Submesoscale symmetric instability and observed rapid horizontal dye dispersion across the Gulf Stream

Jacob O. Wenegrat[1], Leif N. Thomas[1], John R. Taylor[2]

Email: jwenegrat@stanford.edu 1 Stanford University 2 University of Cambridge

Background

Western boundary currents form the sharp interfaces between the subtropical and subpolar gyres. This is evident in both physical and biogeochemical properties, as shown below for observed phosphate in the N. Atlantic (Fig. 1). Phosphate is depleted in the Atlantic subtropical gyre, and enriched in the subpolar gyre, relative to the biological nitrate requirement.

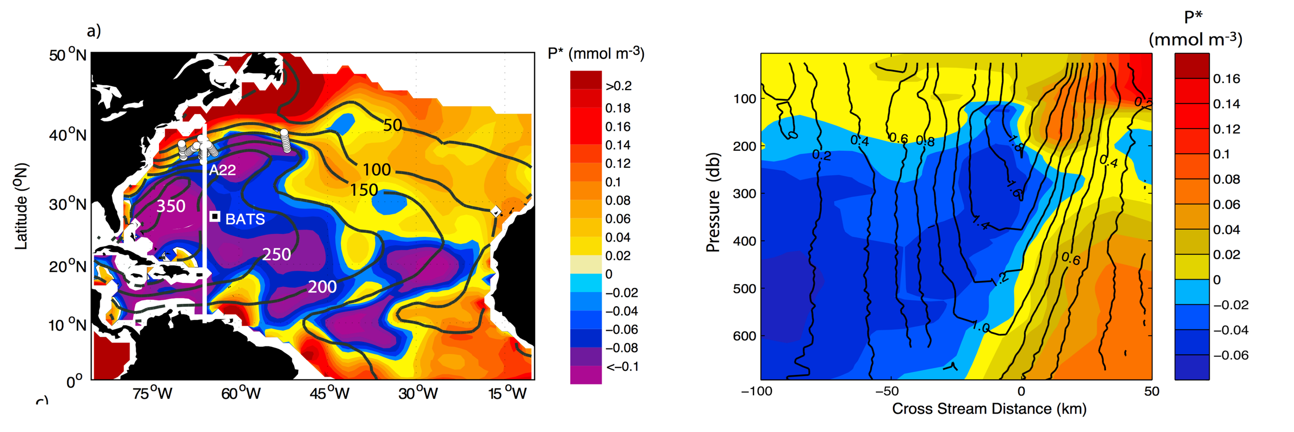


Figure 1: Left, annual mean excess phosphate, $P^* = PO_4^{3-} - NO_3^-/16$, on the 1026.4 kg m^{-3} isopycnal, with average depths shown in labels. Right, P* section across the Gulf Stream, with contours of velocity. Figures from Palter et al. 2011.

It is not currently well understood to what extent sharp WBC fronts serve as material barriers for inter-gyre mixing, and what the relevant dynamical processes for horizontal mixing at sharp fronts are, particularly at the submesoscale.

Recent observational work in the Gulf Stream (LATMIX 2012) included several dye release experiments, which indicated rapid across-front dye dispersion of ~5 km in 0.5 days (Figure 2).

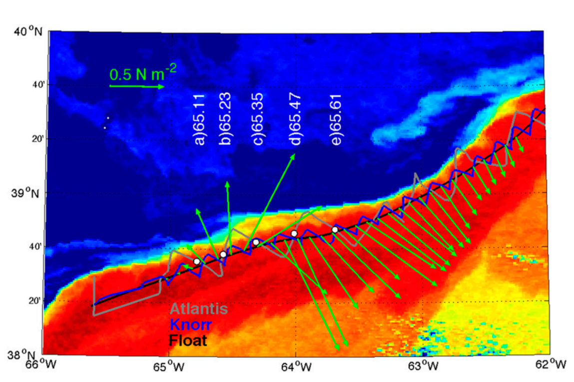


Figure 2: Sea surface temperature, with ship and Lagrangian float tracks indicated. Arrows show the surface winds during the observations. Figure from Thomas et al. 2016

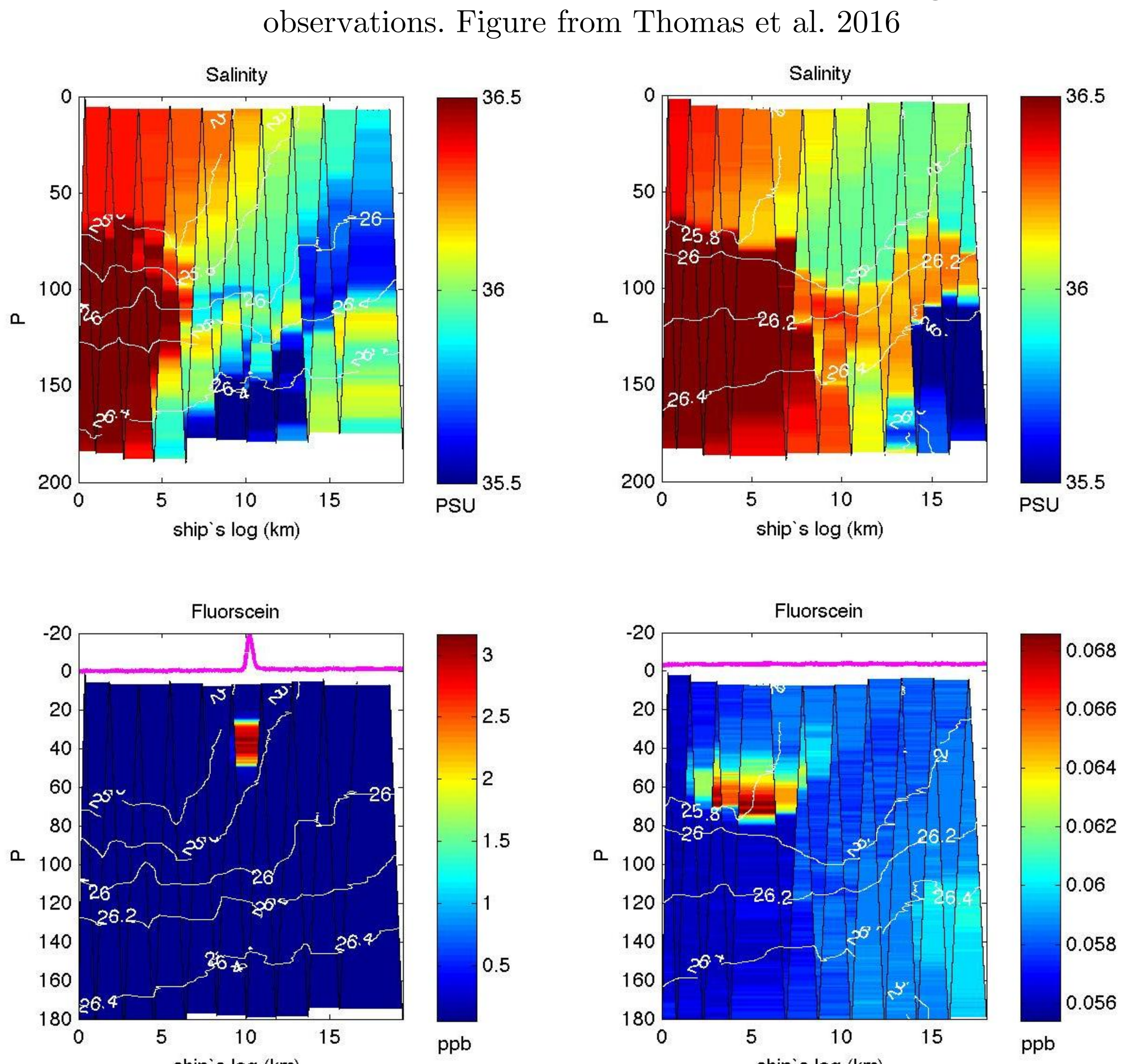


Figure 3: Left, sections of salinity (top) and dye (bottom) from observations immediately following release. Right, as in left but 2 days following release. Figure courtesy of Miles Sundermeyer.

Thomas et al. (2016) showed that differential advection by sheared inertial oscillations tilted the front, modulating the stratification, N^2. This change in stratification resulted in explosive growth of symmetric instability (SI), a submesoscale instability which can grow for flows with negative potential vorticity, $f\,(\omega_a \cdot \nabla b) < 0$.

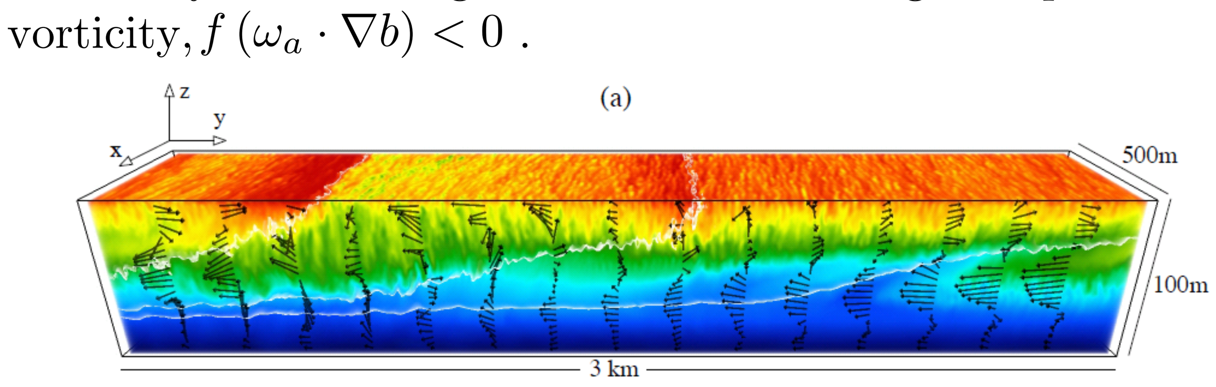


Figure 4: Large-eddy simulation of SI. Along-front velocity (color), buoyancy (white contours), and velocity in the y-z plane (arrows). Figure from Thomas and Taylor 2010.

Guiding questions of the present work:

- What were the dynamical processes involved in creating the observed dispersion across the Gulf Stream front?
- How large is the horizontal diffusivity implied by the dye dispersion, and what are the implications for inter-gyre mixing?
- How do submesoscale processes influence both vertical and horizontal turbulent fluxes, and how does this differ from traditional 1D boundary layer turbulence parameterizations?

Large-Eddy Simulations

Three numerical experiments were performed using large-eddy simulation with passive tracer releases mimicking the observational dye release. Differences between runs are described below, and all runs were forced by observed wind-stress and surface buoyancy flux (fig. 5).

The LES is run in a doubly-periodic, quasi-2D domain (L_x = 5 km, L_y = 125 m, L_z = 150 m, $\Delta x = \Delta y$ = 3.9 m, $\Delta z \approx 1$ m), described in detail in Thomas et al. 2016.

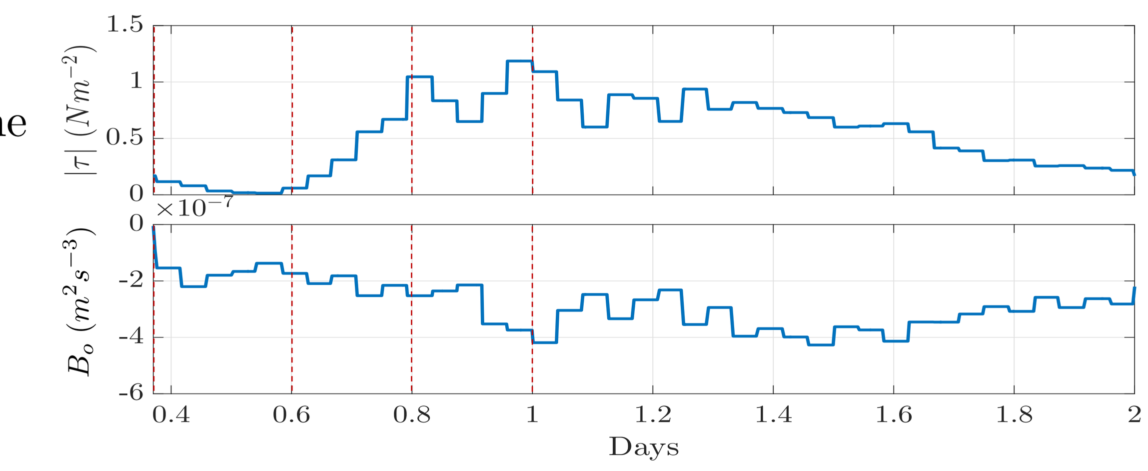


Figure 5: Top, wind stress magnitude. Bottom, surface buoyancy flux, defined positive downwards. Snapshot times for figures 6-8 are indicated by red dashed lines.

1) Frontal Zone: Based on observations, with a uniform background buoyancy gradient, $\frac{\partial \bar{b}}{\partial x}$=-5 x 10^{-7}s^{-2} .

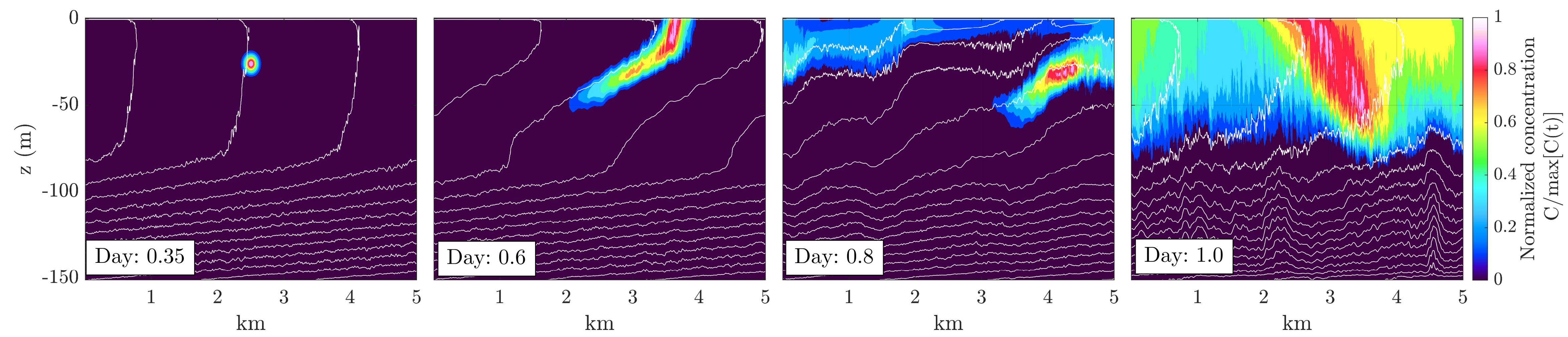


Figure 6: Dye concentration, averaged along-front and normalized by maximum concentration value in each plot. Times are indicated on each plot, and buoyancy contours are shown in white.

2) No Front: Run without a background horizontal buoyancy gradient ($\frac{\partial \bar{b}}{\partial x} = 0$).

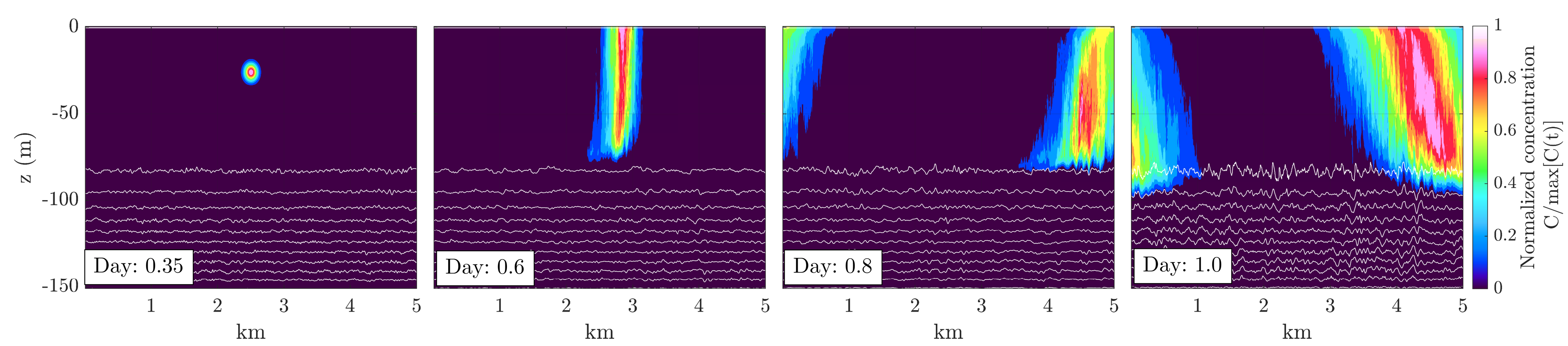


Figure 7: As in Figure 6, for the 'No Front' case.

3) No SI: As in the 'Front' case, but without vertical advection of the geostrophic shear: $\frac{\partial v}{\partial t} + \mathbf{u}\cdot\nabla_h v + w\frac{\partial v_a}{\partial z} + \cancel{w\frac{\partial v_g}{\partial z}} + \ldots$

This allows the background buoyancy gradient and geostrophic flow to affect the evolution of buoyancy and momentum, but removes the energy source for SI, the geostrophic shear production: $GSP = -\langle v'w'\rangle \frac{\partial \langle v_g \rangle}{\partial z}$

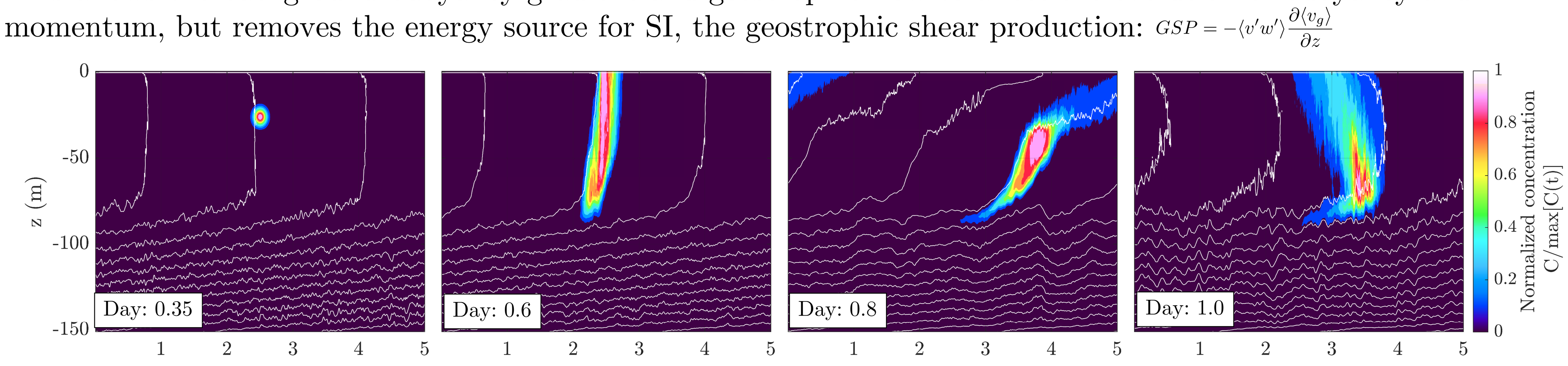
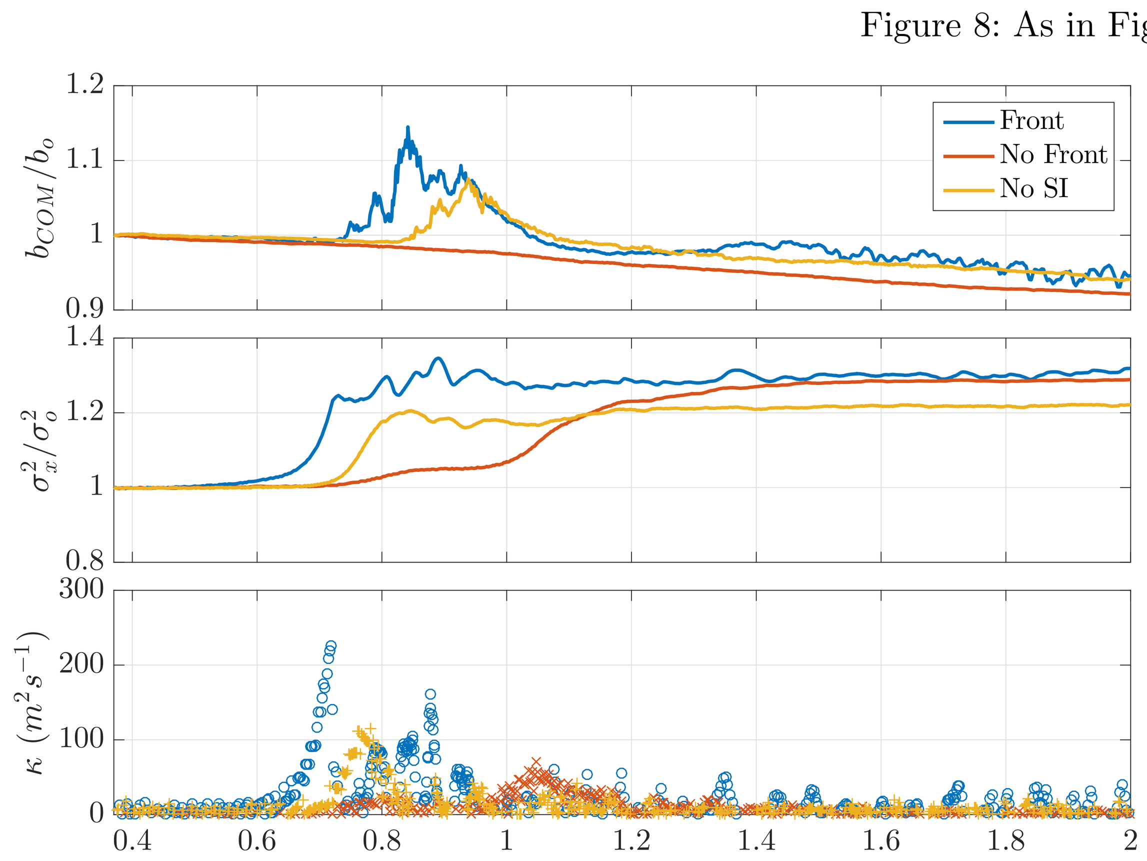


Figure 8: As in Figure 6, for the 'No SI' case.



In each case the dye center of mass (COM) trends towards denser water classes. In the runs with a front, the COM also moves briefly to lighter water due to entrainment during the period of strong wind forcing.

Rapid increase in the across-front variance (σ_x^2) of the dye in the 'Front' run indicates large effective cross-front diffusivities (κ), estimated to exceed **200 m²s⁻¹**.

SI flow leads to shear dispersion of the dye patch before day 0.8 in the 'Front' run, leading to enhanced horizontal diffusivities, $\kappa \propto \left(\frac{\partial u}{\partial z}\right)^2$ (Young et al. 1982). Later, inertial shear contributes to enhanced horizontal diffusivities in both the 'Front' and 'No-SI' runs.

Figure 9: Top, buoyancy of the location of the dye center of mass, normalized by initial buoyancy. Middle, across-front variance in dye concentration, normalized by initial variance. Bottom, estimated effective across-front diffusivity, $\kappa \approx \frac{1}{2}\frac{\partial \sigma_x^2}{\partial t}$.

Summary

- Somewhat counterintuitively, presence of a sharp front may *enhance* horizontal mixing under some conditions.
- Shear-dispersion by vertically sheared flow due to SI appears key to the dye dispersion observed during the LATMIX field campaign. Horizontal diffusivities during this event are of the order of magnitude thought to be required to provide sufficient phosphate to sustain nitrogen fixation in the subtropical Atlantic (cf. Palter et al. 2011).
- The mechanisms for generation of the sheared inertial oscillations are still unknown. Likewise, differences between 'Front' and 'No-SI' runs indicate that interactions between wind-forcing and SI may play an important role in generating horizontal dispersion at a front.

Palter, J.B., S.M. Lozier, J.L. Sarmiento, and R.G. Williams, 2011. The supply of excess phosphate across the Gulf Stream and the maintenance of subtropical nitrogen fixation. *Global Biogeochemical Cycles,* 25.
Thomas, L.N. and J.R. Taylor, 2010, Reduction of the usable wind-work on the general circulation by forced symmetric instability. *Geophys. Res. Lett.* 37.
Thomas, L.N., J.R. Taylor, E.A. D'Asaro, C.M. Lee, J.M Klymak, and A. Scherbina, 2016. Symmetric Instability, Inertial Oscillations, and Turbulence at the Gulf Stream Front. *J. Phys Ocean.* 46.
Young, W.R., P.B. Rhines, and C.J.R. Garrett, 1982. Shear-flow Dispersion, Internal Waves and Horizontal Mixing in the Ocean. *J. Phys. Ocean.*, 12.