Numerical Simulations of Vortical Mode Stirring: Effects of Large-Scale Shear and Strain

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LONG-TERM GOALS

The long-term goal of this effort is to develop scalable, physically based parameterizations for lateral mixing in the stratified ocean on scales of 0.1-10 km that can be implemented in larger-scale ocean models. These parameterizations will incorporate the effects of local ambient conditions including latitude, mean stratification and mesoscale flows. Another ultimate goal is to develop a more comprehensive picture of horizontal and vertical mixing processes in the ocean stratified interior.

OBJECTIVES

The objectives are to work collaboratively with modelers and observationalists involved in the LatMix DRI. My participation in LatMix focuses on understanding the relationship between internal waves, internal-wave breaking, episodic diapycnal mixing and lateral dispersion on scales of 0.1-10km. The objective in the past year has shifted somewhat to emphasize the role of non-breaking internal waves in submesoscale lateral dispersion.

APPROACH

The first objective has involved attending meetings and actively participating in discussions pertaining to the DRI. The second objective has been addressed with process-oriented numerical simulations of lateral dispersion in broadband, Garrett-Munk internal wave flows, with close collaboration with observationalists Miles Sundermeyer and Eric Kunze, and numerical modeler and theoretician Jeffrey Early. The primary numerical tool used for the simulations is a highly optimized Boussinesq model (Winters and de la Fuente, 2012) that has been extensively used by the PI to study internal-wave and dispersion-related problems.

WORK COMPLETED

With respect to the first objective, I participated in the 2 LatMix meetings that were held during Ocean Sciences 2014 in Honolulu, HI. The results of LatMix 2011 were also the topic of an invited talk at the

Nonlinear Effects in Internal Waves Conference held at Cornell University in June 2014, (http://nonlinearinternalwaves2014.com/speakers/). With respect to the second objective, the focus of my research this past year has been has been on isolating the mechanism that causes the significant lateral dispersion observed at Site I of the 2011 LatMix cruise in the Sargasso Sea. This has involved a continuation of the numerical simulations begun in the previous years, this time with close collaboration with my NWRA colleague and fellow LatMixer, Jeffrey Early.

I have continued LES simulations of lateral stirring in broadband fields of internal waves as characterized by Garrett-Munk (GM) spectra. The flow is initialized with a GM spectrum, similar in spirit to what was done in Winters and D?Asaro (1997). Energy levels are maintained at the desired level by continually forcing the flow with linear combinations of near-inertial and tidal-frequency waves (e.g. Sugiyama et al. (2008)). Once the flow has achieved statistical equilibrium, a passive tracer is injected at the same depth as the dye was deployed in LatMix 2011. The flow is also seeded with an array of Lagrangian particles at the same vertical level. Up to now, all simulations had been performed with a linear or exponential background stratification, matching the stratification at the depth at which the dye was deployed during LatMix 2011. This past year, we have used a realistic density profile derived from an ensemble of LatMix 2011 observations (drifters, microstructure profiler, towed Acrobat glider, EM-APEX floats).

RESULTS

Internal-wave dispersion mechanisms: In the absence of a mesoscale flow, an internal wave field can disperse a passive tracer through three mechanisms. If the wave field is weakly energetic and the waves are non-breaking, only internal-wave shear dispersion or Stokes drift can disperse the dye. If the waves are allowed to break, potential-vorticity motions (vortical modes) may contribute to the dispersion. A major difficulty encountered when trying to identify the dominant dispersion mechanism is that the effective horizontal diffusivity, κ_h, derived from very different dynamics scales identically with respect to buoyancy and Coriolis frequencies, vertical diffusivity and energy levels. For example, κ_h internal-wave shear dispersion and vortical-mode stirring both scale as κ_z/f^2 where κ_z is the vertical diffusivity and f is the Coriolis frequency. On the other hand, internal-wave shear dispersion is a function of vertical diffusivity whereas whereas Stokes drift dispersion is not. A comparison of passive tracer and Lagrangian particle dispersion patterns enables an assessment of the relative role of these two mechanisms.

Conditions at LatMix 2011 Site I: Observations at LatMix 2011 Site I confirm that the flow is dominated by a weak internal wave field with energies roughly half of GM levels and very weak mesoscale straining. Therefore, most of the effort in the past year has focused on understanding dispersion in non-breaking internal wave fields in regions devoid of mesoscale activity by means of numerical simulations. The principal result of the past year has been the identification of Stokes drift as a major contributor to the observed lateral dispersion at LatMix Site 1. Vortical-mode stirring was excluded by focusing on numerical simulations where waves are non-breaking (implying no potential-vorticity generation and, therefore, no vortical-mode generation).

Internal-wave shear dispersion: The growth of the second moment of dye concentration in the cross-streak direction for two different values of vertical diffusivity is shown in Figure 1. Both

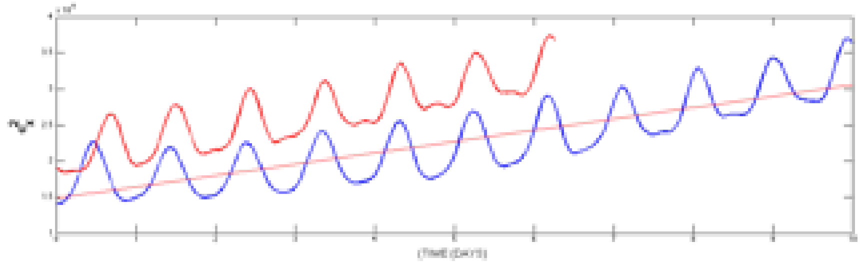

Figure 1: Growth of second moment of passive tracer variance for two different values of vertical diffusivity.

simulations yield the same value of effective lateral dye diffusivity, as evidenced by the fact that both curves exhibit the same linear trend. This set of simulations effectively proves that internal-wave shear dispersion which is directly dependent on vertical diffusivity is not a dominant lateral dispersion mechanism in the LatMix Site I dye experiments.
The joint use of Lagrangian particles and

Internal-wave-driven Stokes drift: An illustration of internal-wave induced Stokes drift is provided by examining the trajectories of Lagrangian particles placed at different vertical levels in a mode-1 wave field. Strong dependence on initial particle position is evident from particle trajectories plotted in Figure 2. The direction and amplitude of particle displacements is clearly a strong function of initial position in the water column. Drift direction is reversed at top and bottom boundaries. Zero drift occurs midway between the boundaries and the center of the vertical domain and it is maximum in the middle of the domain.

A theoretical analysis by Jeffrey Early further illustrates the role of stratification and position in the water column for Stokes drift. The Stokes-drift induced by normal-mode internal waves is a strong function of ambient stratification, as shown in Figure 3. A linear background density yields minimal Stokes drift, an exponential profile roughly twice as much by mode 3, and three times as much in a realistic profile that includes a mixed layer such as LatMix 2011. Therefore, it is entirely plausible that particles or dye placed beneath the mixed layer, as in LatMix 2011, will feel the impact of Stokes drift much more than if they had been placed in, or well below, the mixed layer.
Another question that has been addressed in this year's simulations is the role of linear versus nonlinear processes in the LatMix 2011 dye dispersion. A comparison of linear and nonlinear cases initialized with identical wave fields with 1/2 GM energy levels recorded at LatMix 2011 Site I (Ren-Chieh Lien, personal communication) indicates that the effective dispersion observed in LatMix is primarily a linear process. Linear and nonlinear cases yield very comparable values of effective horizontal diffusivity. Diffusivities inferred from particle trajectories are significantly weaker than those inferred from dye dispersion for LatMix wave energy levels. When wave energy levels are increased, lateral dispersion of the passive tracer becomes larger than that inferred from particle trajectories. This suggests that internal-shear dispersion likely becomes important at higher wave amplitudes. More simulations are planned in the coming year to determine the scaling of each mechanism as a function of wave energy.

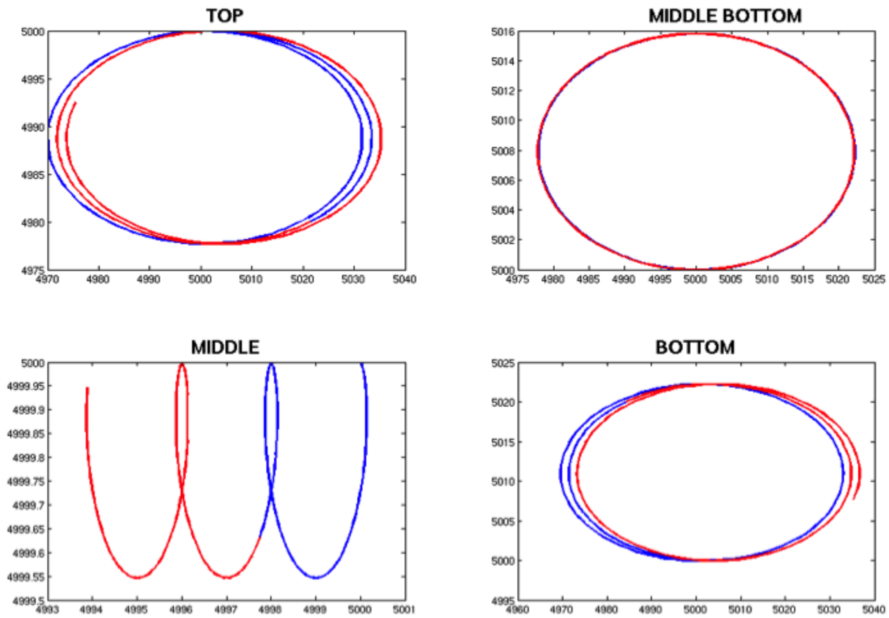

Figure 2: Trajectories of Lagrangian particles initially placed at different vertical positions in a mode-1 internal-wave field. Early-time displacements are in blue, later-time displacements are in red. Axis units are meters and mean stratification is linear.

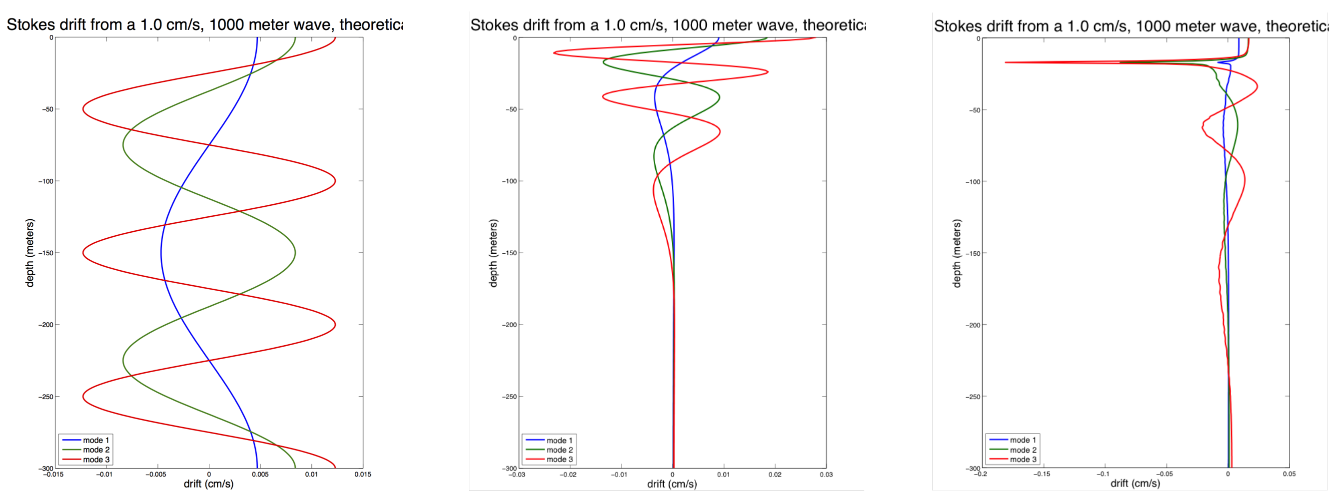

Figure 3: Stokes drift induced by first 3 internal-wave normal modes for linear stratification (left), exponential stratification (middle) and LatMix stratification (right). Figure courtesy of Jeffrey Early.

IMPACT/APPLICATIONS

Results from the current numerical study have enabled us to assess the role of internal waves in the submesoscale dispersion characteristics observed during LatMix 2011. In the long run, it will help design physically based parameterizations for submesoscale lateral dispersion in regions where large-scale mean flows are relatively weak and where a background internal wave field plays a significant role. Since most of the world's oceans are characterized by relatively quiescent ambient conditions, this parameterization will be an asset to global circulation modeling efforts.

TRANSITIONS

none.

RELATED PROJECTS

The work being done under this grant is most closely tied to the observational effort by Sundermeyer of UMass Dartmouth (ONR grant N00014-09-0194), but it generally relates to the concerted LatMix DRI. This effort is also closely related to that of Jeffrey Early of NWRA and Shafer Smith of the Courant Institute of Mathematical Sciences who have been analyzing drifter data from the LatMix 2011 field experiment.

PUBLICATIONS

Shcherbina et al. (2015) (published)
Haza et al. (2014) (published)
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