

## **Tracer Studies of Mixing in Stratified Coastal Waters**

James R. Ledwell

Department of Applied Ocean Physics and Engineering, MS #12

Woods Hole Oceanographic Institution

Woods Hole MA 02543-1053

phone: (508) 289-3305 fax: (508) 457-2194 email: [jledwell@whoi.edu](mailto:jledwell@whoi.edu)

Timothy F. Duda

Department of Applied Ocean Physics and Engineering, MS #11

Woods Hole Oceanographic Institution

Woods Hole MA 02543-1053

phone: (508) 289-2495 fax: (508) 457-2194 email: [tduda@whoi.edu](mailto:tduda@whoi.edu)

Award # N00014-95-1-0633

### **LONG-TERM GOAL**

The long term goal of the experiment is to gain an understanding of the interaction of mixing, stirring, and advection with the optical properties of the water column on the continental shelf in a temperate region. This understanding should ultimately be great enough to enable predictions of optical properties to be made from external forcing of the physical and biological system and conditions of the waters surrounding the shelf region. Understanding and quantification of the diapycnal mixing processes studied in the present project are important to this long-term goal.

### **OBJECTIVES**

The primary objective of the project is to compare diapycnal eddy diffusivities inferred from the dispersion of dye clouds on the density-stratified shelf with those inferred from measurements of the dissipation rates of turbulent kinetic energy and temperature variance. This objective is to be met in close cooperation with the project of Neil Oakey of Bedford Institute of Oceanography, who has measured the dissipation rates from a lightly tethered profiler. Some other objectives which have evolved during the course of the project are the study of lateral processes dispersing the dye patch and comparison of the dye diffusivities near the bottom with estimates of diffusivities from the moored tripod of J. Trowbridge and A. J. Williams of Woods Hole Oceanographic Institution.

### **APPROACH**

The approach of the project has been to release dye patches on an isopycnal surface and to measure the diapycnal and lateral dispersion of the dye over periods of 3 to 5 days (Fig. 1). The dye patches have been sampled with an instrument package that is tow-yo'd at speeds of 1 to 3 m/s. Tracking of the patches has been effectively assisted by integration of the ship-borne ADCP record, and by following a set of satellite-tracked drogues. Sampling surveys lasted the better part of a day, with 12 to 24 hours between surveys. In the hours between surveys, copious measurements of velocity and temperature

| Report Documentation Page                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                    |                                     |                                                           | Form Approved<br>OMB No. 0704-0188                  |                                 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|-------------------------------------|-----------------------------------------------------------|-----------------------------------------------------|---------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. |                                    |                                     |                                                           |                                                     |                                 |
| 1. REPORT DATE<br><b>1998</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                    | 2. REPORT TYPE                      |                                                           | 3. DATES COVERED<br><b>00-00-1998 to 00-00-1998</b> |                                 |
| 4. TITLE AND SUBTITLE<br><b>Tracer Studies of Mixing in Stratified Coastal Waters</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                     |                                                           | 5a. CONTRACT NUMBER                                 |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                           | 5b. GRANT NUMBER                                    |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                           | 5c. PROGRAM ELEMENT NUMBER                          |                                 |
| 6. AUTHOR(S)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                                           | 5d. PROJECT NUMBER                                  |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                           | 5e. TASK NUMBER                                     |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                           | 5f. WORK UNIT NUMBER                                |                                 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><b>Woods Hole Oceanographic Institution, Department of Applied Ocean Physics and Engineering, Woods Hole, MA, 02543</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                    |                                     |                                                           | 8. PERFORMING ORGANIZATION REPORT NUMBER            |                                 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                    |                                     |                                                           | 10. SPONSOR/MONITOR'S ACRONYM(S)                    |                                 |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     |                                                           | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)              |                                 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br><b>Approved for public release; distribution unlimited</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                     |                                                           |                                                     |                                 |
| 13. SUPPLEMENTARY NOTES<br><b>See also ADM002252.</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                    |                                     |                                                           |                                                     |                                 |
| 14. ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                                           |                                                     |                                 |
| 15. SUBJECT TERMS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                    |                                     |                                                           |                                                     |                                 |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                    |                                     | 17. LIMITATION OF ABSTRACT<br><b>Same as Report (SAR)</b> | 18. NUMBER OF PAGES<br><b>6</b>                     | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT<br><b>unclassified</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | b. ABSTRACT<br><b>unclassified</b> | c. THIS PAGE<br><b>unclassified</b> |                                                           |                                                     |                                 |

microstructure were made in or near the dye patches by N. Oakey and his group with a tethered vertical profiler and by us with a towed instrument. From these measurements, dissipation rates and diapycnal diffusivities have been estimated and are in the process of being compared with the dye results.

## **WORK COMPLETED**

Three cruises have been completed. The first, in 1995, was a 5-day test cruise without microstructure measurements. A single 3-day dye experiment was performed. The second cruise was a 15-day cruise in September 1996, during which two 4-day dye experiments were performed, complete with microstructure profiling by N. Oakey. The third and final cruise was a 15-day cruise in August 1997, again with two 4- or 5-day dye experiments, with microstructure profiling by N. Oakey, and with towed microstructure measurements by us.

## **RESULTS**

Five dye release experiments have been completed at depths from 16 meters beneath the surface to 7 meters above the bottom on the continental shelf during the season of summer stratification. Each of these experiments has yielded an estimate, or at least a low upper limit, of the diapycnal diffusivity. Over the course of most of the release experiments there were 3 successful surveys which found most of the dye. The diapycnal diffusivities inferred from the dye dispersion range from 0.2 to  $4 \times 10^{-5} \text{ m}^2/\text{s}$ , including error bars, at buoyancy frequencies that range from 5 to 20 cph. There is a weak tendency for the diffusivity to decrease with increasing buoyancy frequency.

The last dye release was performed 5 to 8 meters off the bottom and has yielded a study of dispersion in the bottom boundary layer as well as in the interior (Fig. 2). Comparison of this experiment with turbulence measurements from a moored tripod by Trowbridge and Williams promises to be fruitful.

Diffusivities inferred from the microstructure profiles of N. Oakey generally are somewhat larger than for the tracer, although in one case agreement is good. Diffusivities inferred from our towed microstructure are somewhat lower than those inferred from dye dispersion (Fig. 3). The causes of disagreement may be spatial and temporal variability in the forcing of the mixing and the uncertainties involved in each of the measurements. These causes will be studied further in the final stage of the project. At this point, it would be premature to seek fundamental theoretical reasons for the differences.

The diffusivities we have found are small, in the sense that many months would be required for them to substantially mix passive tracers across layers tens of meters deep. However, diapycnal eddy diffusion can play a role for the hydrography, biology and optics of layers at scales of less than 10 meters. This conclusion applies to relatively quiet conditions during the season of stratification. Special events such as storms and solitary waves, which were not well sampled by our experiments, may dominate diapycnal mixing during this season.

M. Sundermeyer, in his Ph. D. work within this project, has shown that the interaction of diapycnal diffusivity with diapycnal shear is insufficient to explain the lateral dispersion of the dye patches observed. This is an intriguing surprise. Sundermeyer has hypothesized a mechanism involving laterally relaxing mixed layers as the process dominating the lateral dispersion at scales of 300 to 3000 meters. This hypothesis needs to be tested in future experiments.

## **IMPACT/APPLICATION**

The diffusivities we have measured can be used directly by others working in the field in all disciplines in the interpretation of their data, and by those developing numerical models of the continental shelf system. Our results place real limits on how much diapycnal mixing can be invoked in typical stratified conditions to explain changes in the distribution of biological and chemical optically active species. The comparison of the dye measurements with the microstructure measurements bolsters confidence in the later, which can be made over broader areas and depth ranges than dye experiments.

## **TRANSITIONS**

Our results on lateral dispersion and movement can be used to test simulation models such as that of A. Robinson, of Harvard University. We have discussed this with that group. Also, the results for diapycnal and lateral diffusivity will be of general use, not only for those wishing to estimate optical properties on the shelf, but also for those interested in estimating any biological, chemical or hydrographic properties on the shelf.

## **RELATED PROJECTS**

All of the projects within the Coastal Mixing and Optics Program, and especially:

Oakey, N., Turbulent microstructure studies in coastal ocean boundary layers.

Trowbridge, J. H., and A. J. Williams 3rd, Measurement of the turbulent fluxes and dissipation rates in the coastal boundary layer.

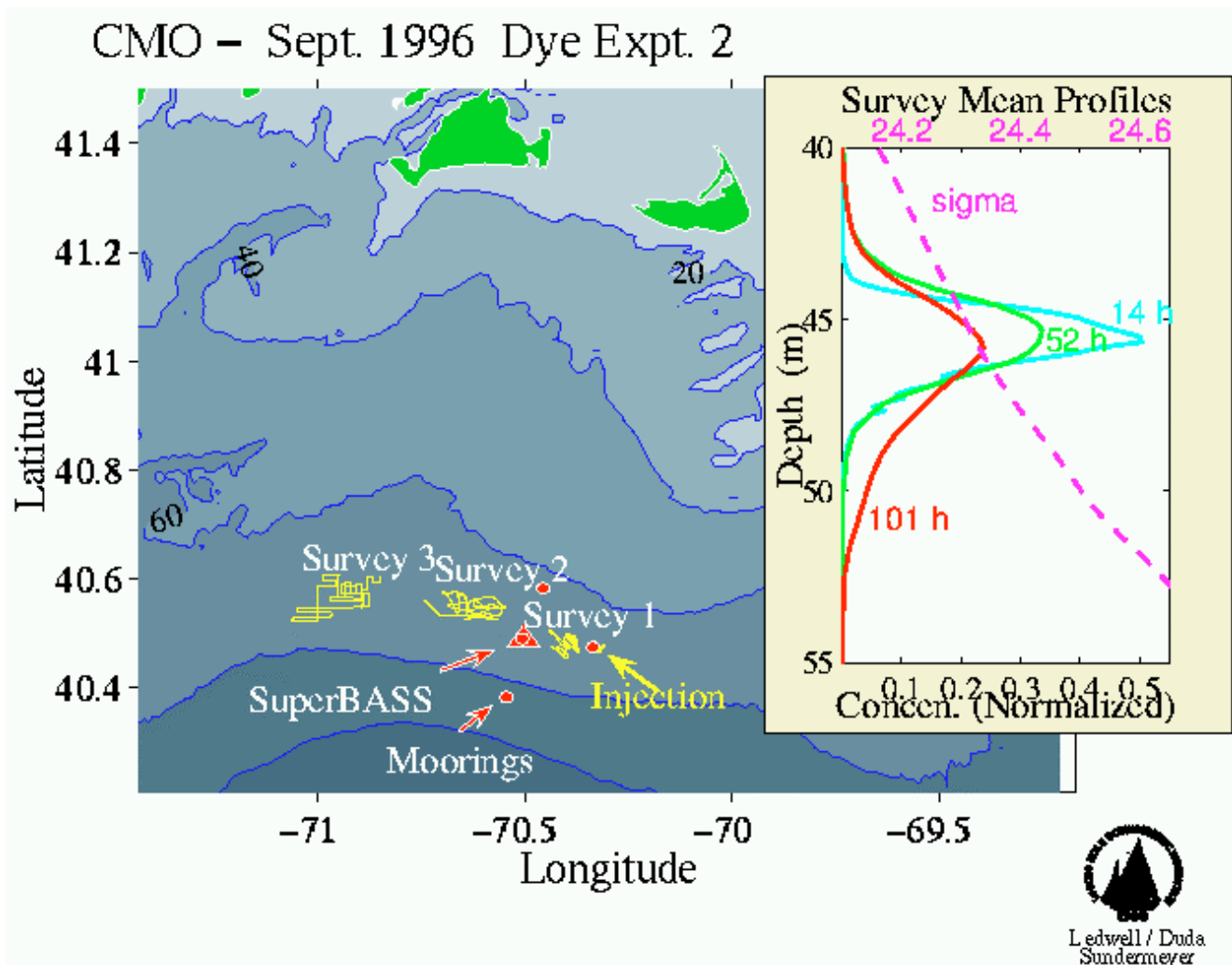
## **PUBLICATIONS**

Duda, T. F., J. R. Ledwell, H. E. Seim, C. R. Rehmann, M. A. Sundermeyer, C. J. Sellers, and S. C. Sutherland, Vertical mixing of dye in stratified shelf waters, 1998 Ocean Sciences Mtg., EOS, Trans. Am. Geophys. U., 79, Supplement, p. OS101, 1998.

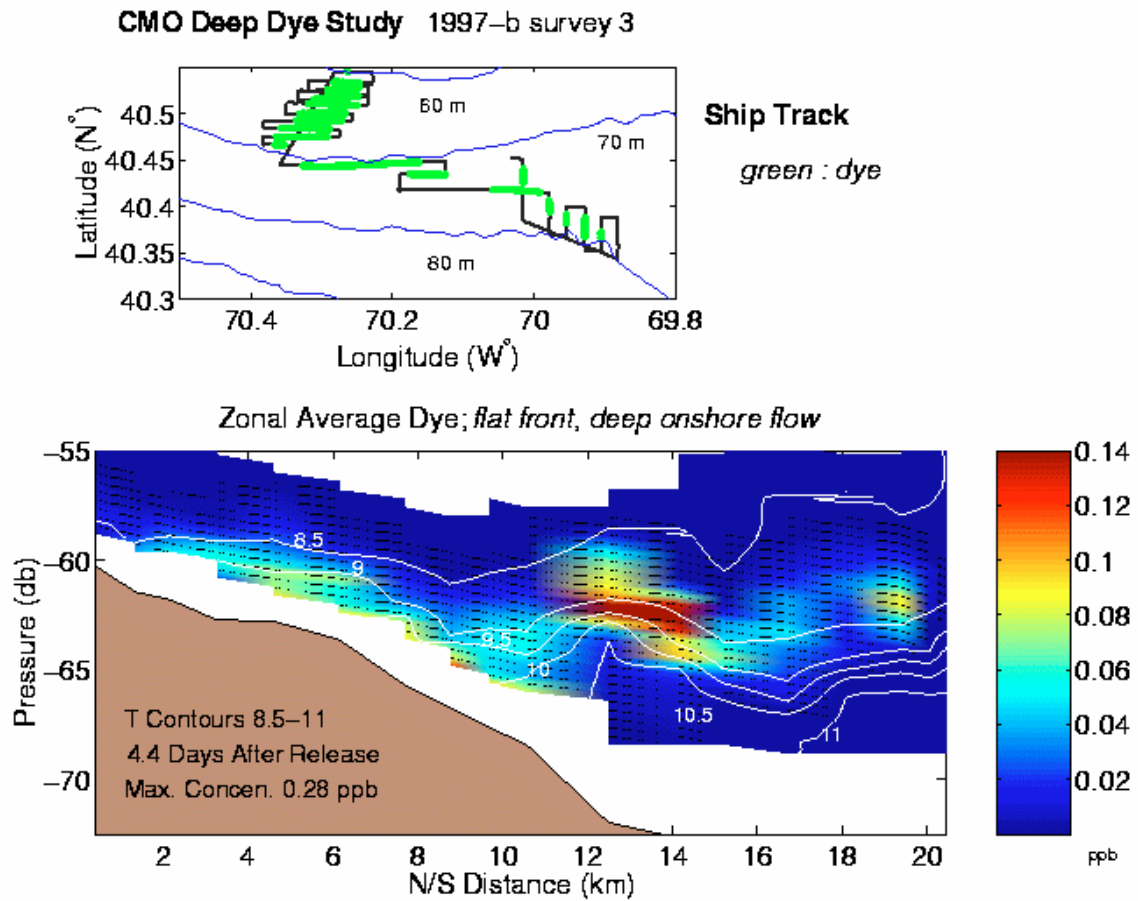
Sundermeyer, M. A., and J. R. Ledwell, Rates and mechanisms of lateral dispersion over the continental shelf, 1998 Ocean Sciences Mtg., EOS, Trans. Am. Geophys. U., 79, Supplement, p. OS140, 1998.

C. R. Rehmann and T. F. Duda, Eddy diffusivity inferred from towed microstructure measurements near the New England shelf/slope front, submitted to J. Phys. Oceanogr., September 1998.

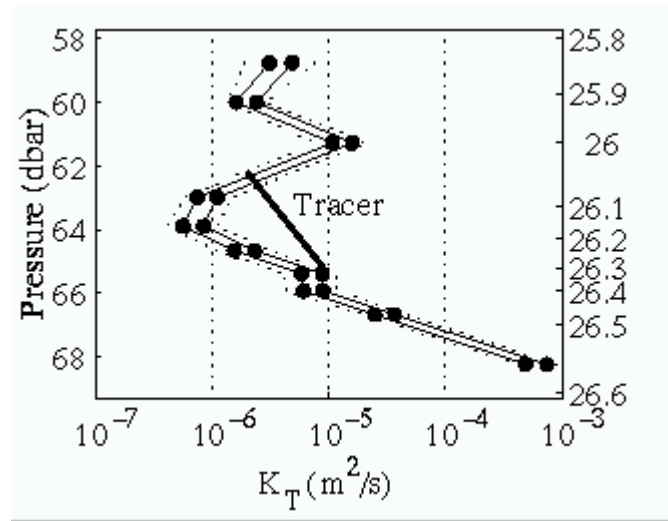
Sundermeyer, M. A., Studies of lateral dispersion in the ocean, Ph.D. Thesis, MIT/WHOI, 215 pp., 1998.



**Fig. 1. The second dye release experiment in 1996. The chart shows the injection point and the three survey tracks, which indicate advection and lateral dispersion of the dye. The tripod of Trowbridge and Williams is marked "SuperBASS." The inset shows the diapycnal dispersion of the dye for the 3 surveys at 14 h, 52 h and 101 h after release. Spreading of the dye in density space gives a diffusivity of approximately  $5 \times 10^{-6} \text{ m}^2/\text{s}$ , but higher in the deeper part of the distribution than in the shallower part. The dashed line shows the profile of potential density anomaly.**



**Fig. 2.** Zonally averaged dye concentration, 4.4 days after a near-bottom release. The top panel shows the survey track, and where dye was found. Temperature is contoured in the lower panel, with dye shown in color. The release was performed at about 10° C above the 70-dbar isobath at 70.5 W, near the SuperBASS tripod shown in Fig.1.



**Fig. 3.** Comparison of diapycnal diffusivity inferred from tracer dispersion (heavy line) with towed microstructure (solid dots) for the deep dye release in 1997.