A dye tracer reveals cross-shelf dispersion and interleaving on the Oregon shelf

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[1] A fluorescent dye tracer was injected into the pycnocline on the Oregon shelf at a depth of 9–10 m. It spread rapidly cross-shelf as two distinct layers, one above the other in the water column, split by interleaving dye-free water. The vertical scale of these layers, and associated density steps, was 1–2 m, and the horizontal extent of interleaving exceeded 1.6 km after an inertial period. The upper dye layer was sharply peaked and embedded in a strong vertical density gradient. The lower layer was slab-like and associated with weak stratification. Both layers were inclined slightly in density space. It is proposed that internal wave-induced mixing and the lateral collapse of mixing patches were important mechanisms. Analogies can be drawn between these dye structures and frequently-observed thin planktonic layers. By approximating the dye dispersion as a Fickian process, estimated isopycnal and diapycnal eddy diffusivities of $\kappa_x = 4.1\ \mathrm{m^2\ s^{-1}}$ and $\kappa_z = 1.4 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$ are obtained. **Citation:** Dale, A. C., M. D. Levine, J. A. Barth, and J. A. Austin (2006), A dye tracer reveals cross-shelf dispersion and interleaving on the Oregon shelf, *Geophys. Res. Lett.*, *33*, L03604, doi:10.1029/2005GL024959.

1. Introduction

[2] The release and tracking of dye tracers is a powerful method for investigating oceanic dispersion. The spreading of a dye patch reveals, in a Lagrangian sense, the cumulative effect of dispersive processes from a well-defined source. Subsurface dye injections into stratified systems [e.g., *Houghton and Visbeck*, 1998; *Sundermeyer and Ledwell*, 2001] have revealed complex Lagrangian pathways and offered insights into dispersive processes. Described here are observations of the cross-shelf dispersion and interleaving of a dye tracer in the pycnocline on the Oregon shelf (Figure 1) during the first inertial period following its release, while the scale of the patch remained a few kilometers or less. The emphasis is on characterizing the evolution of the injected dye relative to underlying density structures. Clear analogies can be drawn with structures seen in naturally-occurring tracers with less well-defined sources, such as thin planktonic layers [*Cowles*, 2003].

[3] An isolated tracer patch may disperse on an isopycnal surface as a result of advective processes within that surface, such as stirring by an eddy field. Mechanisms also exist by which mixing across isopycnals can lead to isopycnal dispersion. Firstly, in shear dispersion [*Young et al.*, 1982], the combination of diapycnal mixing and shear allows a tracer to disperse isopycnally by experiencing the velocity at a range of densities as it mixes before returning to its initial density. Secondly, an isolated mixing event produces a patch of weakly-stratified water which has a tendency to collapse laterally in a geostrophic adjustment, leading to direct isopycnal expansion and vortical stirring [e.g., *Sundermeyer et al.*, 2005]. In an energetic environment, such as the Oregon shelf, all of these processes may contribute to isopycnal dispersion.

2. Methods: Dye Injection and Survey

[4] A density-adjusted solution containing 45 kg of a fluorescent dye, rhodamine-WT, was injected as an along-shelf streak, 1.5 km in length, on June 27 2003. The location was 10 km offshore (Figure 1), in a water depth of 83 m. Mean injection depth and density were 9.7 m and $1025.31 \pm 0.08\ \mathrm{kg\ m^{-3}}$, in the pycnocline beneath a 4- to 5-m mixed layer. Ambient density was monitored during injection, and depth adjustments were made to maintain a near-isopycnal release, although some variation in the injection density was unavoidable (Figure 2) due to internal waves. A drifter, drogued at 15 m, was released with the dye to provide an estimate of its advection.

[5] Survey was by tow-yo, in which a conductivity-temperature-depth (CTD) package was raised and lowered in a continuous cycle while the ship made headway at 0.5–1.5 knots. Sampling was at 24 Hz, for an average vertical

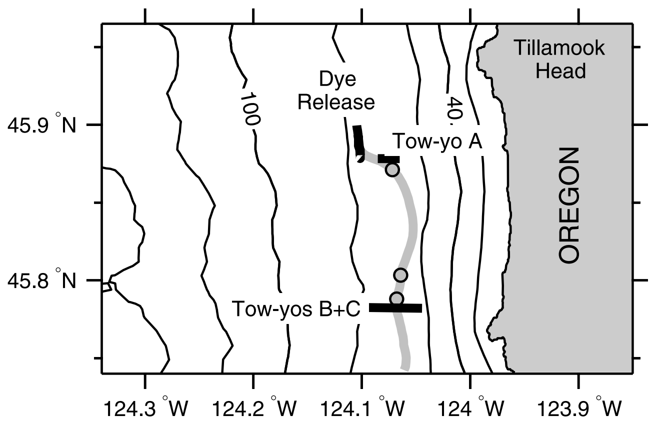

Figure 1. Bathymetry (contoured) of the northern Oregon shelf, showing (black) the location of the dye release and tow-yo lines, and (gray) the path of a 15-m drogued drifter released with the dye. Bullets show the drifter position at the mid-time of each tow-yo.

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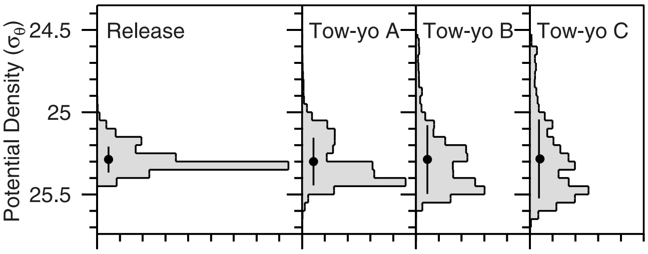

Figure 2. Histograms of dye distribution versus density at the time of release (from CTD density during injection), and during tow-yos A, B and C. Distributions are normalized by area. Means and standard deviations are shown by bullets and bars.

resolution of 0.0175 m. The horizontal spacing of casts was 20–70 m. Dye was detected by a tuned fluorometer with a freely-flushing sensor mounted close to the (pumped) intake of the temperature and conductivity cells. While CTD tow-yos provide excellent vertical and horizontal resolution, forward progress was too slow to bound and fully characterize the evolving dye patch in this advective regime.

3. Observations

[6] The evolving dye patch is described for roughly an inertial period (16.7 hours) from release. Evolution beyond this period will be reported separately. Description focuses on three cross-shelf tow-yo sections, each made in an offshelf direction at times 3.8–5.3 hours (A), 12.9–14.7 hours (B) and 15.4–17.0 hours (C) following release. Tow-yo A was made close to the release location (Figure 1). B and C were made 12 km to the south. During this entire period, hourly-averaged winds were consistently southward at 3–10 m s^{-1}, and the drogued drifter advected southward (Figure 1) at a mean speed of 0.19 m s^{-1}. The dye patch spread rapidly cross-shelf, from a negligible extent at release

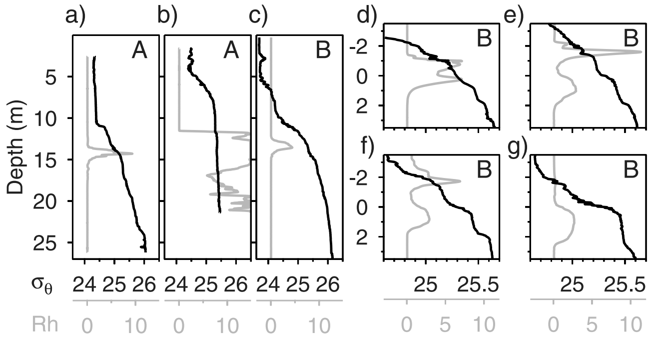

Figure 4. Profiles of potential density (σ_θ) (black) and rhodamine concentration ($\mu g/l$) (gray) from (a and b) two downcasts during tow-yo A (west-east) and (c–g) five during tow-yo B (west-east). Figures 4d–4g show an extract from the water column, with depth relative to σ_θ = 25.29. Profile locations are shown in Figures 3 and 5.

to more than 3.5 km at the time of B and C, becoming bifurcated into two thin (1–2 m) layers (Figure 3) separated vertically by an interleaving dye-free layer.

[7] During tow-yo A, several casts showed two dye maxima in the water column, but these did not yet form an extensive two-layer structure. The cross-shelf extent of the dye was around 1 km. Offshore, dye-laden water formed a thin layer embedded within a strong vertical density gradient (Figure 4a). Onshore, the patch was denser, at least 10 m thick in places, and associated with weak stratification (Figure 4b). It is not known whether this weakly-stratified water existed at the time of release, or was formed by post-release mixing or straining.

[8] Tow-yo B was the first to observe the dye patch split vertically into two distinct and extensive layers. The structure of these layers appears most clearly in individual profiles (Figures 4c–4g). The two layers were joined offshore and inclined slightly in density space, with the

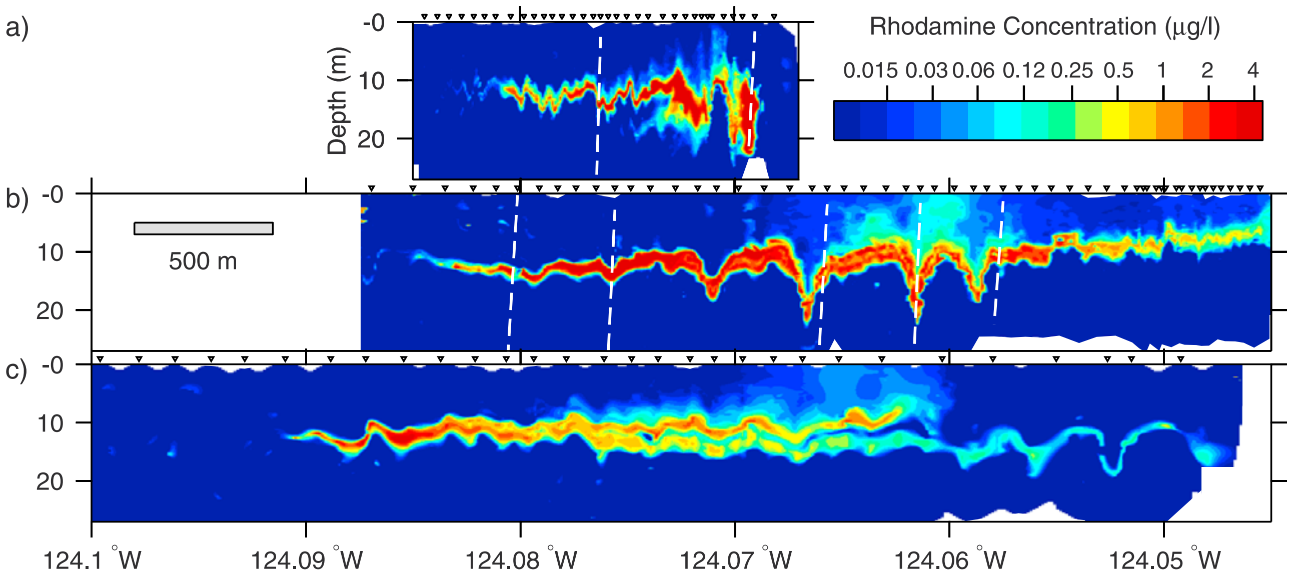

Figure 3. Cross-shelf sections of dye concentration from CTD tow-yos. Triangles on the upper axes show the start of each downcast. (a) Tow-yo A, (3.8–5.3 hours post-release), (b) Tow-yo B (12.9–14.7 hours), (c) Tow-yo C, (15.4–17.0 hours). Gridding was performed in (x, σ_θ) space then transformed to (x, z) space, a method that favors coherence of the gridded field along isopycnals. Dashed vertical lines show the profiles of Figure 4.

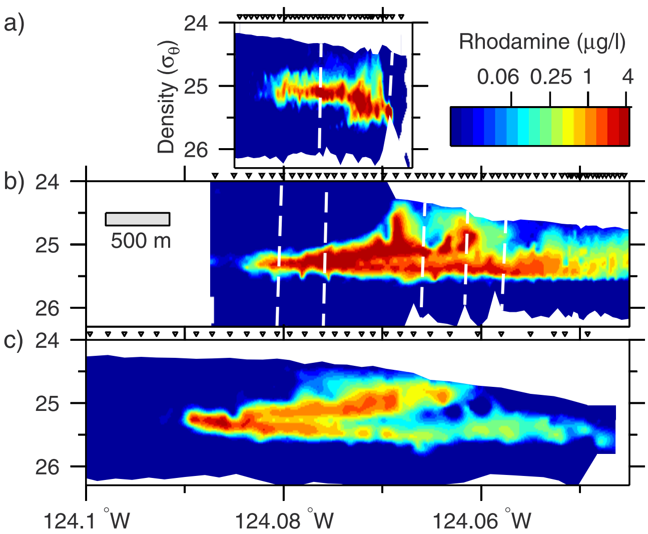

Figure 5. As Figure 3, but showing dye concentration vs density, from downcasts only.

shallower layer becoming lighter inshore and the deeper layer becoming denser (Figure 5). At the farthest point from their bifurcation, their separation was 0.5 kg m^{-3} in density and 2.5 m vertically. The cross-shelf extent of the two-layer structure was 1.3 km, with the lower layer extending at least 1.2 km onshore of the edge of the upper layer. Close to their bifurcation, the layers appeared as two sharp dye peaks in the water column (Figure 4d). Further onshore (Figures 4e and 4f), as these peaks became increasingly distinct, the upper layer remained sharp and embedded in a strong density gradient, but the lower layer became associated with a slab-like feature of weak stratification. This is apparent as a step in profiles of density versus depth (Figure 6). The interleaving dye-free layer was also relatively weakly-stratified (Figures 4e and 4f), appearing to join the surface mixed layer inshore of the upper dye layer (Figure 6). Maximum dye concentrations were greater in the sharp upper layer than in the slab-like lower layer.

[9] A train of four internal waves was encountered during tow-yo B, appearing as depressions of the dye layers in Figure 3b. These waves were presumably propagating onshore and contracted in this view by the offshore ship motion. Each wave consisted of a 5 to 10-m depression of the pycnocline.

[10] Tow-yo C was made shortly after tow-yo B, at the same latitude, following a return transit onshore and redeployment of the CTD. Similar interleaving dye structure was observed, with the cross-shelf extent of the two-layer structure now 1.8 km, and relatively more dye in the sharp upper layer than in the slab-like lower layer (Figure 3).

[11] Assuming that the dye load at the latitude of tow-yos B and C varied linearly with time as the dye patch advected past it to the south, and that advection was constant, at the mean speed of the drogue, it can be inferred that 48% of the dye passed this latitude between the two tow-yos. Since both tow-yos saw a similar cross-shelf structure, this was likely representative of at least 48% of the dye patch. Southward advection of the drogue during this period was 1.6 km, giving an idea of the north-south scaling of the patch, and a lower bound on the extent of interleaving.

4. Discussion

[12] The interleaving dye layers could have formed advectively by flow that was vertically-sheared on scales of 1–2 m. Tilting of the layers in density space is consistent with this, although the process was not purely advective, as spreading occurred both along and across isopycnals (see below). The dye layering was clearly linked to stepped structures in the density field - features which also existed elsewhere in the water column (Figure 6). The presence of these density structures, in what was a double-diffusively stable water column, resembles the result of patchy internal wave-induced shear and mixing [*Alford and Pinkel*, 2000]. In such cases, steps and layers may be inclined relative to isopycnals [*Thorpe et al.*, 1999; *Sundermeyer et al.*, 2005], as are the ray paths of internal waves. Acoustic observations from the Oregon shelf [*Moum et al.*, 2003] have shown that turbulent streaks do exist in the wake of large amplitude internal waves. Cross-shelf microstructure transects have also shown that mixing is patchy [e.g., *Hales et al.*, 2005].

4.1. Lateral Intrusion of Collapsing Mixing Patches

[13] If an isolated patch of stratified water were to mix completely, then collapse horizontally, driven by the resulting pressure gradient, its horizontal expansion prior to being arrested by rotation would equal the local Rossby radius $R = Nh/f$ [*Sundermeyer et al.*, 2005]. N here is the ambient buoyancy frequency, h is the initial height of the patch, and f is the Coriolis parameter. The final state would be a vortex in thermal wind balance. Friction would permit further expansion by opposing the establishment of this balance.

[14] In the case described here, the mean buoyancy frequency in a 5-m bracket centered on the mean dye density was $\overline{N}$ = 0.042 s^{-1} (24 cph), so a patch of height h would expand laterally by R = 404h. The observed interleaving of (at least) 1.6 km could have resulted from the advective intrusion of a collapsing dye-free mixing patch with an initial height of around 4 m. The timescale of this intrusion would be the inertial period.

[15] The lower, slab-like dye layer observed during tow-yos B and C was similar in density to the thick, weakly-stratified, dye-laden layer observed at the inshore end of tow-yo A (Figure 4b). This thick layer was not observed

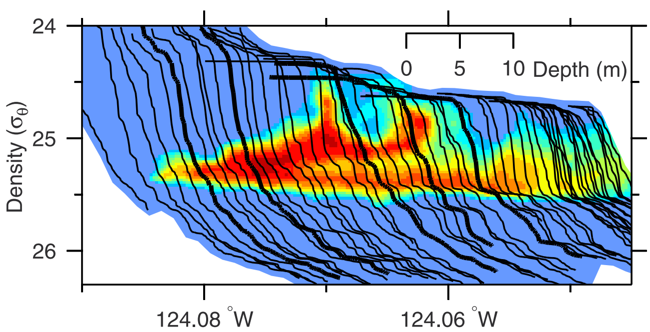

Figure 6. Stacked profiles of density against depth (inset axis) during tow-yo B. Individual profiles are offset by the ship longitude (main axis) at the time the CTD crossed σ_θ = 25.29. Homogeneous layers appear as horizontal steps. The underlying image is of dye concentration, similarly offset by depth and longitude. Bold profiles are those of Figure 4.

subsequently, and may have collapsed laterally to form the lower dye layer, although caution should be exercised in interpreting these structures in two-dimensions.

4.2. Isopycnal and Diapycnal Eddy Diffusivities

[16] In order to estimate an effective eddy diffusivity from observations of a dye patch, it is necessary to map its structure and extent rapidly relative to evolution and advective time-scales. This is a particular challenge for sub-surface patches, which can only be surveyed relatively slowly using profiling or undulating instruments. Meaningful estimates of subsurface isopycnal dispersion have, nevertheless, been obtained from dye injections in a variety of shelf environments [*Houghton and Visbeck*, 1998; *Sundermeyer and Ledwell*, 2001; *Ledwell et al.*, 2004]. Tow-yos A, B and C show an expansion of the dye patch, both isopycnally (cross-shelf; Figure 3) and diapycnally (Figure 2), with little change in its mean density. With reservations, it will be assumed that the dye observed on each tow-yo was representative of the patch as a whole, and eddy diffusivities will be estimated.

[17] Isopycnal dispersion is considered on the $\sigma_\theta = 25.29$ surface, the mean density of the four distributions of Figure 2. Since dye exists at other densities, and can mix to $\sigma_\theta = 25.29$, dispersion on this isopycnal is not independent of the density spread of the patch. A Fickian process is assumed, in which the horizontal variance $\sigma^2{}_x$ of the cross-shelf dye distribution grows linearly with time, $d\sigma_x^2/dt = 2\kappa_x$, where κ_x is an eddy diffusivity. A linear regression to the variance at the time of release (essentially zero) and of the three tow-yos gives $\kappa_x = 4.1\ \mathrm{m^2 s^{-1}}$. A similar calculation for the depth-integrated dye concentration would produce a substantially larger value, reflecting sheared advection at different density levels.

[18] Vertically, a similar approach uses the variance of the four distributions of Figure 2 to obtain an eddy diffusivity in density space. This is transformed to *z*-space, using the mean stratification of the dye patch, to obtain $\kappa_z = 1.4 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$.

[19] Sensitivity studies suggest that errors in these estimates of κ_x and κ_z due to contamination of weak dye fluorescence by natural background fluorescence are 10% or less. Other errors, in particular those due to sampling bias, are unknown. The estimated values of κ_x and κ_z lie within the range of dye-based estimates from similar shelf environments [*Houghton and Visbeck*, 1998; *Sundermeyer and Ledwell*, 2001; *Ledwell et al.*, 2004]. Direct, instantaneous estimates of κ_z from microstructure measurements on the Oregon shelf [*Hales et al.*, 2005] show extreme spatial variability, spanning up to five orders of magnitude (10^{-7} to $10^{-2}\ \mathrm{m^2\ s^{-1}}$). There have been no prior estimates of κ_x in the stratified interior in this region, although $\kappa_x = 4.1\ \mathrm{m^2\ s^{-1}}$ is of the same order as values used in modeling studies (*Allen et al.* [1995] use $\kappa_x = 2\ \mathrm{m^2\ s^{-1}}$).

5. Conclusions

[20] The observations described here, of the initial spreading of a dye patch in the pycnocline on the Oregon shelf, have documented the development of an interleaved structure by lateral transport sheared on vertical scales of 1–2 m. Interleaving of at least 1.6 km in horizontal extent formed in one inertial period (16.7 hours), in the context of a background density field with stepped structures on similar scales. It is suspected that the origin of the density structures was patchy internal wave-induced shear and mixing [*Alford and Pinkel*, 2000], an idea that is supported by acoustic and microstructure observations from this region [*Moum et al.*, 2003; *Hales et al.*, 2005]. The dye observations provide an insight into the lateral processes associated with stepped density profiles of this sort. Length and timescales were broadly consistent with the interleaving having resulted from vertically-sheared flow during the lateral collapse of mixing patches.

[21] The observed relations between dye and density structures resembled those seen in planktonic layers - in particular, the occurrence of thin layers in regions of strong vertical gradients. The fact that the dye structures can be confidently ascribed to advective-diffusive mechanisms, and that vertically sheared transport on short vertical scales has been directly revealed, means that non-conservative processes (growth, behavior, etc.) are not needed to explain similar planktonic structures.

[22] Estimated isopycnal and diapycnal eddy diffusivities, $\kappa_x = 4.1\ \mathrm{m^2\ s^{-1}}$ and $\kappa_z = 1.4 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$ lie within the range of dye-based estimates from similar environments, and provide reasonable estimates for the Oregon shelf. The observed interleaving would have contributed to κ_x through shear dispersion, and potentially also through the direct lateral collapse of mixing patches.

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