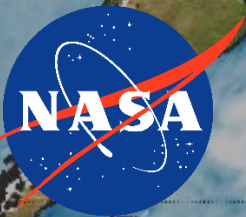


Aquarius, SMAP, and the Ocean's Water Cycle: What Salinity Told Us and Where It Took Us

Julian J Schanze¹,
The SPURS-1&2, SASSIE, & FRESH Teams, and the Salinity Community

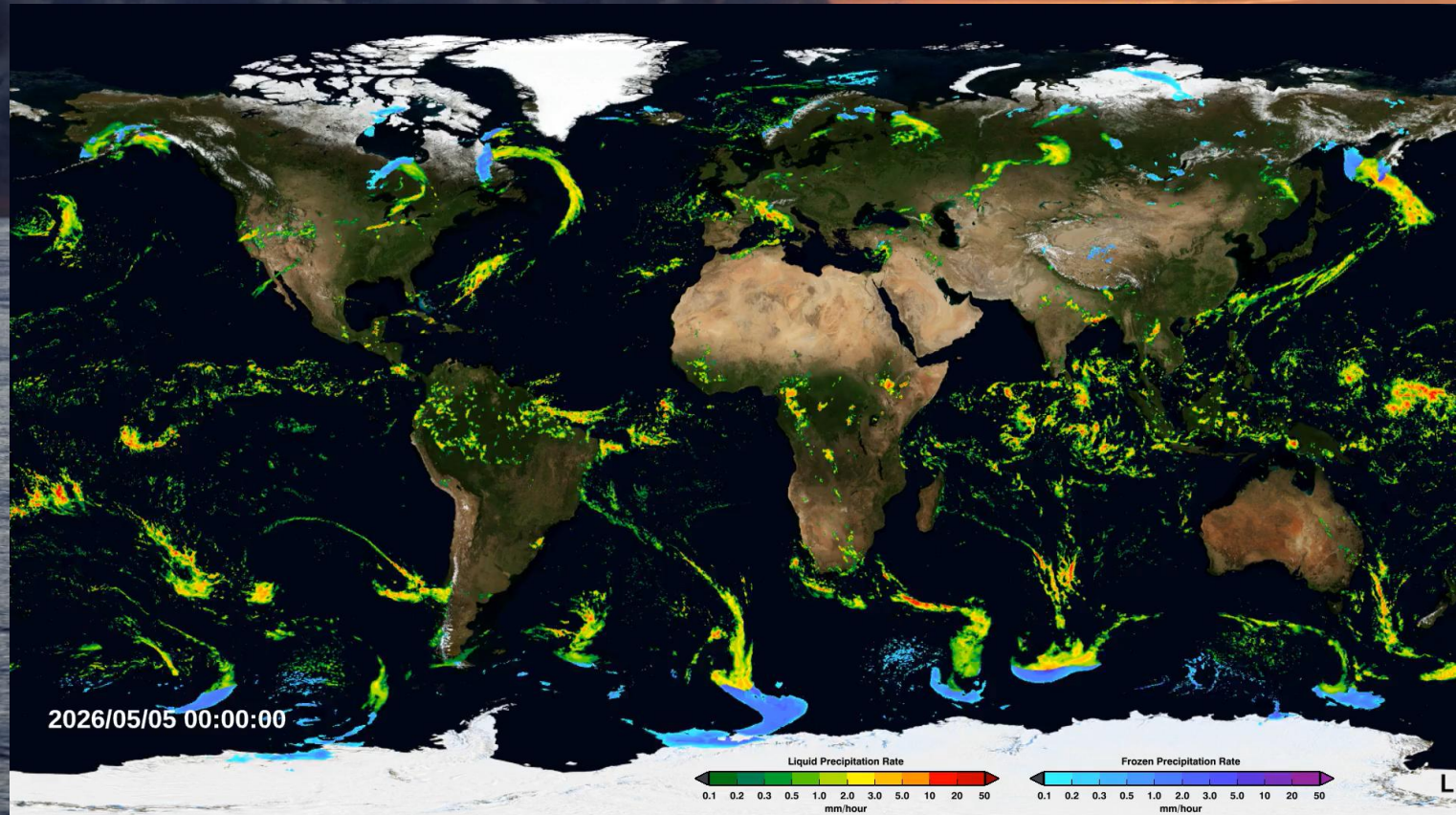
¹ Earth & Space Research

NASA Hydrosphere Science Team Meeting, Washington DC, 1 September 2026



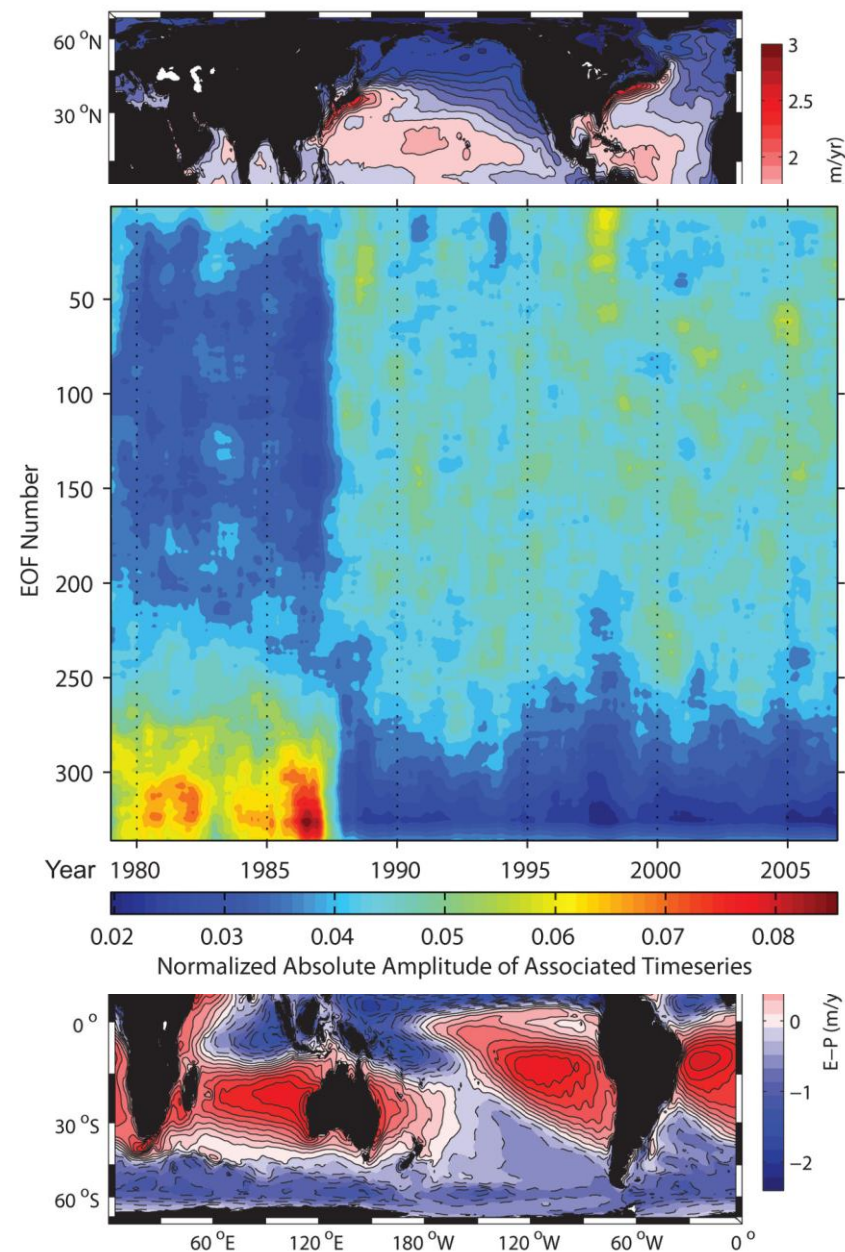
Measurement Challenges

Evaporation and Precipitation do not occur on the same space- or time-scales. They are also difficult to measure over the ocean.



A Rain Gauge Covering 70% of the Planet

- The Ocean is an integrator of E-P-R
- 86% of global evaporation and 78% of global precipitation happen over the ocean
- Flux products are a product of their observing systems.
- Both Aquarius/SAC-D (2011) and ESA's SMOS (2009) were proposed (partially) as the response to that



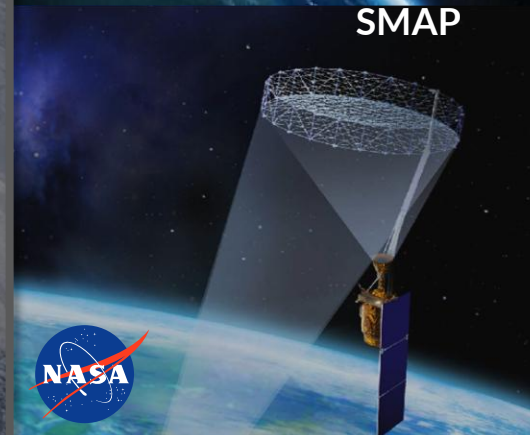
Aquarius Art: NASA.

Figure: Schanze, Schmitt & Yu (2010), J. Mar. Res. 68(3-4), 569-595, Fig. 4.



The Advent of the Satellite SSS Era

- Skylab demonstrated L-Band sensitivity to salinity in 1973
- It took 36 years of aircraft campaigns and dielectric measurements until SMOS was launched in 2009
- Aquarius/SAC-D launched in 2011 as the first dedicated salinity mission
- SMAP has been continuing its legacy since 2015.

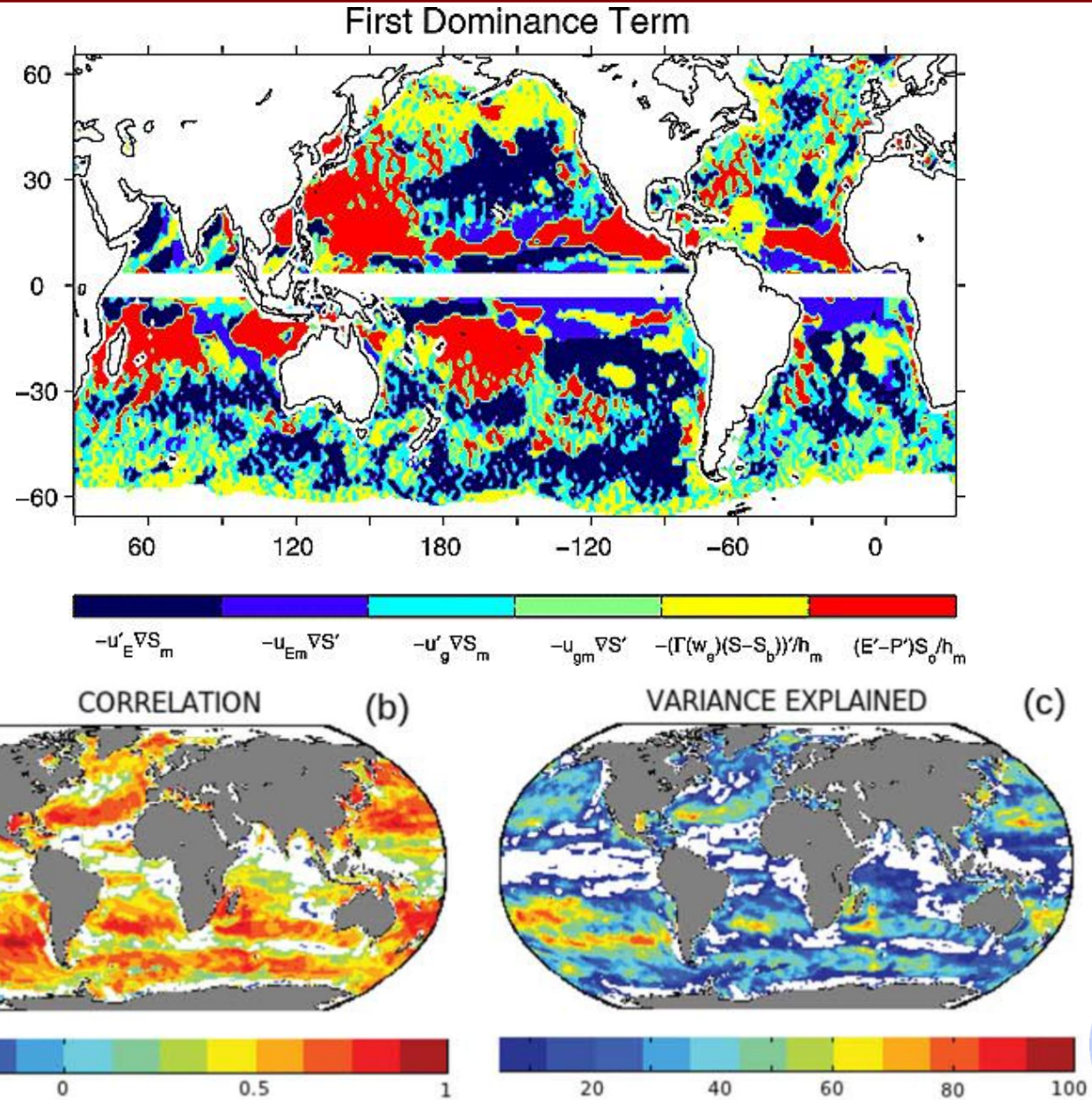


Testing the Ocean Rain Gauge

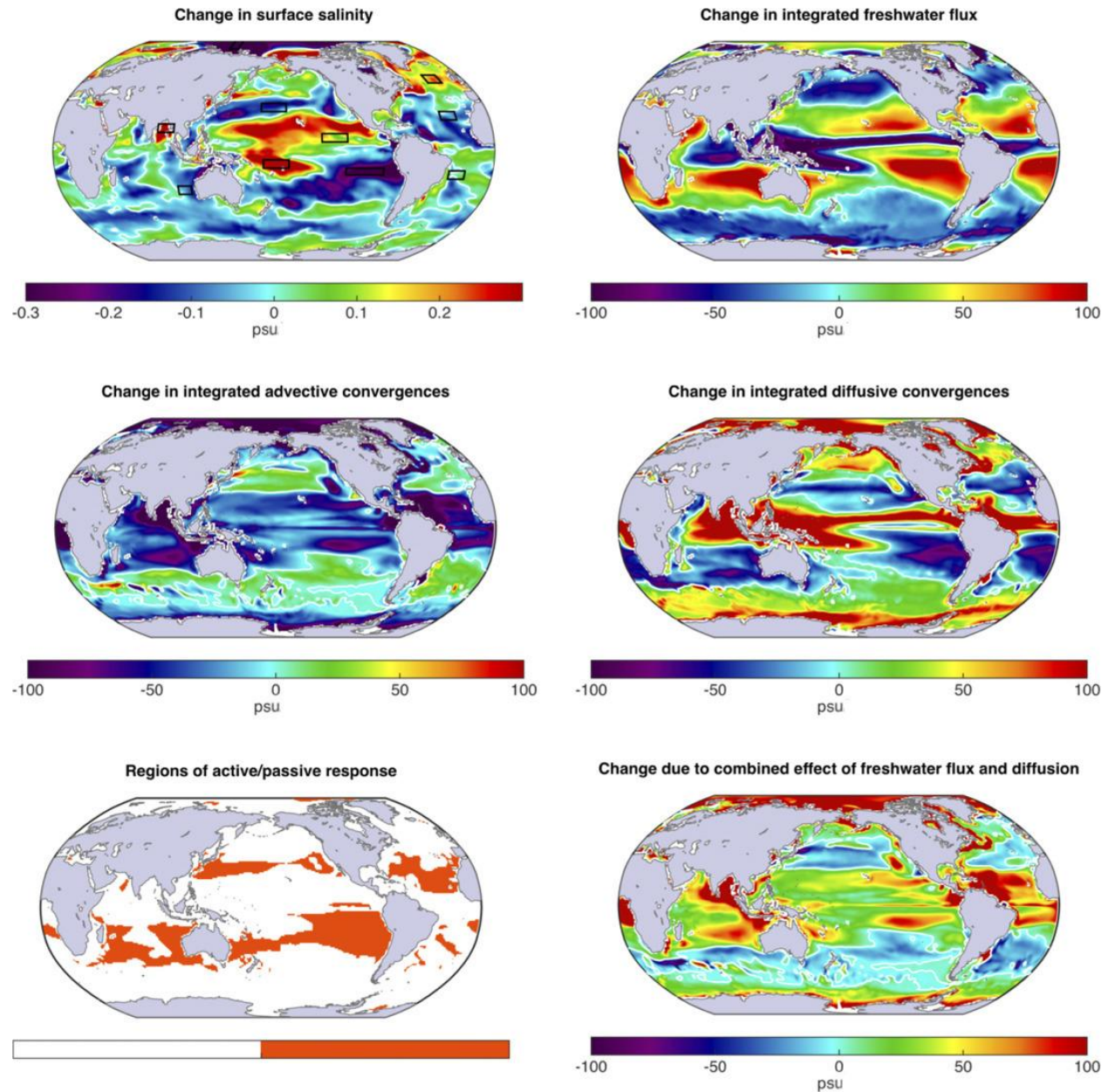
- Can SSS give an indirect estimate of freshwater flux?
- It depends.
- Two independent approaches come to the same conclusion: the mapping of freshwater flux to SSS is set by ocean dynamics, and it varies by region.

Top:
Yu, L. (2011), J. Geophys. Res. 116, C10025,
doi:10.1029/2010JC006937

Bottom:
Vinogradova, N. T., & Ponte, R. M. (2013), J. Geophys.
Res. Oceans 118, 3190–3201, doi:10.1002/jgrc.20200



Ocean Dynamics Is First-Order Almost Everywhere



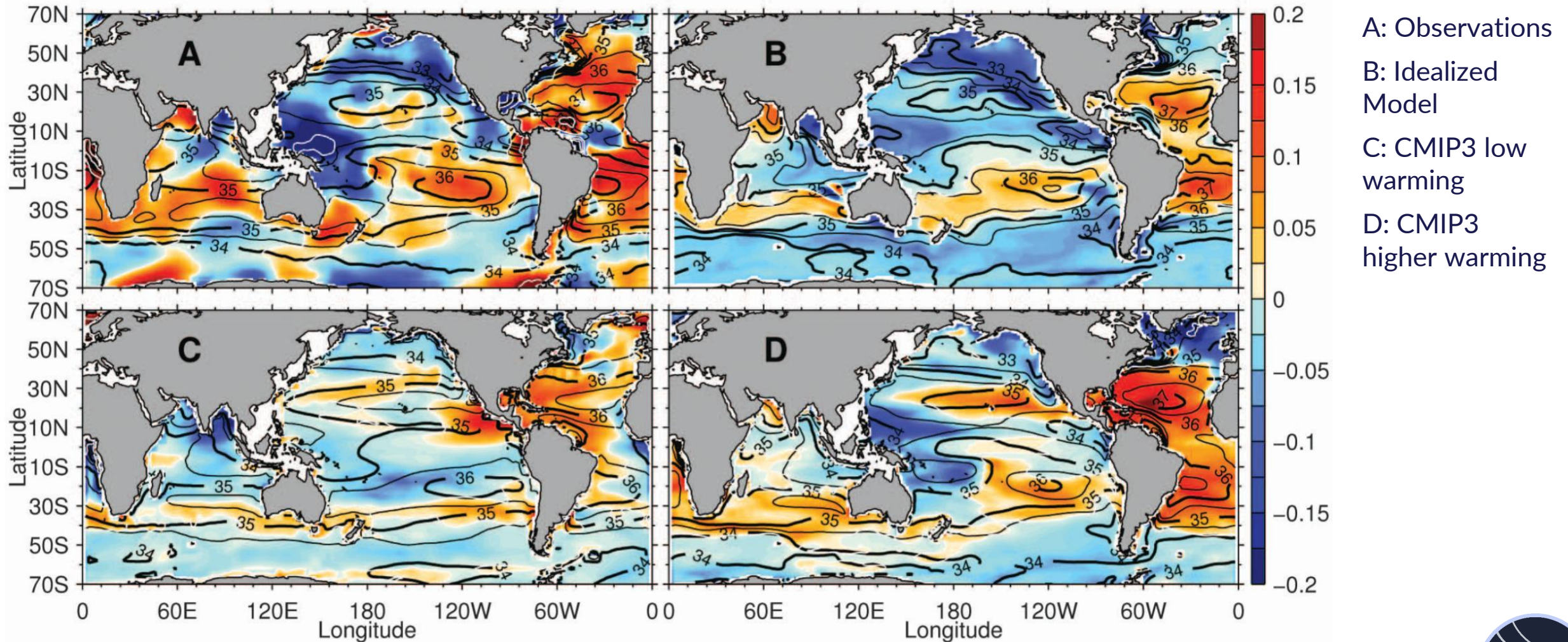
ECCO, closed budgets, 1993–2010, top ten metres

- Diffusion works against the surface forcing
- Surface estimations agree with Clausius–Clapeyron, $\sim 7\% \text{ } ^\circ\text{C}^{-1}$
- Advection matters almost everywhere: advection–diffusion in the Bay of Bengal and Arctic (a bad rain gauge); advection–forcing in the tropical Atlantic and Pacific (somewhat better)
- Ocean dynamics sets the transfer function

Ponte & Vinogradova (2016), GRL 43, 7052–7058,
doi:10.1002/2016GL069857



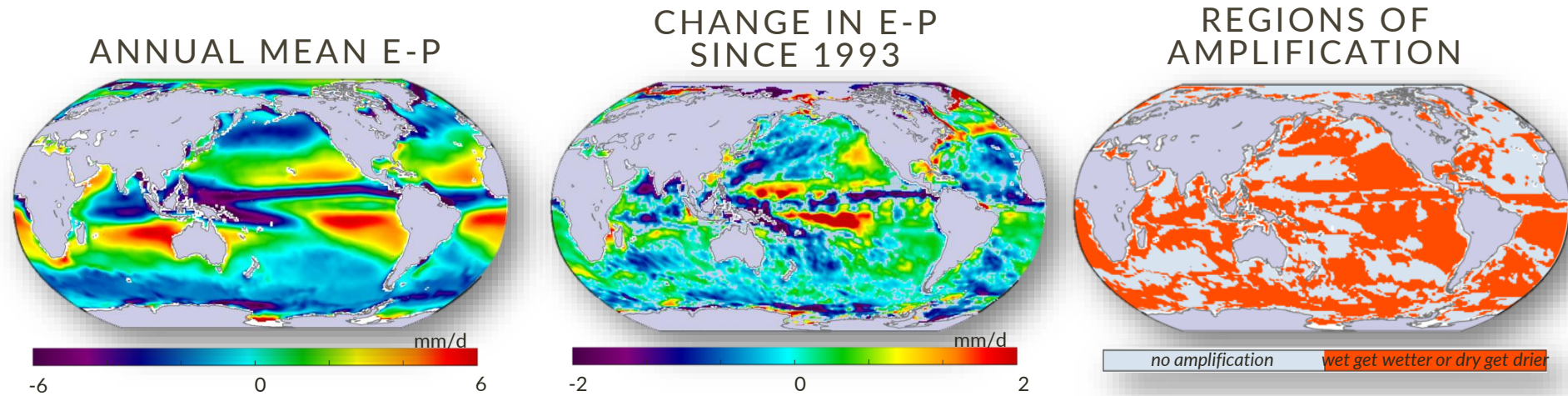
Water Cycle Intensification



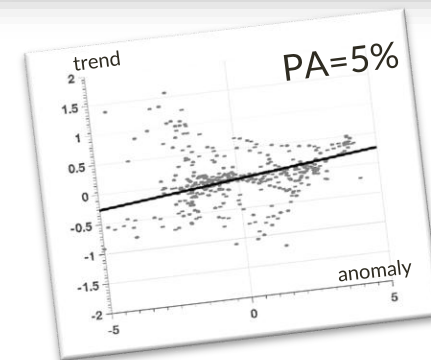
Durack, Wijffels & Matear (2012), *Science* **336**, 455–458, doi:10.1126/science.1212222



E-P Amplified by About 5%



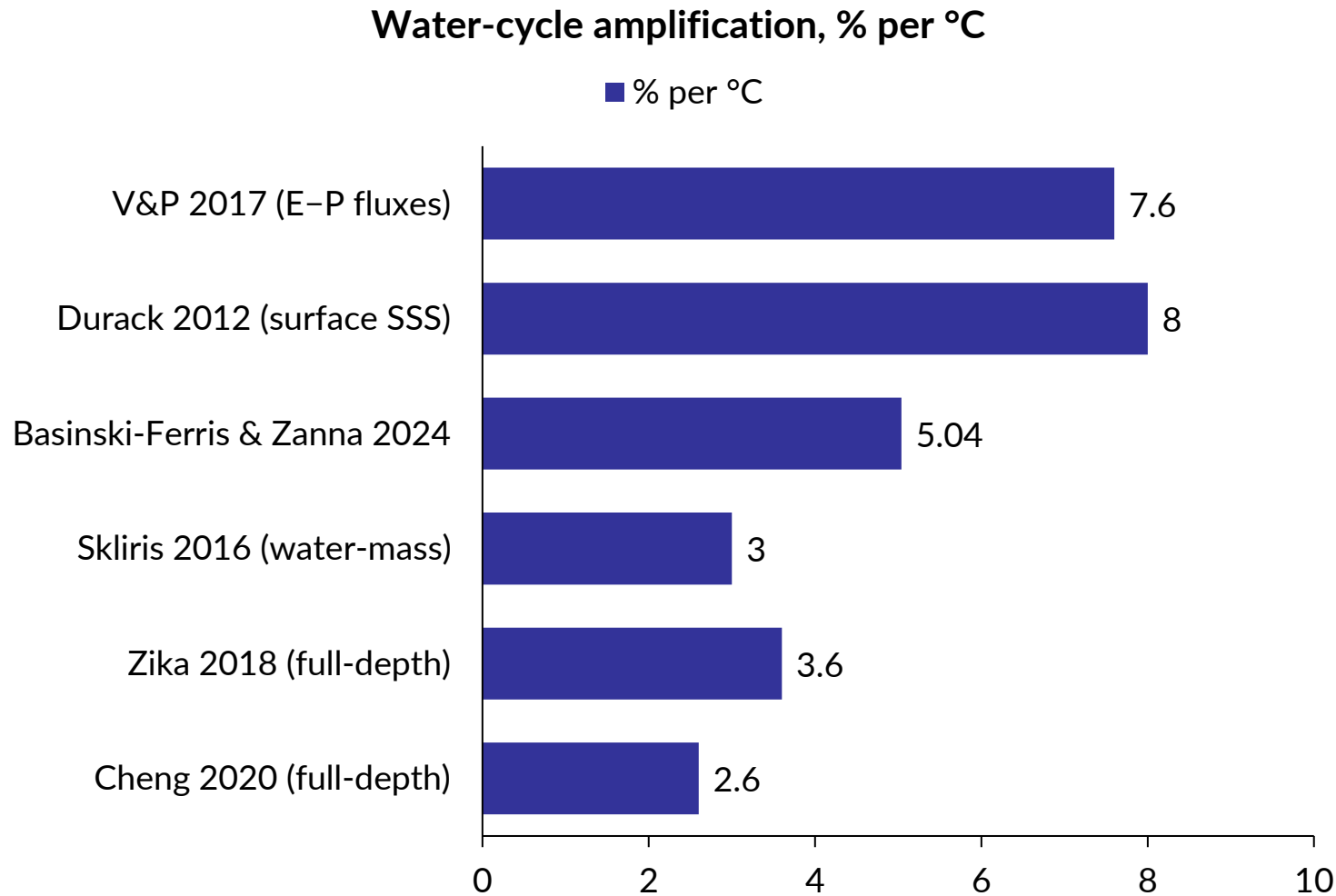
CONTEMPORARY CHANGES IN THE OCEANIC WATER CYCLE



Average amplification
~5%* – consistent with
Clausius-Clapeyron
equation

*Equivalent $7.6\% \text{ }^{\circ}\text{C}^{-1}$ and $0.65 \text{ }^{\circ}\text{C}$ change

Fluxes Say ~7.6% per Degree. Full-Depth Salinity Says ~3%.



- Estimates cluster by method
- Surface estimations agree with Clausius–Clapeyron, $\sim 7\% \text{ } ^\circ\text{C}^{-1}$
- Full-depth and water-mass methods land near half of it
- Zika 2018: about $\frac{1}{3}$ of the pattern amplification is ocean warming, $\frac{1}{6}$ ice-mass loss

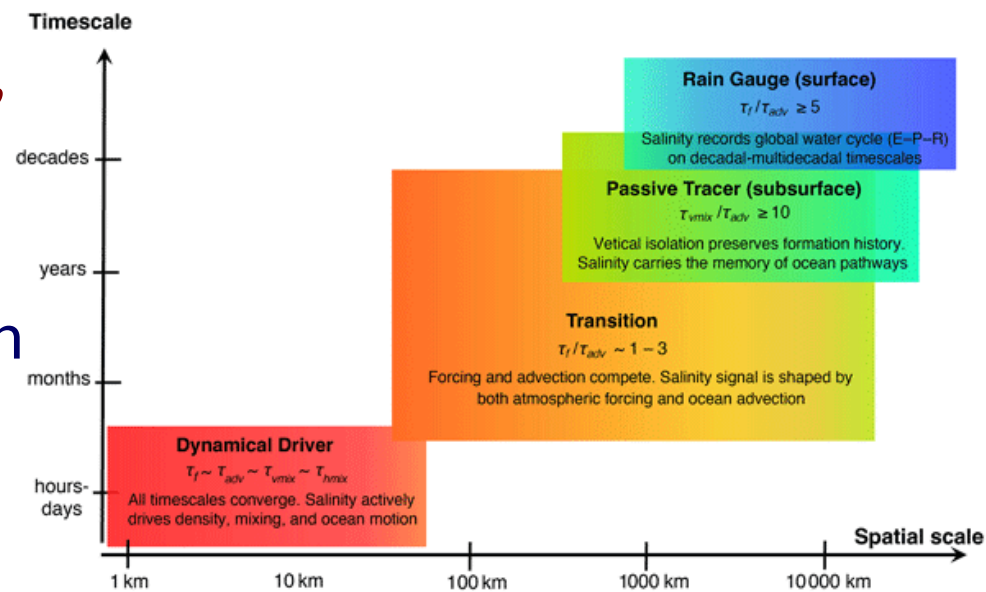
The Three Regimes of Salinity

Which regime you are in depends on the competition among forcing, advection and mixing timescales.

- **The basin scale: decades, forcing-dominated: a water-cycle indicator, the rain gauge**
- **Regional: 10–1000 km, seasonal to interannual, circulation-dominated: a pathway tracer**
- **O(10 km), hours to days, dynamically active: a driver that sharpens fronts and sets stratification**
- **Forcing dominates only about one third of the ocean seasonally**

You cannot characterise the transfer function in one place.

This motivated three very different process studies.

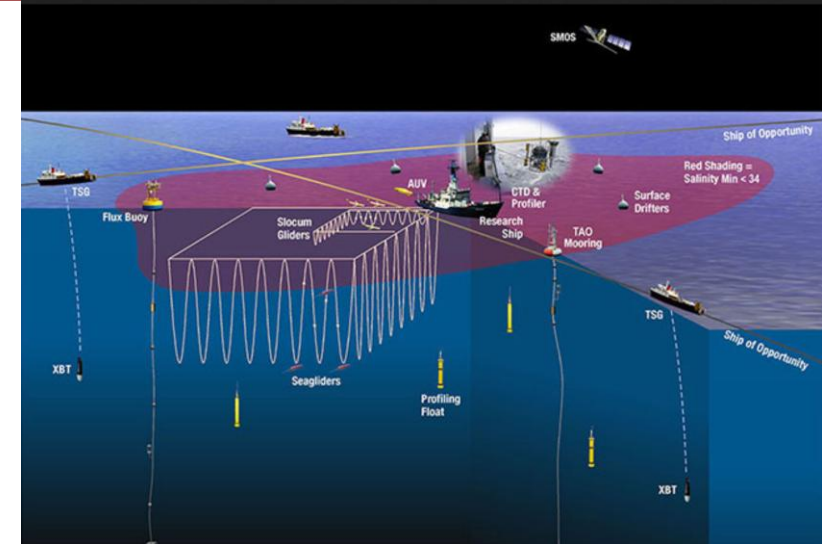
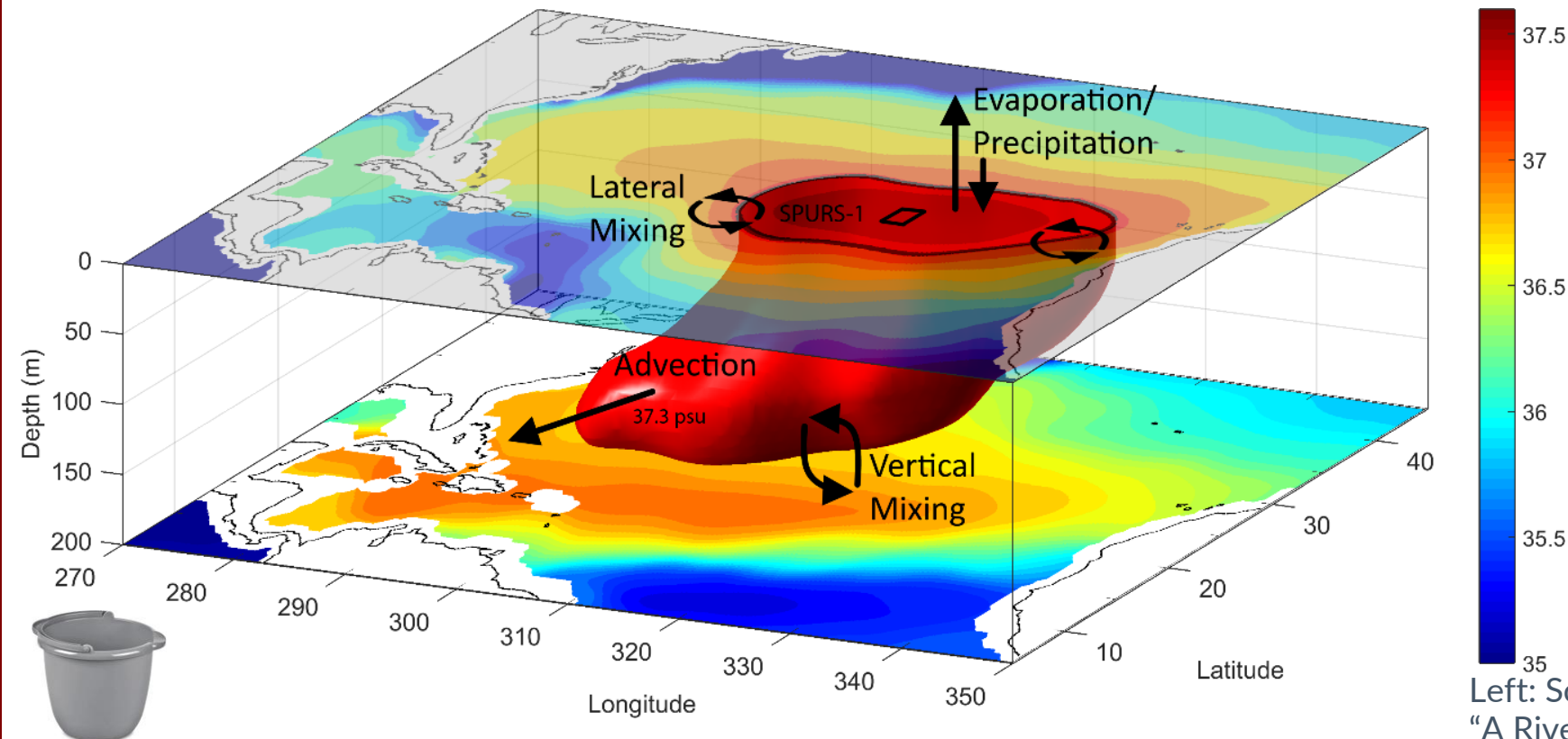


Yu, L. (2026), Ocean Science 22(3), 1651–1679. Open access.



SPURS – The Salty One

- Salinity Processes in the Upper Ocean Regional Study
- We went to the saltiest place in the (open) ocean we could find

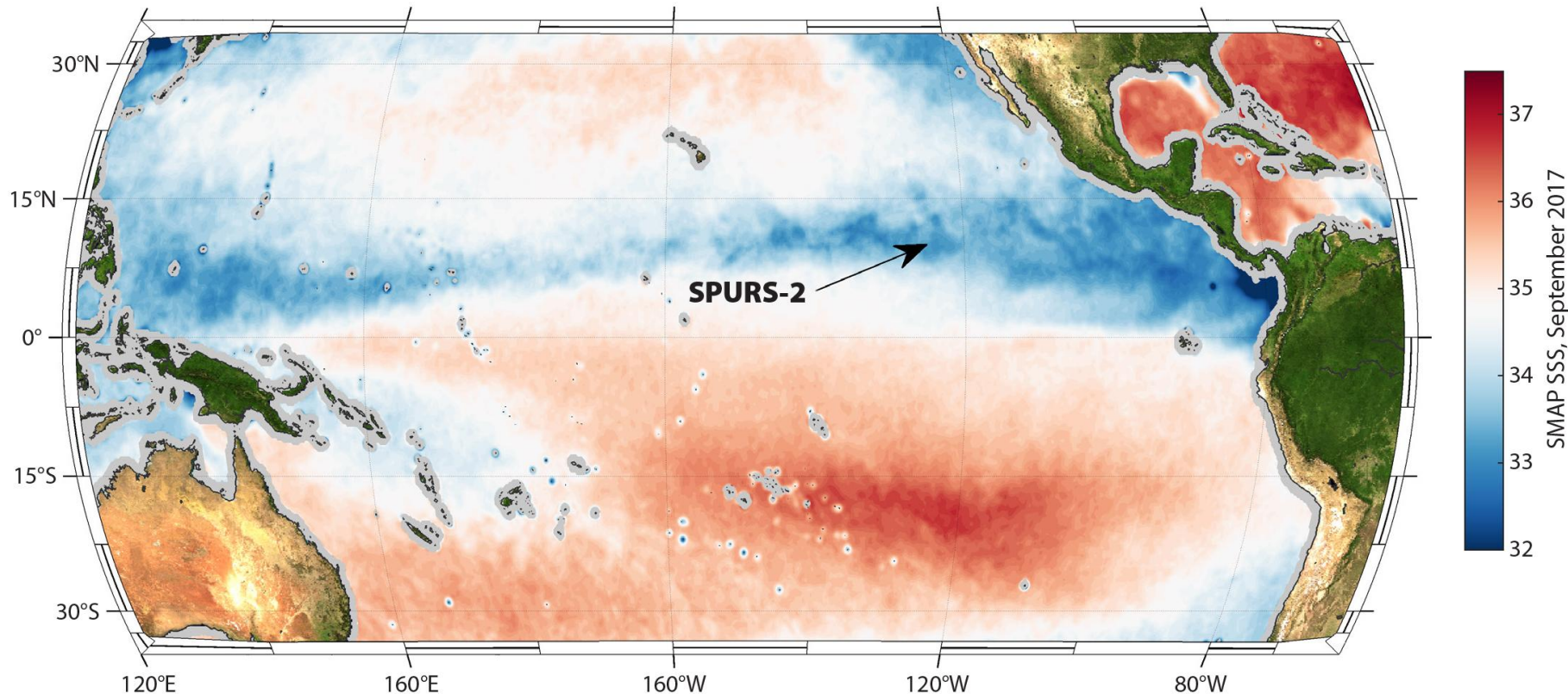


Left: Schmitt, R. W., & Blair, A. (2015), "A River of Salt," *Oceanography* 28(1), 40–45.



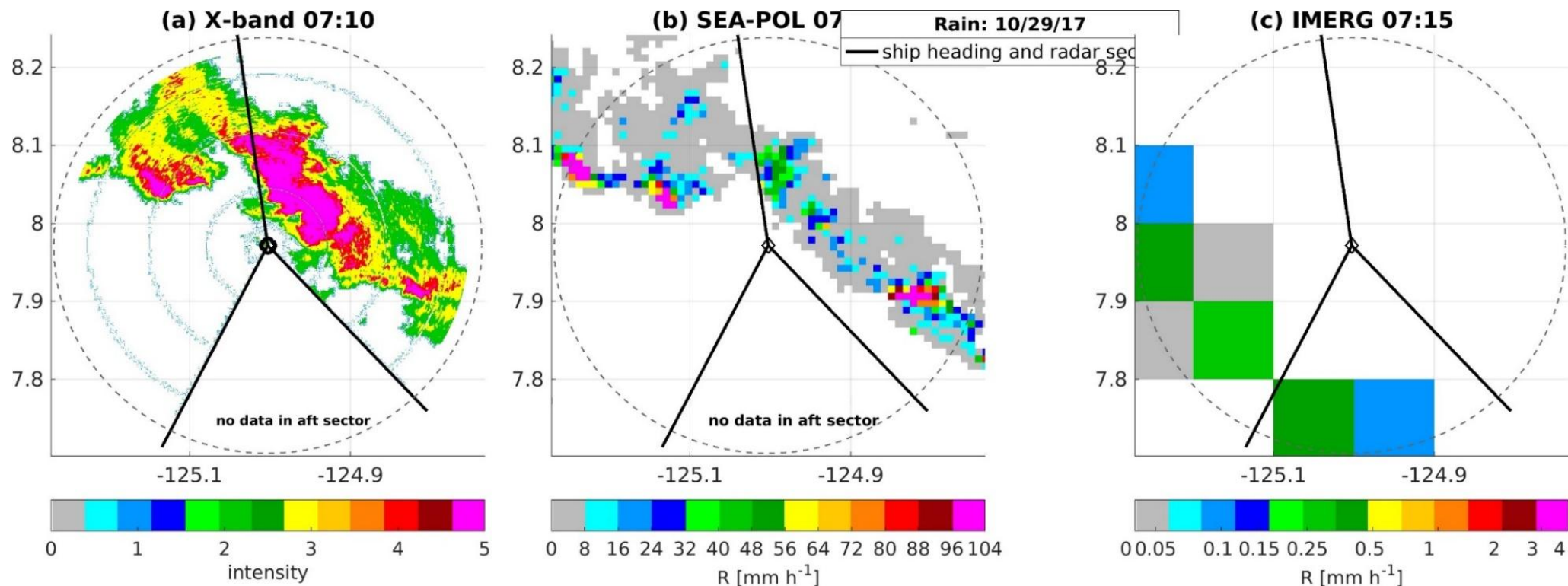
SPURS-2 – The Rainy One

- SPURS had kicked off a quest to understand sub-footprint variability
- SPURS-2 was the ideal place to understand how rain gets integrated into the ocean and to quantify freshwater lenses.

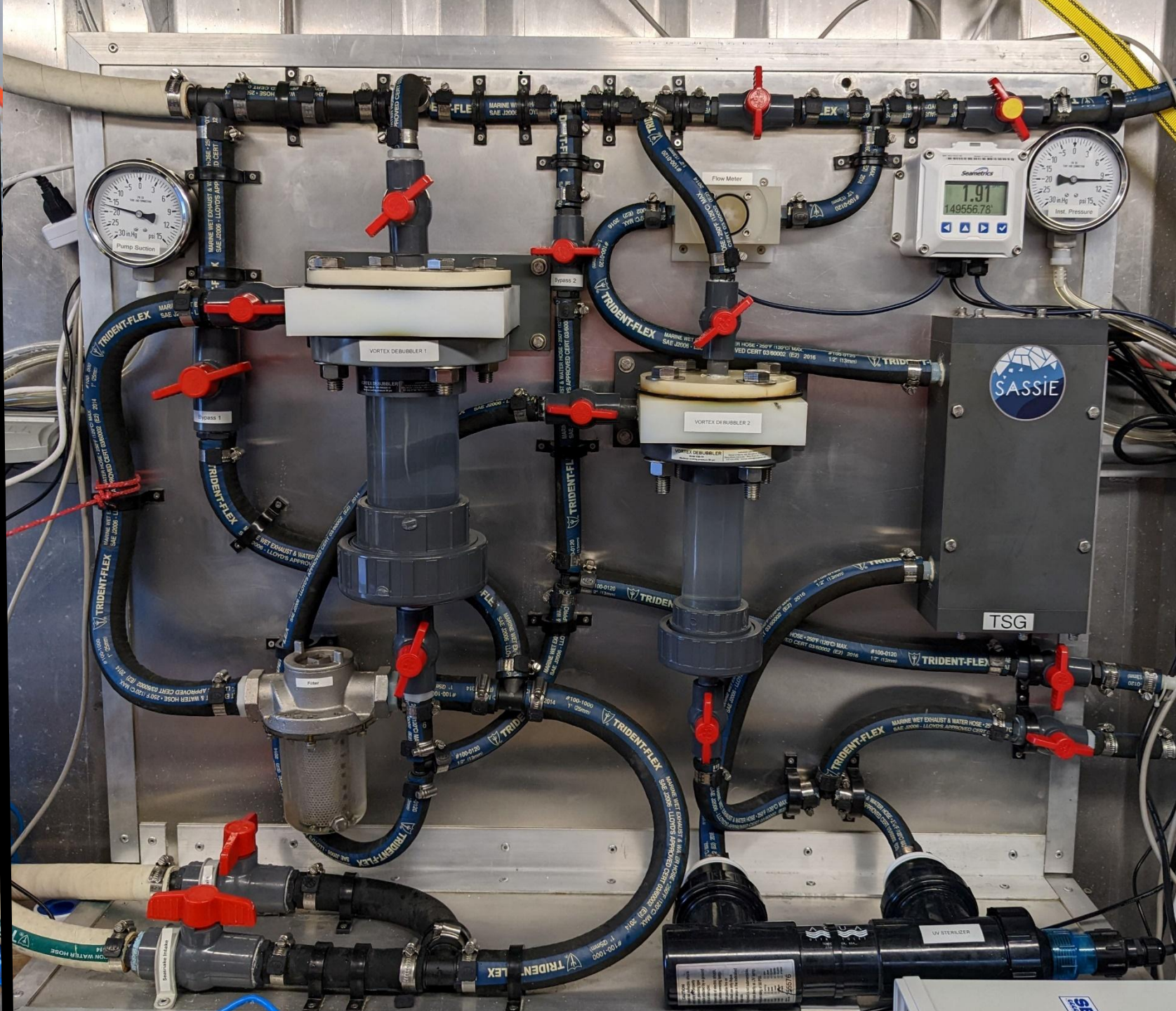
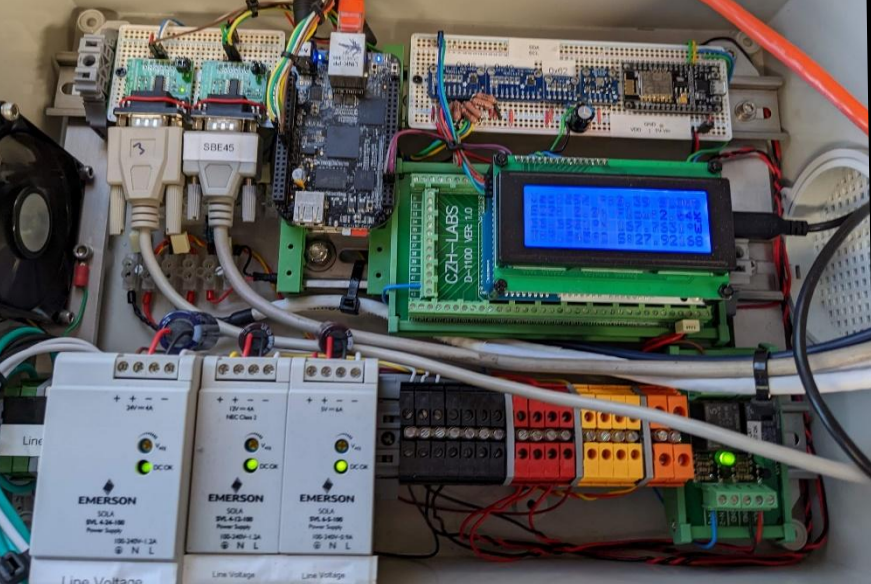


“SPURS Come in Pairs” – EJL

Precipitation

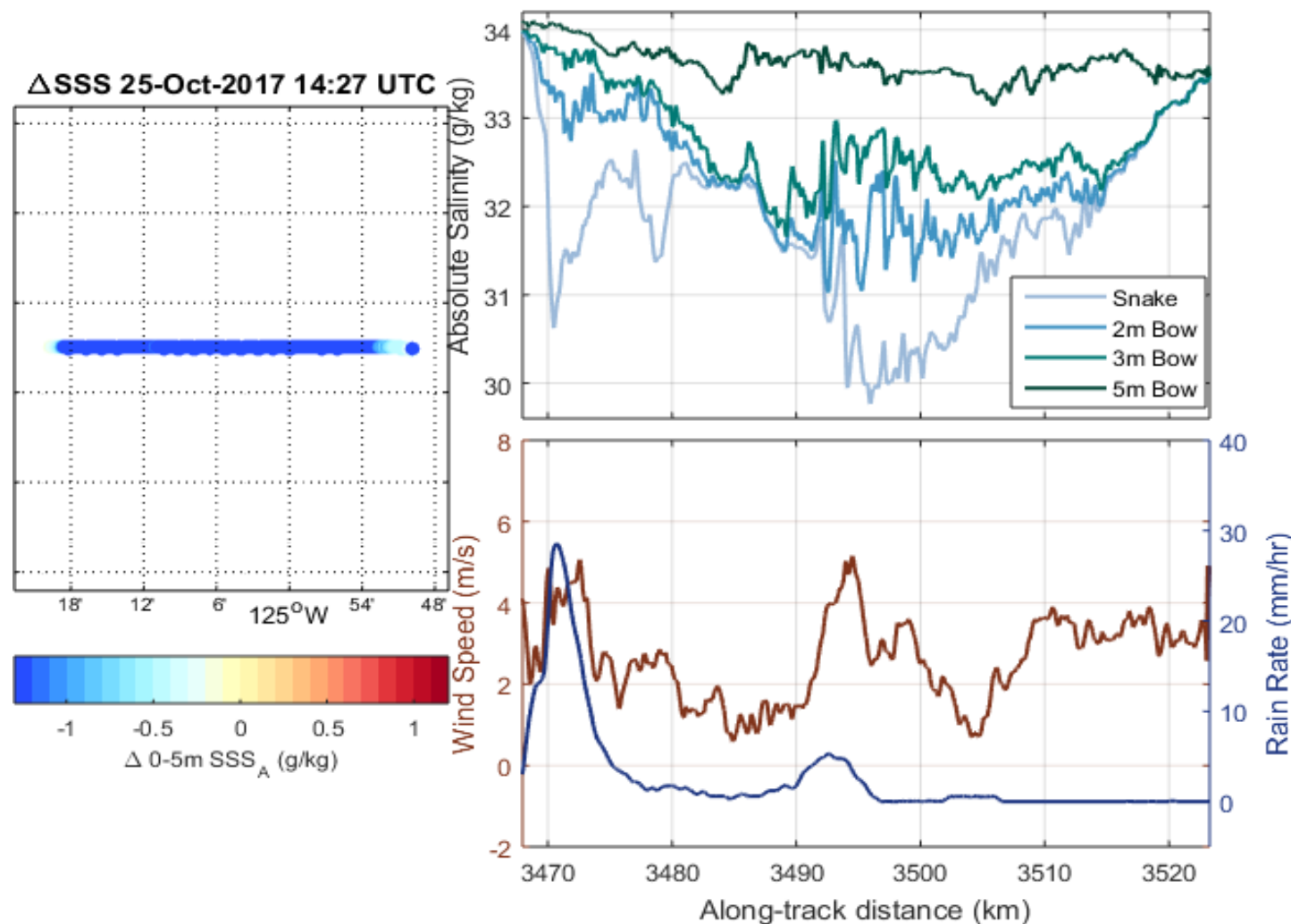


- Evaporation is much smoother than precipitation
- Huge density variance input at different space- and time-scales
- No air-sea feedback like temperature: These features are stable without mixing
- Scales as small as hundreds of meters





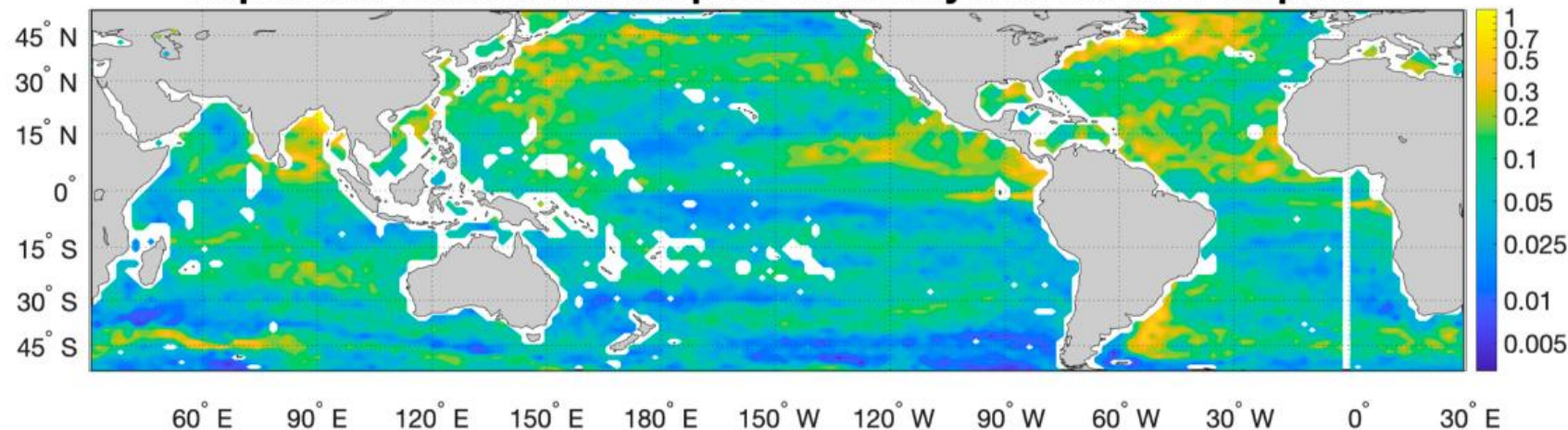
Sub-footprint Variability



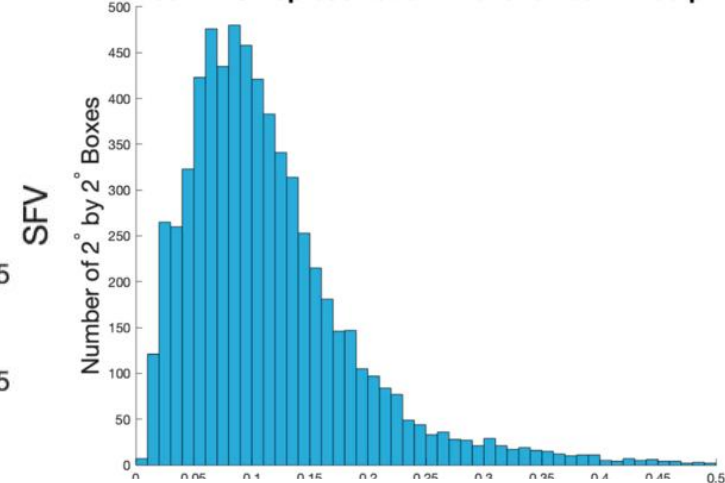
- Freshwater lenses can occur at scales far below the footprint
- A matchup against a single in situ measurement conflates three things:
- Satellite error, in situ error, and two different volumes of water
- RMSD, not RMSE.

Salinity Snake vs. 2/3/5 m bow intakes, SPURS-2, 25 October 2017 — a 50 km feature with <4 g/kg peak freshening.

September Median Subfootprint Variability at a 100 km Footprint



Annual RMS Representation Error at a 100km Footprint



- Bingham et al. (2021) – global high-resolution model
- Significant representation error contribution
- Triple collocation (J. Anderson, ESR) shows very low errors in L2 and continuous improvements.

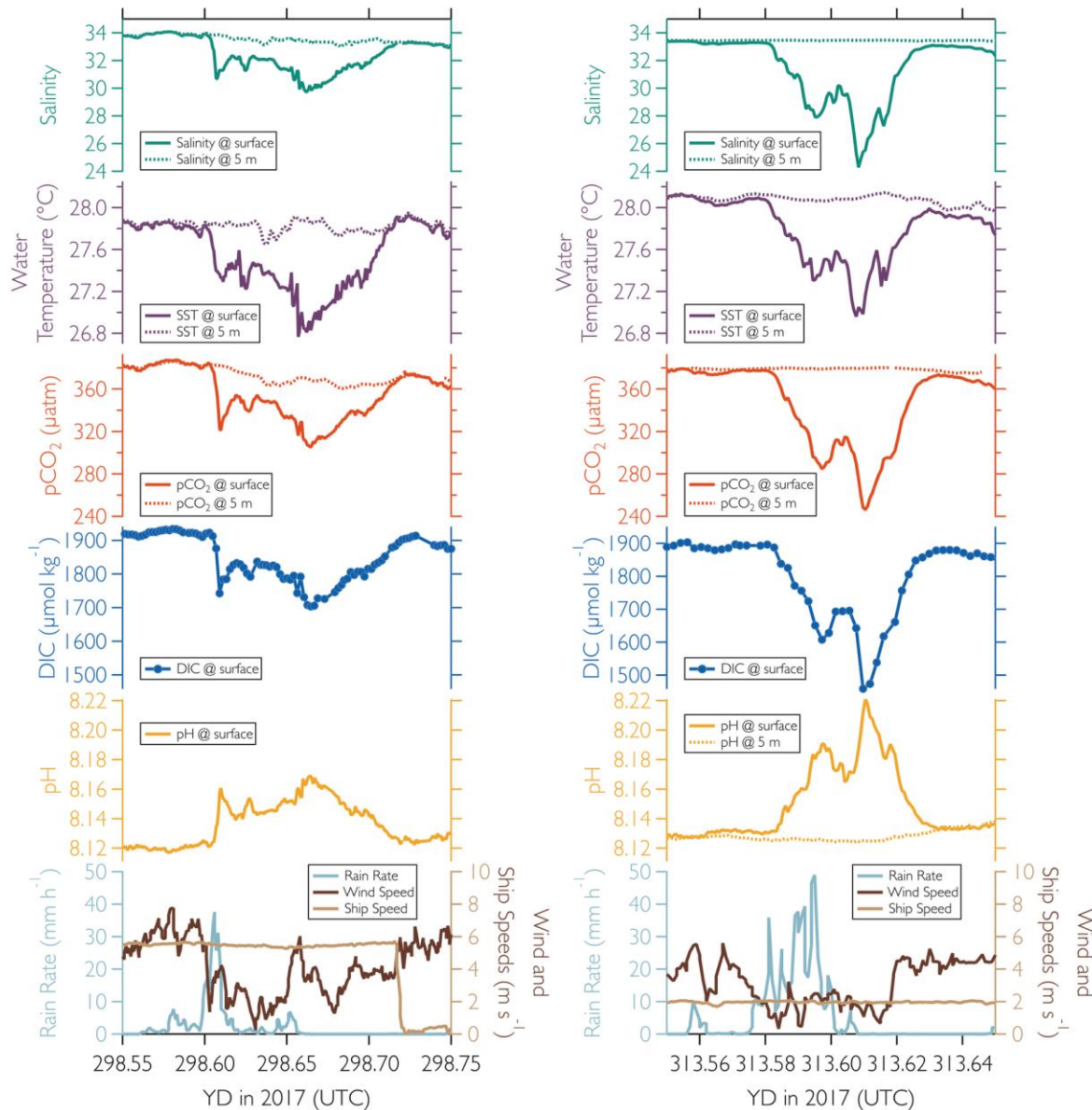
Minimal Flags

	SMAP	SMOS	EN4
v5.0	0.090	0.294	0.065
v6.0	0.110	0.350	0.075
v6.3	0.078	0.242	0.050

All Flags

	SMAP	SMOS	EN4
v5.0	0.053	0.160	0.043
v6.0	0.049	0.147	0.038
v6.3	0.049	0.142	0.035

Rain Lowers Surface $p\text{CO}_2$ — and Ships Miss It



- Carbon Chemistry during SPURS-2: $p\text{CO}_2$, DIC and pH at 2–3 cm and 5 m simultaneously
- Eight freshwater features; the two largest dropped $p\text{CO}_2$ by 84 and 135 μatm
- 88% and 93% of that was dilution, not temperature
- Global $p\text{CO}_2$ maps are built from 5 m shipboard data, so ocean CO_2 uptake may be systematically underestimated

Ho & Schanze (2020), GRL 47, e2020GL088252, Fig. 1 — the 52 km puddle.



SASSIE – The Icy One

Very low salinity lets colder water float above warmer water

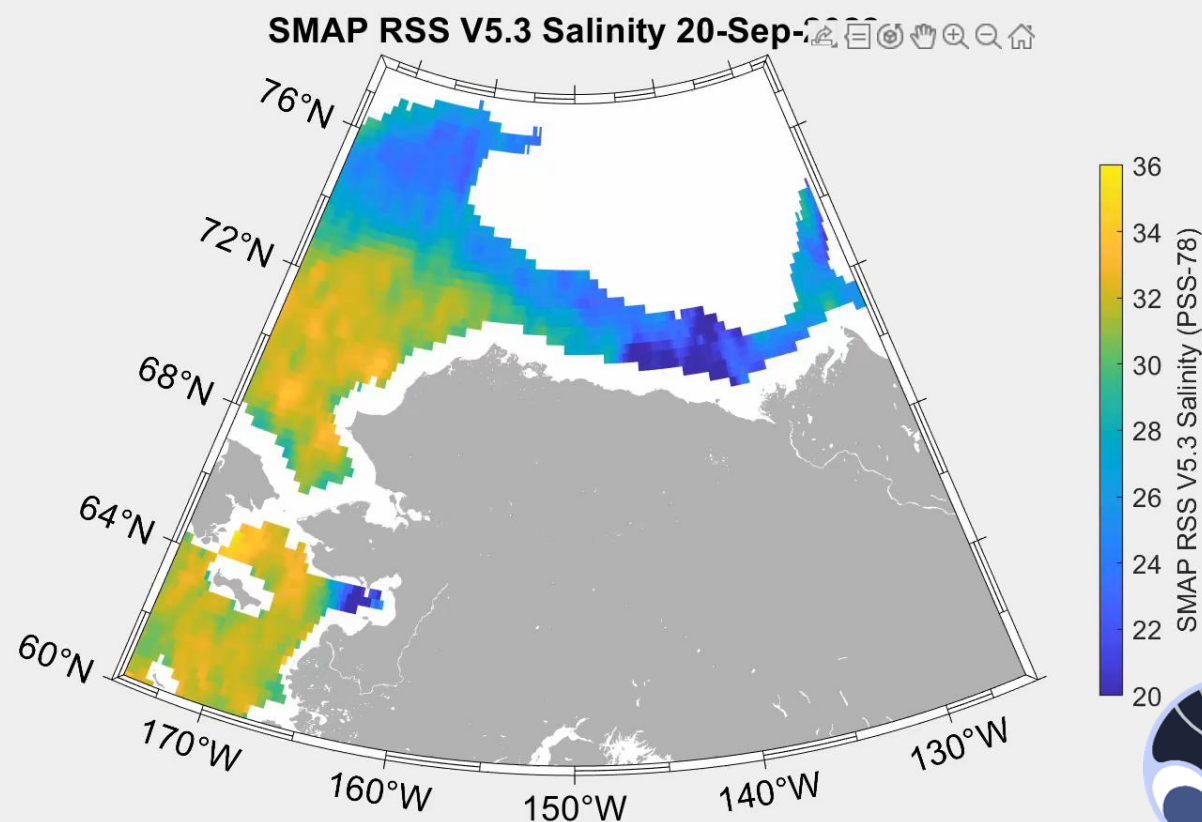


Wind disrupts ocean layering, warming the surface & melting ice

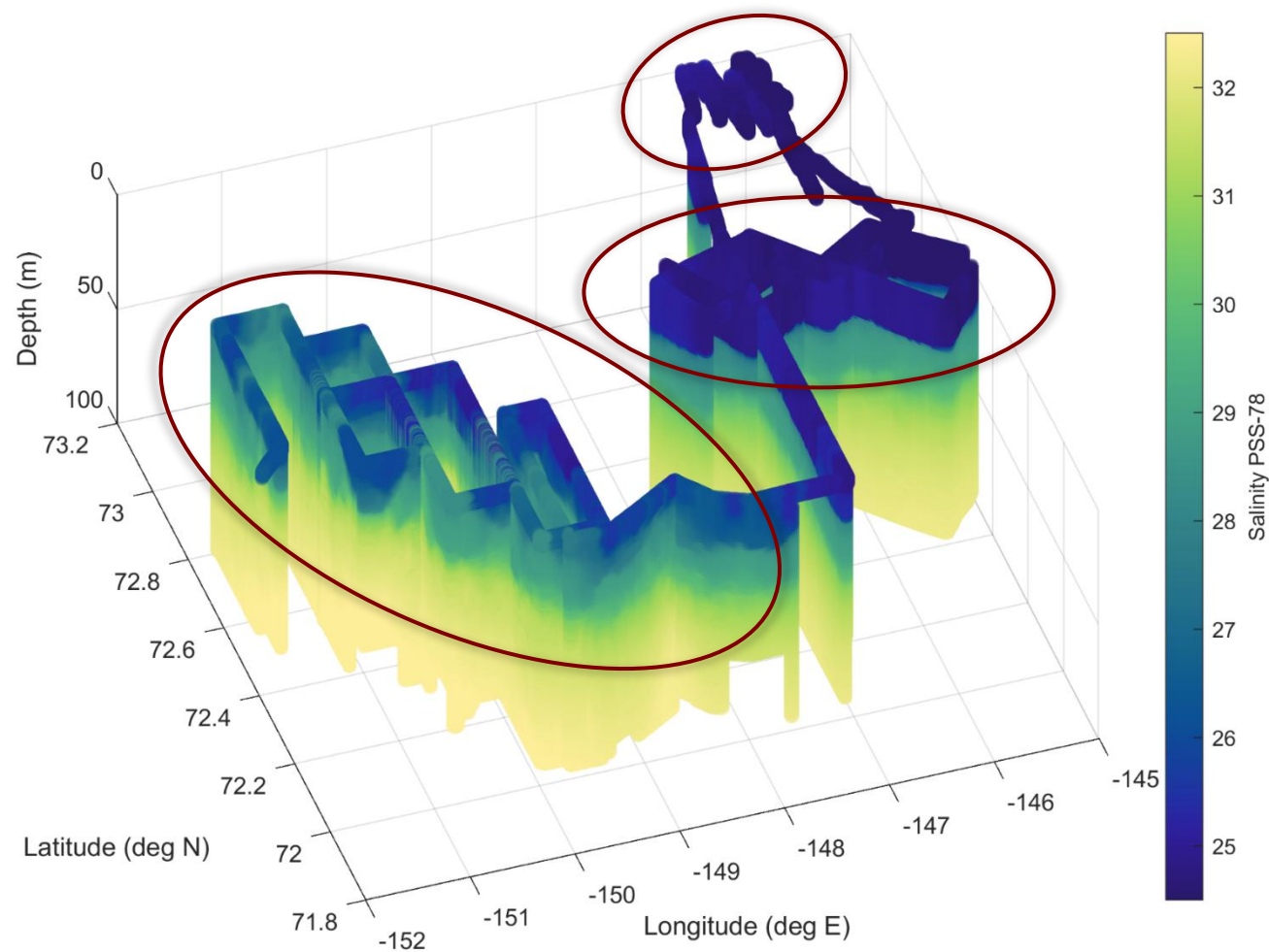


Ocean surface freshens, salinity controls seawater layering & sea ice forms

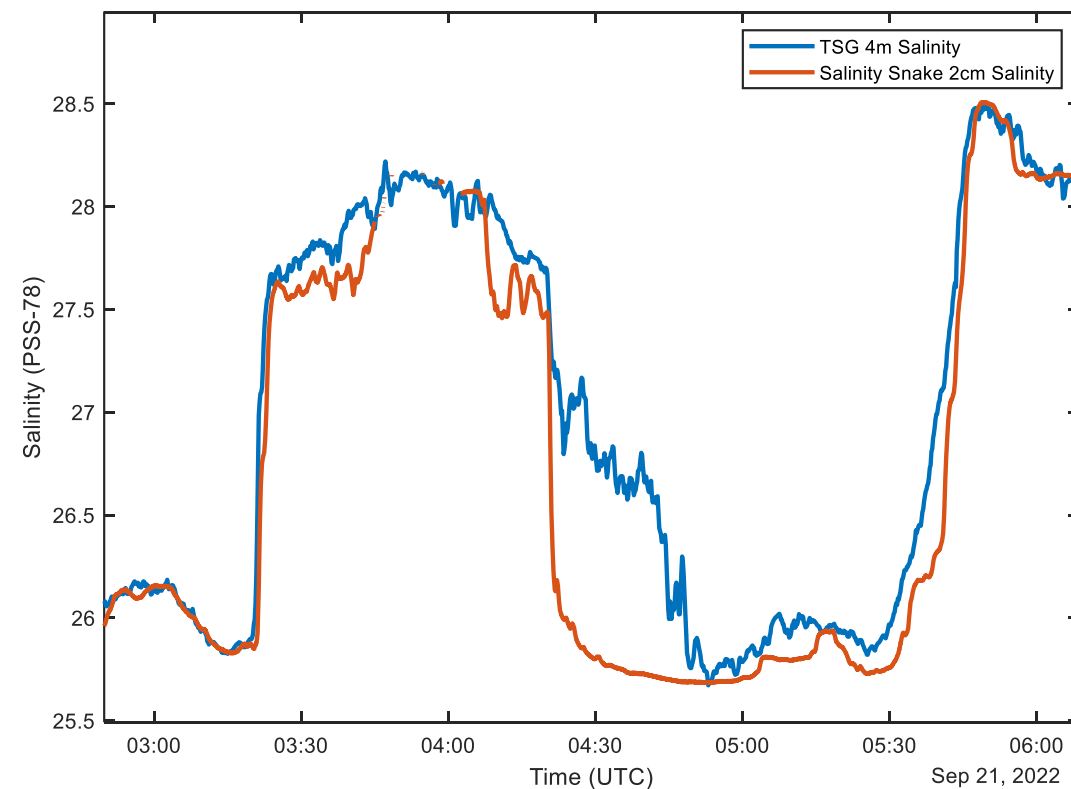
- Salinity and Stratification at the Sea Ice Edge
- Extreme gradients
- Understand the role of SSS in the formation of sea ice
- Understand the persistence of fresh layers



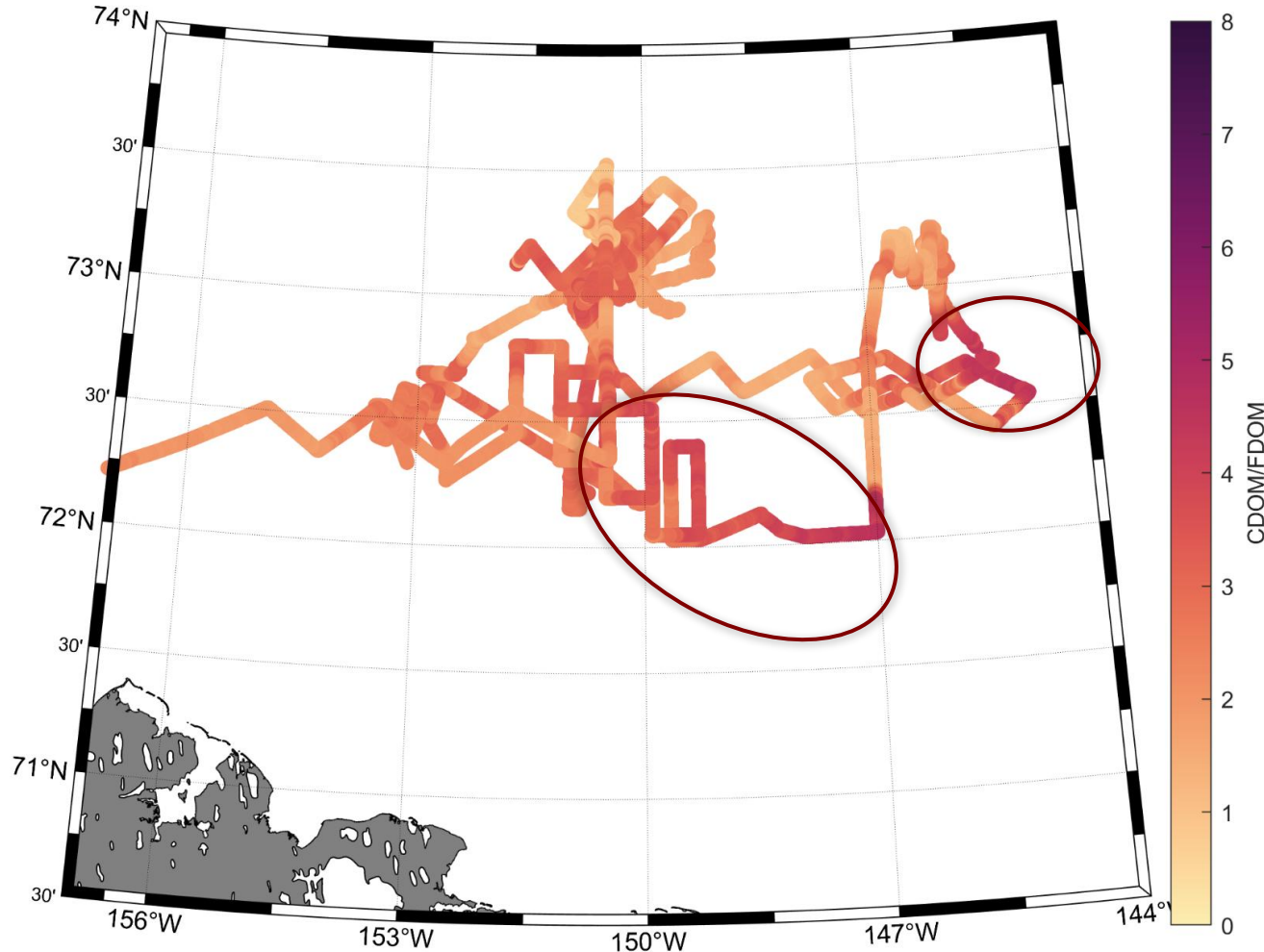
Haline Structure – Barrier for Freeze-Up



- Very low salinities in the MIZ
- Riverine plumes clearly visible
- High variability in the western part
- Still strongly stratified to 20–30 m.



Coming Soon: FRESH – The Arctic River One



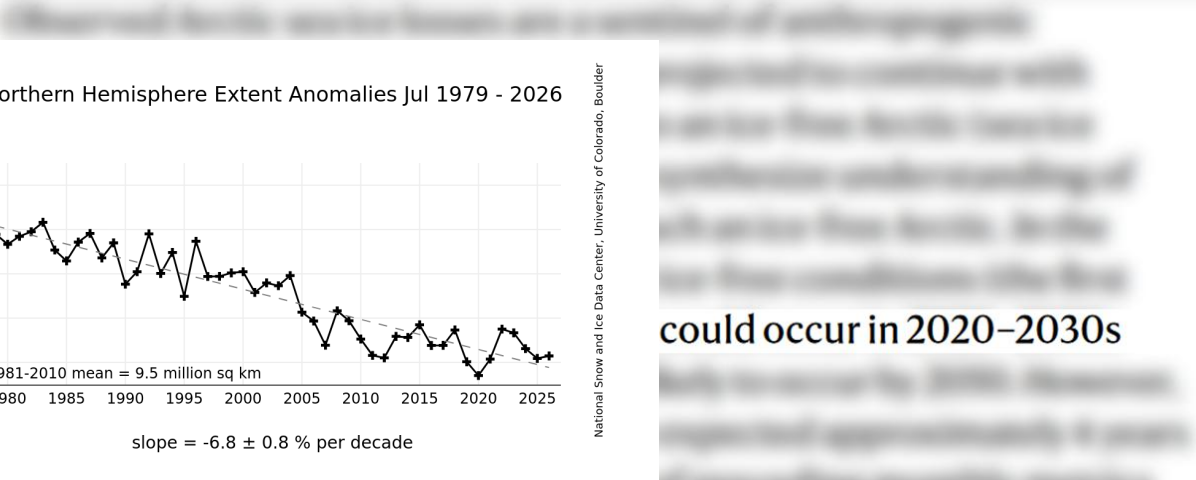
- Mackenzie filaments/plumes visible
- Both Ice Melt and River plumes are fresh.
- They are also both seasonal and increasing.
- Salinity alone cannot separate them
- This partly motivated the upcoming Fate of River Export and Surface Hydrology (FRESH) field campaign (tomorrow)

Review article

Projections of an ice-free Arctic Ocean

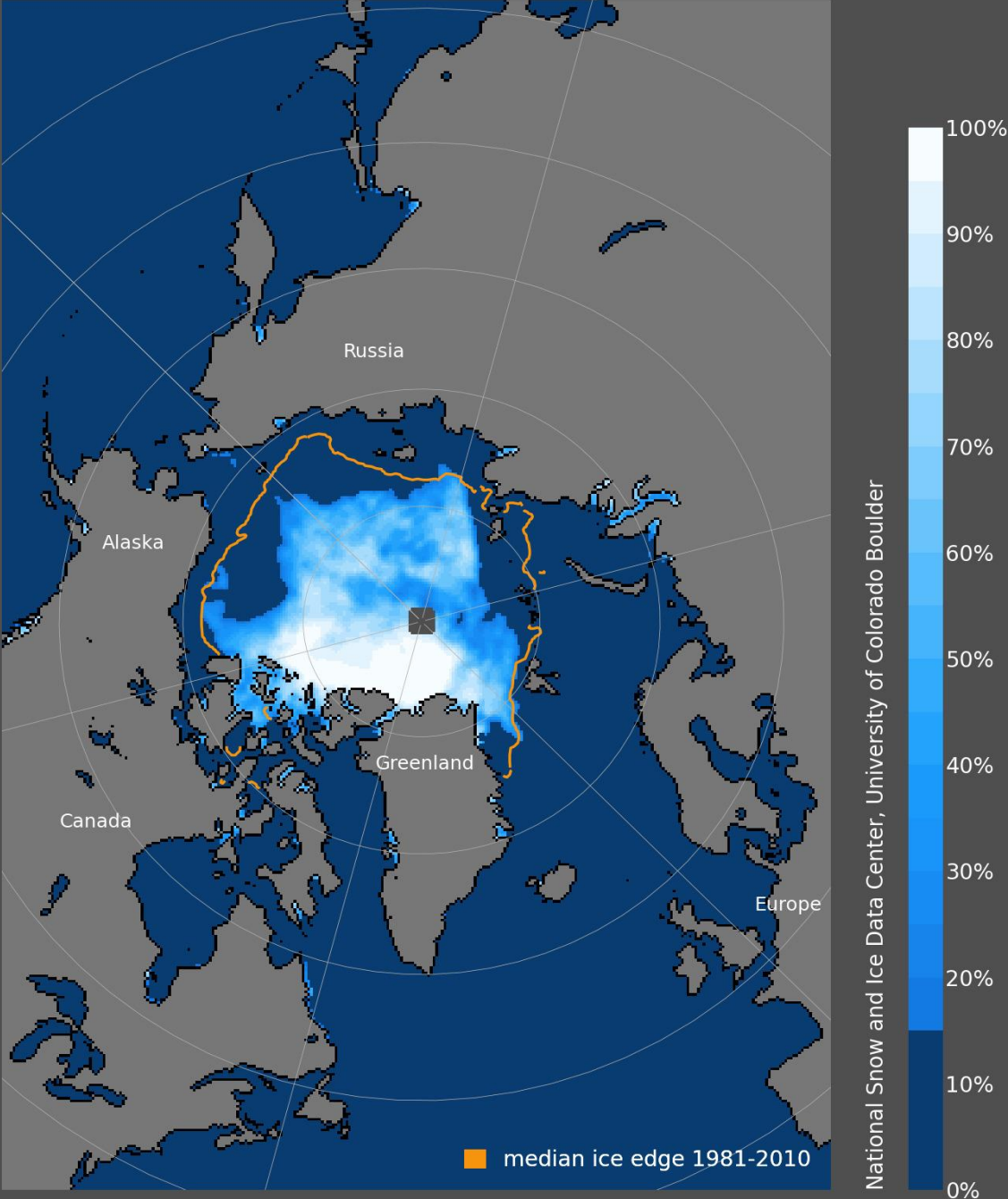
Alexandra Jahn^{1,2}✉, Marika M. Holland³ & Jennifer E. Kay^{1,4}

Abstract



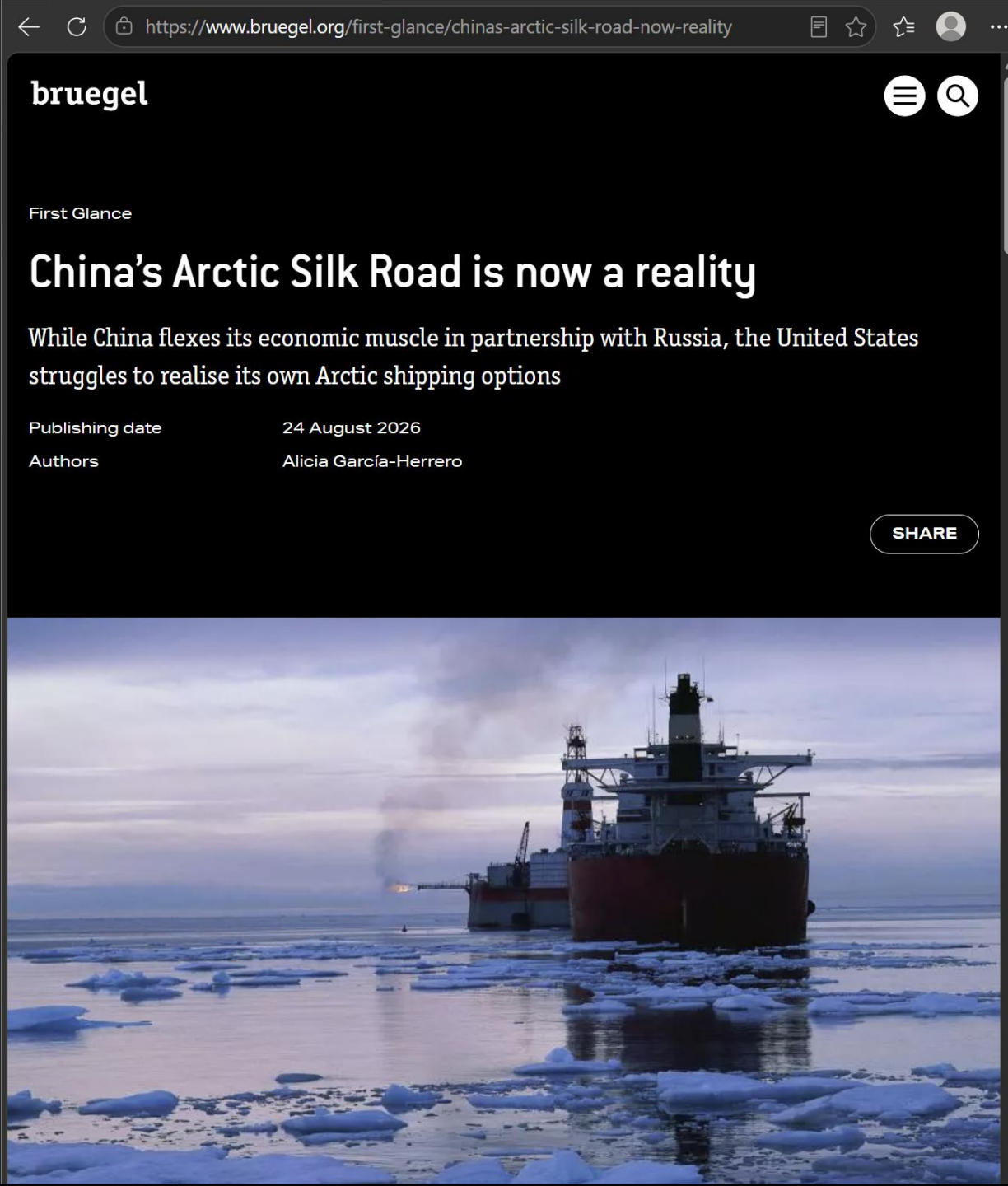
could occur in 2020–2030s

Sea Ice Concentration, 30 Aug 2026





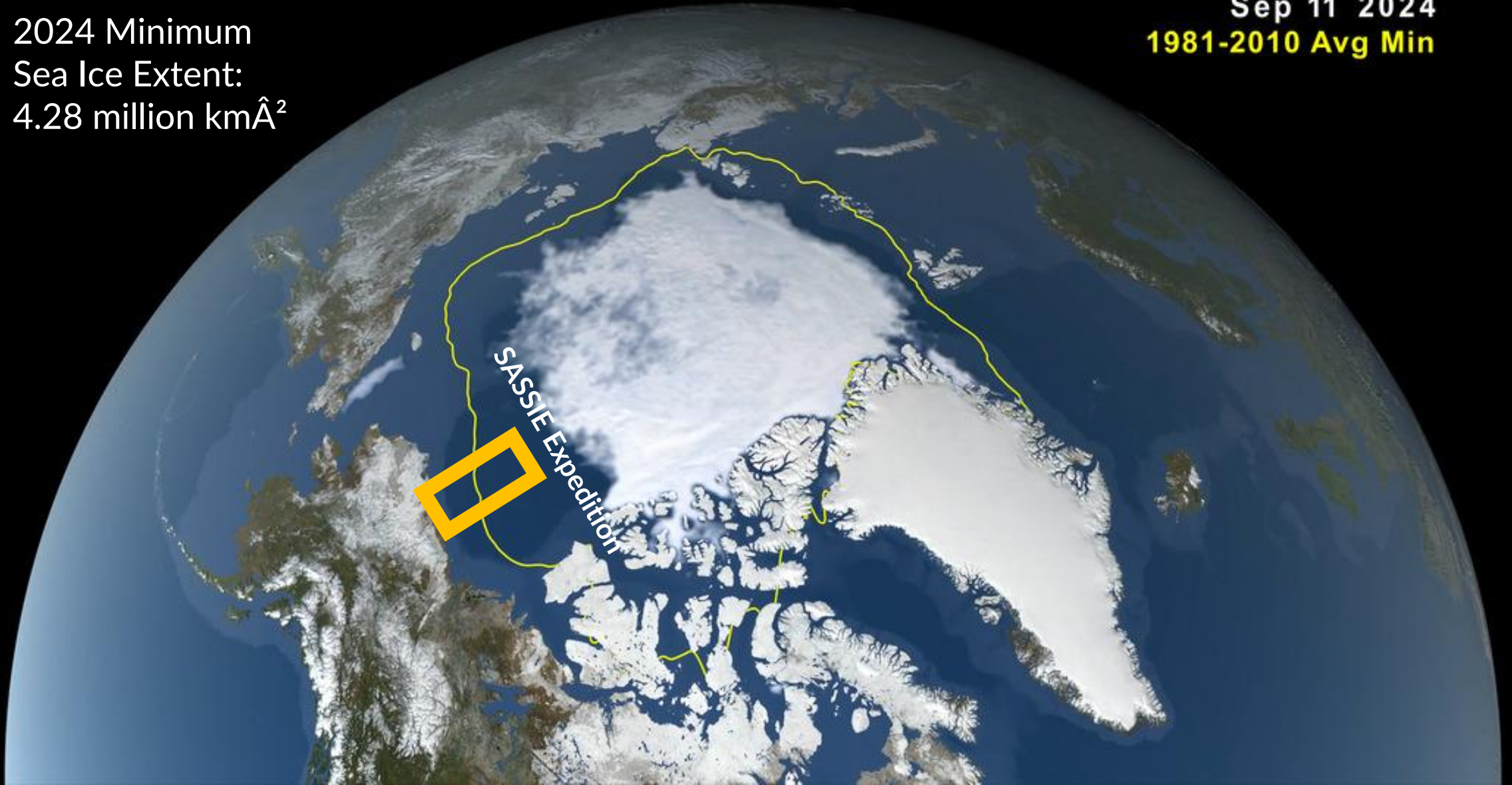
- “The new service marks the first regularly scheduled commercial transit of the Arctic Ocean.”
- "Transiting the Arctic Ocean can be scheduled, priced and repeated, meaning the route can be integrated into supply chains.”
- ICE Pact between US, Canada & Finland: Agreement signed 2024, reaffirmed 2025.
- 11 Arctic Security Cutters on order - Polar Class 4 and 3, first delivery 2028



Can Salinity be Used as a Predictor of Autumnal Sea-Ice Advance?

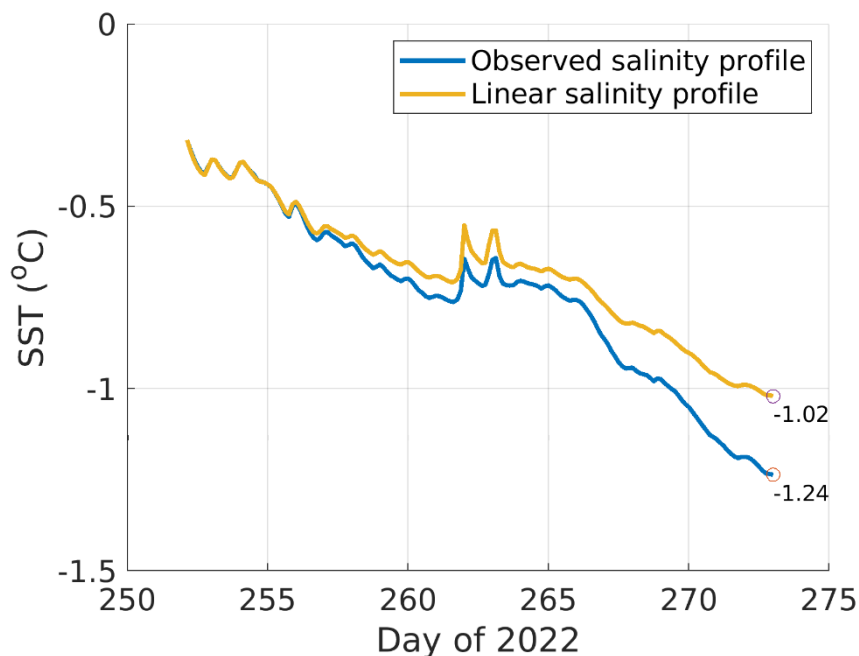
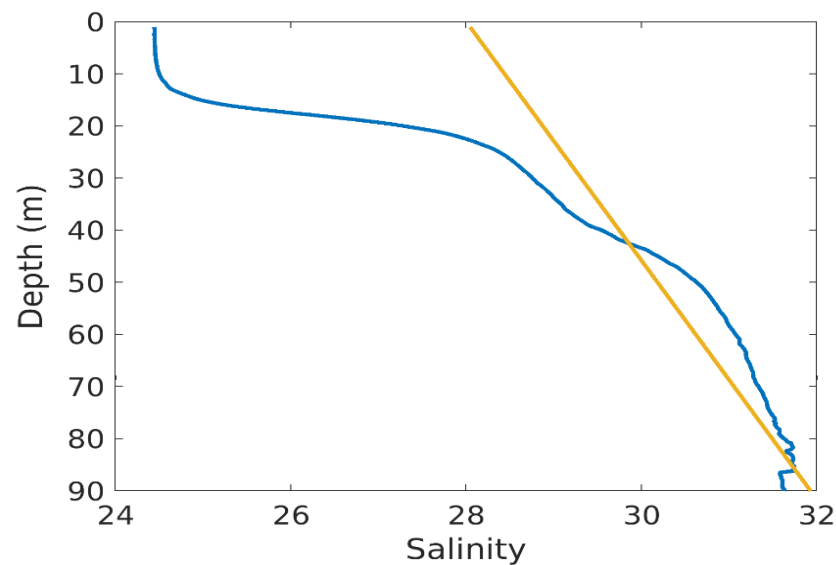
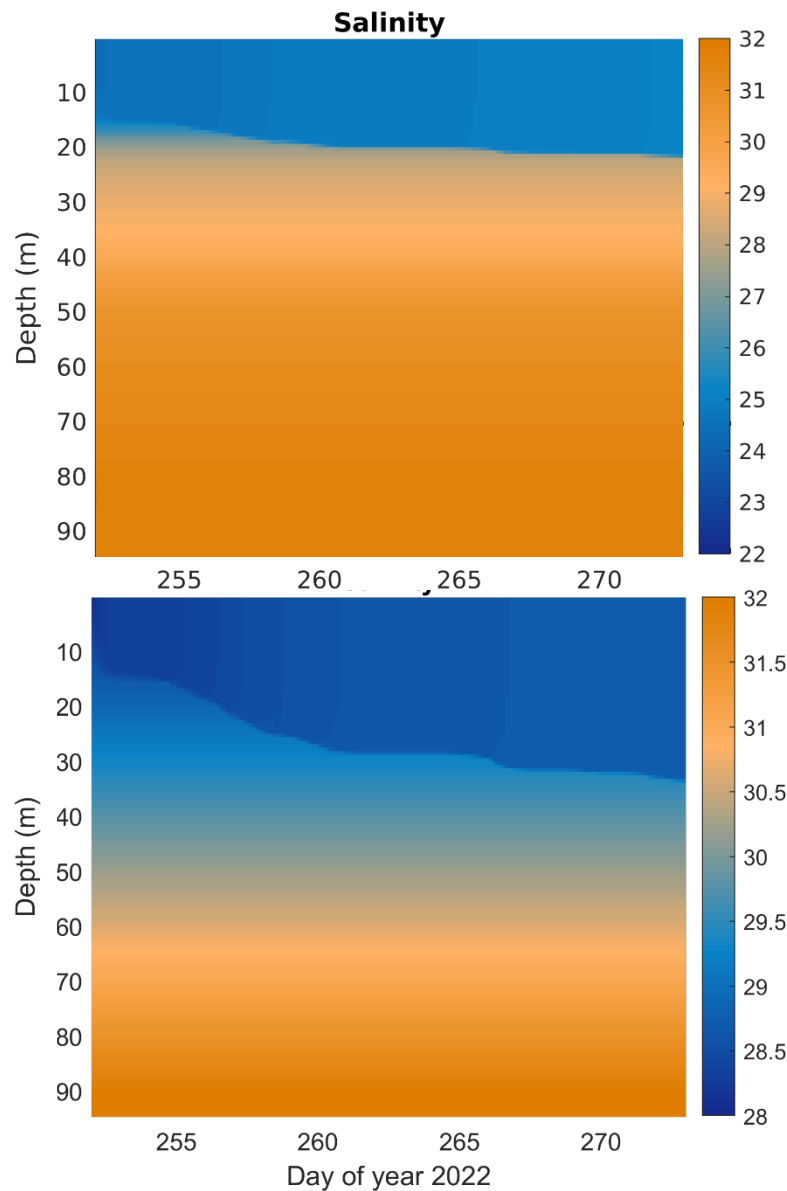
2024 Minimum
Sea Ice Extent:
4.28 million km²

Sep 11 2024
1981-2010 Avg Min





The SASSIE Hypothesis: GOTM Results

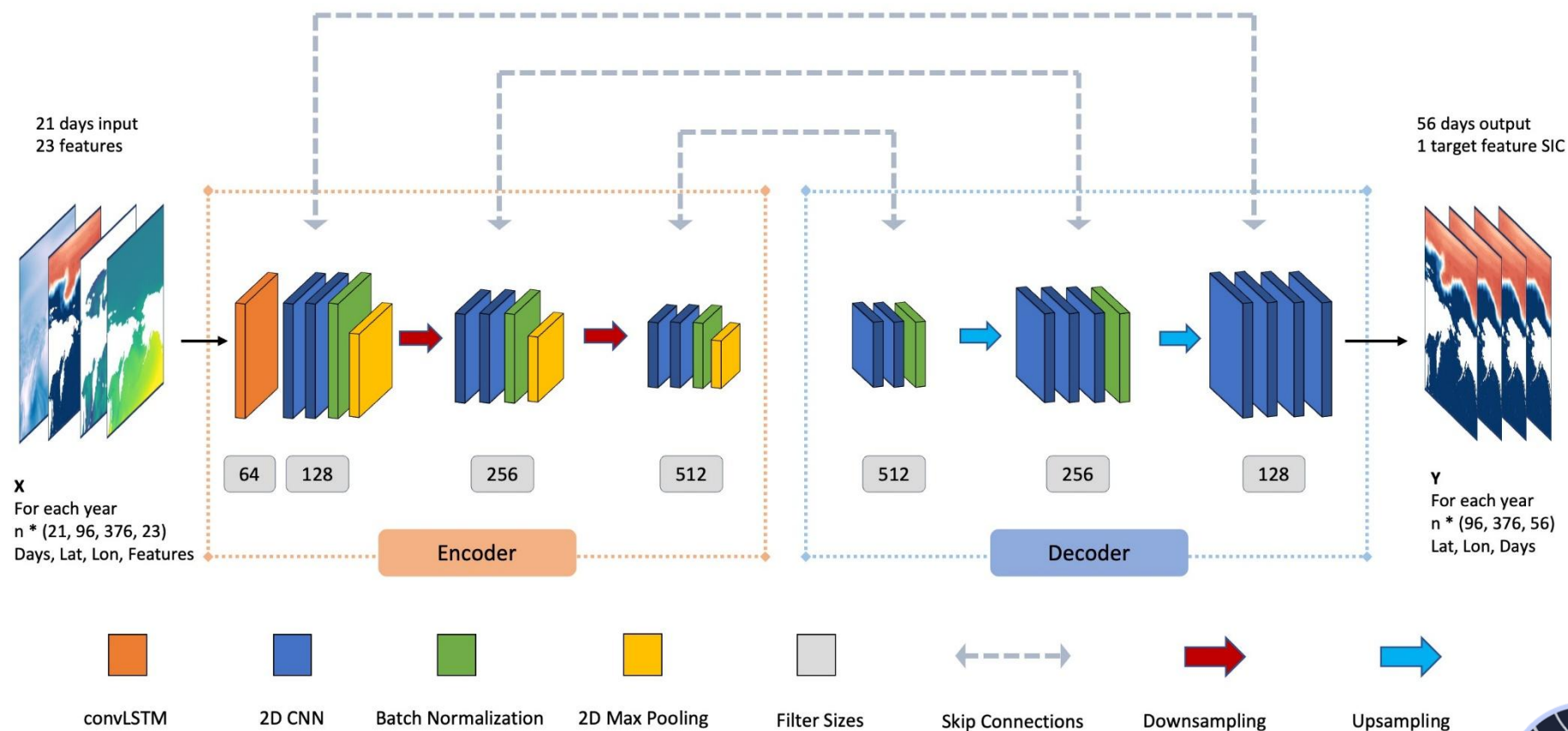


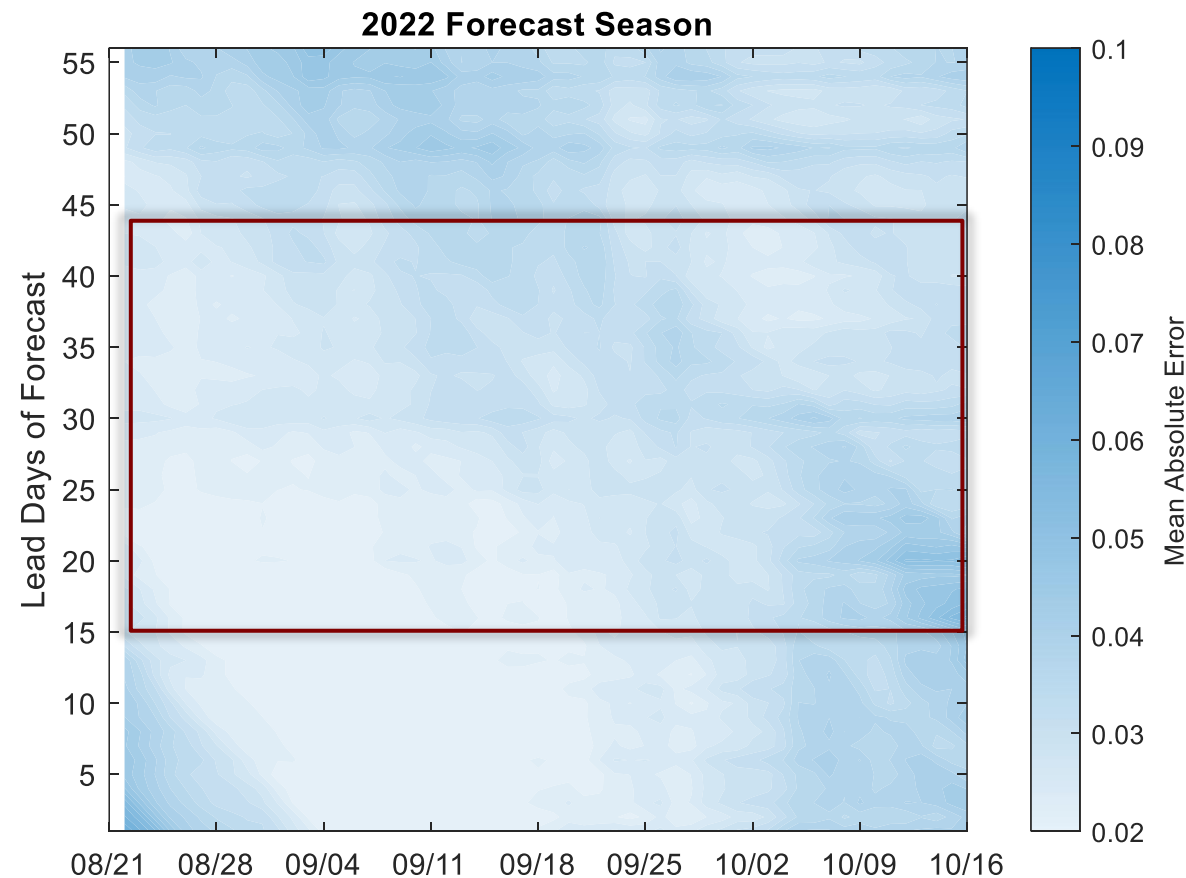
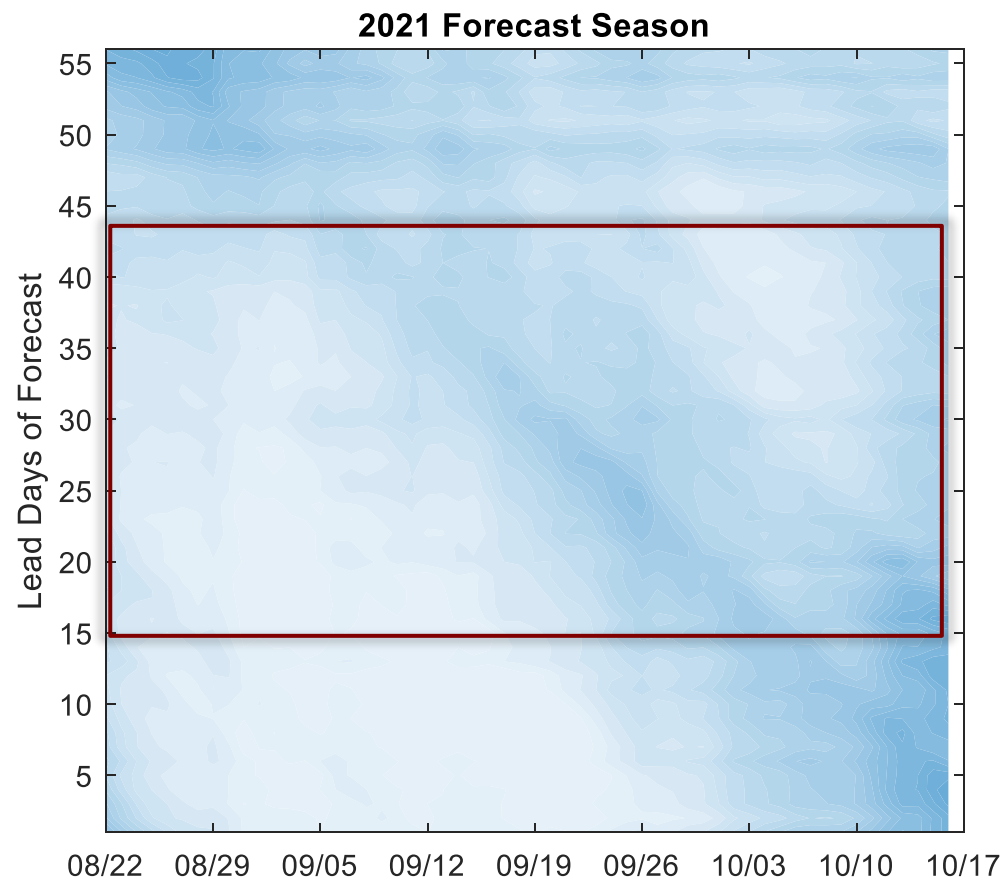
- Same forcing results in significantly different surface cooling
- Deeper convection with reduced stratification
- Stratification crucial for rapid sea-ice advance



- Adapted from MTIceNet
- Custom loader reduces memory use
- Completely Open Source/Open Science
- SSS based on OISSSv3 (Oleg Melnichenko)

The NESSIE Convolutional Long-Short-Term Memory (LSTM) Neural Network model





- Very good performance at lead times of 2–6 weeks
- Area-weighted MAE of 0.031 for 2021 and 2022 seasons

- Regional evaluation shows a likely influence of salt transport through the Bering Strait, as shown by feature importance in Bering and Chukchi Seas:
- Beaufort: SST, SIC, Qnet, **SSS**
- Bering: SST, **SSS**, SIC, Qnet
- Chukchi: SIC, **SSS**, SST, Qnet
- East Siberian: SIC, Qnet, SST, **SSS**
- Laptev: SST, Qnet, **SSS**, SIC

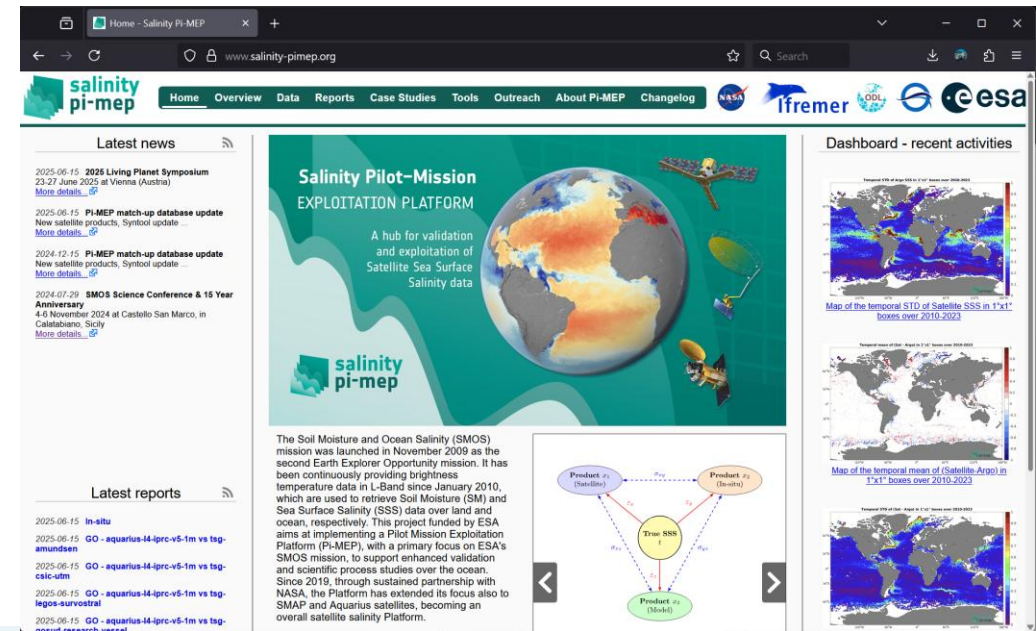


SATELLITE AND IN SITU SALINITY

Understanding Near-Surface Stratification and Subfootprint Variability

BY J. BOUTIN, Y. CHAO, W. E. ASHER, T. DELCROIX, R. DRUCKER, K. DRUSHKA, N. KOLODZIEJCZYK, T. LEE, N. REUL, G. REVERDIN, J. SCHANZE, A. SOLOVIEV, L. YU, J. ANDERSON, L. BRUCKER, E. DINNAT, A. SANTOS-GARCIA, W. L. JONES, C. MAES, T. MEISSNER, W. TANG, N. VINOGRADOVA, AND B. WARD

- The salinity community has been remarkably harmonious and collaborative
- Two independent dielectric models, reconciled by co-authorship
- Shared projects, international collaborations



Everyone depends on the same small set of common inputs: the dielectric model sits upstream of every retrieval, and validation data constrains everyone's product. Cooperation is the only way forward.



Thank You!
Questions?

A blue-tinted photograph of a seascape. In the foreground, there are several large, irregular icebergs and many smaller chunks of ice floating in the water. The ice appears to be melting or breaking apart. In the background, a large, flat expanse of ice or a distant shoreline is visible under a pale sky. The overall color palette is monochromatic, consisting of various shades of blue and white.

Backup

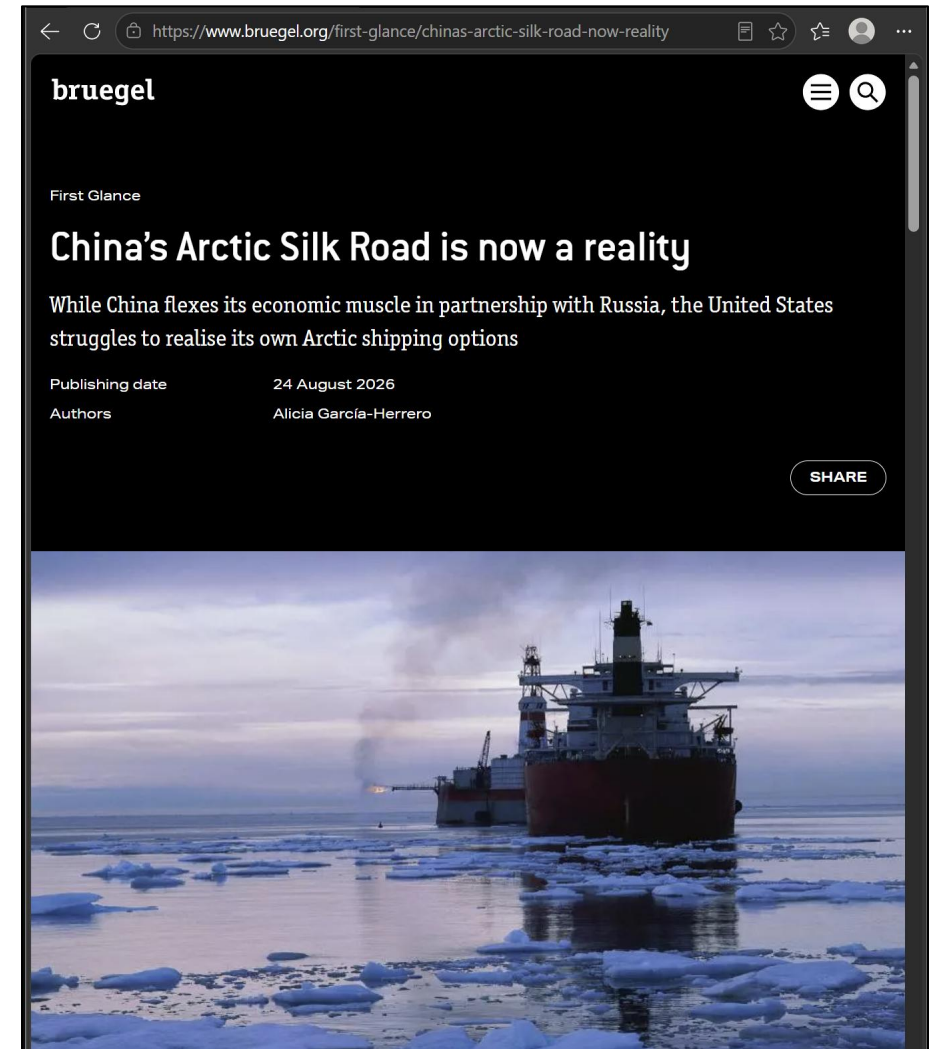
It Is Not a Voyage Any More. It Is a Timetable.

- **2025 — the trial:** Istanbul Bridge left Ningbo-Zhoushan in September with 4,890 containers, Felixstowe in about 20 days
- **2026 — a scheduled service:** Sea Legend's China-Europe Arctic Express, eight weekly sailings, 15 August to 3 October, seven vessels
- **Now — running as we speak:** lead vessel Dubai Tower departed Ningbo 15 August, arrives Felixstowe 5 September

The threshold crossed is not feasibility. It is schedulability — the route can be scheduled, priced and repeated, so it can be integrated into supply chains.

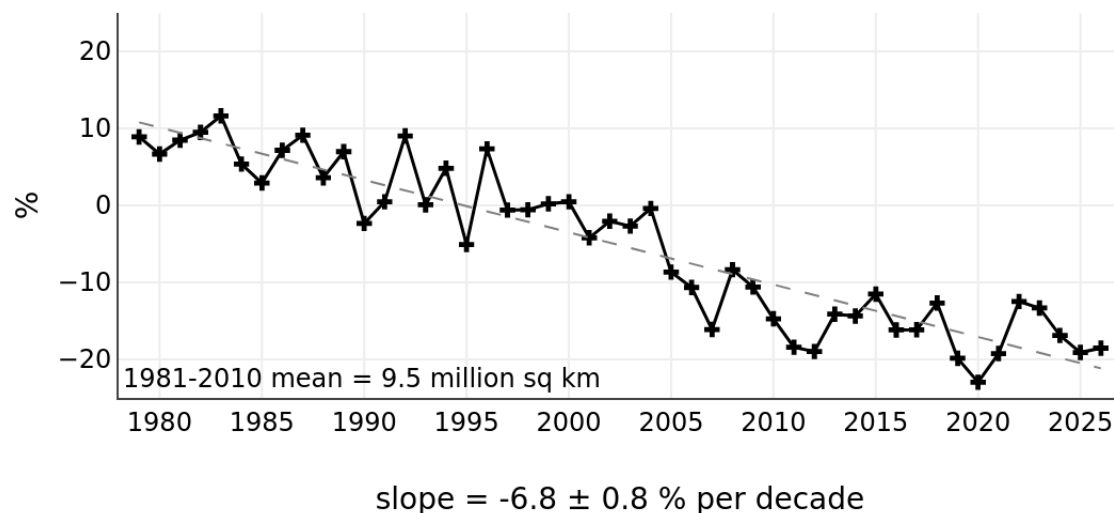
The season runs 15 August to 3 October. Seven weeks. Why those dates? Ice — and when the window opens and closes is freeze-up timing.

Bruegel, 24 August 2026. Context: 15 container transits in 2025, up from 11 in 2024 — a niche seasonal service, not a replacement trunk route.

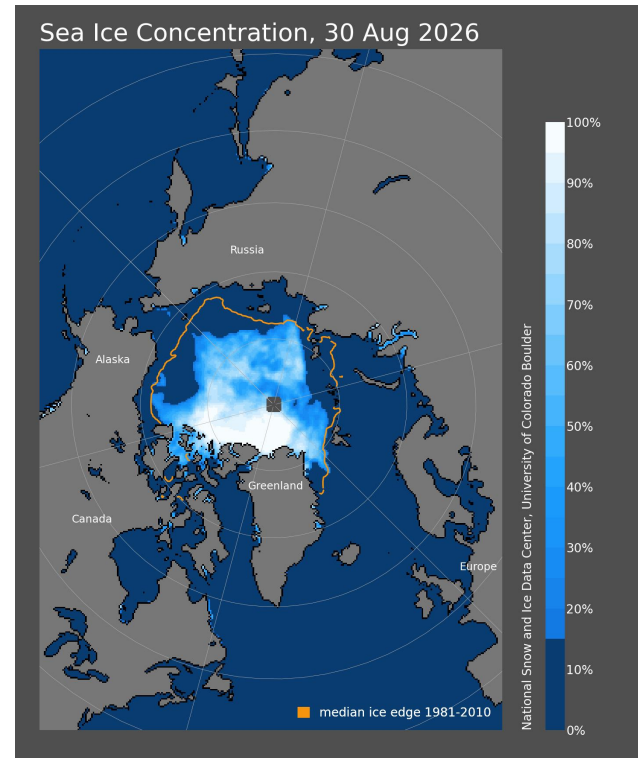


~7 Million to ~4.5 Million Square Kilometres

Northern Hemisphere Extent Anomalies Jul 1979 - 2026



National Snow and Ice Data Center, University of Colorado, Boulder



- September mean extent: 6.85 million km² (1979–1992) → 4.44 (2007–2019)
- 2025 minimum 4.60 on 10 September – tenth lowest. NSIDC trend 12.1% per decade
- Concentration is not thickness: 70% concentration is 30% open water in leads

- **Salinity:** total freshwater fraction
- **$\delta^{18}\text{O}$:** meteoric water vs. sea-ice melt
- **$\delta^{18}\text{O}$ + d-excess:** river vs. river, and precipitation vs. glacial melt

d-excess = $\delta^2\text{H} - 8 \cdot \delta^{18}\text{O}$ — the deviation from the global meteoric water line.

Healy transect: Western Arctic freshwater is dominated by meteoric input — specifically the Mackenzie — with a smaller sea-ice melt component. Eastern Baffin Bay is local precipitation and glacial meltwater.

- Rain has no alkalinity and almost no DIC; sea-ice melt is low in both
- The dilution mechanism is identical — only the freshwater source changes
- Kitikmeot Sea: two ships disagree on surface $p\text{CO}_2$, sampling at 7 m and 1 m
- Their fix is simultaneous intake-and-interface measurement, as in Ho & Schanze (2020)
- Surface $p\text{CO}_2$ varies by up to $142 \mu\text{atm}$ between years

One instrument, three problems — satellite salinity validation, rain-driven bias in global CO_2 flux, melt-driven bias in Arctic CO_2 flux.

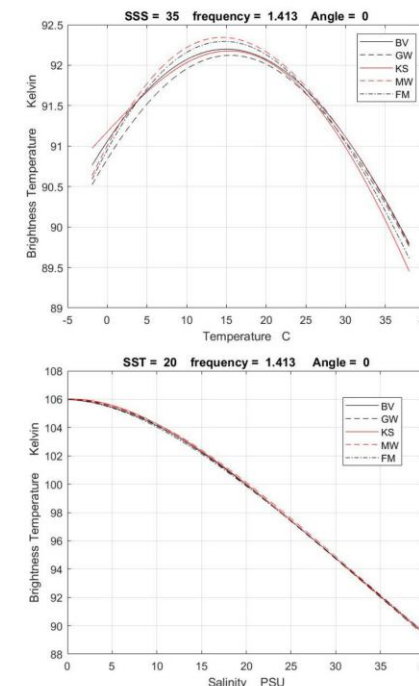
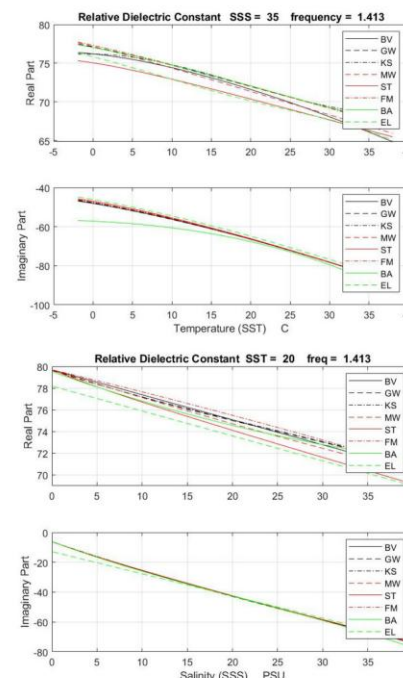
How does freshwater move through the land–delta–ocean system, and what controls its fate in the Beaufort Sea?

- **Continuous seawater isotopes** — freshwater contributions and mixing, delta to open ocean, at high resolution
- **Isotopic tracing in river and delta waters** — separating snowmelt, new precipitation, and lake and wetland exchange
- **Precipitation sourced from the Beaufort itself** — as a function of sea ice coverage

That third objective closes a loop: precipitation sourced from a newly ice-free ocean, falling back into it. Ice retreat changes where the local water comes from.

➤ **Joint salinity + isotopes + discharge.** Stronger than “more salinity.” Connects to SWOT and to terrestrial hydrology.

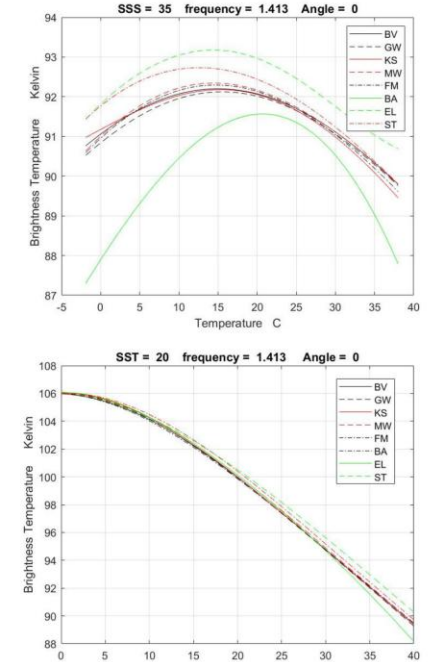
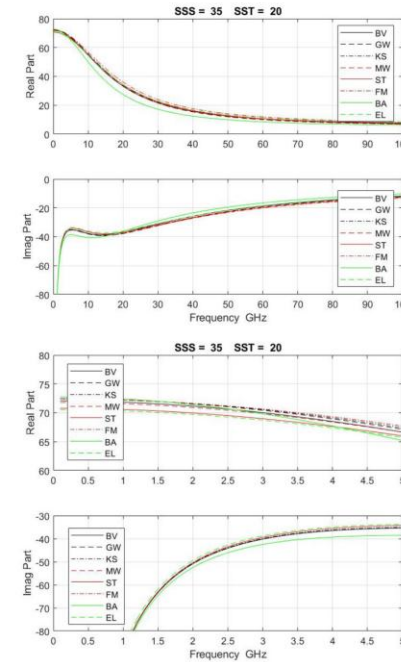
- **Better SSS in cold water.** The sensitivity problem at 1.4 GHz is physics, not processing.
- $\partial T_B / \partial S$ collapses toward freezing; dielectric model uncertainty compounds it
- **Why Lang has run a resonant cavity for fifteen years, and why the P-band work exists**



GW2020 → GW2022. Conductivity taken from the definition of practical salinity, freeing a degree of freedom for a salinity-dependent relaxation time.

Klein–Swift and GW2020 produce an unphysical sign change at high salinity. GW2022 does not.

SMOS v700 uses Boutin et al. 2021, not Klein–Swift. KS is the historical baseline, superseded.



Two fully independent approaches.

The BV model came from SMOS multi-angular brightness temperatures. The GW model came from a laboratory resonant cavity at George Washington University.

Different methods, different failure modes, different disagreements — and by 2023 the people responsible for each were on the same paper.

Boutin, Vergely, Bonjean, Perrot, Zhou, Dinnat, Lang, Le Vine & Sabia (2023).

Reflector size. Beamwidth $\propto \lambda/D$. Aquarius 2.5 m; SMAP 6 m mesh. P-band at 707 MHz doubles the wavelength.

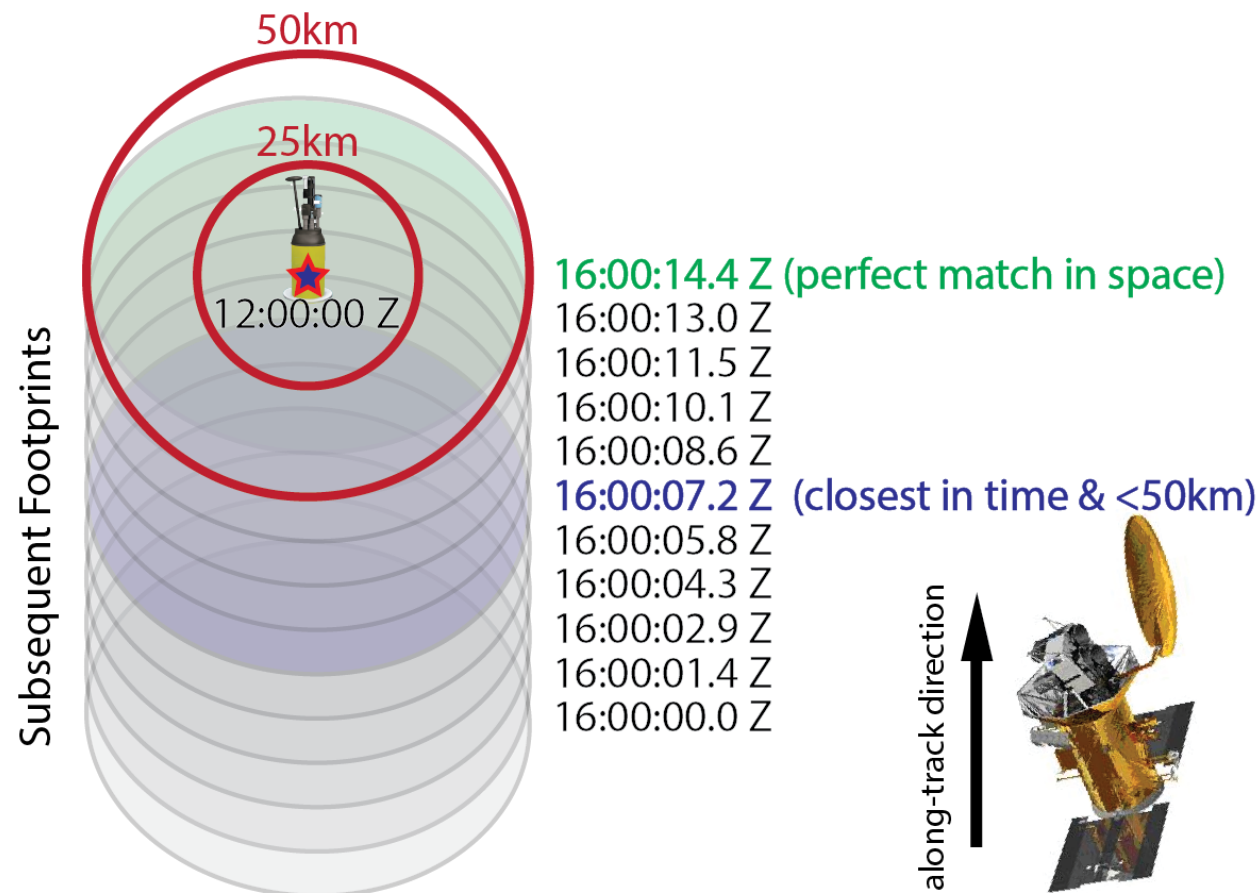
RFI. 1400–1427 MHz is passive-only by allocation and still contaminated. 707 MHz has allocated services and no protection.

Cost.

Brown and Misra at JPL push wideband — notable because they come from the radiometer/RFI side, which implies detection and excision are good enough, and that many channels give redundancy a single channel cannot.



- The most common way of assessing the quality of a satellite SSS product is to use matchups
- To average or not to average in time or space?
- Matchup criteria whitepaper: [doi://10.5281/zenodo.4769713](https://doi.org/10.5281/zenodo.4769713)
- **Both horizontal and vertical mismatches contribute significantly and are frequently unaccounted for in error estimates**



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