Studies of stirring and mixing at the submesoscale in the ocean: FY2015 Annual Report

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LONG-TERM GOALS

We seek to understand the physics driving submesoscale diffusivity in the ocean in order to better characterize and predict the diffusivity in different oceanic environments.

OBJECTIVES

J. Early was originally subcontracted under this grant to investigate the effects of lateral density gradients and other quasigeostophic contributions on submesoscale stirring and mixing during the LatMix summer 2011 field experiments. However, in the course of analyzing the data, it was found that the null hypothesis could not be disproven—namely that linear internal waves were the primary source of the observed diffusivity. The objective then shifted to investigating this hypothesis.

APPROACH

The approach taken here is to use the observations surrounding the two dye release experiments during the Lateral Mixing summer 2011 field campaign in order characterize the environment (stratification, mean flow, energy levels) and determine the diffusivity from the dye and the drifters. These observations are then compared to a numerical model of linear internal waves under the same conditions. Key metrics, including diffusivity and the shape of Lagrangian frequency spectrum, are then used to determine whether or not the observations are consistent with the hypothesis.

WORK COMPLETED

- Found analytical solutions to a hierarchy of vorticity-strain-diffusivity diffusivity models and create a robust statistical test (with Adam Sykulski) to fit the models to the drifter deployments (Miles Sundermeyer).
- Identified an internal wave-like frequency spectrum in the unstrained drifter spectra and then derived a theoretical Lagrangian internal wave spectrum modified for the local stratification and center-of-mass coordinates (with Shafer Smith).

- Analyzed density profiles from the gliders (Kipp Shearman) in order to create a typical density profile at site 1, estimate the potential energy and determine the principal modes of variability (with Shafer Smith).
- Advanced the numerical methods for creating internal wave modes from variable stratification using Chebyshev polynomials (a spectral method)—this was a necessary component for the analytical estimate of the internal wave spectrum and the numerical model.
- Created a numerical model that advects dye-like particles and drifter-like particles from the *analytical* solution to the linear internal wave equations (with Pascale Lelong). Using the analytical solution prevents any errors from numerical diffusivity associated with numerical solutions.
- Corrected key mistakes in the Garrett-Munk spectrum used to initialize numerical models (with Pascale Lelong).
- Analyzed the output from the a linear internal wave model that also includes a background linear strain field, fully replicating our hypothesized dynamical conditions of LatMix site 1 (with Pascale Lelong and Shafer Smith).

RESULTS

Drifter diffusivity The submesoscale diffusivity at the LatMix summer campaign sites 1 and 2 were found to be $O(0.1)$ m^2/s and $O(1)$ m^2/s, respectively. To determine these values we found analytical solutions to a hierarchy of vorticity-strain-diffusivity models and fit the models to the observations. The background mesoscale strain field at site 1 was found to be relative weak and constant over the six day observation period, whereas the the mesoscale strain field at site 2 was of moderate intensity and found to be time varying. The inferred parameters of the mesoscale strain field are consistent with the parameters deduced from the dye release experiments (Birch, Ledwell, Sundermeyer). However, **the diffusivity of the drifters at site 1 is an order of magnitude lower than the diffusivity of dye, whereas the diffusivity of the drifters and the dye are the same at site 2.**

Drifter dynamics Analysis of the velocity time series from the drifters at site 1 suggests the drifters' dynamics are controlled by internal waves. After removing the effects of the mesoscale strain field from the drifter's velocity time series, the Lagrangian frequency spectrum appears highly asymmetric, with significantly greater energy in anticyclonic motions at frequencies above the inertial frequency as seen in figure 1. This was shown to be consistent with a theoretical Lagrangian frequency spectrum that we derived for linear internal waves in center-of-mass coordinates. Only the zero-frequency of the spectrum (which is the diffusivity) was not consistent, because we did not continue the expansion to the next order.

Model-observation comparisons A linear internal wave model initialized with conditions matching the observations at site 1 was found to reproduce both the observed drifter diffusivity of $O(0.1)$ m^2/s and the observed dye diffusivity $O(1)$ m^2/s. Using a mean density profile constructed from the gliders (Kipp Shearman), we constructed an numerical model that uses the *analytical* solution to the linear internal wave equations in order to advect drifter-like and dye-like particles. Because the model is analytical, it does not suffer from numerical diffusion and can be run in a partial domain—allowing for high vertical resolutions. The model spectra (including diffusivity) shown in figure 2 are consistent with

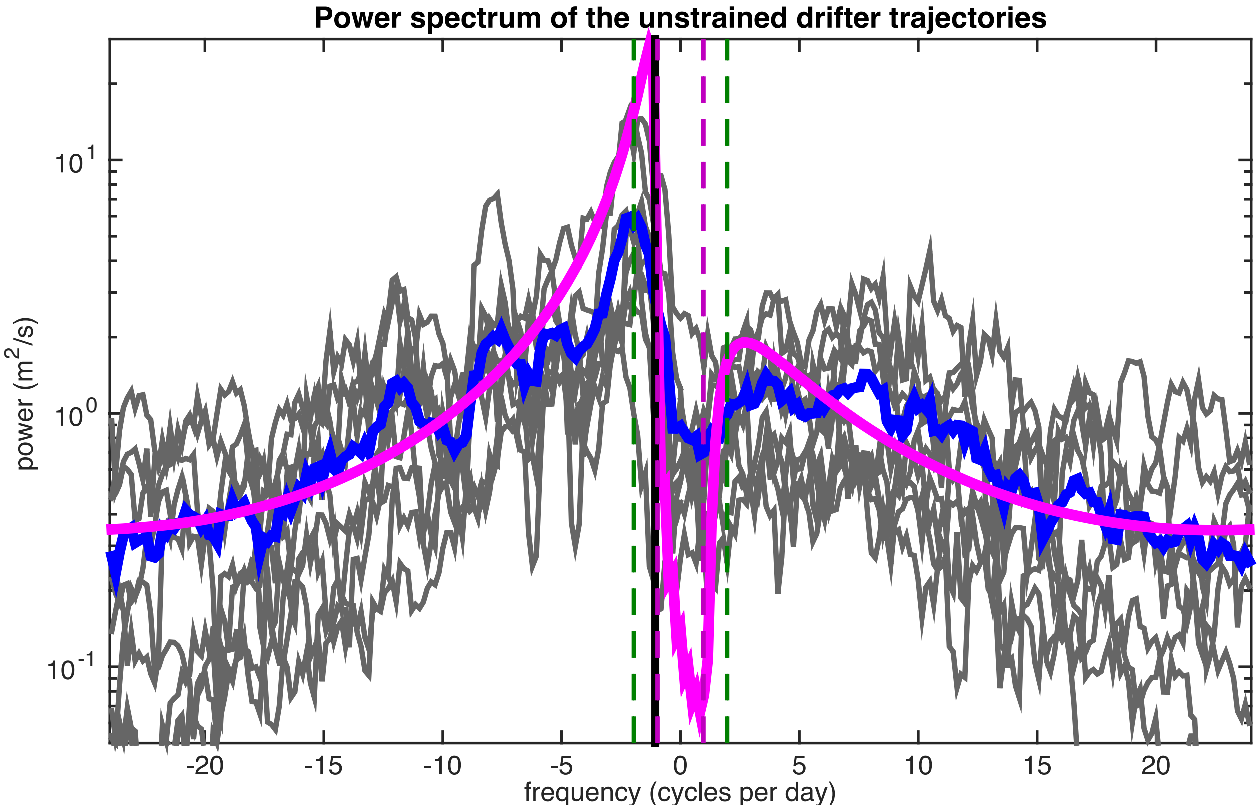

Figure 1: The Lagrangian frequency spectra of the unstrained drifter trajectories in center-of-mass coordinates. Negative frequencies represent anticyclonic motions and positive frequencies represent cyclonic motions. The value at zero is the inferred diffusivity. Dashed vertical lines represent tidal frequencies and the solid black line is the inertial frequency. The grey lines are the spectra from the 9 individual drifters, and the blue line is their mean. The magenta line the predicted spectrum for linear internal waves in center-of-mass coordinates at lowest order (a non-zero diffusivity would appear at the next order).

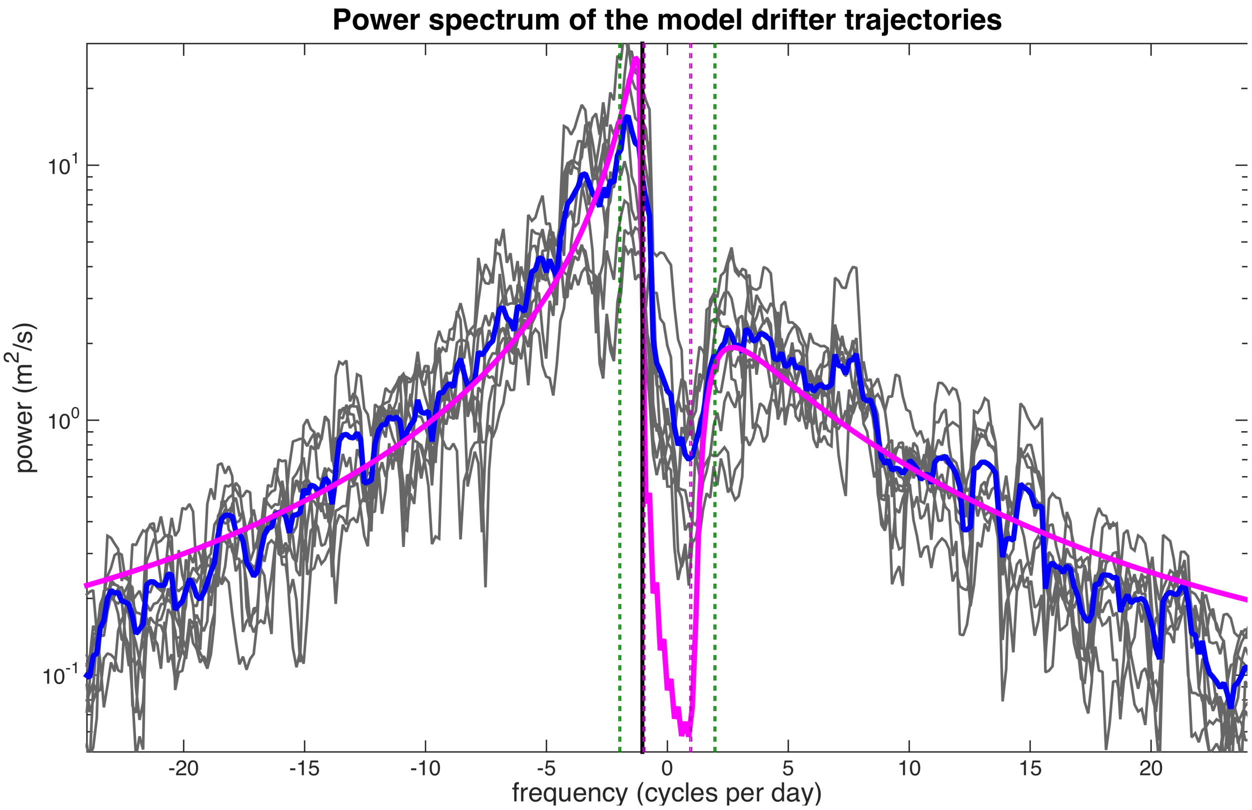

Figure 2: Same as figure 1, but for the synthetic drifters from the linear internal wave model. This shows that the observed diffusivity at site 1 is consistent with the linear internal waves dynamics.

the observed spectra in figure 1.

These results are significant because they suggest that Stokes drift from linear internal waves may be responsible for the observed submesoscale diffusivity. Our results suggest that the amount of observed Stokes drift will be highly dependent on the local stratification, and have likely been previously underestimated because they have not included a realistic stratification with a strong pycnocline. Furthermore, our results are able to explain the observed difference between the drifter and dye diffusivities at site 1. We have not yet investigated why site 2 is different.

IMPACT/APPLICATIONS

In addition to improving our understanding of submesoscale physics from internal waves, many of the techniques developed here for analyzing drifter trajectories will be useful for designing and analyzing future drifter deployments.

RELATED PROJECTS

This project is closely related to the follow-on project, ‘Lateral stirring by internal waves’ (N00014-15-1-2465), which will 1) take the theoretical Lagrangian frequency spectrum to the next order to determine a theoretical diffusivity from internal waves that depends on the local stratification and 2) identify if the same diffusive mechanism holds in non-linear internal wave simulation.

PUBLICATIONS

A. Y. Shcherbina, M. A. Sundermeyer, E. Kunze, a. G. B. Eric DAsaro, D. Birch, A.-M. E. G. Brunner-Suzuki, J. Callies, B. T. K. Cervantes, M. Claret, B. Concannon, J. Early, R. Ferrari, Louis Goodman, R. R. Harcourt, J. M. Klymak, C. M. Lee, M.-P. Lelong, M. D. Levine, R.-C. Lien, A.Mahadevan, J. C. McWilliams, M. J. Molemaker, S. Mukherjee, J. D. Nash,T. Ozgokmen, S. D. Pierce, S. Ramachandran, R. M. Samelson, T. B. Sanford, R. K. Shearman, E. D. Skyllingstad, K. S. Smith, A. T. J. R. Taylor, E. A. Terray, L. N. Thomas, and J. R. Ledwell. The Latmix Summer Campaign: Submesoscale Stirring in the Upper Ocean. *Bull. Amer. Meteor. Soc.*, 96:12571279, 2015.