LES of the wind-driven boundary layer with vertical and horizontal gradients of buoyancy

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Motivations

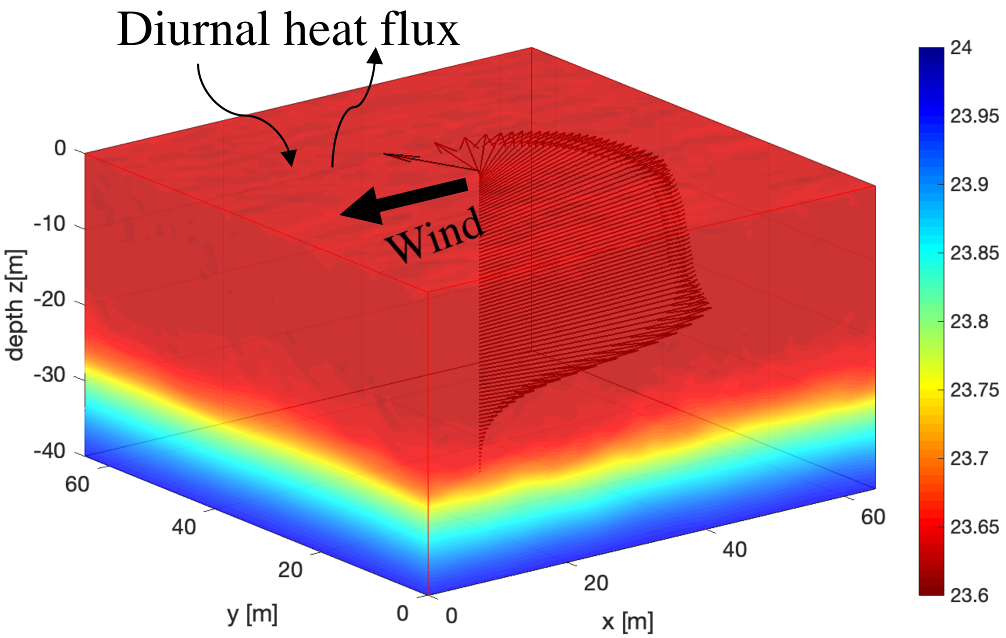
- High-resolution LES studies of upper-ocean turbulence in two process studies whose environmental parameters (stratification, wind stress, etc.) are guided by recent observational campaigns in the Bay of Bengal.

- Process # 1: Simulations of **a diurnal warm layer** to quantify turbulent fluxes and surface temperature in response to the diurnal cycle of heat flux.

- Process # 2: Simulations of **a fresh water filament** influenced by wind to explore frontal instabilities and turbulence that emerge and lead to qualitative differences in the vertical structure between the two sides of the front.

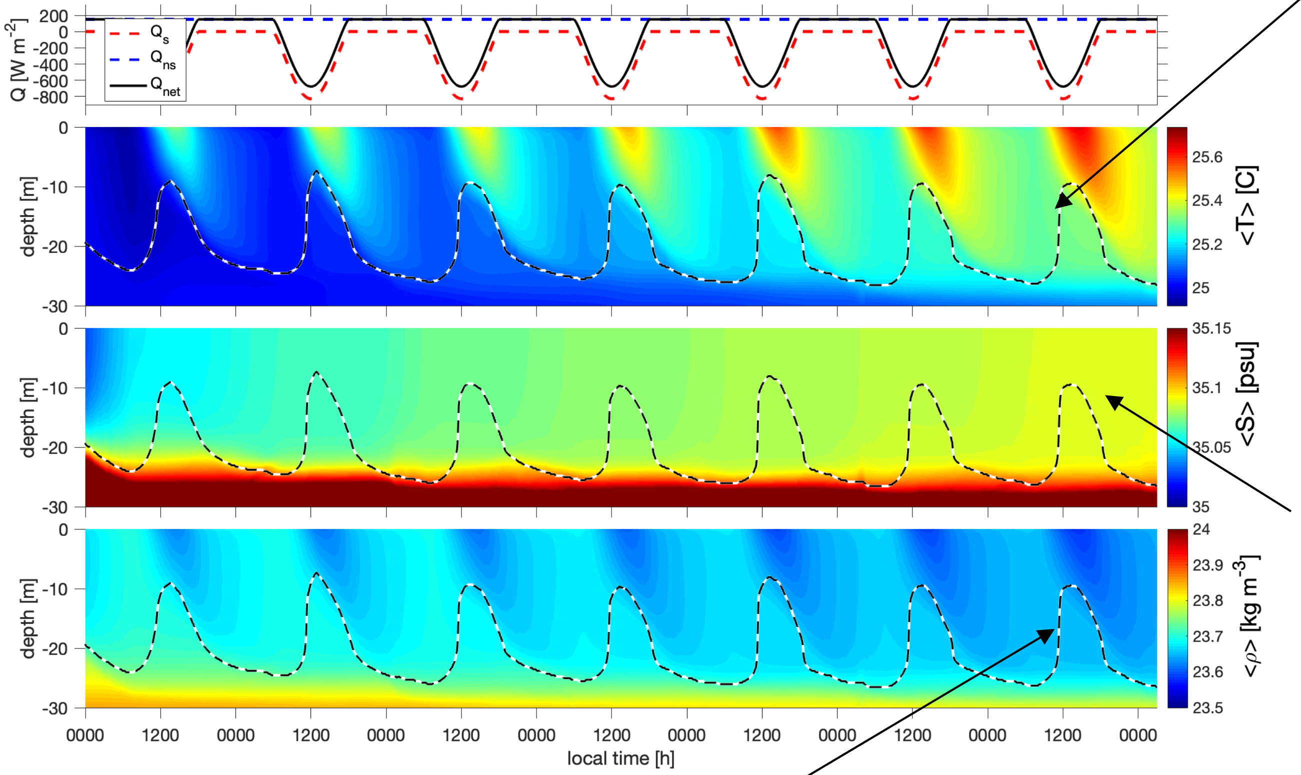
- Additional objectives:
    - provide a benchmark solution for use in a coordinated study with other modelers in MISO-BOB to evaluate the accuracy of 1-D mixing parameterizations
    - provide upscaled fluxes in regional-model computations of the Bay of Bengal in flows with both vertical and horizontal buoyancy gradients.

LES of a diurnal warm layer (DWL)



- A 20-m mixed layer driven by a constant westward wind stress $\boldsymbol{\tau}$ = -0.06 N m^{-2} on top of a halocline with N^2 = 10^{-4} s^{-2} at 18 N. The temperature is constant with depth to model the isothermal layer inside a barrier layer.
- Spin-up of turbulence for 15 hours to generate the 20-m mixed layer with a surface current.
- Diurnally heat flux: Q_{ns} = 150 W m^{-2} and Q_s with a peak of -827 W m^{-2}.
- Evolution of the diurnal warm layer is simulated for 7 days.
- Domain: 64 m x 64 m x 85 m with a grid of 128 x 128 x 256.
- Grid resolution: horizontal: 0.5 m; vertical: 0.1-0.2 m in the top 30 m, stretched at 3% in the halocline.

Variability of Temperature and Salinity



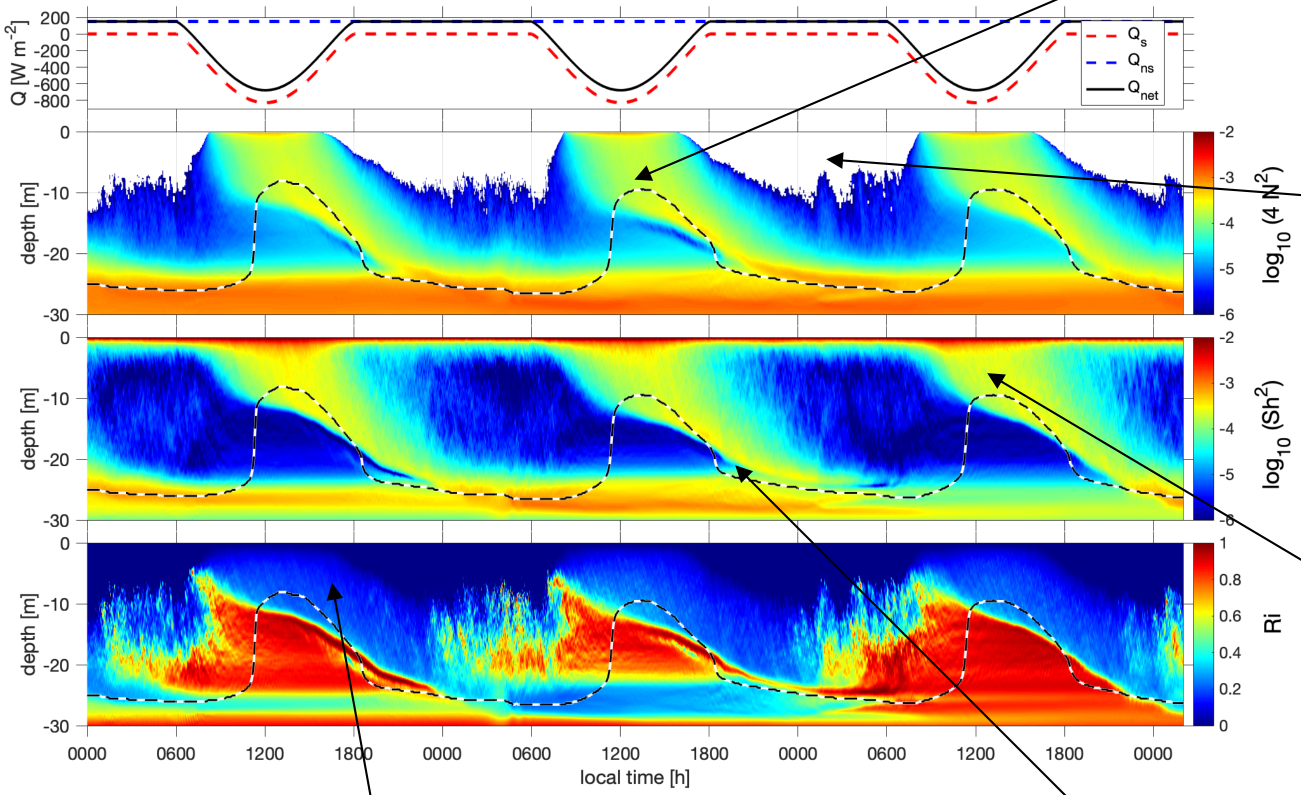
Daily-averaged temperature in the SML increases due to a daily net heat flux of Q = -95 W m^{-2} through the surface

Salinity in the mixed layer increases in time due to turbulent entrainment of saline water from the halocline

In spite of the salinity increase, density in the mixed layer decreases in time due to the heat accumulation in response to the surface heat flux.

Diurnal warm layers

Enhanced stratification during day-time in the top 10 m layer.



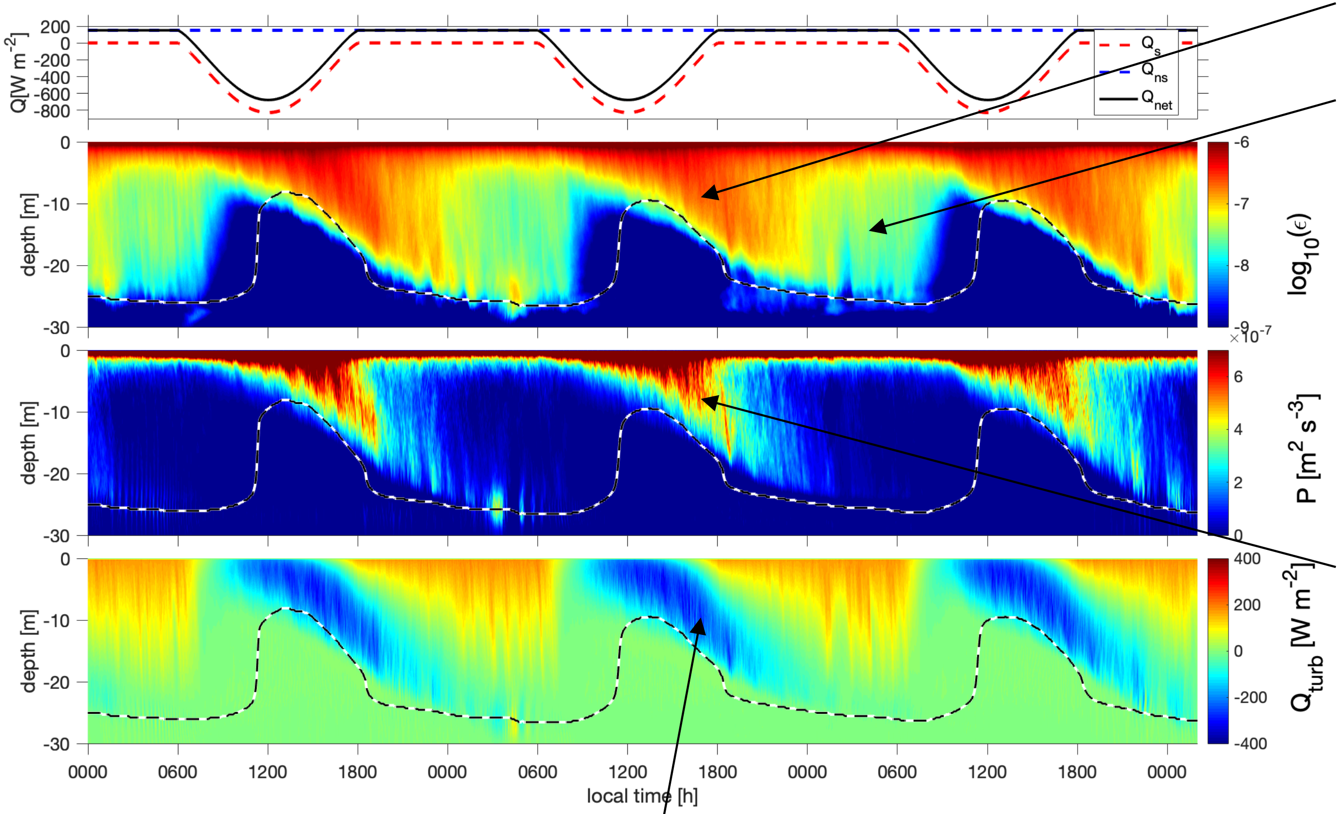
Night-time 10-m deep convective layer with $N^2 < 0$

Diurnally-enhanced surface jet (Moulin et al. , JPO 2018)

The diurnal surface jet and the descending shear layer have a narrow range of Ri ~ 0.25.

Descending shear layers from 10 to 20 m depths (analog to EUC study by Pham et al. , JPO 2017)

Variability of turbulence

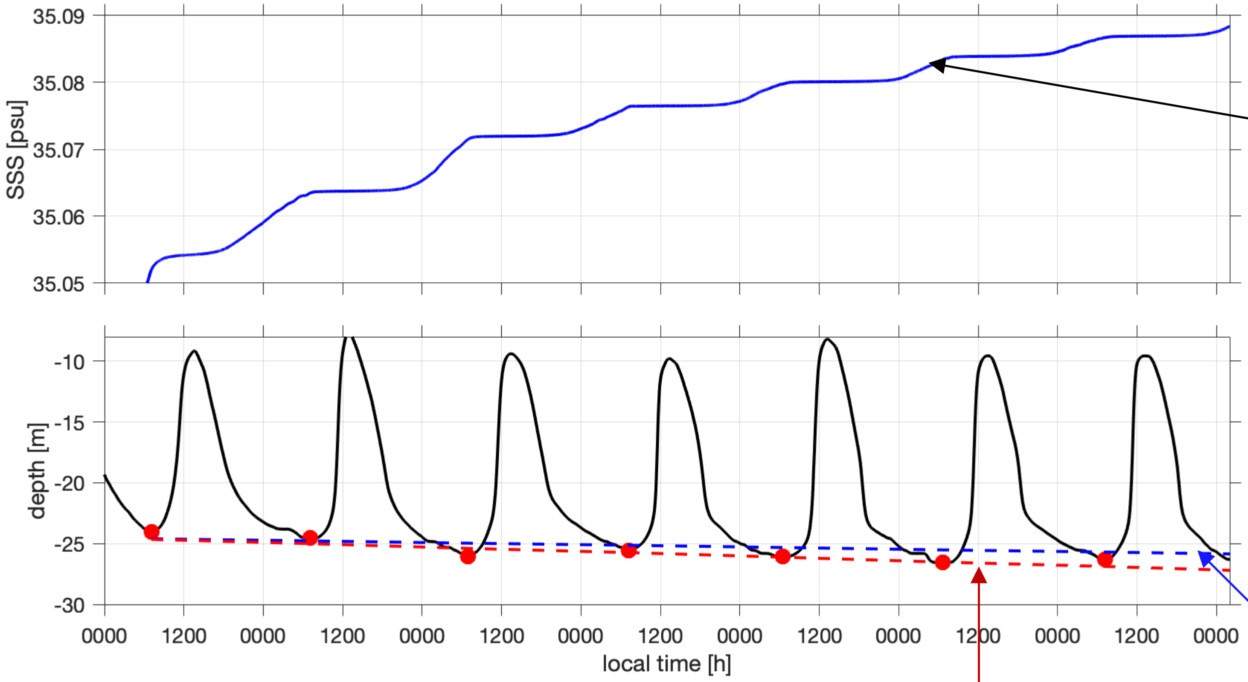


Night-time dissipation: strong during evening and weaker after midnight by an order of magnitude.

The strong dissipation is driven by shear production associated with the DWL and the descending shear layer

During the late afternoon, turbulence transports nearly all solar heat flux from the surface to 20-m depth in just a few hours.

Turbulent entrainment



Diurnal variability of SSS: SSS increases only at night time when the MLD is farthest from the surface. The time rate of change of SSS decreases as the MLD gets larger.

Late-time entrainment rate with no diurnal heat flux (Pham & Sarkar, 2014):

$$\boxed{\frac{dh}{dt} = 0.049\frac{u_*^2}{N_0 h(t)}}$$

Entrainment rate with diurnal heat flux is slightly larger:

$$\frac{dh}{dt} = 0.1\frac{u_*^2}{N_0 h(t)}$$

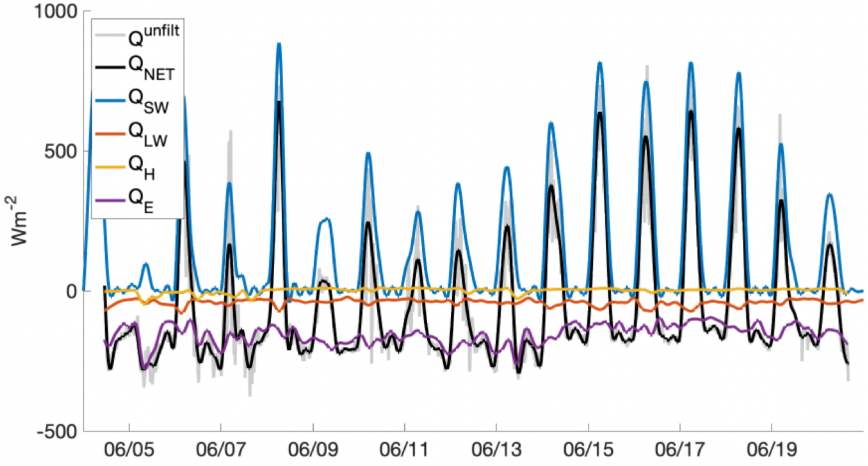
Diurnal Warm Layer Summary

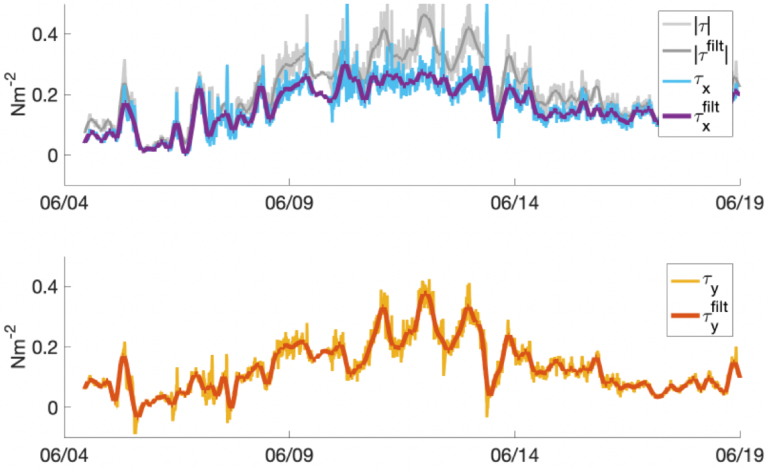
- The diurnal cycle of the heat flux drives diurnal variability of stratification, shear, Richardson number and turbulent mixing of heat and salinity in the SML.

- The dissipation is strongest during the late afternoon when the surface jet and the corresponding shear layer become unstable.

- Nearly all downward heat flux is transported to the bottom of the ML by the turbulent flux associated with the surface jet.

- Future work: LES using initial conditions and surface forcing that was observed during the summer 2018 cruise including evaporation and precipitation.

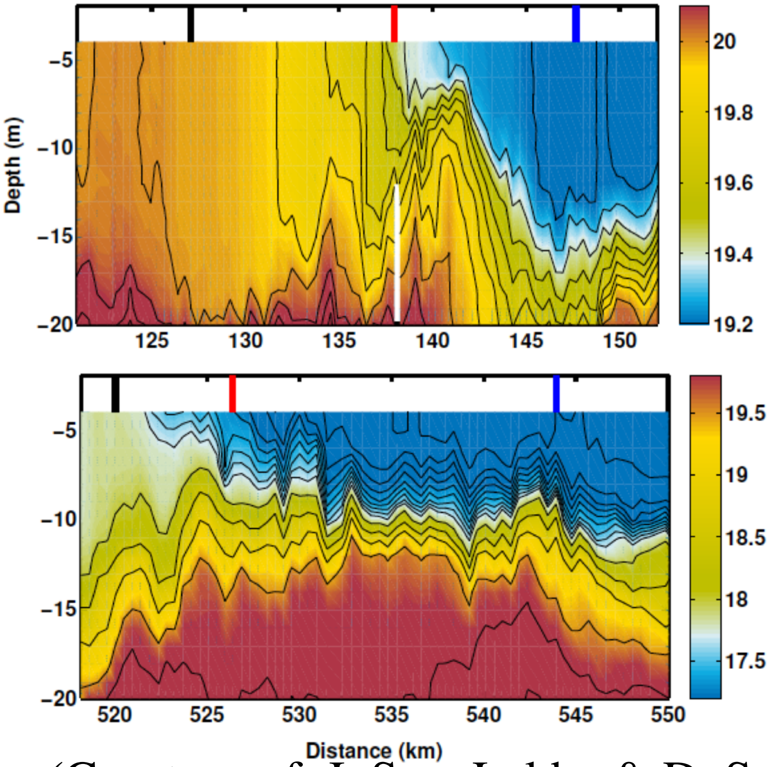




Courtesy of Leah Johnson & Baylor Fox-Kemper

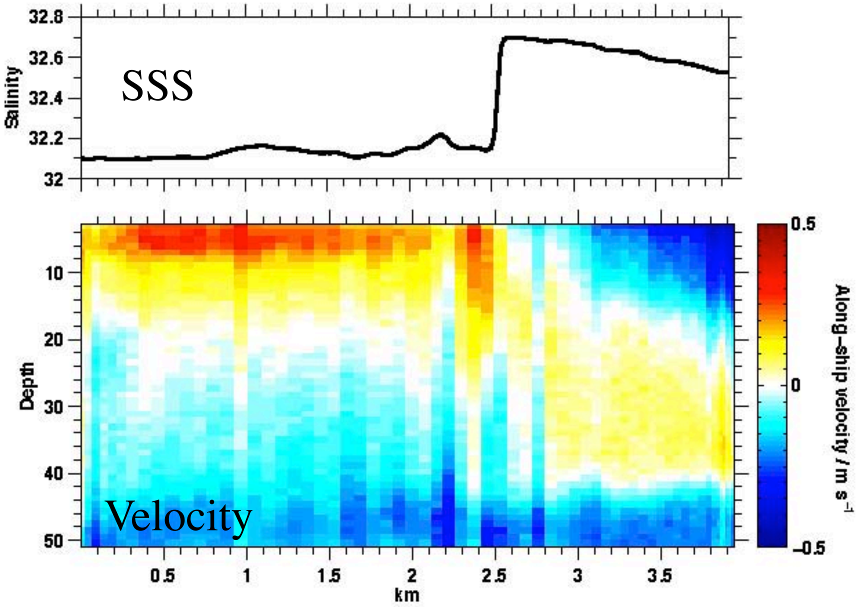
Fronts and Bores in Bay of Bengal

Shallow fronts



(Courtesy of J. Sree Lekha & D. Sengupta)

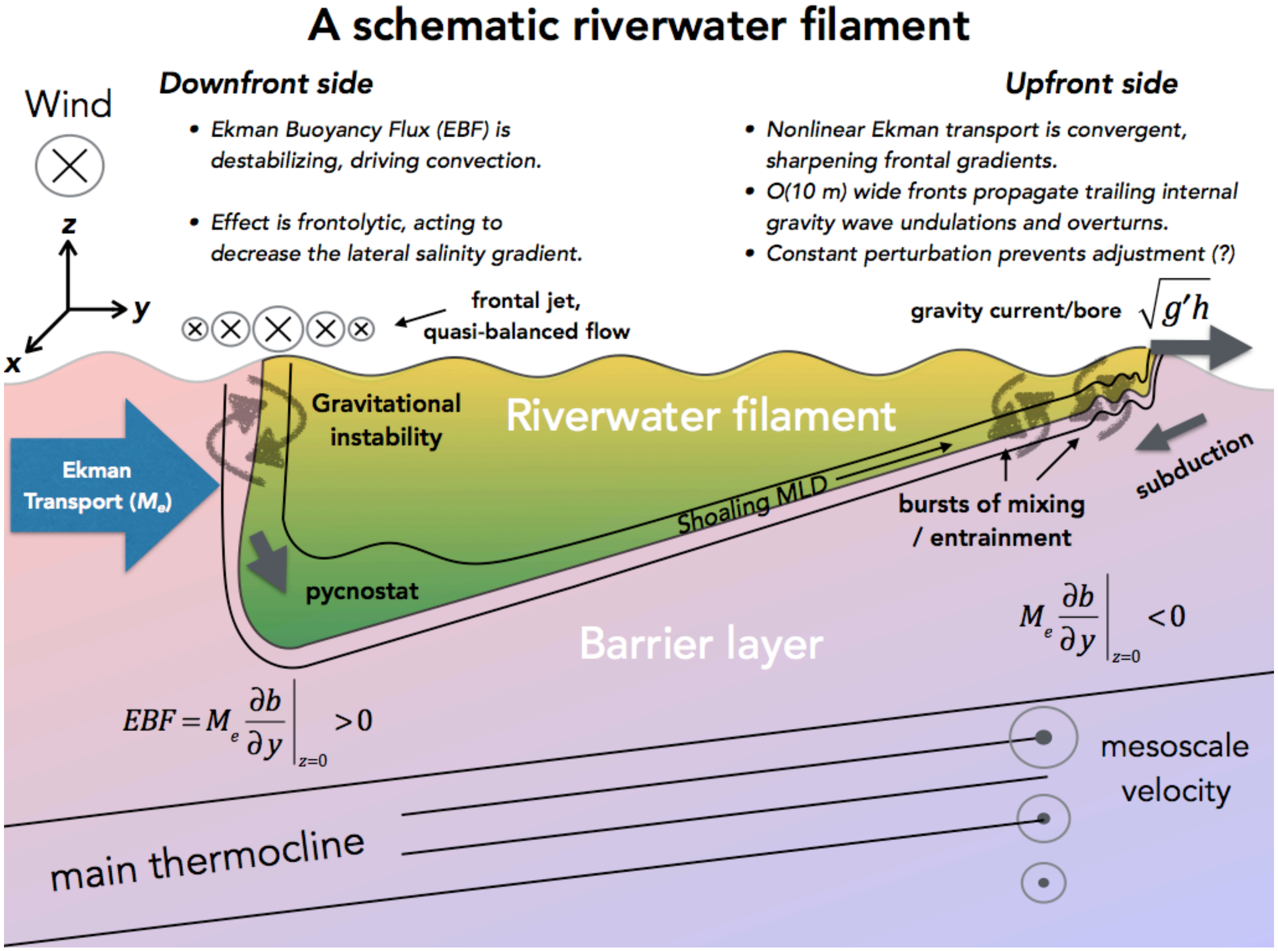
Gravity currents / Nonlinear bores



(Courtesy of J. Nash, J. MacKinnon & A. Lucas)

- Shallow fronts: width ~ 10 km, depth ~ 20 m, strong lateral density gradient $M^2/f^2 \sim 500$, with geostrophic jet, vertical density gradient N^2 varies with Ri_g between 0 and 1.
- Nonlinear bores: sharp salinity and temperature increase over a few meters,
- Shallow MLD (< 5 ma t front & bores) influences the air-sea fluxes.
- Initially-balanced front, if strong, can develop bores. Pham & Sarkar, JPO (2018).
- What is the role of surface wind in thickening / thinning the MLD at fronts?

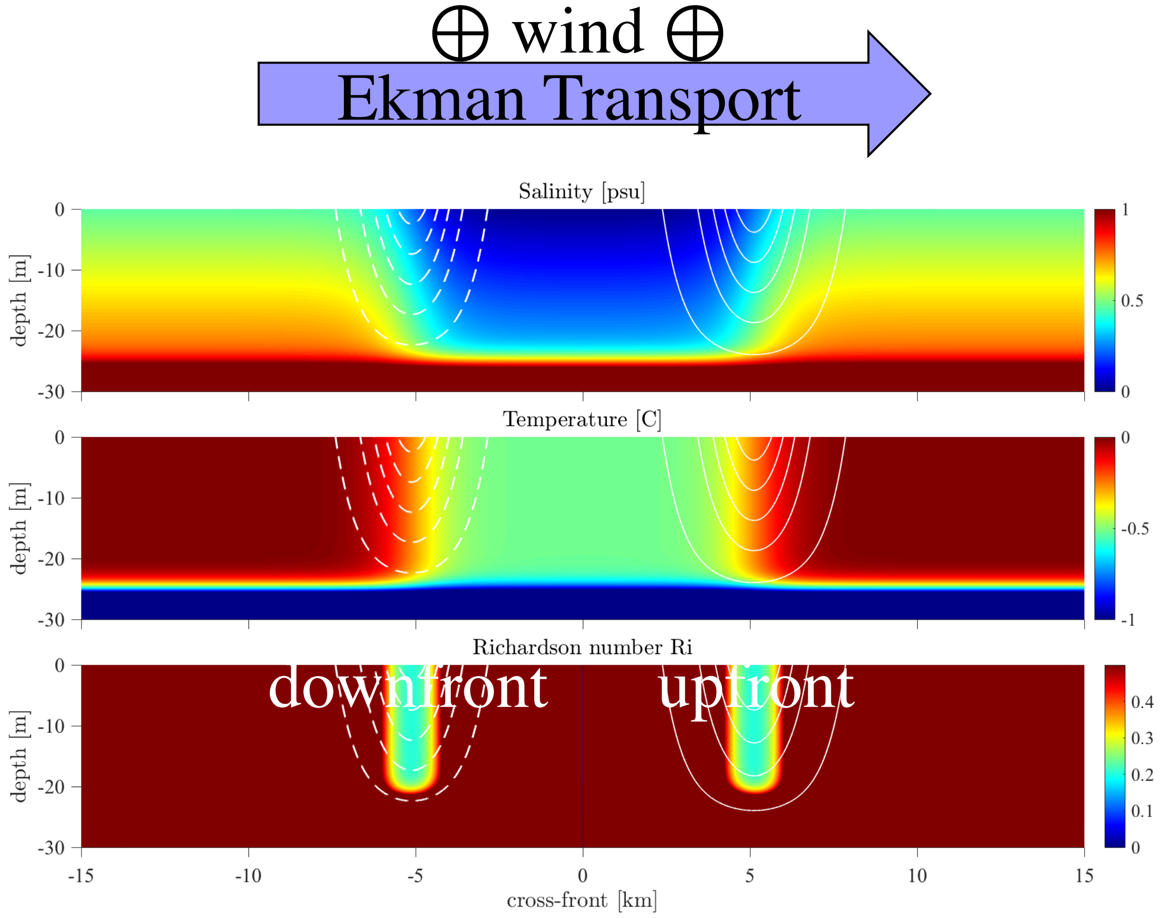
Hypothesis: from fronts to bore



(Courtesy of A. Lucas)

- Process study of the evolution of the MLD on the downfront and upfront sides of the filament.
- Explore how turbulence (from wind-driven BL and from frontal instabilities) controls the MLD at shallow fronts.

A fresh water filament



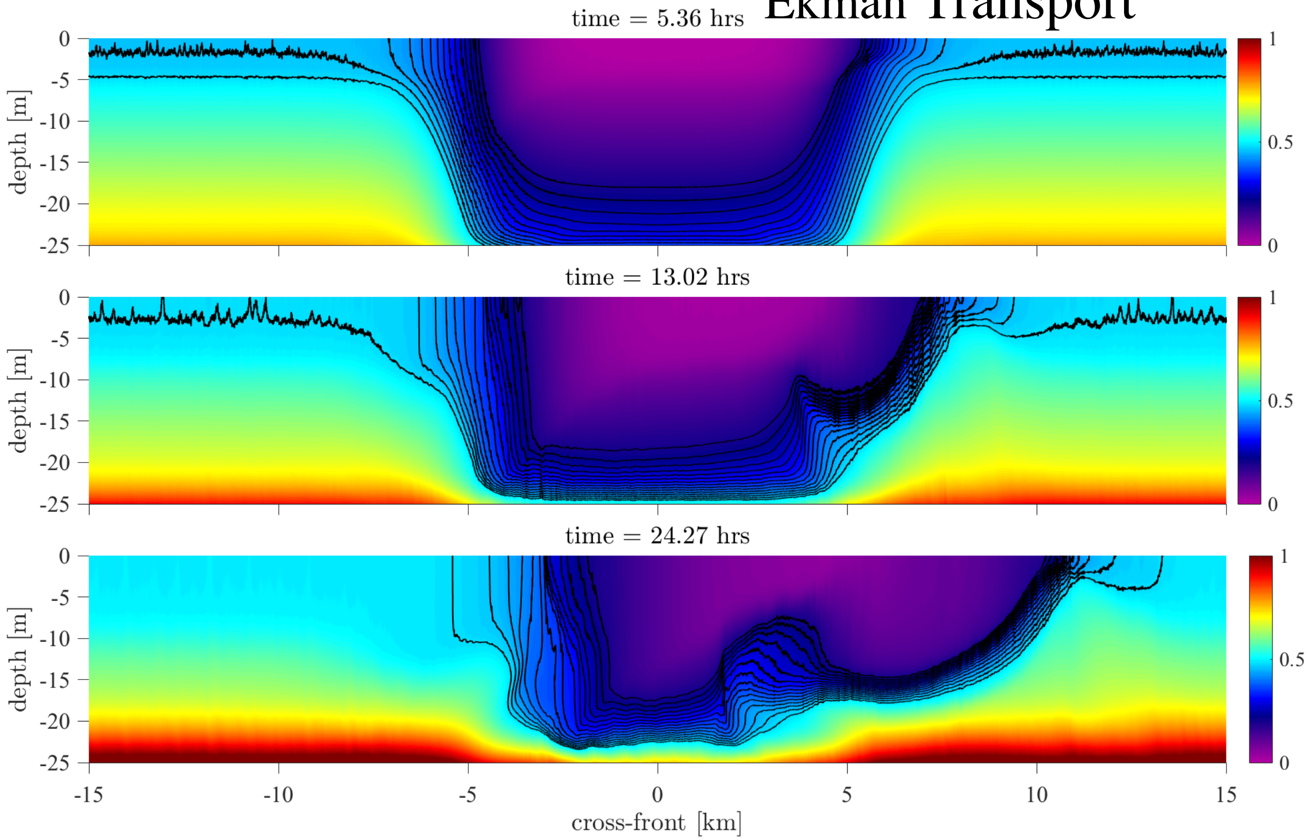
- A partially compensated salinity-controlled geostrophically-balanced light,fresh filament with a uniform **weak** wind stress of -0.02 N m^{-2}
- Front characteristics: depth (30 m), width (2.56 km), stability (Ri_{min} = 0.2)
- Domain: 50 km (cross-front) x 160 m (along-front) x 75 m (vertical) with a grid resolution of 1.25 m x 1.25 m x 0.25 m
- LES parameterization utilizes filtered structure function (Ducros et al. 1996)

Evolution of salinity

Salinity

⊕ wind ⊕

Ekman Transport



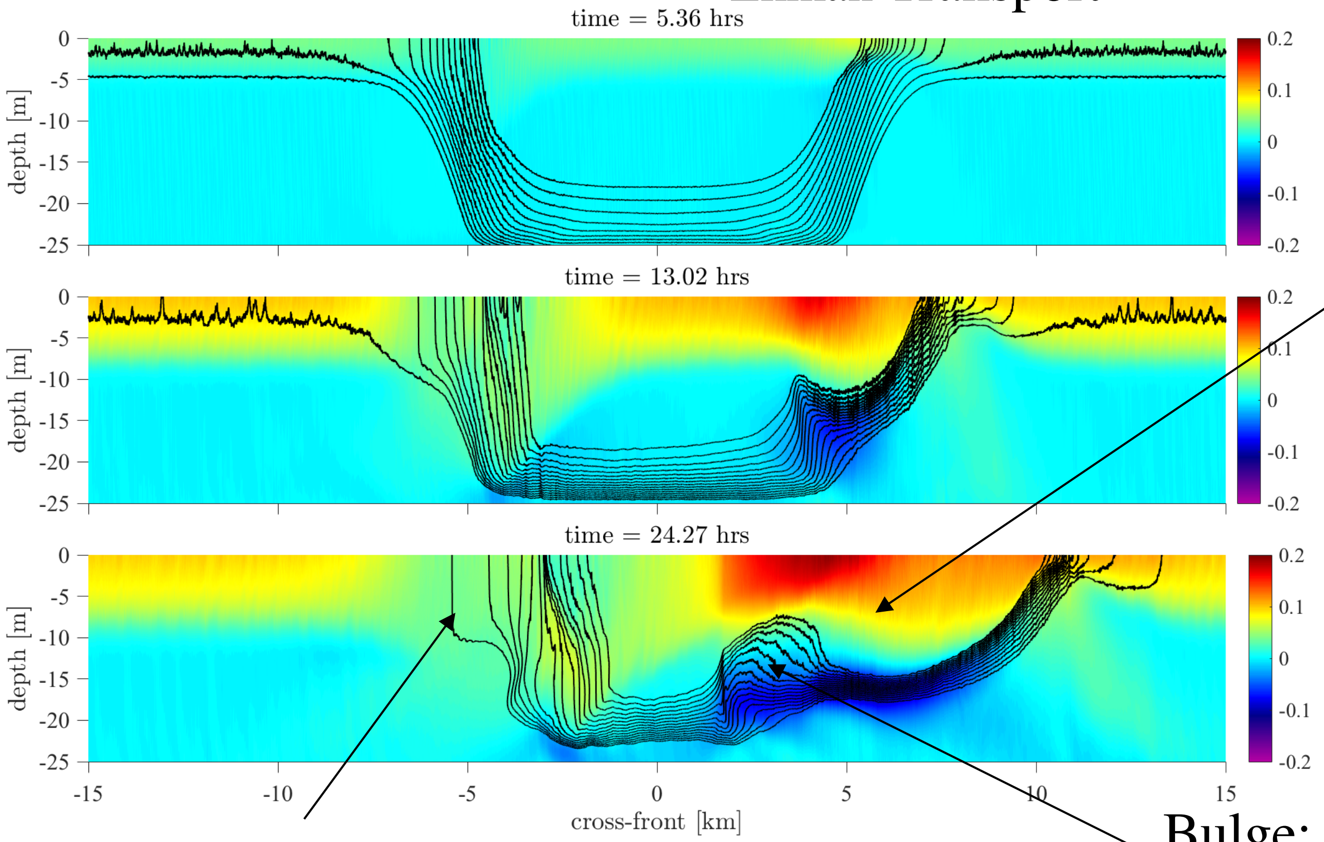
- Overall, the entire filament is advected laterally by the Ekman transport.
- **Upfront side** Enhanced spreading of surface water since pressure gradient and Ekman transport are co-directed. Both, vertical and lateral density gradient, increase.
- **Downfront side** Ekman transport overcomes the pressure gradient. Decrease in vertical and lateral density gradient.

Cross-front circulation

Lateral velocity (v)

⊕ wind ⊕

Ekman Transport

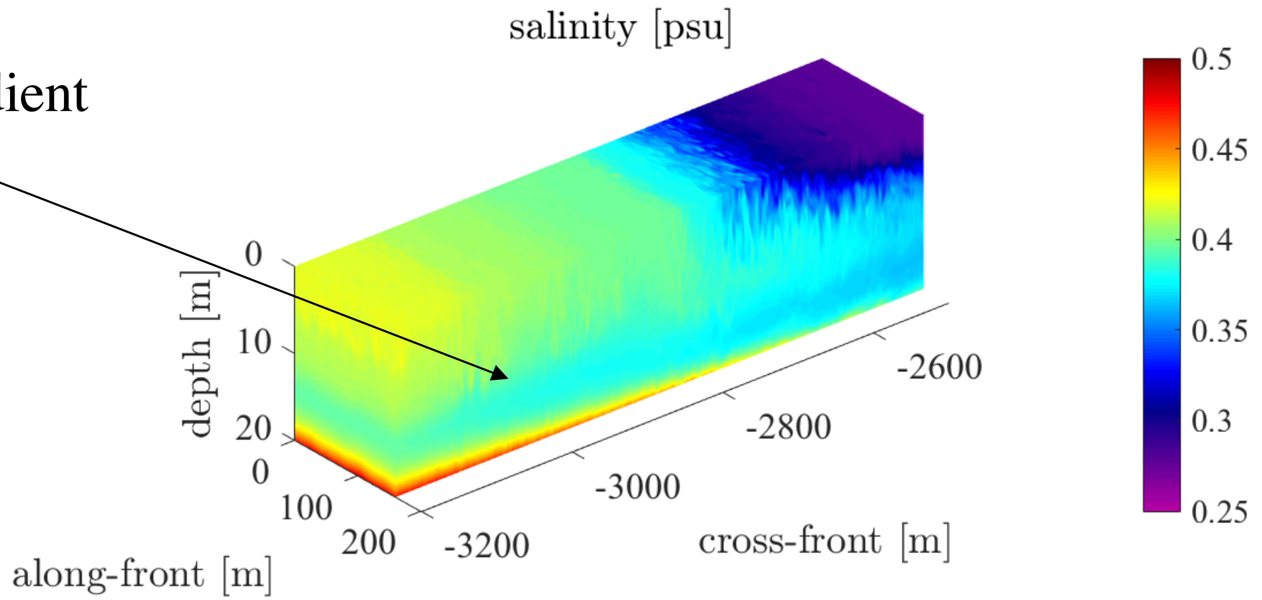


Upfront side: strong ageostrophic secondary circulation (ACS). Positive velocity at surface (gravity current) + negative velocity at depth (countercurrent / subduction).

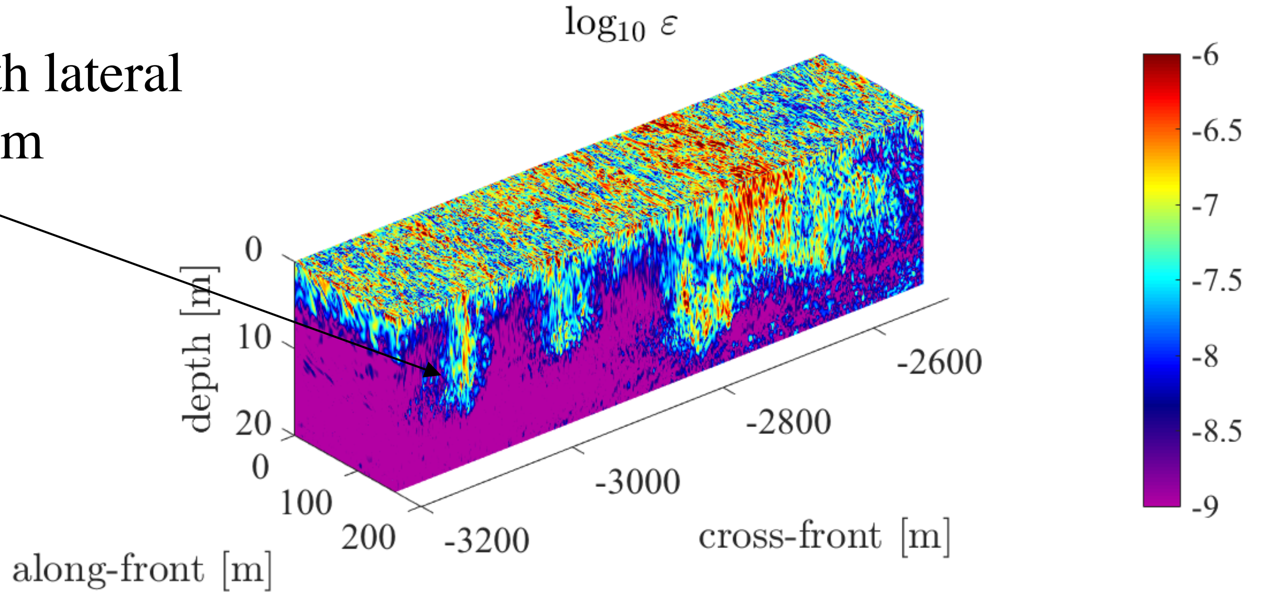
Downfront side: weak cross-front velocity. Ekman transport is disrupted due to convective turbulent mixing

Bulge: enhanced turbulent mixing at the leading nose of the counter current

Turbulence Structure: Downfront Side

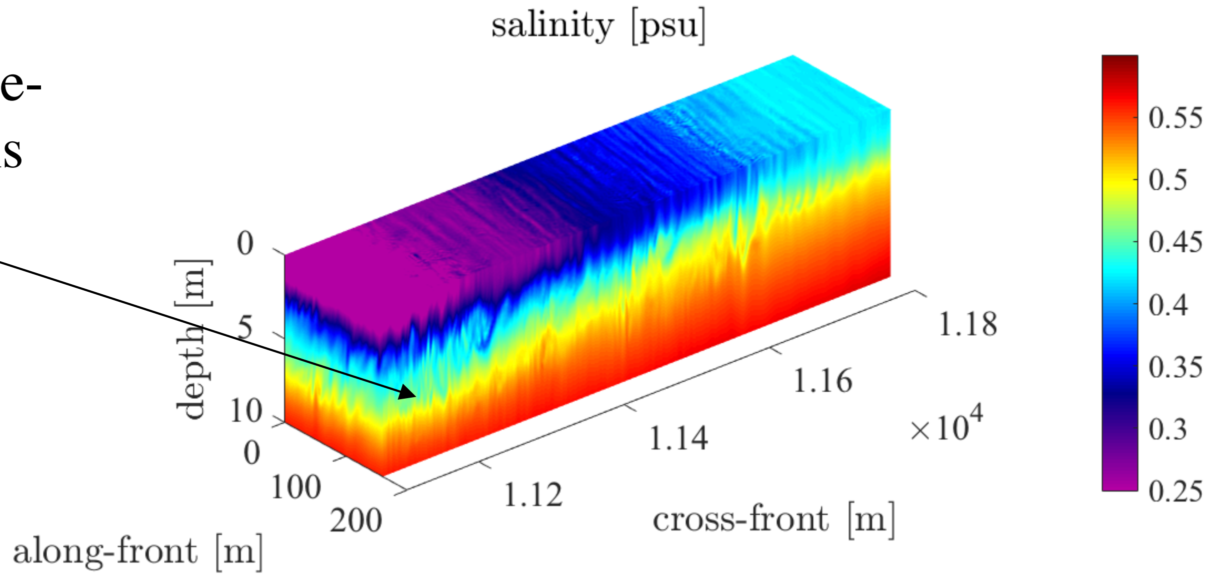


Unstable salinity gradient

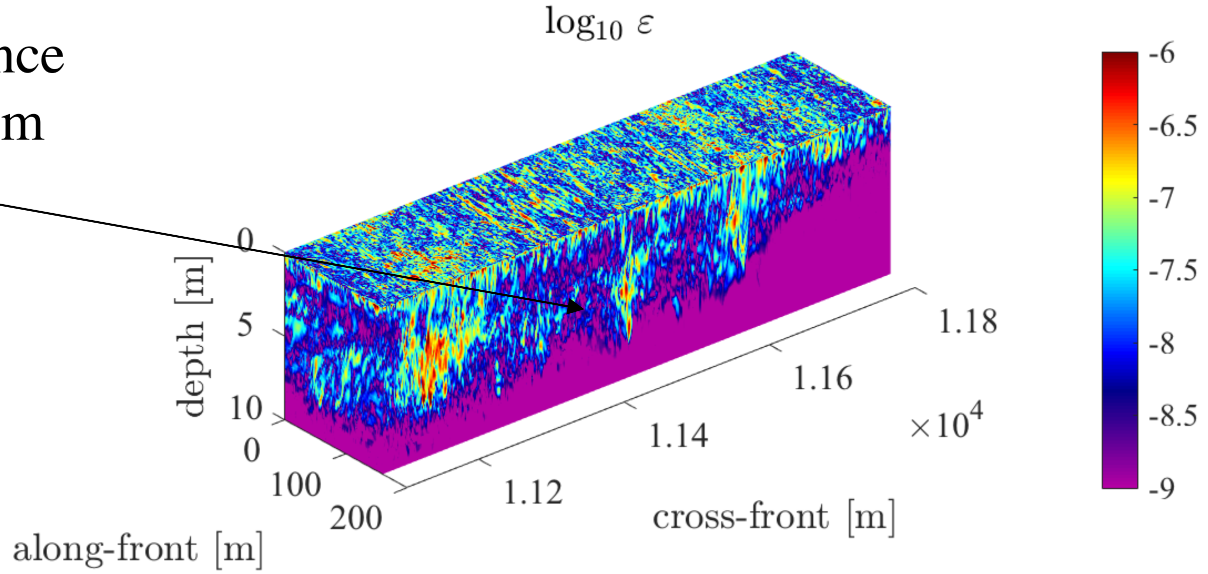


Convective plumes with lateral spacing of ~300 m

Turbulence structure: Upfront Side

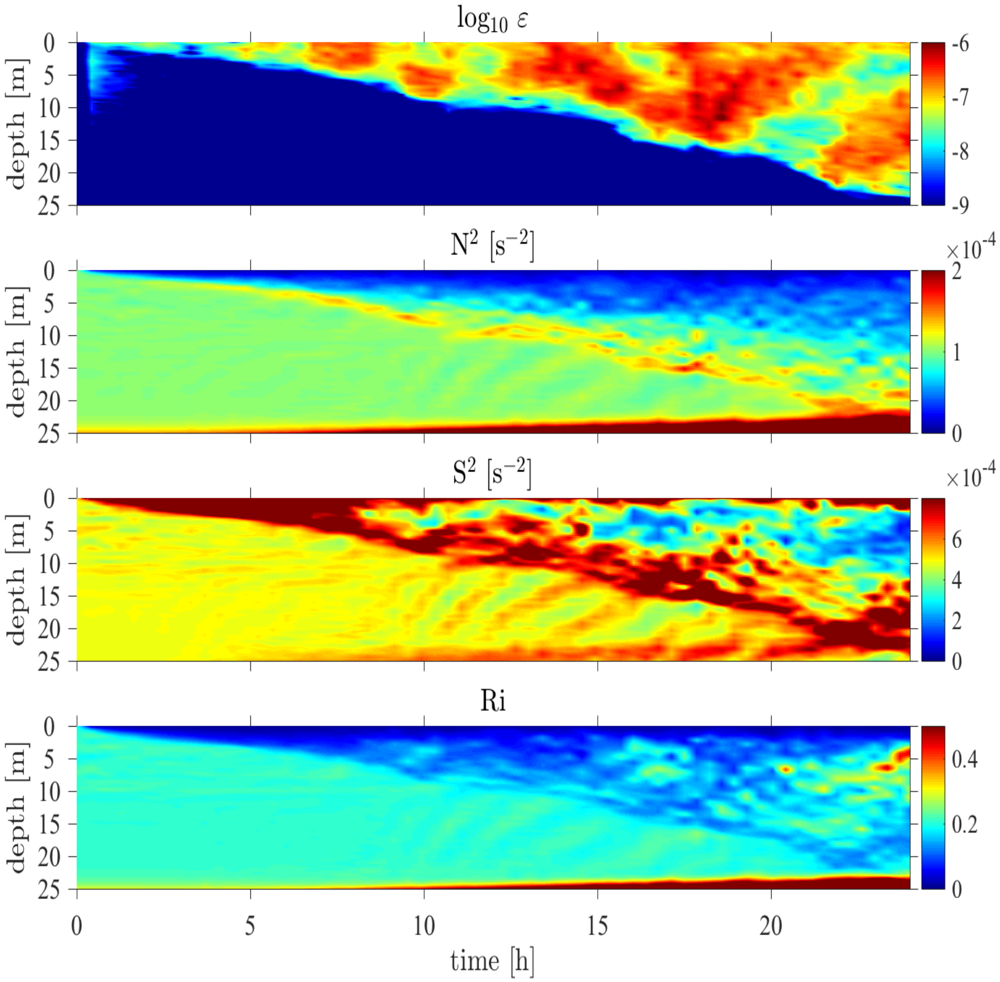


Shoaling isohalines with fine-scale shear-driven overturns

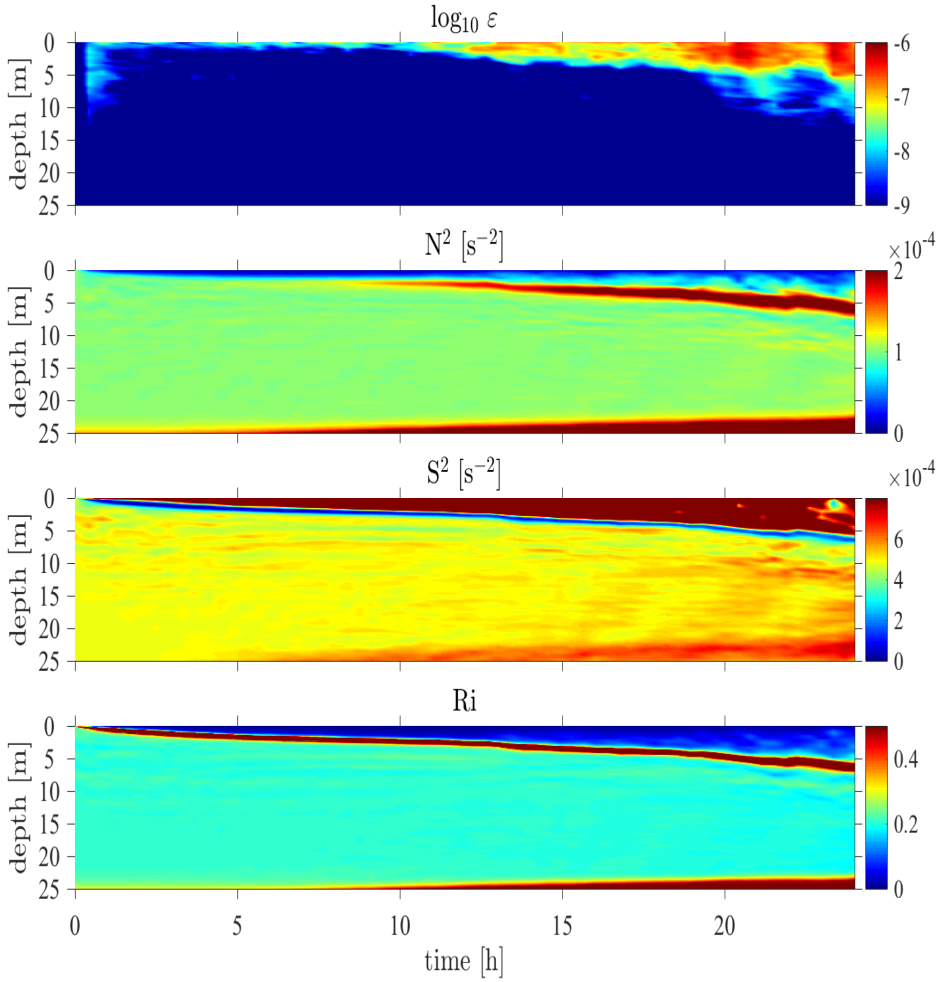


Localized patches of turbulence with lateral spacing of ~100m

Mixed layer depth



Downfront side: deep ML; enhanced shear and stratification at the base; layers of complex N^2, S^2, Ri in the ML; oscillations with period of ~ 1h.



Upfront side: shallow ML with strong shear and weak stratification

Fresh Water Filament Summary

- Asymmetric behavior at the two sides of the filament

- Deep MLD on the downfront side is driven by Ekman buoyancy flux. Shallow MLD on the upfront side is driven by advection of fresh water over saline water.

- On the downfront side, the frontogenesis is weaker than what is seen in case with no wind (Pham & Sarkar, JPO 2018). The convective turbulence prevents the gravity current to develop.

- The upfront side sharpens until a surface gravity current shoots out