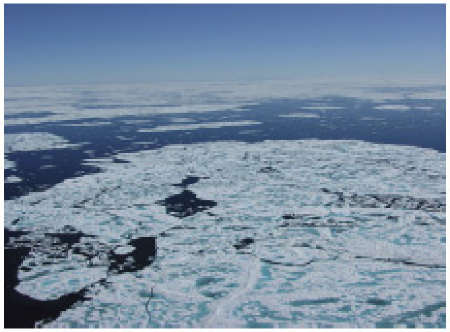
Autonomous Investigations of Marginal Ice Zone Processes- Changing Feedbacks and Observational Challenges

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






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)

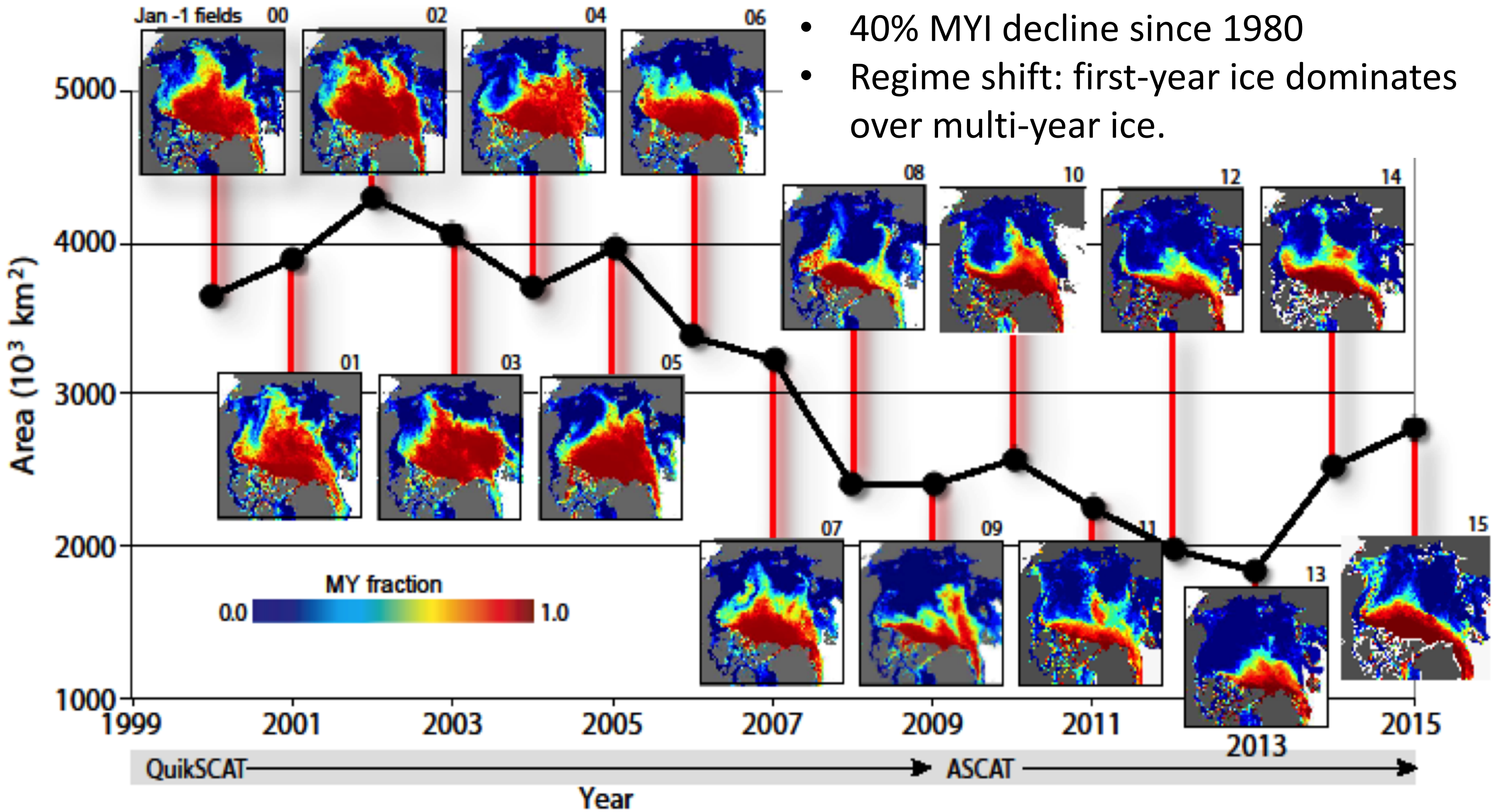
Melt Ponds, Biology, Biogeochemistry- Kang, Yang & colleagues (Korean Polar Research Institute)

External Collaborations- NRL, NASA, NOAA, ESA

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

Declining Extent & Multi-Year Fraction

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



Kwok, JPL

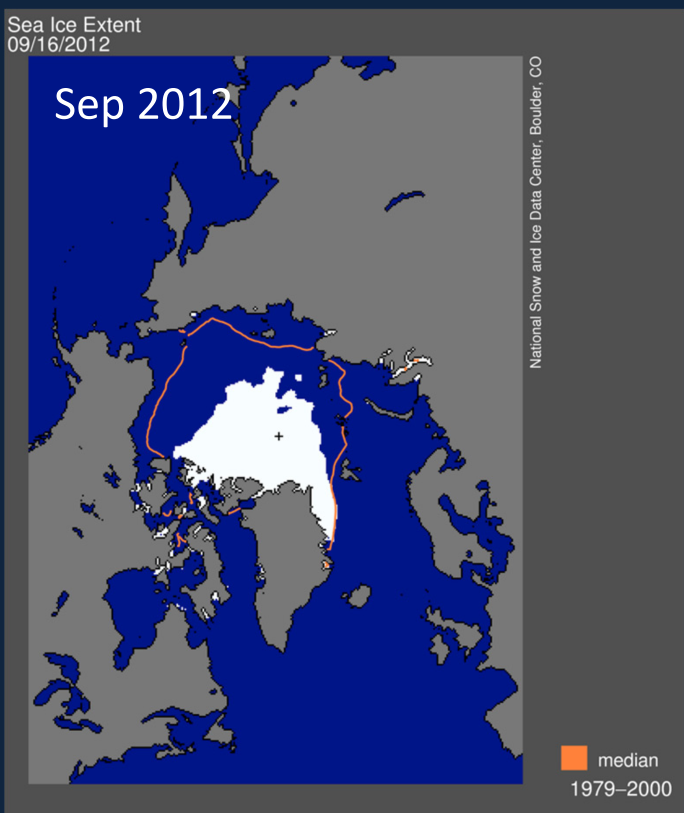
⇓ Extent + ⇓ Thickness = ⇓ sea ice volume

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

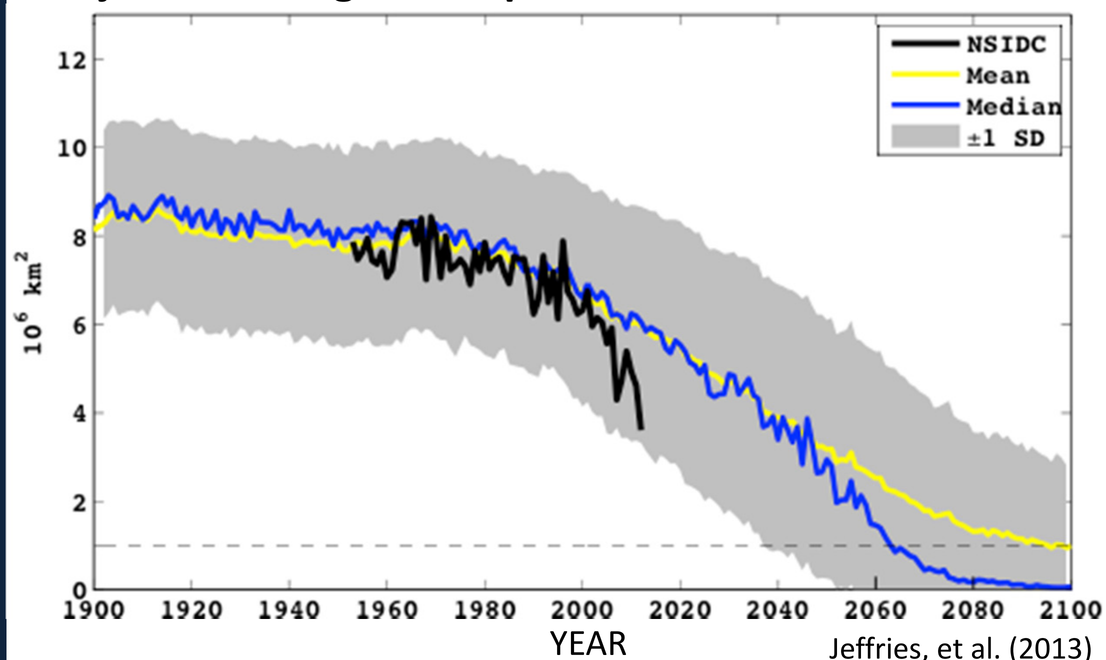
Models Struggle to Reproduce Dramatic Reduction in Summertime Sea Ice Extent

- 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



Jeffries, et al. (2013)

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

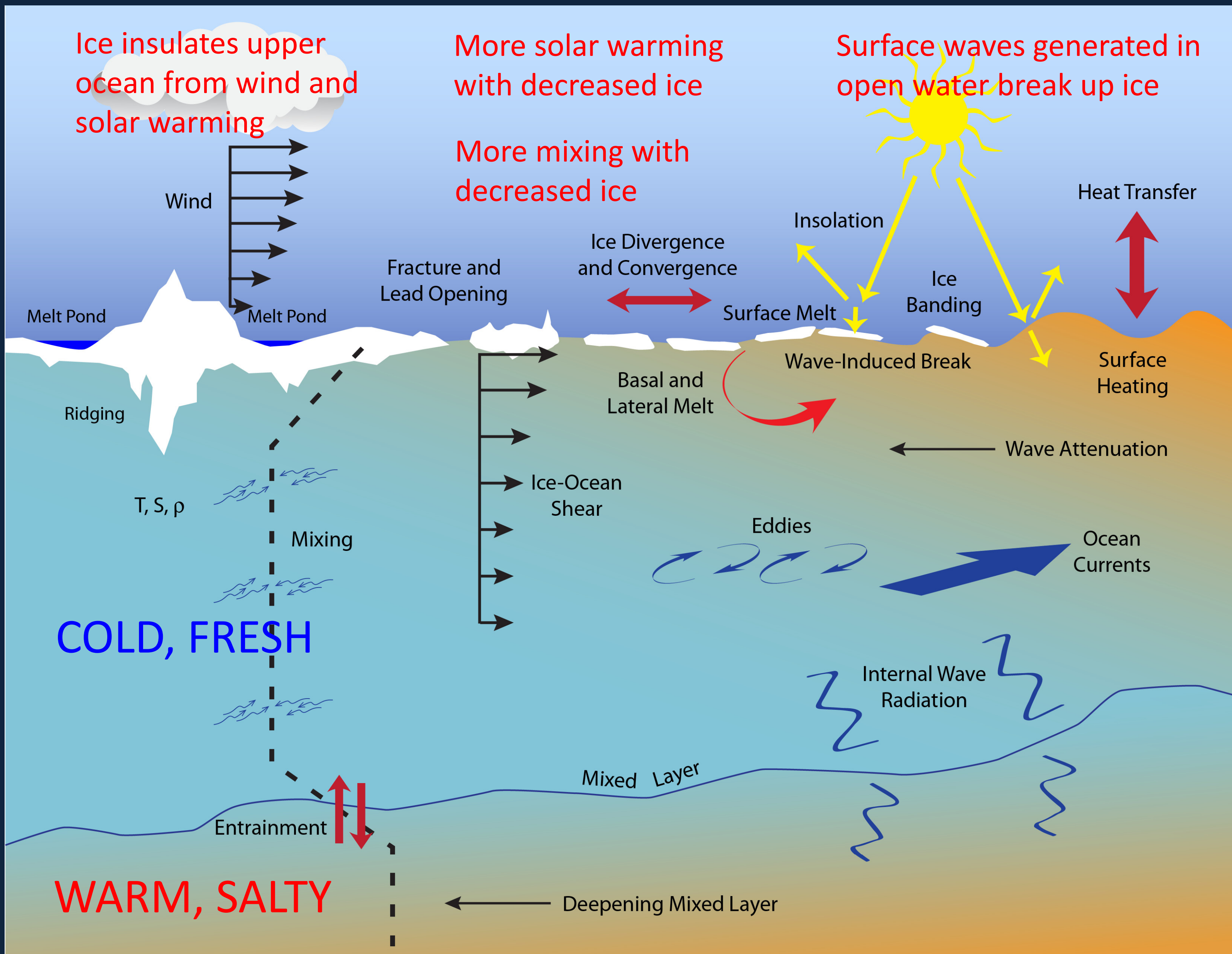
Science

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.

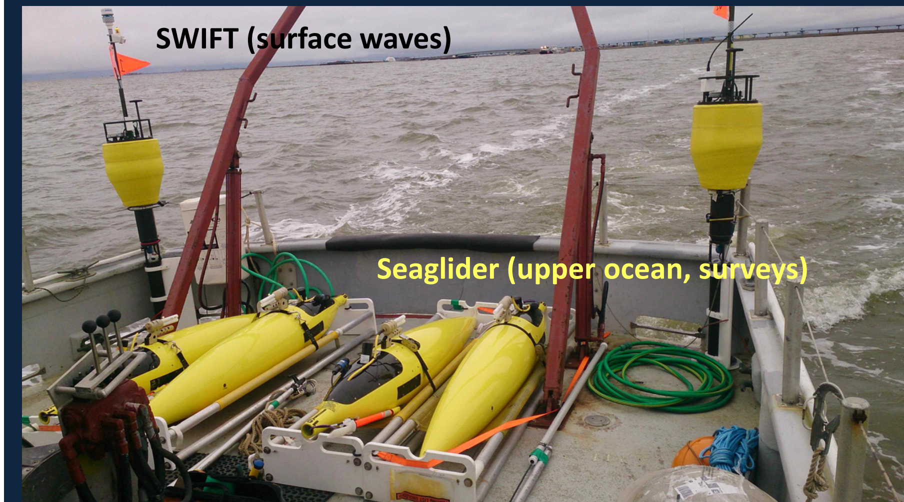
Atmosphere-Ice-Ocean Interaction

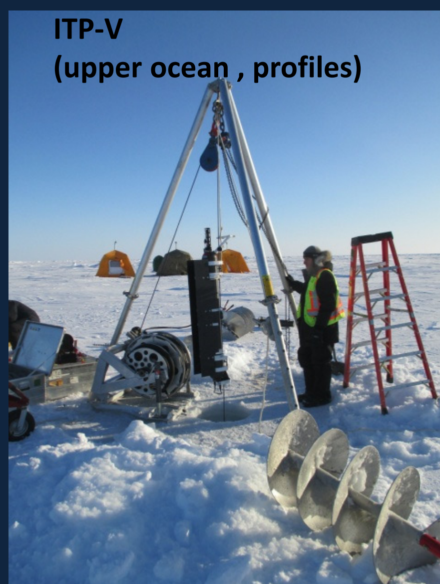


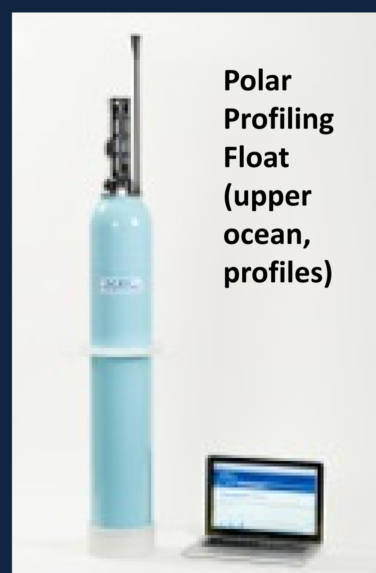
Challenges

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

The Revolution in Robotic Observing

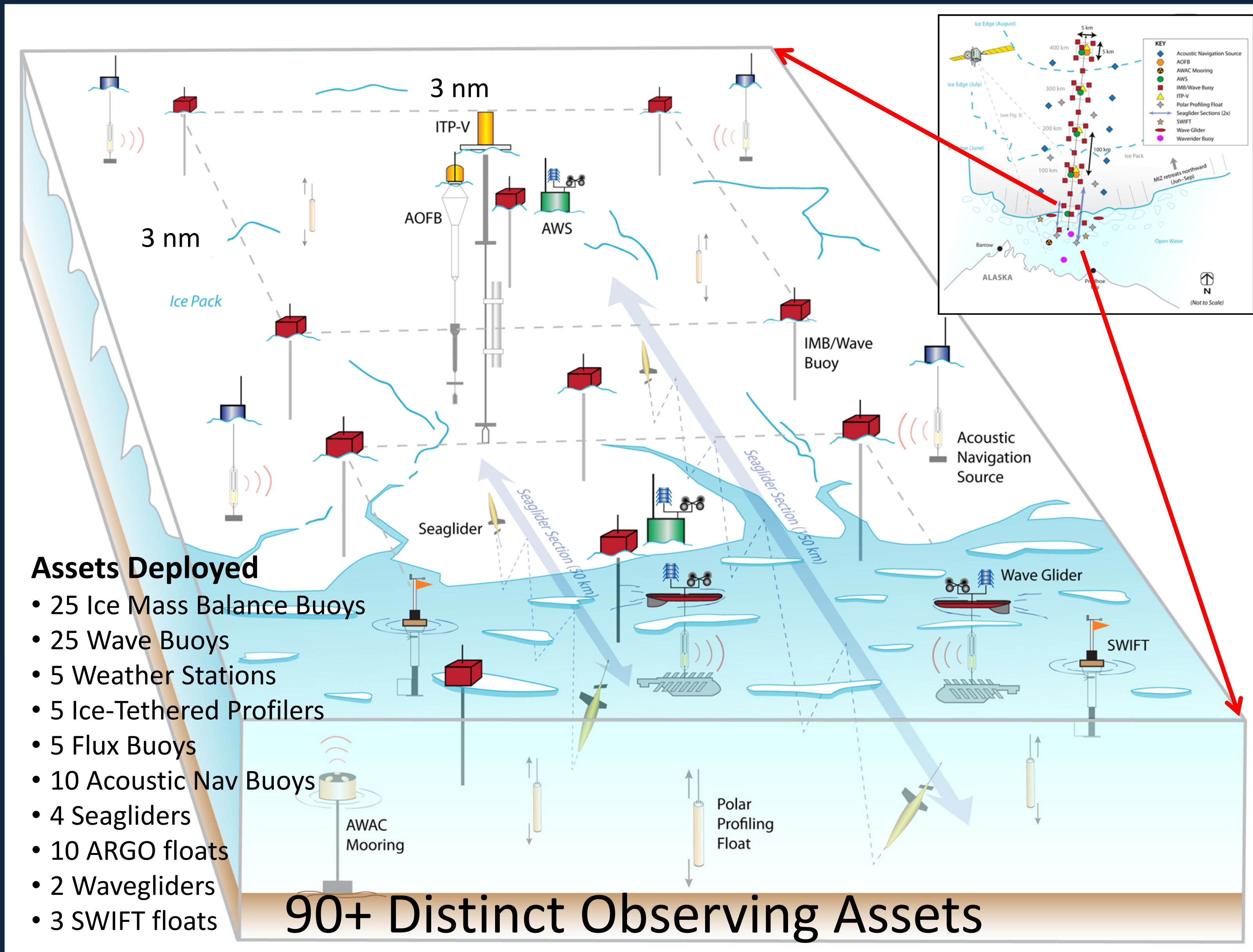






MIZ

Putting the Pieces Together



Assets Deployed

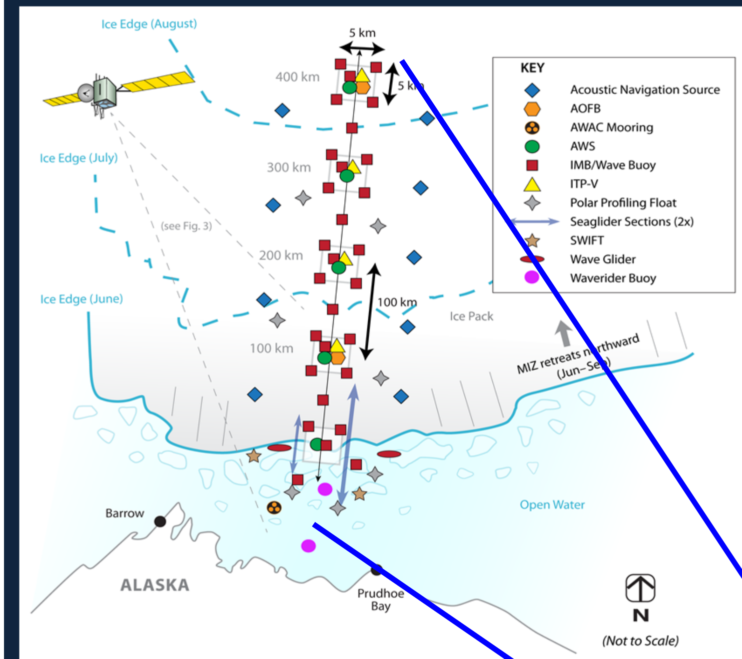
- 25 Ice Mass Balance Buoys
- 25 Wave Buoys
- 5 Weather Stations
- 5 Ice-Tethered Profilers
- 5 Flux Buoys
- 10 Acoustic Nav Buoys
- 4 Seagliders
- 10 ARGO floats
- 2 Wavegliders
- 3 SWIFT floats

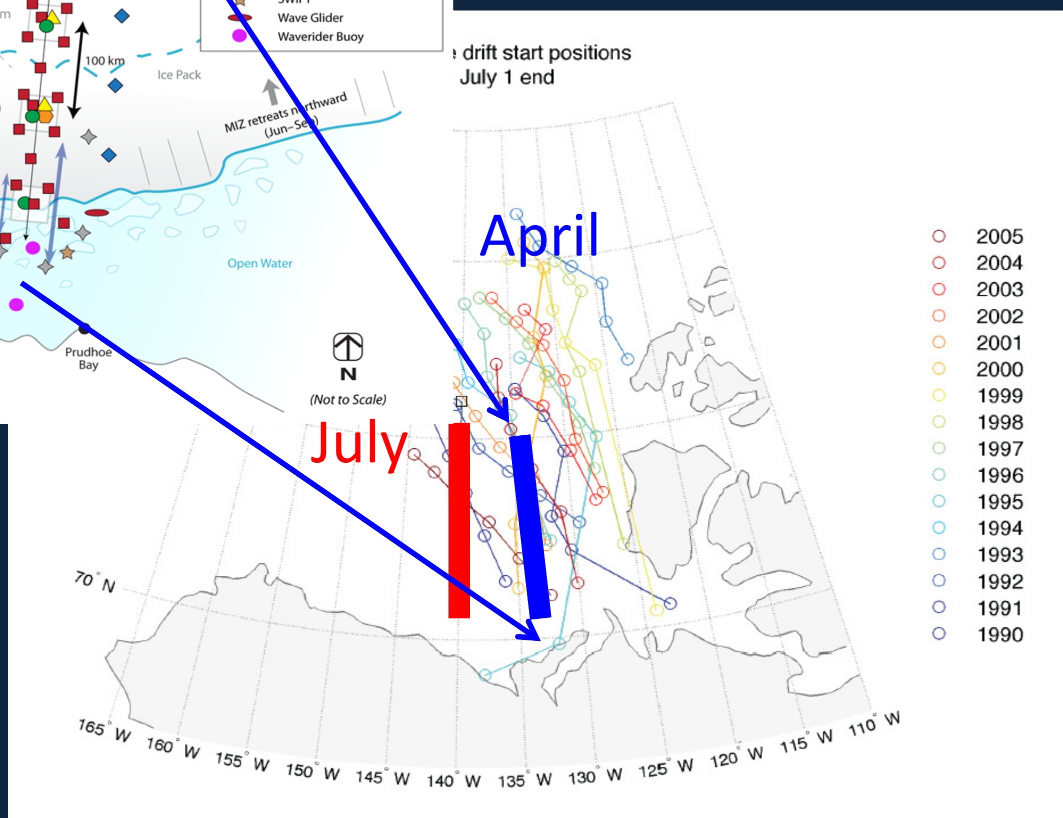
90+ Distinct Observing Assets

Autonomous Approach

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

Drifters & gliders deployed in July, immediately after open water forms along the coast.





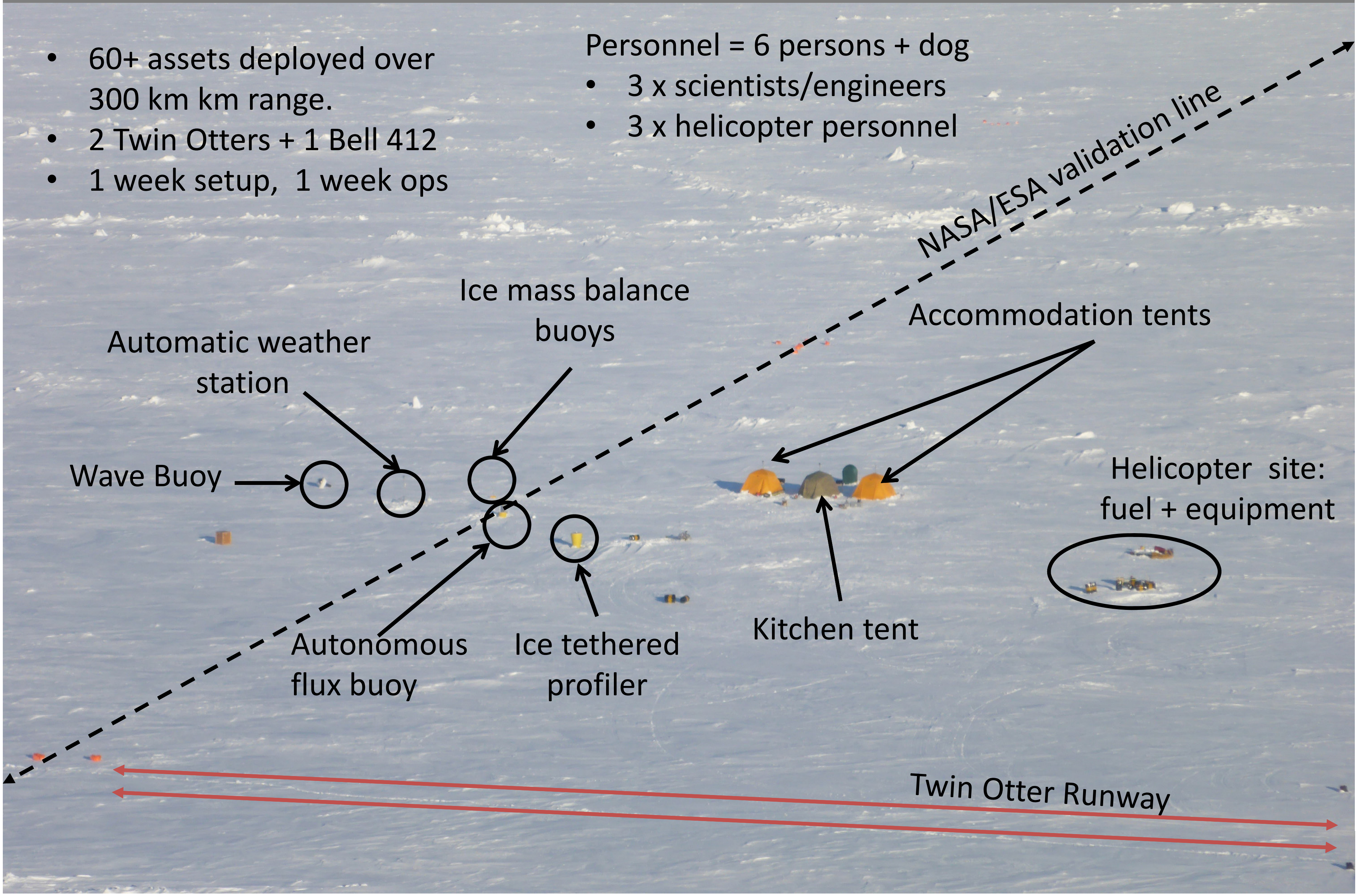
Risk Mitigation: 20% of assets held for deployment in August at northernmost site using Korean icebreaker Araon.

- Array drifts with ice pack- follow evolution along the line.
- Maintains focus on MIZ by following northward retreat of ice edge.
- Ice-based array samples ice-covered area.
- Drifting platforms in open- and ice-covered water.
- Mobile platforms span ice-free, MIZ and ice-covered regions.
- Follow MIZ retreat northward through September 2014.

'Fast & Light' Ice Camp Logistics

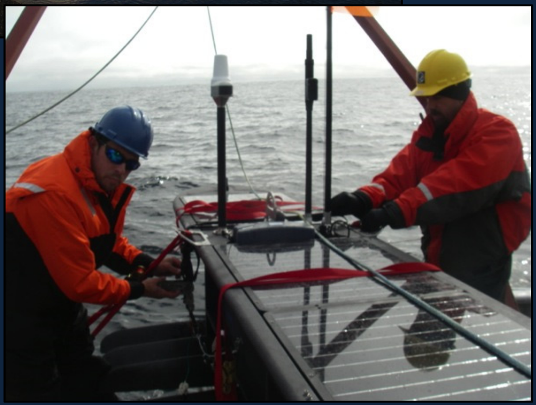
MIZ

ONR
Revolutionary Research . . . Relevant Results



'Fast & Light' Vessel Logistics

R/V Ukpik, July 2014



Deploy:
4 seagliders
3 SWIFT buoys
2 wavegliders

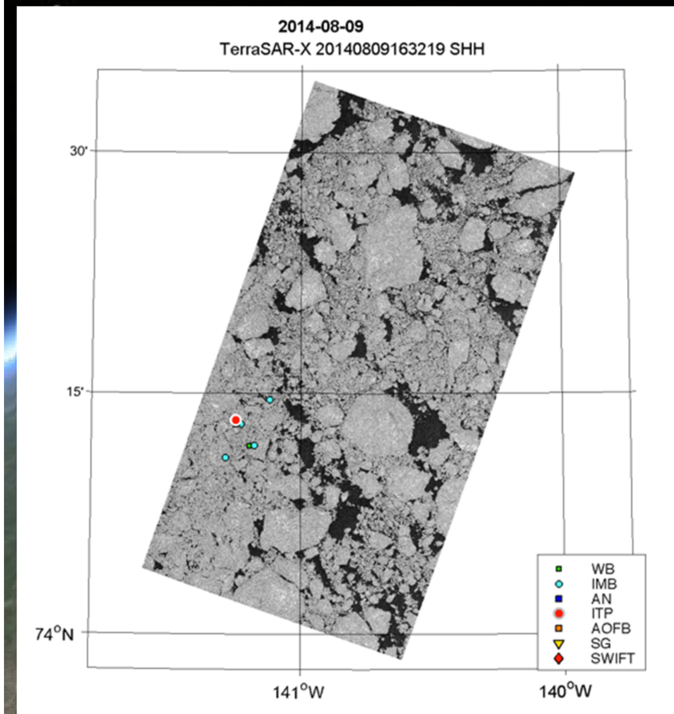
Ice edge measurements
(turbulence wave attenuation)

R/V Norseman II, Sept 2014

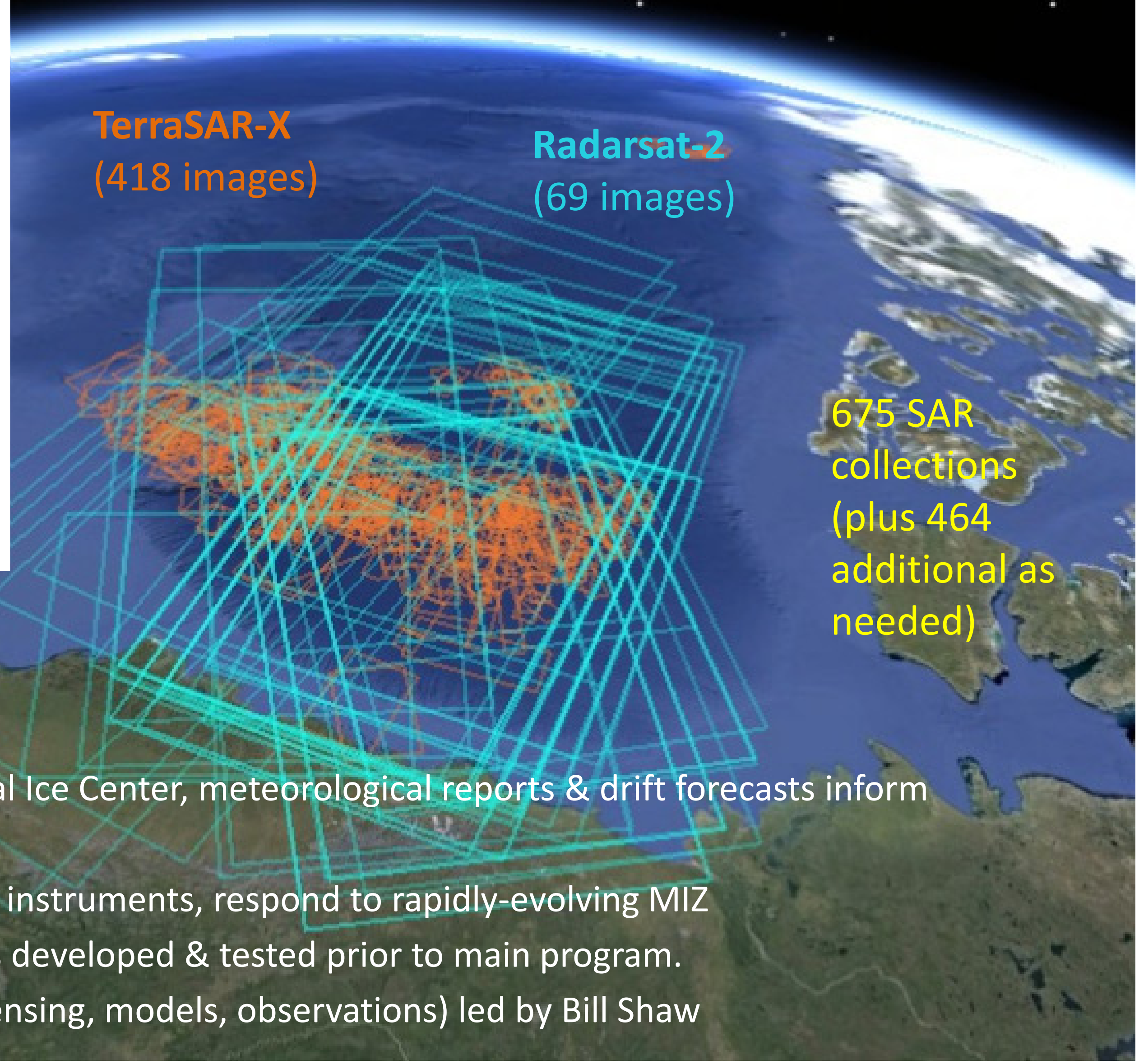
Recover:
4 seagliders
3 SWIFT buoys
1 wavegliders

Ice edge measurements
(CTD and wave attenuation)

MIZ Remote Sensing



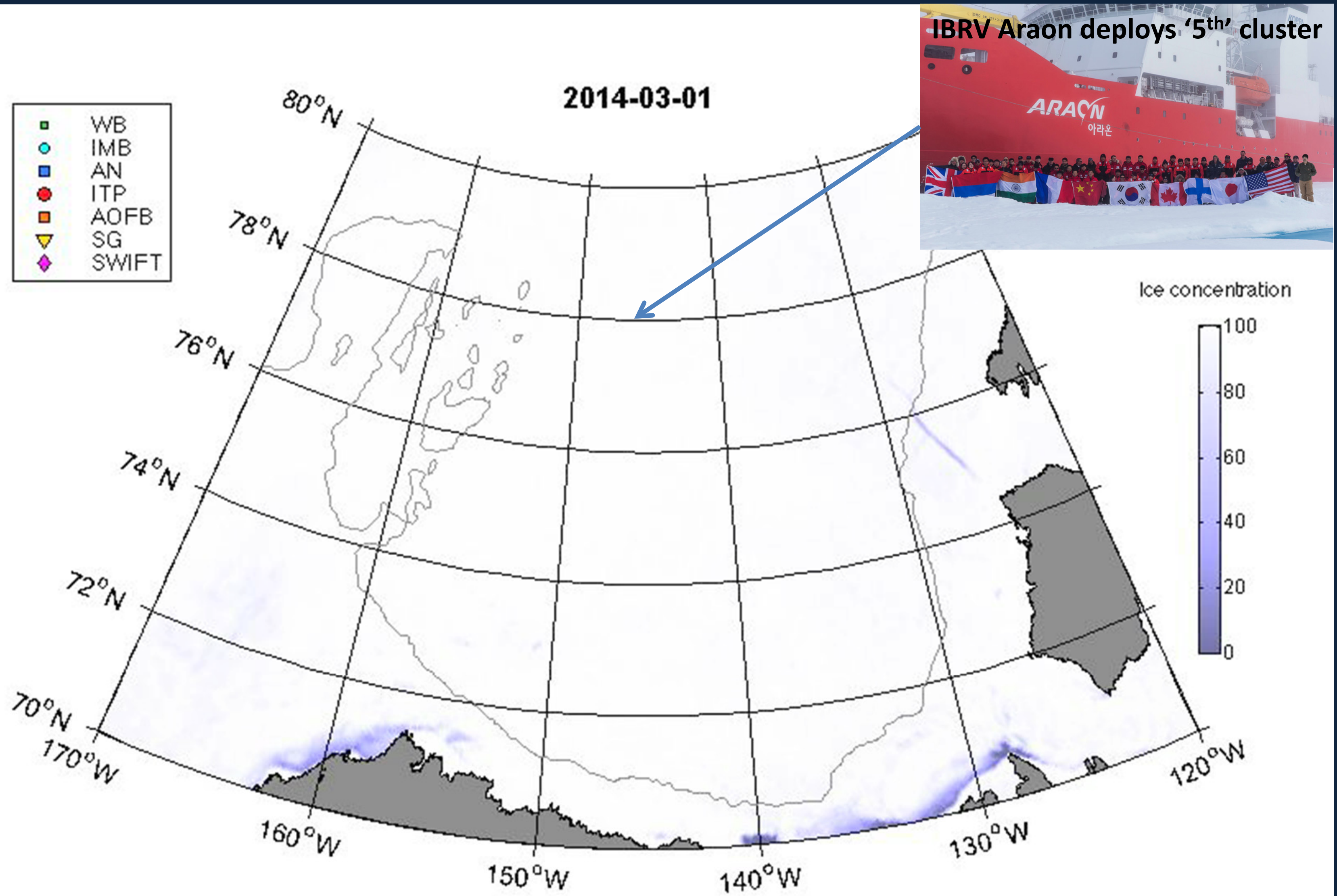
Experiment planning, execution and analysis.



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

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



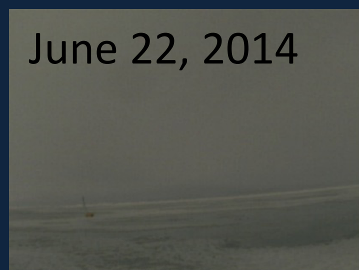
Ice concentration maps (AMSR2) from U. Bremen

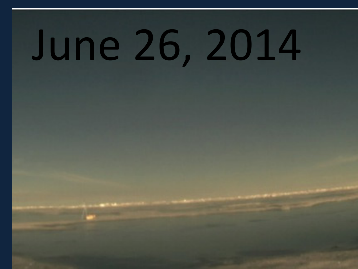
Sea ice mass balance

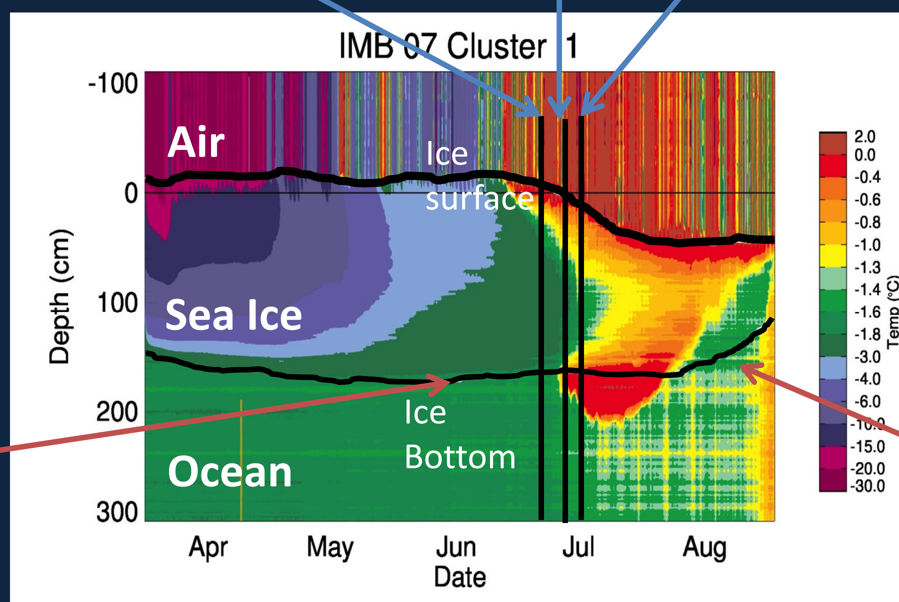
Wilkinson, Maksym and Hwang

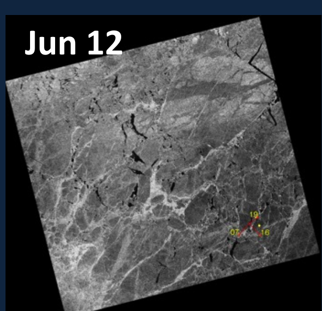
Cannot directly measure ice thickness from space
Need autonomous platforms

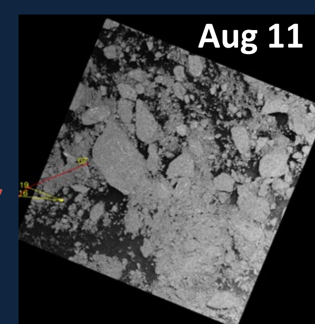
20 x ICE MASS BALANCE BUOYS





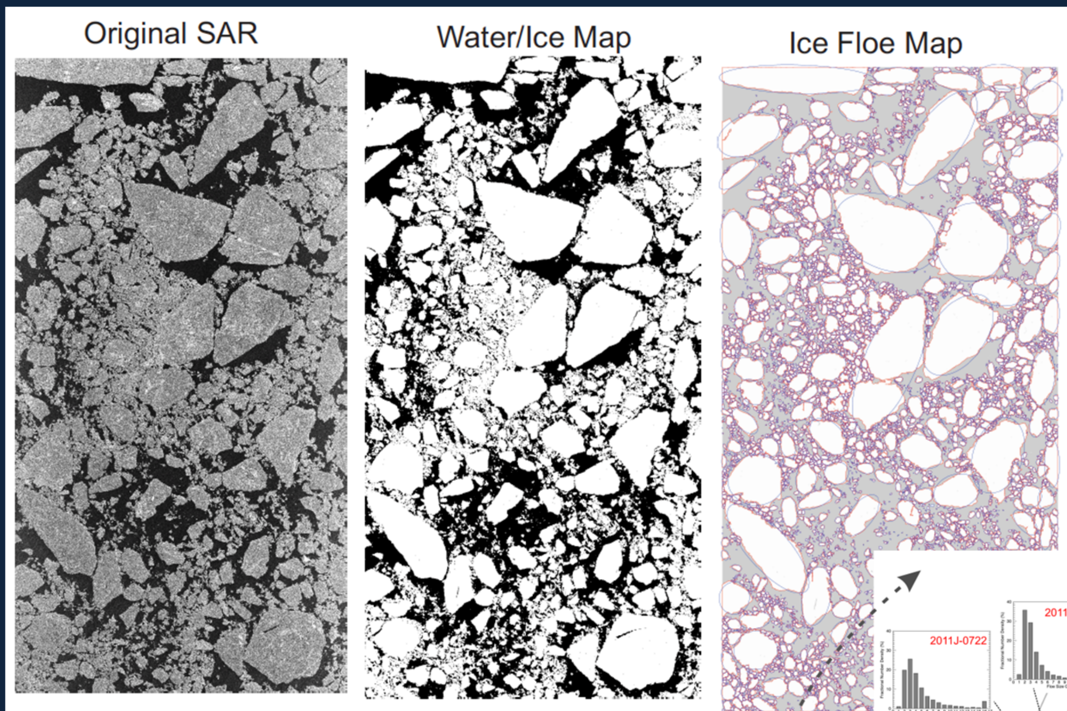






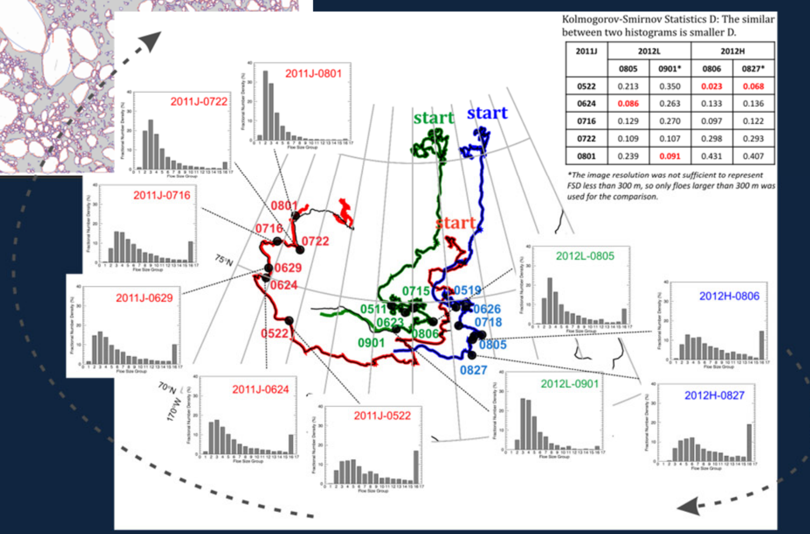
Open Water Fraction & Floe Size Distribution

Wilkinson, Maksym and Hwang



- 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.



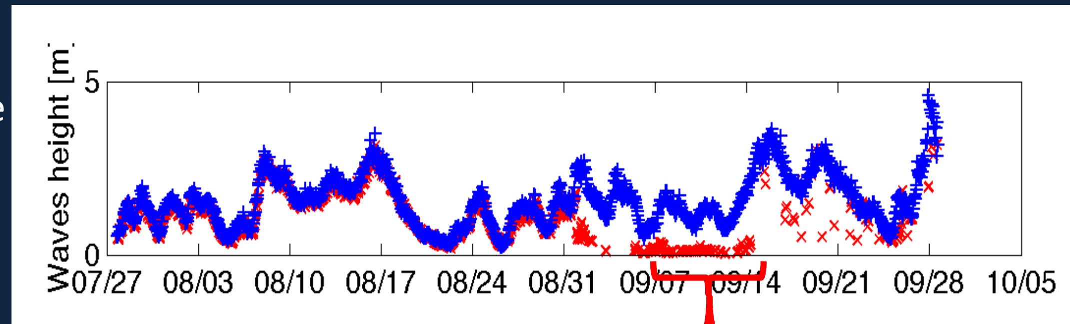
2011J	2012L		2012H	
	0805	0901*	0806	0827*
0522	0.213	0.350	0.023	0.068
0624	0.086	0.263	0.133	0.136
0716	0.129	0.270	0.097	0.122
0722	0.109	0.107	0.298	0.293
0801	0.239	0.091	0.431	0.407

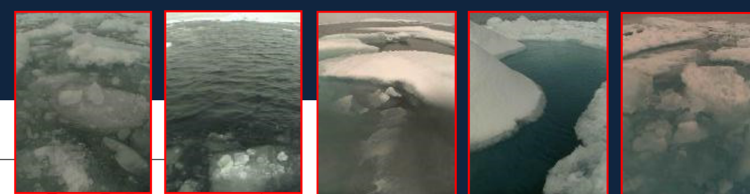
**The image resolution was not sufficient to represent FSD less than 300 m, so only floes larger than 300 m was used for the comparison.*

Surface Wave Attenuation in Sea Ice

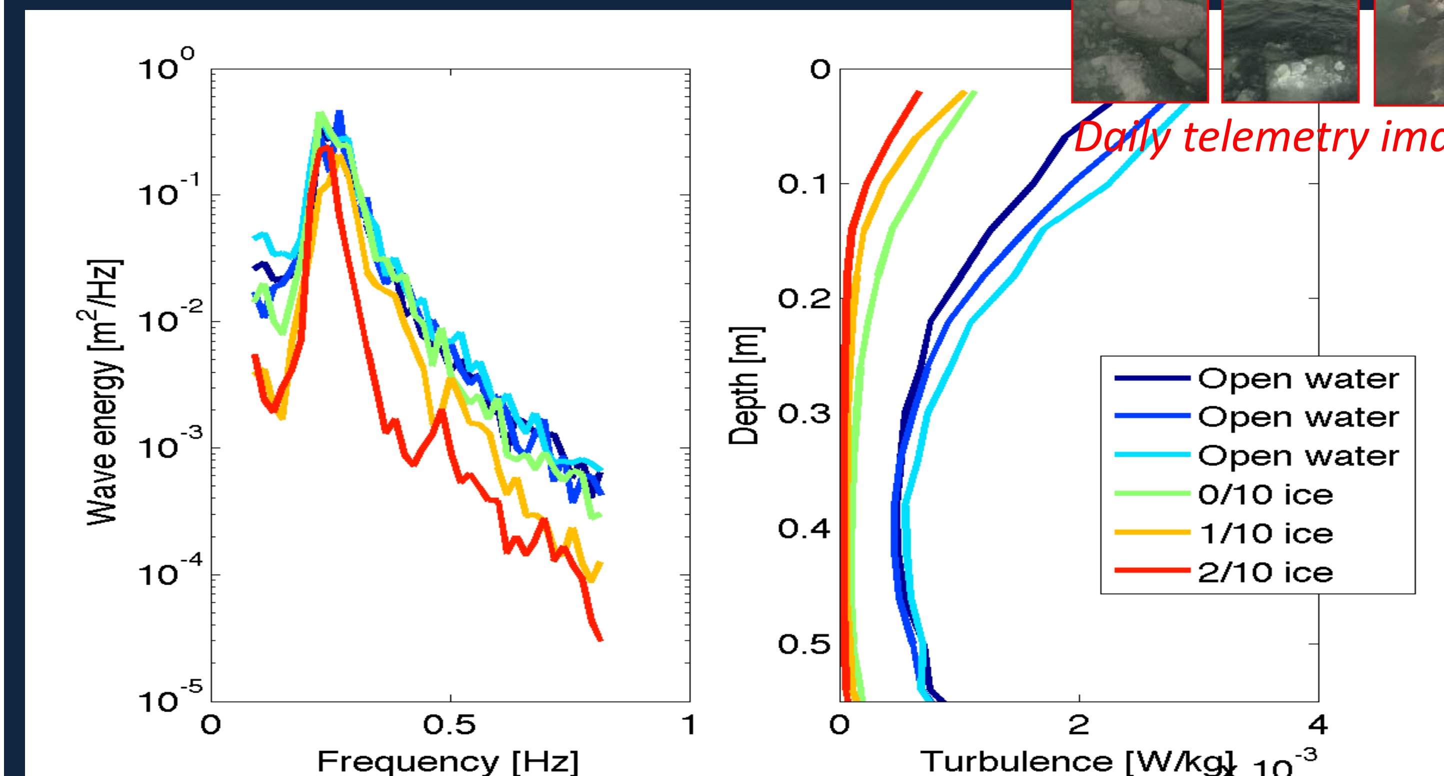
Thomson (APL-UW)

- 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



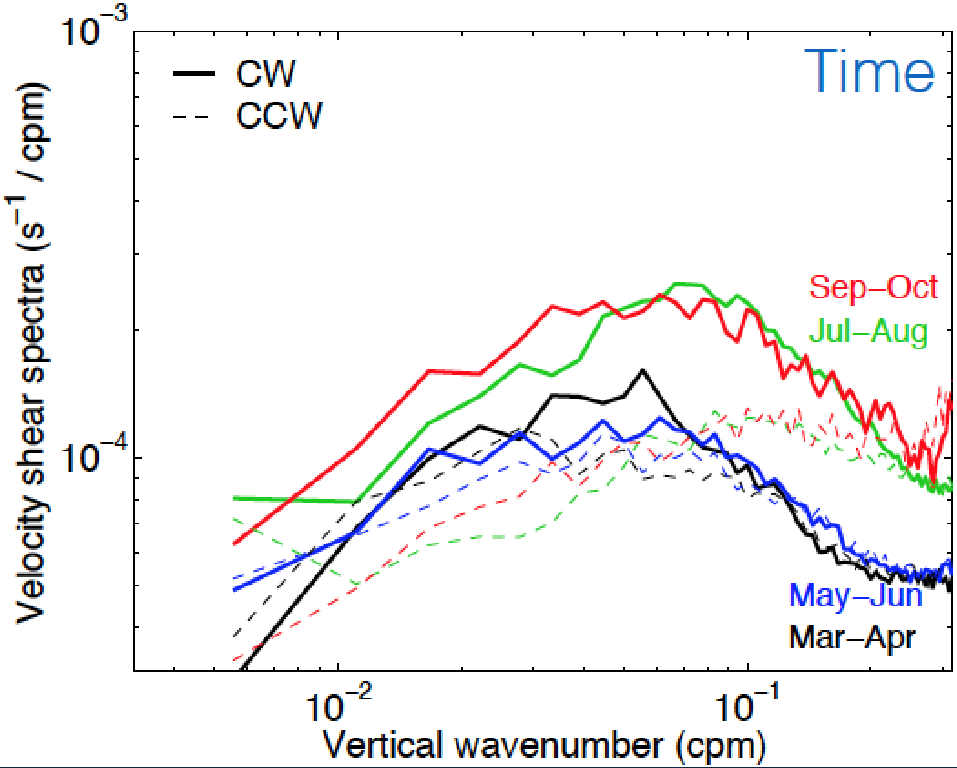


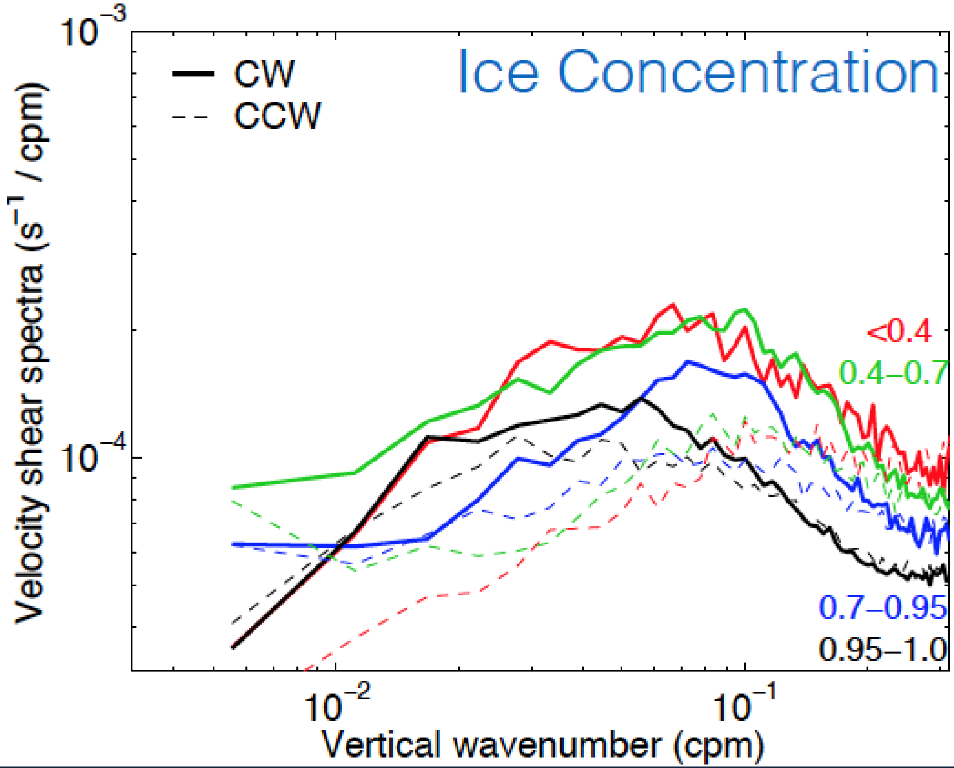
Daily telemetry images from SWIFT 10



Internal Wave Energy Changes with Ice Cover

Cole, Toole, Timmermans, Krishfield

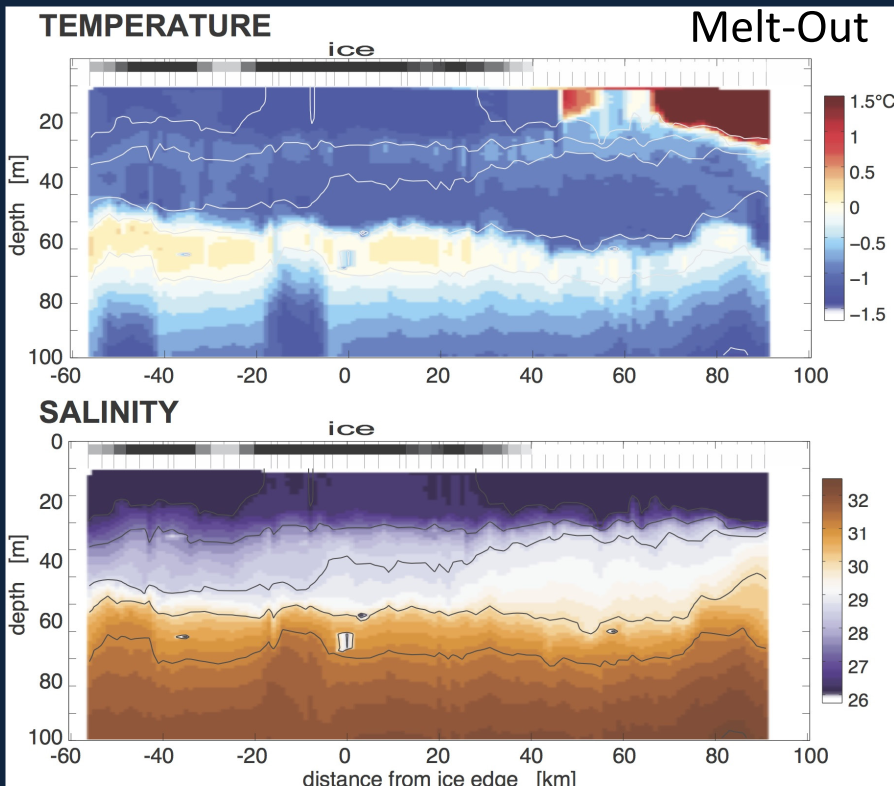


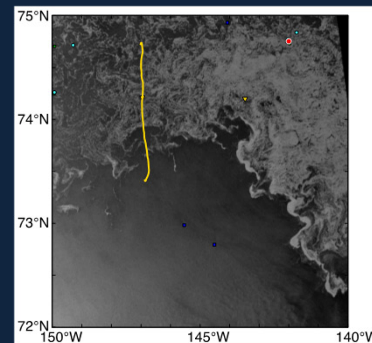


- Ice-Tethered Profilers at C2 and C4
- 70-250 m depth
- IW energy increases from spring into summer
- IW energy appears to increase with increasing open water fraction.

Glider sections across the MIZ

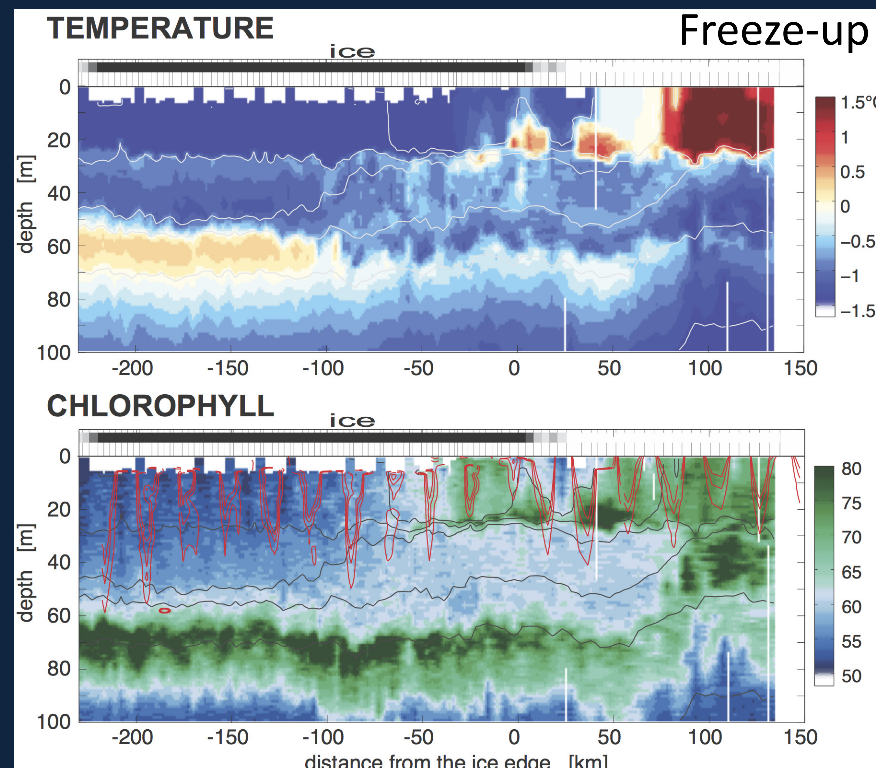
Lee, Rainville, Gobat, Webster, Freitag





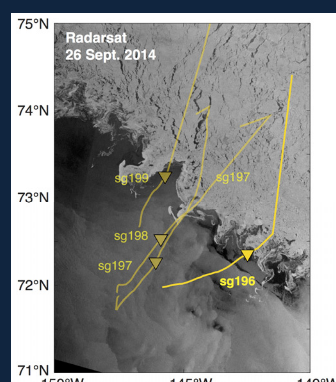
Melt-Out (5 Sep 2014)

- Warmer, fresher out of the ice.
- Thickening isopycnal layer at ice edge.
- Ice-edge upwelling?
- Ice-edge mixing?



Freeze-up (26 Sep 2014)

- Deeper mixed layers.
- Elevated lateral variability.
- Near-surface temperature maxima formation?
- Sharp contrast in chl fluorescence across MIZ.



Early Results

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'.
5. Secondary bloom during freeze-up, associated with elevated mixing.

Technical

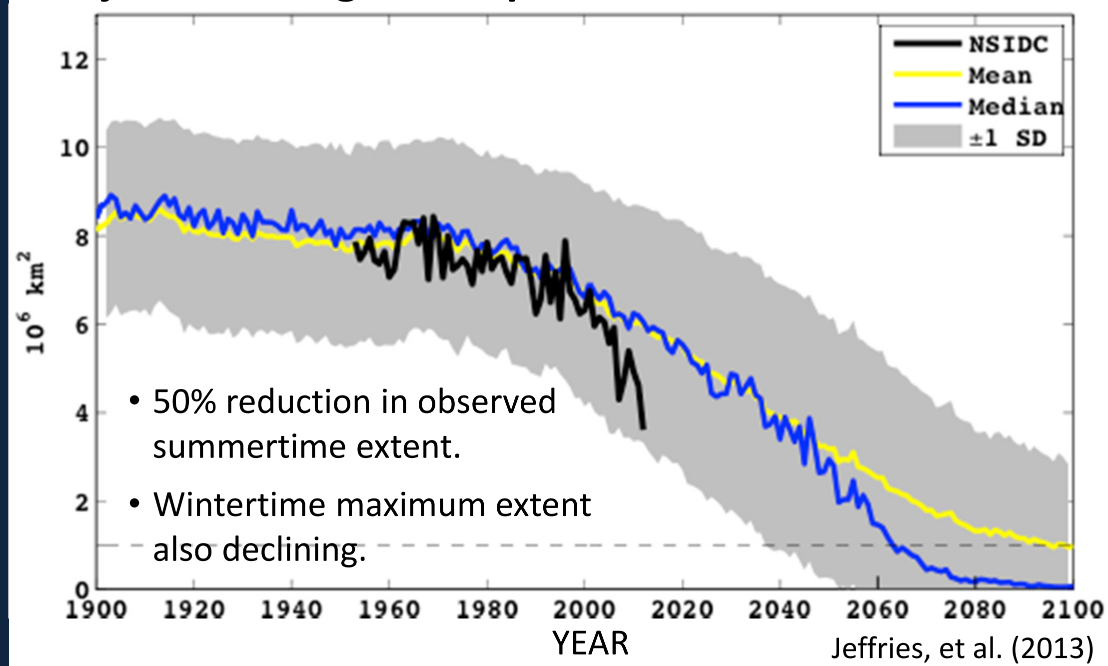
1. Autonomous observing from pack ice, though the MIZ and into open water spanning an entire melt season (March – October 2014).
2. Under-ice glider operations using new, drifting broadband sources.
3. Acoustic receptions at 400+ km due to shallow sound channel associated with Beaufort Sea near-surface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

Models Struggle to Reproduce Dramatic Reduction in Summertime Sea Ice Extent

- Regime shift from multi-year (thick) to 1st year sea ice.
- Decline primarily thermodynamic, other processes may increase in importance.
- Quantity *and* quality of sea ice impact processes and feedbacks.

Minimum Sea Ice Extent

Projected Changes in September Arctic Sea Ice Extent



Improve Predictability – Refine Models

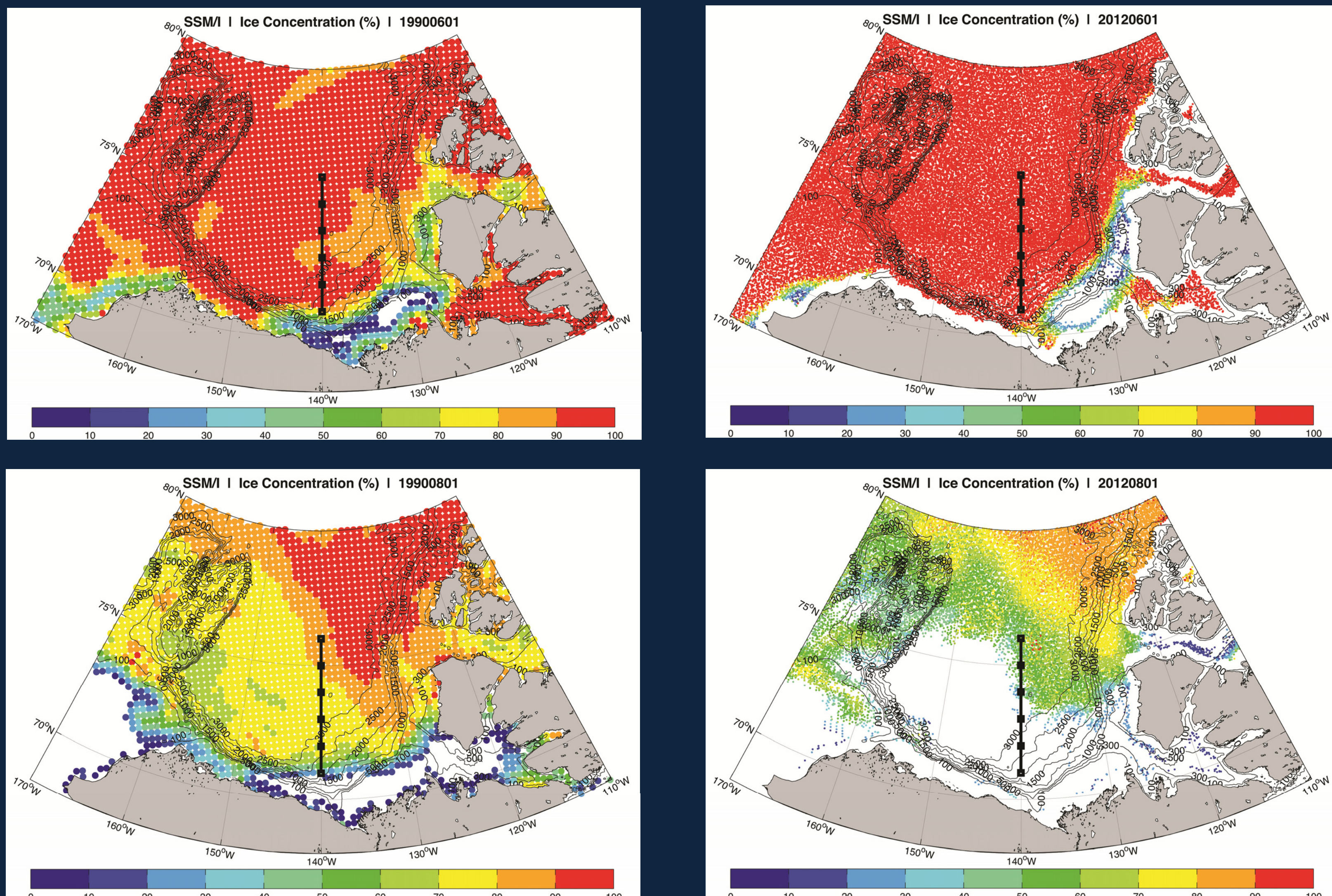
- Process-level investigations
- Improve physics, parameterizations
- Continued testing against sustained observations

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

Evolving Beaufort MIZ

1990 | 2012

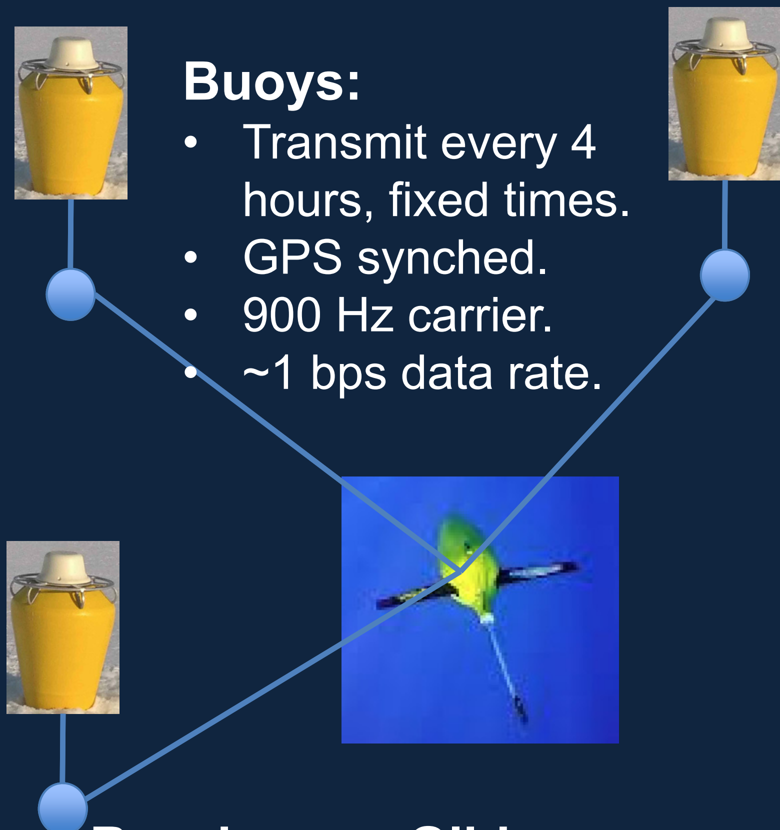
June | August



SSM/I - Posey

Acoustic Navigation System

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

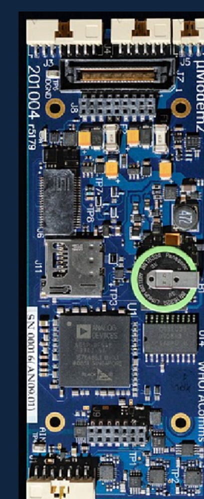


Receiver on Glider:
- Measures time, computes range.
- Decodes location of buoy.
- Ranges and source locations used to compute real-time position.

How Does it Work?
- Ice-based sensor array is <u>mobile</u>.
- Therefore <u>must transmit source positions</u> to allow real-time geo-location by gliders.
- Data transmission capability also means <u>commands can be sent to glider</u>.

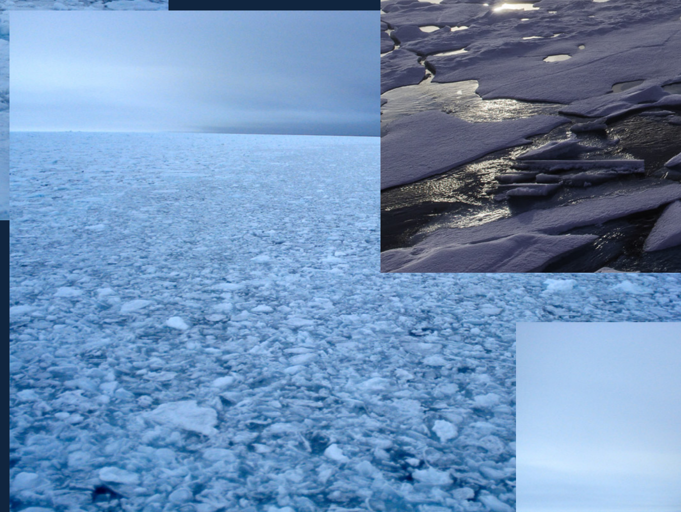
Glider Receiver Hydrophone

Glider Receiver Board



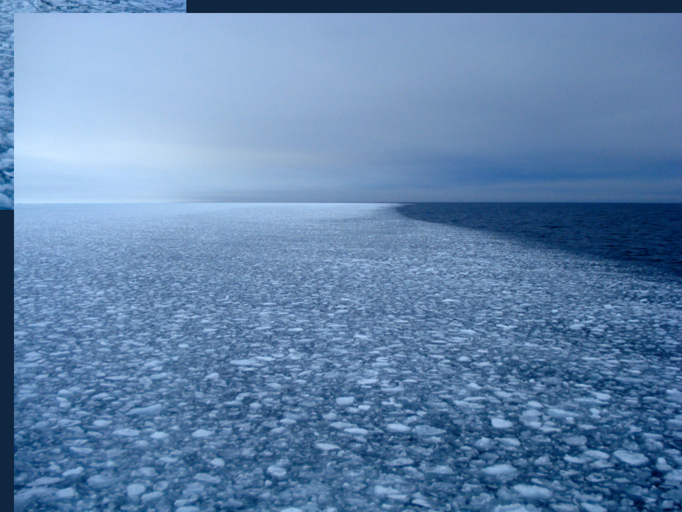
The 2014 Beaufort MIZ


Fram Strait MIZ




Beaufort Sea MIZ, August 2014

Pack Ice



Open Water

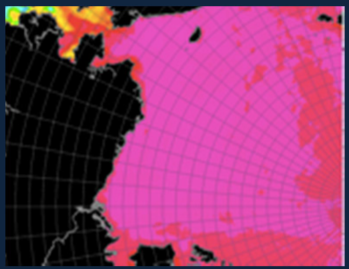
MIZ Sea Ice Evolution through the Spring Melt

To understand the processes that govern sea ice melt:

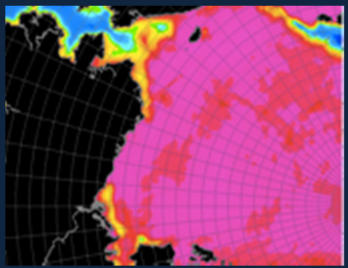
- Ice mass balance.
- Sea ice dynamics (locally and regionally).
- Open water fraction/floe size distribution.
- Surface wave penetration and dissipation.
- Meteorological forcing.
- Upper ocean variability.

Ice extent 2014

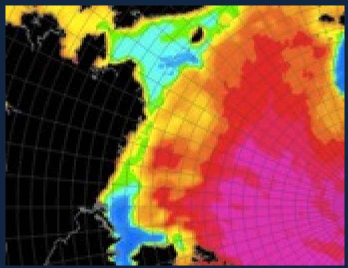
April



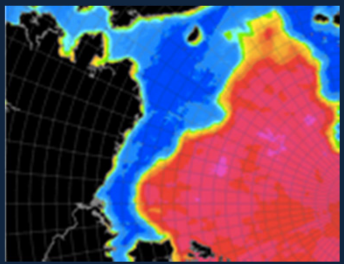
June



August

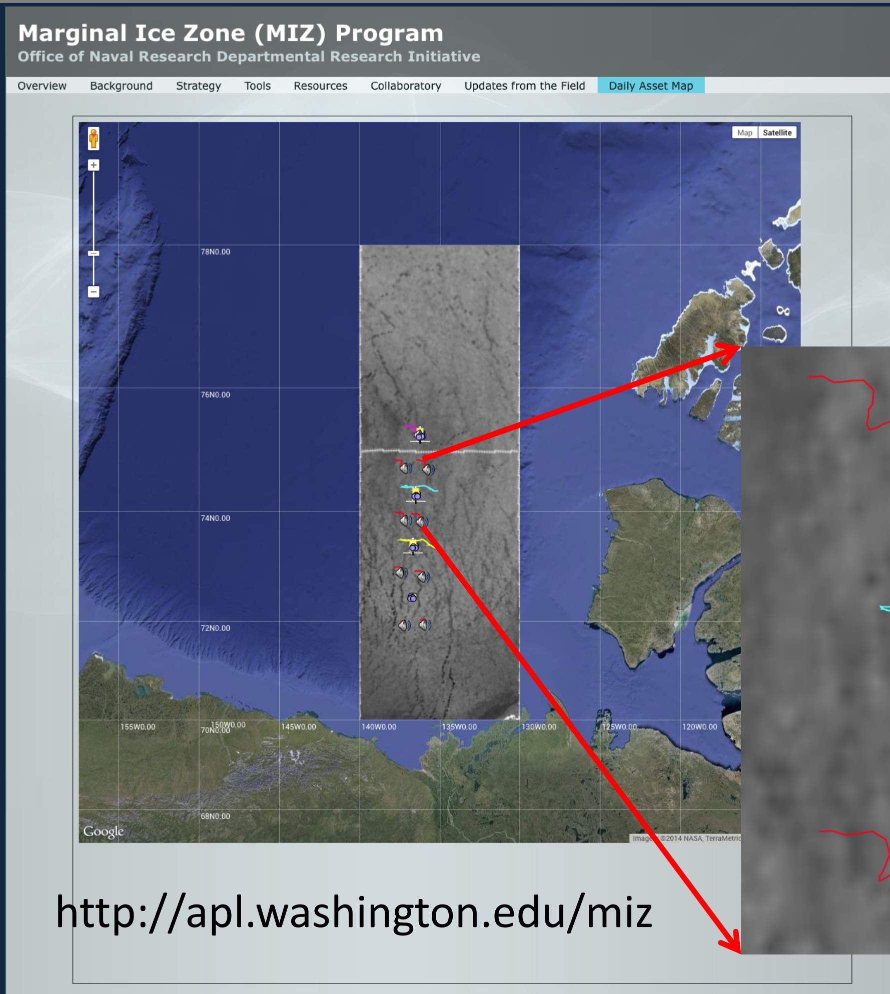


October

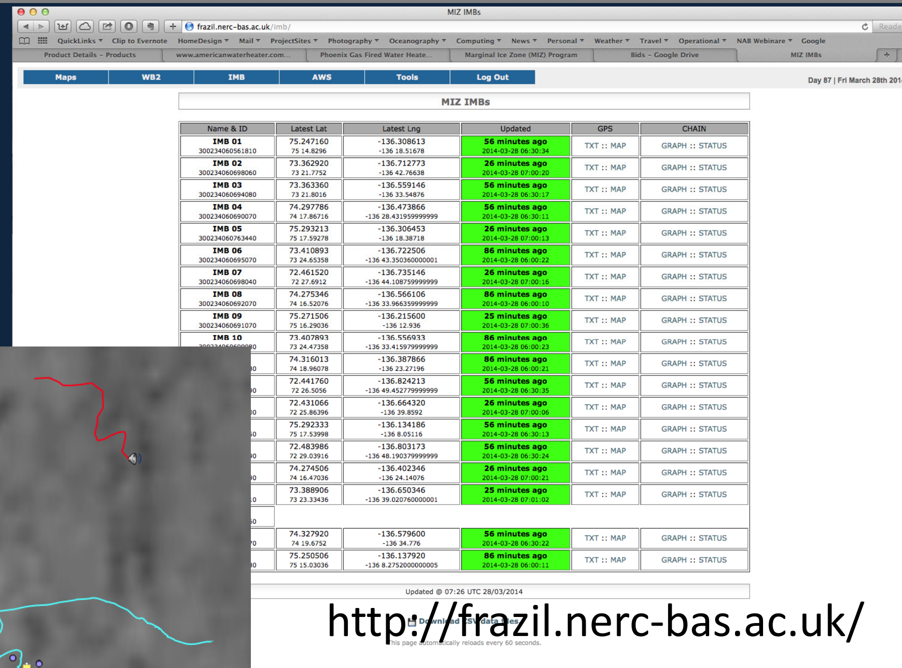


Courtesy: www.seaice.dk

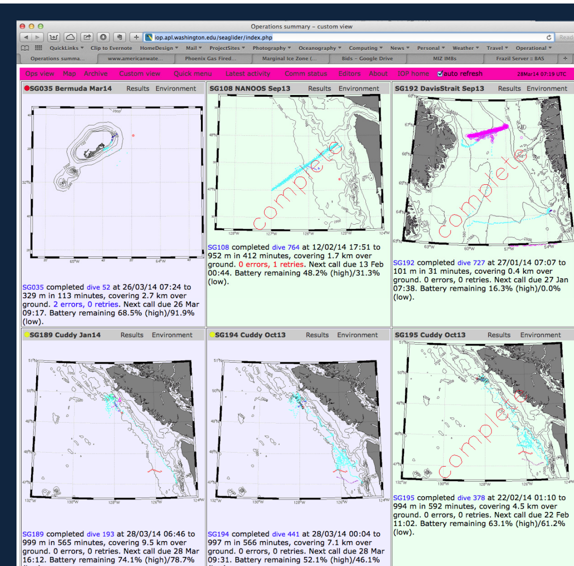
Real Time Data Display and Asset Maps



http://apl.washington.edu/miz



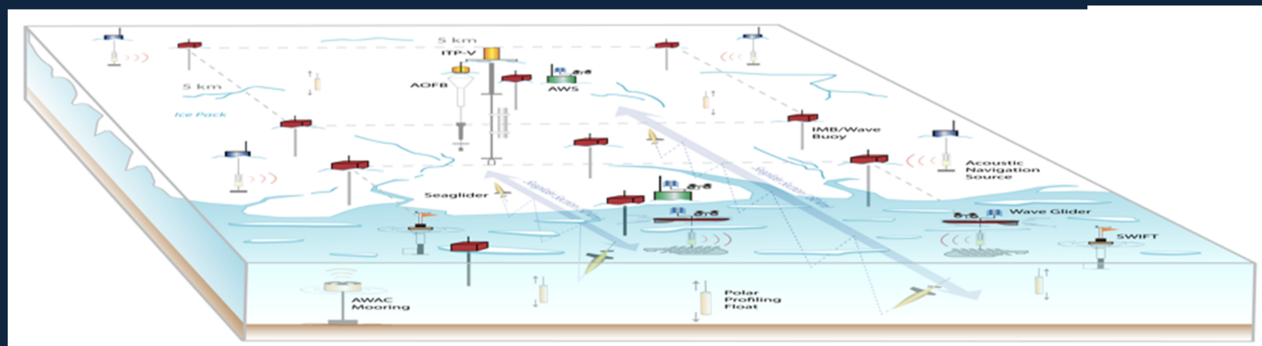
http://frazil.nerc-bas.ac.uk/



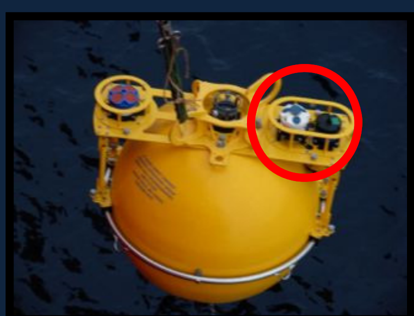
http://iop.apl.washington.edu/seaglider

http://www.whoi.edu/itp/data/

Wave measurements



Under the ice



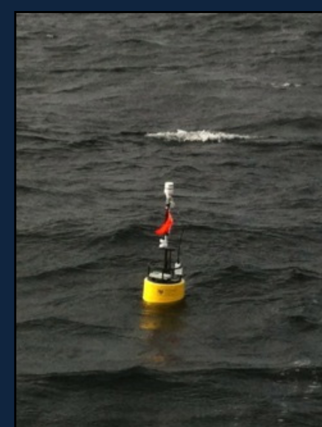
Nortek AWAC at 50 m sub-surface

WHOI BGEP mooring “A”
75 N, 150 W

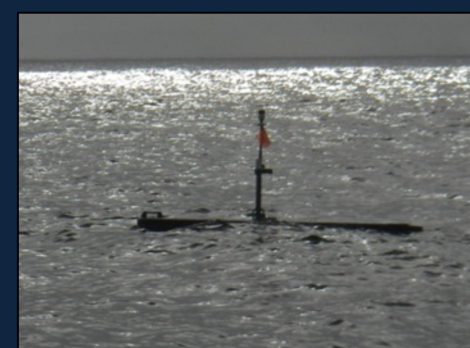
On the ice

Wave buoys (drifting)

In open water (and ice)



SWIFT buoys (drifting)



waveglider (piloted)

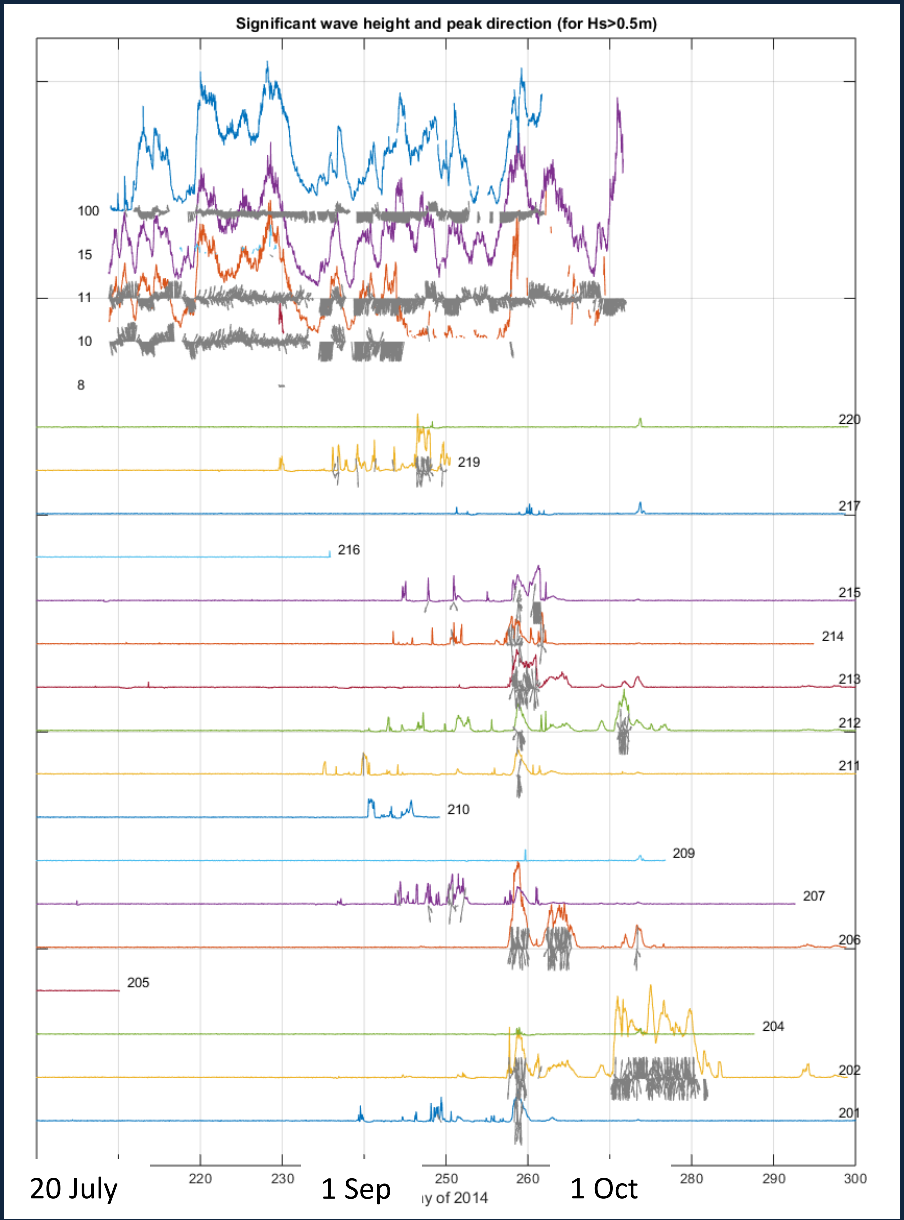
Surface Wave Attenuation in Sea Ice

Doble (LOV), Thomson (APL-UW)

SWIFT
open water
Low ice conc.

increasing ice

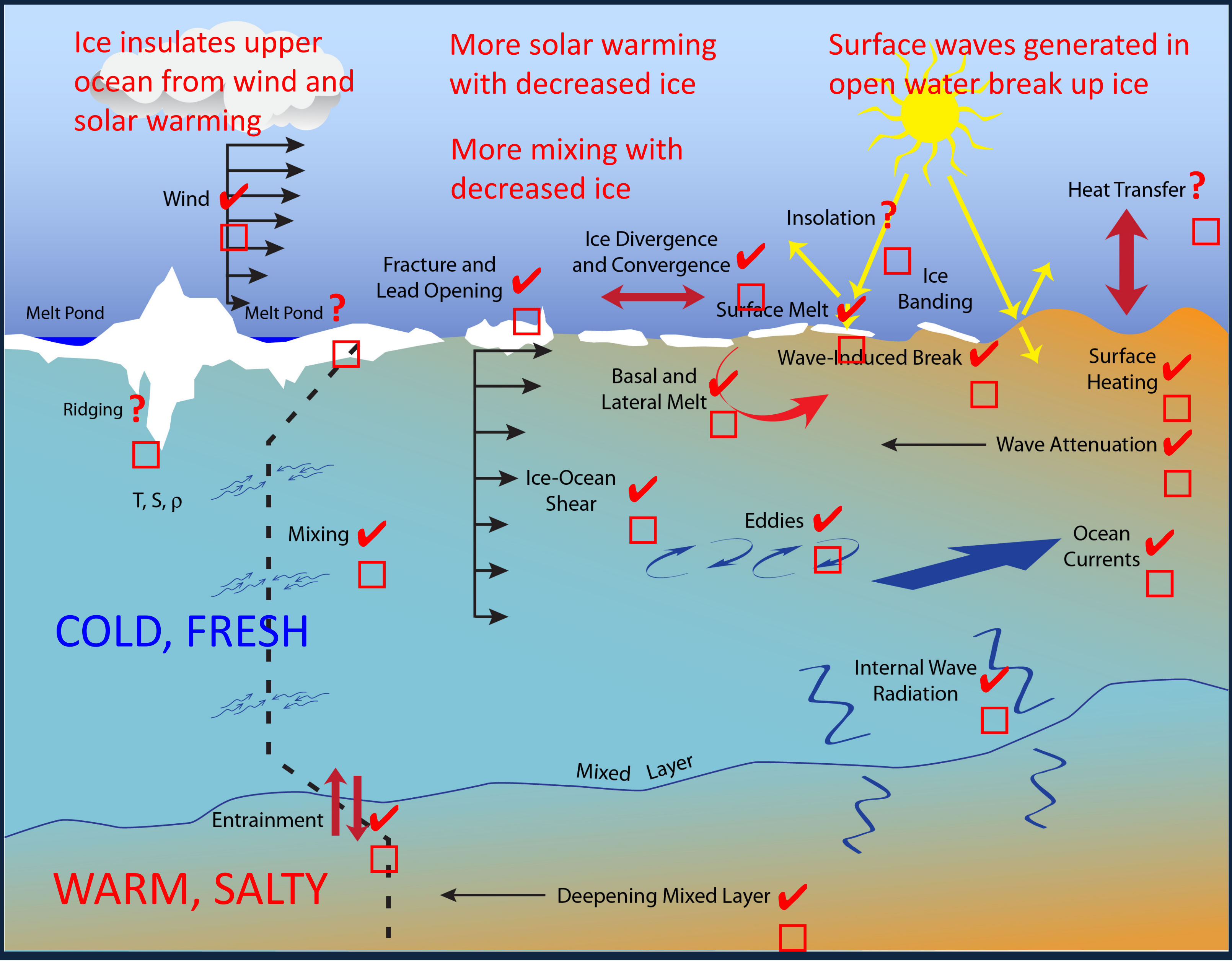
Wave Buoy
high ice conc.



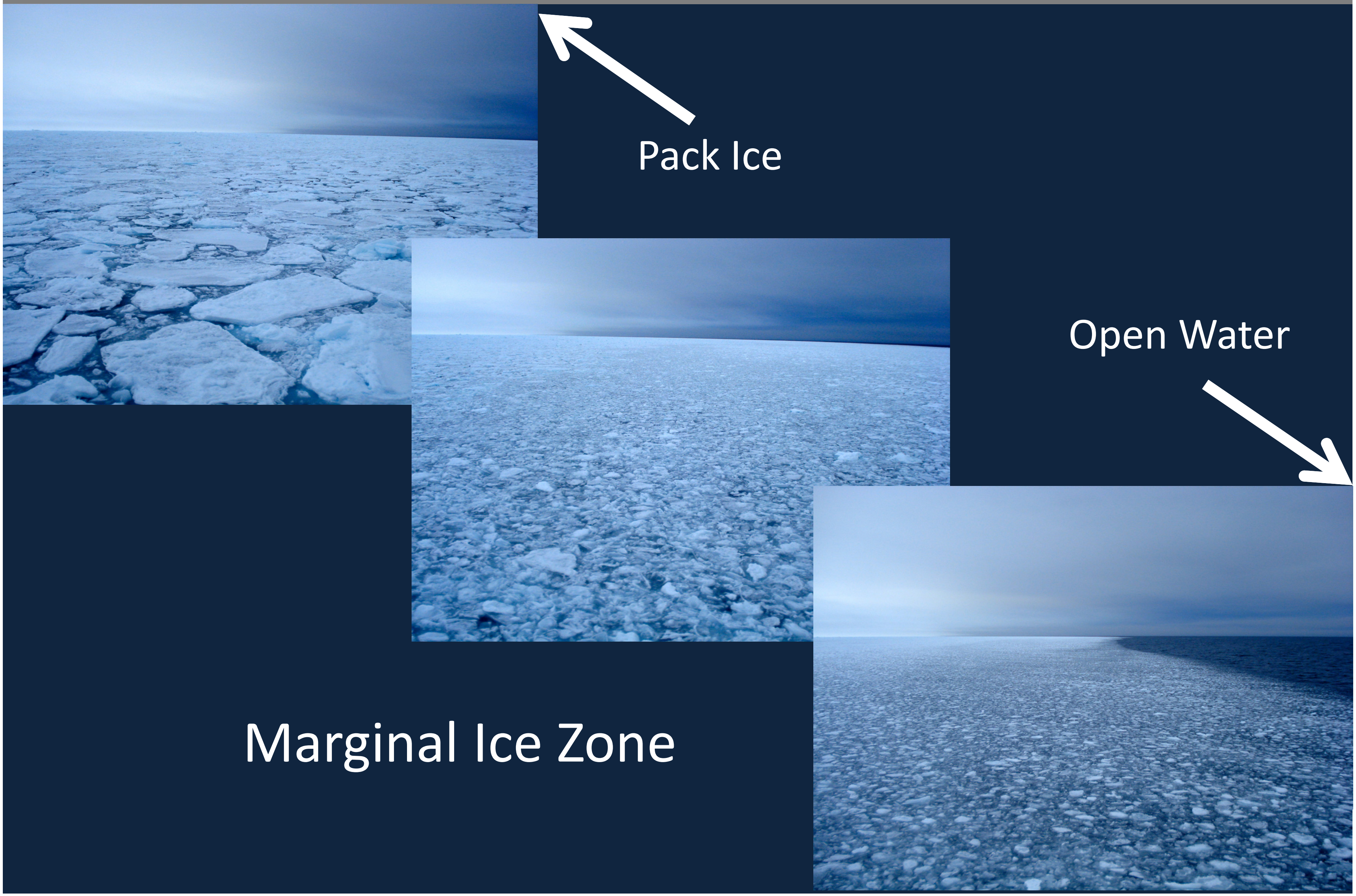
- Waves strongly modulated by even small concentrations of sea ice.

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

MIZ Atmosphere-Ice-Ocean Interaction

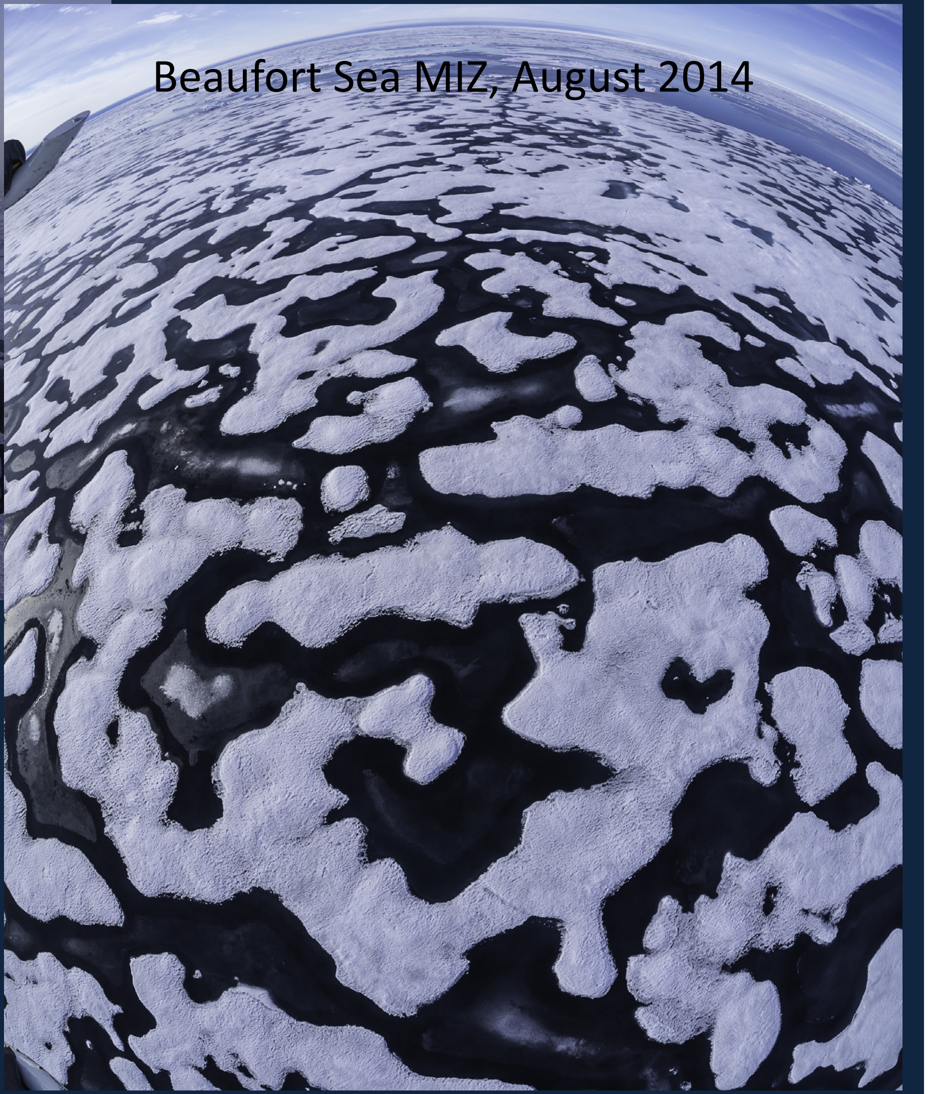


Conceptual MIZ (Fram Strait)



The 2014 Beaufort MIZ

Beaufort Sea MIZ, August 2014



Beaufort Sea MIZ, August 2014

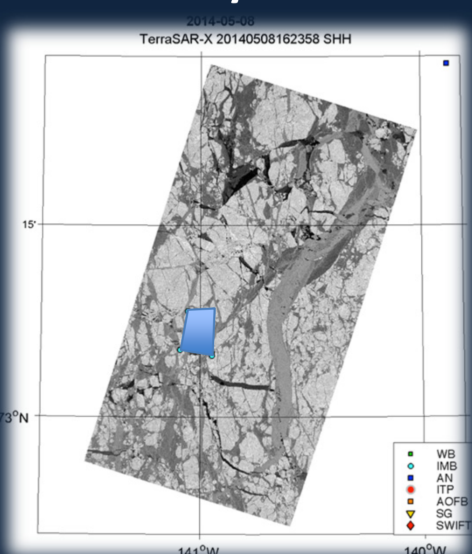
Fram Strait MIZ

Sea ice dynamics

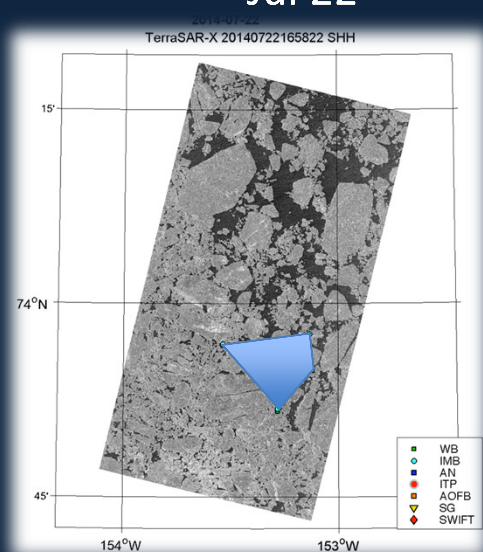
Wilkinson, Maksym and Hwang

Local: GPS is the key **Regional: Satellites are the key**

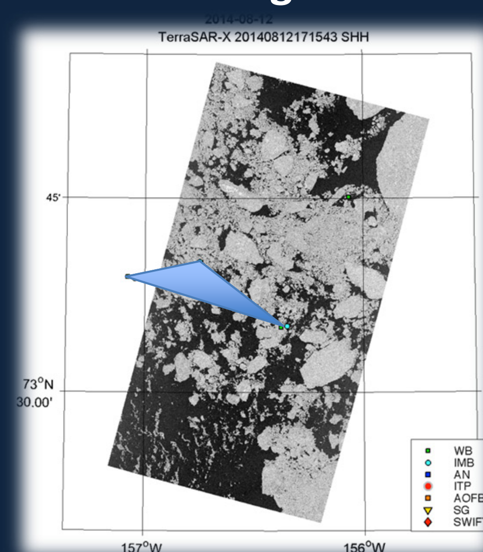
May 8



Jul 22



Aug 12



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

Outline

1. Background – The changing Arctic
2. Objectives – Science and technology development
3. Emerging Physics of the Marginal Ice Zone
4. A New Approach – Light-weight logistics and sustained, autonomous observing
5. The MIZ measurement program
    1. Acoustic navigation
    2. The changing wave climate
    3. Sea ice dynamics
    4. Upper ocean physics and biology
6. Summary

Multi-faceted Impacts

Climate

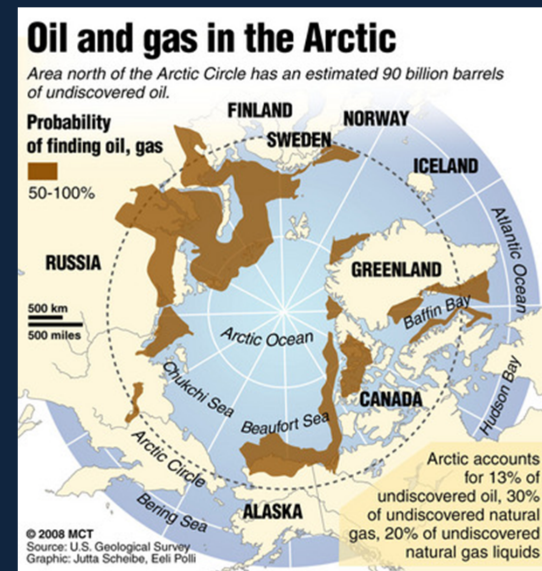
- Global links… changes in atmospheric circulation linked to heat and drought in US and cold stormy weather in Europe

Industry

- Shipping, oil/gas, minerals, fisheries, tourism…

Economics

- UK Stern Review on the Economics of Climate Change (2006). £3.68 trillion
- The cost of Arctic change?



Indigenous communities

- Loss of traditional way of life

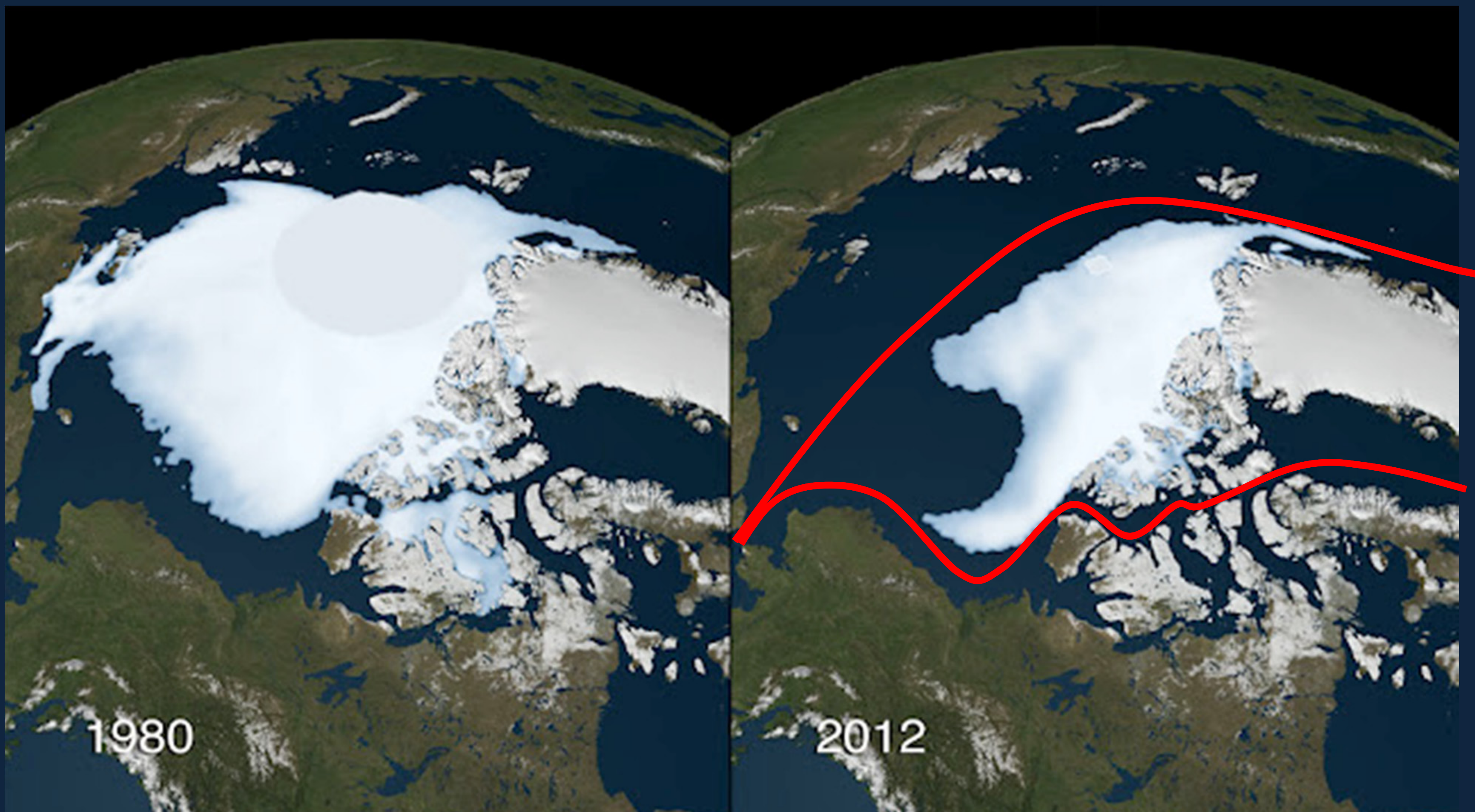
Coastal changes

- Coastal erosion due to enhanced wave energy

Environmental pressures

- Loss of habitat/species
- Increase in ocean acidification
- Change in ocean properties

A New, Emerging Physical Regime

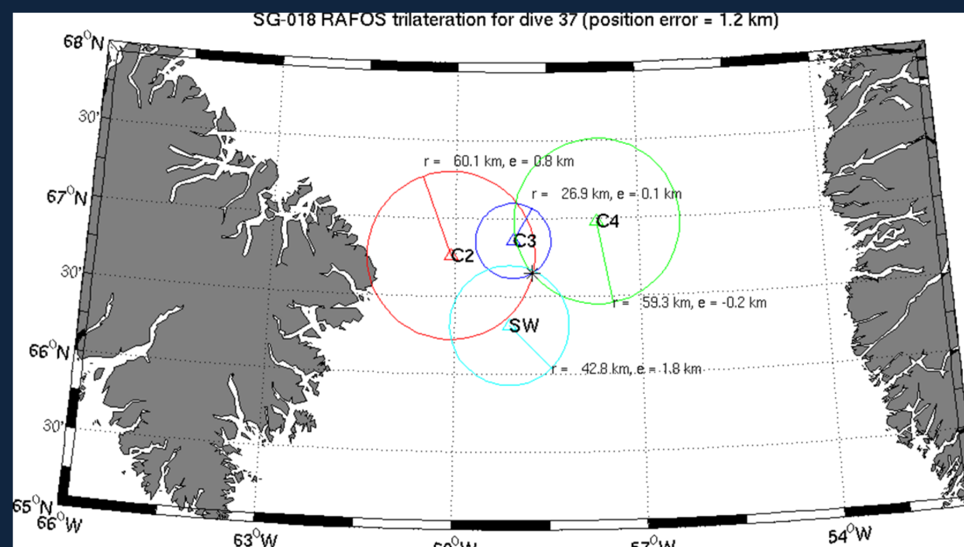


A lot more open water in summer months

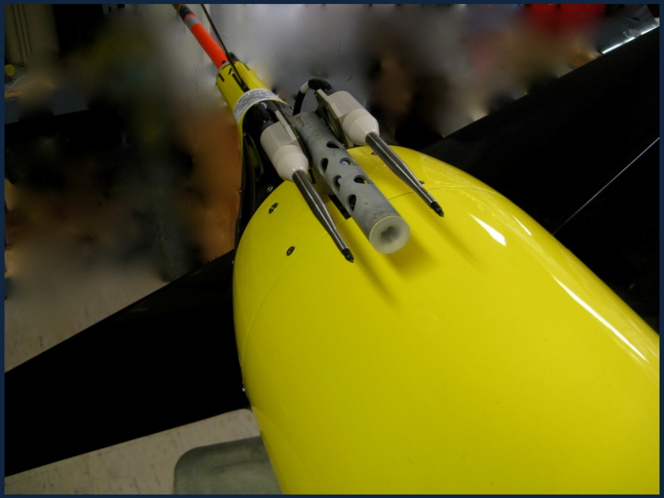
Autonomous Seagliders for Ice-Covered Oceans

- 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.



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).

Navy Needs and Key Questions

Task Force Climate Change "Arctic Roadmap":

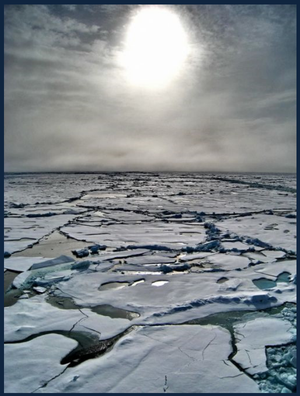
- Must have Arctic environmental information and predictions to support investment and policy decisions, and future operations.

NORTHCOM:

- Must improve ability to observe and predict the Arctic environment.

N2N6E CBA: Better Environmental Information

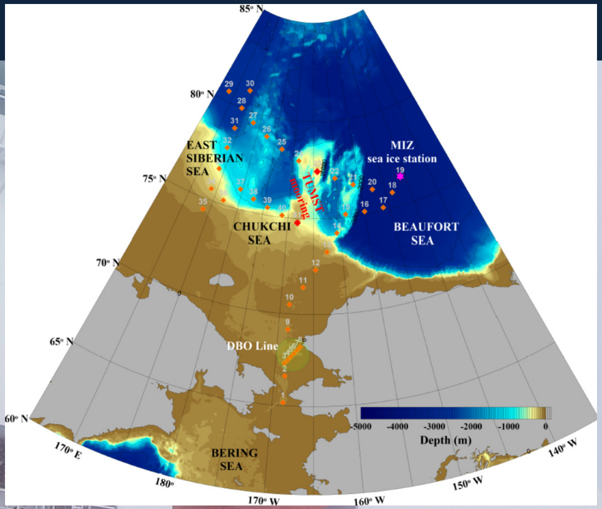
- Insufficient ability to provide oceanographic information, ice reports, accurate navigation charts, meteorological analysis and forecasts



- ❑ How little sea ice will there be, and when will the key changes occur?
  - Need better prediction capability underpinned by basic research.
- ❑ How is the Arctic region as a whole going to be different?
  - Need research into how the entire Arctic environmental system functions.
- ❑ What does the Navy need to know to operate in the Arctic?
  - Need sustained observations and improved predictions of the state of the Arctic.
- ❑ How will the changing Arctic affect the rest of the earth, and vice-versa?
  - Need an Arctic environmental system model integrated within global prediction models

IBRV Araon 31 July – 25 August 2014

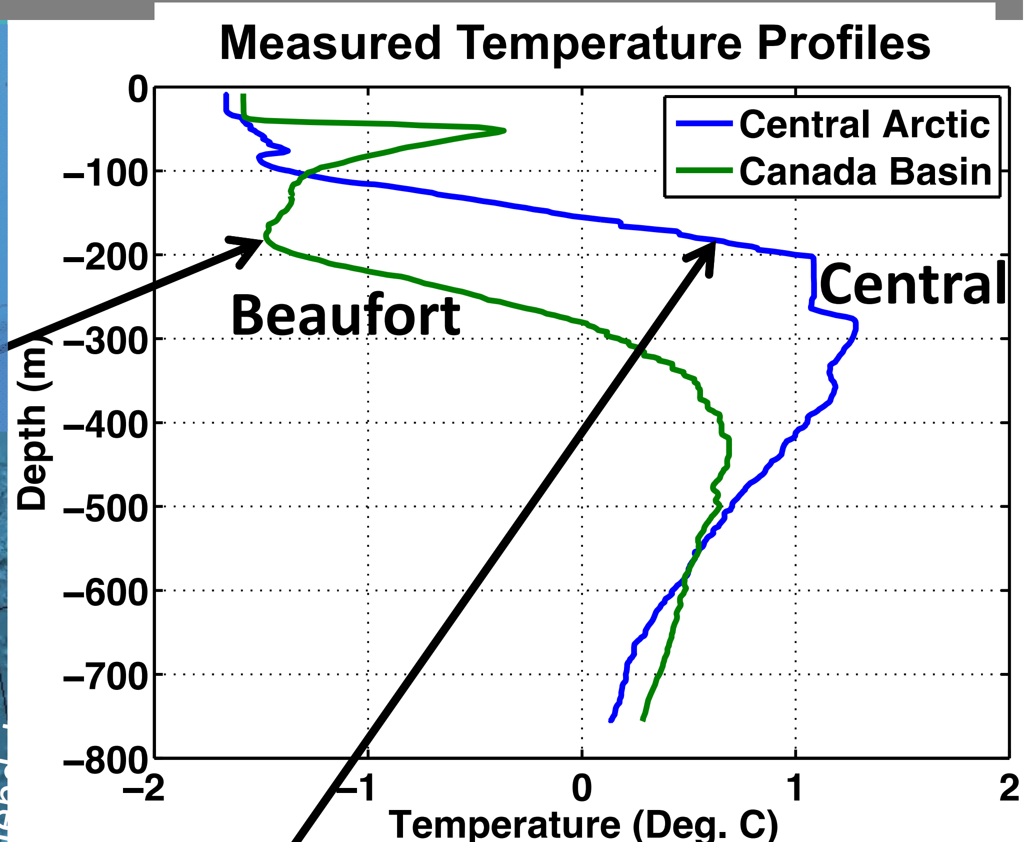
- Collaboration with the Korea Polar Research Institute (KOPRI)
- Deploy Cluster 5
- Deploy 2 navigation sources
- Calibration data
- Support KOPRI science operations



With thanks to Dr. Sung-Ho Kang and Eun Jin Yang, Captain and crew of IBRV Araon, Maritime Helicopters team: Eric Richard, Dave Guy and Howard Reed and the USCG

Arctic Profiles and Propagation

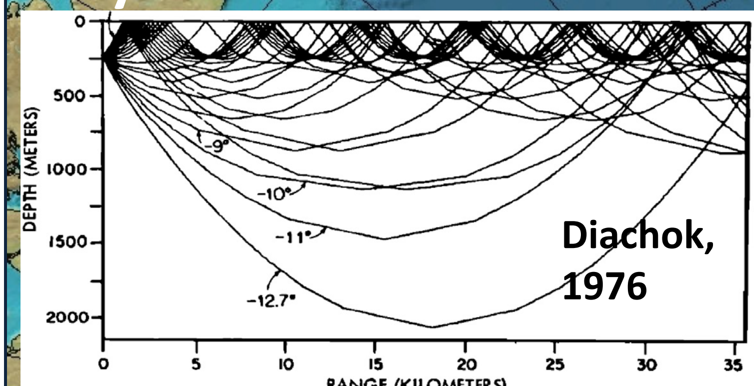
- Central Arctic temperature profile has perpetual cold surface layer.
- Sound reflects from the ice, suffering loss at each bounce.
- Range limited by number of reflections.



Beaufort

Canada Basin

Ray Paths – Classic Profile



Diachok, 1976

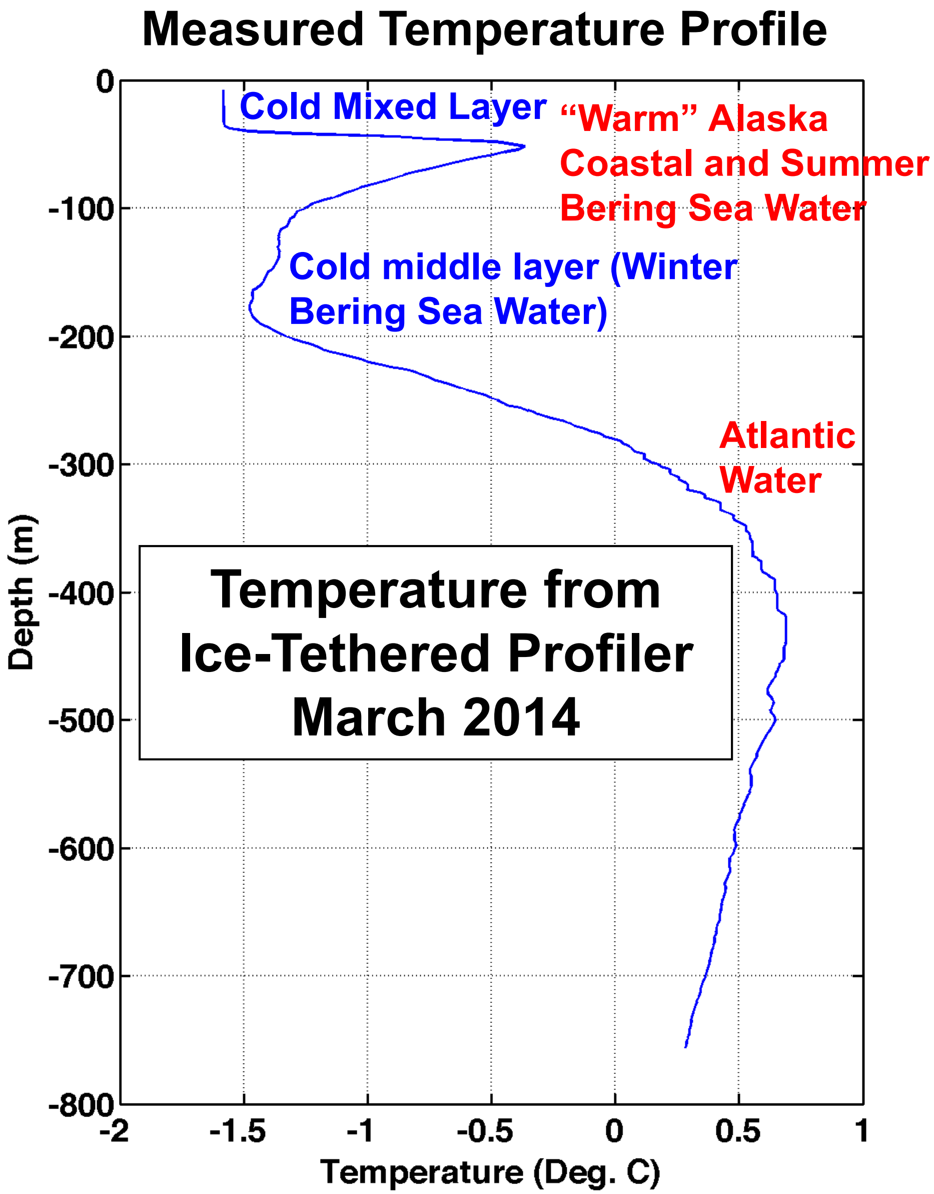
Alpha

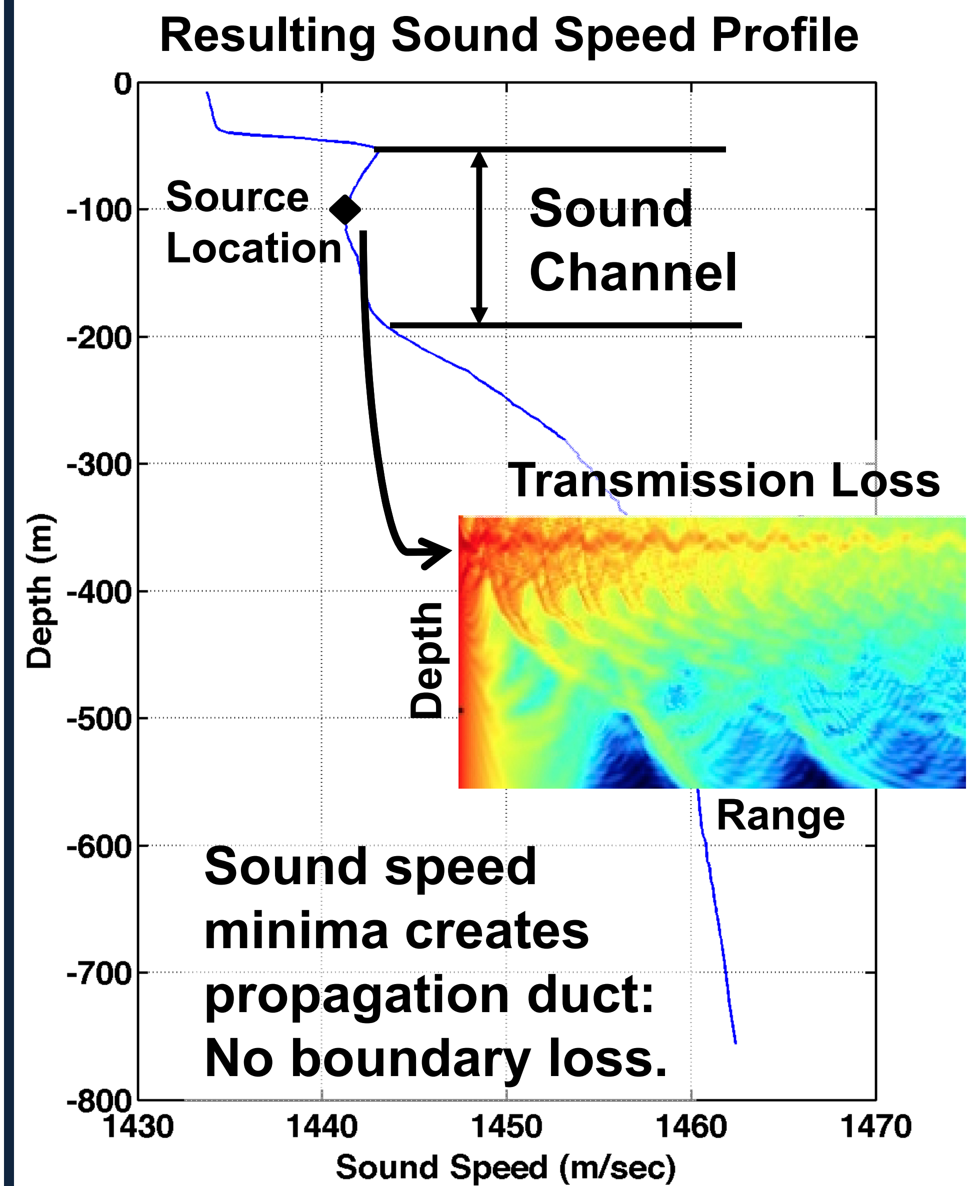
Central

North Pole

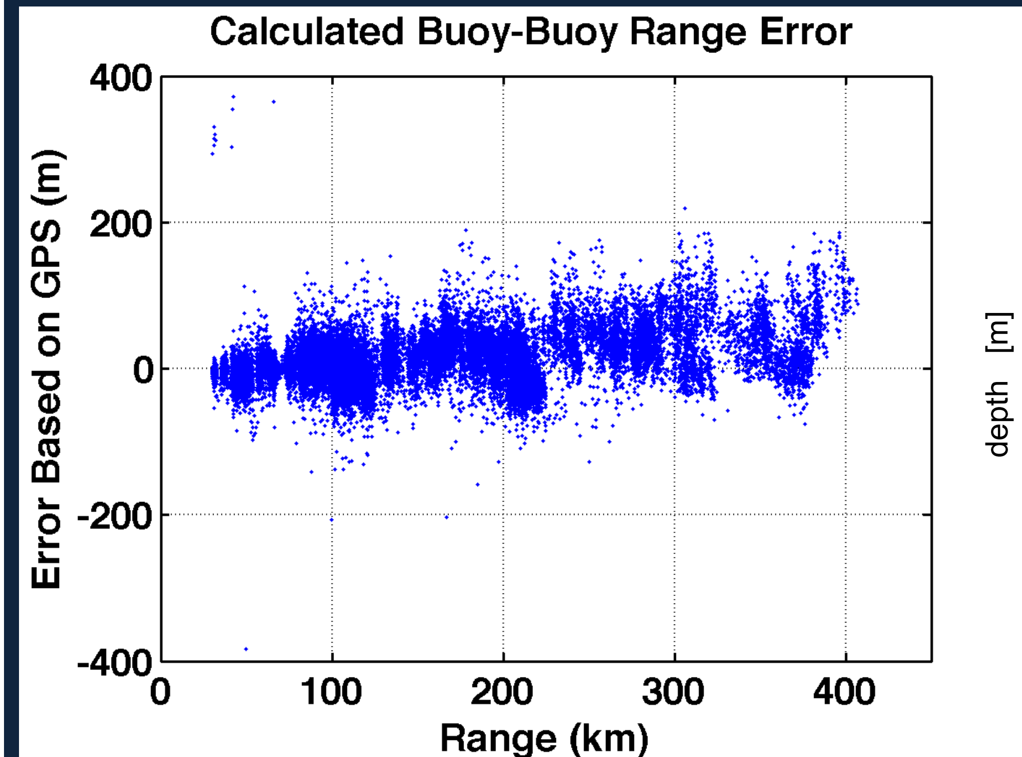
Beaufort and Chukchi have warm layer of coastal and Bering Sea water, <u>offering potential for ducted propagation</u>.

What Creates the Sound Duct?

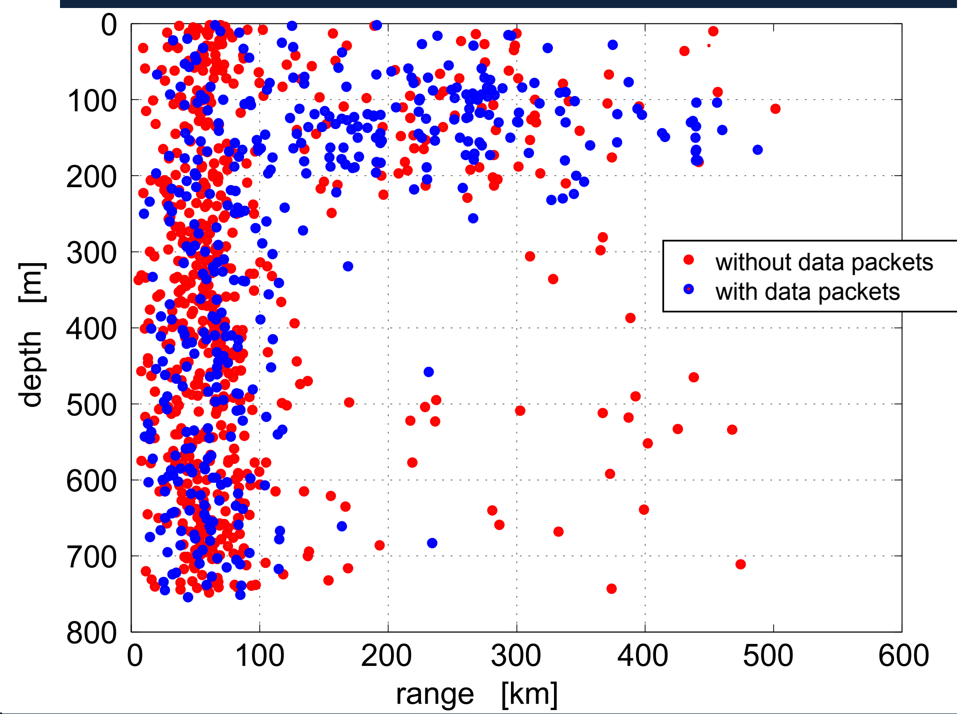




Achieved Ranges of 400 km!



Glider Receptions vs. Depth



Buoy to buoy performance:

Ranges to 400+ km, *due to ducted propagation.*

Standard Deviation of 40-60 m.

Glider performance:

To 100 km at all depths.

To 400 km when in duct.

What's Changed in 30 Years? Warmer Bering Sea Water