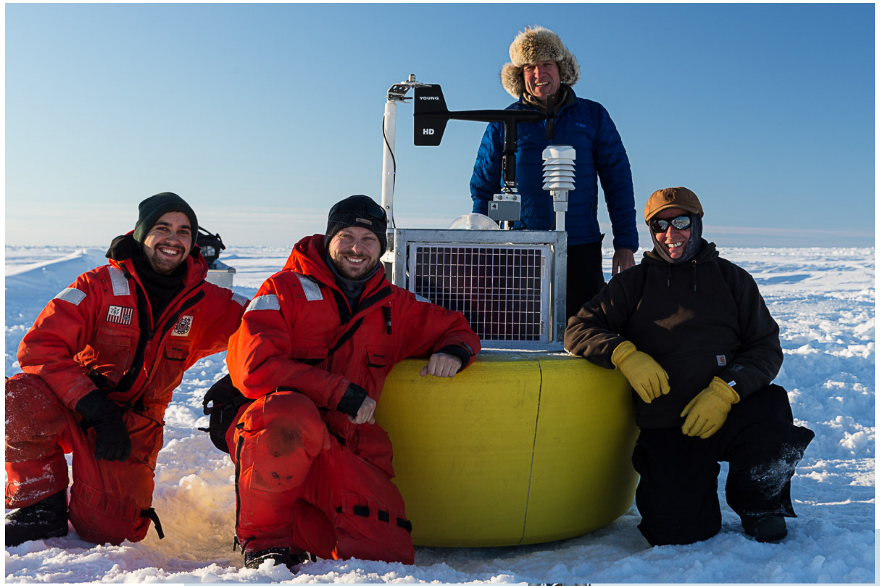
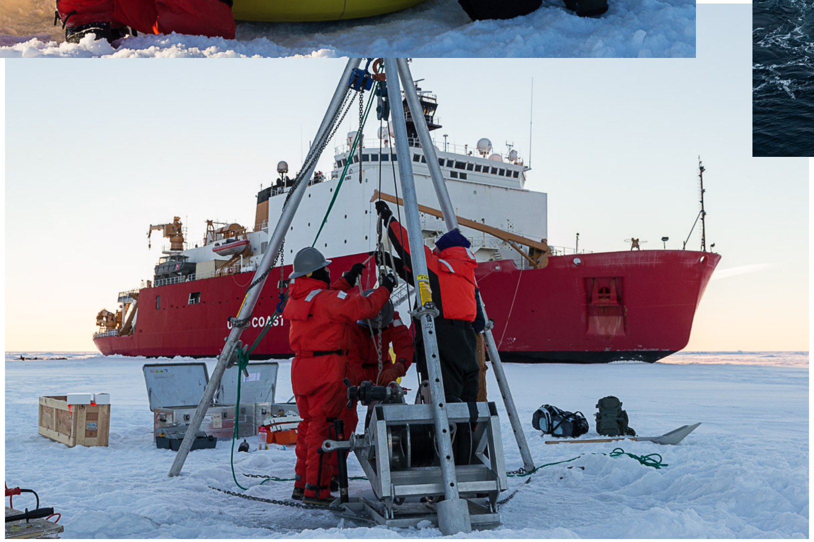
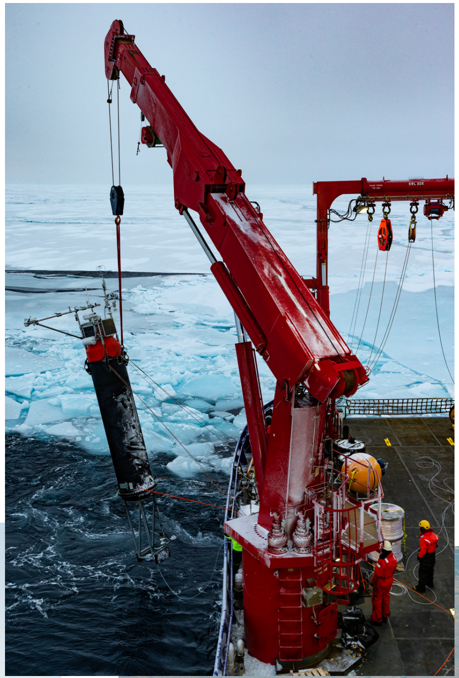
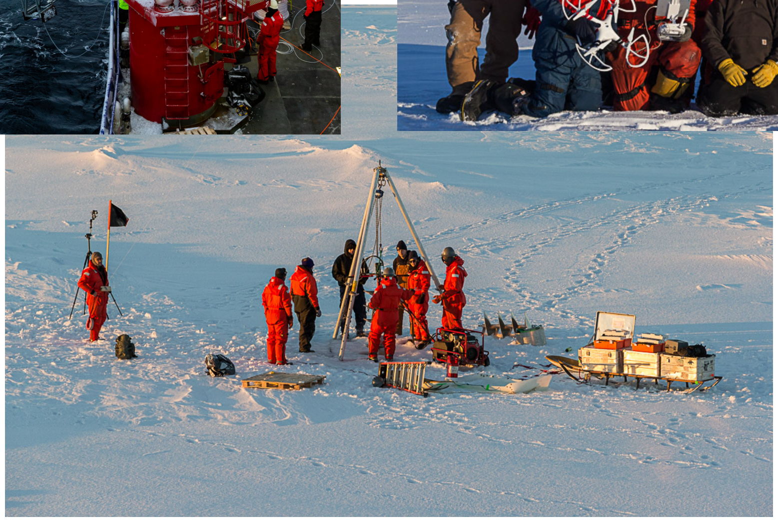
Ocean, Ice and Atmosphere in the Changing Arctic:
Science & Technology Development in the Office of Naval Research Arctic Program

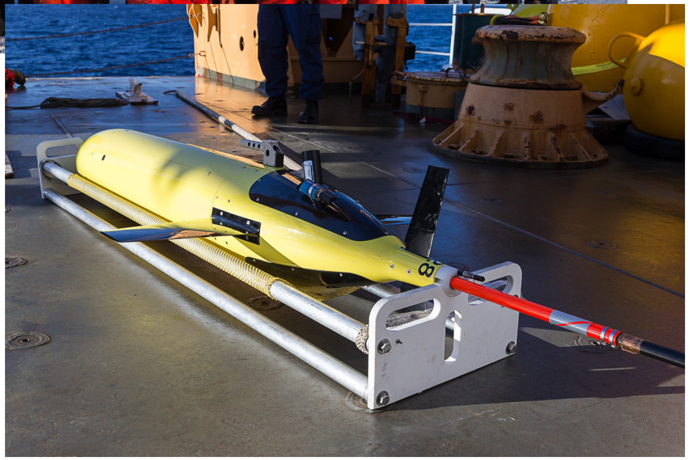
Craig M. Lee, Applied Physics Laboratory, University of Washington
Stratified Ocean Dynamics of the Arctic & Arctic Mobile Observing System Teams







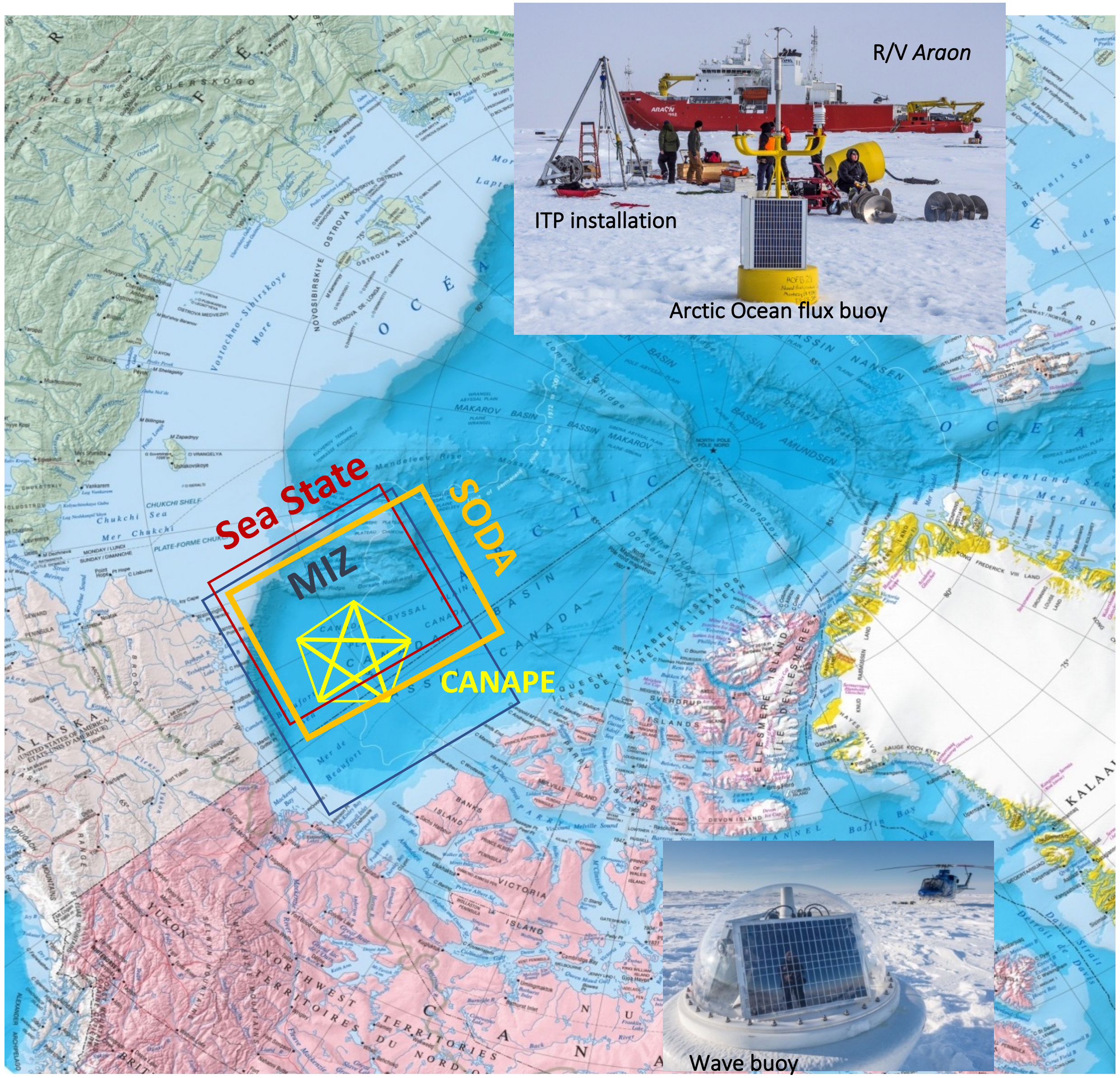




ONR Major Arctic Research Initiatives (2012 – present)

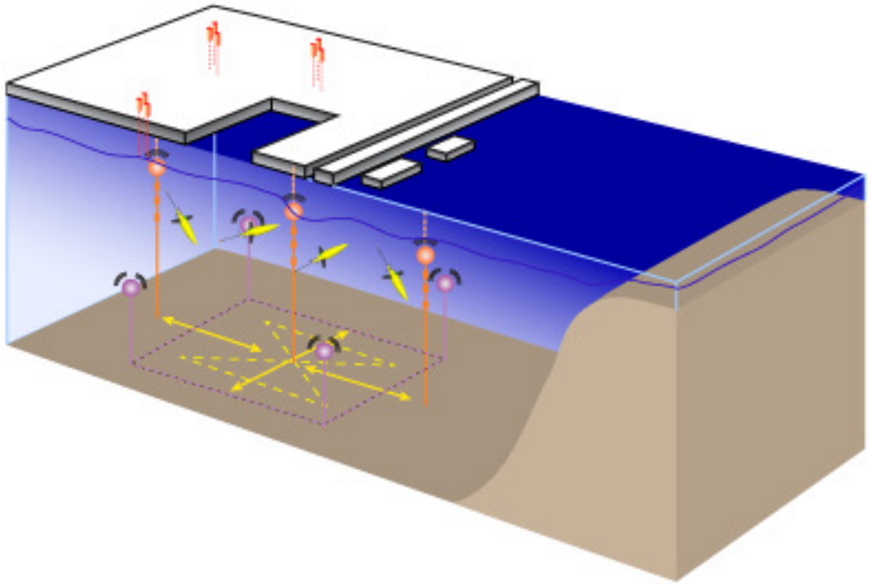
2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Office of Naval Research Arctic and Global Prediction and Acoustics Programs													
Marginal Ice Zone (MIZ)													
	Waves and Sea State												
			CANAPE (acoustics)										
				Stratified Ocean Dynamics (SODA)									
							Arctic Mobile Observing System (AMOS)						
							CAATEX (acoustics)						
							Sea Ice Dynamics Experiment (SIDEX)						
											Arctic Argo Pilot		

- **Marginal Ice Zone (MIZ) Initiative**
  - *2014 Field Program*
- **Waves and Sea State Initiative**
  - *2015 Field Program*
- **Canada Basin Acoustic Propagation Experiment (CANAPE)**
  - *2015, 2016-2017 Field Programs*
- **Stratified Ocean Dynamics in the Arctic (SODA)**
  - *2017-2019 Field Programs*
- **Arctic Mobile Observing System (AMOS)**
  - *2019-2023 Field demonstrations*
- **Coordinated Arctic Acoustic Tomography Experiment (CAATEX)**
  - *2019-2020 Field Programs*
- **Sea Ice Dynamics Experiment (SIDEx)**
  - *2020-2021 Field Programs*

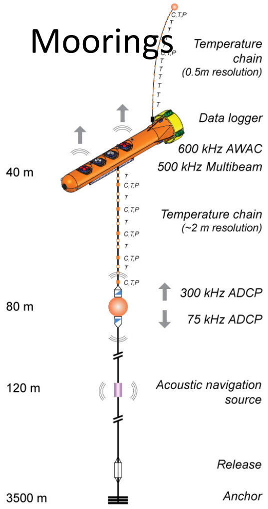


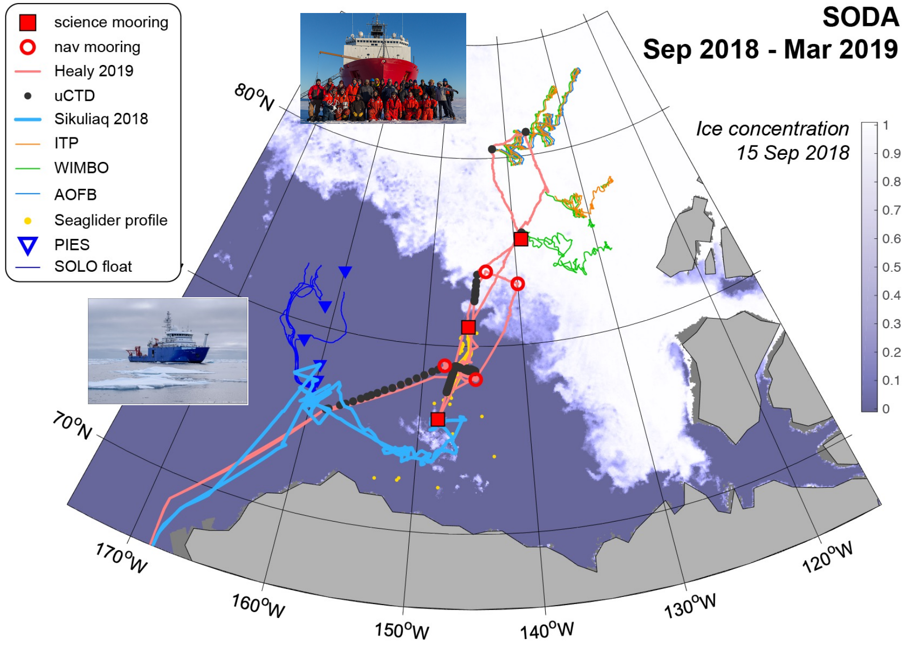
Stratified Ocean Dynamics of the Arctic (SODA)

https://apl.uw.edu/project/project.php?id=soda

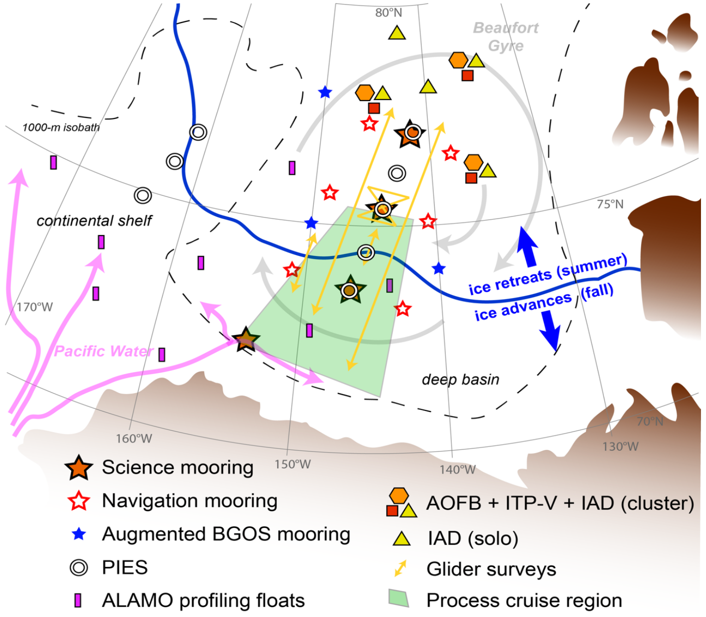


Moored and Mobile Instruments Maintain Focus on Fixed Domain





- Understand how the upper Beaufort Sea, particularly stratification and sea ice, responds to changes in inflow and surface forcing.
- Mobile instruments operate within broad field of moored (fixed) assets that provide acoustic infrastructure and sampling.
- Ice-based instruments deployed to drift through mooring array.
- Good for sustained focus on fixed geographic sites.

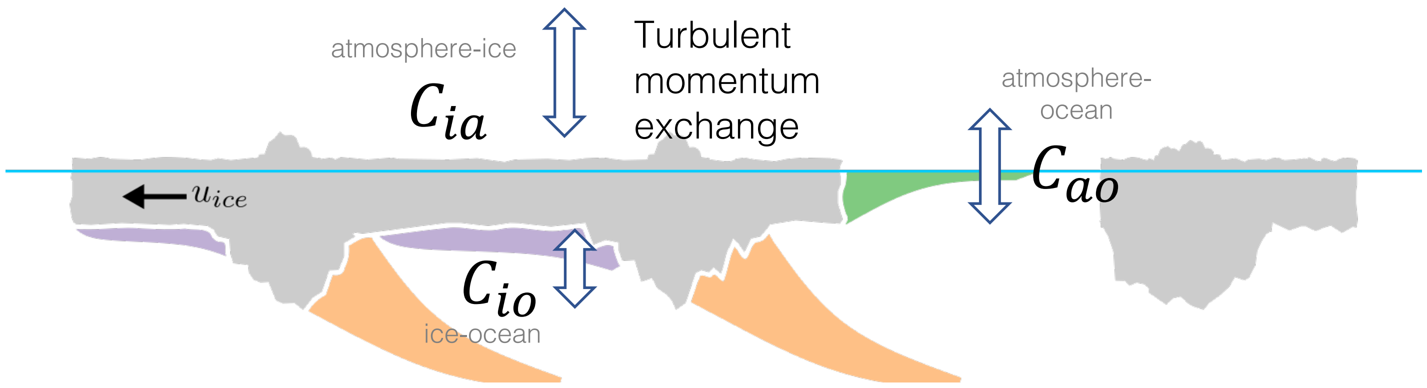


Results include new understainding of…

- Ice-ocean drag parameterizations.
- Role of sea ice melt water in modulating freeze-up.
- Seasonal modulation of near-inertial motions within mixed layer.
- Episodic offshore heat transport within filaments.

Observations of Ice-Ocean Drag Across a Range of Ice Shapes

Brenner, Rainville, Thomson, Lee (APL-UW), Cole (WHOI)

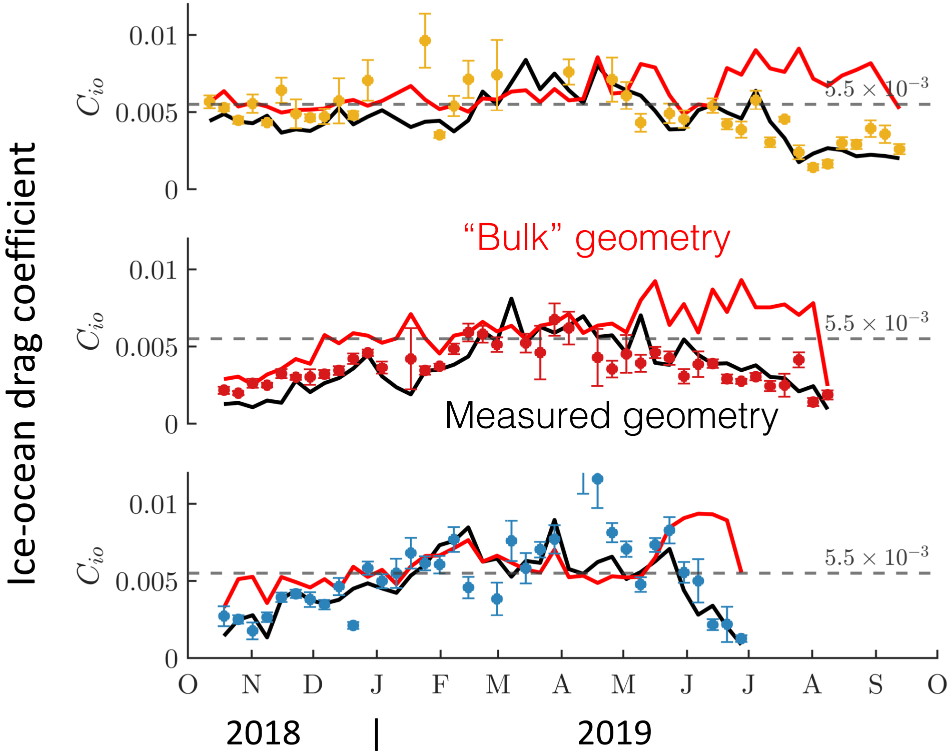


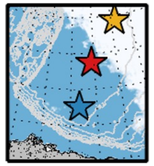
(*Lu et al., 2011; Tsamados et. al., 2014*)

$$C_{io} = \text{skin drag} + \text{keel drag} + \text{floe edge drag}$$

Important for improving forecasts of sea ice evolution and ocean currents

- Ice-ocean drag coefficient varies seasonally and spatially.
- Bulk parameterizations for ice geometry produce poor fits to observed ice-ocean drag.
- Can explain and predict these variations if ice geometry is known.
- Variability primarily driven by keel shapes.
- Dominance of first year over multi-year ice will drive large changes.



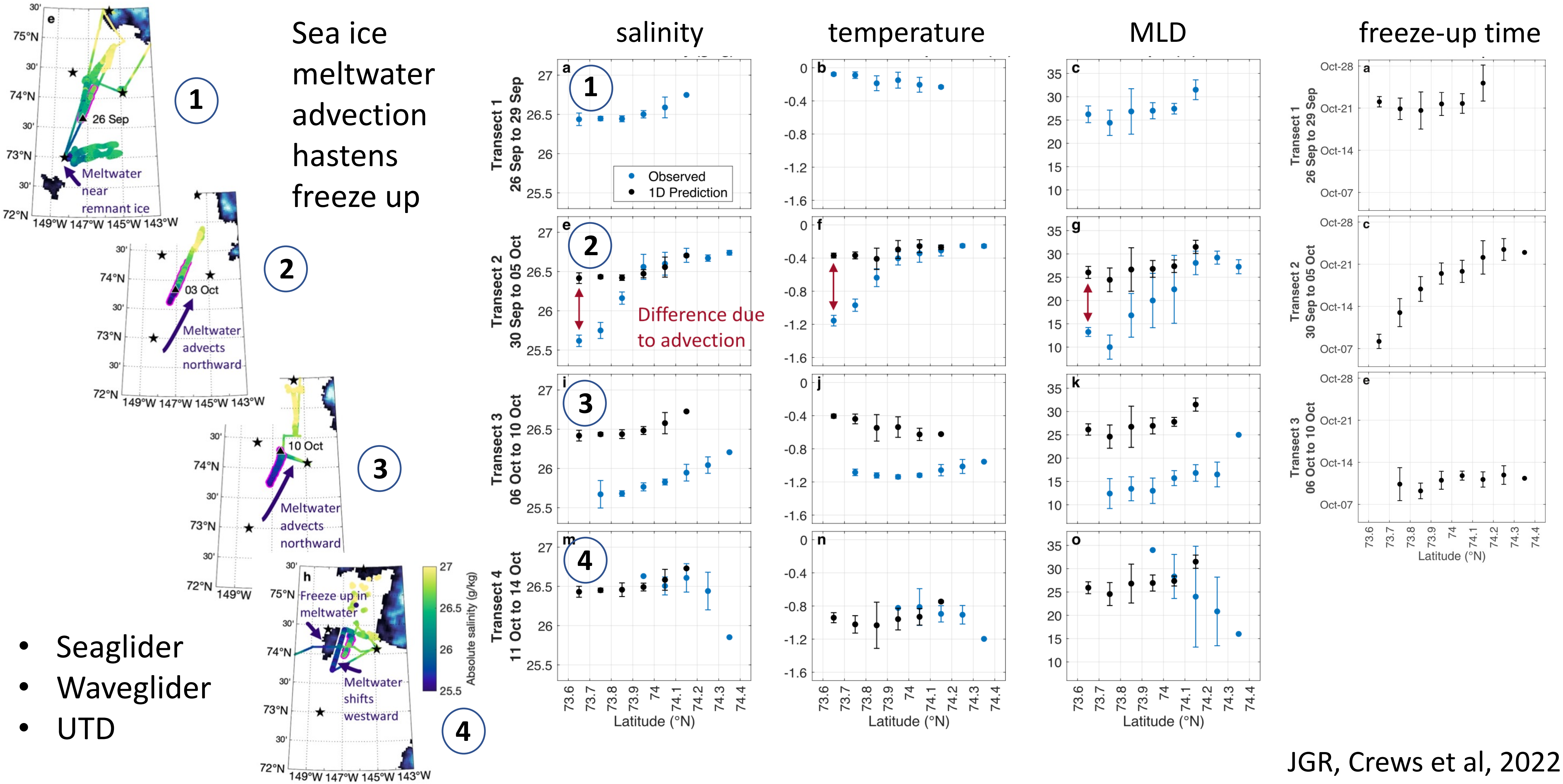


JGR, Brenner et al, 2021

Small-scale Circulation of Meltwater Accelerates Freeze-up

Crews, Lee, Rainville, Thomson (APL-UW)

Sea ice meltwater advection hastens freeze up



- Seaglider
- Waveglider
- UTD

JGR, Crews et al, 2022

Arctic Mobile Observing System (AMOS)


Ice Gateway Buoy - Heavy

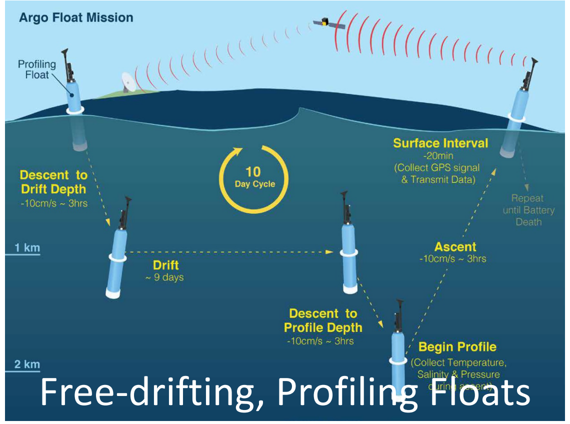

Ice Gateway Buoy - Light

Persistent, year-round monitoring, event-driven sampling/response

- Data exfiltration and control for instruments operating under ice through 'gateway' buoys that bridge ice-ocean interface.
- Store and forward network of mobile instruments.
- Robust, broad acoustic navigation:
  - Long-range (trans-basin) very low frequency (35 Hz) beacons – 'underwater GPS.'
  - Range and bearing from single 900 Hz beacons on gateway buoys – expand utility of drifting systems.
- Persistent presence, multi-scale sampling – gliders, floats & fast UUVs operating with 'gateway' buoys.
- Situational awareness and control center – in situ environmental data, remote sensing, numerical predictions inform decisions.

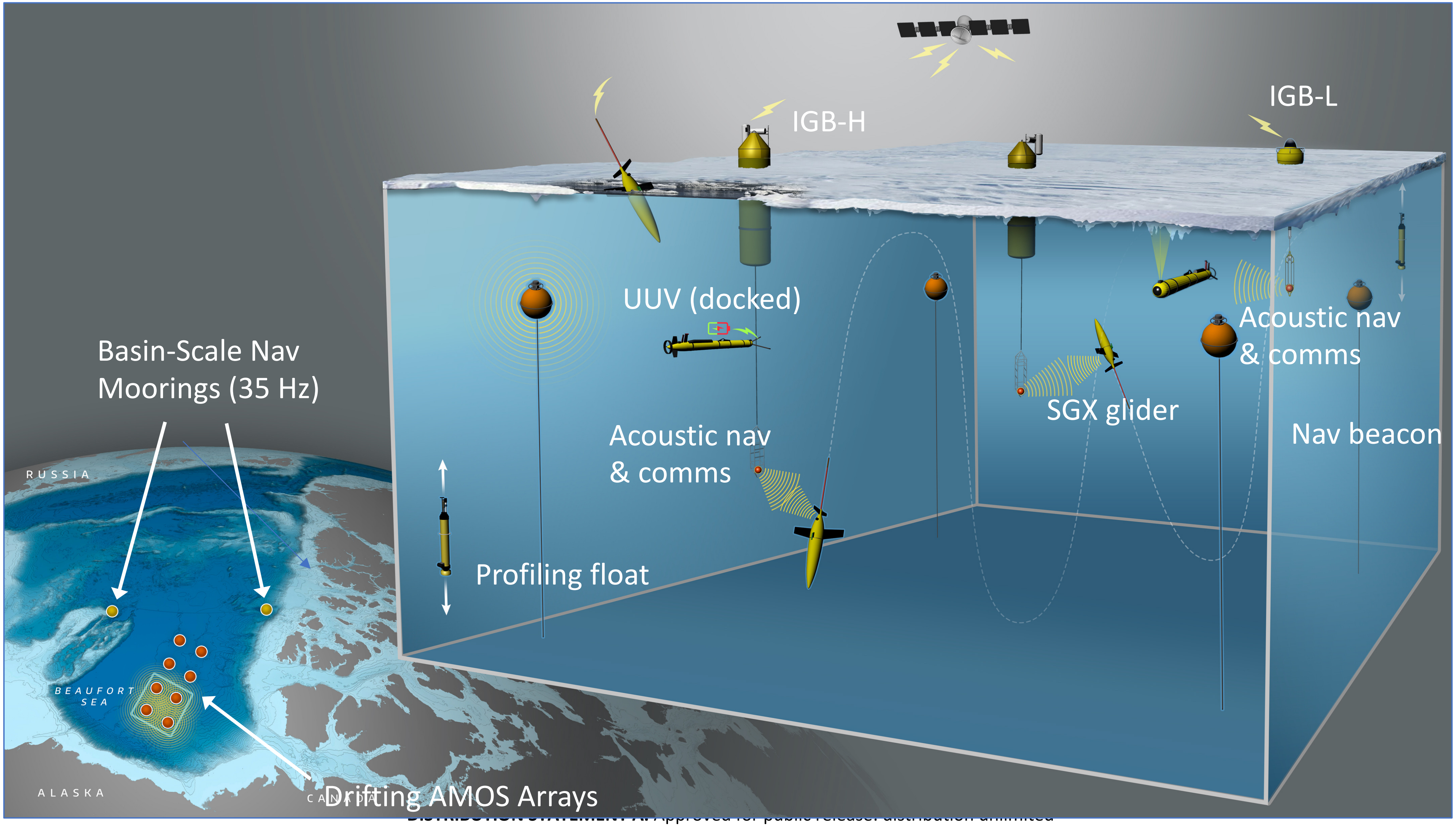

Long-Endurance Gliders


Fast Unmanned Underwater Vehicles



Free-drifting, Profiling Floats

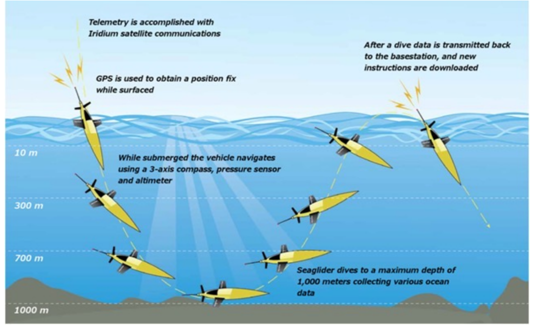
Arctic Mobile Observing System (AMOS)



Acoustic Nav & Comms for Autonomous Platforms in Ice-covered Environments

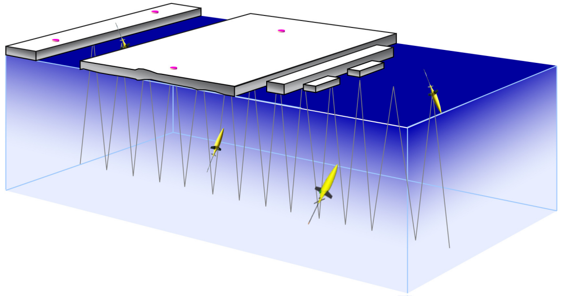
Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Lee Freitag (WHOI)

OPEN WATER – SATELLITE ACCESS



- Satellite nav & comms
- Human in the loop – high latency remote control.

ICE – SATELLITE SERVICES BLOCKED

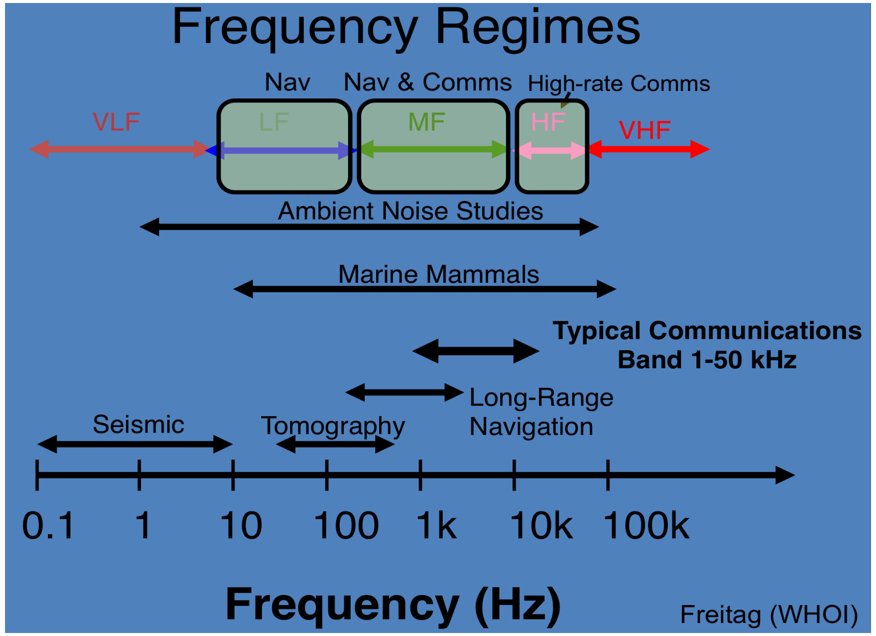


- Acoustic nav & comms – underwater GPS.
- Operate for months, years without human intervention.

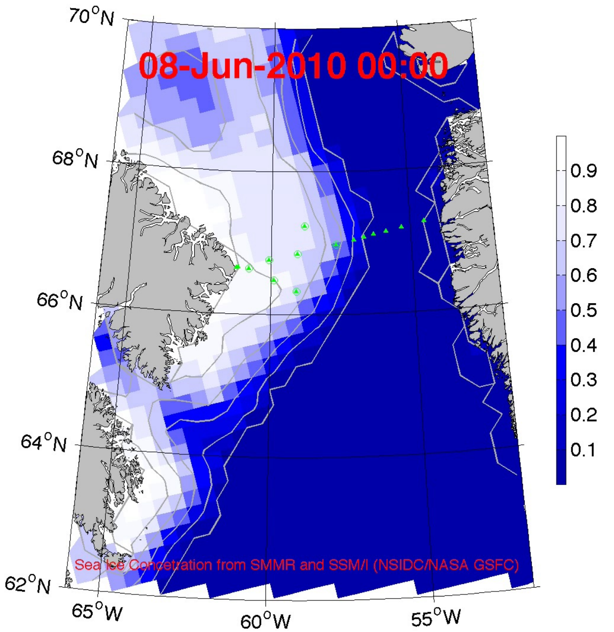
10 kHz
Data transfer

LF 1 kHz
Regional nav & command transmission

VLF 100 Hz
Basin-scale nav

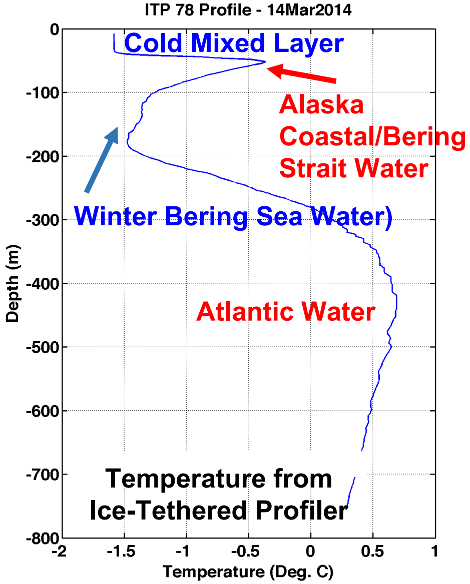


Acoustic Multilateration in Baffin Bay

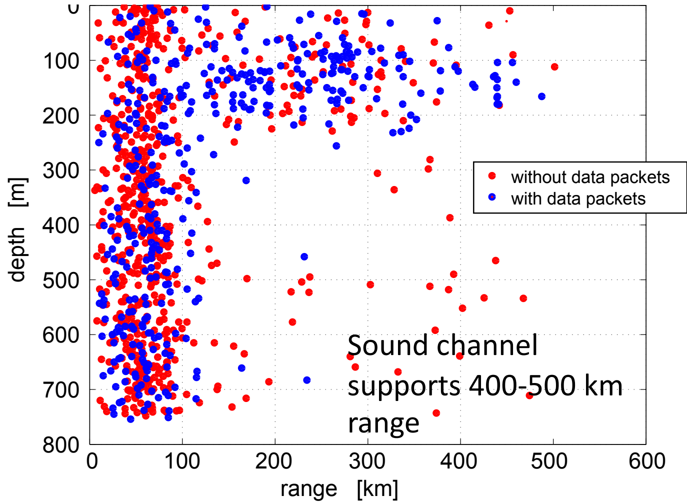


Surface ducting in many polar regions limits LF acoustic range to ~100 km.

Warm Pacific layer in Beaufort creates sound channel, allows long-range propagation.

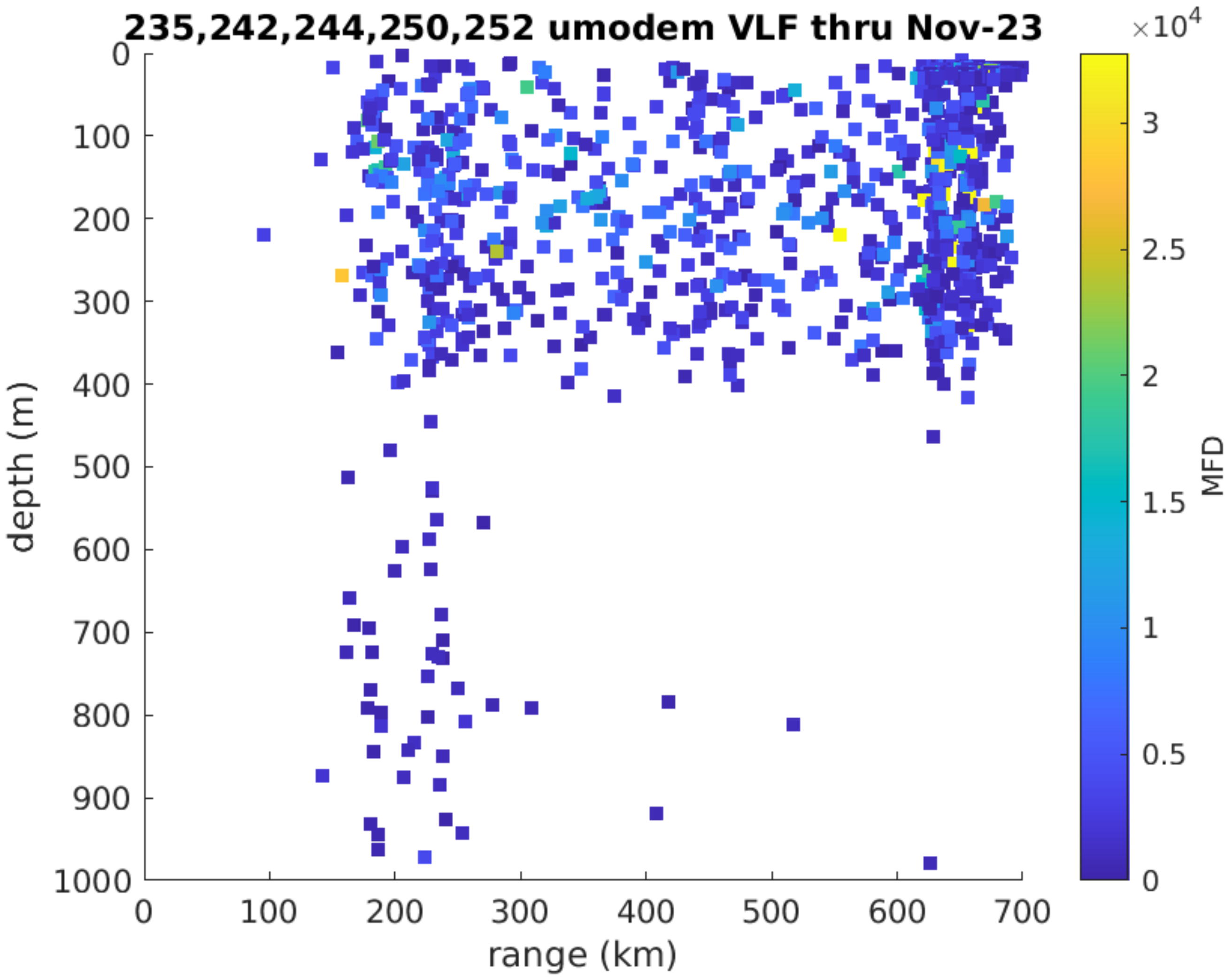


Glider Receptions vs depth and range

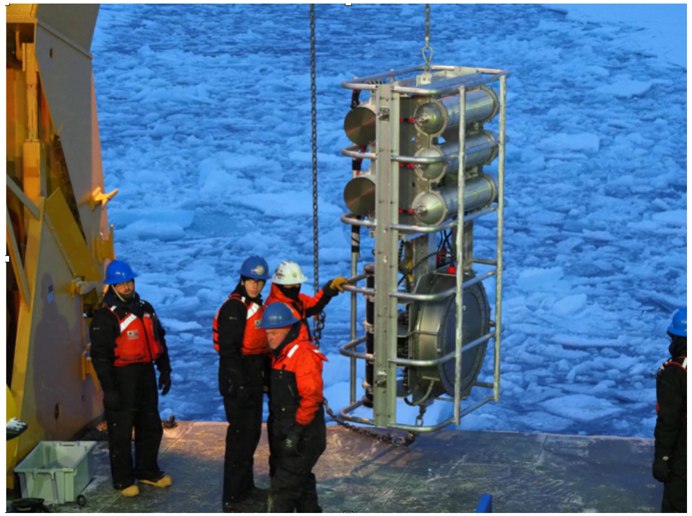


35 Hz VLF Geolocation Developments

Lee Freitag (WHOI), Jason Gobat, Craig Lee (APL-UW), Matt Dzieciuch (SIO)

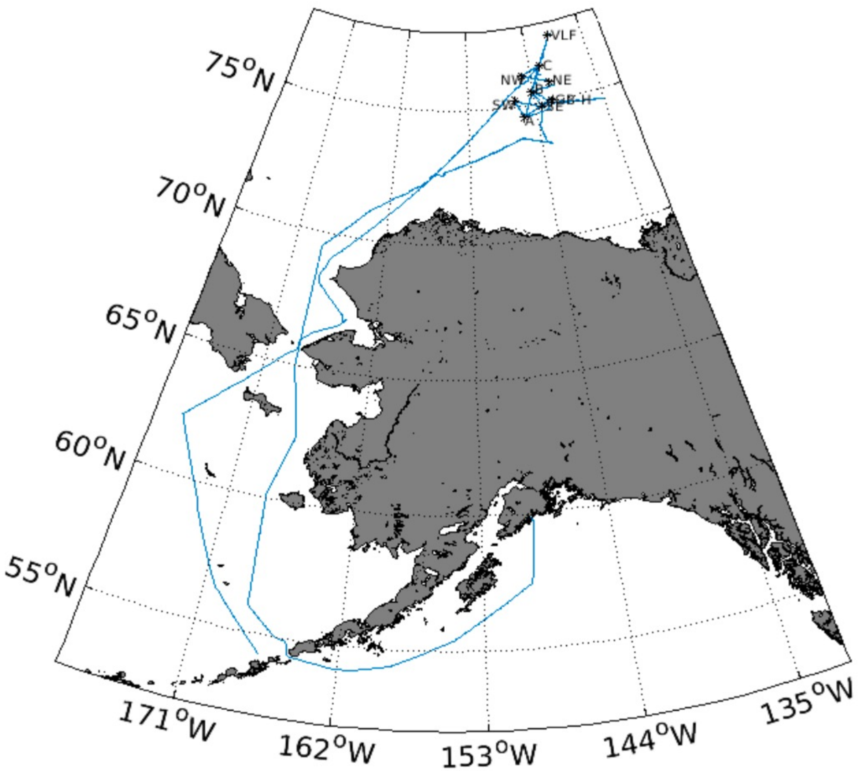


- Package 35 Hz VLF source for year-long deployments with more frequent broadcasts of shorter signals.
- 35 Hz, NTE 190 dB.
- 1-4 broadcasts per day.
- Local testing followed by central Beaufort deployment on a single mooring in summer 2022.
- Range tests with SGX gliders in autumn 2022.
- Deployed two-element array in 2023 to provide geolocation in Beaufort Sea. Currently in operation providing geolocation for floats and gliders.



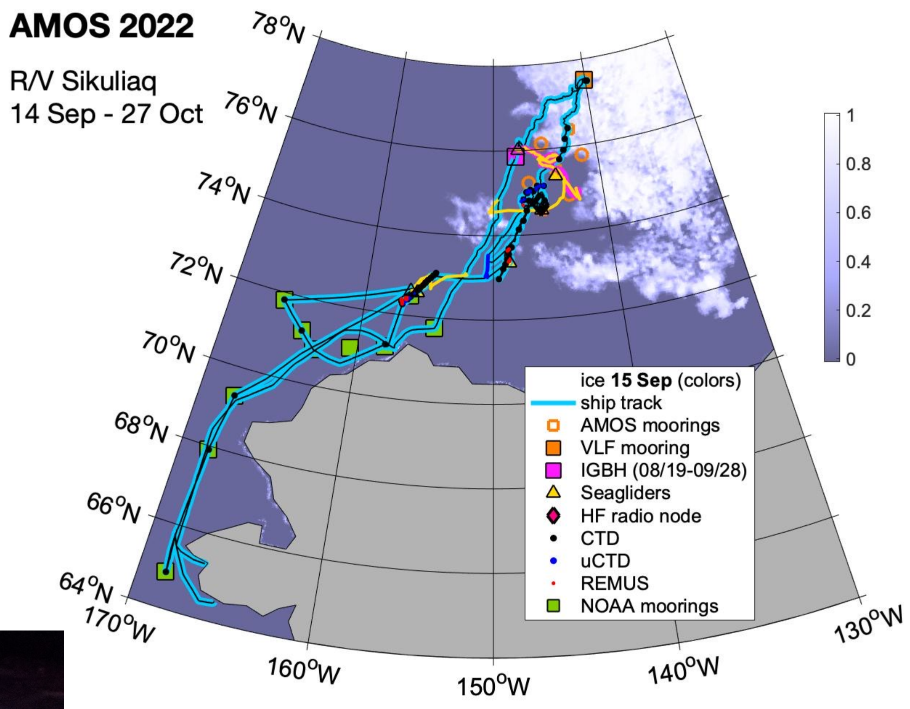
AMOS Field Operations 2022

USCGC Healy 27 Jul – 30 Aug 2022



- Service mooring array
- Deploy 35 Hz nav source
- Deploy IGB-H drifting buoy
- Deploy REMUS AUV
- Deploy gliders
- Test gliders, float and gateway buoys

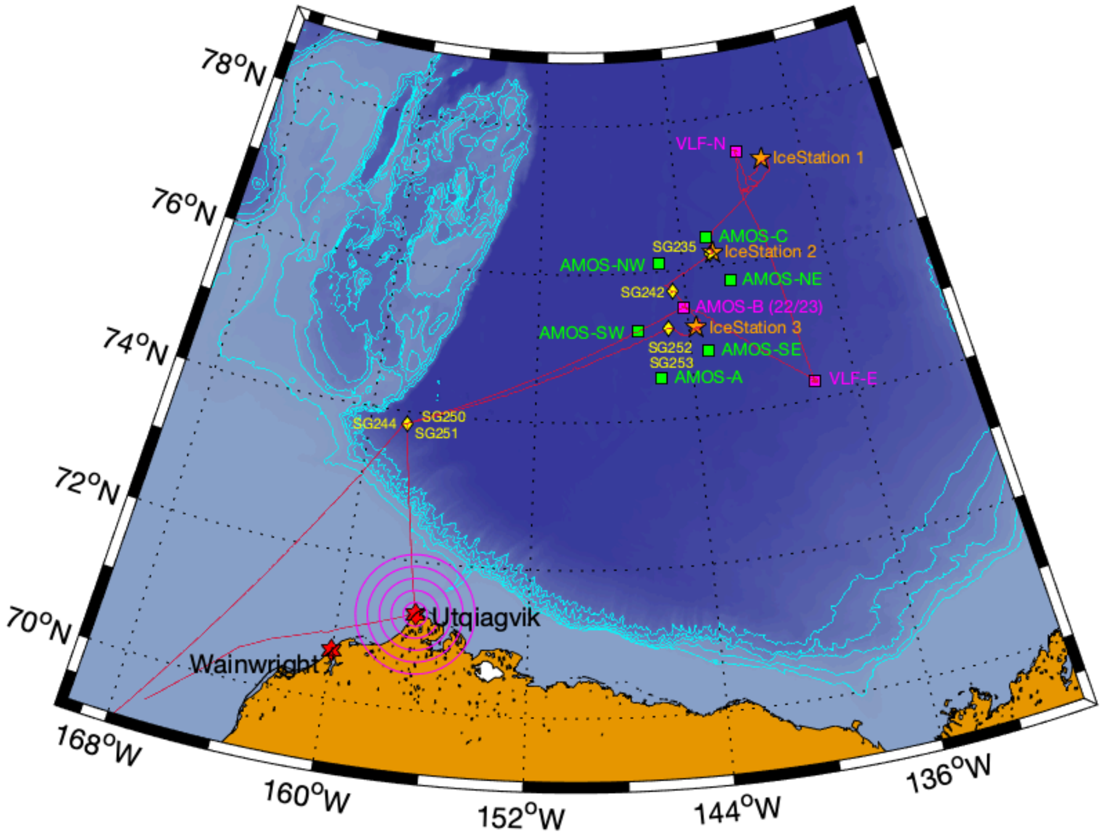
R/V Sikuliaq 14 Sep – 27 Aug 2022



- Recover 35 Hz nav source
- Recover REMUS AUV
- Test REMUS AUV
- Science sampling
- Service NOAA mooring array

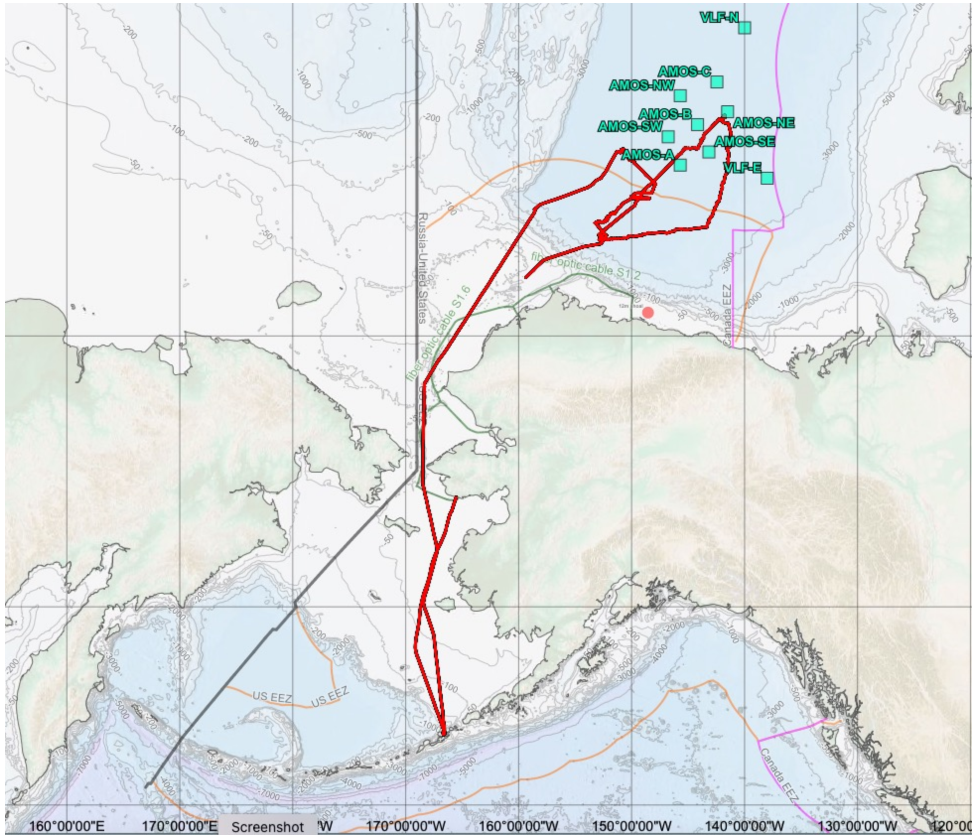
AMOS 2023

USCGC Healy 21 Jul – 22 Aug 2023



- Service mooring array
- Deploy two 35 Hz nav sources
- Deploy Light Gateway Buoys
- Deploy ice-based science instruments
- Test comms (gliders-floats-buoys)
- Deploy gliders and profiling floats

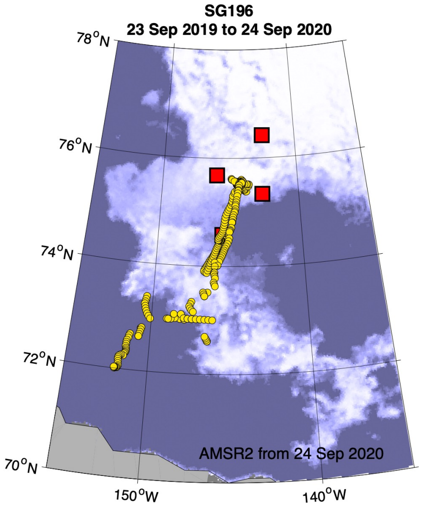
R/V Sikuliaq 23 Oct – 15 Nov 2023



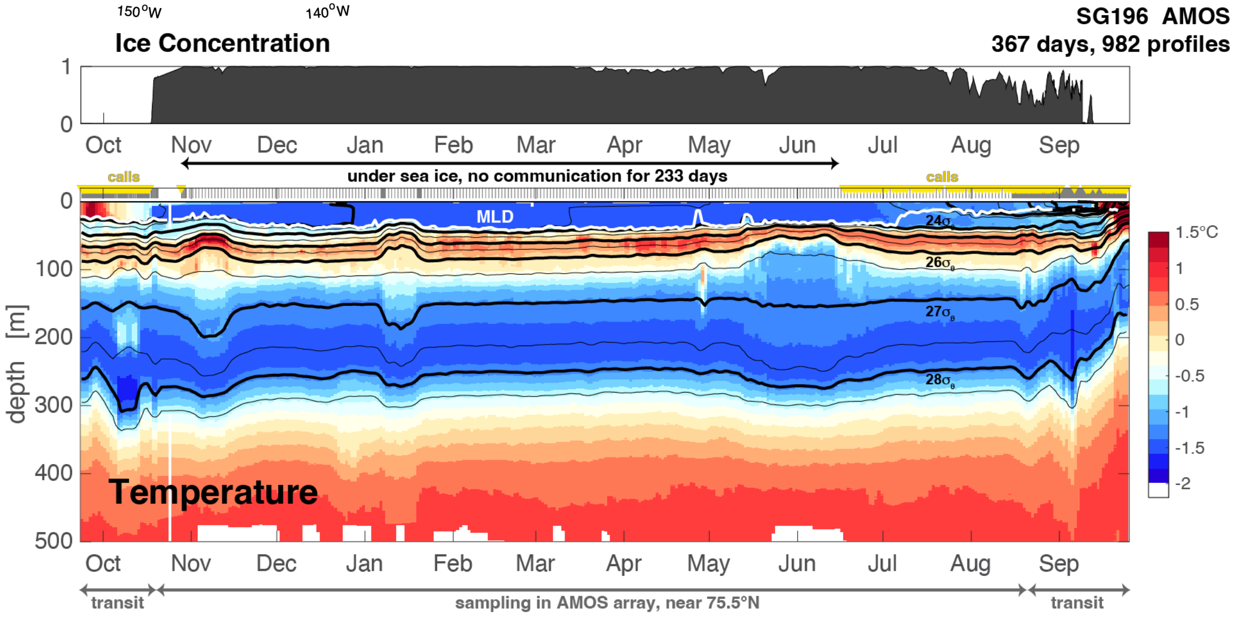
- Deploy Heavy Gateway Buoy
- Test REMUS AUV
- Deploy REMUS AUV
- Service gliders
- Science sampling

AMOS Autonomous Operations

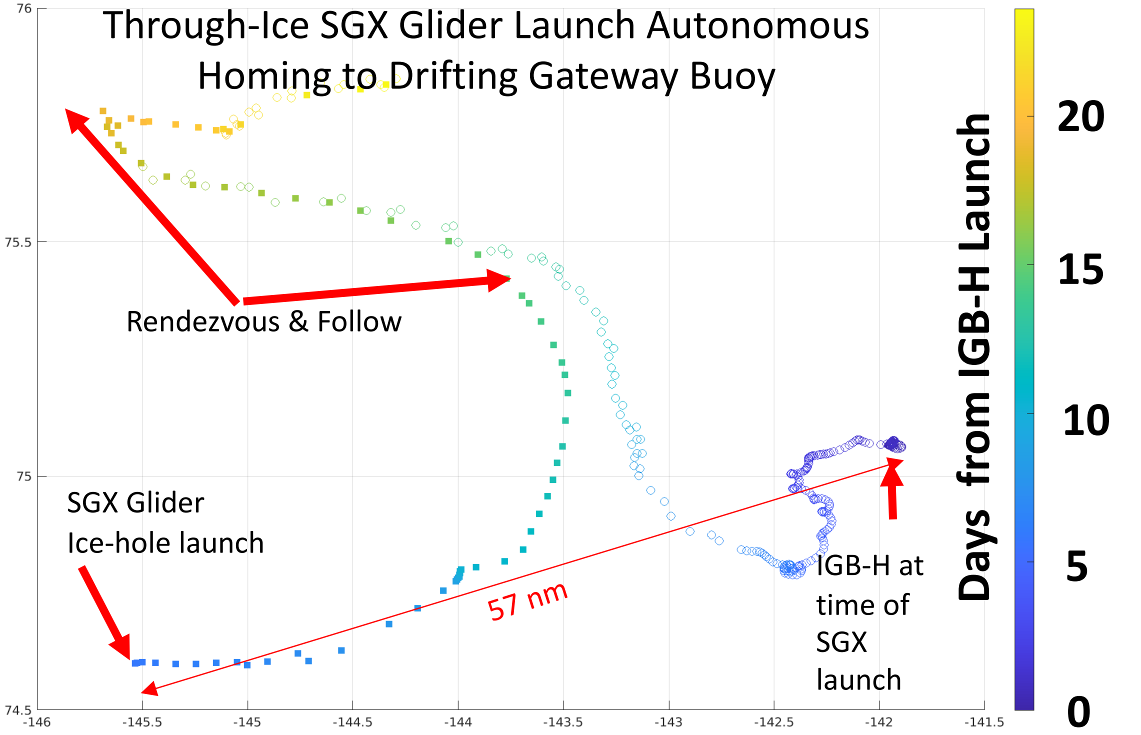
Year-Long Autonomous Glider Missions Under Ice



- 367 days, 982 profiles
- 233 **consecutive days** under sea ice - fully-autonomous operation, diving once per day.
- Localization and navigation from 900 Hz acoustic array.
- Navigate to target. Maintain position though winter, navigate south for recovery in summer.

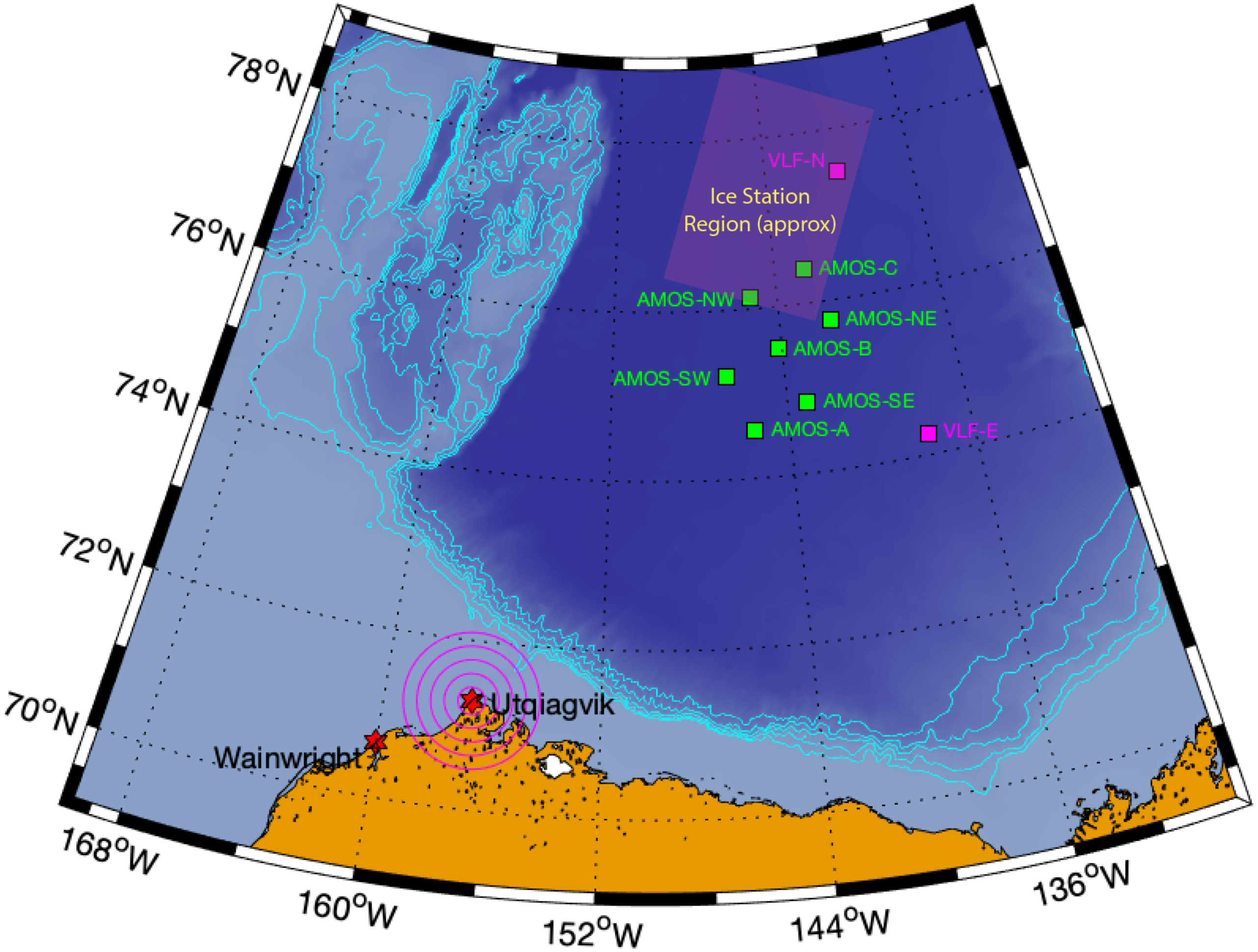


Integrated Nav, Comms, Networking and Autonomy



- Fully-autonomous ice-hole deployment.
- Homing, rendezvous, follow and mission retarget all fully autonomous – no human interaction/intervention.
- Glider homes based on positions communicated by IGB-H.
- Glider transmits data to IGB-H for exfil, receives commands.
- Identical demonstrations with IGB-L as target/gateway.

AMOS 2024



USCGC Healy, R/V Sikuliaq ?

- Recover all 2022/2023 moorings.
- Rendezvous with Heavy Ice Gatway Buoy and recover REMUS deployed in 2023
- Deploy two 35 Hz navigation moorings (VLF-N, VLF-E) and four 900 Hz navigation moorings.
- Deploy two Light Gateway Buoys
- Recover 2023 gliders.
- Deploy floats and gliders.
- Continued testing and refinement of buoy-glider-float communication.

ICEEX 2024

- Deploy Light Gateway Buoy, gliders and floats from Navy ice camp.

APEX Float Developments

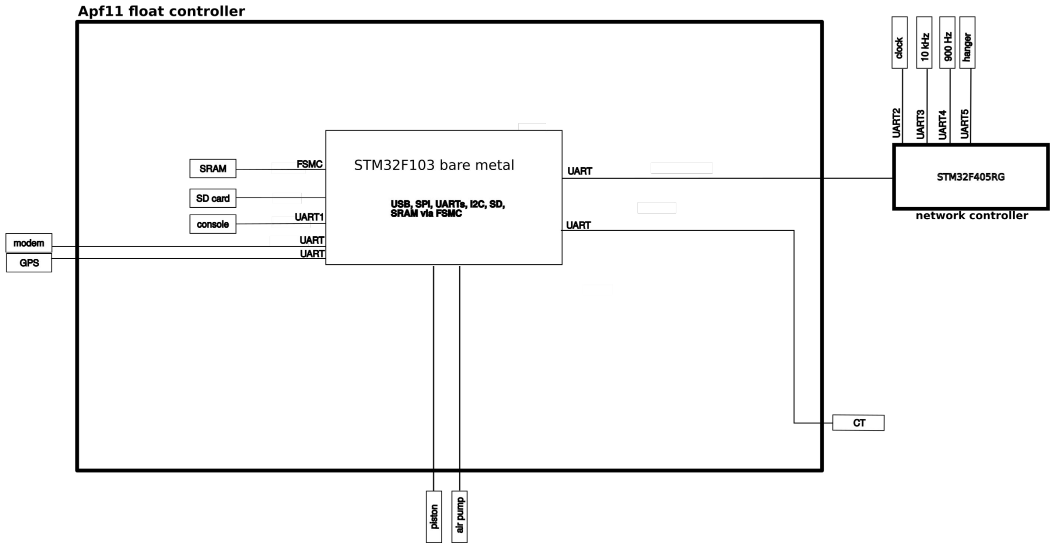
Jason Gobat, Craig Lee, Luc Rainville (APL-UW)

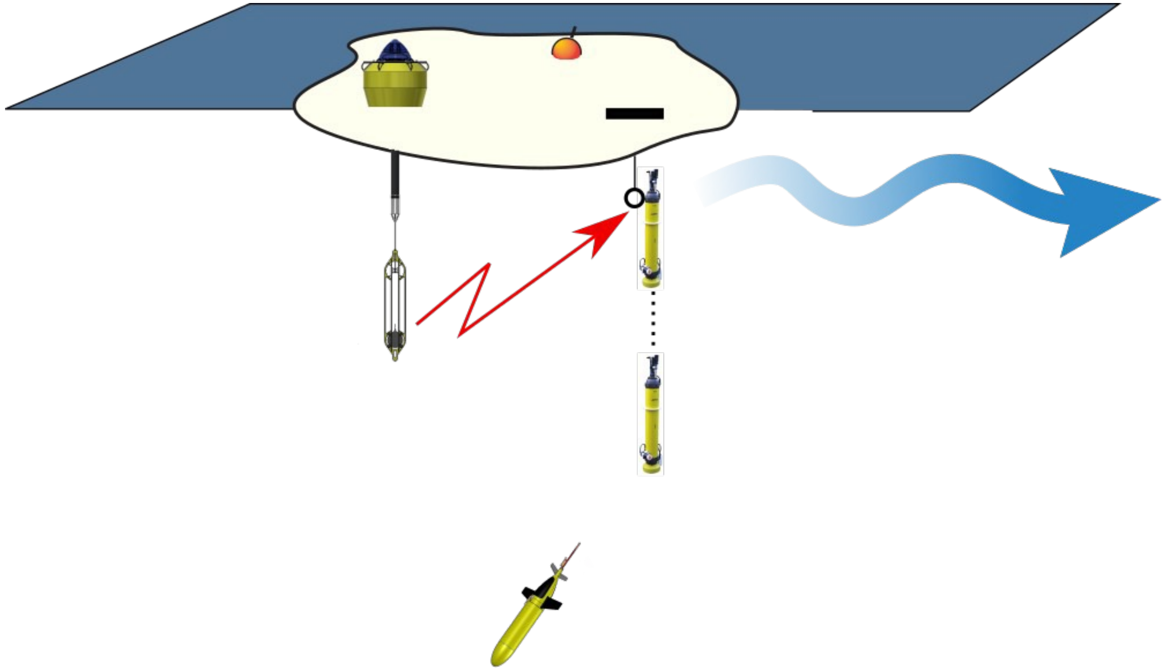
'Ice Guard'

Independent Network Controller

- Acoustic modem/900 Hz nav (900 Hz carrier, 3-25 bps, Rx only)
- Acoustic modem/Nav source 2 (10 kHz carrier, 300-5000 bps)
- Clock
- Hanger release

Ice avoidance and backlog management



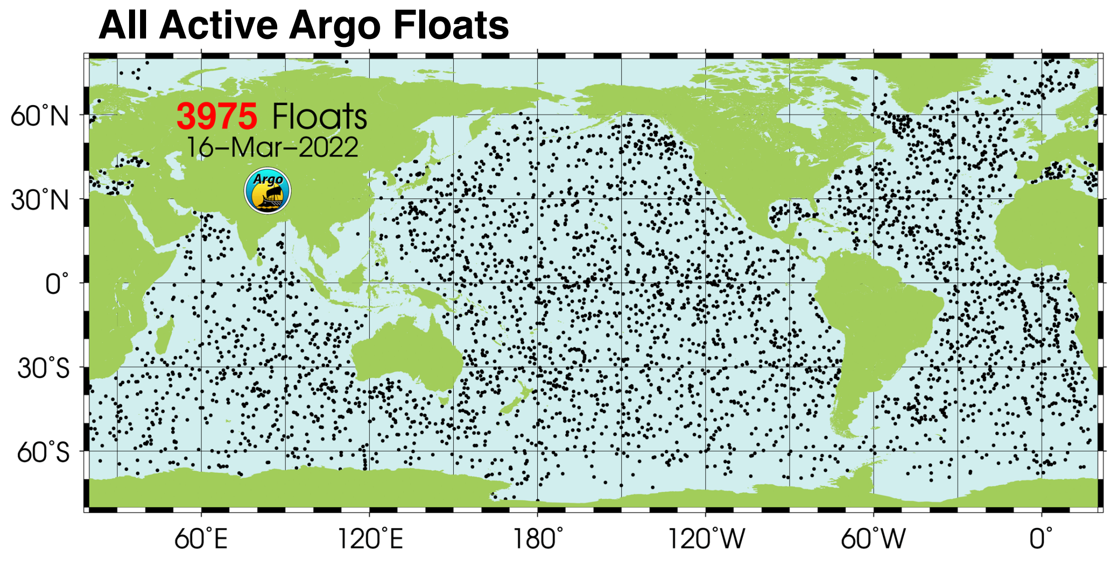


Ice-Based Float Hanger

- Exploit ice drift to distribute floats, release on command.
- Floats suspended from ice, attached via burn wire.
- Network controller listens for release signal (currently from independent, drifting 900 Hz acoustic source, but could transition to system integrated into Hanger).
- Float released on command to begin profiling mission.
- Design aims for simplicity, low cost.

Arctic Argo Pilot – Tech Development

Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Dan Rudnick, Jeff Sherman (SIO), Lee Freitag (WHOI)



SOLO-II Hardware changes

- Integrate 9523 modem for higher rate telemetry of backlog
- Hardened antenna
- Ice avoidance mast
- Hydrophone port

SOLO-II Software changes

- Interface with acoustic controller
- Backlog handling
- Integrate acoustic payload and configuration into telemetry stream

Electronics to support acoustic navigation (broad applicability)

- New low-power acoustic navigation receiver: 50 mW vs current 500 mW
- New low-power RTC (10-50 ppb) for navigation: 0.1 mW vs current 5 mW
- Modular acoustic controller isolates most mission specific software functionality

Arctic Argo Pilot – Operations

Craig Lee, Jason Gobat, Luc Rainville (APL-UW), Dan Rudnick, Jeff Sherman (SIO), Lee Freitag (WHOI)

Acoustic Geopositioning in the Beaufort Sea

ONR Arctic Mobile Observing System (AMOS-INP)

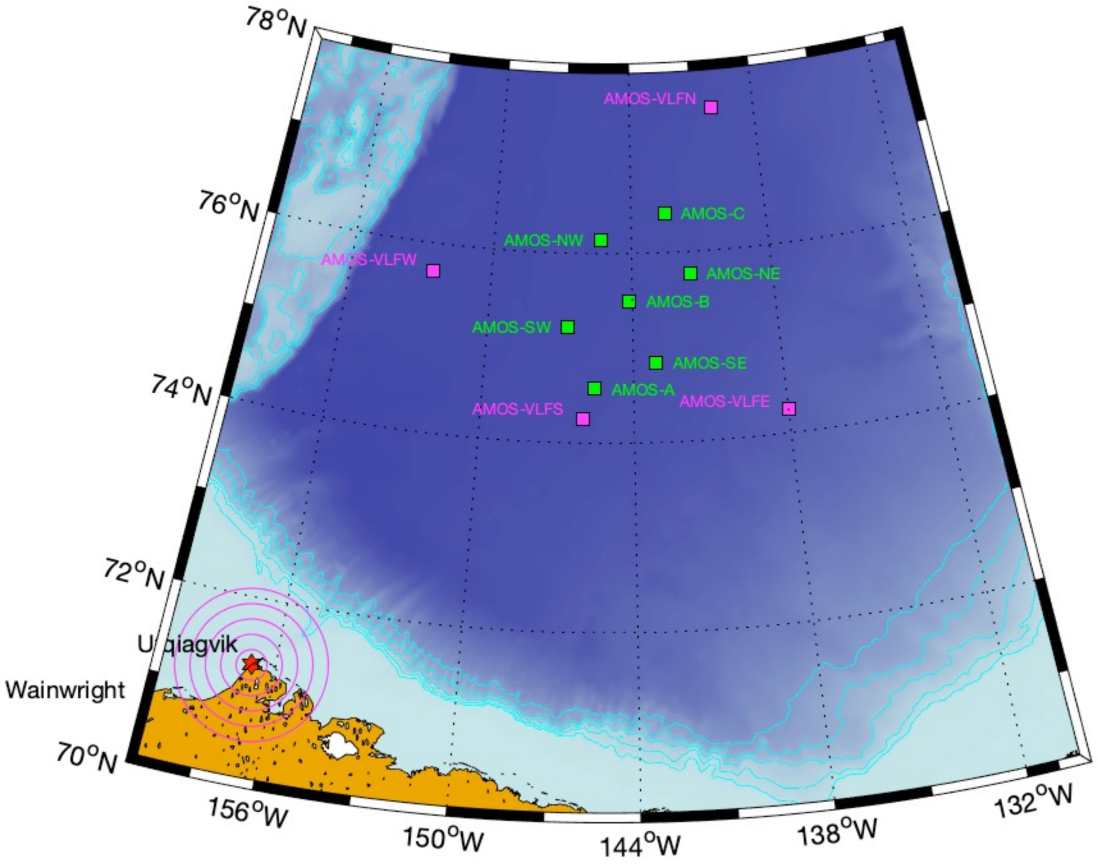
- 7-element 900 Hz array (2018-2025)
- 2-element 35 Hz array (2023-2025)

SOLO-II Pilot Deployments

- Fabricate 30 SOLO-II floats (10 per year beginning in 2022).
- Local testing in year 1.
- Arctic deployments begin in autumn 2023 (coincident with deployment VLF array).
- Data will flow to Argo DAC.

Logistics

- AMOS-INP cruises and/or ice camps.
- Collaboration with other Beaufort Sea programs.



Float Position Error and Reporting Interval Estimated using ASTE

Nguyen et al (2020)

Questions:

How far would floats drift?

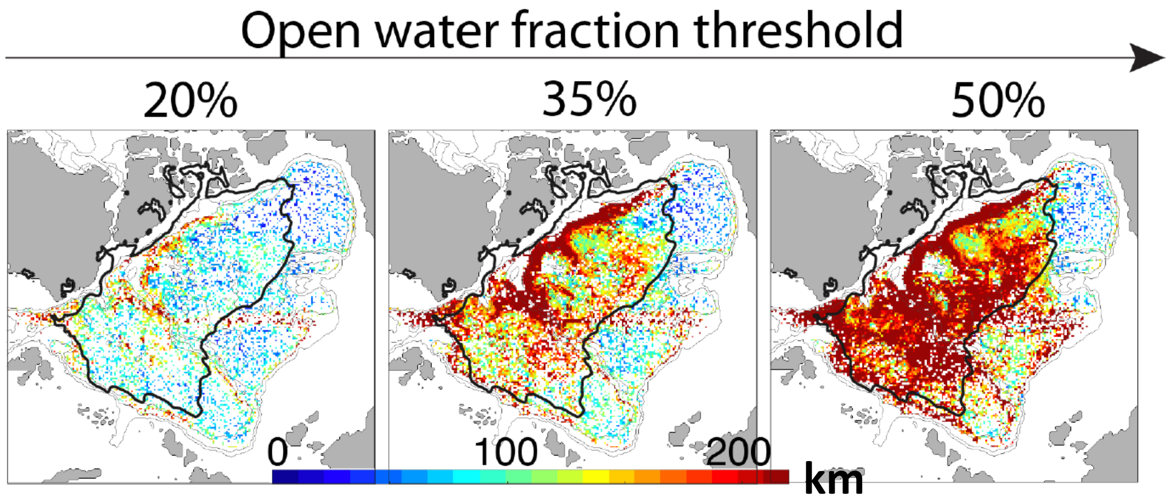
What would the resulting errors be in estimated profile positions between surfacings?

How often would floats surface (and thus exfiltrate data)?

Would the resulting data, with position errors, be useful for improving the state estimate?

Ability to surface in partial ice cover valuable.

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



Large uncertainties:

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

- 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.

Time Between Surfacing