Numerical Simulations of Episodic Mixing and Lateral Dispersion by Vortical Modes

Miles A. Sundermeyer
School for Marine Science and Technology
University of Massachusetts Dartmouth
706 South Rodney French Blvd.
New Bedford, MA 02744-1221
phone: (508) 999-8892 fax: (508) 910-6371 email: msundermeyer@umassd.edu

James R. Ledwell
Mail Stop # 12
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
phone: (508) 289-3305 fax: (508) 457-2194 e-mail: jledwell@whoi.edu

M. Pascale Lelong
Northwest Research Associates
PO Box 3027
Bellevue, WA 98009
phone: (425) 644-9660 (ext. 336) fax: (425) 644-8422 e-mail: pascale@nwra.com

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LONG TERM GOALS

Our long term goal is to gain a better understanding of rates and mechanisms of lateral dispersion in the ocean. The specific goal of these numerical simulations is to provide a quantitative evaluation of current hypotheses about the importance of lateral dispersion by vortical modes.

OBJECTIVES

We seek to provide quantitative predictions, guided by observations, of rates of lateral dispersion by vortical-mode stirring over the continental shelf. A significant contribution of this work is the direct comparison of numerical simulations to observations and theoretical predictions from the ONR-funded Coastal Mixing and Optics (CMO) experiment (Sundermeyer, 1998; Sundermeyer and Ledwell, 2001). A second major contribution of this work is to provide a basis for parameterizing vertical and horizontal dispersion rates due to vortical-mode stirring in stratified coastal waters.

APPROACH

Lateral dispersion caused by the relaxation of diapycnal mixing events, i.e., vortical-mode stirring, may account for observed dispersion on scales of 1 – 10 km in the ocean. To test this hypothesis, we conduct numerical simulations of lateral dispersion associated with the generation, adjustment, and

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14. ABSTRACT
Our long term goal is to gain a better understanding of rates and mechanisms of lateral dispersion in the ocean. The specific goal of these numerical simulations is to provide a quantitative evaluation of current hypotheses about the importance of lateral dispersion by vortical modes.

15. SUBJECT TERMS

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decay of vortical modes. Specifically, we focus on two fundamental questions: 1) What are the relative contributions of the generation, adjustment, and decay of vortical motions to lateral dispersion in the ocean? 2) How do nonlinear interactions among vortical modes, between vortical modes and the ambient internal wave field, and between vortical modes and a large-scale shear or strain field affect the efficiency of vortical-mode stirring? We further address the relevant over-arching question of how lateral dispersion by vortical modes is affected by external parameters including stratification, rotation, and the scales of the diapycnal mixing events themselves.

The numerical simulations are being conducted by Dr. M. Sundermeyer at the University of Massachusetts Dartmouth, and Dr. P. Lelong at Northwest Research Associates under a subcontract agreement. Dr. J. Ledwell (Co-PI under a subcontract to the Woods Hole Oceanographic Institution) is providing relevant data from oceanic tracer release experiments, and assisting in the interpretation of these data in support of the numerical simulations.

WORK COMPLETED

The performance period for this grant is June 15, 2001 – May 31, 2003. Work on this project began in July, 2001 and has continued under Year 1 support through FY02. Year 2 support for this project will be released from ONR at the start of FY03.

The numerical experiments use a fully optimized and parallelized pseudo-spectral model developed by Kraig Winters of the University of Washington to solve the Boussinesq equations in three dimensions. To quantify vertical and horizontal dispersion rates, we have added the advection/diffusion of a passive tracer to this model. We force the model by periodically injecting potential energy (PE) in the form of randomly placed Gaussian-shaped density anomalies. This is done by imposing a short-lived Gaussian diffusivity profile at random locations in the model, the result of which subsequently adjusts to form small-scale vortical motions as well as internal waves (Figure 1). This approach is intended to represent episodic mixing events caused by a random internal wave field. An inverse calculation using a 1-dimensional diffusion equation reveals that a depth dependent diapycnal diffusivity which varies as a Gaussian in x, y, and z, applied to a linear density profile yields a stratification anomaly which is also approximately Gaussian in form. We use this parameterization for the anomalies in our model to compare our numerical solutions with analytical solutions by McWilliams (1988).

Using the above method of forcing, the model is spun up to a statistically stationary state in which the input of PE and subsequent conversion to KE is balanced by dissipation. Once equilibrium is reached, a passive tracer is released in the model and used to estimate infer lateral dispersion rates. Results from a typical simulation, including KE and PE statistics, are shown in Figure 2.

Simulations are conducted on dual processor Linux workstations at resolutions of 64x64x64 and 128x128x64 grid points, and on a Cray T3E at resolutions of 256x256x64, using up to 32 processors. Runs to date have focused on the nonlinear adjustment of a single anomaly, and the combined effects of many anomalies on the displacement of Lagrangian particles and a passive tracer. Model output is evaluated in terms of a variety of statistics, including net buoyancy flux, PE & KE, potential vorticity, shear:strain ratios, and effective vertical and lateral dispersion rates of tracer. Of particular interest is how the lateral dispersion of tracer by a random field of vortical modes depends on external parameters such as mean stratification and rotation, and the size, frequency and strength of the anomalies.

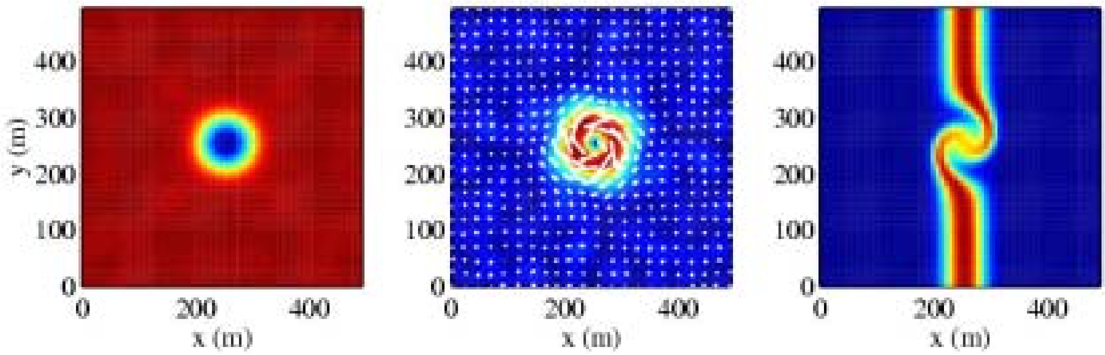

Figure 1: Plan views of a) density, b) velocity, and c) tracer after 8 inertial periods for a single anomaly placed at the center of the model domain. Tracer was released in a narrow streak at the beginning of the simulation, and shows the cumulative azimuthal displacement due to the vortex.

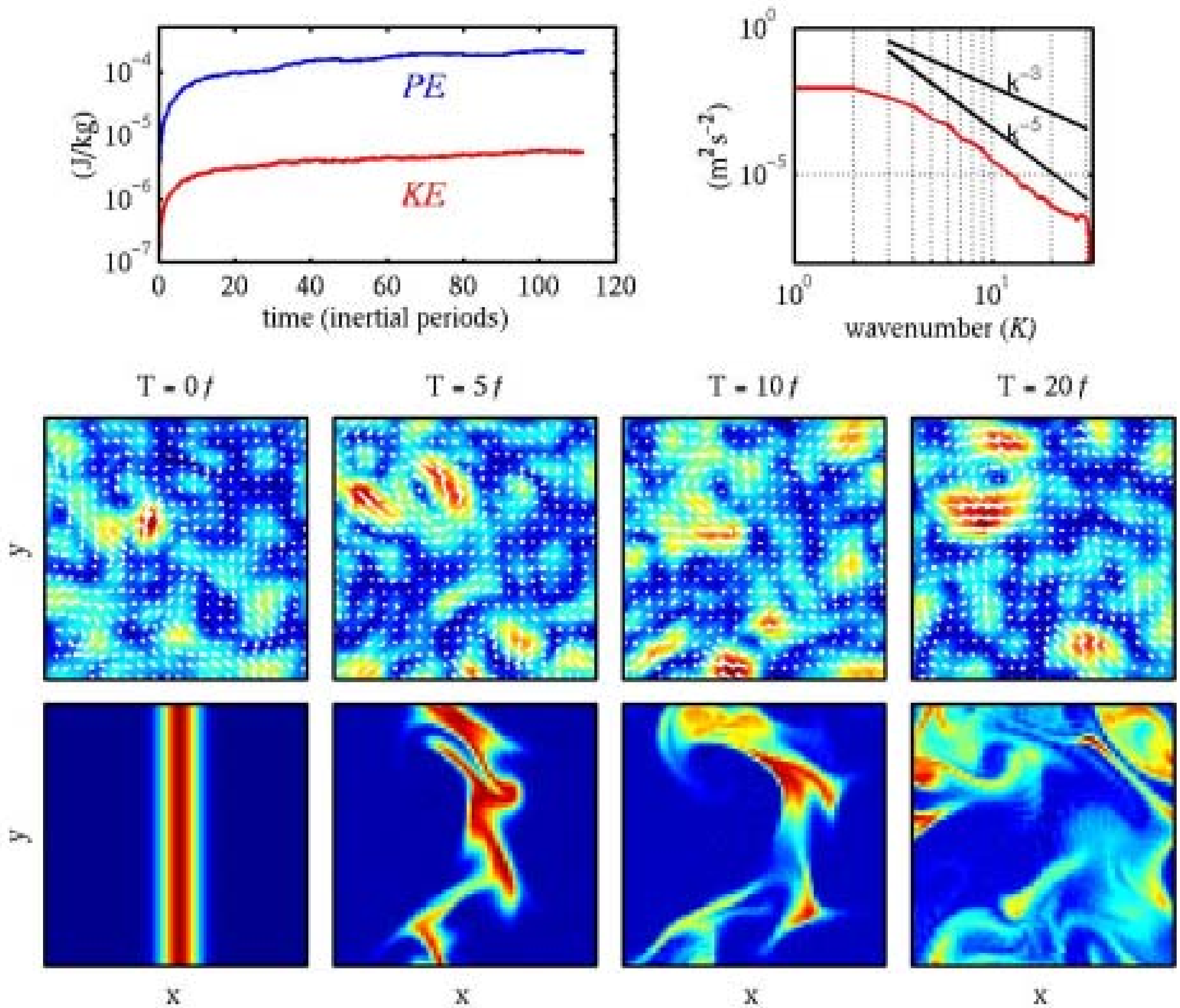

Figure 2: (Top left:) Time series of PE and KE for a typical model spin-up and equilibration, and (top right:) KE spectrum after statistical equilibrium has been reached. (Bottom 2 rows:) Plan views of velocity and tracer at T = 0, 5, 10, and 20 inertial periods after KE equilibrium is reached.

RESULTS

Numerical simulations of the adjustment of a single stratification anomaly are generally consistent with our expectations for a classic Rossby adjustment problem. Specifically, there is an initial phase of radial slumping of the well-mixed fluid, followed by the gradual spin-up of a localized vortex, both modulated by the radiation of internal waves during the early phases of adjustment (Figure 2). Analysis to date shows that the effect of this adjustment on a passive tracer is consistent with description by Sundermeyer (1998), with two exceptions. First, numerical simulations reveal that the azimuthal velocity associated with the geostrophically adjusted vortex has a much greater effect on the overall lateral displacement of a passive tracer than does the radial velocity associated with the early phase of the adjustment. This was not evident from scaling results by Sundermeyer (1998). Second, the geostrophic velocity associated with a fully adjusted Gaussian shaped vortex is considerably smaller than predicted by simple geostrophic scaling. The extent to which this depends on the details of the shape of the initial stratification anomaly is still under investigation. Whether the combination of these two factors leads to an increase or decrease in the effective horizontal diffusivity predicted by Sundermeyer (1998) is also still under investigation.

Numerical simulations of the dispersion of a passive tracer in a random field of vortical modes are also qualitatively and quantitatively consistent with the predictions of Sundermeyer (1998). In particular, we have found that to first order the effective horizontal diffusivity, κ_h, caused by a random field of vortical modes scales with the vertical scale of the anomalies, h, and buoyancy frequency, N, both to the fourth power; and linearly with the frequency of the anomalies, ν (Figure 3). These dependencies can be derived from geostrophic scaling of the horizontal momentum equations combined with random walk theory, i.e.,

$$\kappa_h \approx \left(\frac{1}{2}\right)\frac{h^4 \Delta N^4}{L^2 f^4}\nu = \left(\frac{3}{2}\right)\left(\frac{N^2}{f^2}\right)\left(\frac{R^2}{L^2}\right)\kappa_z \qquad (1)$$

where h is the half-height of the anomalies, ΔN is the change in the stratification associated with the anomalies, L is the horizontal scale, f is the Coriolis parameter, $R = h\,\Delta N / f$ is the local deformation scale, and κ_z is the diapycnal diffusivity (Sundermeyer, 1998). Simulations are currently underway to examine the dependence of κ_h on other parameters in equation (1), namely f, L, R, and κ_z.

While our numerical simulations to date have shown good agreement between the effective horizontal diffusivity and the theoretical predictions above, they have also shown an omission in the parameter dependence given by (1). Specifically, it is clear from our model results that in addition to f and N, the effective horizontal diffusivity caused by vortical mode stirring depends on an additional time scale, namely the characteristic decay time of the vortical motions themselves. We believe that this time scale can be simply expressed in terms of a diffusive or viscous time scale, which effectively sets the total amount of KE causing the stirring. We are currently testing this hypothesis.

Finally, using results from the above simulations, we have begun to explore to what extent the vortical modes in our model can be distinguished from the internal wave field. This will allow us to determine if and how we might detect and study vortical modes in the field. To this end we are exploring the possibility of using shear:strain ratios and other higher order statistics to determine the partition of energy between vortical modes and the internal wave field. Our results are being compared, for example, to studies by Polzin et al. (2002) from the North Atlantic Tracer Release Experiment, as well as to theoretical predictions currently underway by Ferrari and Polzin (see Related Projects).

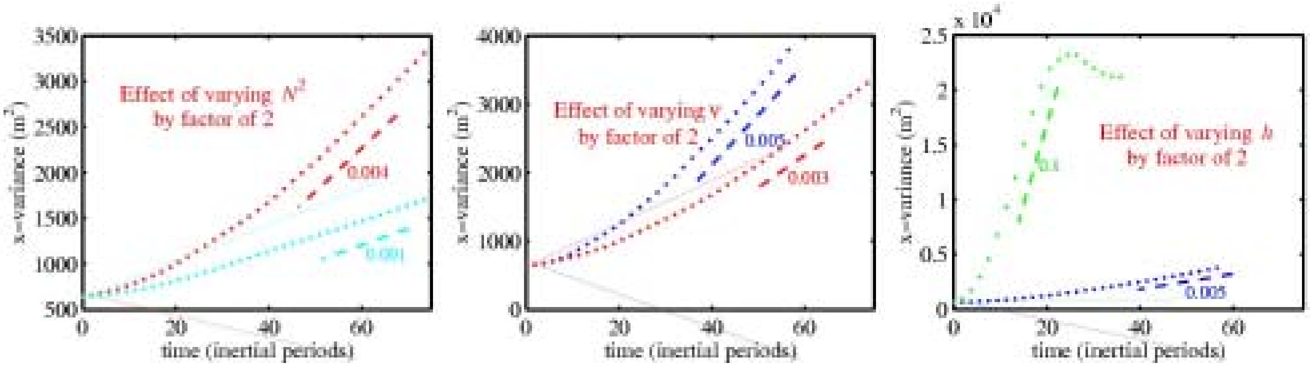

Figure 3: Growth rates of the second moment of tracer for successive pairs of model runs showing the change in the effective horizontal diffusivity caused by varying a) the buoyancy frequency, N^2, b) the rate of anomaly input, ν, and c) the height of the anomalies, h, by a factor of 2 in each instance.

IMPACT/APPLICATIONS

These numerical experiments provide a quantitative test of theoretical predictions of the rates of lateral dispersion by vortical-mode stirring (Sundermeyer, 1998; Sundermeyer and Ledwell, 2001). Specifically, we examine the relationship between effective vertical and horizontal diffusivities, the background stratification, the Coriolis parameter, and the vertical and horizontal scales of diapycnal mixing events. An understanding of these relationships will be valuable to future studies, particularly the problem of parameterizing vertical and horizontal dispersion rates due to vortical-mode stirring.

TRANSITIONS

None.

RELATED PROJECTS

Dye-release studies by J. Ledwell and T. Duda (http://www.whoi.edu/science/AOPE/cofdl/cmodye) and microstructure observations by N. Oakey (http://www.mar.dfo-mpo.gc.ca/science/ocean/epsonde/CMOfrm.html) conducted during the ONR-funded Coastal Mixing and Optics experiment provide an observational underpinning for our numerical simulations. Our model results are also being compared with analytical results by R. Ferrari and K. Polzin in which they estimate effective lateral dispersion rates directly from vortical mode and internal wave KE spectra. Finally, this work also relates to P. Lelong's work under an NSF grant, "Mixing and the production of potential vorticity at small scales in the ocean" [OCE-9811939], and to a grant under the Department of Defense High Powered Computing Challenge entitled "Numerical Modeling of Wake Turbulence for Naval Applications: Vortex Dynamics and Late-Wake Turbulence in Stratification and Shear" (http://www.hpcmo.hpc.mil/Htdocs/Challenge/FY00/24.html; PIs: S. Arendt, D. P. Delisi, D. Fritts, M. P. Lelong, J. Riley, R. Robins).

The latter represents part of P. Lelong's experience running highly optimized, state-of-the-art numerical models on parallel architectures such as the Cray T3E.

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