Observations for a Changing Arctic-Autonomous Approaches

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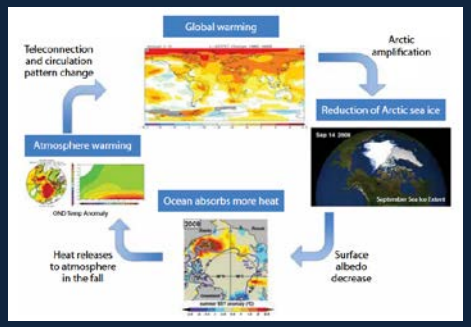
…with input from many others

1. Arctic change
2. Observational framework
3. Autonomous platforms
4. Float feasibility study
5. Opportunities

Elements of Arctic Change

- Increased air temperature (surface and aloft).
- Dramatic reduction in summertime sea ice extent.
- Loss of multi-year sea ice (reduction in mean thickness).
- Increased upper ocean freshwater content.
- Increased oceanic heat content (Atlantic and Pacific inflows, solar warming).
- Amplified ocean acidification.
- Accelerated Greenland ice sheet melting.
- Warming permafrost.



- Large impacts on Arctic ecosystems and northern residents.
- Changes in the balance of physical processes
- Strong feedbacks
- Impacts on lower latitude climate and weather.

Multi-faceted Impacts

Climate

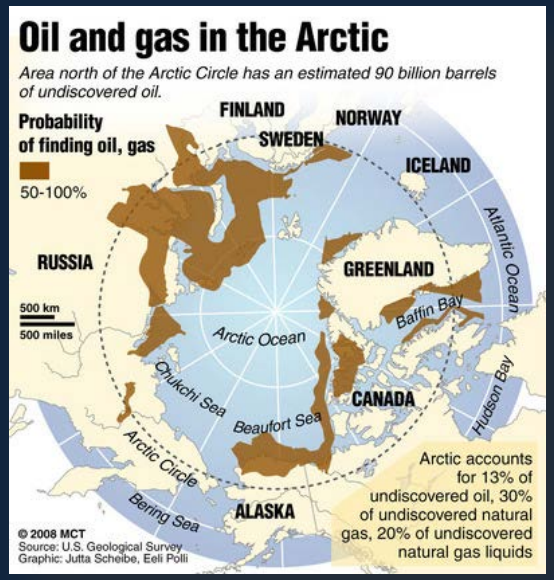
- Global links… changes in atmospheric circulation linked to heat and drought in US and cold stormy weather in Europe

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

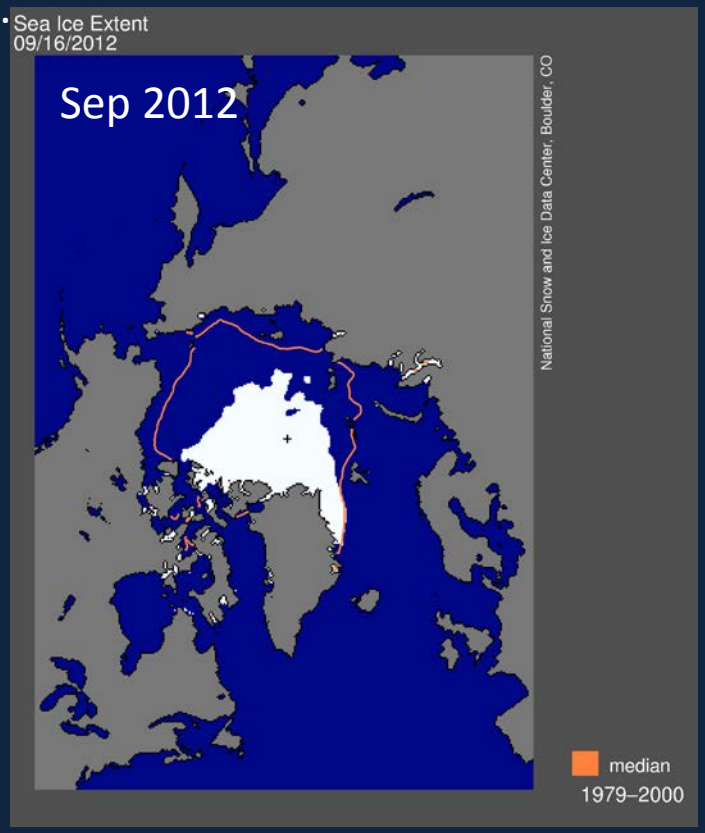
Environmental pressures

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

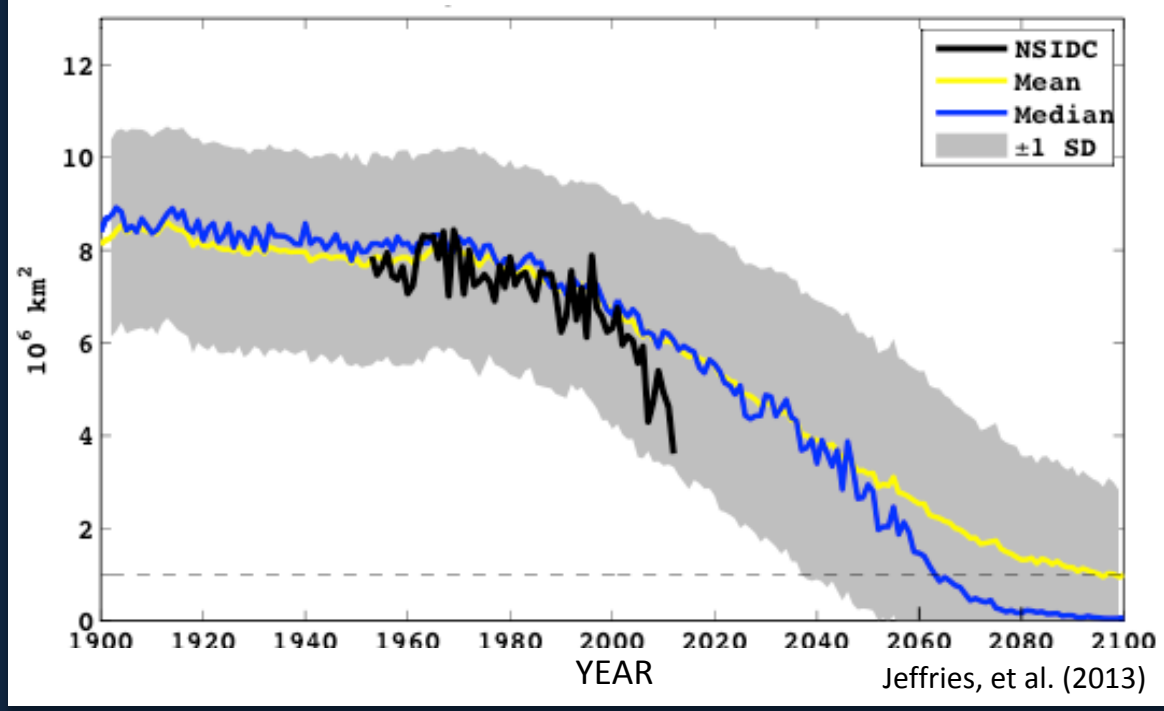
Dramatic Reduction in Summertime Sea Ice Extent

- Over 50% reduction in summer sea ice extent since the 1970s.
  - 7 million km^2 in the 1970s
  - 4.2 million km^2 in 2007
  - 3.4 million km^2 in 2012
- Wintertime sea ice maximum also declining (more slowly).
- Decline primarily thermodynamic, but other processes may increase in importance.

Minimum Sea Ice Extent

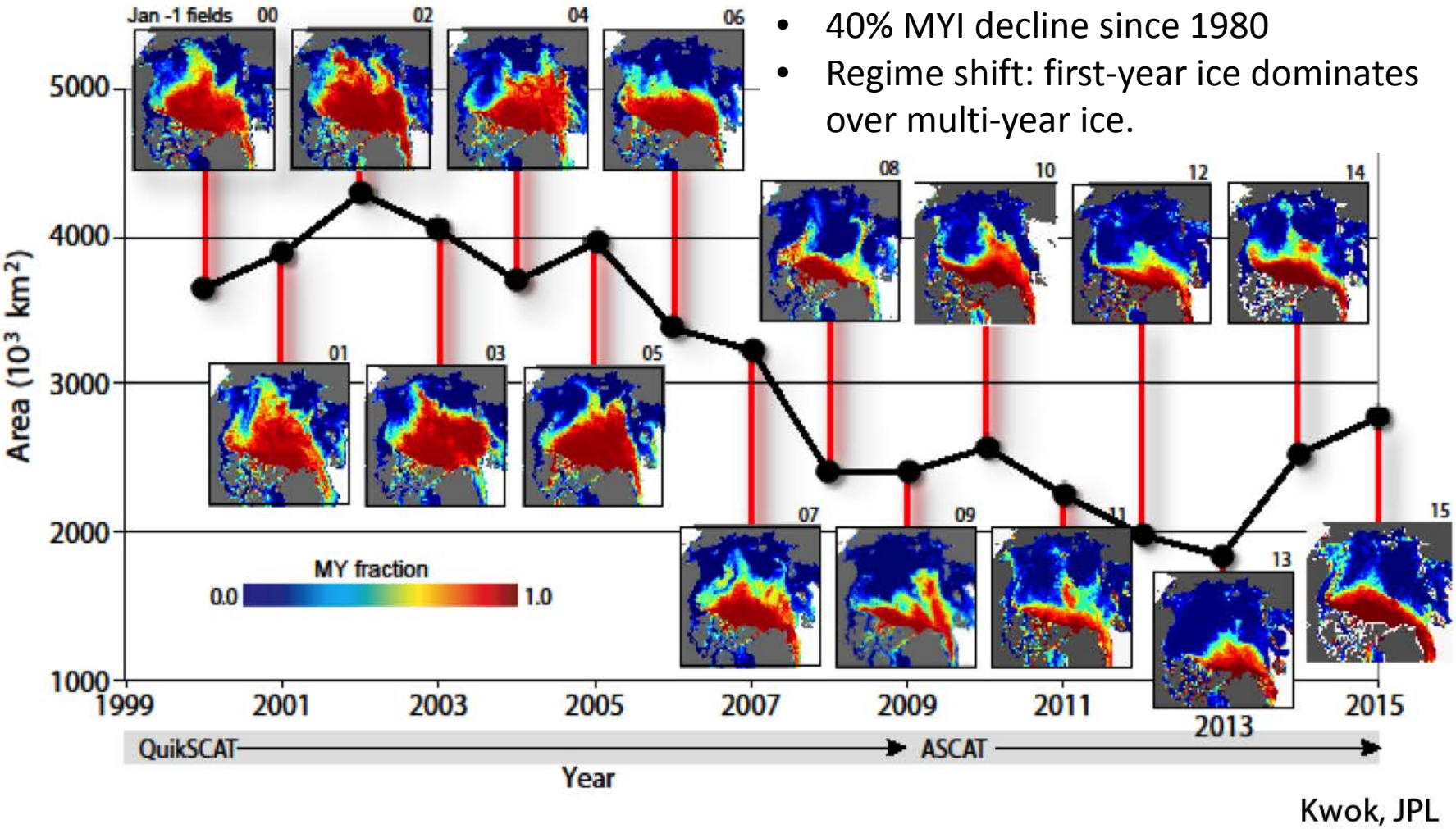


Projected Changes in September Arctic Sea Ice Extent



Jeffries, et al. (2013)

Declining Multi-Year Sea Ice Coverage

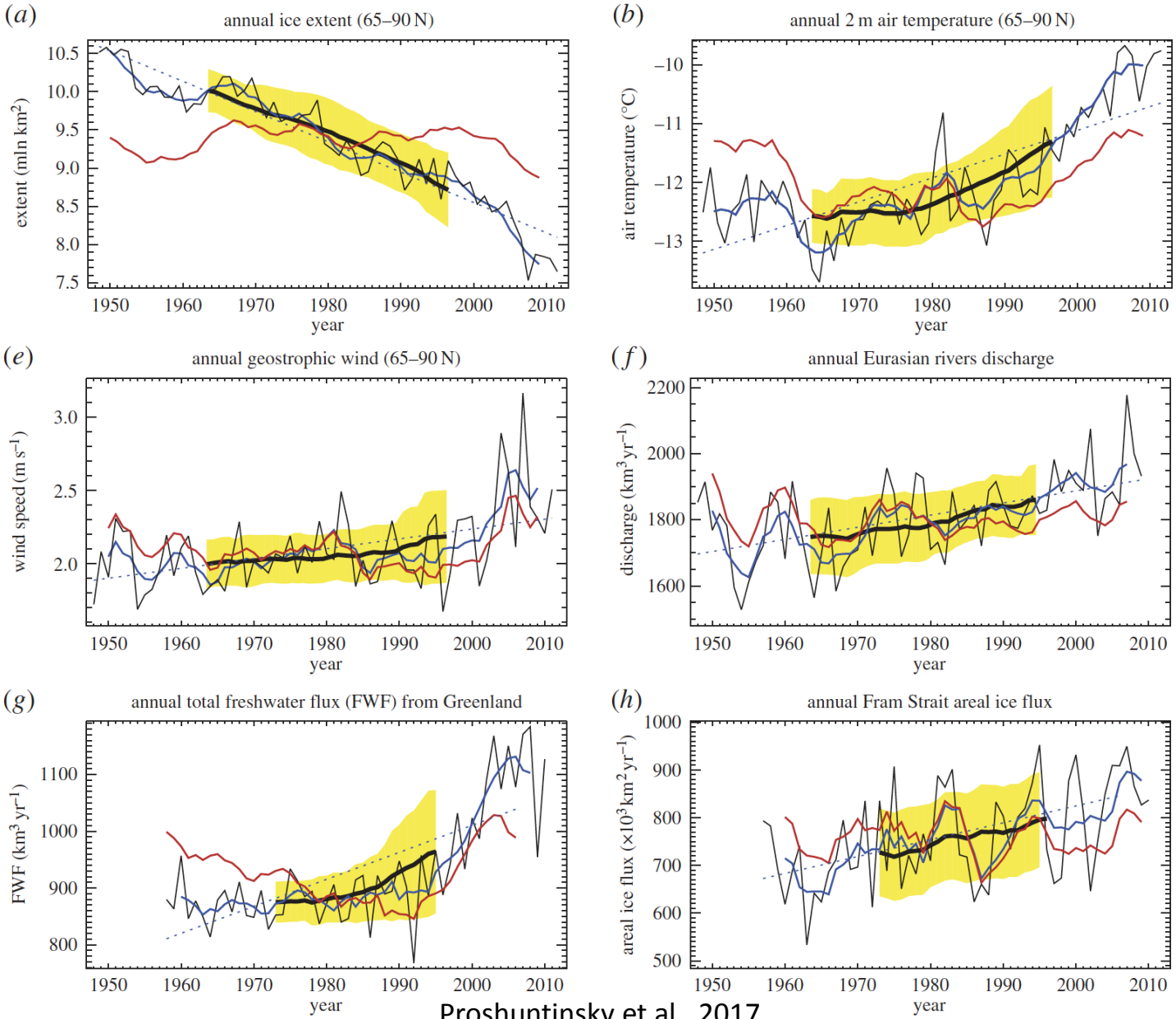


- 40% MYI decline since 1980
- Regime shift: first-year ice dominates over multi-year ice.

⇓ Extent + ⇓ Thickness = ⇓ sea ice volume

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

Timescales of Arctic Change



Proshuntinsky et al., 2017

WMO/IPCC 30-year 'climate'

- Climate scale trends
- Decadal and interannual variability
- Increased seasonality

1-year running mean

5-year running mean

30-year running mean

Detrended 5-year running mean

1 STD on 30-year mean

Ocean Obs 09 Arctic Priorities

AN INTEGRATED INTERNATIONAL APPROACH TO ARCTIC OCEAN OBSERVATIONS FOR SOCIETY (A LEGACY OF THE INTERNATIONAL POLAR YEAR)

John Calder[1], Andrey Proshutinsky[2], Eddy Carmack[3], Igor Ashik[4], Harald Loeng[5], Jeff Key[6], Moll McCammon[7], Humfrey Melling[3], Donald Perovich[8], Hajo Eicken[9], Mark Johnson[10], Ignatius Rigor[11]

AUTONOMOUS PLATFORMS IN THE ARCTIC OBSERVING NETWORK

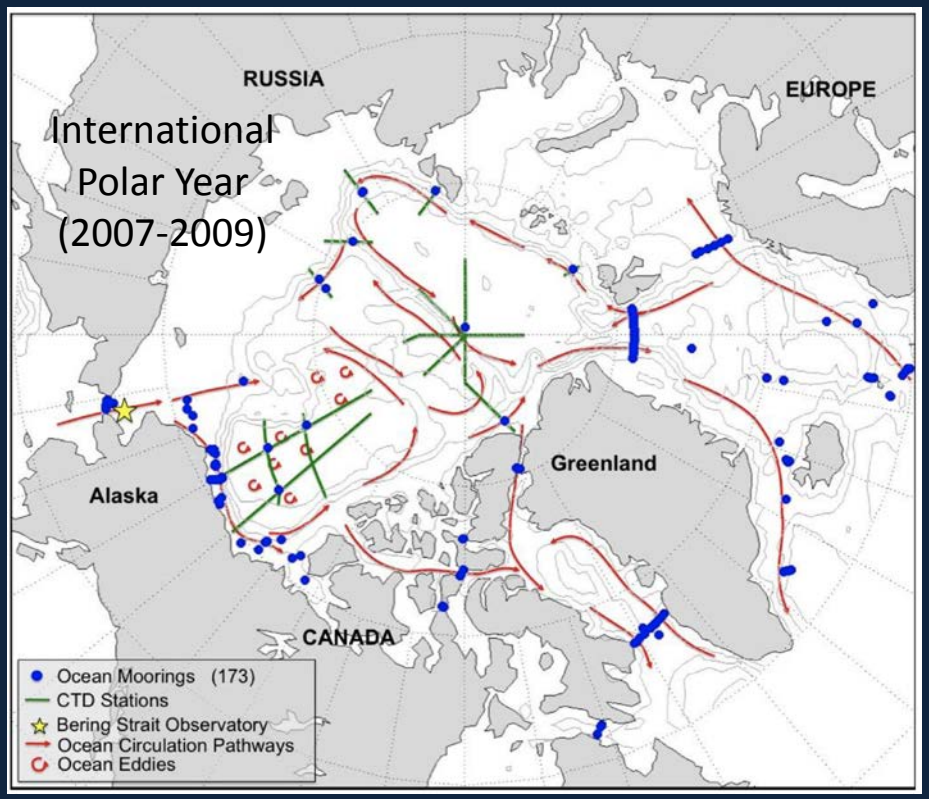
Craig M. Lee[1], Humfrey Melling[2], Hajo Eicken[3], Peter Schlosser[4], Jean-Claude Gascard[5], Andrey Proshutinsky[6], Eberhard Fahrbach[7], Cecilie Mauritzen[8], James Morison[1], Igor Polyakov[9]

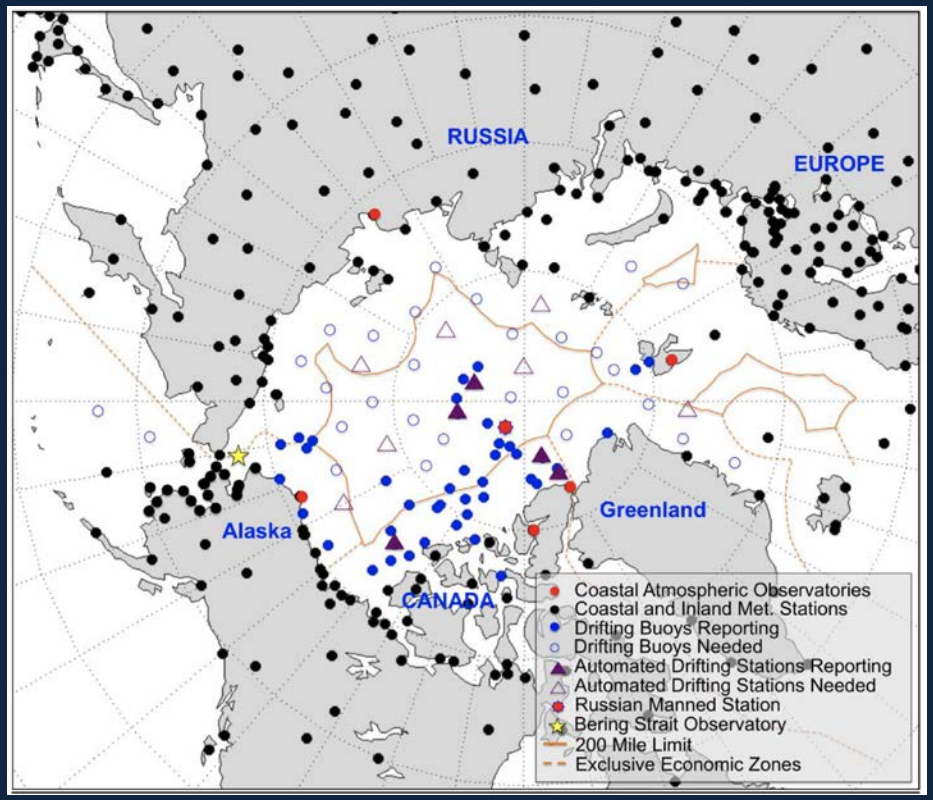
REMOTE SENSING OF SEA ICE

Lars-Anders Breivik[1], Tom Carrieres[2], Steinar Eastwood[1], Andrew Fleming[3], Fanny Girard-Ardhuin[4], Juha Karvonen[5], Ron Kwok[6], Walter N. Meier[7], Marko Mäkynen[5], Leif Toudal Pedersen[8], Stein Sandven[9], Markku Similä[5], Rasmus Tonboe[8]

Priorities for Sustained Observations

- Heat and freshwater storage, exchange with Atlantic & Pacific.
- Processes that control sea ice, document extent and thickness.
- Seasonal variability in ice and coastal circulation.
- Baseline and change in biogeochemistry and ecosystem structure.
- Sustained (decades), persistent (year-round), distributed observations.
- Exploit developments in autonomous platforms.





NOAA Arctic Action Plan

Security

- Sea ice forecast
- Weather and water forecast

Stewardship

- Fundamental understanding of climate and ecosystem changes
- Resource management
- Communities and economies

Cooperation

- National and international partnerships

These missions require observations across a broad range of temporal and spatial scales.

Flexibility Through Nested Observing Activities

Policy- climate observations

- Focus: Characterize environmental change, planning.
- Time scale: Decades. Long, consistent records. Committed observing.
- Spatial scale: Distributed, may be far from population centers.
- Data: Real-time data return not necessary.

Strategy- process studies, planning support

- Focus: Planning for high-risk activities (extraction, navigation).
- Time scale: Seasons to decades, long records valued.
- Spatial scale: Limited geographic scope, perhaps near population centers.
- Data: Rapid data access (near real time) may be required.

Tactical- stakeholder-driven collection

- Focus: Support for specific activities.
- Time scale: Rapid spin-up, spin-down. Flexible design,.
- Spatial scale: Tightly focused, often near regions of human activity.
- Data: Useful products delivered in real time. Data have little shelf life.

Challenges

Build a sustainable Arctic Observing capability that resolves a broad range of temporal and spatial scales (climate to process) and meets the needs of basic research, policy makers and stakeholders.

- Persistence- Resolve important timescales, transient events.
- Access- Far from areas of human activity.
  - Poor for ships, good for aircraft (for now…).
  - Exploit ice as measurement platform.
  - Limited access to critical services (GPS, Iridium).
- Risk- Unforgiving operating environment, extended development arc.
- Cost/Scalability- Sustain broad, long-term activity.
- Adaptability/Flexibility
  - Sea ice decline- seasonal ice cover, marginal ice zone.
  - Needs evolve with changing environment and understanding.
  - Meet disparate stakeholder needs: climate to tactical.

The Changing Arctic Environment

Carmack et al., 2015

Arctic Change- A Freshwater Framework

A Framework for Quantifying & Understanding Change:

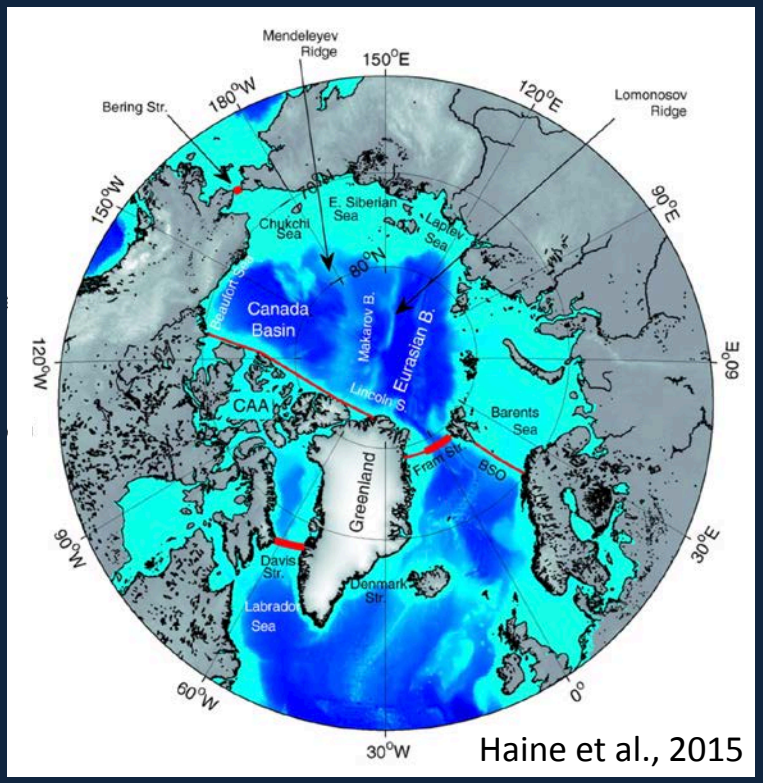
- Salinity controls Arctic Ocean stratification ('β ocean', Carmack, 2007).
- Cold, buoyant surface layer isolates sea ice from heat stored below.
- Modulates sea ice evolution, coupling between atmosphere & ocean.

Global Impacts

- Sea ice growth and melt important component of meridional atmospheric energy transport (Nakamura and Oort, 1988).
- Atlantic Meridional Overturning Circulation (AMOC) sensitive to buoyant Arctic outflow into deepwater formation regions (e.g. Holland et al., 2001; Arzel et al., 2008).
- Changes in Arctic freshwater outflow also modulate:
  - Extent and strength of the North Atlantic subpolar gyre.
  - Northward penetration of warm subtropical waters. Impacts fisheries (Hátún et al., 2009) and carbon uptake and storage (e.g. Schuster and Watson, 2007).

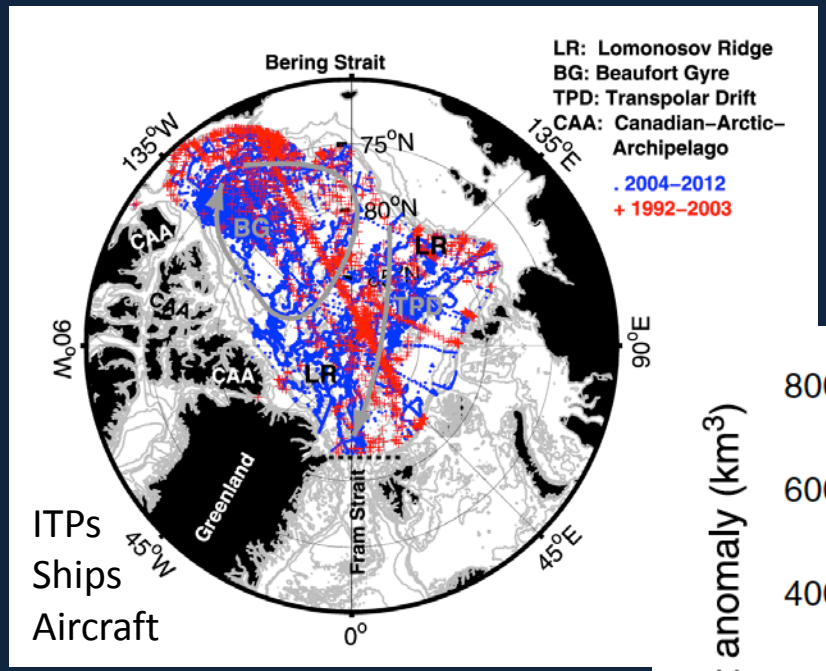
Challenges

- Distributed water column measurements in Arctic interior.
- Resolve dynamically wide straits.
- Measure near ice-ocean interface.
- Sea ice volume.
- Resolve broad range of timescales… seasonal (and shorter) to interannual.
- System undergoing rapid change during observing period.
- Measurements entire FW system.
- Constrain uncertainties to resolve anticipated changes.
- Sustained measurements required to resolve secular change.

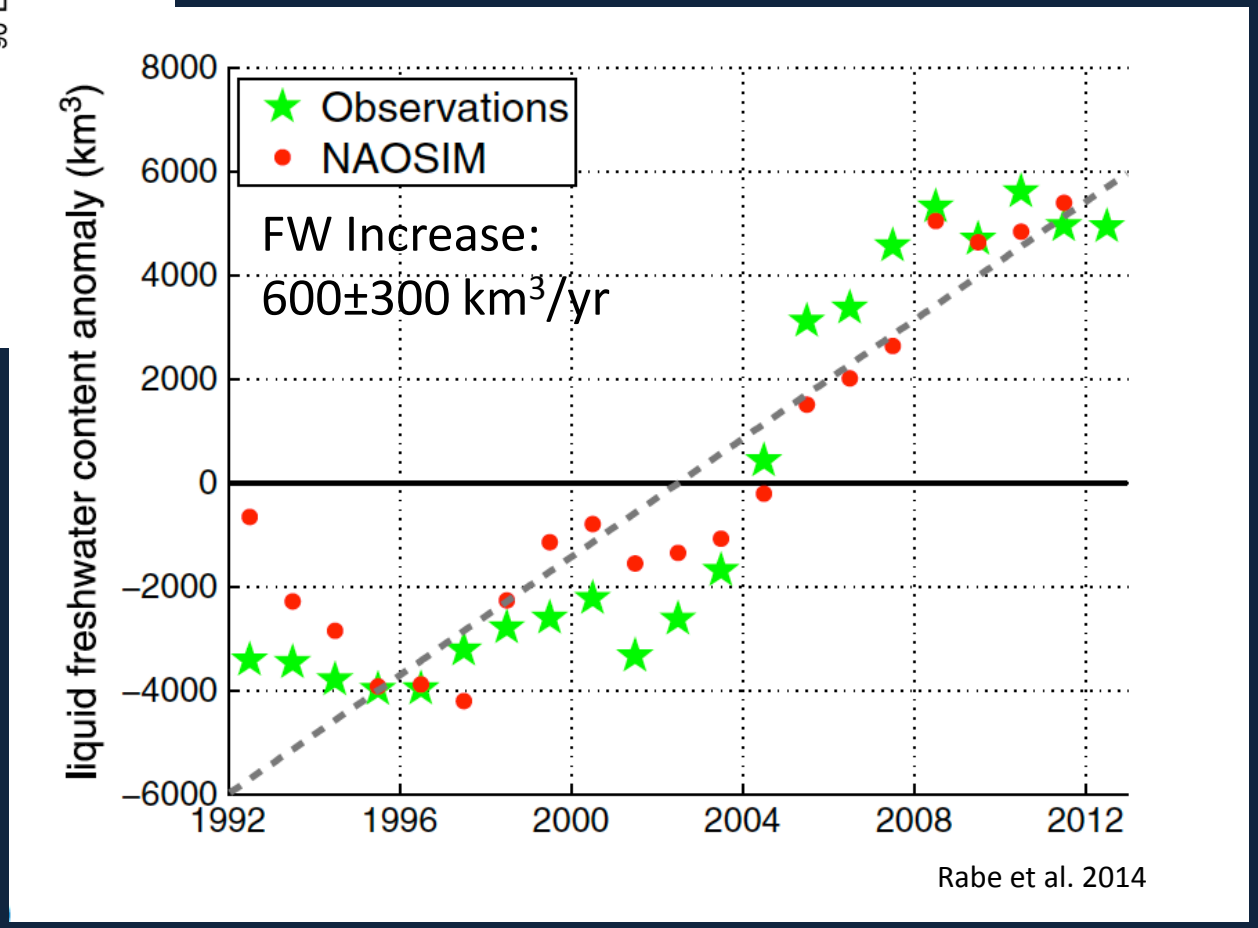


Haine et al., 2015

Increasing Interior Freshwater Content



- 1992 – 2012, Distributed measurements (ITPs, ships, aircraft).
- Sea ice melt + FW inflows
- Upper layer thickening (30%)
- Upper layer freshening (0.6 psu, 60%)

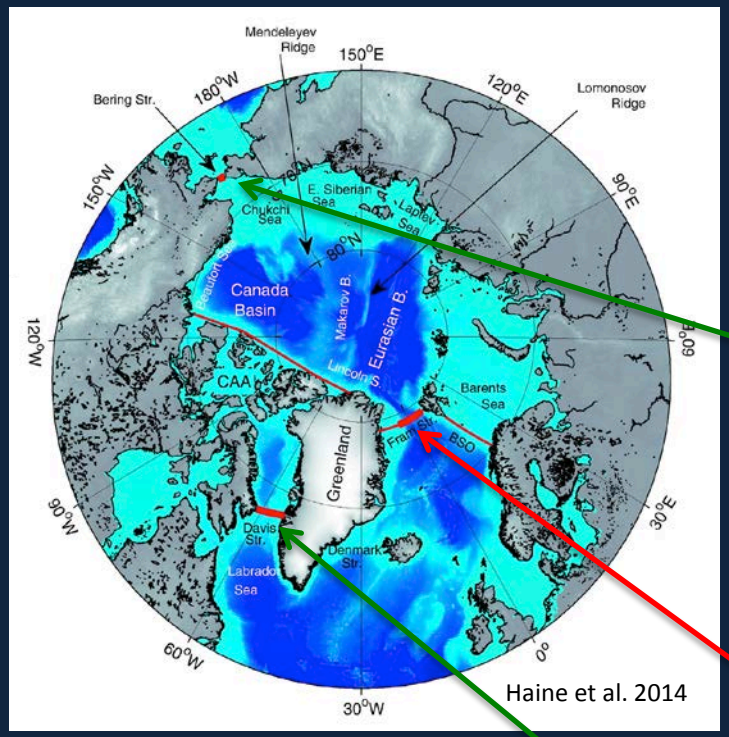


Rabe et al. 2014

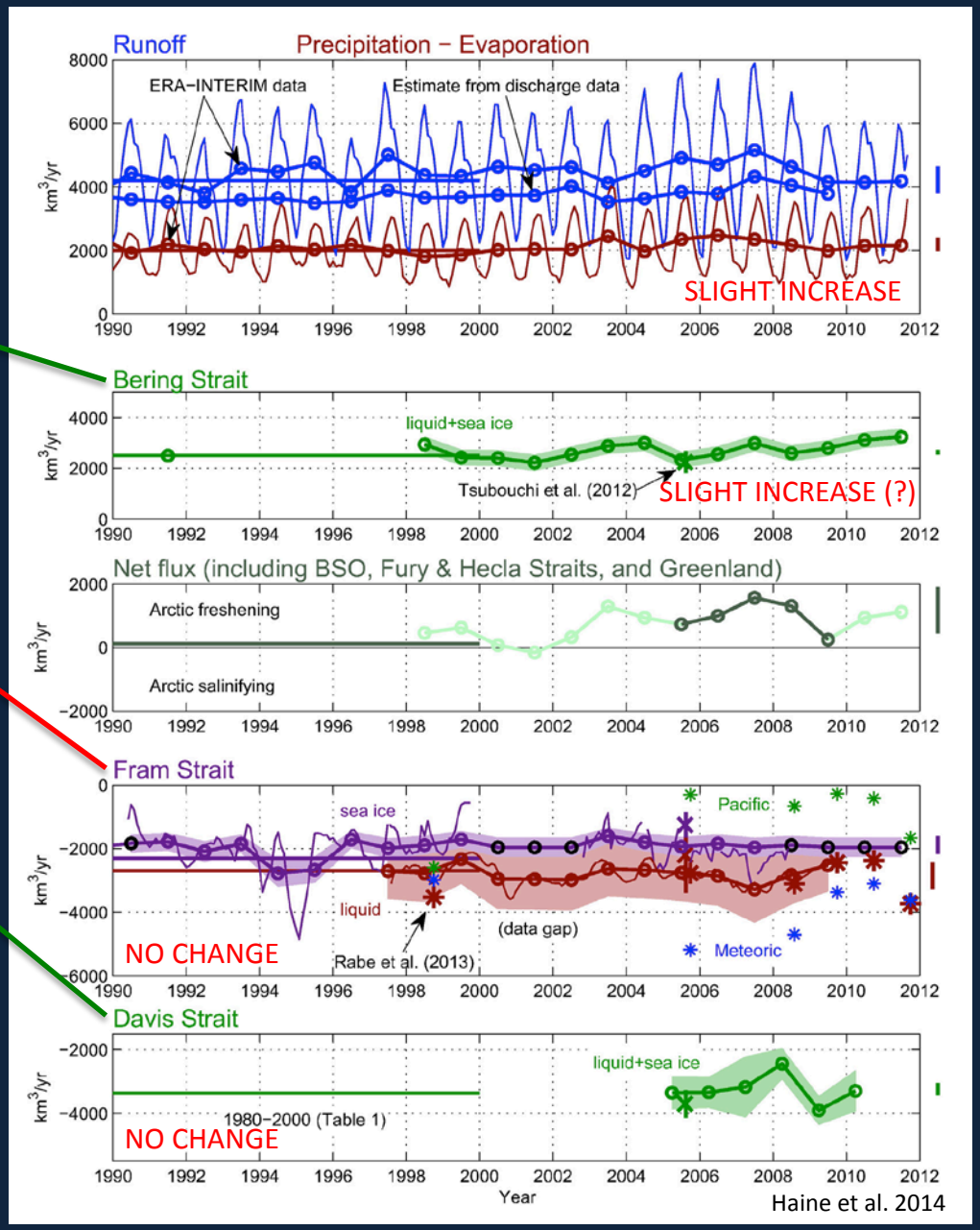
Impacts

- Increased stratification
- Modulates mixing
- Productivity
- Downstream-meridional overturning circulation

Quantifying FW Inflows and Outflows



Haine et al. 2014



Haine et al. 2014

2000 – 2010

Gateway flux measurements.

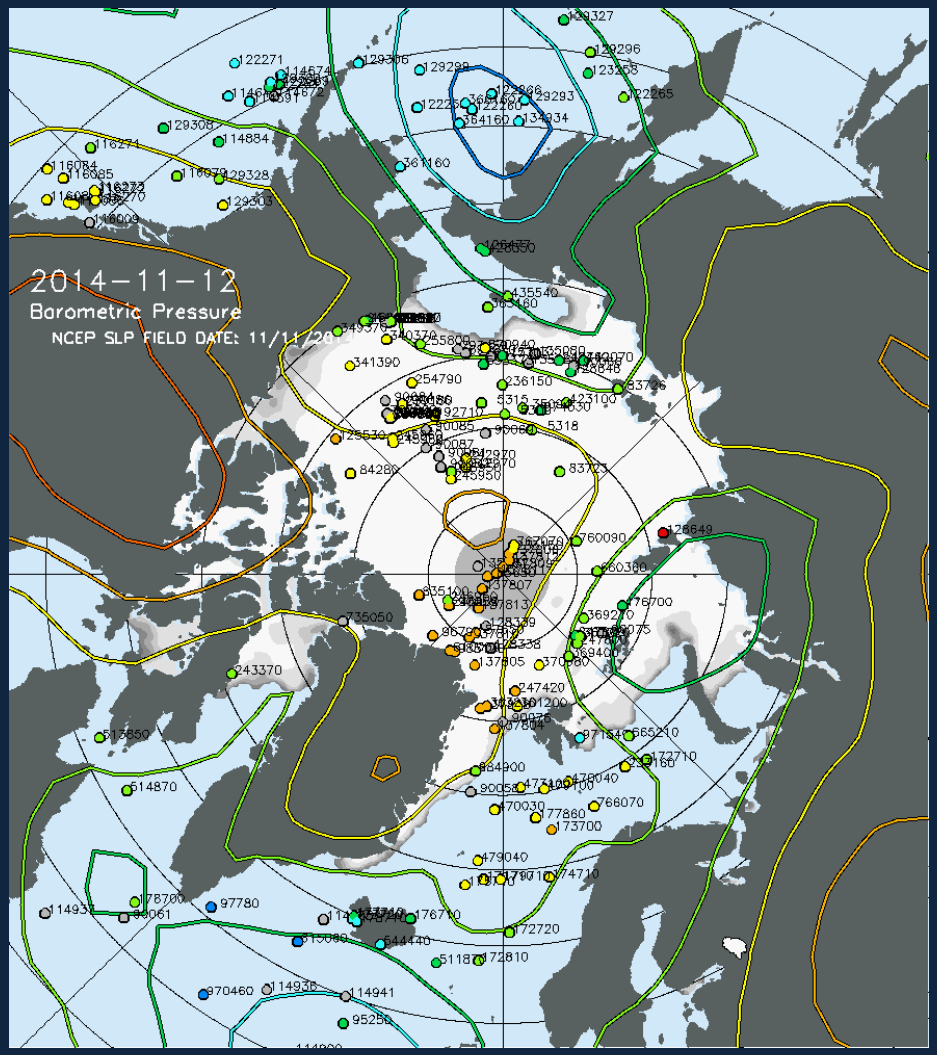
- Net 1200±730 km^3/yr freshening.
- Increases in precipitation, runoff & Bering inflow.
- Outflows unchanged.

<u>Sustained, pan-Arctic obs. network.</u>

International Arctic Buoy Program

Rigor (APL-UW) and many others

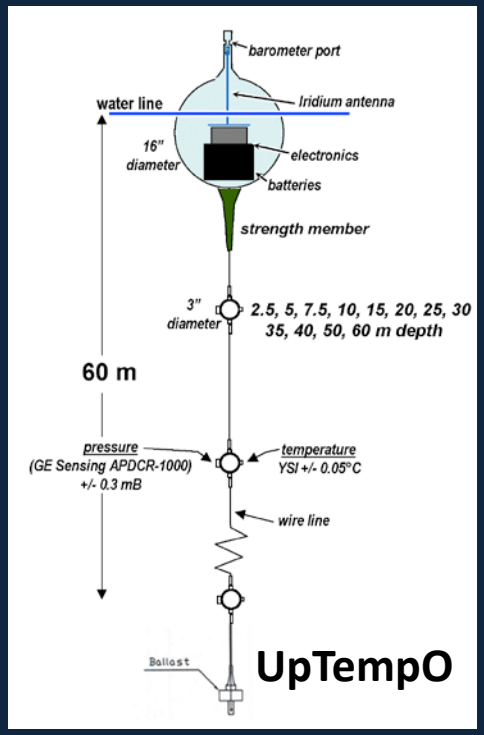
- Ice-mounted, drifting instruments.
- International, sustained, distributed network.
- 9 countries, 20 institutions.
- 1979 – present.
- Ice drift, surface temperature, sea level pressure.
- Climate studies, synoptic forecast, sea ice prediction.
- Other ice-mounted instruments:
  - Meteorological stations (challenging…)
  - Ice-mass balance
  - Waves
  - Atmospheric Chemistry (Matrai et al)
- Co-locate complementary systems.

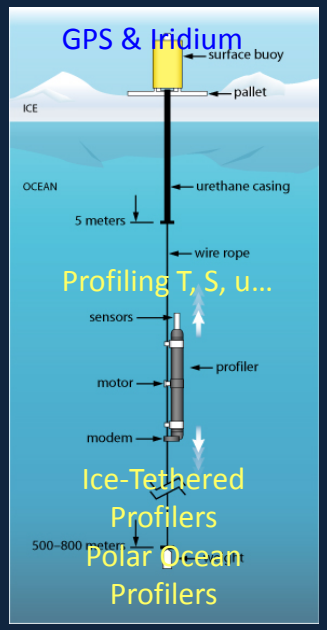


Ice-based Observatories (ITP, POPS, AOFB, UpTempO)

Stanton, Shaw (NPS) ; Krishfield, Toole, Proshutinsky (WHOI) ; Kikuchi (JASMTECH) ; Shimada (Tokyo Univ); Steele (APL-UW)

- Critical component of Arctic observing system.
- Collocated deployments- synergistic system.
- Only autonomous approach for concurrent measurements of Upper ocean, ice & atmosphere.
- Drift with the ice
- Potential data relay for subsurface platforms.



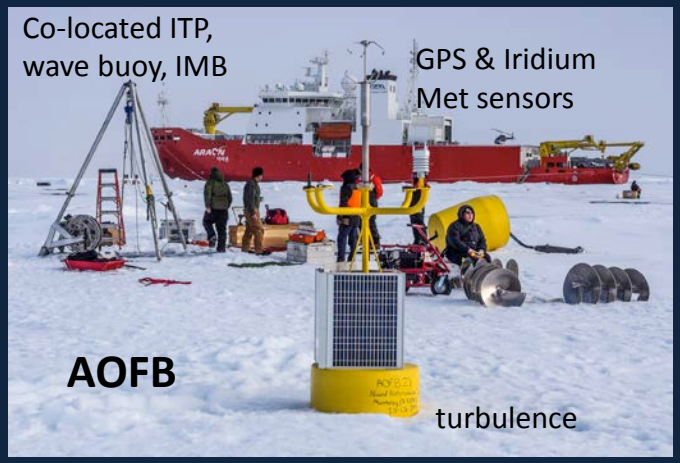


Access
- Distributed deployments and drift

Risk
- Break-up and refreeze, open water drift.
- Real-time data return mitigates risk.

Persistence/Cost/Scalability
- Persistent presence, long endurance.
- Moderate cost and deployment logistics.

Adaptability/Flexibility
- Adapted for use in seasonal ice.

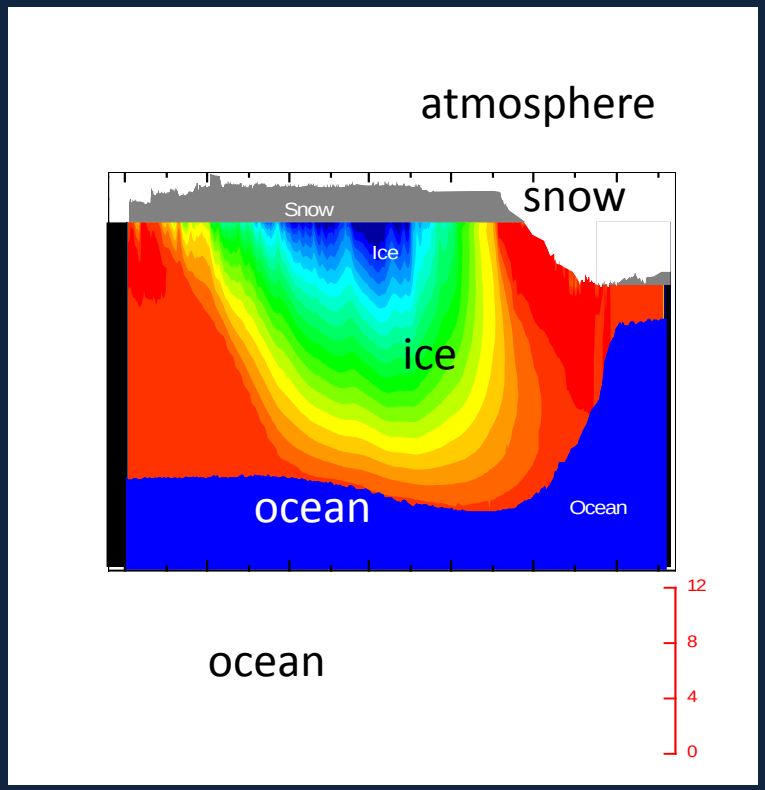


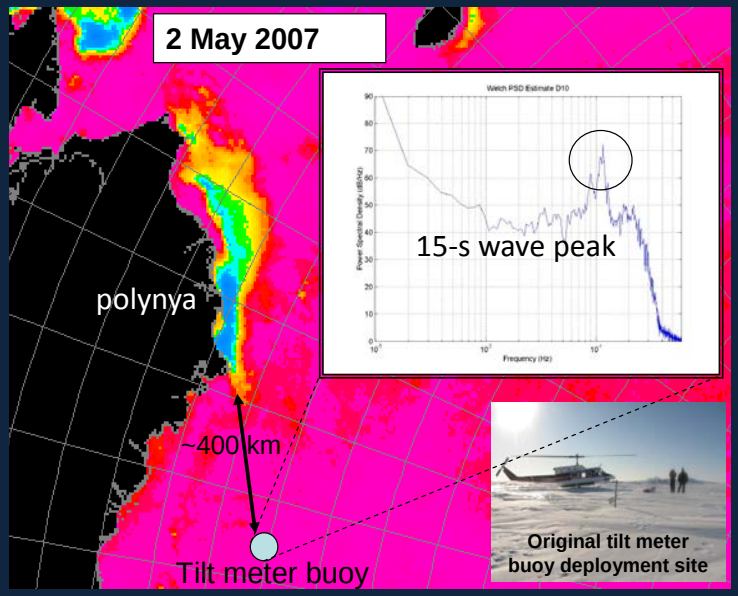
Ice Mass Balance and Wave Buoys

Wilkinson (BAS), Hwang (SAMS), Maksym (WHOI), Perovich, Richter-Menge (CRREL), Wadhams (Cambridge), Doble (LOV), Thomson (APL-UW)

- Snow accumulation & melt
- Ice growth
- Ice surface & bottom ablation
- Air, ice, ocean temperature
- Net surface heat budget
- Ocean heat flux

Perovich et al., 2008

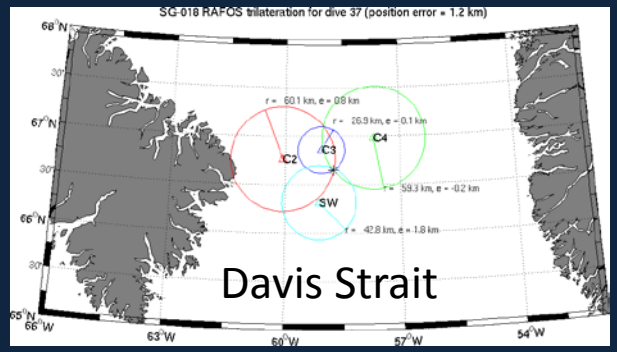


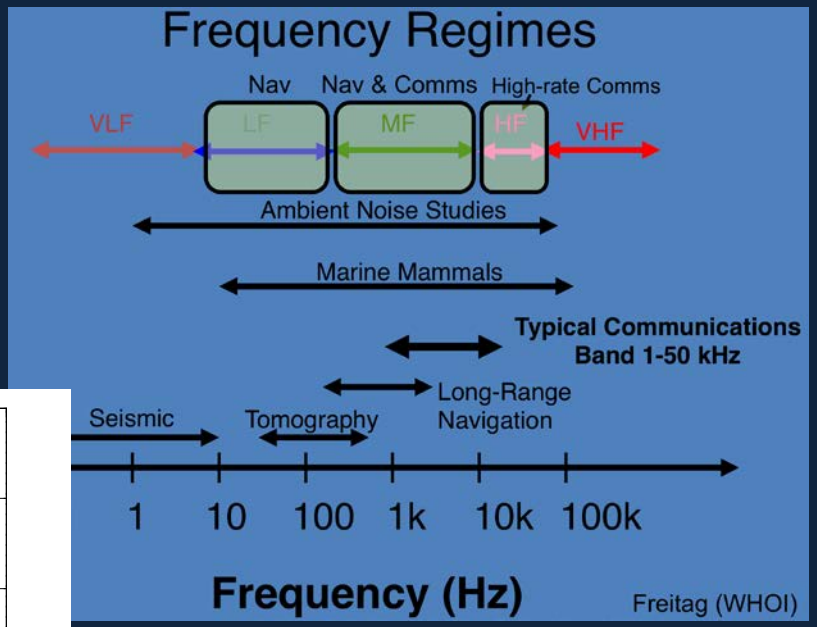


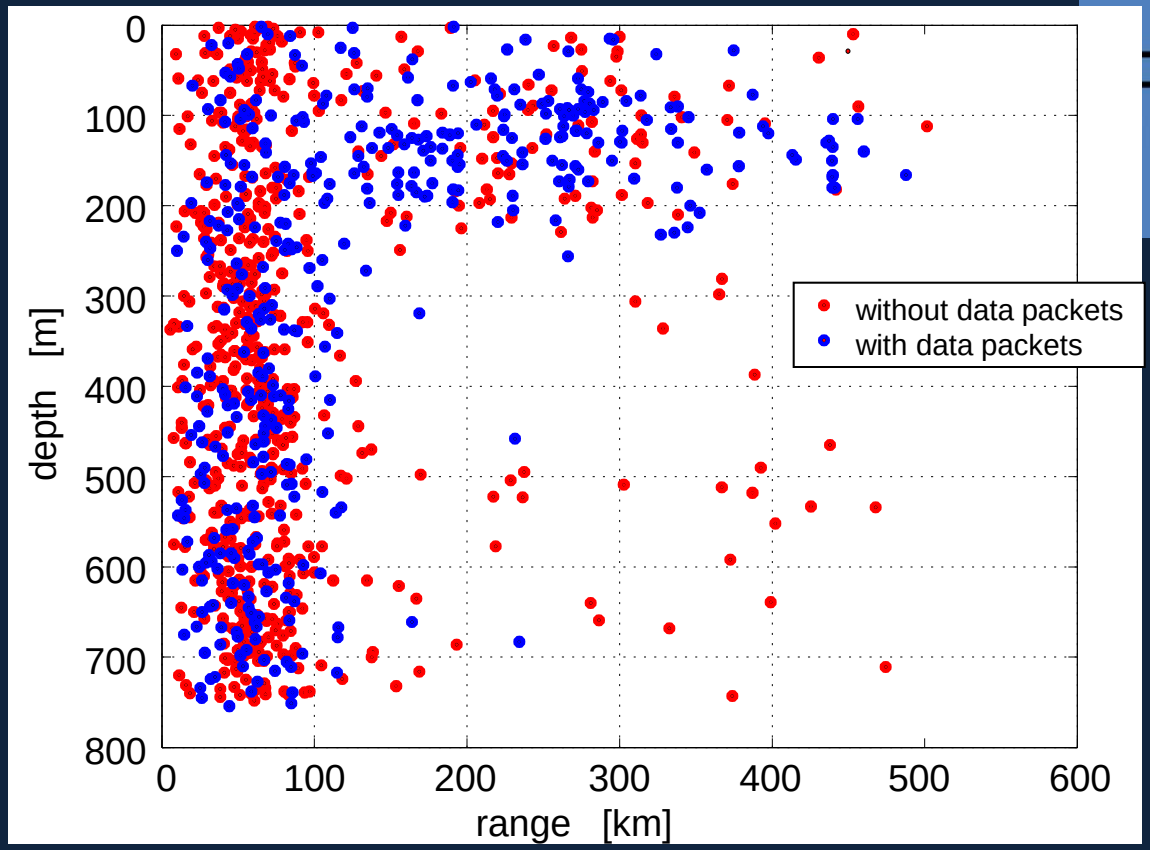
Subsurface Acoustic Navigation

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

Multi-lateration (+ extended Kalman filter) for positions from acoustic receptions







- Under ice geolocation.
- Ice cover greatly reduces range of mid-freq O(1 kHz) signals.
- Surface ducted: 120 km range.
- Sound channel: 500 km range.
- Broadband signal allows encoding of source position, commands. Drifting, ice-tethered sources.
- Accuracy ~1 km.

Mobile Platforms: Long-Endurance Gliders

Lee, Gobat, Shilling, Rainville, Webster (APL-UW)

Ice-capable Gliders

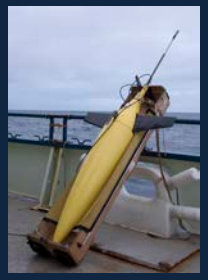
- Enhanced endurance, reliability
- Compass calibration/check for high-latitudes ops
- Real-time acoustic navigation
- Ice detection
- Enhanced autonomy with 'ice behaviors'
- Acoustic communication for data transfer

Access
- Remote regions, full ice cover
- Ice-ocean interface, marginal ice zone.
- Persistent sampling- long endurance

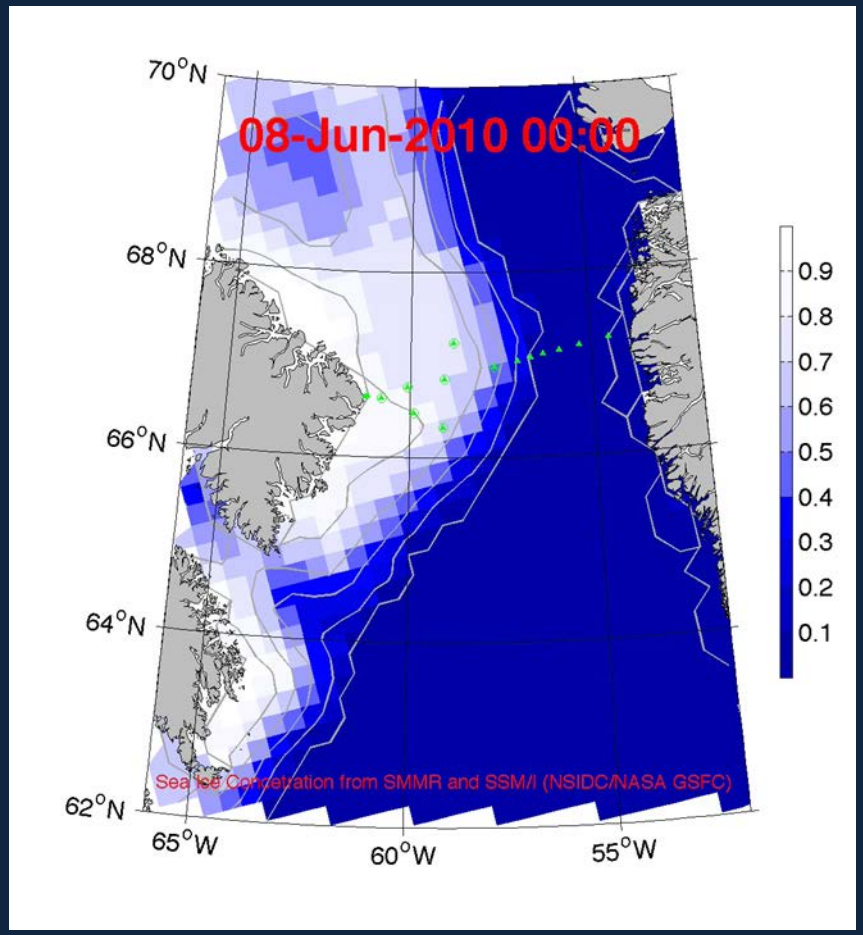
Risk
- Limited exposure to ice-ocean interface.
- Data return when open water available.
- Acoustic date upload under ice.

Persistence/Cost/Scalability
- Moderate cost, simple logistics.

Adaptability/Flexibility
- Real time reprogramming.



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

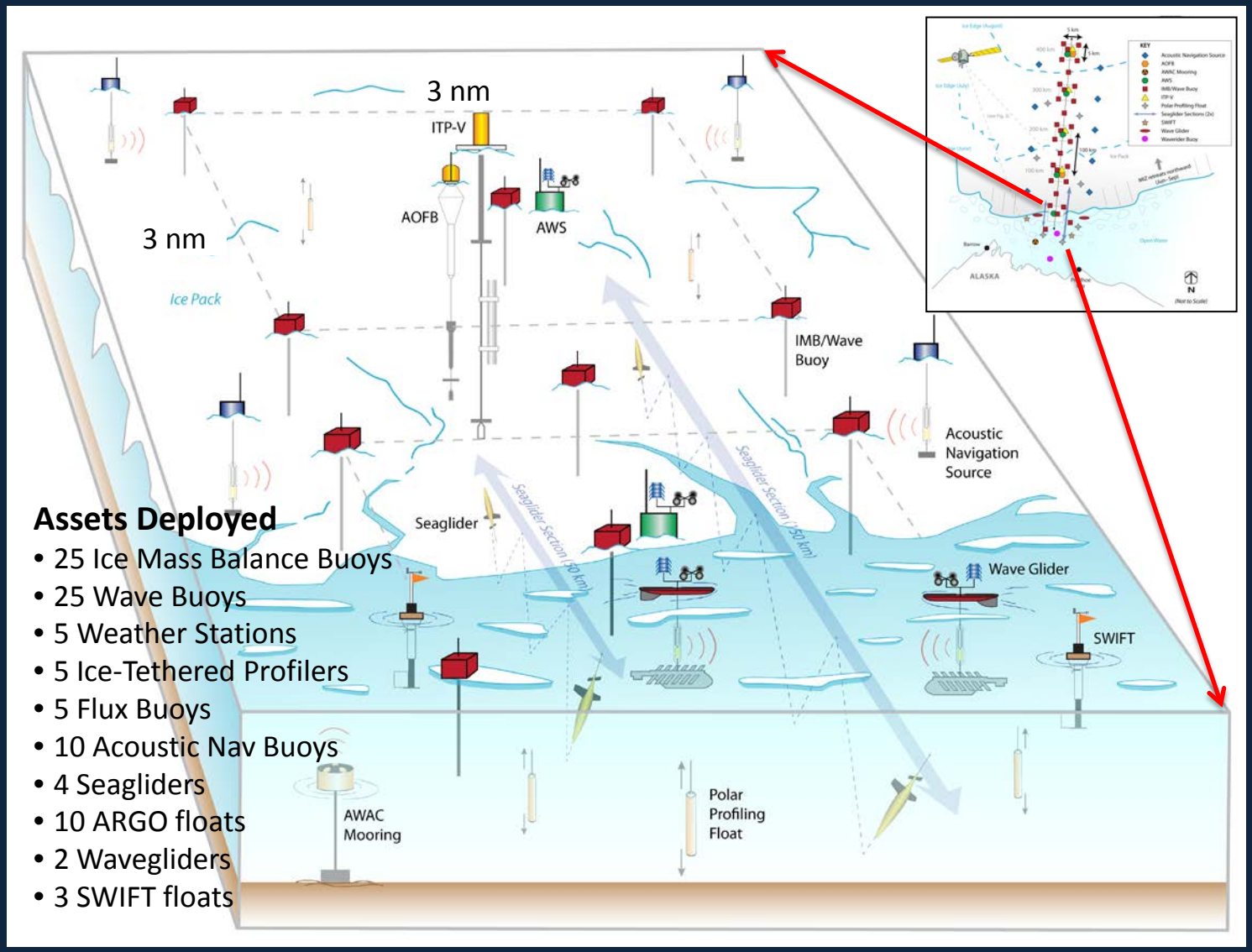


Jan-May:	ice-covered
Jun:	transition
Jul-Nov:	ice-free
Dec:	transition

Putting the Pieces Together:

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

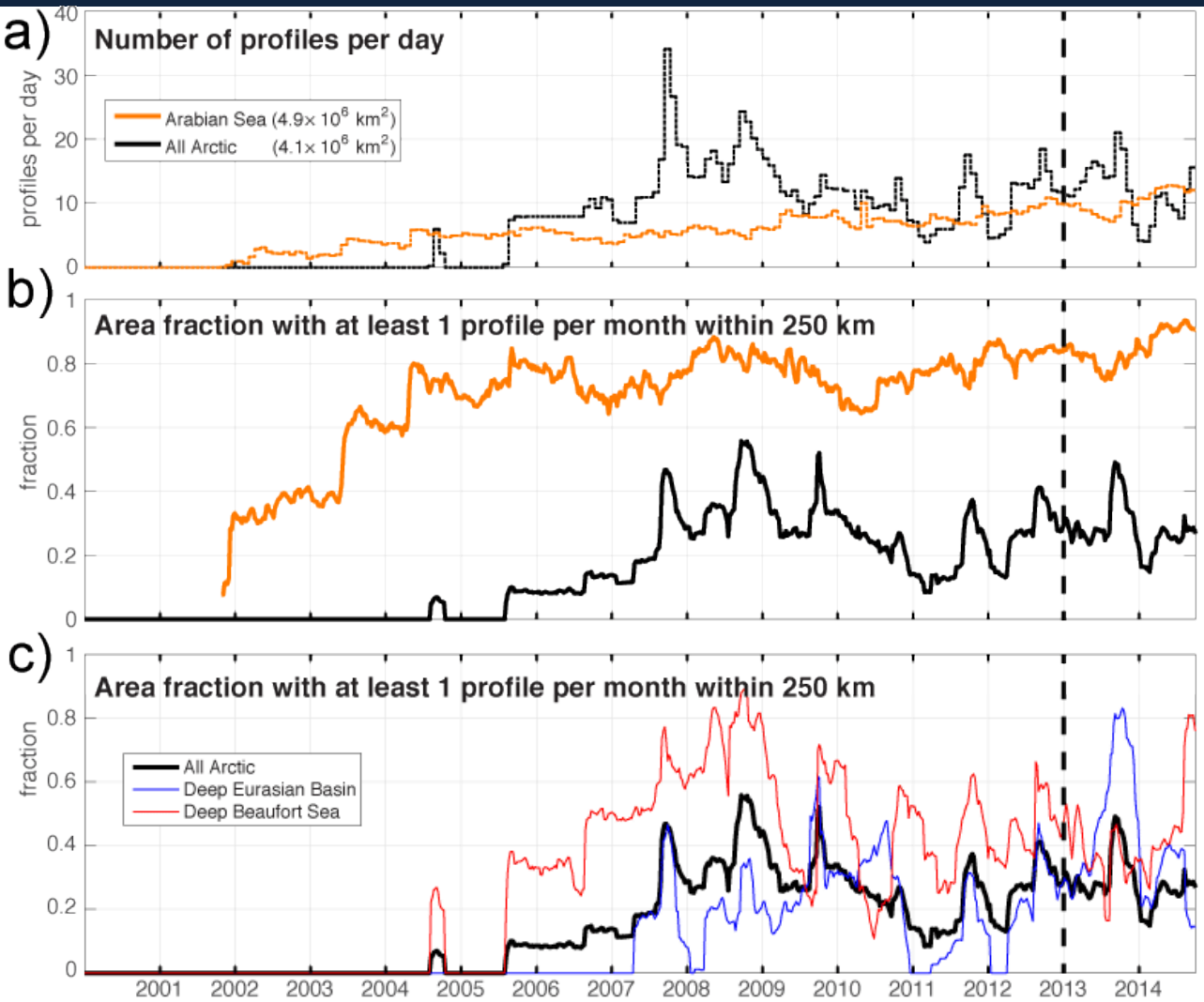
https://www.elementascience.org/collections/special/special-feature-marginal-ice-zone-processes-in-the-summertime-arctic/

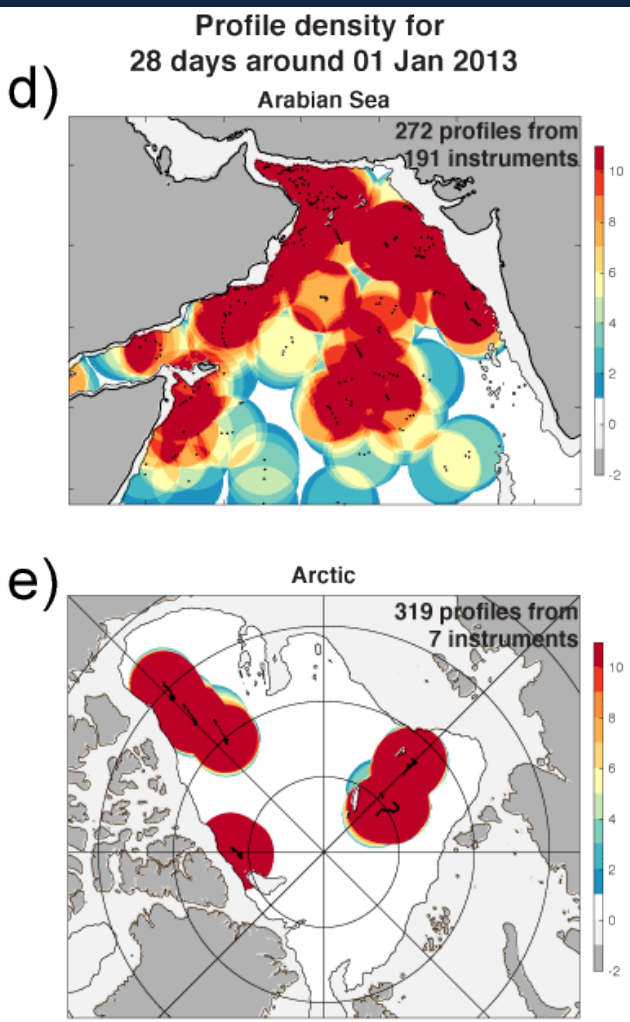


Assets Deployed

- 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

Can the ITP Array be Augmented to Provide Argo-like Spatial Coverage?



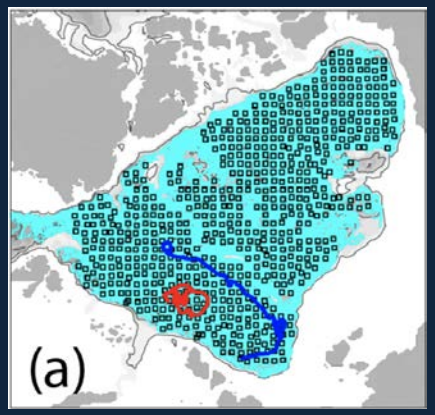


Perhaps for the ocean profiling (but maybe not for ice and atmosphere)…

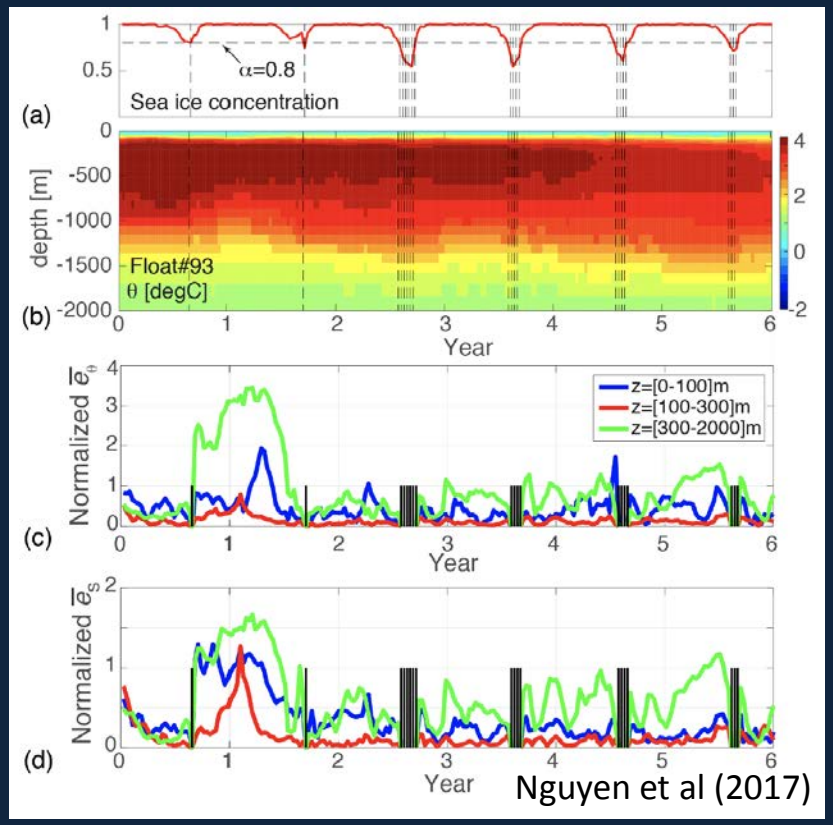
Feasibility Study for Floats in the Ice-Covered Arctic

Nguyen, Heimbach (UT-Austin), Lee, Rainville (APL-UW), Jayne (WHOI)

Would large-scale Argo float deployments be useful without acoustic geolocation?



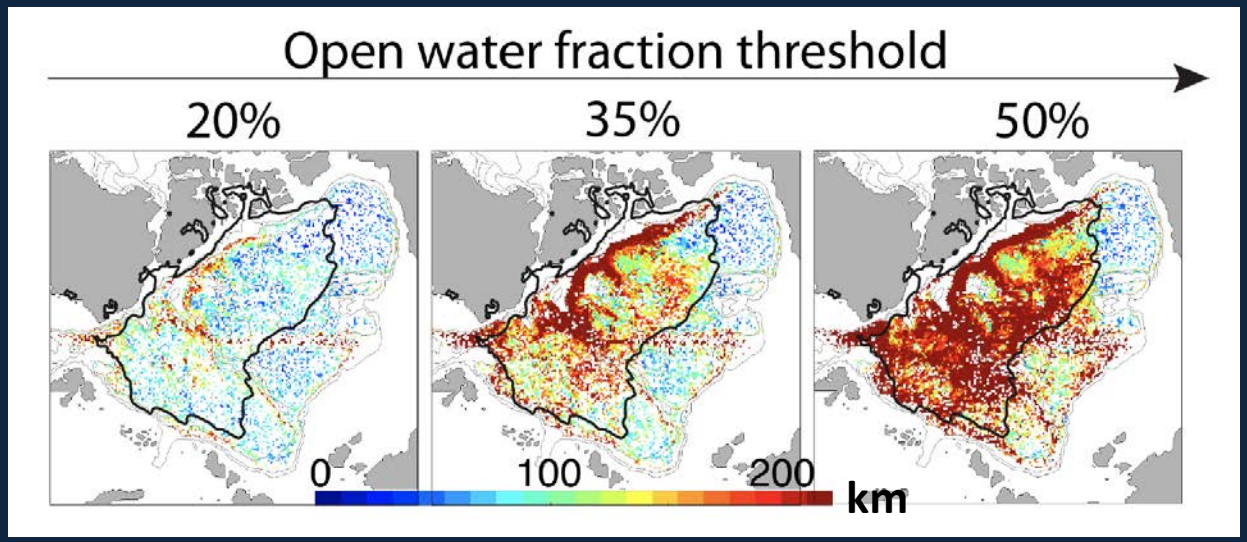
- How far would floats drift between surfacing?
- What are the resulting position uncertainties?
- Given the rapid decline in summertime ice extent, what fraction of the potential data return (for 5-year float missions) could be transmitted back to shore given surfacing in fractional ice cover and in summertime open water?
- Is the resulting data useful for constraining the ECCO state estimate for the central Arctic?



Nguyen et al (2017)

Position Uncertainty and Data Return

Mean Separation Distance (true vs. simulated, 100 samples)



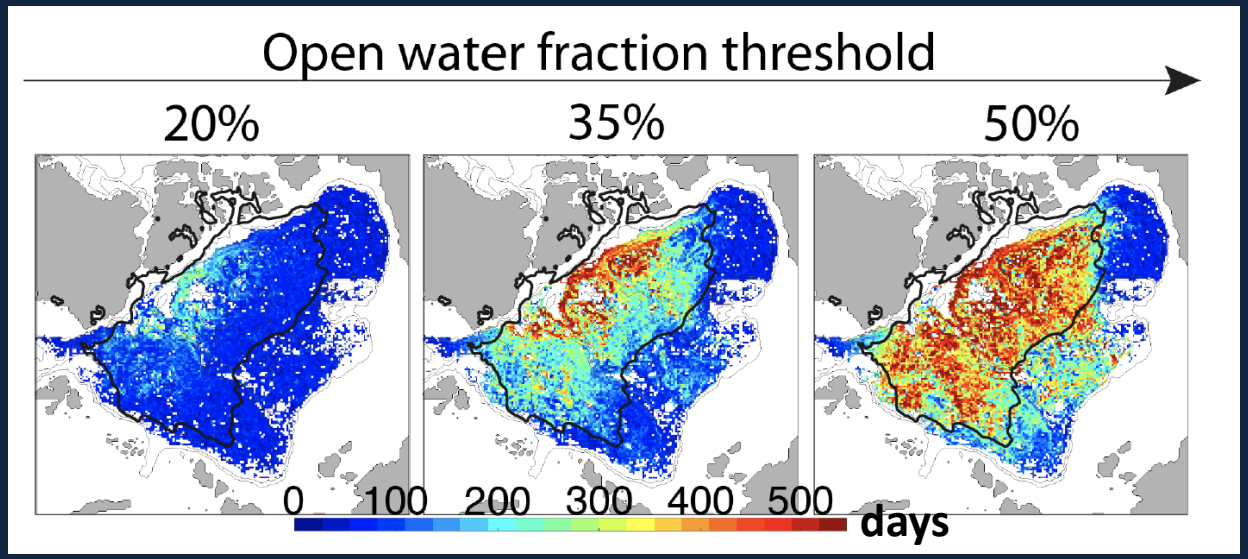
Large uncertainties:

- Heavy ice cover (long drift intervals).
- Energetic currents

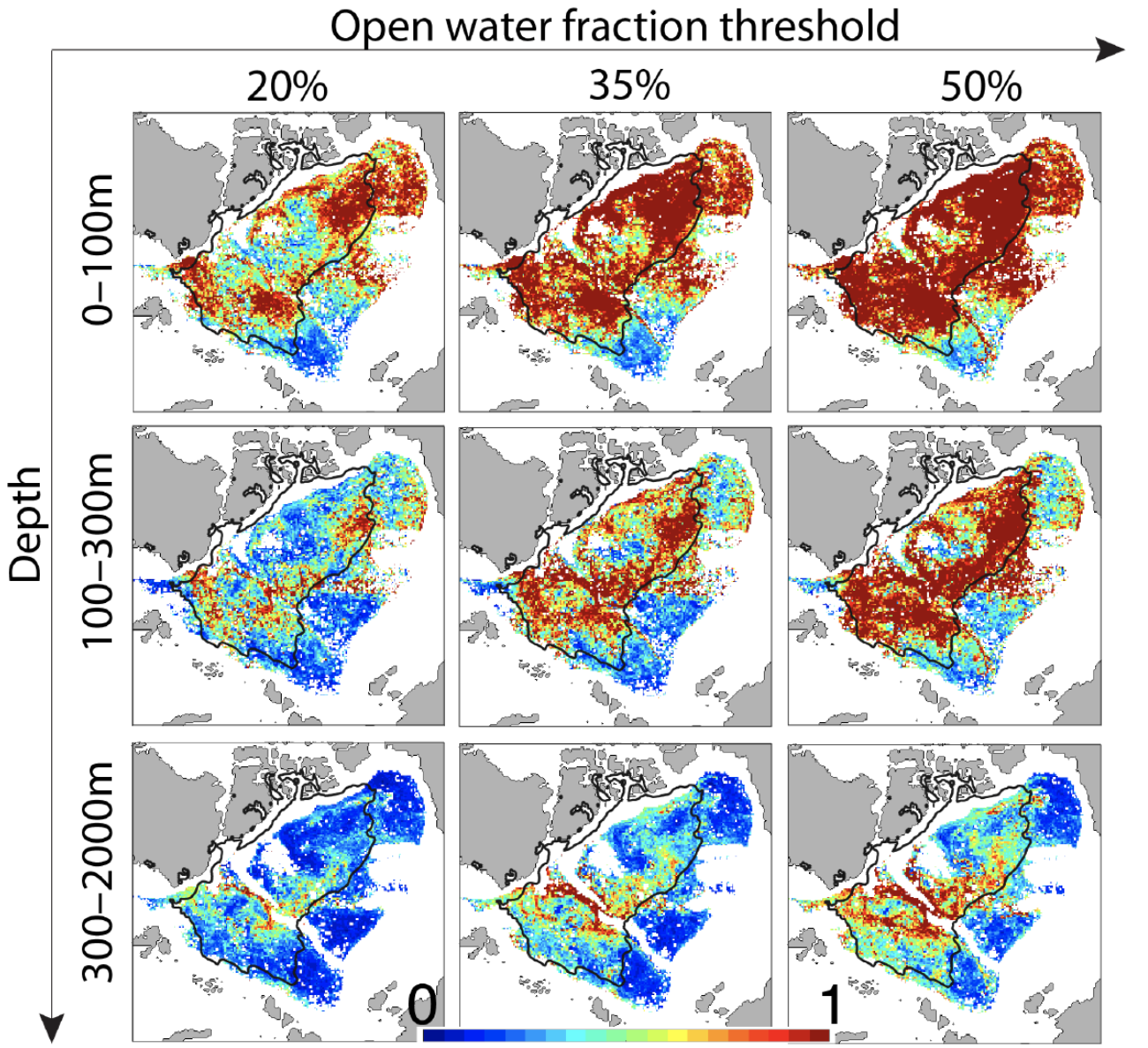
Nguyen et al (2017)

Time Between Surfacing

- High probability of surfacing multiple times per year.
- In regions of multi-year ice, floats may drift for years, until they move to area of seasonal ice cover.



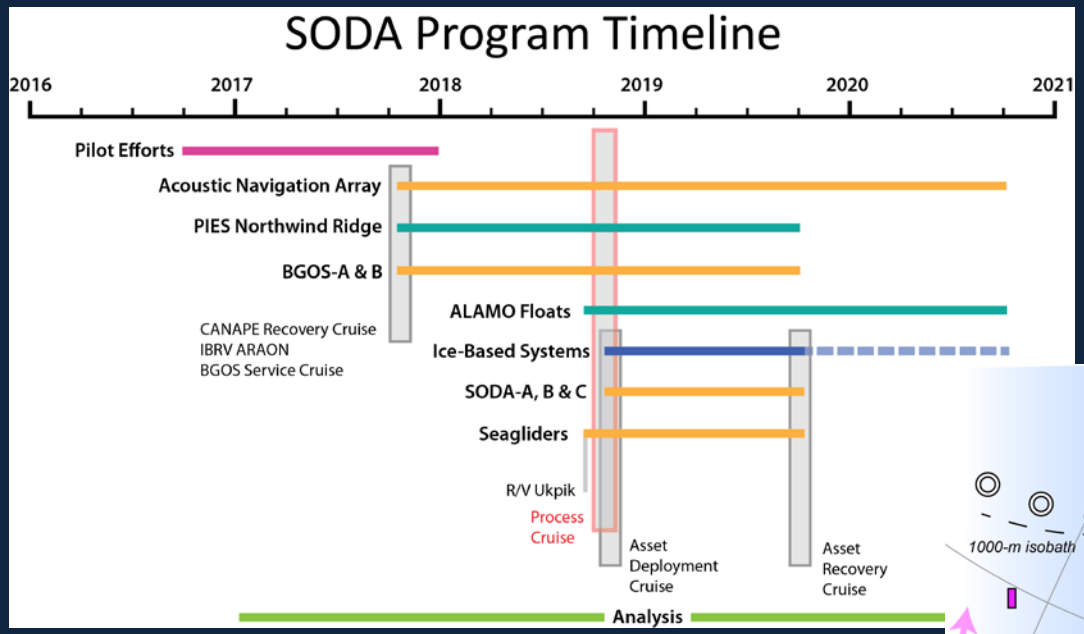
Mean Normalized Salinity Error



Nguyen et al (2017)

- $e_s < 1$ improves state estimate.
- e_s (0-100 m) large as spatial & temporal scales small relative to drift scales.
- e_s (0-100 m) low in where salinity uncertainty high.
- Deeper, longer spatial and temporal scales result in lower e_s.
- In areas with little data, even observations with large position uncertainties can be useful.

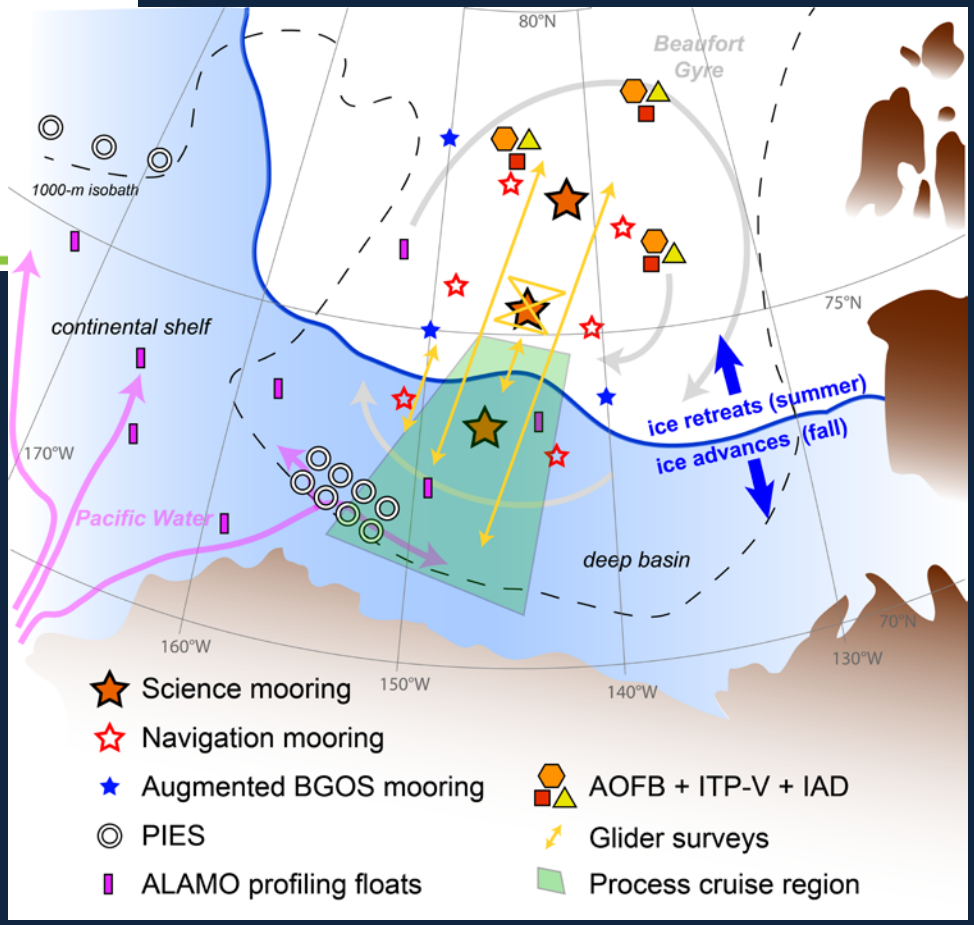
Stratified Ocean Dynamics of the Arctic



Project info and science plan:

http://www.apl.uw.edu/soda

- Science moorings 2018-2019
- Acoustic navigation 2018-2019
- Ice-based instruments, gliders and floats 2018-2019.
- Possibly extending beyond 2020 (Arctic Mobile Observing System)
- Exploit acoustic infrastructure, mooring array?



Summary

The Arctic is undergoing rapid change, with amplified variability at decadal, interannual and seasonal timescales.

Decadal scale observations required to quantify climate state and trends relative to shorter timescale variability.

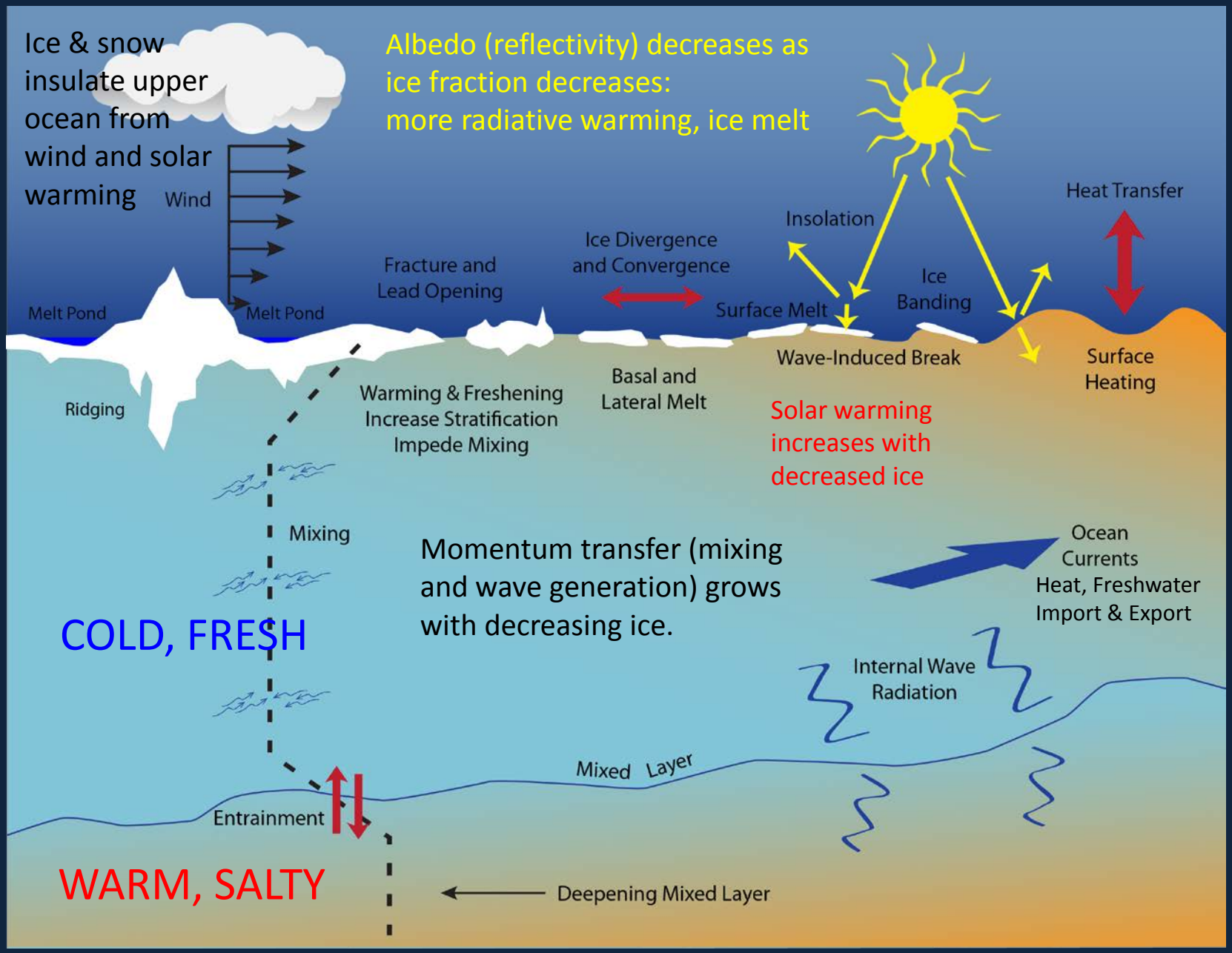
Priorities

- Measurements across ocean, ice and atmosphere.
- Persistent, sustained (decades) measurements.
- Distributed, pan-Arctic observations.
- Boundary measurements (atmospheric fluxes, rivers, gateways, Greenland melt).
- Remote sensing
- International collaboration! Operations, EEZ access, data sharing…

Opportunities and Recommendations

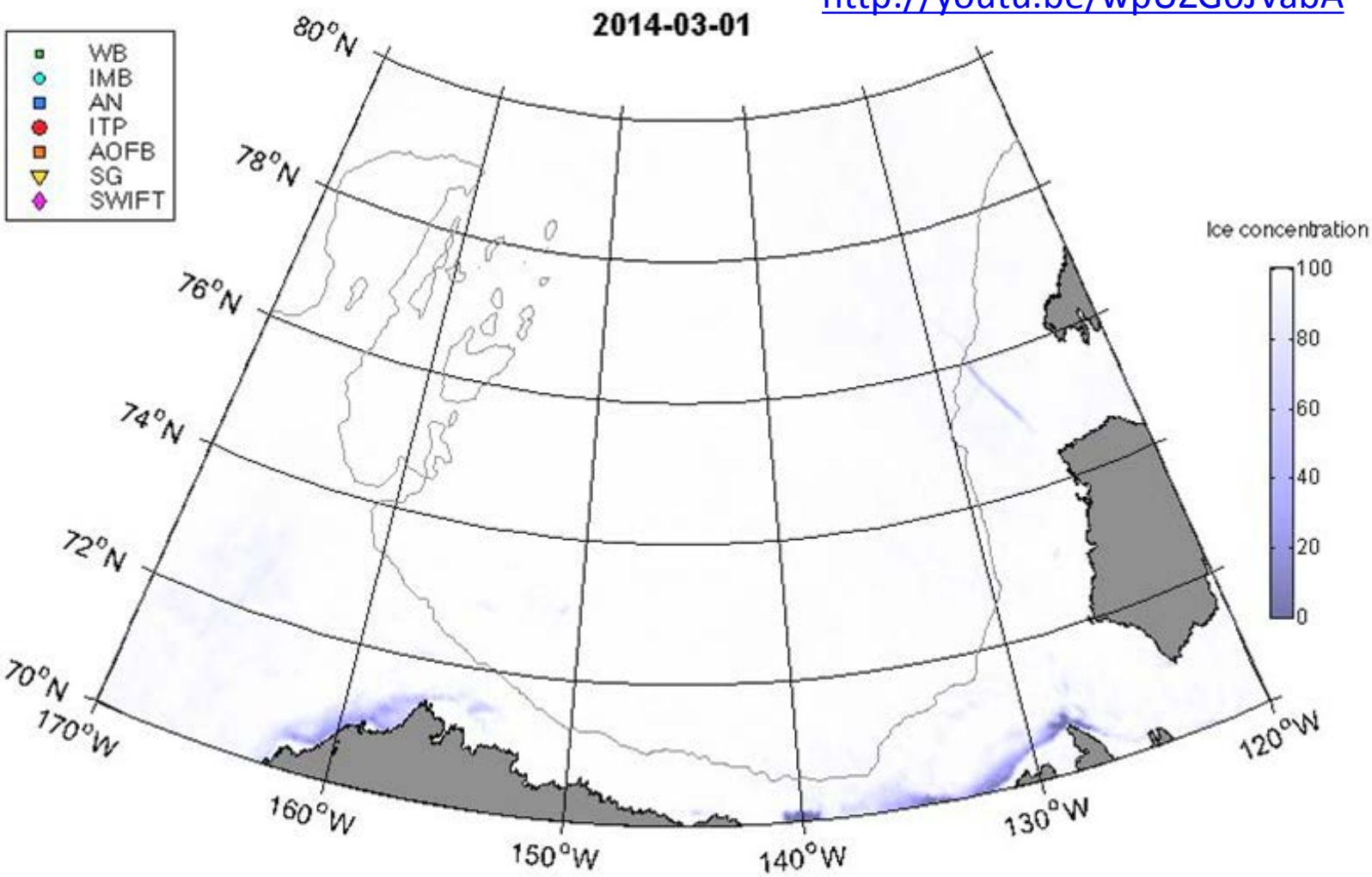
- Framework for prioritizing core measurements, ongoing evaluation for relevance and performance.
- Sustain/augment existing long-term activity:
  - Expand ice-based observatories (more sites, biology, biogeochemistry)
  - Gateway and boundary current systems
- Beaufort Sea pilot for sustained, basin-scale (distributed + boundaries) autonomous obs.
- Pilot Argo effort (exploit SODA infrastructure).
- Autonomous surface vessels for atmospheric fluxes and surface ocean (Meinig, later this morning).

Physical Processes Change with Declining Ice



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

http://youtu.be/wpUZG0JVabA



Ice concentration maps (AMSR2) from U. Bremen