Where Salinity Takes Control:

The Meso-Submesoscale Thermohaline Transition and the Need for 10-km Salinity Sensing

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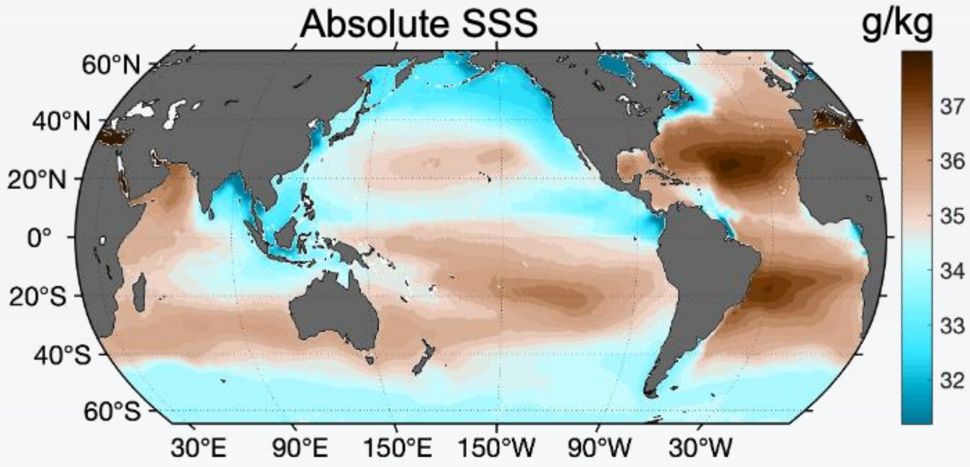
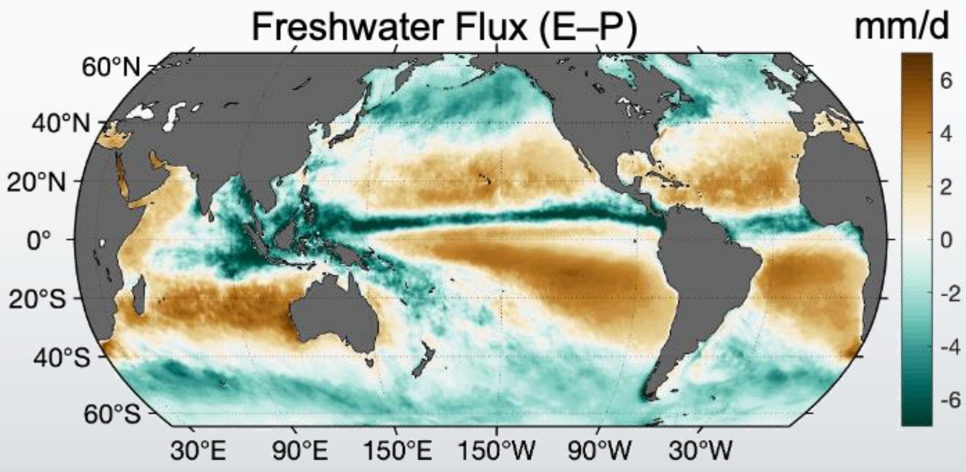
Same salt. Same ocean. Different physics.

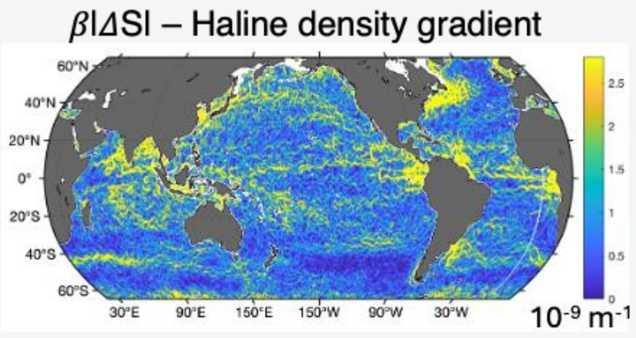
Rain Gauge:
At basin scales, salinity mirrors the water cycle

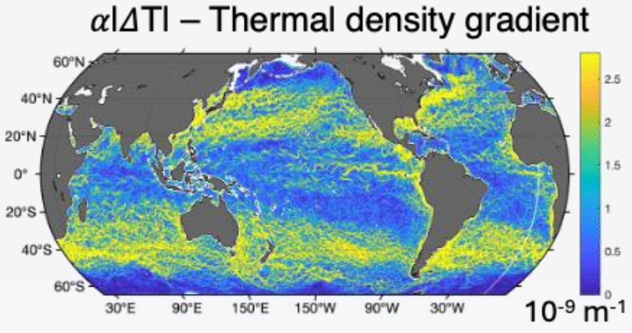
Passive Tracer
1000km → 100-10km

Dynamical Driver:
At frontal scales, salinity rivals temperature in shaping density

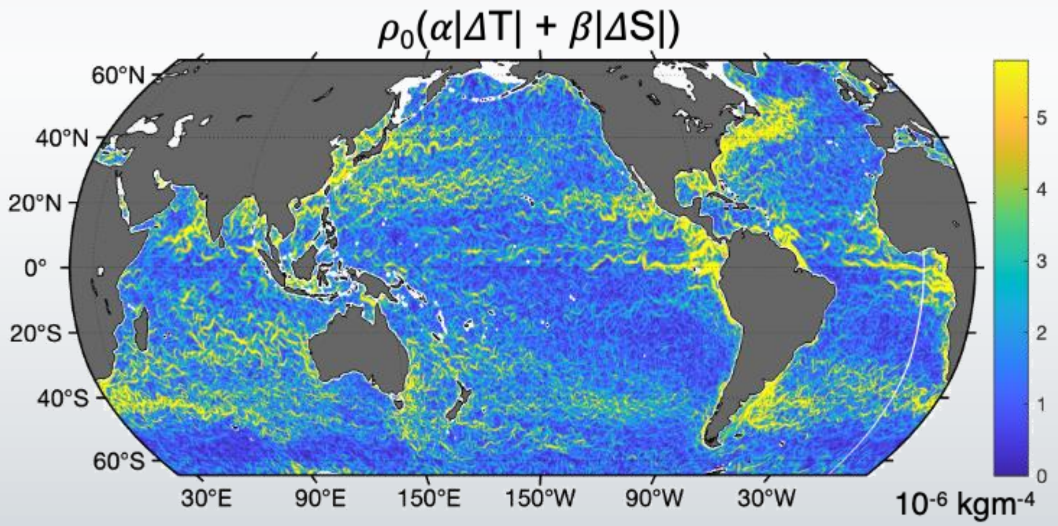

Absolute SSS


Freshwater Flux (E–P)


$\beta|\Delta S|$ – Haline density gradient


$\alpha|\Delta T|$ – Thermal density gradient

At frontal scales, SSS rivals SST in shaping density variability


$\rho_0(\alpha|\Delta T| + \beta|\Delta S|)$

SSS: OISSS; SST: OSTIA; E: OAFlux2; P: IMERG

Main Questions

(1) How does salinity’s role change with scale — from tracing the water cycle to shaping frontal density gradients?

(2) What sets the transition to salinity-driven frontal dynamics near O(10 km) — and why does it remain under-resolved by current satellite salinity?

(3) What thermohaline front types emerge at the submesoscale, and what are their implications for vertical exchange, productivity, carbon cycling, and Earth system model fidelity?

(4) What missing dimension does O(10–20 km) SSS add to SWOT, SST, and PACE observations of ocean fronts?

From Rain Gauge to Dynamical Driver: A Scale Framework

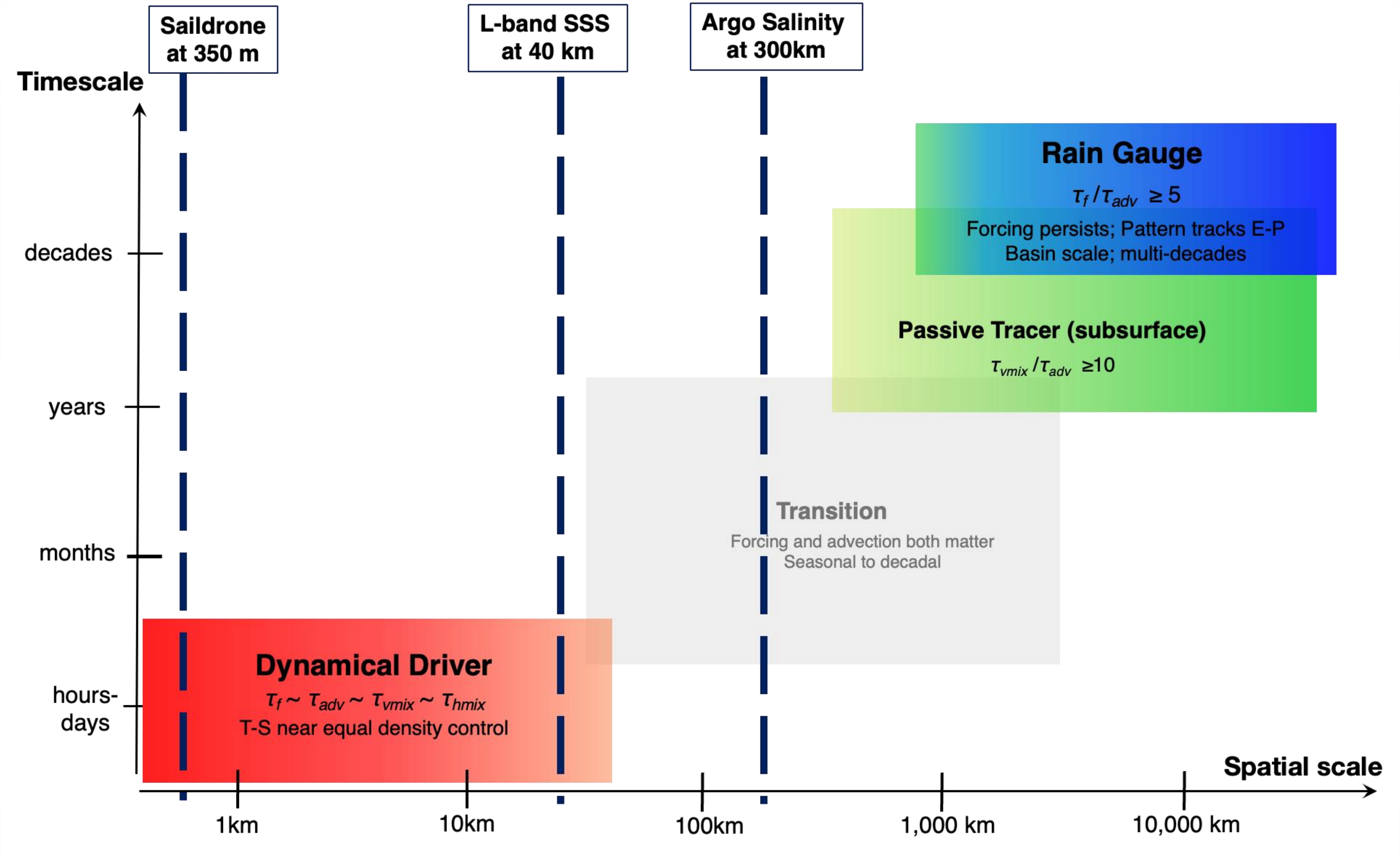
$$\frac{\partial S}{\partial t} = \underbrace{-\mathbf{u}_h \cdot \nabla S}_{\tau_{adv}=L/U} + \underbrace{-w\partial_z S}_{\tau_{vmix}=h^2/K_v} + \underbrace{K_h \nabla^2 S}_{\tau_{hmix}=L^2/K_h} + \underbrace{\frac{S_0}{h}(E-P-R)}_{\tau_f}$$

$\tau_{adv} \sim L$, $\tau_{hmix} \sim L^2$. Dominant balance shifts as scale changes.

Regime	Controlling Ratio	Key Signature
Rain Gauge	$\tau_f/\tau_{adv} \geq 5$	Salinity pattern follows E–P
Passive tracer	$\tau_{vmix}/\tau_{adv} \geq 10$	Subsurface trends ≳2× surface
Dynamical driver	All τ converge at ~hours–days	Salinity rivals temperature in density control at O(10 km)

Yu, L. 2026: Ocean salinity across space-time scales: From water cycle indicator to dynamical driver. *Ocean Sci.* https://doi.org/10.5194/egusphere-2025-6562. *In press.*

Salinity's Role in Space and Time



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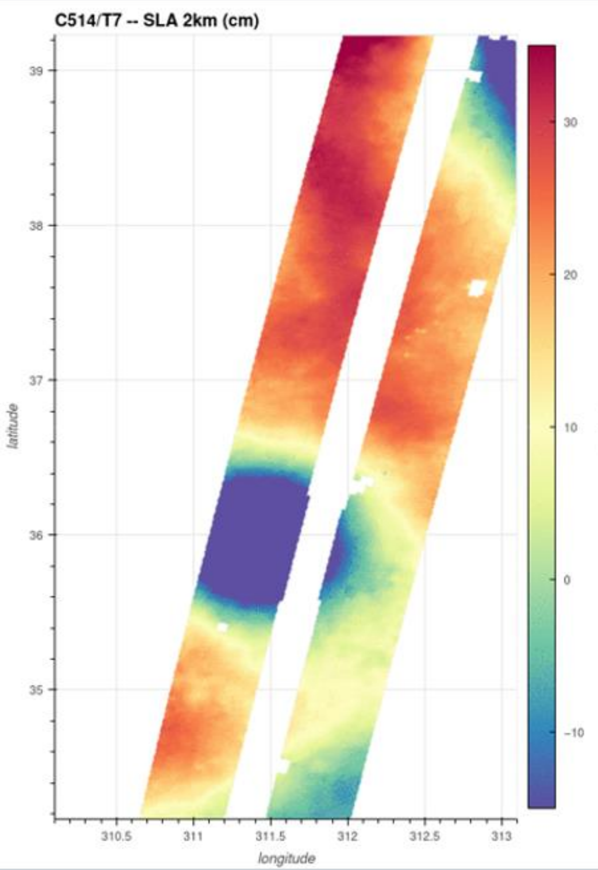
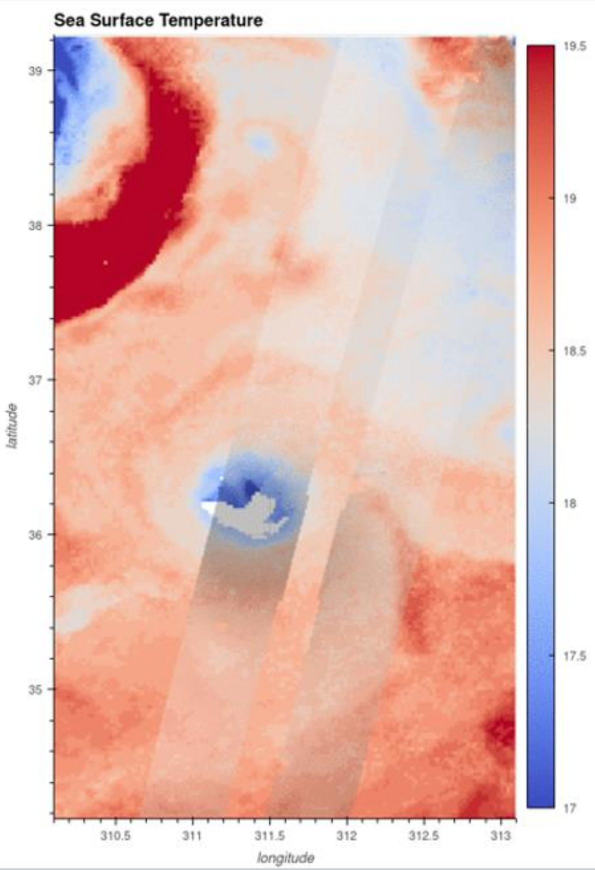
SSS at 40 km: Submesoscale Structure Unresolved

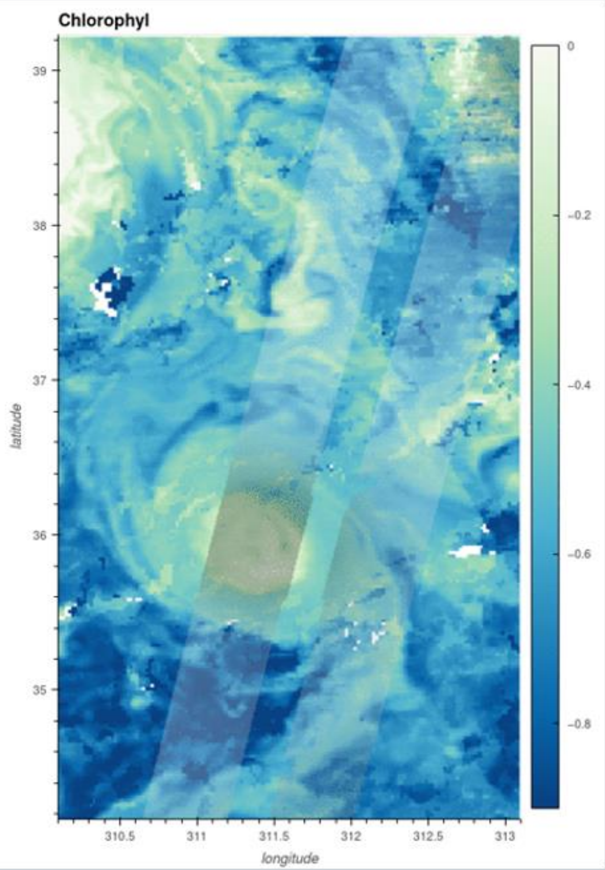
SWOT 2 km



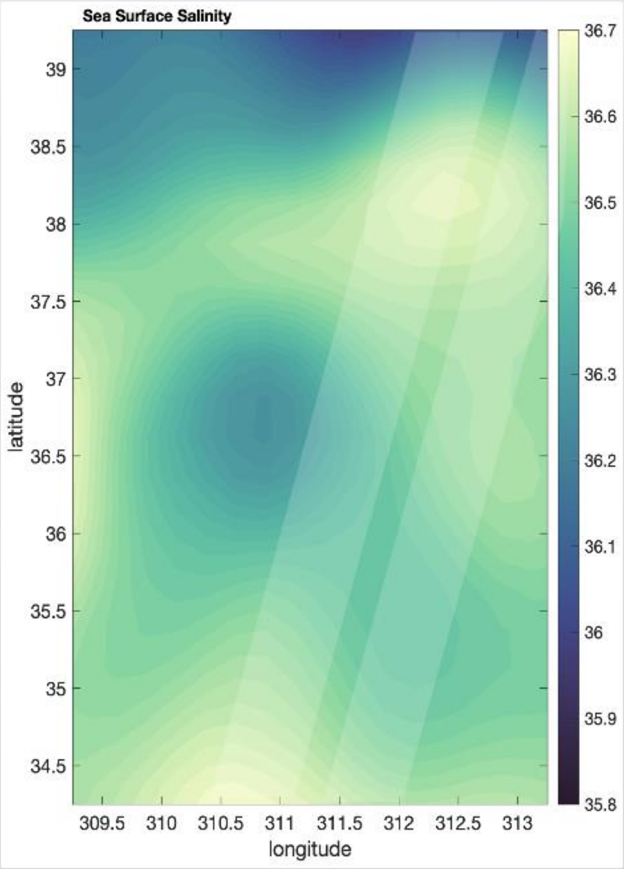
SST ~1–5km



Chl-a (CLS) ~ 1–4 km



OISSS ~ 40 km



Credit: AVISO SWOT's detailed view of the ocean

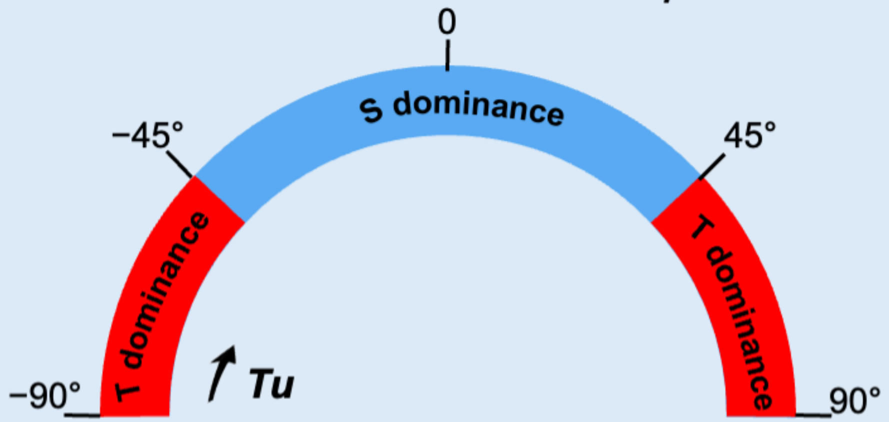
The Doubly Stratified Ocean: Density Fronts Reflect Both T and S

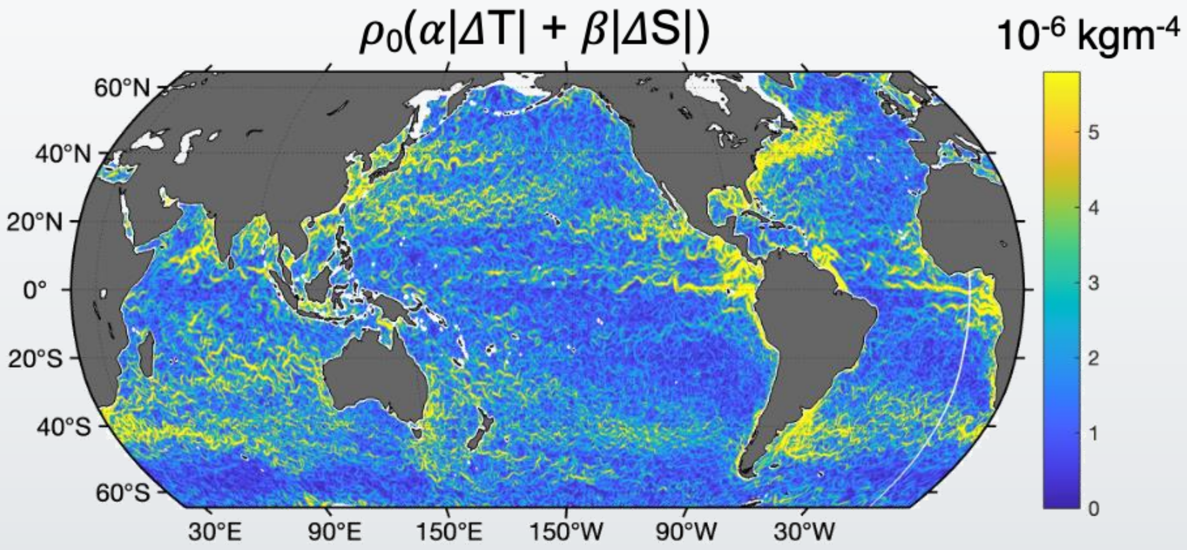
- Sea Surface Density (SSD) fronts:

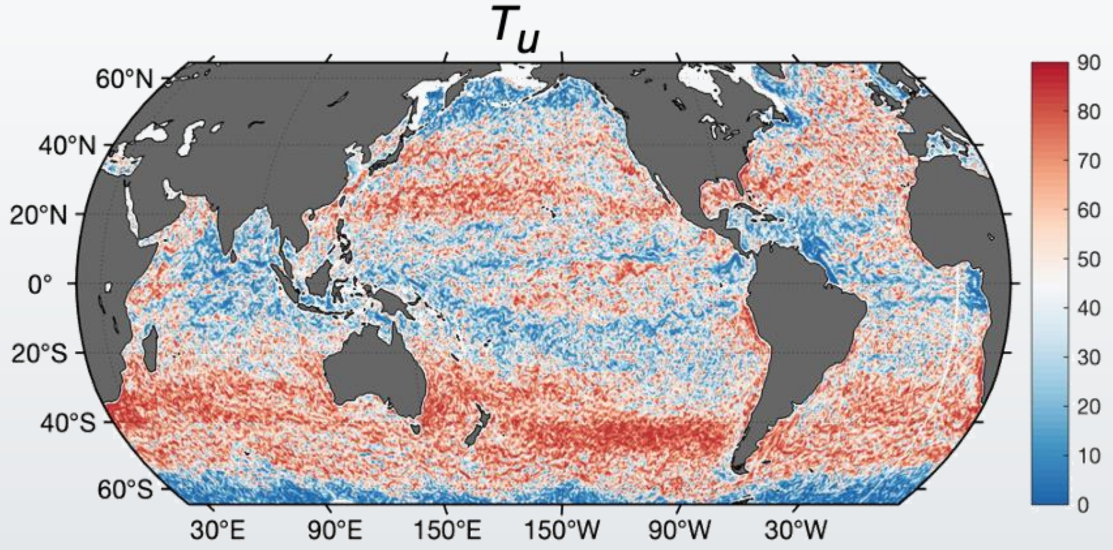
$$\Delta\rho = \rho_0(\alpha\Delta T + \beta\Delta S)$$

- At frontal scales, $\beta\Delta S$ is comparable to $\alpha\Delta T$
- T-S compensation is quantified by density ratio $R_\rho = \frac{\alpha\nabla T}{\beta\nabla S}$ or Turner Angle T_u

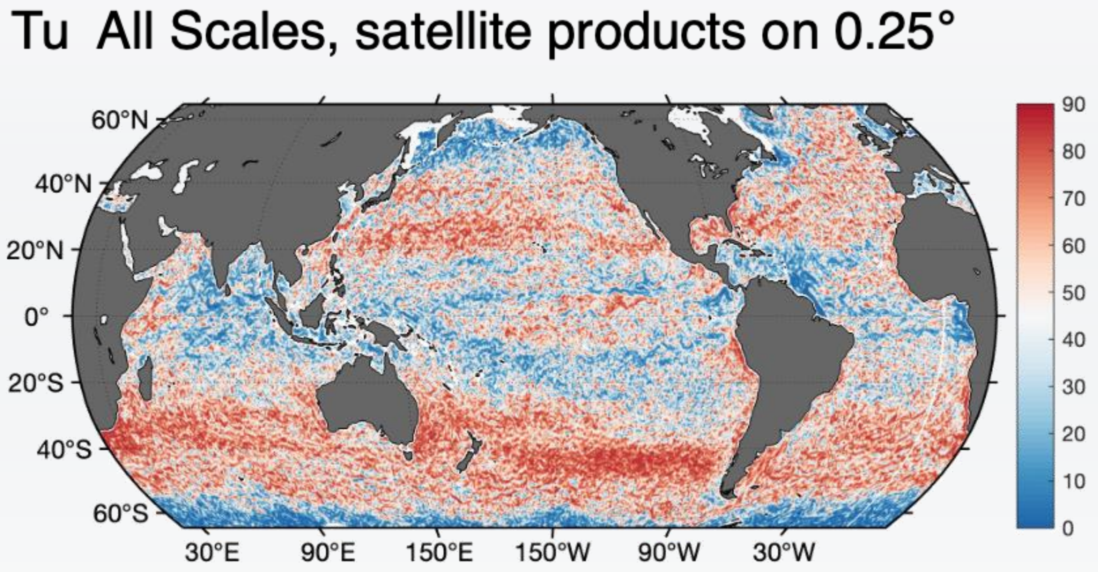
- Turner Angle $T_u = \tan^{-1}(\frac{\alpha\nabla T}{\beta\nabla S})$

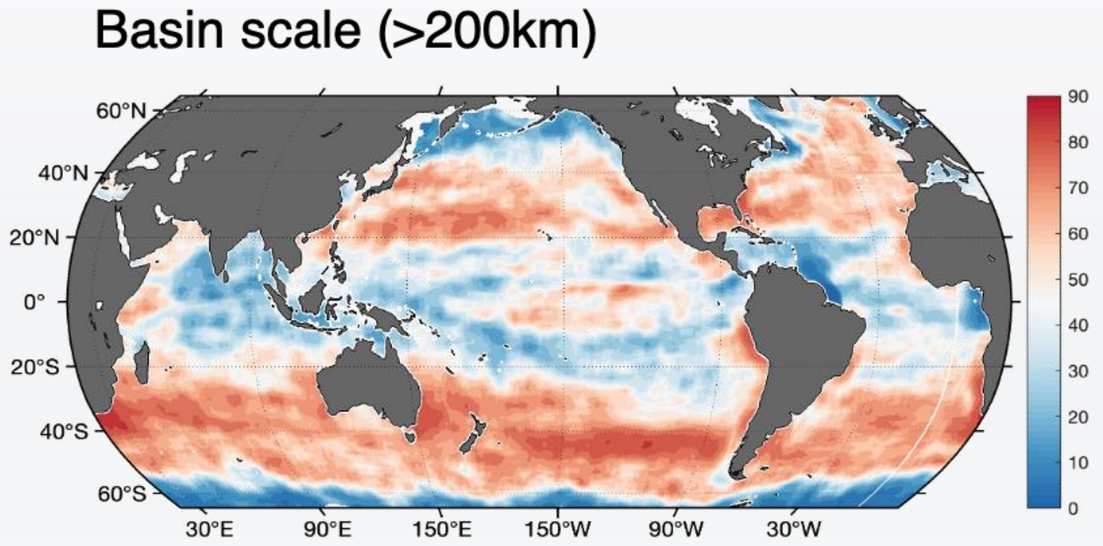


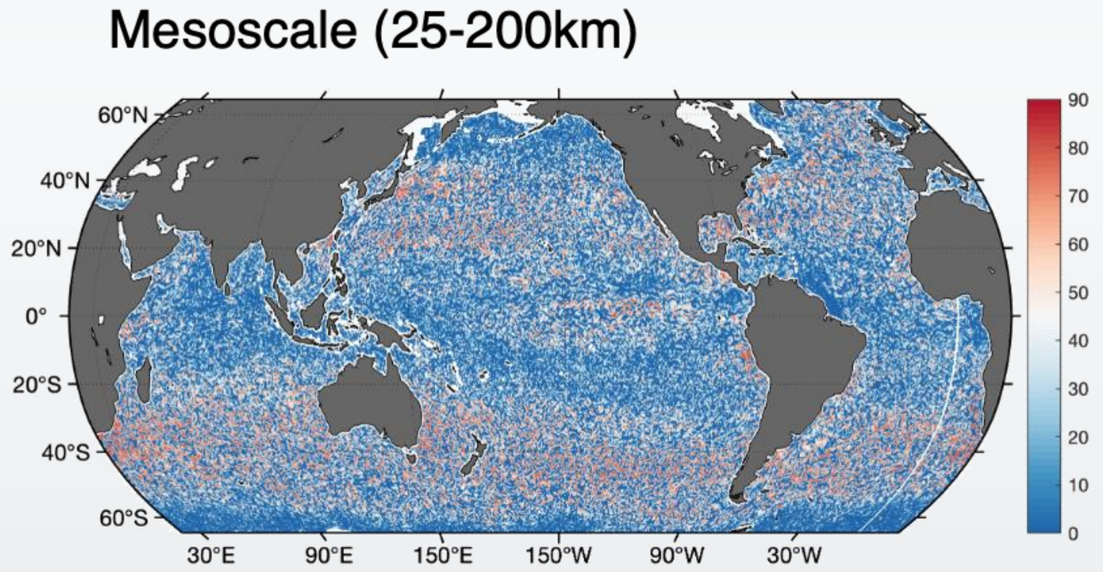




T-S Compensation Increases as Scale Decreases

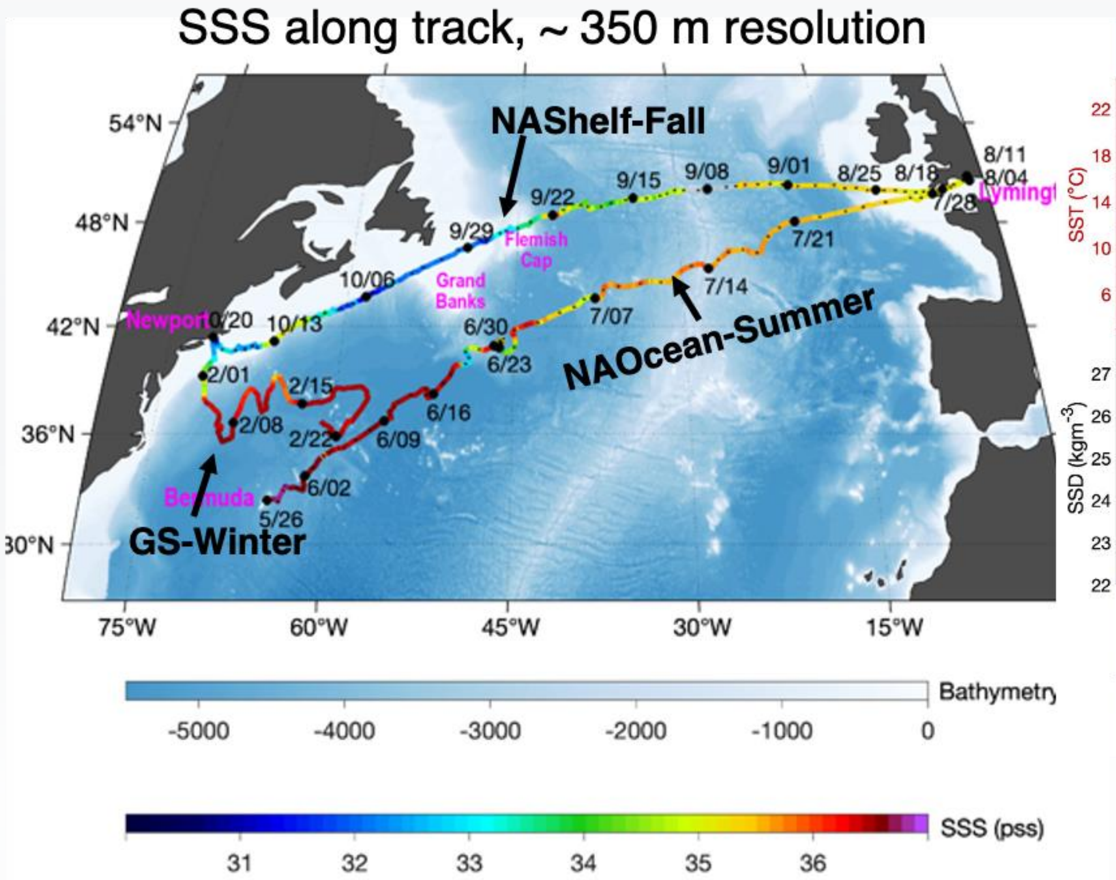

Tu All Scales, satellite products on 0.25°

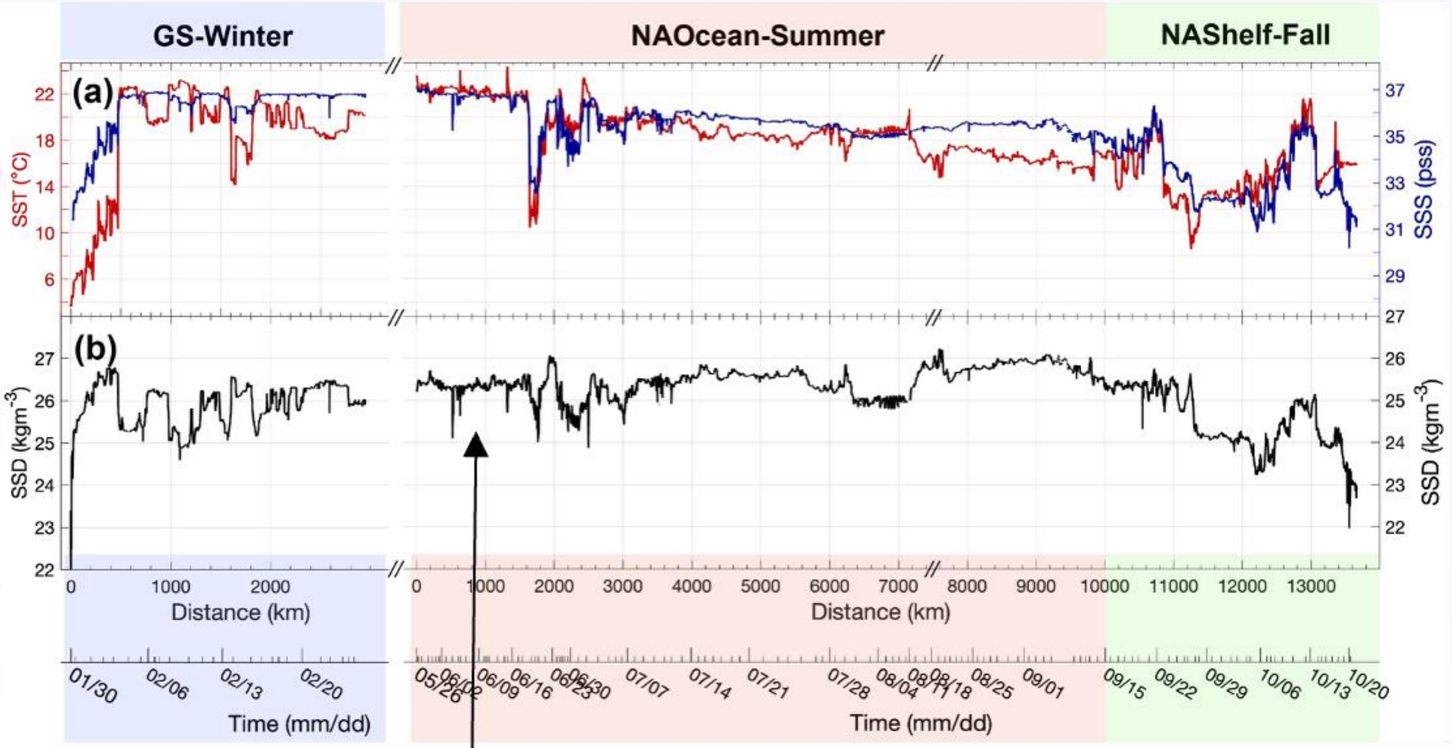

Basin scale (>200km)


Mesoscale (25-200km)

As scale decreases, salinity's contribution to density gradients becomes increasingly important relative to temperature.

T-S Compensation at Fine Scales: 2019 North Atlantic Saildrone



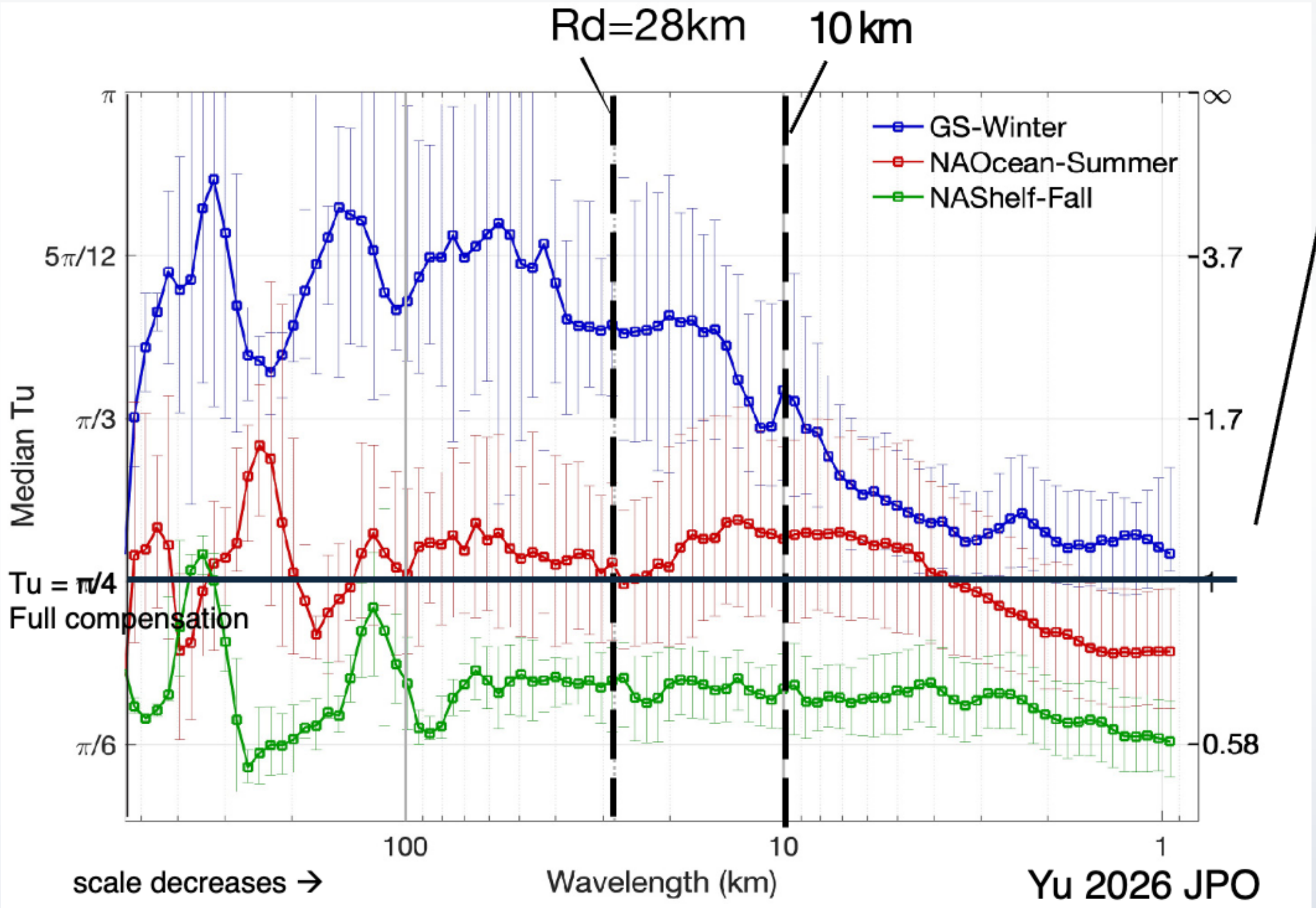


SSD variability < SST or SSS → density partially compensated

Yu, L. 2026. Meso-Submesoscale Surface Temperature-Salinity Compensation and Density Gradient Variability in the North Atlantic from Saildrone Observations. J. Phys. Oceanogr., DOI: https://doi.org/10.1175/JPO-D-25-0037.1.

T-S Compensation Intensifies Below the Deformation Radius (Rd)

Rossby deformation radius $\boldsymbol{R_d} = c_1 / f$: Mesoscale ←→ Submesoscale boundary



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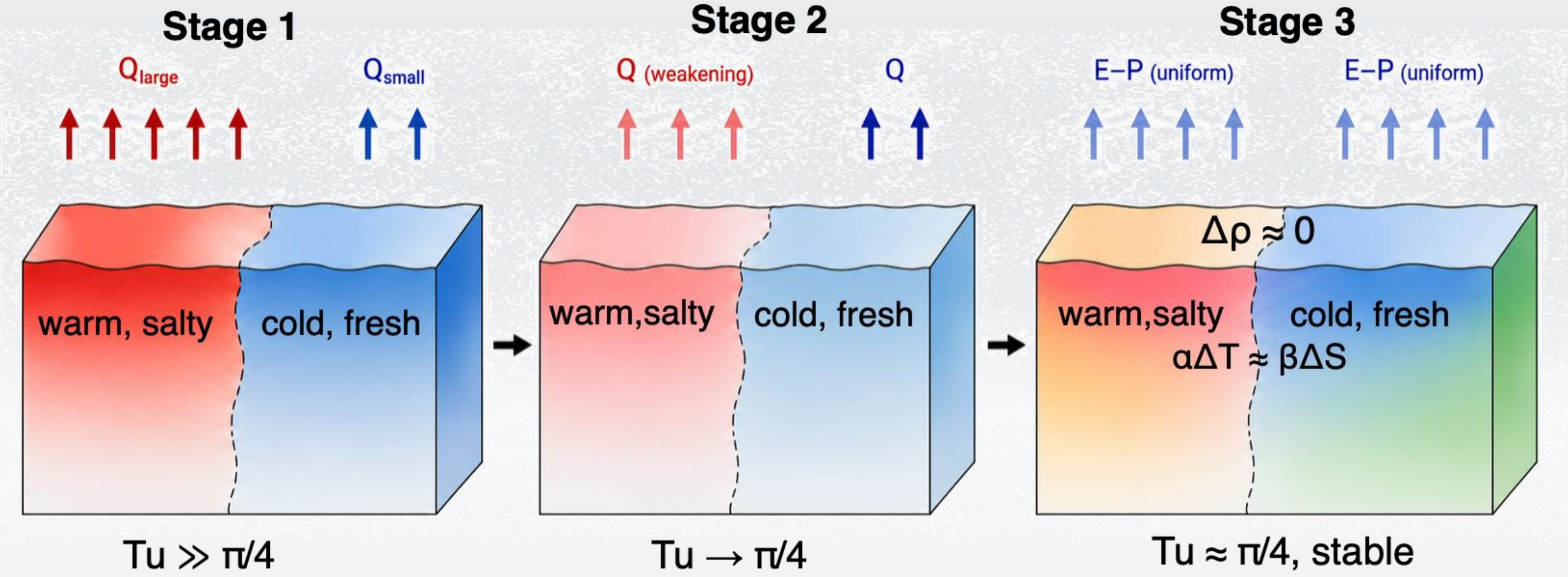
Three behaviors:

- Blue (GS-winter):
  T-dominated at large scales
  → progressively compensated below R_d
  → Tu approaches π/4 at ~10 km
- Red (NAOcean-Summer):
  Near-compensated across all scales, with weak scale dependence under summer stratification.
- Green (NAShelf-Fall)
  S-dominated at all scales, set by large-scale freshwater input, not by submesoscale dynamics.

→ AT O(10 km), two front types lie beyond current satellite SSS resolution:

- T-S compensated fronts, $\Delta\rho \approx 0$
- S-dominated fronts.

Why does compensation intensify below Rd? The atmosphere is the answer.



Salinity winds at fine scales because of differential damping.

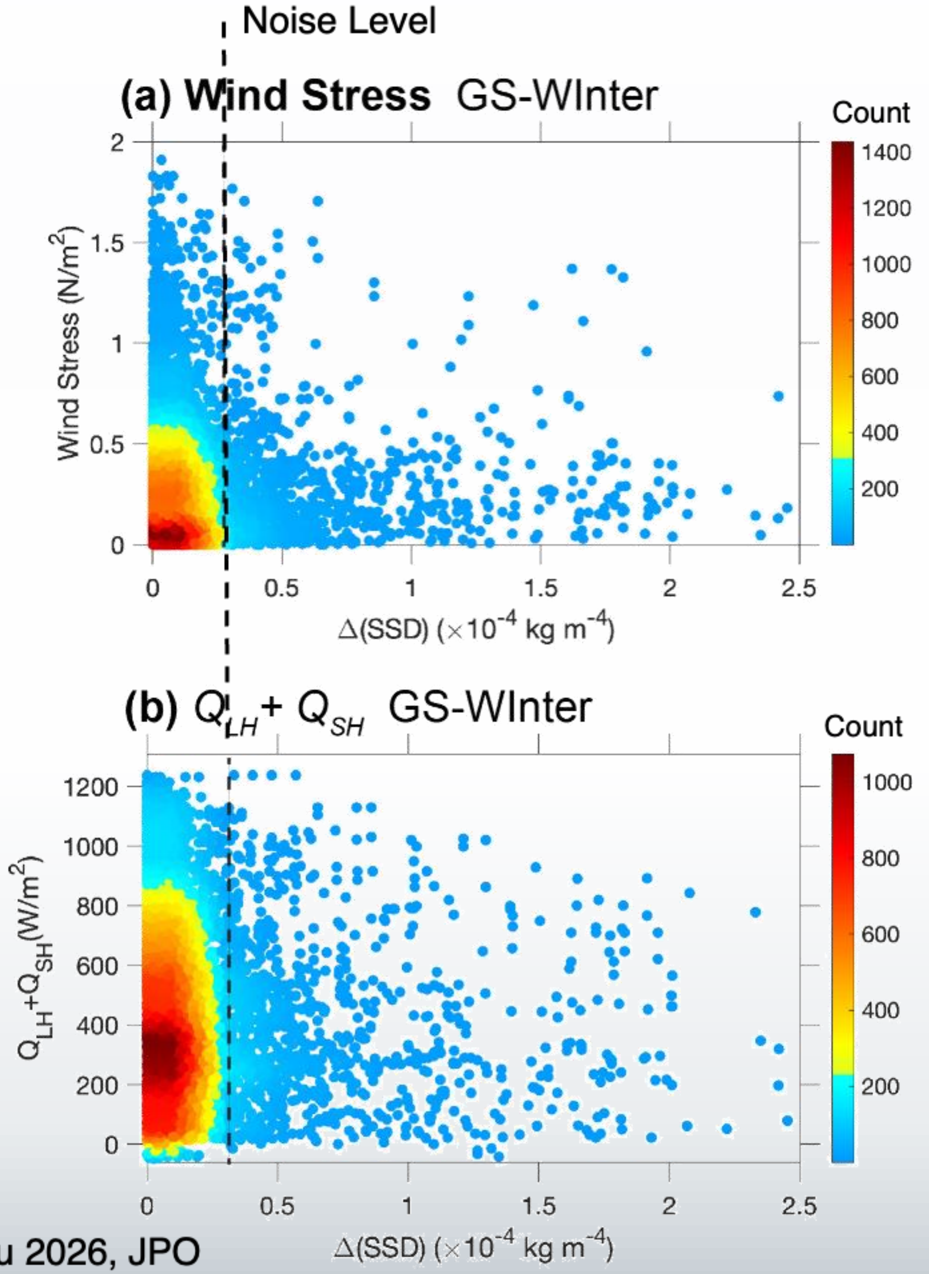
The atmosphere damps temperature fronts, but does not damp salinity.

→ At O(10 km): $\tau_{adv} = L/U \sim \tau_T$. Differential damping drives αΔT toward βΔS.

→ $\tau_T \sim$ days. $\tau_S >> \tau_T$.

→ End state: compensated front. Both T and S gradients present, Δρ ≈ 0.

Compensated Fronts: Stable, Persistent, Invisible to Density Sensors

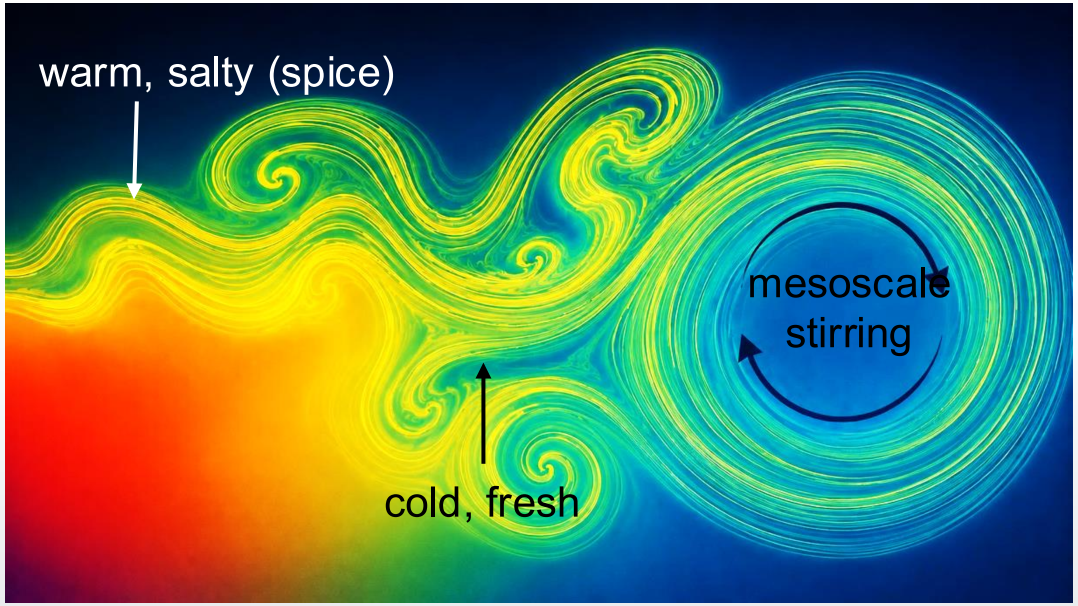


Yu 2026, JPO

Strong forcing drives differential damping
→ $\alpha\Delta T$ is reduced toward $\beta\Delta S$
→ when $\alpha\Delta T \approx \beta\Delta S$: $\Delta\rho \approx 0$
→ compensated end state

Compensated fronts:

sharp gradients visible in T and S field — density field flat ($\Delta\rho \approx 0$)



Compensated T-S: No buoyancy drive, sustained by eddy stirring.

(*Stommel 1993; Ferrari & Young 1997; Rudnick & Ferrari 1999; Smith & Ferrari 2009*)

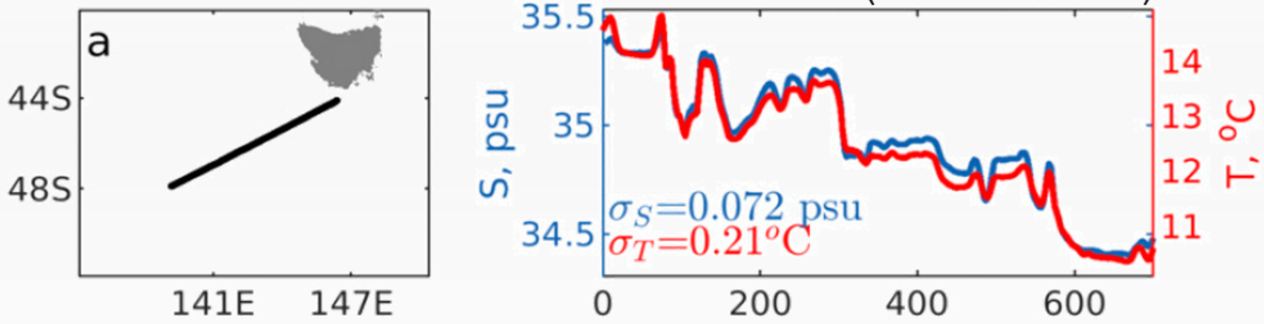
Compensated Fronts: Hidden Density, Active Thermohaline Structure

- $\alpha\Delta T \approx \beta\Delta S \quad \Rightarrow \quad \Delta\rho \approx 0$
- Strong T-S front, weak density front.
- SST alone cannot diagnose compensation.

(*Rudnick & Ferrari 1999*)

TSG data in the southwest of Tasmania (data from 1–2 Jan 2015)

(*Drushka et al. 2019*)



T↑ S↑ → high spice
T↓ S↓ → low spice

Spice: strong T-S structure, weak density signal

Density anomaly:

$$\underbrace{\delta\rho/\rho_0 = \beta\delta S - \alpha\delta T \approx 0}_{\text{terms cancel — weak density front}}$$

Spice:

$$\underbrace{\delta\pi = \alpha\delta T + \beta\delta S \neq 0}_{\text{terms add — strong spice front}}$$

(*Munk 1981; Flament 2002*)

- Water-mass boundary — nutrient, oxygen, carbon, and ecosystem contrasts persist undetected despite strong T and S gradients (*Smith & Ferrari 2009; d'Ovidio et al. 2010; Rudnick & Ferrari 1999*).
- SST sees ΔT. Altimetry sees no height signal ($\Delta\rho \approx 0$). Neither identifies the thermohaline water-mass boundary without salinity.

M^2: The Buoyancy Gradient that Drives Submesoscale Fronts

(1) M^2 measures the front strength:

Surface buoyancy: $b = -g\frac{\rho - \rho_0}{\rho_0}$

Lateral buoyancy gradient: $M^2 \equiv \nabla_h b = g\left(\alpha \nabla_h T - \beta \nabla_h S\right)$

The balance between the thermal term ($\alpha \nabla_h T$) and haline term ($\beta \nabla_h S$), quantified by the Turner angle Tu, determines the front type and dynamical behavior.

(2) M^2 drives vertical exchange at fronts:

Vertical velocity: $w \sim \frac{H^2 M^2}{fL}$

At fronts, w can reach 10–100 m/day, far larger than mesoscale vertical velocities (~ 1 m/day), essential for nutrient supply ↑ and carbon export ↓

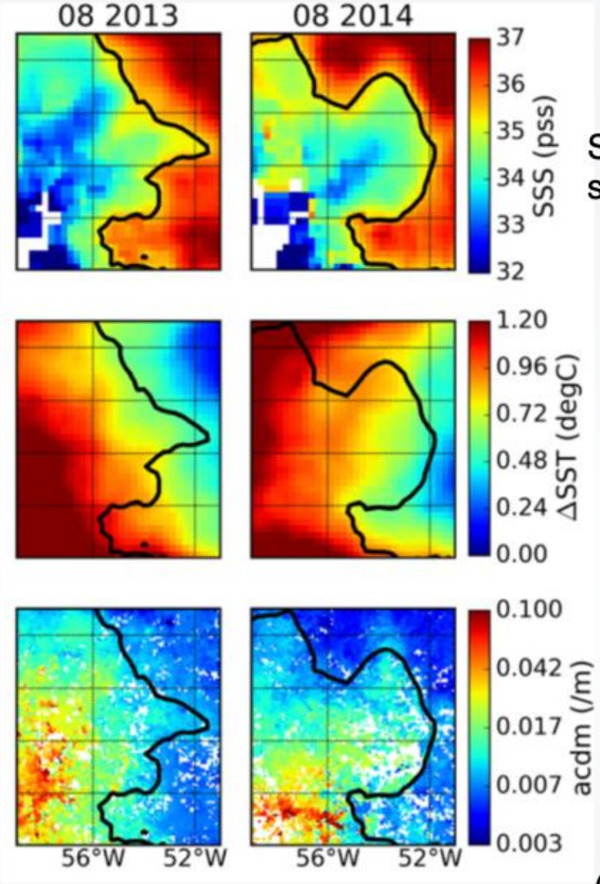
Fox-Kemper et al. (2008); *Klein & Lapeyre* (2009); *Thomas et al.* (2008); *Lévy et al.* (2012); *Mahadevan* (2016)

→ Without SSS at O(10 km), the haline contribution to M^2 is unresolved.

S-dominated (haline) fronts: When Salinity Controls the Density Front

$$\beta \Delta S \gg \alpha \Delta T \quad \Rightarrow \quad T_u < \frac{\pi}{4} \quad \Rightarrow \quad \Delta\rho \approx \rho_0 \beta \Delta S$$

- Origin: freshwater forcing.
- SST signal weak or ambiguous



SSS:
sharp S front visible

SST:
flat – no front

Chl-a:
bloom concentrated
at S front

(*Fournier et al. 2017*)

Salinity Sets M²: The Vertical Pump

Vertical velocity: $w \sim \dfrac{H^2 M^2}{fL}$

~ 10 – 100 m/day vs mesoscale ~ 1 m/day

- $w \uparrow \rightarrow$ nutrients $\rightarrow$ N_2 fixation, phytoplankton bloom.
- $w \downarrow \rightarrow$ carbon subduction $\rightarrow$ biological pump.

Region	**S forcing**	**Biological consequence**
Amazon plume	River discharge:	N_2 fixation *(Subramaniam et al. 2008)*
Bay of Bengal	Monsoon freshwater	bloom modulation *(Jaeger & Mahadevan 2018)*
Arctic meltwater	Ice melt	Under-ice bloom *(Giddy et al. 2021)*

Without SSS at O(10 km), M² cannot be resolved and vertical exchange remains unquantified.

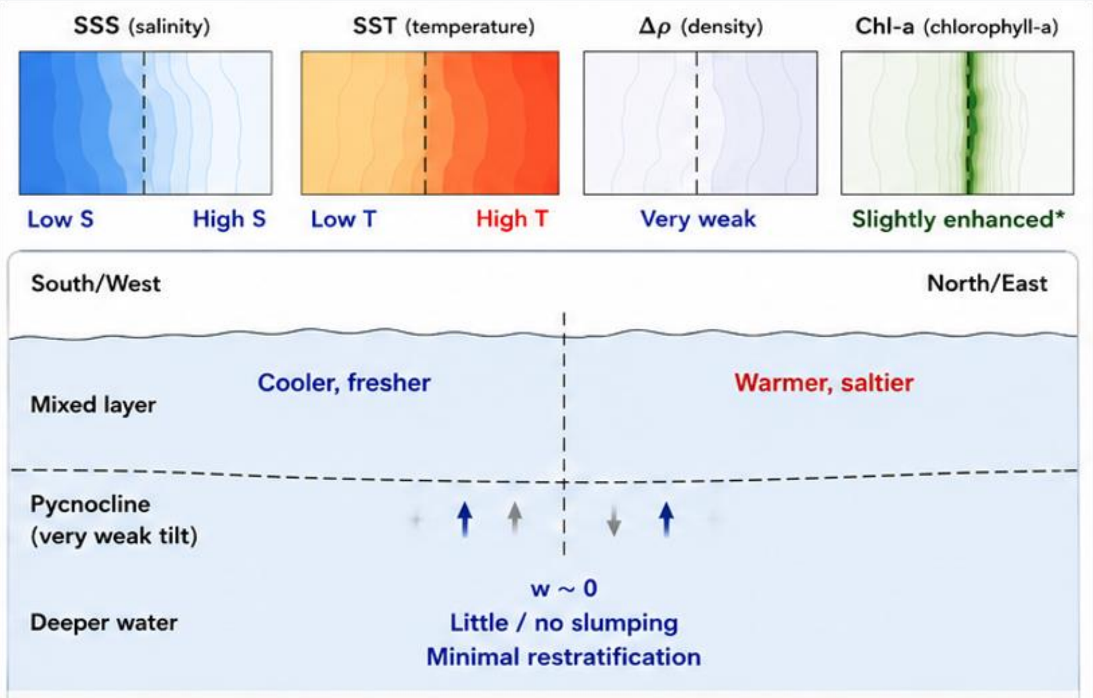
Compensated and S-Dominated Fronts: M2, Vertical Exchange, and Biology

Compensated (Spice) Front

- *Hidden thermocline structure*
- $\Delta\rho \approx 0$ (M^2 small, residual). Strong T&S gradients, weak density signal

Surface (plan view)

Vertical Cross-section



SSS (salinity)

SST (temperature)

$\Delta\rho$ (density)

Chl-a (chlorophyll-a)

Low S High S

Low T High T

Very weak

Slightly enhanced*

South/West

North/East

Mixed layer

Cooler, fresher

Warmer, saltier

Pycnocline (very weak tilt)

Deeper water

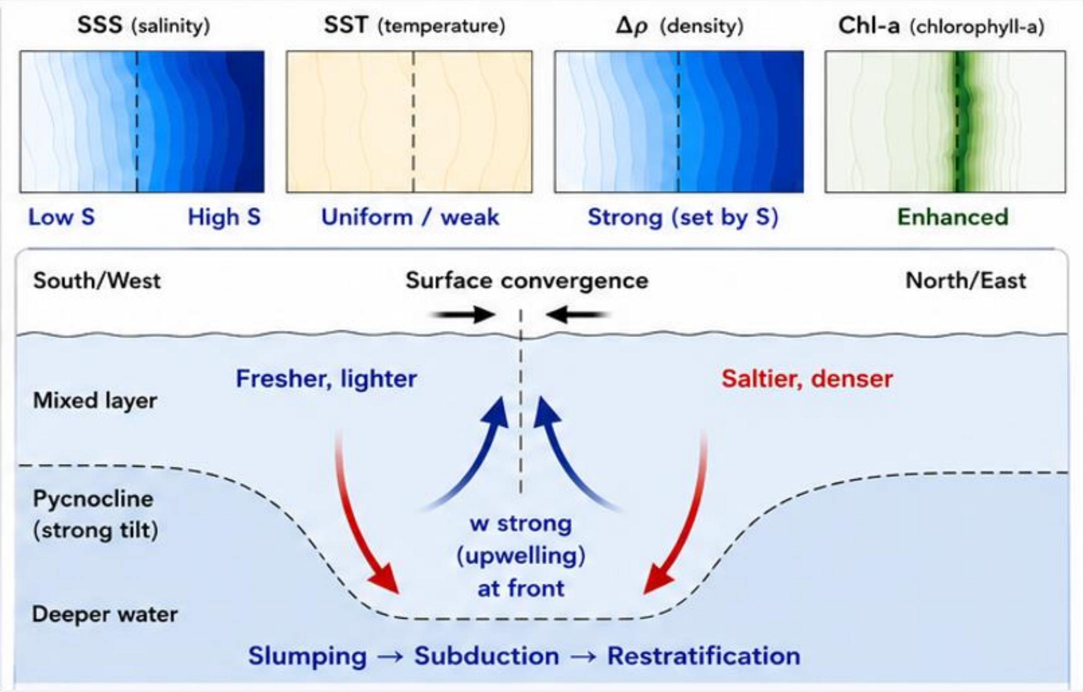
w ~ 0

Little / no slumping

Minimal restratification

S-dominated Density (Haline) Front

- *Active density front and vertical pump*
- $\Delta\rho \approx \rho_0 \beta \Delta S$ (M^2 large). Salinity sets the density front



SSS (salinity)

SST (temperature)

$\Delta\rho$ (density)

Chl-a (chlorophyll-a)

Low S High S

Uniform / weak

Strong (set by S)

Enhanced

South/West

Surface convergence

North/East

Mixed layer

Fresher, lighter

Saltier, denser

Pycnocline (strong tilt)

w strong (upwelling) at front

Deeper water

Slumping → Subduction → Restratification

- Not all salinity fronts are density fronts
- Compensated (spice) fronts store and transport thermohaline structure; set water mass and ecosystem boundaries.
- S-dominated (haline) fronts convert salinity gradients into circulation and vertical exchange; fuel productivity and carbon cycling.
- Both requires finer-resolution SSS to identify correctly

The physics raises three questions

(1) Thermal fronts also drive M^2 and the vertical pump — what makes the salinity contribution unique?

(2) Are compensated and haline fronts local exceptions — or a global ocean feature?

(3) What does O(10 km) SSS add that SWOT, PACE, and SST — together — cannot provide?

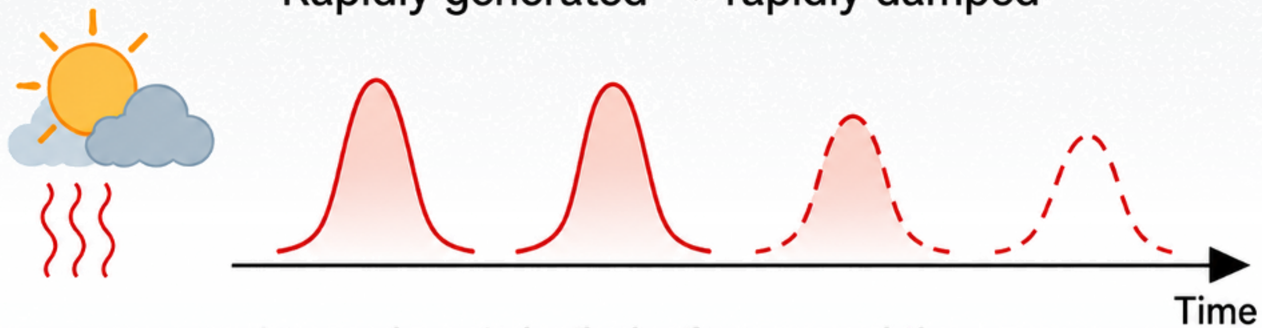
(1) Thermal vs Haline Fronts: Same Vertical Pump, Different Lifetime

	T-dominated (thermal)	**S-dominated (haline)**
M^2 magnitude	Large (when front exists)	Large (when $\beta\Delta S$ large)
Instantaneous *w*	Yes	Yes — same mechanism
Atmospheric restoring	$\tau_T \sim$ days	$\tau_S \gg \tau_T$
Individual front	Transient	Longer lived
Detectable from	Current SST sensor generally sufficient	**Require resolved SSS**

- Same M^2 dynamics, different damping timescale.
- Salinity changes when and where that dynamics survives.

Thermal fronts (SST-dominated)

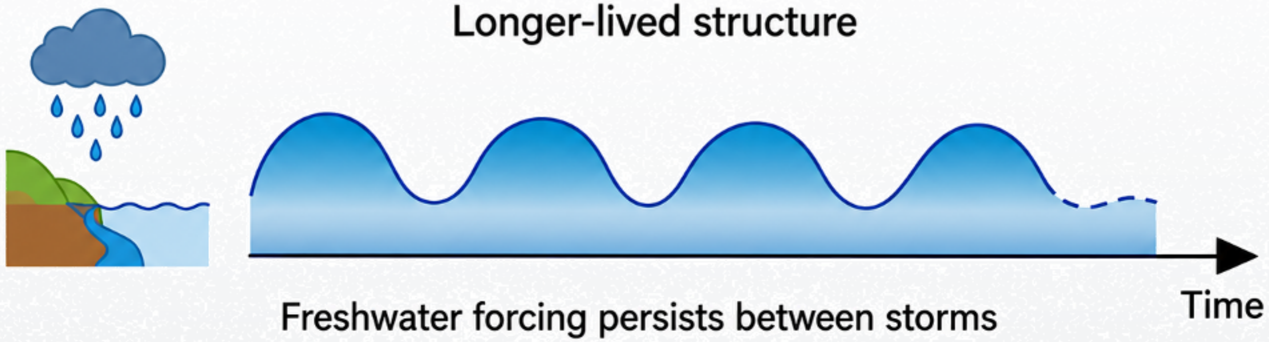
Rapidly generated → rapidly damped



Atmosphere is both the factory and the eraser.

Haline fronts (SSS-dominated)

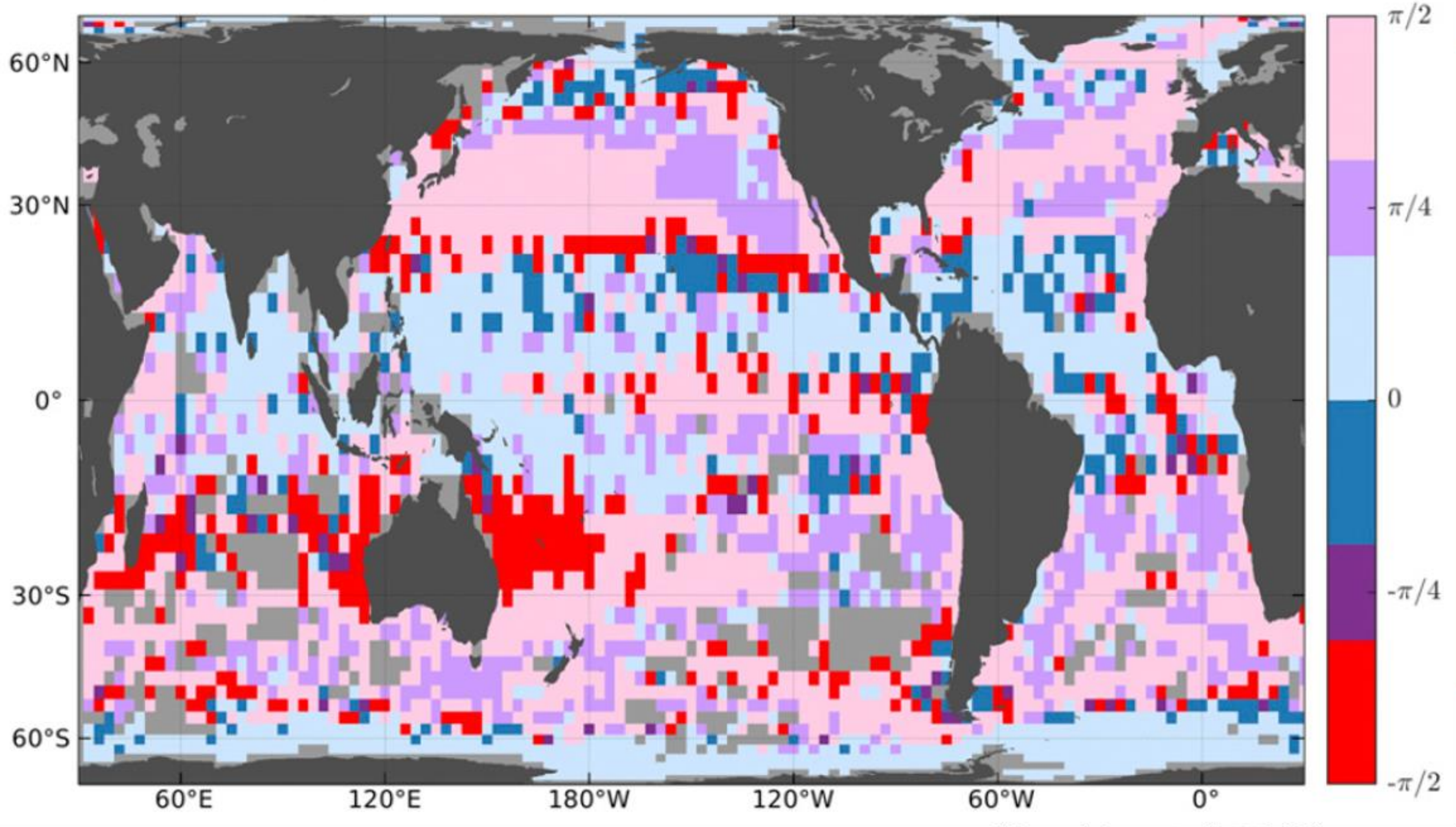
Longer-lived structure



Freshwater forcing persists between storms
— no atmospheric restoring.

(2) Global Reach: Compensated and S-Dominated Fronts in Every Basin

Turner angle (Tu) computed over 10-km horizontal scales

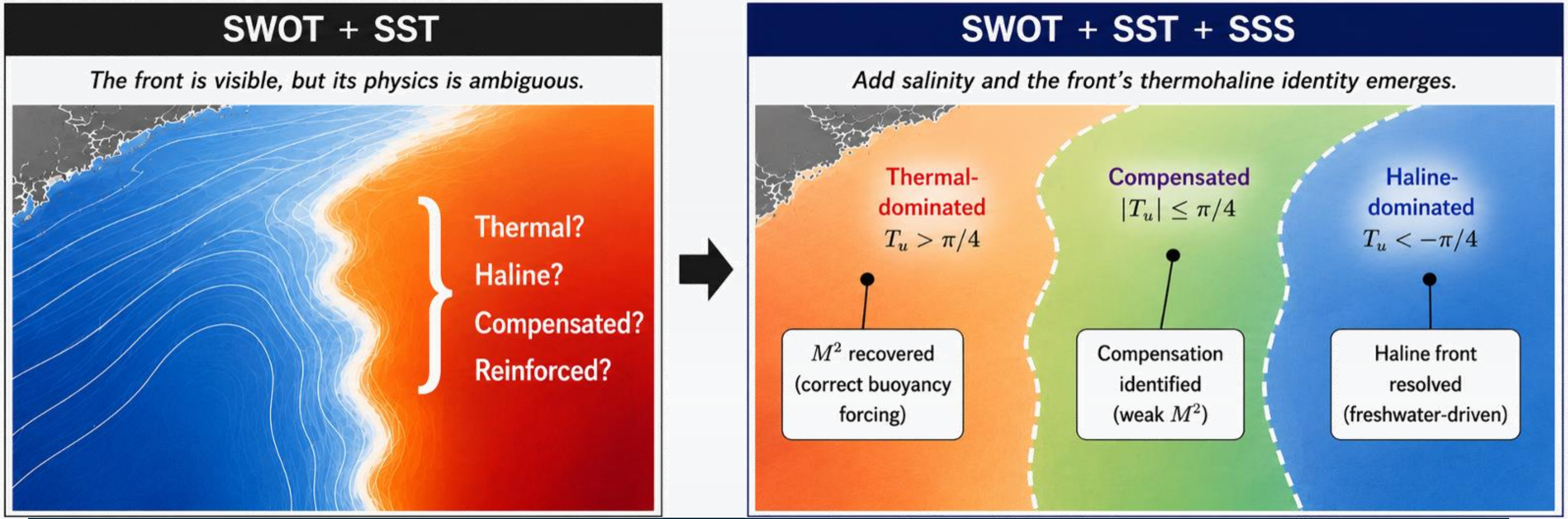


(*Drushka et al. 2019*)

- This map shows statistical occupancy, not front lifetime.
- Short-lived does not mean rare — the atmosphere continuously regenerates thermal fronts. That explains the thermal dominance over large regions.
- Haline dominance requires a freshwater source to outcompete the background thermal gradient — concentrated, but not absent.

(3) What O(10 km) SSS Adds that SWOT, PACE, and SST cannot?

- SWOT sees the height of the front
- PACE sees the biological response to buoyancy structure
- SST sees the temperature structure



SWOT + SST

The front is visible, but its physics is ambiguous.

SWOT + SST + SSS

Add salinity and the front's thermohaline identity emerges.

SSS reveals the front's thermohaline identity.
Implications:

- Completes buoyancy forcing (M^2) → more accurate restratification
- Constrains compensation state → better mixing parameterizations
- Connects salinity structure to biological productivity, carbon exchange, and biogeochemistry.

Summary

- **From rain gauge to dynamical driver: Dominant balance shifts as scale changes.**
  - At 1,000 km, SSS records the water cycle; in the interior it traces circulation; at O(10 km), it rivals temperature in frontal density control.

- **Differential atmospheric damping makes SSS a dynamical driver at O(10 km).**
  - Air-sea heat flux restores temperature fronts (τ_T ~ days), but salinity has no restoring ($\tau_S >> \tau_T$).
  - Below Rd, timescales converge and this asymmetry accumulates salinity gradients, driving fronts toward compensation.
  - Two front types emerge: compensated and S-dominated – neither resolved by 40-km satellite SSS.

- **Not all salinity fronts are density fronts.**
  - Compensated fronts carry strong T–S gradients at $\Delta\rho \approx 0$ — their spice sustains water-mass contrasts in nutrients, oxygen, and carbon invisible to density sensors.
  - S-dominated fronts ($\Delta\rho \approx \rho_0\beta\Delta S$) convert salinity gradients to circulation, fueling productivity and carbon cycling where thermal fronts have been damped.
  - Salinity helps reveal the front's thermohaline identity.

- **Implications:**
  - O(10 km) SSS adds the missing freshwater–buoyancy dimension, linking frontal dynamics to biological productivity, carbon cycling, and Earth system model fidelity.