Lateral Mixing DRI Analysis: Submesoscale, Fine- and Microstructure Surveys of Internal Waves, Turbulence and Water-Mass Variability

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LONGTERM GOALS

My main interest is in smallscale ocean physics as it contributes to stirring and mixing in order to understand and better parameterize its impact on larger scales. Processes of interest include phenomena ranging from the microscale (1 cm) up to the mesoscale (10-100 km) including near-inertial and internal tides, vortical mode, fronts, turbulence production and salt fingers.

OBJECTIVES

To better understand isopycnal stirring impacts and mechanisms on horizontal lengthscales between 0.03-30 km (meso- to submesoscale) as part of the Lateral Mixing DRI (LatMix).

APPROACH

1. My contribution to the 3-ship June 2011 LatMix field program in the Sargasso Sea was to towyo a Rockland Scientific platform (Hammerhead) to characterize water-mass anomalies along isopycnals. This platform carried finescale Sea-Bird sensors for temperature, conductivity and pressure as well as Chelsea and WetLab optical sensors for chlorophyll, fluorescence and backscatter. Nine 5-9 h towyos were carried out over the course of the cruise, spanning lateral scales of O(0.01-10 km) at two sites: a low-energy 'big nothing' site with little or no eddy activity and a region of moderate O(0.1*f*) confluence. The 2-km radius Hammerhead towyo surveys were centered on Lou Goodman's drogued Gateway buoy and enclosed the box surveys by his T-REMUS AUV. In the vertical, they were centered within ± 5 m of the dye-injection target density in order to capture as the finest horizontal resolution possible. They were embedded in larger-scale towyo surveys by Craig Lee and proximal to towyo surveys by Jody Klymak and Miles Sundermeyer. These data span 20-60 m depth in the seasonal pycnocline of the Sargasso Sea. Horizontal wavenumber spectra of salinity gradients along isopycnals from these 5 platforms were synthesized over wavenumbers 0.1-30 cpkm, extending such spectra to factor of three higher wavenumbers than previous. By working on isopycnals, the much larger internal-wave signal is filtered out, allowing us to focus on products of submesoscale stirring. Here, salinity gradients represent water-mass (spice) anomalies on isopycnals so serve as passive tracers. These spectra were compared with existing theories and models.

2. In addition, I explored the possible role of turbulent intermittency in internal-wave strain dispersion $K_h = \langle K_z \chi_z^2 \rangle$ (Young *et al.* 1982) where the off-diagonal vertical strain $\chi_z = \int V_z dt$ with Miles Sundermeyer. Previous dye experiments (Ledwell *et al*. 1998; Sundermeyer and Ledwell 2001) have found submesoscale dye-inferred diffusivities an order of magnitude larger than internal-wave strain dispersion predictions based on average vertical diffusivities, average shear variances or both, e.g., $\langle K_z \rangle \langle V_z^2 \rangle / f^2$. However, higher strain dispersion can result through $\langle xy \rangle = \langle x \rangle \langle y \rangle + \langle x'y' \rangle$ exceeding $\langle x \rangle \langle y \rangle$ if these properties are intermittent and positively correlated. This was explored analytically based on what is known about ocean turbulence intermittency and its correlation with vertical shear V_z.

WORK COMPLETED

I am the lead author on two completed manuscripts (Kunze *et al*. 2015; Kunze and Sundermeyer in press). In addition, I contributed significantly to the writing of a LatMix 2011 overview MS that has just appeared in BAMS (Shcherbina *et al*. 2015) and am a contributing author to an MS in preparation on evaluating shear dispersion –

Birch, D.A., M.A. Sundermeyer, J.R. Ledwell, E.A. D'Asaro and E. Kunze, 2015: Evaluation of shear dispersion from observations in the seasonal pycnocline. in prep.

RESULTS

1. In Kunze *et al*. (2015), horizontal wavenumber spectra of salinity gradients along isopycnals are approximaely flat with slopes –0.2 ± 0.2 over submesoscale wavenumbers 0.1-30 cpkm (Fig. 1).

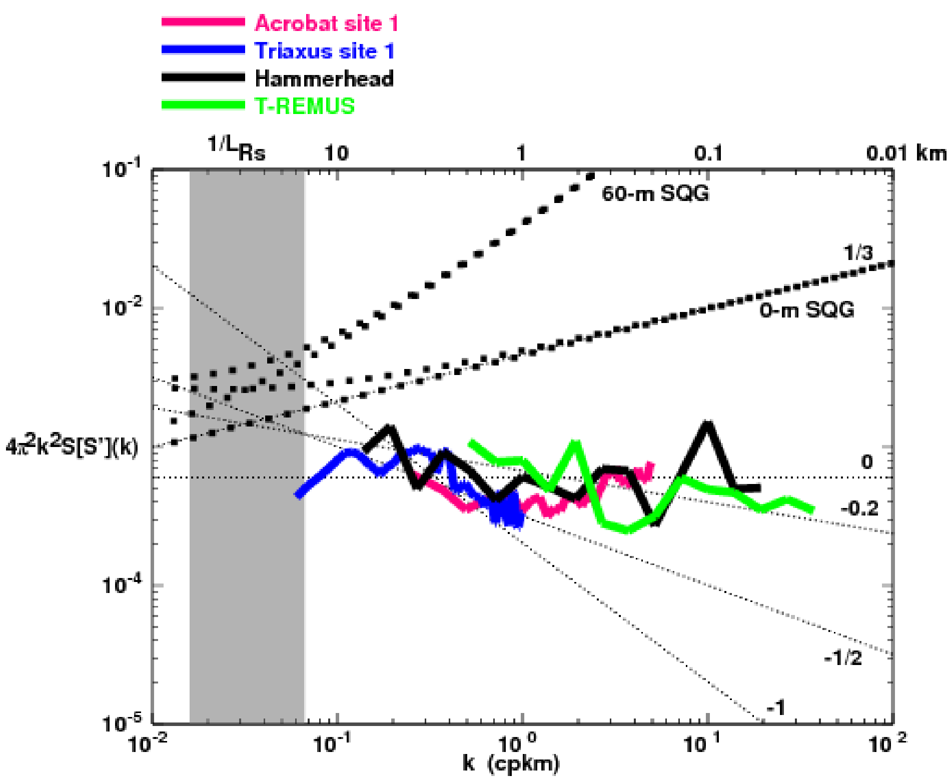

Figure 1: Comparison of horizontal wavenumber spectra for salinity gradients on isopycnals $4\pi^2 k^2 S[S'](k)$ (lines) with surface QG turbulence theory (Scott 2006).

A flat salinity gradient spectrum on isopycnals has previously been reported for wavelengths larger than 1 km (Ferrari and Rudnick 2000; Cole and Rudnick 2012; Callies and Ferrari 2013; Klymak *et al.* 2015). Similar spectral shapes are also seen in primitive-equation models (Capet *et al.* 2010; Molemaker *et al*. 2010) but not QG numerical models (Smith and Ferrari 2009). These slopes are not consistent with QG predictions of a k^1 Batchelor spectrum (Fig. 1) in this band driven by horizontal confluences at the Rossby radius lengthscale at the low end of our resolution (Charney 1971; Scott 2006). We also ruled out atmospheric forcing, vertical-mode stirring and horizontal diffusion by shear dispersion.

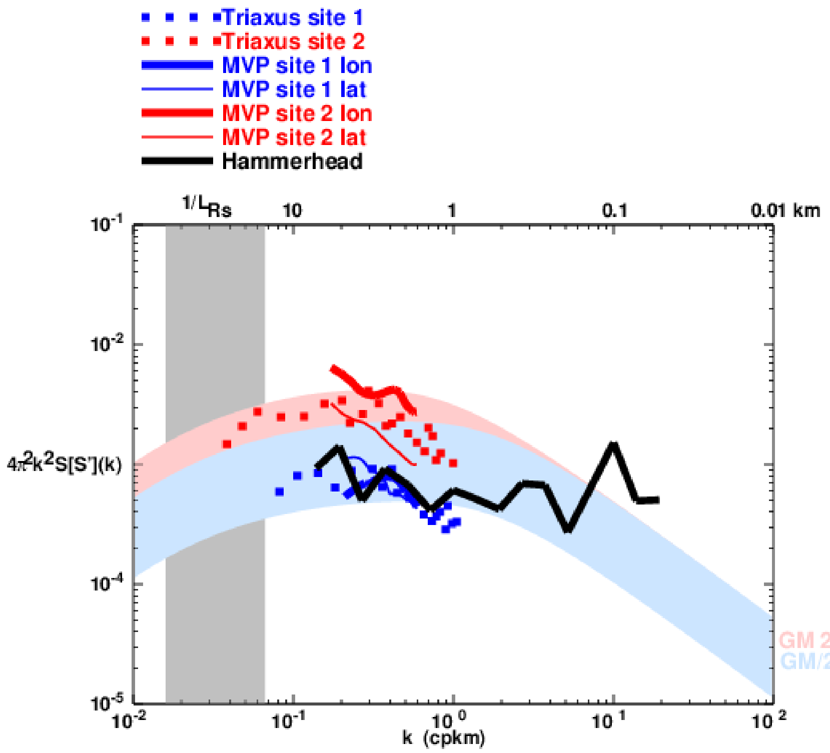

Figure 2: Comparison of horizontal wavenumber spectra for salinity gradients on isopycnals $4\pi^2k^2S[S'](k)$ (lines) with the normalized horizontal strain spectrum for the Garrett-and-Munk internal-wave model spectrum (Gregg and Kunze 1991) at the two LatMix sites.

A redder passive-tracer spectrum implies submesocale stirring processes. Internal-wave horizontal strain spectra deduced from the Garrett-and-Munk model spectrum are consistent with spectral levels and shapes for wavenumbers $k < 10$ cpkm but not the highest wavenumbers resolved by Hammerhead and T-REMUS which are flat while the GM model rolls off (Fig. 2). Most GM horizontal strain is contributed by finescale (1-m vertical wavelength) near-inertial waves with horizontal wavenumbers of 0.1-1 cpkm. Higher wavenumbers may be due to nonQG finescale subinertial stirring.

2. Kunze and Sundermeyer (2015) find that, for typical ocean intermittencies $r = 0.05$-0.1, internal-wave shear dispersion cannot be discounted as a mechanism for submesoscale horizontal diffusivities of $K_h \sim 1\ \mathrm{m^2\ s^{-1}}$ inferred from dye spreading (Fig. 3). So-called shear dispersion is better described as strain dispersion $K_h \approx \langle K_z X_z^2 \rangle$ where $X_z = \int V_z dt$ is 90° out-of-phase with V_z so that elevated diapycnal mixing K_z and shear V_z must persist for at least f^{-1}, where f is the Coriolis frequency, for K_z and X_z to be correlated. While turbulence has been reported to persist for f^{-1} or longer associated with near-inertial wave packets (Gregg *et al.* 1986), the measurements needed to establish correlation between K_z and X_z with any statistical reliability have yet to be collected.

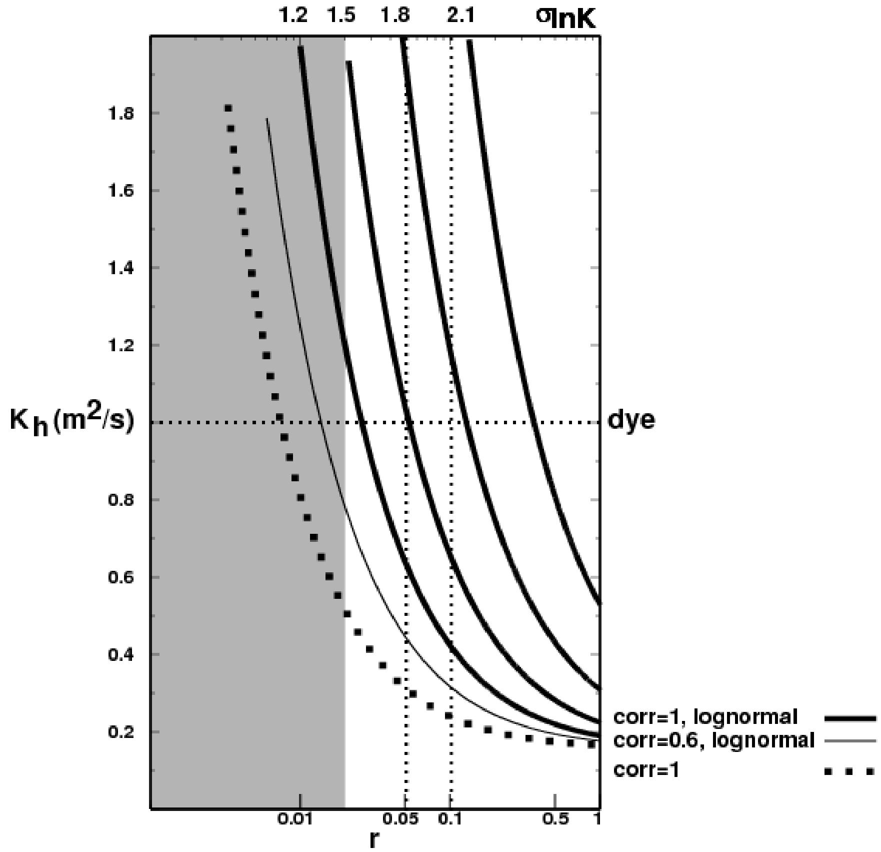

Figure 3: Horizontal diffusivity K_h as a function of turbulent intermittency r. The thick solid curves correspond to $K_z = \langle K_z \rangle / r$ having a lognormal distribution during the r fraction of time turbulence is present and perfect correlation (corr = 1) between K_z and unstable shear variance $V_z^2 > \delta_c^2 N^2$ and lognormal standard deviation σ_{lnK} as indicated along the upper axis The thin solid curve uses a lower-bound correlation of 0.6 and $\sigma_{lnK} = 1.2$. The thick dotted curve assumes intermittency and perfect correlation but no lognormality for K_z. The thin dotted horizontal line at $K_h = 1$ m^2 s^{-1} corresponds to the dye-inferred lateral diffusivity. $\langle K_h \rangle$ increases as intermittency r $\rightarrow 0$ and with lognormality and increasing σ_{lnK}. Gray shading for r < 0.02 indicates where $\{K_z\}_b = \langle K_z \rangle / r$ is high enough to violate the weak-mixing approximation in (8) because $\{K_z\}_b \delta t > m^{-2}$ for durations $\delta t \sim f^{-1}$ but impact of this remains to be assessed.

IMPACT/APPLICATIONS

1. Submesoscale stirring is not captured by QG dynamics so cannot be assessed with QG simulations, instead requiring primitive-equation models. The physics remains to be determined but is clearly important for issues related to dispersal of natural and anthropogenic tracers and rescue operations on lengthscales O(1-10 km).

2. Future dye-release studies intent on understanding 1-10 km horizontal diffusivities need to account for intermittency in diapycnal turbulent diffusivity K_z and its correlation with, not so much shear V_z, but the corresponding strain $X_z = \int V_z dt$. This makes the problem more challenging but within reach of contemporary seagoing observational capabilities.

Overall, the submesoscale remains poorly understood but is important for understanding the cascade of tracer variance to eventual dissipation and may play a role in the dissipation of the largescale QG circulation.

RELATED PROJECTS

1. I am attempting to quantify internal-wave energy-fluxes in the EM-APEX float array collected during the summer LatMix field campaign by Tom Sanford. Since the profiles do not span full water depth as usually needed to quantify internal-wave pressure anomalies, vertical wavenumber spectral approach is being used to try to isolate the energy-flux in the resolved 20-150 m wavelengths. If successful, this methodology may find application in other similar data sets.

2. Prior to the 2011 LatMix summer fieldwork, Jody Klymak (UVic), Patrick Cummins (IOS BC) and I conducted a 2-ship dye-release experiment in Saanich Inlet. During the week of measurements following the injection, the dye traveled around the inlet in a boundary current and was stirred into the interior. This data set being analyzed to learn more about horizontal stirring in coastal waters.

3. ONR grant Finescale Water-Mass Variability from ARGO Profiling Float (N00014-12-1-0336, N00014-13-1-0484) is supporting postdoctoral research Cimarron Wortham to quantify mesoscale water-mass variability on isopycnals in the global ARGO profiling float data set at larger scales than considered here. Eddy stirring lengthscales and 300-km horizontal diffusivities has been quantified globally to a depth of 2000 m in Cole *et al.* (2015). Ongoing work is testing eddy suppression theories, characterizing density ratio geography and statistics, and testing whether a finescale strain parameterization for turbulence production can be used in the upper pycnocline where stratification changes sharply.

4. Nagai *et al*.'s (2015) numerical study of spontaneous generation of near-inertial waves in strong meandering fronts has found generation comparable to the wind. However, the inertial energy is reabsorbed in the front so represents a redistribution of QG energy rather than a dissipative sink. . This emphasizes our lack of understanding of how the ocean's largescale circulation is dissipated.

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