Lateral Mixing DRI Analysis: Submesoscale Water-Mass Spectra

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LONGTERM GOALS

My longterm goals are understanding the smallscale ocean processes responsible for stirring and mixing in the ocean so that their impact on larger scales can be realistically parameterized. My interests includes phenomena ranging from the microscale (1 cm) up to the mesoscale (10-100 km) including internal waves, fronts, potential vorticity finestructure, turbulence production and salt-fingering.

OBJECTIVES

As part of the Lateral Mixing DRI, I seek to improve understanding of the subinertial submesoscale on horizontal lengthscales of 0.1-10 km. These scales of the subinertial fields are not well understood dynamically for subinertial flows as modeling efforts have only recently begin to explore this range and have been challenging to characterize observationally because internal waves dominate dynamic variables such as velocity and isopycnal displacement.

APPROACH

I participated in the 3-ship LatMix June 2011 field program to determine submesoscale variability in the Sargasso Sea under weak-to-moderate mesoscale conditions. Two sites were examined, a quiet site characterized by weak confluences (rates of deformation) less than $0.01f$ and water-mass variability, and a moderately-active site characterized by $O(0.1f)$ confluences acting to sharpen an upper-ocean water-mass front and accelerate a NNW jet. This fieldwork included an unprecedented number of towyoed and autonomous horizontally mapping platforms. My contribution to this suite was to towyo the Rockland Scientific Hammerhead in 2-km radius circles about Lou Goodman's 1-km T-REMUS fine- and microstructure surveys and Gateway buoy to characterize the subinertial stirring fields in water-mass anomalies and dye streaks. Hammerhead carries finescale Sea-Bird sensors for temperature, conductivity and pressure as well as Chelsea and WetLab optical sensors for chlorophyll, fluorescence and backscatter. Eight 5-9 h towyos were carried out over the course of the cruise, centered within ± 5 m of dye-injection target densities. They were embedded in 35-km towyo grid surveys by Craig Lee's Triaxus and 15-km butterfly surveys by Jody Klymak's MVP. These surveys were designed to span a range of horizontal scales ranging from 35 km down to 100 m with Hammerhead trying to capture the smallest scales. These surveys are now being synthesized into

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horizontal wavenumber spectra of water-mass along isopycnals. Previous surveys (e.g., Ferrari and Ruddick 2000; Cole and Ruddick 2012; Callies and Ferrari submitted; Klymak *et al*. submitted) have resolved water-mass variability down to 1-km wavelengths. Klymak and Moum (2007) resolved scales as small as 0.5 m but had horizontal tows at fixed depth so could not isolate water-mass stirring on density surfaces.

WORK COMPLETED

All the above platforms measured temperature *T* and salinity *S* over different overlapping depth and lengthscale ranges. These data were transformed onto density σ_θ coordinates, on which temperature and salinity anomalies are redundant so either can be used as a measure of water-mass or spice anomalies. On these horizontal scales, isopycnal displacements ξ are dominated by internal waves which are not believed to play a role in isopycnal stirring. Therefore, we have focussed on the variability of water-mass (salinity *S'*) anomalies as well as the dye signatures which should filter out internal-wave influences to first order. Using Lou Goodman's Gateway buoy, I have transformed the Hammerhead towyo tracks into laterally Lagrangian coordinates which collapses the front/filament structure (Fig. 1).

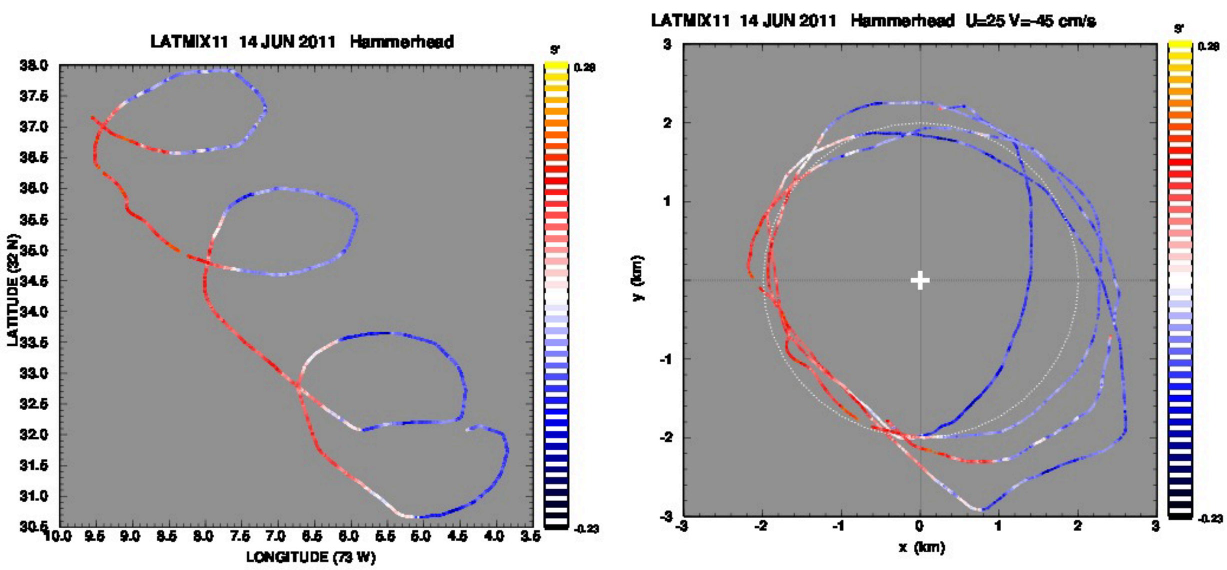

Fig. 1: Water-mass variability along a density surface from the 14 JUN Hammerhead survey in Eulerian (left) and Lagrangian coordinates. The Lagrangian transformation collapses the frontal structure running NNW.

While Triaxus and MVP data were collected along straight lines so could easily be gridded and Fourier transformed using standard techniques, the circular Hammerhead surveys require a different approach. For each survey, the correlation as a function of horizontal separation Δr was computed. They exhibit zero-crossings of 0.5-3 km. These are then fit to J_0 Bessel functions following D'Asaro and Perkins (1984). This requires tapering at large separations to avoid ringing and multiplying by Δr which reduces the signal near $\Delta r = 0$ where it is most critical to resolve the shape of the correlation in order to correctly characterize high wavenumbers *k*. Hammerhead spectra will be synthesized with Lee's Triaxus and Klymak's MVP when finished. Data from Goodman's T-REMUS and possibly Sundermeyer's Acrobat towyos, Levine's finescale MVP towyos and Shearman's glider surveys will be included in the synthesis if feasible once the software has been fully tested.

RESULTS

Triaxus and MVP data find gradient spectra that are flat or very weakly red ($k^{-1/3}$) for wavenumbers $k < 1$ cpkm. This is consistent with theoretical expectations for surface rather than interior quasi-geostrophic turbulence (e.g., Scott 2006). However, other measurements have found flat water-mass gradient spectra at all depths (Ferrari personal communication), inconsistent with the expected transition from k^0 to $k^{1/3}$ with increasing depth Scott 2006), so these results may be ambiguous; Raf Ferrari suggests a vertical process may be removing variance at higher wavenumber. Hammerhead spectra are also flat for $k < 1$ cpkm but, for higher wavenumbers, becomes blue as k^2 (Fig. 2).

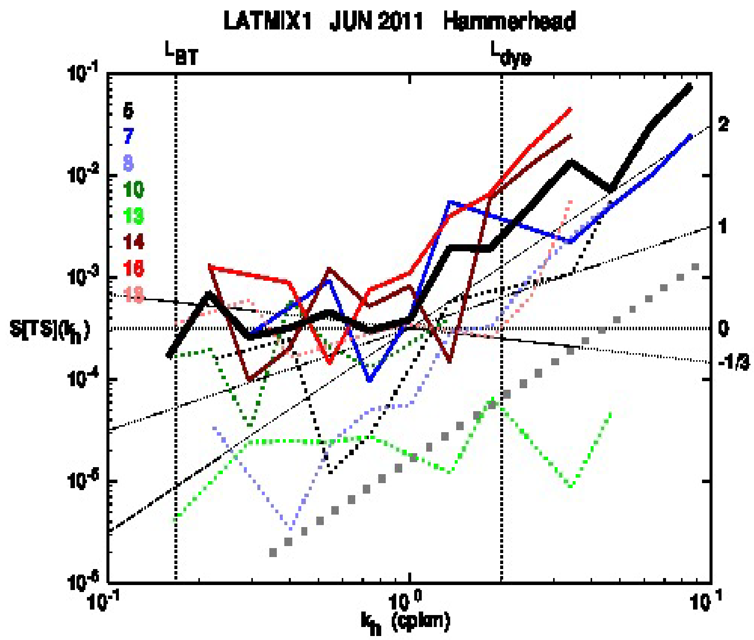

Fig. 2: Gradient spectra for salinity anomalies S' along isopycnals as a function of hoirzontal wavenumber k from the Hammerhead. Spectra are shown for the eight days in June Hammerhead was deployed (colors labeled by date). The average spectrum (thick black) is flat for $k < 1$ cpkm and increase as k^2 for $1 < k < 10$ cpkm. Also shown are labeled slopes (–1/3, 0, 1 and 2) and an upper-bound estimate for sensor noise (gray diagonal).

A k^2 slope was not expected as it is not consistent with any existing stirring theory. Moreover, a k^2 gradient spectra is commonly a signature of noise. Ongoing analysis seeks to determine whether this result might be an artifact of the analysis by testing the software with artificial data sets with known spectra. However, CTD chain data collected by Ren-Chieh Lien in Luzon Strait that resolves horizontal wavenumbers as high as 100 cpkm shows an order-of-magnitude jump in spectral level near 1 cpkm (Fig. 3) which is much harder to explain as noise. Since it is consistent with the Hammerhead results, we are also looking to dynamical explanations. In physical space, these spectra can be likened to a field of 0.1-1 km filaments.

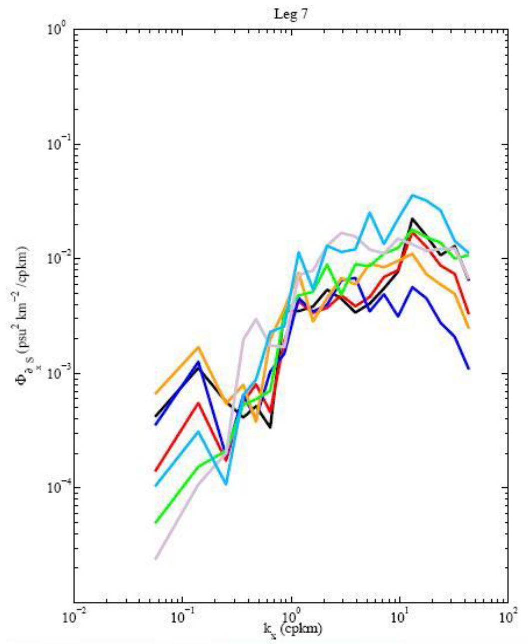

Fig. 3: Gradient spectra from salinity anomalies S' along isopycnals as a function of horiozntal wavenumber k from Ren-Chieh Lien's CTD chain tows in Luzon Strait spanning 0.05 < k < 50 cpkm. Spectra are flat for low and high wavenumbers but exhibit a shift in level near k ~ 1 cpkm.

For surface quasi-geostrophic turbulence, the tracer gradient spectra should behave as $\chi/(\mathrm{APE})^{1/2}$ where χ is the dissipation rate of water-mass variance and available potential energy is a measure of buoyancy anomalies along the surface, i.e., APE ~ $<b'^2>/N^2$. Thus, one explanation for the change in spectral level in Lien's CTD chain data would be loss of most of the cascading QG energy at 1 cpkm. This might occur due to frontal instability radiating internal waves (Nagai *et al.* submitted).

These spectral results will be presented at Ocean Sciences and an MS of the synthesis across horizontal wavenumber is planned.

IMPACT/APPLICATIONS

In contrast to the microscale (1 cm - 1 m), little is known about lateral stirring and tracer variability spanning the submeso- and finescale (1 m - 10 km) (Fig. 4). Internal waves dominate dynamic signatures on these scales but should contribute little to the cascade of tracer properties. Microscale turbulence may occupy horizontal wavenumbers as low as $k_f = (f^3/\varepsilon)1/2$ but measurements have yet to confirm this. Quasi-geostrophic theory predicts that stirring driven by surface buoyancy should have a flat tracer gradient spectra at wavenumbers below $k_{QG} \sim f/N/z$, transitioning to $k^{1/3}$ at higher wavenumbers, while interior QG turbulence should behave as $k^{1/3}$ at low wavenumbers and k^1 constrained by PV conservation at higher wavenumbers. However, observations find flat spectra independent of depth for $k < 1$ cpkm (Ferrari personal communication). Hammerhead spectra find blue spectra for $k > 1$ cpkm. These appear to be supported by higher-resolution CTD chain data from Luzon Strait (Lien) which show an order-of-magnitude shift in spectral level near $k \sim 1$ cpkm which is not predicted by any theory. Correct characterization of these scales is clearly important for high-resolution models and might potentially impact acoustics.

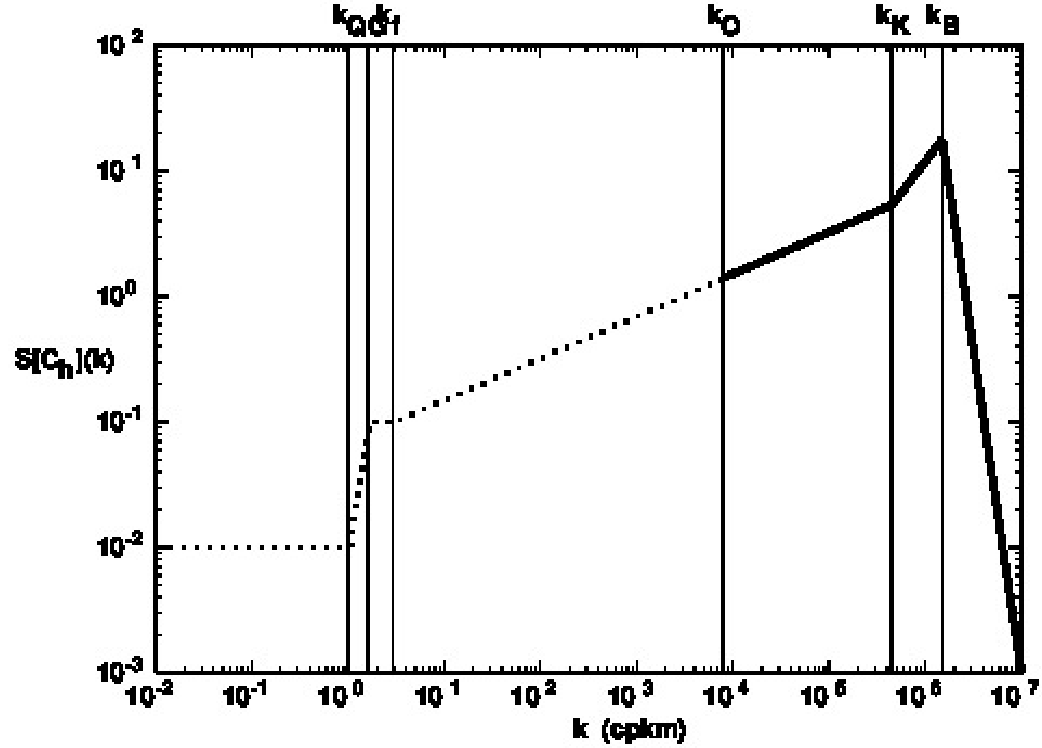

Fig. 4: Cartoon tracer spectrum as a function of horizontal wavenumber spanning the submesoscale to the microscale. The spectrum for wavenumbers above the Ozmidov $k_O = (N^3/\varepsilon)^{1/2}$ (thick solid) are well-understood in terms of turbulent microstucture theory and observations which describe a Kolmogorov wavenumber $k_K = (\varepsilon/\nu^3)^{1/4}$ where molecular viscosity ν damps velocity fluctuations and Batchelor wavenumber $k_B = (\varepsilon/\nu/\kappa^2)^{1/4}$ where molecular diffusion κ damps tracer variability, while lower wavenumbers (thick dotted) are less well understood. Intermediate wavenumbers k_{QG}, and k_f shown above may or may not exist.
The spectra at $k > k_O$ used LatMix turbulence patch kinetic energy dissipation rates $\varepsilon \sim 0.5 \times 10^{-8}$ W kg^{-1} and buoyancy frequencies $N \sim 0.015$ rad s^{-1}.

RELATED PROJECTS

ONR-funded project, Finescale Water-Mass Variability from ARGO Profiling Floats (N00014-12-1-0336, N00014-13-1-0484) is examining water-mass variability along isopycnals in the global ARGO profiling float data set and is supporting new postdoctoral researcher Dr. Cimmaron Wortham (MIT) who arrived 1 September 2013. While smoothed hydrographic data have previously been examined, the mesoscale variability has not been described globally. It contains important signatures of stirring and the background conditions driving double-diffision. This analysis will examine lengthscales intermediate between basin scales and those captured in LatMix. We have downloaded all the data through 2012 and begun examination of data in the Indian Ocean.

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