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EVOLUTION OF A VERTICALLY DISTRIBUTED PASSIVE SCALAR IN THE SEASONAL THERMOCLINE

A towed chain of fluorometers was used to measure the evolution of the concentration field of a dye deposited in the seasonal thermocline. The large number of high-frequency sensors employed resulted in a degree of spatial resolution that is substantially greater than has been reported in previously published thermocline data. Examples of the data obtained are presented along with some of the analysis that has been performed.

INTRODUCTION

In the experimental study of all but the simplest fluid flows, one is faced with the challenge of describing, at some useful level of detail, the very complex motions of an essentially infinite number of fluid elements. One way to do this is to inject tracer elements into the flow field and take either long-exposure photographs or a series of short-exposure photographs. The pictures then reveal the particular flow pattern under consideration. Tracer elements such as hydrogen bubbles, fluorescent dyes, smoke, lampblack, and kerosene vapor have been used for this purpose quite effectively in the laboratory, the atmosphere, and the ocean. This technique gives a qualitative insight into the physical mechanisms governing the observed fluid flow by enabling one to visualize a large portion of the flow pattern. A fundamental difficulty, however, is that the film records only a kind of integrated tracer concentration field along each line of sight with the result, for example, that nothing is revealed about concentrations at various points within a tracer cloud.

A more quantitative approach than photography is the use of an array of high-frequency *in situ* sensors to measure the temporal variations of the tracer concentration field. The digitized time series from each sensor is combined with that sensor's trajectory in space and time. By combining results from the various sensors, one may reconstruct many features of a tracer cloud not accessible by photography.

Both photographic and sensor techniques have been used to advantage in oceanographic research. Woods[1] created a vertical streak of dye in the Mediterranean Sea by dropping a fluorescein pellet. A series of photographs was taken, and the water velocity profile through the entire thermocline was deduced. These measurements, combined with other information, enabled him to identify internal wave shear instabilities as a mechanism for the generation of oceanic turbulent patches. Kullenberg[1-5], Kullenberg *et al.*[6] and Ewart and Bendiner[7] investigated oceanic turbulent diffusion in relation to environmental conditions such as density stratification, vertical current shear, and current variability. They injected a point source of dye into the ocean and traversed the dye field horizontally and vertically with a single fluorometer for postgeneration times of several minutes to several days. Kullenberg established the connection between horizontal and vertical diffusion and identified vertical current shear as the primary mechanism causing the observed horizontal spreading of the tracer element. Bendiner *et al.*[8] assessed the environmental impact of cooling water discharge that would be produced by a nuclear steam-generating plant. In this case, dye concentration was related to the excess temperature resulting from the thermal discharge. Billig *et al.*[9] studied the geometric and meandering characteristics of artificially generated turbulence in the ocean with an array of fluorometers towed from a surface vessel.

This paper reports results obtained from data collected by a towed array of sensors used to study advection-diffusion processes in the oceanic thermocline. The technique employed featured a thin vertical sheet of dye deposited in the seasonal thermocline. A vertical array of fluorometers was towed by a surface ship back and forth across the dye sheet for several hours. Because successive crossings were close to each other in physical space, the time evolution of an initially low-turbulence dye patch could be monitored, thereby allowing the characterization of certain background oceanic processes.

EXPERIMENTAL TECHNIQUES

In studying oceanic advection-diffusion processes, it is useful to monitor the time evolution of dye patches of different initial turbulent intensities and physical dimensions. For this purpose, several types of dye trails have been produced in the ocean using the generalized towed dye-dispensing system illustrated in Fig. 1.

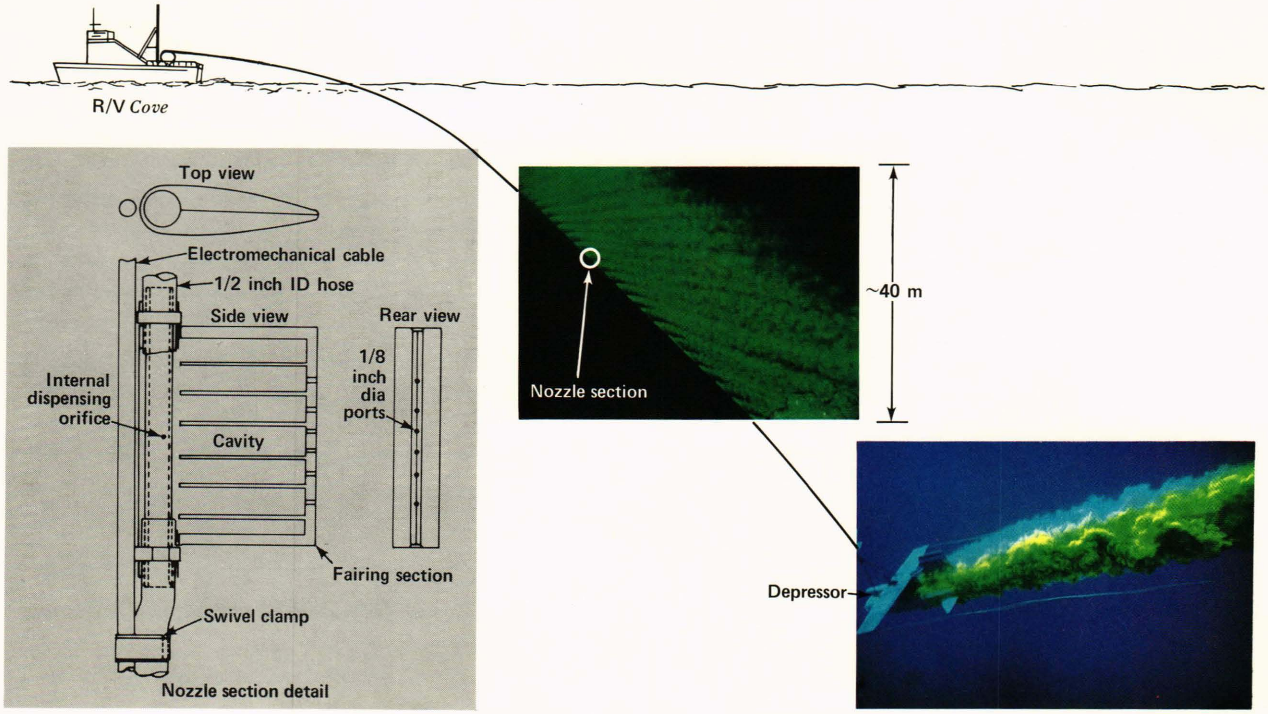

Figure 1 — Surface towed dye system. The inserts are underwater photographs showing two alternate modes of operation. In the upper picture, dye is being continuously emitted from a series of 91 nozzle sections to form an initially vertical sheet of dye roughly 40 meters high. Also shown is an expanded view of one of the nozzle sections. In the lower picture, dye is being pumped from the depressor, allowing the study of turbulent wake effects on the dye concentration field. The data discussed in this article are for the dye-sheet mode of operation.

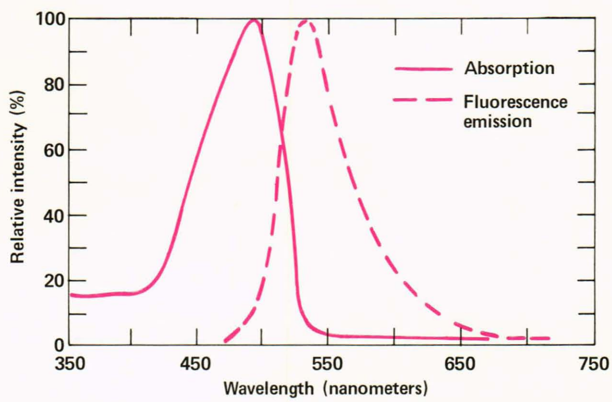

Figure 2 — Absorption and fluorescence emission curves for disodium fluorescein.

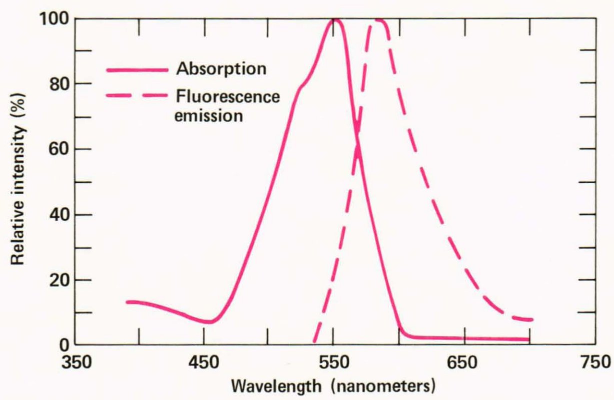

Figure 3 — Absorption and fluorescence emission curves for rhodamine WT.

Two water-soluble organic dyes suitable for ocean use are disodium fluorescein and rhodamine WT. The absorption and emission curves for these dyes are shown in Figs. 2 and 3. The fluorescence peak is at the same wavelength regardless of the excitation wavelength, whereas the intensity of the peak emission will vary with the relative strength of the absorption at the excitation wavelength. Because light is transmitted through water with relatively less attenuation at wavelengths corresponding to the absorption and emission peaks of fluorescein, it is preferable to use that dye for underwater photography when appreciable distances are involved. For the fluorometry measurements discussed here, a dye mixture that contained 5% fluorescein and 5% rhodamine WT was used.

Towed by a surface ship, this dye system can produce several types of dye trails in the ocean. Single-orifice dispensing produces a horizontal line of dye, whereas multiple-orifice dispensing produces a vertical sheet of dye of narrow initial width. It is also possible to dye the turbulent wake of the depressor by ejecting dye from its forward portion. The inserts in Fig. 1 are underwater pictures illustrating the vertical sheet and turbulent wake dye-dispensing modes of operation.

Fluorometry data were obtained during an experiment performed with two surface ships on September

11, 1979, in the Atlantic Ocean in the vicinity of 28°N 78° 25′W. A dye mixture containing 5% fluorescein and 5% rhodamine WT was dispensed from R/V *Cove* at a flow rate of 2 gallons per minute, producing a dye sheet about 40 meters high and 7 kilometers long. The towing speed was about 3.5 meters per second, and the vertical dye sheet was laid in the thermocline with its center at a depth of 80 meters where the typical buoyancy frequency was 6 to 8 cycles per hour. A second ship, M/V *State Rebel*, towing a vertical array of thermistor-fluorometer-conductivity (TFC) sensors, repeatedly crossed the dye trail on a course normal to the trail. Seventeen such perpendicular crossings of the dye trail were made at dye ages from about 6 minutes to over 3 hours. To minimize oceanic variability between adjacent crossings, the lateral spacing between successive crossings was typically 300 to 500 meters.

Results of analysis of the data obtained from the 25 fluorometers on the TFC chain are presented in the next section. The fluorometers were made sensitive to either fluorescein dye or rhodamine WT dye. A brief description of the fluorometers used in this experiment can be found in a paper by Keyes and Hochheimer.[10] The TFC chain also carried depth measurement transducers.

QUANTITATIVE RESULTS FROM DYE SHEET CROSSINGS

Description of Data

A large amount of quantitative data was gathered by the sensors on the TFC chain during the 17 crossings of the dye sheet. These crossings correspond to dye sheet ages (at the point of crossing) of from about 6 minutes to over 3 hours. Voltage output versus time plots for the 25 dye sensors are shown in Fig. 4 for the third crossing of the dye trail at a point where the trail was about 21 minutes old. The digitization rate for each fluorometer was 40 hertz. If one knows the horizontal speed of the chain (typically 3.5 meters per second) and the crossing angle, it is a straightforward task to construct an abscissa corresponding to relative horizontal displacement in meters transverse to the dye trail. This is done along the upper boundary of the plot. As another example, a similar plot for crossing 15 at an age of 180 minutes is shown in Fig. 5. Note how much more the cross section has been "sheared out." Data were also obtained from the 40 thermistors and the six conductivity cells that were on the TFC chain, but attention here is confined to quantitative results calculated from the fluorometer time series.

Analysis

Although the very extensive literature and widespread practical interest in this general area make a categorical claim impossible, it is very likely that advection-diffusion processes in the oceanic thermocline have never before been probed with such high resolution and with so many sensors.

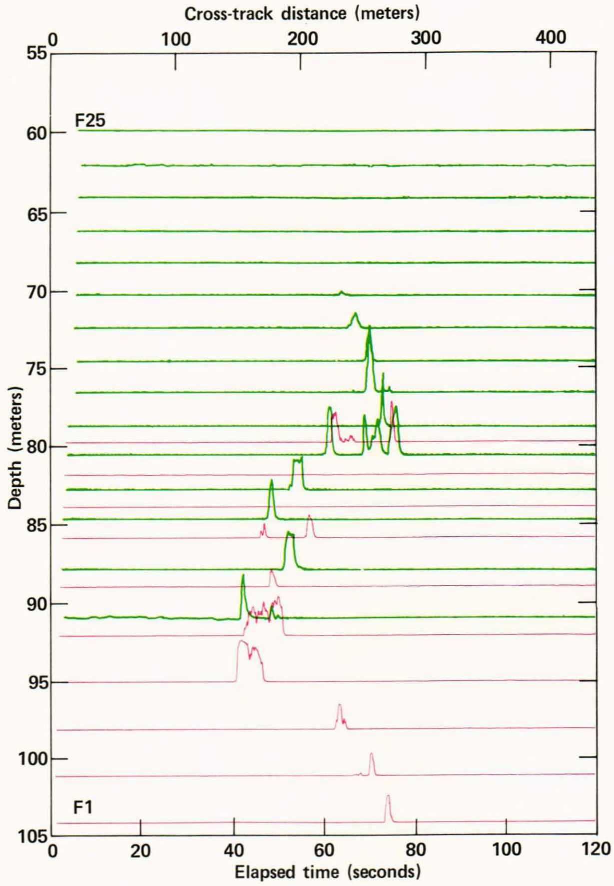

Figure 4 — Fluorometer time series for the third dye-sheet crossing. The dye detected here has been in the water approximately 21 minutes. The fluorometer outputs have been arranged to reflect the geometry of the dye distribution. The green and red traces correspond to fluorescein- and rhodamine-sensitive fluorometers, respectively. The speed at which the fluorometer chain was towed is used to convert elapsed time into cross-track distance. Fluorometers 11 and 13 were not operating during the 17 crossings of the dye sheet.

These attributes, of course, do nothing to relieve the well-known difficulty that the amount of insight into a data set is not necessarily proportional to its volume. To see what it really means to understand the data, we first note that the concentration field $c(\vec{x},t)$ of a given passive scalar such as dye satisfies the fundamental equation

$$\frac{\partial c}{\partial t} + \vec{u} \cdot \vec{\nabla} c - \mu \nabla^2 c = s(\vec{x},t) \;, \qquad (1)$$

where μ is the molecular diffusion coefficient and $\vec{u}(\vec{x},t)$ is the Eulerian velocity field for the ocean. Here $s(\vec{x},t)$ is the rate (in units of mass per unit time per unit volume) at which the scalar is being dispensed at position $\vec{x}$ and time t. The deeper our insight, the more fully the data will be understood in terms of this equation. By this criterion, our understanding is rather primitive.

Nonetheless, some interesting regularities have been observed in the data thus far. They are related

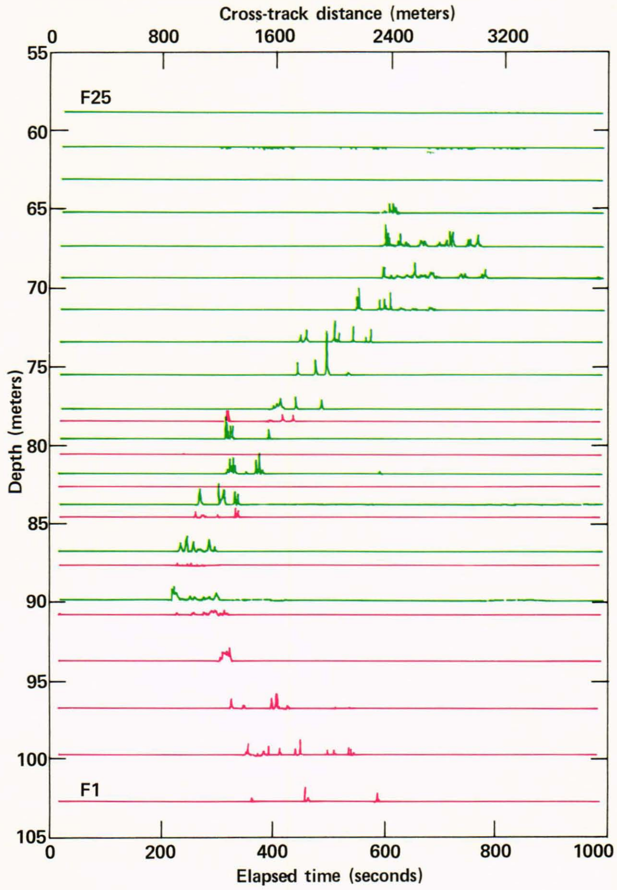

Figure 5 — The same as Fig. 4 but for the fifteenth crossing. The dye detected here has been in the water approximately 180 minutes. This crossing is aligned so that the fluorometer chain was towed in the same direction as it was for Fig. 4. Note that the horizontal scales are completely different in magnitude in order to accommodate the large amount of spreading that has occurred. It is evident from the plots that a primary cause of the spreading is the variation of horizontal current with depth, otherwise known as current shear.

primarily to the overall geometric properties of the dye field and, for the most part, are independent of the very fine detail that abounds in the fluorometer time series.

General Observations and Definitions — The fundamental property of the oceanic thermocline is that it is stably stratified — that is, the density of the water increases with depth. Thus, energy is required for water elements to be displaced vertically. One would therefore expect natural motions to be predominantly horizontal. This elementary expectation is quite consistent with the dye line data. In particular, note how much more spread out horizontally the dye field is in Fig. 5 than it is in Fig. 4. On the other hand, the area integrals of both the fluorescein and the rhodamine for these two crossings calculated over the vertical plane swept out by the chain (corrected for the crossing angle) indicate no loss of dye, just as one would expect if there were no significant vertical transport.

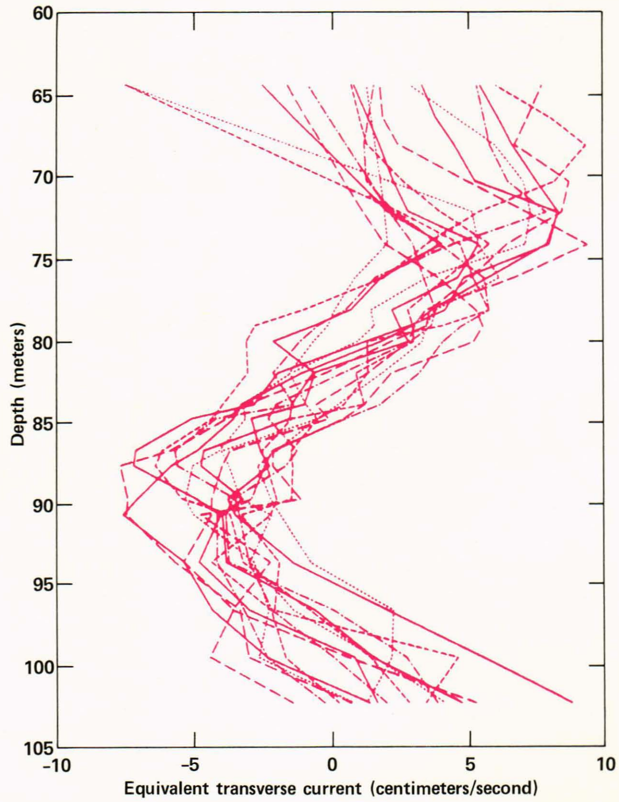

Figure 6 — Equivalent transverse current versus depth for 16 dye-sheet crossings. This plot is oriented to be compatible with Figs. 4 and 5. Each current profile has been moved independently so that its integral over depth vanishes. The overall similarity of these profiles is consistent with the Garrett-Munk internal wave model. Correlation coefficients between pairs of these profiles are displayed in Fig. 7.

The horizontal spreading of the dye is treated in two different ways for a given crossing. First, the "center of mass" for each fluorometer time series is calculated. These centers are then connected (after correcting for the fact that the chain does not hang perfectly vertically while under tow) to form a dye centerline that corresponds approximately to the vertical profile of the background current component transverse to the direction along which the dye sheet was laid. A second approach is to calculate the width of each fluorometer time series. This calculation has been made, with the result that each crossing has multiple widths associated with it. (The "width" of a crossing means the average of these widths.) In practice, these widths and centers of mass are calculated using the three lowest moments of the dye concentration time series for each fluorometer.

Centerline Profiles — From Figs. 4 and 5, it is apparent that the dye centerlines for at least these two crossings have some overall similarity. In Fig. 6, the centerlines for 16 of the crossings[11] are plotted on the same graph. Each centerline has been *independently* translated along the abscissa so that its integral over depth vanishes. Furthermore, the centerline displacements have all been divided by the age of the dye trail for that crossing, so that the abscissa has units of relative horizontal current velocity in centimeters per second. Clearly, the profiles exhibit an underlying similarity.

This similarity can be expressed quantitatively by calculating correlations between all pairs of crossings. Sixteen crossings yield 120 independent nontrivial correlation coefficients. For two crossings having profiles $u_i(z)$ and $u_j(z)$, we define the correlation coefficient by

$$c_{ij} = (N_i N_j)^{-1} \int dz\, u_i(z)\, u_j(z) \qquad (2)$$

with

$$N_i^2 = \int dz\, u_i^2(z) \; . \qquad (3)$$

Thus, for all ij we must have $-1 \leq c_{ij} \leq 1$, with $c_{ij} = 1$ signifying a perfect correlation. Figure 7 shows a plot of the correlation coefficients as a function of age difference and the age of the younger wake. Note that there is a clear preponderance of correlations toward the $+1$ end of the range. This result is consistent with the Garrett-Munk model[12] of background internal waves, which predicts that the horizontal currents should have length scales of many kilometers and a dominant time scale of an inertial period (24 hours in this case). Note also that as the age of the younger crossing increases, there is a marked tendency toward the higher correlations. A possible explanation of this latter effect is that the centerline is initially affected rather strongly by the turbulence of the wake of the dye line but that this effect eventually subsides and the more highly correlated background currents take over.

Average Widths — Figure 8 is a plot of the previously defined average width versus age of the dye trail for the 17 crossings. Note that the points lie quite close (correlation coefficient = 0.98) to a straight line in logarithmic coordinates. The slope of this line corresponds to a $t^{1.48 \pm 0.08}$ dependence.

A well-known argument,[13] formulated originally by Prandtl, asserts that, for a towed cylinder, the width of the turbulent wake should be proportional to $t^{1/2}$. In this type of argument, however, only the turbulence created by the towed body itself is considered and the environment is completely ignored. Evidently, the environment is quite important here.

The width dependence of 1.48 ± 0.08 is tantalizingly consistent with the well-known $t^{3/2}$ dependence that arises[14] from a constant vertical shear interacting with relatively small-scale vertical motions that are parameterized by a turbulent diffusivity μ. Theoretical calculations[15] indicate that the exponent increases further as the current profile becomes more complicated than linear. Unfortunately, it is not satisfactory to invoke this mechanism to explain our results. First, it is obvious from the profiles of Fig. 6 that the shear is, in fact, not even close to being constant over the span of the fluorometers. One might attempt to

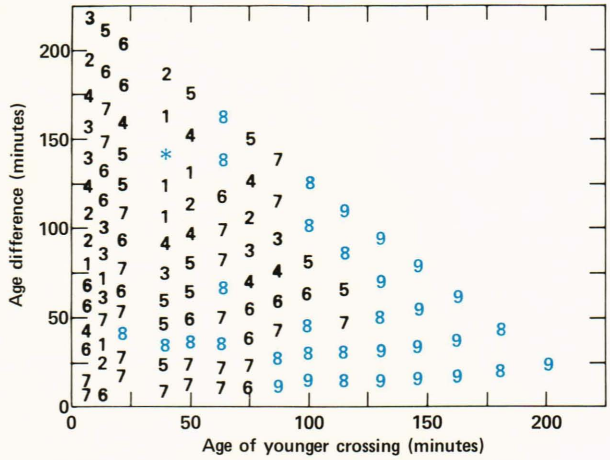

Figure 7 — Lumped centerline correlations in a plane defined by age difference and age of the younger crossing. If a correlation lies between 0.9 and 1, it is assigned a "9"; if it is between 0.8 and 0.9, it is assigned an "8," etc. Negative correlations are denoted by an asterisk. The colored portion specifies regions of high correlation (8 or 9).

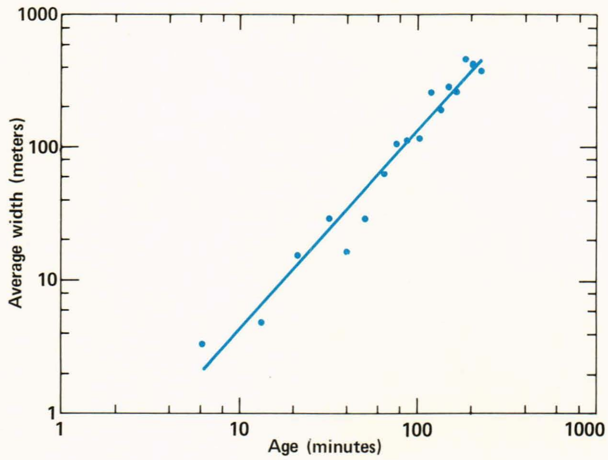

Figure 8 — Average width versus age for the 17 dye-sheet crossings. The slope of the regression line gives a $t^{3/2}$ time dependence, which indicates that the width growth is dominated by geophysical processes.

overcome this difficulty by relating the width and shear as evaluated at a particular fluorometer. When this relationship is established and the corresponding values of μ are calculated, one obtains values of turbulent diffusivity that vary widely, with no indication of clustering around a particular value or set of values. Hence, the agreement in time dependency appears at this point to be fortuitous.

At present, it appears that not much more can be said than that the widths clearly reflect the importance of the oceanic environment. Widths of dye patches deposited at the surface of the ocean also exhibit time exponents somewhat greater than unity.[16] To the best of the authors' collective knowledge, no other published thermocline data on dye widths exist with which comparisons can be made.

A striking aspect of the data that remains to be considered is the intermittency of the dye signals. As is the case in Figs. 4 and 5, the signals in general become increasingly intermittent in the later crossings. A possible explanation is that the dye is being advected up and down by relatively large-scale motions associated with background internal waves. The hypothesis that this intermittency can be accounted for by a Garrett-Munk type of internal wave model is currently being investigated using Monte Carlo simulations. To be useful, these simulations must, of course, also give results that are consistent with observed centerline and width results.

CONCLUDING REMARKS

The use of tracers as a tool to infer or measure directly oceanic background processes such as current, current shear, internal wave displacements, and other advective-diffusive related parameters is well established, documented, and perhaps somewhat neglected. This paper reveals that a vertical array of closely spaced fluorometers combined with a search strategy intended to map a previously laid dye trail can provide significantly more useful information than might be obtained with a single sensor. It has been found that a dye sheet that is initially 40 meters high

1. Is highly correlated from crossing to crossing for time scales of up to a few hours;
2. Is distorted horizontally to widths of several kilometers at a few hours time late (the current shear producing this distortion is reasonably constant and probably of inertial internal wave origin);
3. Is also distorted horizontally on smaller scales, probably reflecting the current shear effects produced by higher frequency internal waves;
4. Ceases to evolve vertically in the seasonal thermocline;
5. Becomes nearly horizontal and highly convoluted (owing to vertical displacements, current shear, and diffusive processes), exhibiting an apparent patchiness that increases with time.

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[12]For a summary of and further references pertaining to the Garrett-Munk model, see C. Garrett and W. Munk, "Internal Waves in the Ocean," *Annu. Rev. Fluid Mech.* **11**, 339-369 (1979).

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