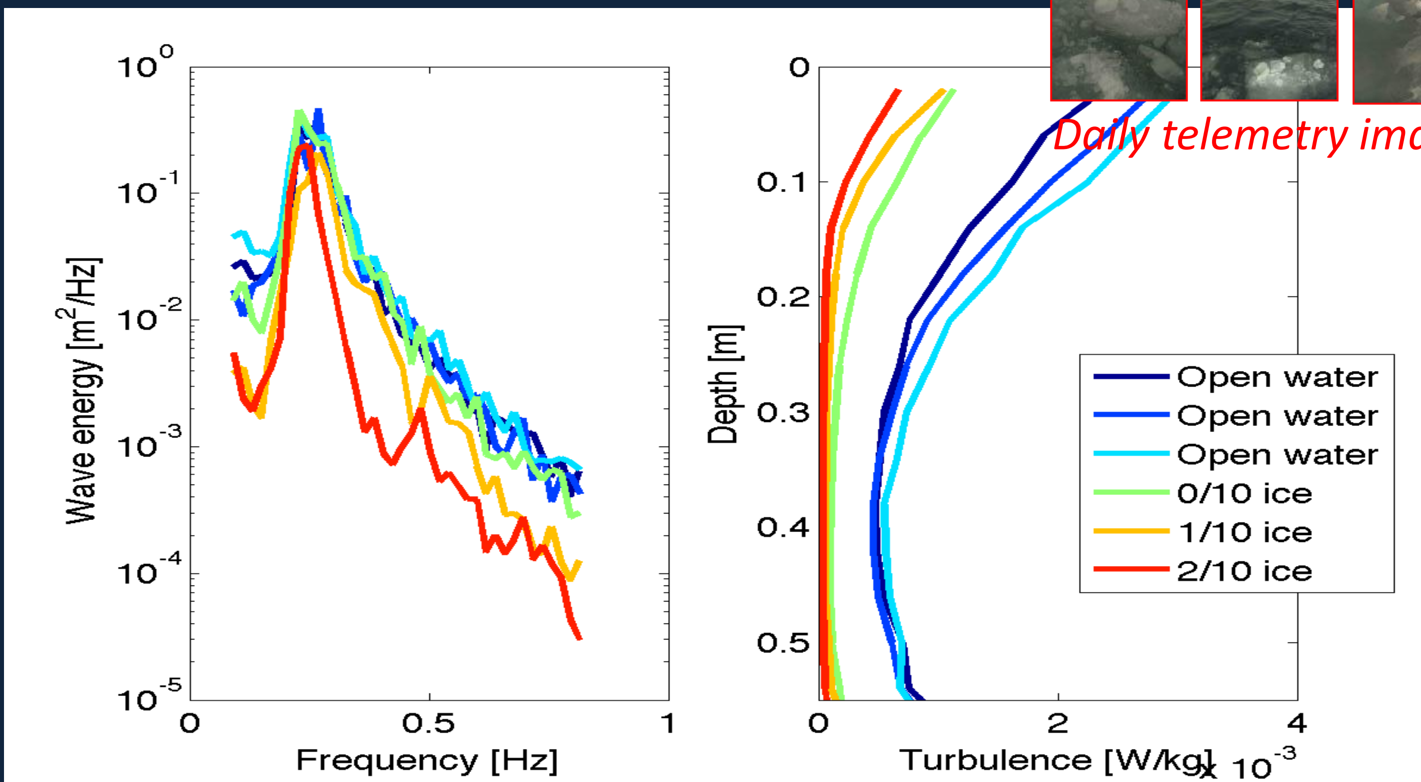
Thomson (APL-UW)

- Fetch-limited waves in the Beaufort sea are rapidly attenuated at ice edge, because wavelengths are short
- Ice effectively protects itself from the waves, like a beach protects the coast… and thus interior of ice pack is likely controlled by thermodynamics





Daily telemetry images from SWIFT 10



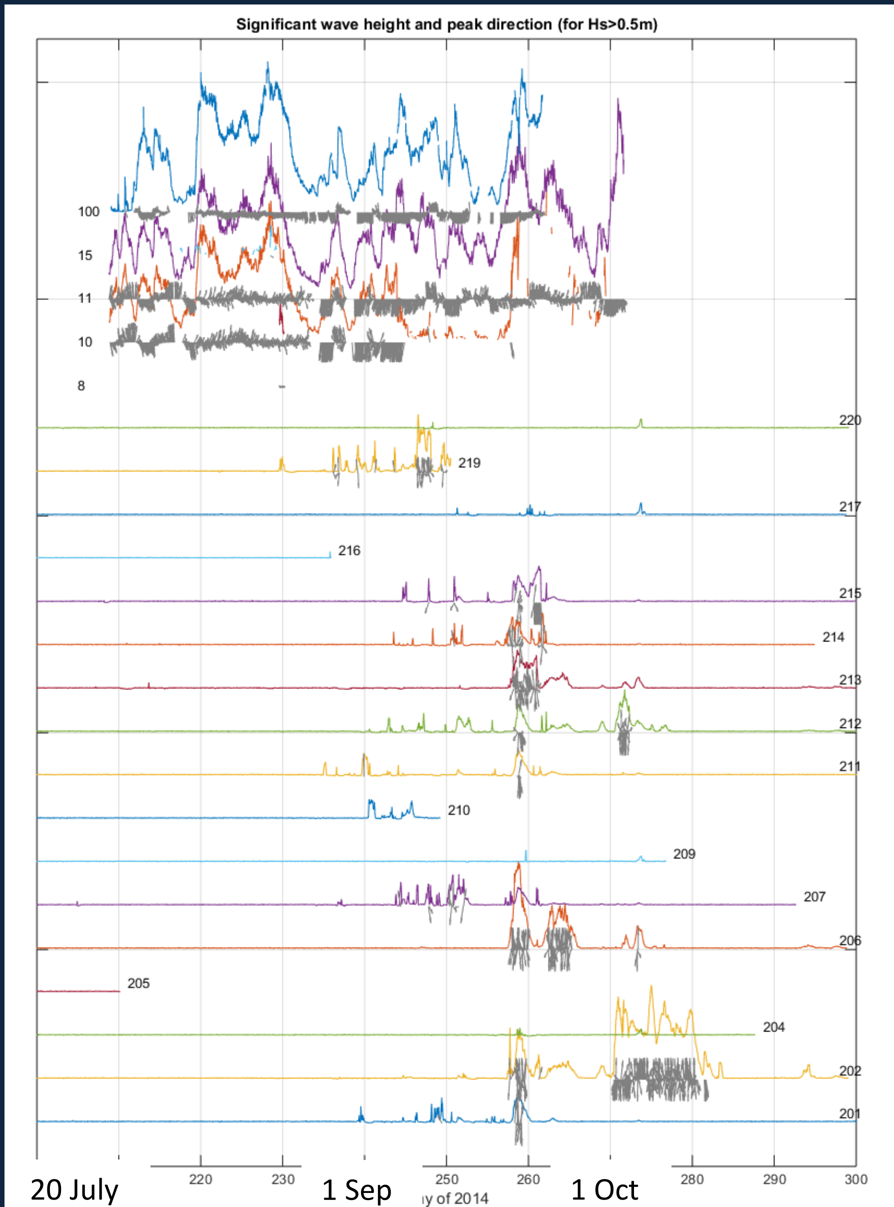
Surface Wave Attenuation in Sea Ice

Doble (LOV), Thomson (APL-UW)

SWIFT
open water
Low ice conc.

increasing ice

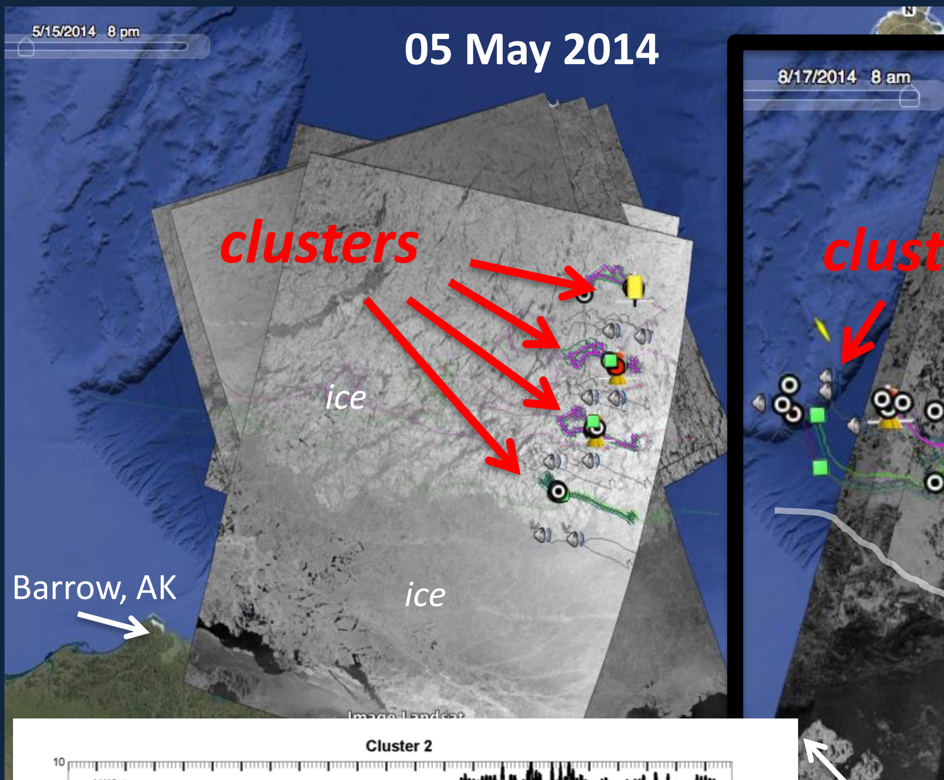
Wave
Buoy
high ice conc.

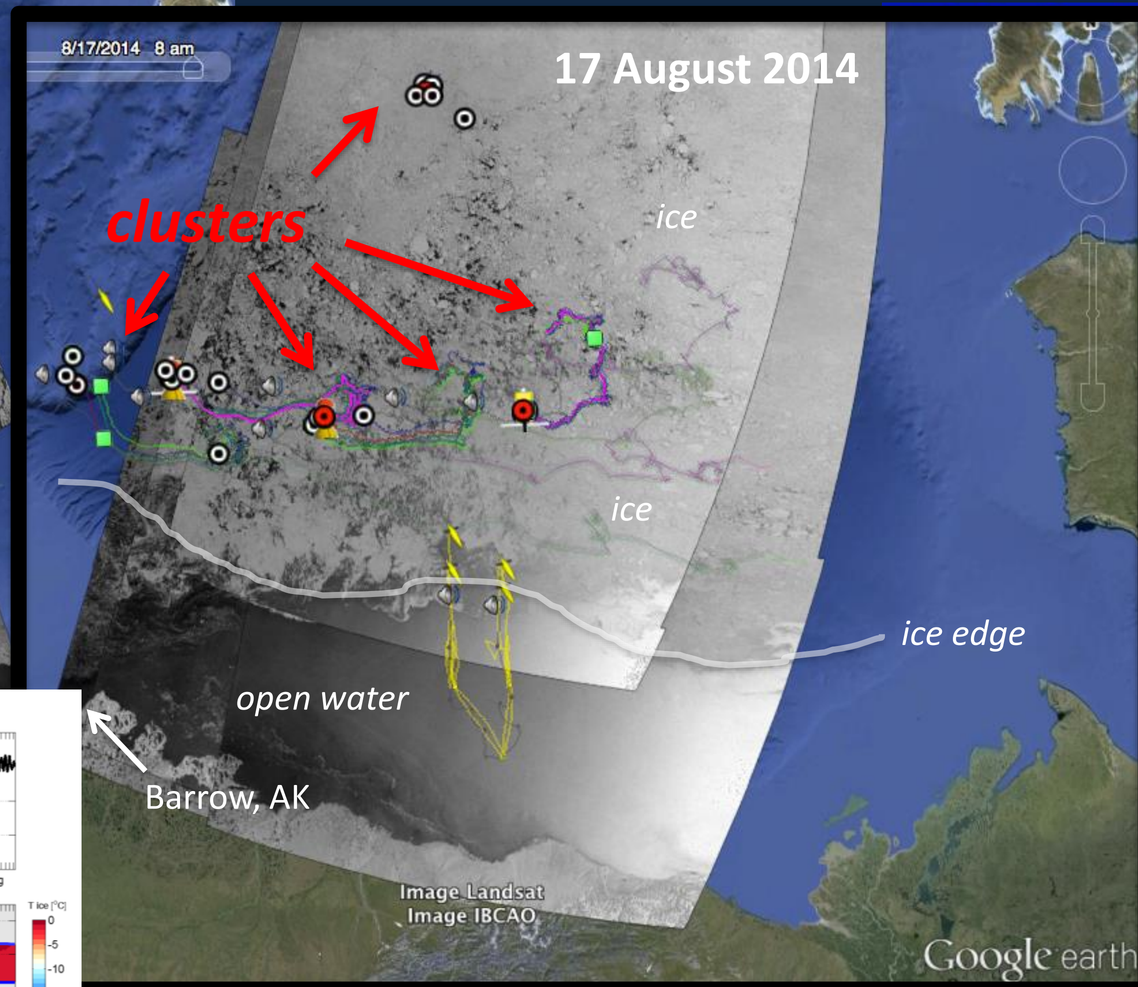


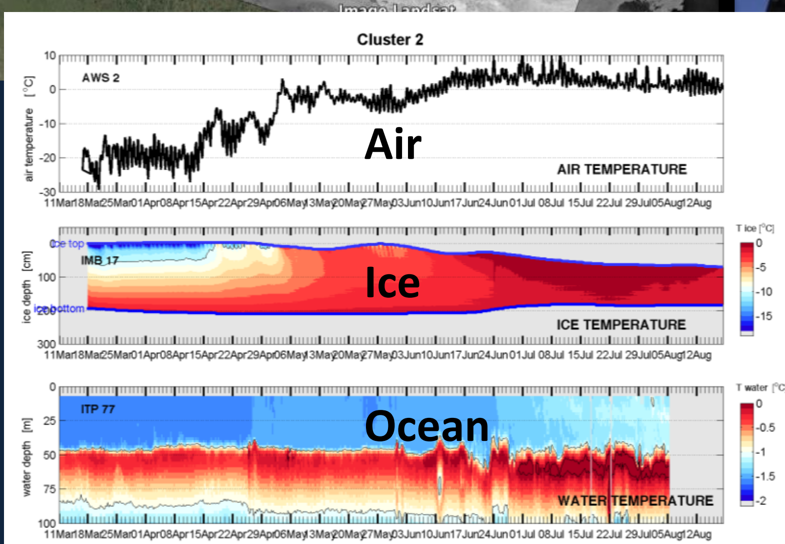
- Waves strongly modulated by even small concentrations of sea ice.

- Waves in sea ice only after early September, when there is significant open water south.
- Episodic wave events, but seen at multiple sites.

Real Time Situational Awareness





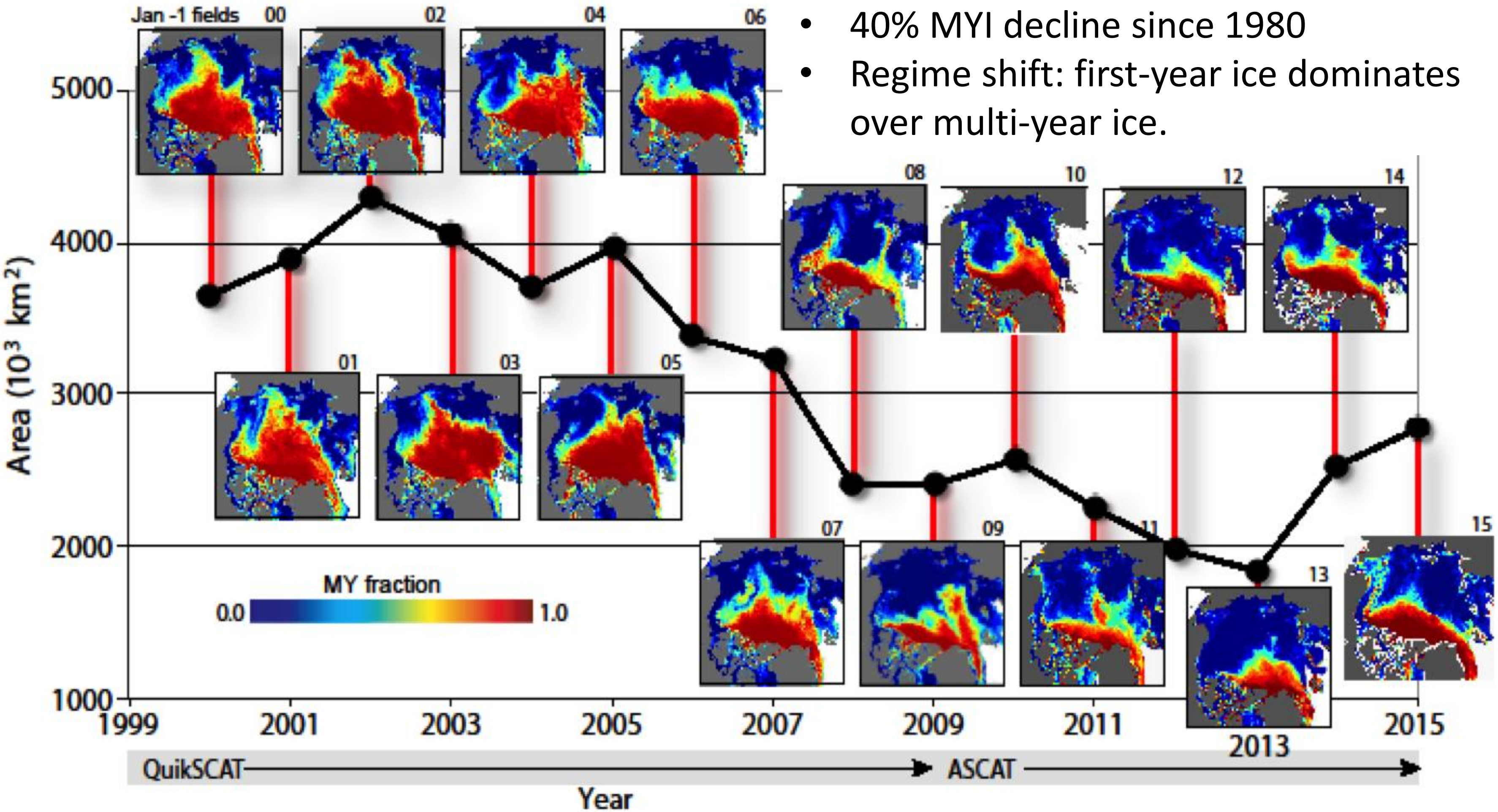


- SAR and visible images
- models

- ITPs, IMBs, WBs
- Seagliders
- SWIFTs and AWAC

Declining Extent & Multi-Year Fraction

- 40% MYI decline since 1980
- Regime shift: first-year ice dominates over multi-year ice.



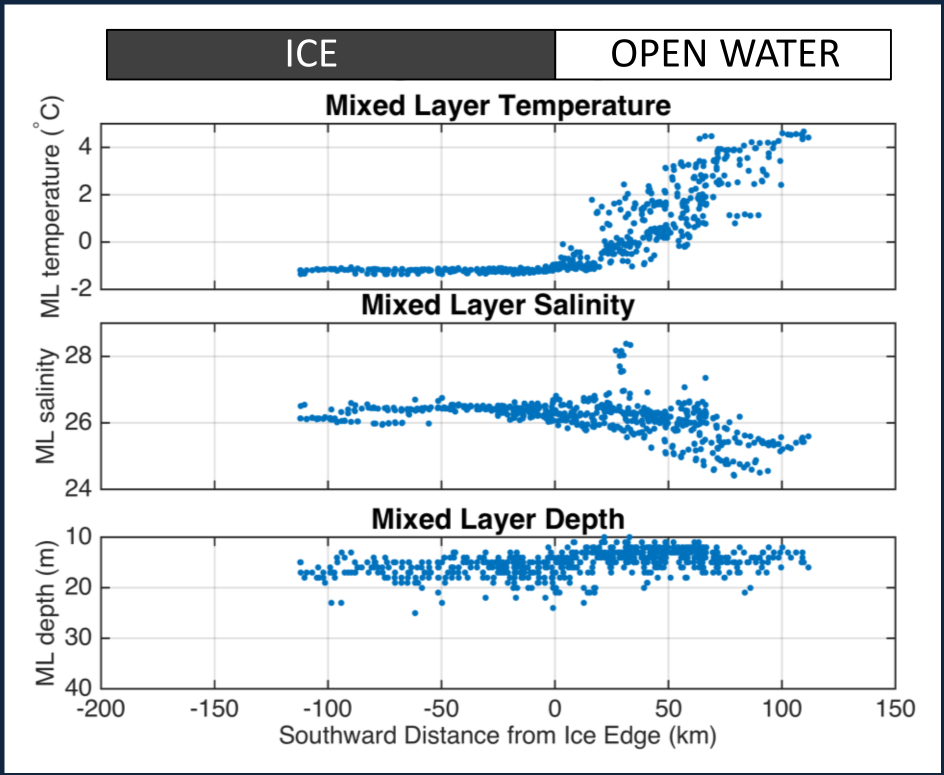
Kwok, JPL

⇓ Extent + ⇓ Thickness = ⇓ sea ice volume

Quantity *and* quality of sea ice impact processes and feedbacks.

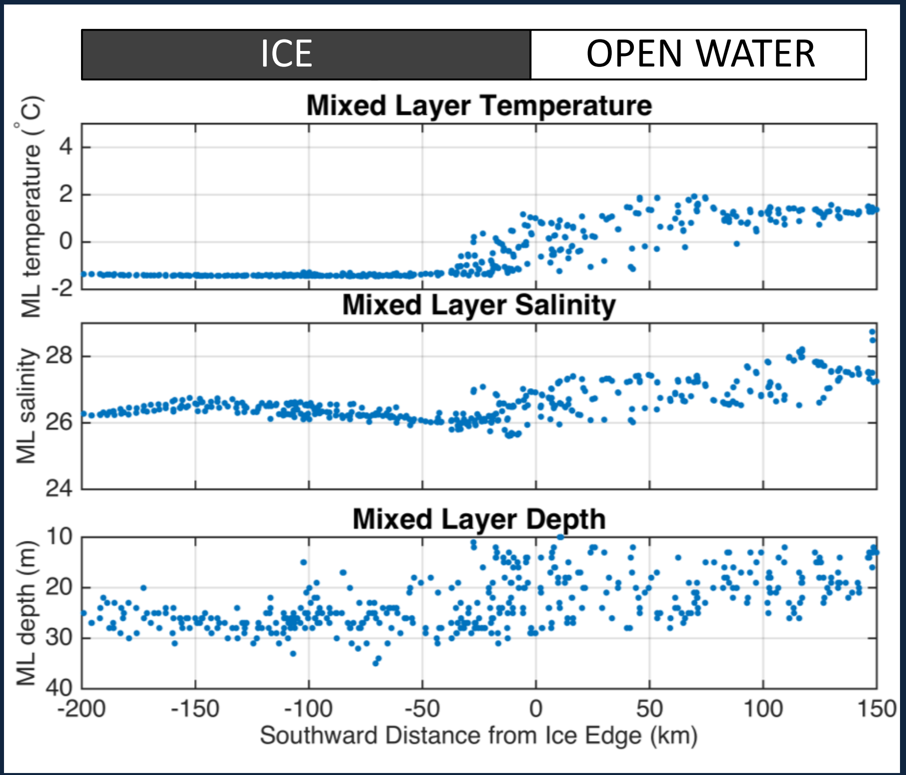
Mixed Layer Contrasts

15 Aug –01 Sep 2014 (ice retreat)



- Open water: Warm/fresh (melt + solar warming + PSW entrainment)
- Ice covered: Cold/salty, deeper MLD
- Open water, ice edge largest lateral variability

15 Sep – 01 Oct 2014 (ice advance)



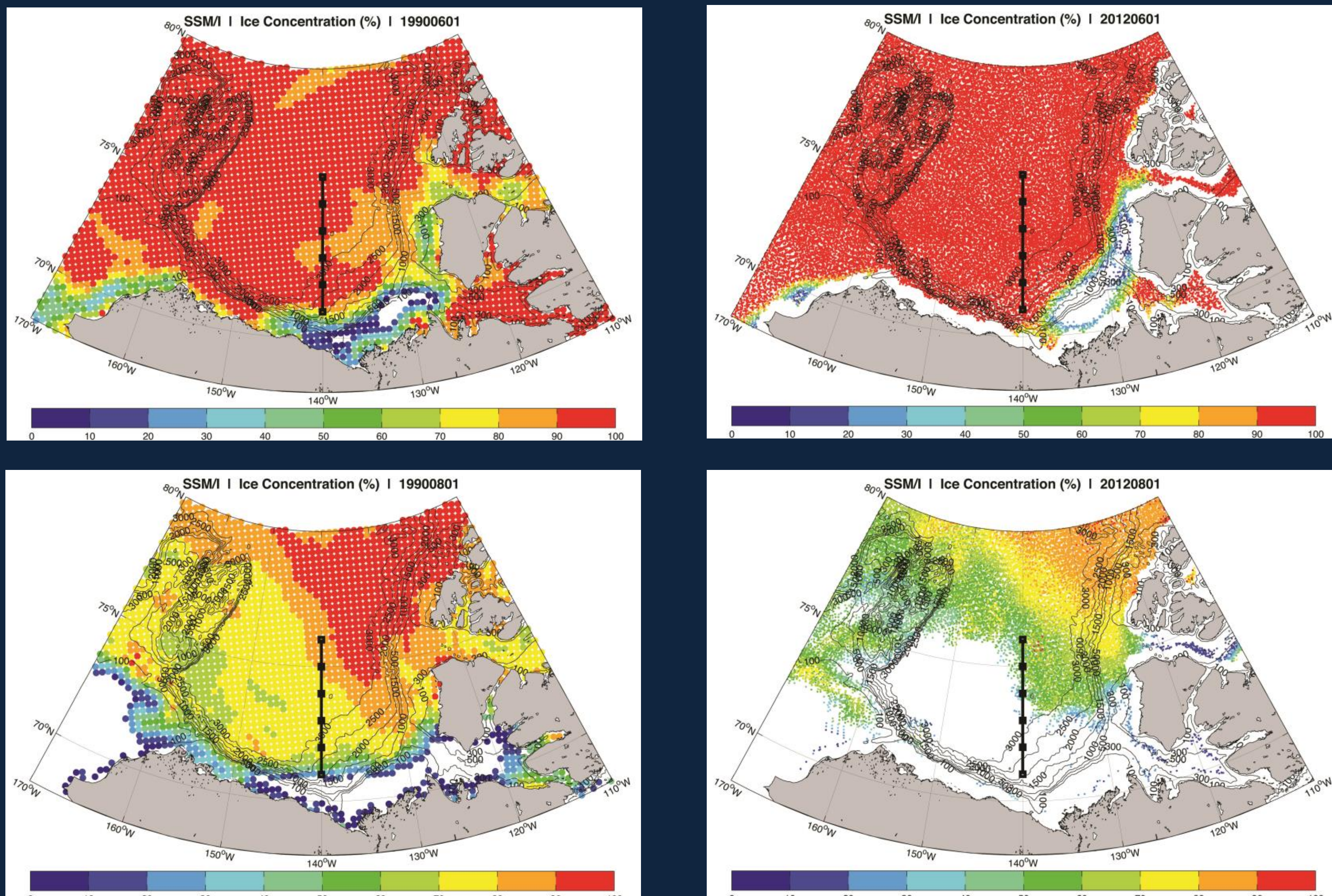
- Open water: Warm/salty (melt + solar warming + PSW entrainment)
- Ice covered: Cold/fresh, deeper MLD
- Lateral variability further into ice

Evolving Beaufort MIZ

1990 | 2012

June

August



SSM/I - Posey

Conceptual MIZ (Fram Strait)

Pack Ice

Open Water

Marginal Ice Zone

The 2014 Beaufort MIZ

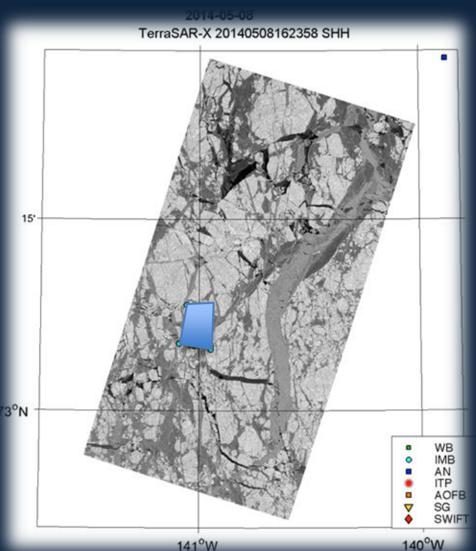
Fram Strait MIZ

Sea ice dynamics

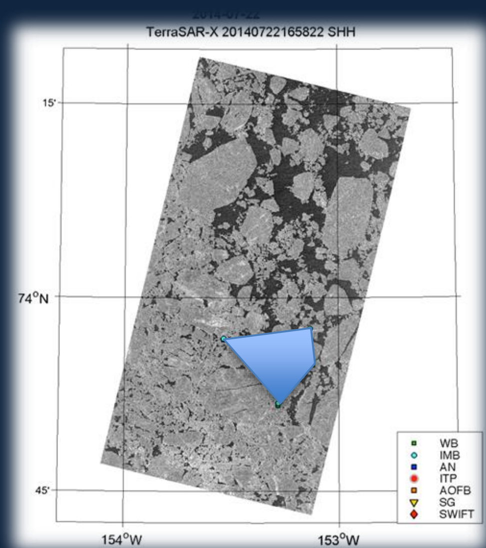
Local: GPS is the key

Regional: Satellites are the key

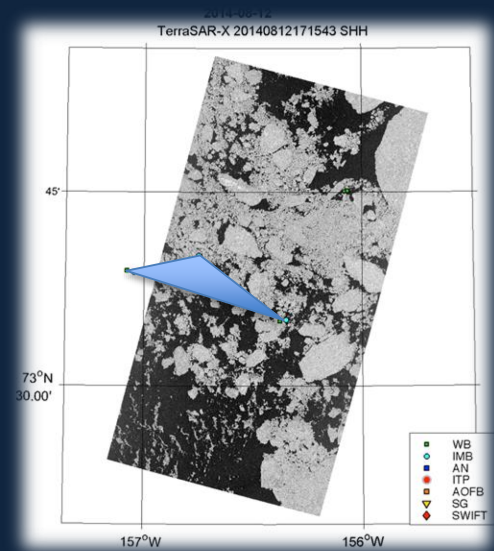
May 8



Jul 22

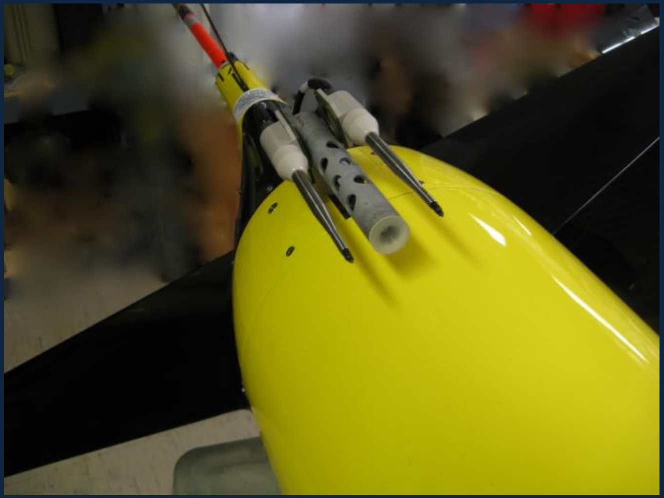


Aug 12



- **Understanding ice dynamics leads to a better knowledge of ice deformation processes.**
- **Need information on local and regional level**

Micro-temperature Seaglider



Luc Rainville and Craig Lee
Applied Physics Laboratory, U. of Washington

Extended (many months) dissipation measurements from autonomous platforms.

Fully integrated system.

Does not affect flight and endurance.

Real-time data processing and transmission of turbulence profile after each dive.

Data quality comparable to free-falling systems.

Successful 1-month deployment, 6-month deployments in-progress (SPURS- 3 gliders).