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Vertical Mixing and Horizontal Transport in Stratified Flow at a Near Coastal Site

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1. Abstract

Frequent stratification (and restratification) episodes, strong along-shore tidal flows and variable local bathymetry characterize near coastal environments. These features are thought to control vertical mixing and horizontal transport in such near shore regions. To better understand this environment, a dye-dispersion study was performed in an area off San Clemente Island, CA in March 1999, along with detailed measurements of the flow and vertical mixing. The major result of this work is that observed horizontal dispersion rates of towed fluorometer data are about 2 orders of magnitude larger than generally accepted values. Even when scale dependant dispersion (Stacey et. al, 2000) is applied to the problem, the coefficient of the dispersion term are $0.08 \text{ cm}^{2/3} \text{ s}^{-1}$, substantially larger than observed values.

2. Introduction

The purpose of this study is to characterize stratified flows in near-coastal environments. It is essential to understand the physics of such flows because they determine the transport and dispersion of scalars, such as contaminants, nutrients, and biota near-shore. Vertical stratification and the interaction of along-shore tidal flows with the local bathymetry are important aspects of these coastal flows. When the water column is stratified, vertical dispersion will be reduced and the transport of scalars may be limited to layers. Further, where the stratified flows interact with the bottom, mixing at the boundary can create horizontal density variations, which may drive offshore intrusions, which can transport scalars cross-slope.

The ADCP velocity data collected during the study indicate that the flow during this period was predominantly along isobath, although instances of significant cross-isobath flow occurred. Therefore, the dye is largely advected along-isobath and constrained by the stratification to the bottom boundary layer. The lateral dispersion of the dye within the boundary layer is well approximated by a solution to the dispersion equation with a scale-dependent dispersion coefficient (Stacey et. al, 2000), which is to be expected in this environment where the velocity structures are characterized by a broad range of lengthscales. Interestingly, there is evidence of offshore transport of dye in a lens at a depth of about 10 meters. This depth is consistent with the location of the strongest thermocline and would suggest the presence of density-driven intrusions created by the interaction of the stratified tidal currents with the sloping bottom. Vertical density/microstructure profiles reinforce this interpretation. These profiles

indicate that the water column may be divided into three main sections: 1) A surface layer affected by wind events; 2) a near bed layer, dominated by bottom stress; and, 3) an intermediate section which can be mixed by shear at the base of the thermoclines.

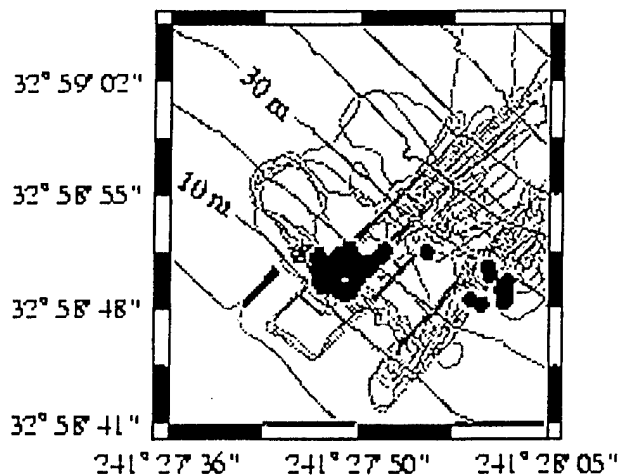


Figure 1. Plan view of test site showing bathymetry contoured at 10 meter intervals, the shore and pier in the lower left corner, the source marked by the star off of the end of the pier.

3. Experimental Setup

A series of dye experiments were performed the week of 24 - 26 March 1999 at the San Clemente Island site, see Figure 1. Each day, a zero-momentum, zero-buoyancy, near-bed source of Rhodamine WT (30% solution diluted with seawater to 2%) at 15 meters depth was turned on at the beginning of a particular tidal phase. The velocity field was measured using a 600 kHz RDI acoustic Doppler Current profiler mounted on a small boat. Sets of transects were made every several hours along six lines which were perpendicular to the isobaths. Each of these transects was approximately 600 meters in length with an along-shore spacing of 100 to 400 meters. Two microstructure profilers were also deployed from this boat to measure the density field and to determine the vertical mixing which was occurring. One profiler was a modified Ocean Sciences OS100 used in downward profiling mode and the other was a self-contained autonomous microstructure profiler (SCAMP), made by Precision Measurement Engineering. These measurements were used to determine the thickness of the bottom boundary layer (BBL) or the thickness of the layer to which the dye was constrained. Microstructure profiles were normally taken at the beginning, middle and end of a line, but occasionally at the beginning, end and four intermediate points. We will focus our discussion here on the morning of 26 March 1999 during a period typified by along-isobath flow from Northwest to Southeast.

4. ADCP Observations

The tidal currents for the period 25 to 27 March are nearly reversing on flood and ebb with an along-isobath ($45^\circ - 315^\circ$ True) maximum component of 15 cm s^{-1} and maximum across-isobath component of 5 cm s^{-1} . Here 'reversing' means that the direction of the ebb current is 180° different from the flood direction and the magnitudes are nearly equal. The flow during the morning of 26 March 1999, is

towards the Southeast (45° True) at approximately 10 cm s^{-1} , the across-isobath component is practically 0 cm s^{-1}). The ADCP directional shear indicates a BBL thickness of 7 meters.

5. Dye Observations

The dye measurements consisted of towed fluorometers from two vessels: the R/V HSB was transecting near the source (100-200 meters downstream) and the R/V ECOS was transecting further downstream (400-500 meters downstream). Each vessel followed a fixed-grid sampling plan which involved setting the tow body at a particular depth and driving two parallel transects (one towards shore, one away from shore) which extended in the inshore direction to just outside the isobath at the depth the fluorometers were sampling. The fluorometer depth was then adjusted and the transects were repeated (see Figure 1). The result was a three-dimensional cross-section of the plume during the period of the measurements.

6. Horizontal Advection

On the morning of 26 March the dye release began at 0845 PST along with the ADCP/microstructure transecting while the dye detection tows began later that morning at 1100 PST. Focusing in Figure 1 on the near-source vessel, HSB, the dye is detected primarily along the isobath of the source (at a depth of about 15 meters). This result indicates that in the near-field, the dye is advected primarily along-isobath, as would be expected based on the ADCP observations. In the data from the far-field vessel, the ECOS, the dye is detected further offshore, indicating significant cross-isobath advection.

The local bathymetry is also shown in Figure 1 (contour lines at 10 meter intervals); two characteristics of the plume are evident. First, uniform slope and parallel isobaths characterize the region extending from the source to a few hundred meters downstream. This is the region of along-isobath advection of the dye, which would be expected. Further downstream, however, at a distance of approximately 600 meters from the source, a sill shoals significantly compared to the near-source region. This sill is just downstream of the location of the ECOS transects and we hypothesize that the cross-isobath advection of dye is due to the interaction of the flow with this sill creating cross-isobath flow at depth.

7. Vertical Distribution

Collapsing the data into the cross-isobath - vertical plane produces the dye distribution displayed in Figure 2. This figure illustrates the location of the transect measurements and the location relative to the bed of the dye detections (looking upstream to the Northwest). It is clear that the vast majority of the dye detections are contained in the near-bed region, which indicates that the dye is being retained in the bottom boundary layer. The near-field data, from the HSB, is centered around the location of the source, which is located at a depth of 15 meters and a horizontal position of 150 meters on this figure. In the ECOS data, however, the dye detection is seen to occur much deeper and in the offshore direction, but still within the bottom boundary layer, from 12 to 18 meters depth and a horizontal location of 150 to 270 meters. This indicates that the cross-isobath flow evident in the horizontal advection of the dye is also a down-slope flow. We conclude that the sill located at about 600 meters downstream of the source is influencing the near-bed flow just upstream of it, producing down-slope flow in the bottom boundary layer. Figure 2 also shows that the dye is trapped in a bottom boundary that is approximately 7 meters thick.

Although most of the dye is retained in the bottom boundary layer, there are two notable exceptions, at depths of about 10 and 12 meters. At these depths, lenses of dye are seen to extend from the bottom

boundary layer into the interior of the flow. The locations of these potential intrusions are consistent with the location of the thermoclines and are suggestive of density-driven intrusions resulting from the elevated mixing in the bottom boundary layer. At this point, however, a quantitative analysis of this dynamic is limited by the sparse data set, but the velocity and density (see Figure 4) transects are consistent with this interpretation.

8. Horizontal Dispersion

Focusing on the near-source portion of the data set, from the HSB, we can examine the extent of horizontal dispersion within the bottom boundary layer. In Figure 2, we see that the lateral extent of the dye within the bottom boundary layer at a distance of about 200 meters downstream of the source is approximately 150 meters. This lateral extent would suggest a Fickian dispersion coefficient of more than $11 \text{ m}^2 \text{ s}^{-1}$, a value that is two orders of magnitude larger than would be expected in a turbulent boundary layer. Using a scale-dependent dispersion analysis (Stacey, et al. 2000), the coefficient on the dispersion term would be $0.8 \text{ cm}^{2/3} \text{ s}^{-1}$, which is also much larger than the values previously observed, which were consistently about $0.01 \text{ cm}^{2/3} \text{ s}^{-1}$ in the coastal ocean (Brooks 1960, Okubo 1971, Stacey et al. 2000). The scale-dependent analysis in Stacey et. al. (2000) was applied to the current data to estimate

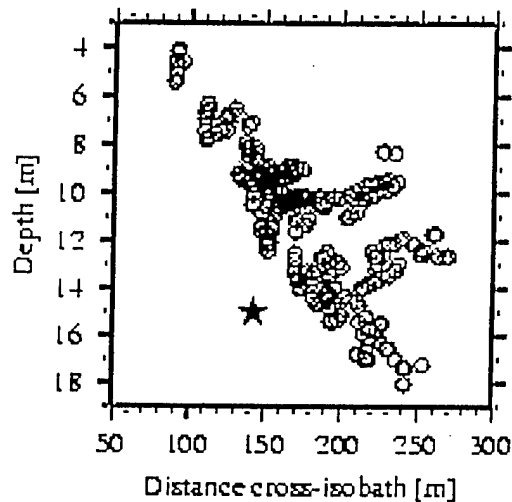


Figure 2. Lateral cross section of dye hits measured from an arbitrary horizontal datum. The source is marked with a star at a depth of 15 meters depth and 140 meters distance.

the dispersion coefficient in a reference frame centered along the plume centerline to remove any meandering or unsteadiness effects in the plume structure. The fact that the horizontal dispersion appears to exceed the expected value by a large amount indicates that over the period of the measurements - which took place over about 1.5 hours - the plume was meandering within the bottom boundary layer. Based on the scale of the dye distribution, we would estimate this meander lengthscale to be about 60 meters on either side of the centerline (along-isobath), which at a distance of 200 meters indicates an angle of about 15° .

9. Plume Summary

The plume structure in this stratified coastal flow is dominated by the bottom boundary layer. The dye, which is released in the near-bed region, is largely constrained to remain in the bottom boundary layer.

Within this layer, it advects along isobaths in the near field, until it is forced downslope by a sill in the bathymetry at about 600 meters downstream. Vertical dispersion is capped by the stratification above the bottom boundary layer, but evidence of density intrusions appear in the form of lenses extending into the interior of the flow. Finally, the horizontal dye distribution within the bottom boundary layer appears to be dominated by extensive meandering of the plume centerline, with a maximum meandering angle of about 15° .

Subsequent to the March 1999 study, an autonomous underwater vehicle (REMUS) was used to sample a similar plume at the same location. Figure 3 shows the dye concentration data collected by REMUS. In this case the flow was to the Northwest at approximately 7 cm s^{-1} along-isobath with the source located on the 15 meter isobath on the right side of Figure 1. This data set was collected in less than 20 minutes and each individual plume crossing was accomplished in less than 20 seconds so the meandering detected in the towed data set does not appear. The plume width expands from 10 to 30 meters at downstream ranges of 30 and 130 meters and the maximum concentration decreases from 15 to 4 ppb at the same ranges.

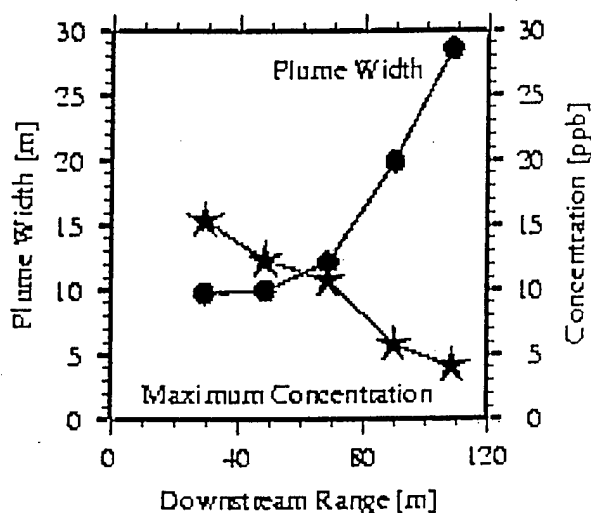


Figure 3. Plot of REMUS dye plume crossing data. The lateral plume width in meters (circles) is shown as a function of range downstream from the source and the maximum dye concentration measured as a function of range is also shown (stars).

10. Microstructure Observations and Discussion

The microstructure profiles show that the water column may be divided into three main sections: 1) A surface layer where, during wind events, active mixing takes place; 2) a near bed layer where mixing is predominantly driven by bottom stress; and, 3) an intermediate, often quiescent, section which is punctuated by areas of shear induced mixing and may contain multiple mixing events. These layers are seen in Figure 4. This cast was taken at 0932 PST on 26 March 1999. The segments were calculated by cumulatively summing the Thorpe displacement and taking the zero turning points as the section boundaries. The resultant kinetic energy dissipation rate ranges from 2.3×10^{-8} to $1.6 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$, while the vertical diffusivity (K_z) has a range of 2.7×10^{-4} to $1.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$. The calculated kinetic energy dissipation rates (epsilon) are calculated by fitting the Bachelor spectrum (Imberger and Ivey 1991), and the flux Richardson number was computed as in Ivey and Imberger (1991), and $K_z = R_f / (1 - R_f) \times \text{epsilon} / N^2$, where N^2 is the Brunt-Viasalla frequency.

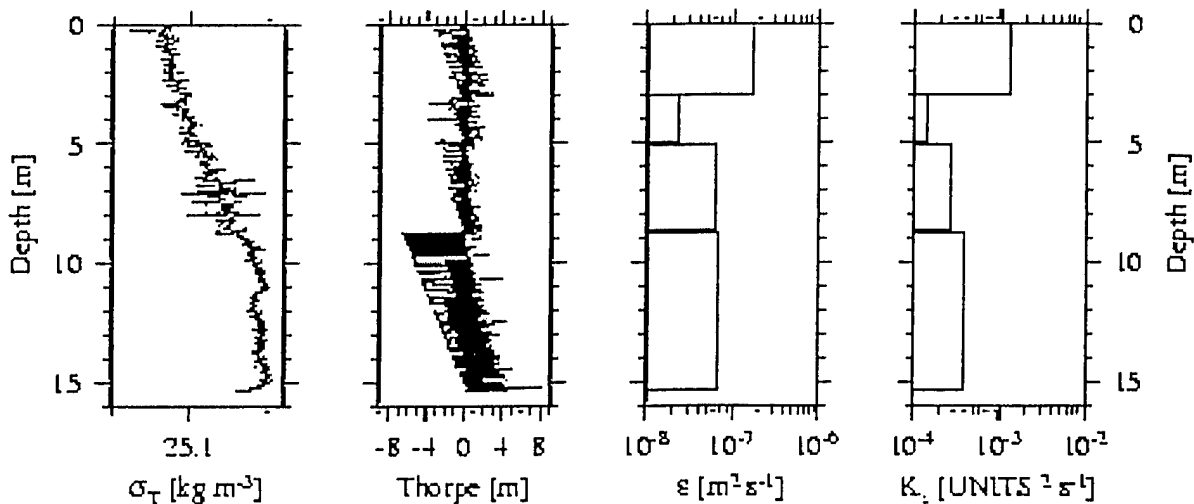


Figure 4. Typical microstructure profile taken at 0932 PST, 26 March 1999. The vertical scale on all plots is depth in meters. Panels a, b, c and d are: density, Thorpe displacement, turbulent kinetic energy dissipation rate and vertical eddy diffusivity.

11. Conclusions

The conclusions drawn from this work are as follows: 1) In the near-shore environment, the flow may be approximated as along-isobath, though there are periods of across-isobath flows. 2) When stratification is strong enough to limit vertical mixing across interfaces, dye released in a layer is necessarily constrained within that layer. 3) The interaction of stratification with a sloping bottom can generate lenses of bottom layer water at the stratification interface which extend seaward possibly transport scalars such as contaminants, nutrients or biota offshore. 4) Observed horizontal dispersion rates of towed fluorometer data (which took 1.5 hours to characterize the plume) are about 2 orders of magnitude larger than generally accepted values. If scale dependant dispersion (Stacey et. al, 2000) is applied to the problem, the coefficient of the dispersion term would be $0.08 \text{ cm}^{2/3} \text{ s}^{-1}$, substantially larger than observed values. And, 5) that the kinetic energy dissipation rate observed for this period is in the range of 2.3×10^{-8} to $1.6 \times 10^{-7} \text{ m}^2 \text{ s}^{-3}$, while the vertical diffusivity has a range of 2.7×10^{-4} to $1.3 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$.

13. References

- Brooks, N. H. Diffusion of Sewage Effluent in an Ocean-Current. Proc. First International Conference on Waste Disposal in the Marine Environment., UC-Berkeley, 1960.
- Imberger, J. and Ivey, G.N. *On the Nature of Turbulence in a Stratified Fluid. Part II: Application to lakes.* Journal of Physical Oceanography, Vol. 21, No. 5, May 1991.
- Ivey, G.N. And Imberger, J. *On the Nature of Turbulence in a Stratified Fluid. Part I: The Energetics of mixing.* Journal of Physical Oceanography, Vol. 21, No. 5, May 1991.
- Okubo, A. Ocean Diffusion Diagrams. Deep-Sea Research, 18, 789-802, 1971.
- Stacey, M. T., A. E. Cowen, T. M. Powell, E. Dobbins, S. G. Monismith and , J. R. Koseff. *Plume Dispersion in a Stratified, Near-Coastal Flow: Measurements and Modeling.* CSR, x.20, 637-663. 2000.