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Observations of shear-augmented diffusion processes and evaluation of effective diffusivity from current measurements in Corpus Christi Bay

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Abstract

Studies on the process of diffusion in fluids have shown that in the presence of a shear structure within the current field, the observed spreading of a marked fluid can be augmented significantly. Shear-diffusion becomes the dominant diffusion process after a time T_n, the initialization time has elapsed. Given the existence of a vertical shear structure within the flow field, the characteristic vertical mixing time, T_c having an inverse relation to vertical turbulent diffusivity, K_z governs this initialization time.

This study focuses on the observation of shear-augmented diffusion process in a shallow wind-driven body of water leading up to the development of numerical algorithms for obtaining an *effective diffusivity*, K_e from shear-current measurements at spatial scales ~1000 m. This was part of a series of dye-tracer experiments conducted in Corpus Christi Bay, Texas. Numerical estimates are provided for T_n using the value of K_z determined from the temporal current fluctuations based on velocity correlation function, R_τ of the velocity time-series. An algorithm was developed by discretization of an equation of the form $K_i = \overline{u_i'^2} T_c I_i$ $(i = x,y)$ which was then used in the evaluation K_e based on numerical estimates of T_c and the shear coefficient I_i.

It was found that in the presence of shear-current structure, predicted K_e values along two orthogonal directions were ~10^4 and $10^5\,cm^2/s$, respectively, about 10–20 times higher than estimates obtained based on turbulence alone and confirmed through visual observations and statistical estimates of the size of the diffusing dye cloud.

Keywords: Current shear; Diffusion coefficients; Dispersion; Mixing processes; Turbulence; Vertical shear; USA; Gulf of mexico; Texas; Corpus Christi Bay

1. Introduction

This is the second part of a series of studies in support of ongoing efforts within our research group aimed at developing an integrated environmental and oceanographic assessment system for coastal environmental monitoring. The overall scheme combines real-time measurements from fixed and mobile platforms with data-driven numerical transport modeling and it becomes imperative that the coefficients required within this framework be quantifiable from direct observations of hydrodynamic data. In the first part of these series of

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studies on mixing processes within the bay (Ojo et al., in re-review), we examined the role of turbulent diffusion with a view to develop a numerical scheme for the evaluation of coefficients required to drive a transport model using direct observations of water currents.

Constituent transport and water quality models are often employed in environmental studies in order to derive the time evolution and concentration profile of constituents of interest. The underlying advective-diffusive numerical models rely on coefficients that are used in characterizing the physical phenomena that lead to the evolution of the concentration with time of constituents of interest in surface waters. Collectively termed transport coefficients, there exists essentially two components viz. the advective component and the diffusive component. A number of different methods can be applied to determine the diffusive component and four of these, from the literature are outlined:

- *Method I*: Based upon the temporal variation of the magnitude and direction of currents;
- *Method II*: Based upon the spatial variation of the currents field;
- *Method III*: Relies upon the evaluation of first and second moments of the distribution of concentration profile over time, of a diffusing cloud typically a dye patch;
- *Method IV*: Similar to Method III, this is an inverse problem based upon the governing transport equation of advection and diffusion. Requires the concentration profile of a diffusing substance over time.

Methods I and II, following on Taylor's analysis (Taylor, 1954) has been extended to other fluid flow regimes such as flow through open channels (Elder, 1958). In the first part of this study, Method I which characterizes the turbulence field was applied to Corpus Christi Bay in Texas. By using direct observations of the currents field returned by an Acoustic Doppler Current Profiler (ADCP) along with a numerical algorithm that was developed and calibrated against a diffusing dye patch (Ojo et al., in re-review), estimates were provided for turbulent diffusivity in three dimensions. The study presented in this paper is based on Method II and characterizes the shear structure within the flow field in order to develop a numerical algorithm for estimating shear-augmented diffusion coefficients or effective diffusivity, K_e. In conjunction with the estimates provided for vertical turbulent diffusivity, the scheme was parameterized by calibrating against an evolving dye-patch with K_e having a dependence on a characteristic timescale, T_c and the hydrodynamic conditions captured in the characteristic velocity, $\sqrt{\overline{u'^2}}$.

The dispersion of constituents of interest such as pollutants in the natural environment can be significantly enhanced by the process of shear diffusion. Involving the interplay between vertical turbulent diffusion and shear-currents, this becomes especially important within the coastal and near-shore environments (for instance in shallow wind-driven bays and estuaries) where the existence of complex shear current structures coupled with rapid variation in magnitude and direction of currents will be typical. Through a series of studies conducted by Csanady in the Great Lakes (Csanady, 1966), the observation was made that there exists a marked variation in the observed diffusion of constituents within a fluid body, the spreading being more pronounced under certain conditions than would have been expected. In other words, the growth of a diffusing cloud would appear to be much higher than expected if one were to consider only turbulence. Compounding these seemingly inconsistent observations is the fact that weak vertical turbulence appears to favor an increased rate of horizontal spreading hence, the concept of shear-augmented diffusion similar to that observed by Taylor (1954) and Elder (1958) in pipe and channel flow, respectively.

Two stages of shear diffusion are identified namely, first and second stage depending on the type of shear currents encountered by fluid elements in the flow field or whether boundaries (physical or virtual) have been encountered. In a general sense, lateral shear will be more likely to lead to first stage diffusion while vertical shear will be more likely to lead to second stage diffusion (Elliot et al., 1997). Particularly for shallow bays and estuaries, far away from vertical boundaries, lateral shear will therefore be less significant in terms of the contribution to shear diffusion when compared to vertical shear. From observation, it was determined that in the presence of shear currents, the direct contribution by turbulence to the overall diffusivity value becomes negligible when compared to the contribution from shear. In light of this, the process of turbulent diffusion in shallow wind-driven bays and estuaries can be augmented significantly by the

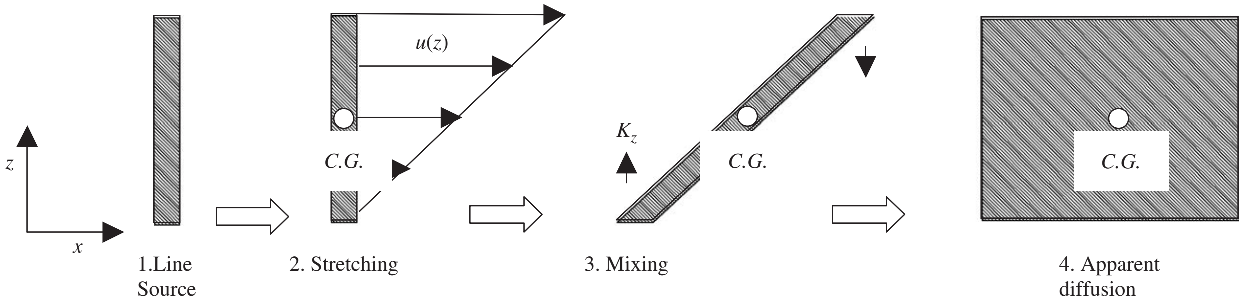


Fig. 1. This is a depiction of the effect of a vertical shear current on a line source leading up to shear diffusion. The line source is first displaced under the influence of the velocity (linear) profile, shifting the center of mass. Next, vertical (turbulent) mixing redistributes the constituent as shown. The overall effect is the apparent diffusion of a line source into a plane under the combined effect of a vertical shear current and vertical mixing.

shearing action of a spatially varying currents field (Fig. 1).

During the first stage of diffusion, K_e will have a linear dependence on turbulent diffusivity, K_d (vertical or horizontal) and during the second stage, say for vertical shear, there exists an inverse dependence on vertical turbulent diffusivity, K_z. Turbulent diffusivity itself can be evaluated either by Methods I, III or IV. Method I uses the auto-correlation function, R_τ of the fluctuating velocity time series and is based on Taylor's statistical treatment of diffusion as a random process (Taylor, 1920). Researchers (Bowden, 1965; Csanady, 1966) have put forward expressions for determining the effective diffusivity, K_e following on Taylor's work and based on Method II. Predicated on previous work done in this area (Okubo and Carter, 1966), Elliot developed expressions for K_d from which the time taken to complete vertical mixing or the characteristic mixing time, T_c can be determined (Elliot et al., 1997).

The objectives of this study: (i) to examine the role of vertical turbulence and shear structure with respect to shear-augmented diffusion in a shallow wind-driven bay; (ii) to determine the initialization time based on the characteristic time scale as well as provide an estimation of the range of values for the shear coefficient dependent on prevailing hydrodynamic conditions; (iii) to develop a numerical algorithm based on direct observations of hydrodynamic conditions from which effective (shear-augmented) diffusivity values can be determined. In this study, hydrodynamic observations were made in a wind-driven bay, Corpus Christi Bay, Texas with an ADCP and were used to elucidate information on the shear current structure within the bay.

Predicated on recent developments in surface current measurements and the widespread availability of current profilers, the numerical scheme developed which was used in evaluating effective diffusivity values is important within the framework of constituent transport and water quality models with specific application to the nearshore and coastal environment (Ernest et al., 1991; Sterling et al., 2004a ,b).

1.1. Background theory

The phenomenon manifesting as shear-augmented diffusion, first observed and published in the mid-part of the last century (Taylor, 1954), has been extended by other researchers to different flow regimes in both natural and engineered systems. The concept of an effective diffusivity is introduced within the framework of diffusive transport processes. Shear-augmented diffusion can be modeled as Fickian diffusion with constant coefficients, conditionally dependent on the time to complete vertical mixing (Taylor, 1953).

1.1.1. Shear-augmented diffusion and effective diffusivity

Following the work of Taylor on laminar and turbulent flow through pipes, the subject of research spanning the successive years has been the extension of this work to natural systems as is the focus of this paper. Under the effects of lateral or vertical shear currents structure and turbulence, a dye patch will spread at a rate that has been observed to be much higher than could be attributed to turbulence only. In a shallow wind-driven bay, the velocity gradients that produce shear will be more pronounced in the vertical than in the lateral (horizontal) plane, except near the shore or close to land boundaries. Estimates on the value of horizontal shear (Elliot, 1986; Ojo et al., in re-review) indicates up to six orders of magnitude difference between these velocity gradients (vertical and horizontal) in coastal waters, which in subsequent analysis, will be an important factor especially as it relates to the onset of second-stage shear diffusion in a shallow embayment.

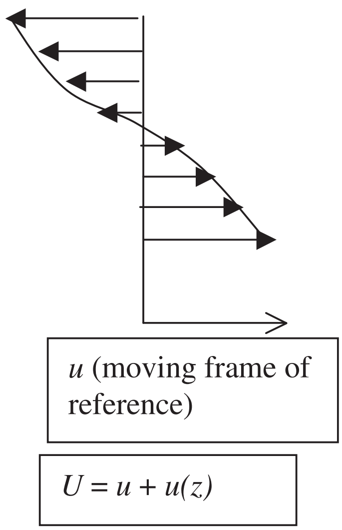
Analogous to the Lagrangian time-scale of turbulence (a statistical property), the condition for the application of the Fickian diffusion model in shear-diffusion is the initialization time, T_c. However, unlike the treatment of turbulent diffusion, Taylor's starting point for the analysis of shear-diffusion was not from a statistical standpoint. Rather the advection-diffusion equation incorporating knowledge of the shear structure in pipe flow was used in deriving analytical forms for the shear diffusivity, K_e and subsequently establishing the basis for its application through certain prescriptions.

$$\frac{\partial S}{\partial t} + u' \frac{\partial S}{\partial x} = \frac{\partial}{\partial z}\left(K_z \frac{\partial S}{\partial z}\right)$$

with the quasi steady state assumption, frame of reference moving at the mean flow velocity, solute fully mixed in the vertical

$$\frac{\partial S}{\partial t} = 0,$$

$$u' \frac{\partial S}{\partial x} = \frac{\partial}{\partial z}\left(K_z \frac{\partial S}{\partial z}\right).$$



Writing the governing equation of constituent transport in terms of cross-sectional averages of the variables rests on the following assumptions:

(a) the concentration distribution is at steady-state relative to a plane moving at the mean speed of the flow;
(b) the flux through the boundaries is zero;
(c) the effect of advection in the longitudinal direction is late to appear relative to that due to the cross-sectional variation of velocity.

Given the cross-sectional velocity

$$u(z,t) = \overline{u(t)} + u'(z,t) \tag{1}$$

for two-dimensional flow an expression for the effective diffusivity K_x based on the shear structure is

$$K_x = -\frac{1}{h}\int_0^h u' \left[\int_0^z \frac{1}{K_z}\left(\int_0^z u' \, dz\right) dz\right] dz. \tag{2}$$

Bowden presented a practical form

$$K_x = \Omega(h^2 u^2 / K) \tag{3}$$

and Riddle and Lewis were able to derive analytical expressions of this form for K_x by carrying out a parametric fit between Ω^{-1} (the shear parameter) and a coefficient β obtained from a power law general expression for shear-current (Riddle and Lewis, 2000). Considering the variability and complexity of the shear current encountered in natural systems, it may be difficult to represent the depth profile of the current by typical analytical expressions necessary for performing the integral in Eq. (2). There is therefore a limitation when considering the applicability of Eq. (3) to natural systems such as bays or estuaries. Fischer developed a method for performing this analysis through the introduction of dimensionless quantities into Eq. (2) leading to another form for K_x similar to that in Eq. (3) (Fischer et al., 1979):

$$K_x = (h^2 \overline{u'^2} / \overline{K_z}) I,$$

$$I = -\int_0^1 u'' \left[\int_0^{z'} \frac{1}{K_z'}\left(\int_0^{z'} u'' \, dz'\right) dz'\right] dz, \tag{4}$$

where I is a dimensionless integral having dependence on dimensionless quantities $u'' = u' / \sqrt{\overline{u'^2}}$, $K_z' = K_z / \overline{K_z}$, $z' = z/h$, the overbar again indicating cross-sectional averages. The quantities $\sqrt{\overline{u'^2}}$, $\overline{K_z}$ are the characteristic velocity and characteristic turbulent diffusivity, respectively. This reveals the rather interesting inverse dependence of shear diffusion on vertical turbulent diffusivity, K_z and $\sqrt{\overline{u'^2}}$, the mean-square of the deviation of the velocity from the cross-sectional average.

This is conditional though considering the steady-state condition as prescribed for the cross-sectional concentration distribution relative to a moving frame i.e. the solute concentration is well mixed vertically. For this condition to apply, there is the consideration of an initialization time, T_n proportional to a characteristic time scale, T_c and is given by

$$T_n = \psi h^2/\overline{K_z} = \psi T_c,$$
$$T_c = h^2/\overline{K_z}. \quad (5)$$

Different values have been suggested for the constant of proportionality in Eq. (5), the dimensionless time, Ψ by several researchers who have studied diffusion processes in both natural and engineered systems as summarized in Table 1.

This implies another form of (4) that can be written as follows:

$$K_x = \overline{u'^2}\, T_c I, \quad (6)$$

where the dimensionless integral, I quantifies the structure of the shear as well as its variability, and by analogy to Ω in Eq. (3), I can be described as a shear coefficient. Typical values of I suggested for rivers and estuaries (Fischer, 1973) fall within a very narrow range from 0.06 to 0.15 and for practical applications, a suggested value of 0.1 would suffice. The implication of (5) and (6) is that for times $t \geqslant T_n$, the size of the diffusing cloud measured by its variance grows at a constant rate and the process can be modeled as Fickian diffusion with constant diffusivities given in Eq. (6).

Similar expression can be found for effective diffusivity, K_y in the orthogonal y-direction, hence the general expression in two dimensions:

$$K_i = \overline{u'^2}\, T_c I_i,$$
$$I_i = -\int_0^1 u_i'' \left[\int_0^{z'} \frac{1}{K_z'} \left(\int_0^{z'} u_i''\, \mathrm{d}z' \right) \mathrm{d}z' \right] \mathrm{d}z \quad (7)$$

for $i = x$, y and $u_i'' = u'_i/\sqrt{\overline{u'^2_i}}$ being derived from the respective horizontal components of the current along the respective x, y coordinate axes.

Although the preceding analyses would apply in the case of lateral shear (first stage diffusion) as well, this study was limited to the case of vertical shear on the premise of the study area being within a shallow body of water, far enough away from land boundaries against the backdrop of Elliot's findings. In other words, the assumption was made that the process of shear diffusion proceeded as second-stage diffusion after a time $t \geqslant T_n$ that will be determined as part of this study. An effective diffusivity along the *x, y*-coordinate axis, K_i computed on the basis of Eq. (7) with dependence on the vertical turbulent diffusivity, K_z and vertical shear current (collectively embodied in the quantity I_i) as well as T_c will apply. The discretized form of Eq. (7) used in this study which numerically integrates the data set obtained from the various current measurements made during these set of experiments is as follows:

$$\left[\frac{h^2 \sum_{z=0}^{h} u_{i,z}^2 - \left((1/h) \sum_{z=0}^{h} u_{i,z} \right)^2}{\sum_{z=0}^{h} K_z} \right] \times \sum_0^1 \left\langle \frac{u_{i,z} - (1/h)\sum_{z=0}^{h} u_{i,z}}{\sqrt{(1/h)\sum_{z=0}^{h} u_{i,z}^2 - \left((1/h)\sum_{z=0}^{h} u_{i,z} \right)^2}} \times \sum_0^{z/h} \left\{ \frac{\sum_{z=0}^{h} K_z}{h K_z} \times \left[\sum_0^{z/h} \left(\frac{u_{i,z} - (1/h)\sum_{z=0}^{h} u_{i,z}}{\sqrt{(1/h)\sum_{z=0}^{h} u_{i,z}^2 - \left((1/h)\sum_{z=0}^{h} u_{i,z} \right)^2}} \right) \right] \right\} \right\rangle. \quad (8)$$

Table 1
Typical values proposed for the value of dimensionless time, Ψ based on different shear current structures

Proponent	Dimensionless time, ψ
Chatwin (1972)	1.0
Fischer (1968)	0.4
Sayre (1969)	0.5
Okubo and Carter	$1/\pi^2$ (≈ 0.1)
Yasuda (1984)	0.5

2. Method

The preceding analyses were applied to a shallow wind-driven bay by examination of shear-augmentation of the diffusion process using vertical turbulent diffusivity evaluated from the velocity autocorrelation, the dataset being derived from 3D current measurements. The condition for the application of Fickian diffusion dependent on the initialization time was determined for the selected bay as well as the characteristic time and the value of the dimensionless time.

Current measurements of the area in 3D were obtained using a fast response Acoustic Doppler Current Profiler (ADCP, RD Instruments, Inc., San Diego, CA). The ADCP was installed on a rigid mount on the bow of a small craft that also had a towed instrument array used for obtaining horizontal profiles of the concentration distribution of the dye. The current profiles were obtained within a 300–500 m radius dictated by the spatial extent of the dye patch over a period between 0 and 150 min following dye application. The profile was well localized both temporally and spatially enough to filter out horizontal variations in current structure and the effects of tides, an important factor in emphasizing the turbulence and vertical shear structure within the scale of the experiment.

Summary of the three studies conducted are given Table 2 below and the data obtained will be used in subsequent sections. For reference, identification numbers have been assigned to each study. Two studies were conducted at two different locations on August 28, 2003 at two different times in the tidal cycle (study 0828_1 and 0828_2). Studies 0828_1 and 1007 were conducted at location 2747.937N, 9721.451W on two different dates (August 28, 2003 and October 7, 2003) and at different times in the tidal cycle. With this experimental design, information can be obtained as to the existence of a spatial-temporal variability of diffusivity values due to the coupling between meteorological conditions and oceanographic forcing within the study area.

2.1. Site description

Located within Corpus Christi Bay in the Texas Gulf of Mexico about 200 miles south west of Houston, TX (Fig. 2) the study area is part of a system of bays. Comprising of four interconnected embayments namely Oso Bay in the southwest, Nueces Bay in the northwest, Upper Laguna Madre in the south and Redfish Bay in the northeast, Corpus Christi Bay is the main bay within the system. Along the northernmost half of the bay, a shipping channel that is ~15 m deep runs east to west while an intra-coastal waterway runs north to south.

The deepest of the four, it is bounded on the east by Mustang and North Padre Islands and on the west by the city of Corpus Christi. Other characteristics of the bay are:

Size: Approximately 500 km^2.
Bathymetry: Relatively uniform, ~3 m.
Tidal range: Relatively low, ± 0.5 m.
Residual currents: Predominantly along the east-west coordinate axis; counterclockwise circulation, tidally driven.
Main forcing: Winds from a southeasterly direction. "Northers" from the northerly direction during the winter months.
Drainage area: ~49,700 km^2, daily average freshwater flow of ~34 m^3/s.
Average salinity: 22 psu and as high as 33 psu.

2.2. Instrumentation

The ADCP was a 1200 kHz broadband workhorse that was installed in a bottom-tracking, downward-looking configuration on the bow of a 10 m watercraft as part of an instrument array for environmental measurements that included a conductivity-temperature-depth (CTD) sensor, a fluorometer and particle size distribution analyzer. The other instruments were mounted on a tow-body capable of performing undulating profiles throughout the water column. Data logging from the instruments were carried out on-board the craft with an integrated data acquisition (DAQ) computer incorporating a GPS unit.

The ADCP was equipped with bottom-tracking capability that allowed absolute current measurements

Table 2
Summary of experimental and meteorological conditions

ID	Location	Date	Time (UTC)	Tide	Wind
0828_1	2747.937N, 9721.451W	Aug. 28, 2003	15:44	High water, ebb	7 kn, SE
0828_2	2743.571N, 9718.297W	Aug. 28, 2003	21:20		14 kn, SE
1007	2747.937N, 9721.451W	Oct. 07, 2003	14:34	High water, flood	4–12 kn, NE

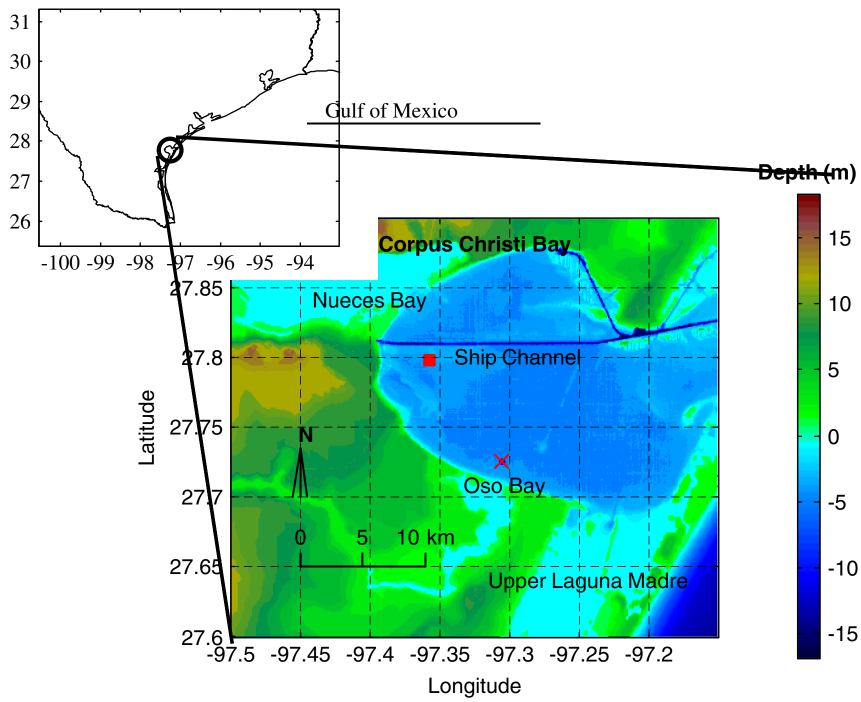


Fig. 2. Top; map of Corpus Christi Bay in the Texas Gulf of Mexico. Approximate location for each study is indicated (■, Study 0828_1 and 1007; ◘, Study 0820_2). Bottom; bathymetry of the study area.

to be taken on a moving platform by compensating for the velocity of the moving platform. A time series of the horizontal and vertical velocity components u_i ($i = x, y, z$) corresponding to the East–West, North–South, Up–Down coordinate axes were returned in layers or bins spaced equally at 0.1 m apart throughout the water column. Given the bathymetry of the study area as shown in Fig. 2 with depth ~3–4 m, the maximum number of bins used in this study was thirty taking into account 0.25 m blanking zone for the instrument. Three dye-tracer studies were carried out between the summer and winter months of 2003 within Corpus Christi Bay during which ~20,000 current samples were obtained during each exercise along with fluorescence data. Analysis of the data from ADCP current measurements used in this study is described below. Supplementary data were obtained for meteorological conditions at the Port Aransas Station of the National Data Buoy Center (NDBC at http://www.ndbc.noaa.gov/station_page.php?station=PTAT2).

2.3. Data analysis

With the ADCP set for single pings at 2.5 Hz sampling rate, data post-processing which includes spectral analysis and low-pass filtering was performed on the ensemble of velocity measurements to generate the velocity time-series having acceptable error levels. Along with the bottom-tracking data, ship movement was compensated for and the current measurements referenced to the geographic coordinate axes. For each coordinate axis, a matrix ($N \times 30$) of velocities (where N, the size of the samples depends on the duration of the exercise and sampling rate, 30 being the number of horizontal layers or bins in the water column at 0.1 m apart) was analyzed.

The velocity autocorrelation $R_i(\tau)$ was first obtained and then applied in the numerical evaluation of vertical turbulent diffusivity, K_z based on Method I as described in the first part of this series of studies. Following this, numerical evaluation of the dimensionless integral, I_i given in Eq. (7) was subsequently performed using these results along with the value of T_n determined from Eq. (5) from which estimates were made for shear diffusivity, K_i ($i = x, y$). All data post-processing and analysis were performed with a set of MATLAB® based routines developed in our laboratory as part of the integrated scheme for environmental and oceanographic assessments.

3. Results

Results of characterizing the flow field in terms of the shear structure and numerically evaluating the initialization time, T_n along with the shear coefficient (dimensionless integral), I_i from direct observations of the 3D currents field are presented in this section. The range of values determined for I_i from this study was compared with those recommended by Fisher and the estimates made for the shear diffusivity, K_i are summarized in Table 3. Using the numerically computed values of K_i, the size of a diffusing cloud was estimated. The predicted size of the cloud was compared with the observed spatial distribution of an evolving dye patch reconstructed from fluorescence measurements that were taken during the study to validate the numerical algorithm.

3.1. Characteristic velocity distribution, shear coefficient and initialization time

Figs. 3–5 show 3D instantaneous current profiles at six successive time intervals from each of the three studies, the evolution of the shear structure within the currents field in response to meteorological conditions being clearly evident from these plots. The 3D current profiles are stick-plot representation of current vectors. These have been scaled in length to correspond with magnitude of the current and color coded from blue to red for both magnitude and direction to highlight the velocity gradient, red being maximum-positive (northerly) direction and blue being minimum-negative (southerly) direction.

To ensure data quality, the statistics of the sampling distributions of characteristic velocities are presented in the box-and-whisker plots (Fig. 6) for each of the three studies while the corresponding density distribution functions are displayed in Fig. 7. Box-and-whisker plots provide a graphic representation of the sample statistics given the position of the notch and the corresponding line drawn through the middle of the box which represent the median values of the measurements. Given the density distribution and the statistics of this distribution, it would appear that the characteristic velocities exhibit log-normality. This would be expected given the fact that random environmental process typically would: (a) have a narrow spread; (b) be constrained by a zero minimum value and (c) have a few extreme values, hence the long tail as observed with this distribution.

Table 3
Summary of shear-diffusivity results for all three studies conducted

	Dimensionless integral, I			Initialization time, T_n (s)		Characteristic velocity, $\sqrt{\overline{u'^2}}$ (cm/s)			Characteristic diffusivity, $\overline{K_z}$ (cm^2/s)	Shear diffusivity, K_{ie} ($\times 10^5$ cm^2/s)
	Mean	Max.	SD	$\Psi = 0.1$	$\Psi = 0.4$	Mean	Max.	SD		
Study 0828_1										
East–West	0.12	0.22	0.03	177	709	41.65	123.93	12.76	50	3.67
North–South	0.12	0.22	0.03			18.24	42.18	5.10		0.70
Study 0828_2										
East–West	0.11	0.24	0.04	85	342	47.52	101.06	12.15	104	2.15
North–South	0.11	0.24	0.04			20.84	42.60	5.15		0.41
Study 1007										
East–West	0.12	0.19	0.02	114	456	38.60	94.85	11.74	76	2.09
North–South	0.12	0.21	0.02			17.50	49.27	4.96		0.43

Mean and maximum values of the dimensionless integral, initialization time and shear diffusivity are given for each of the three coordinate axes, *x*, *y*.

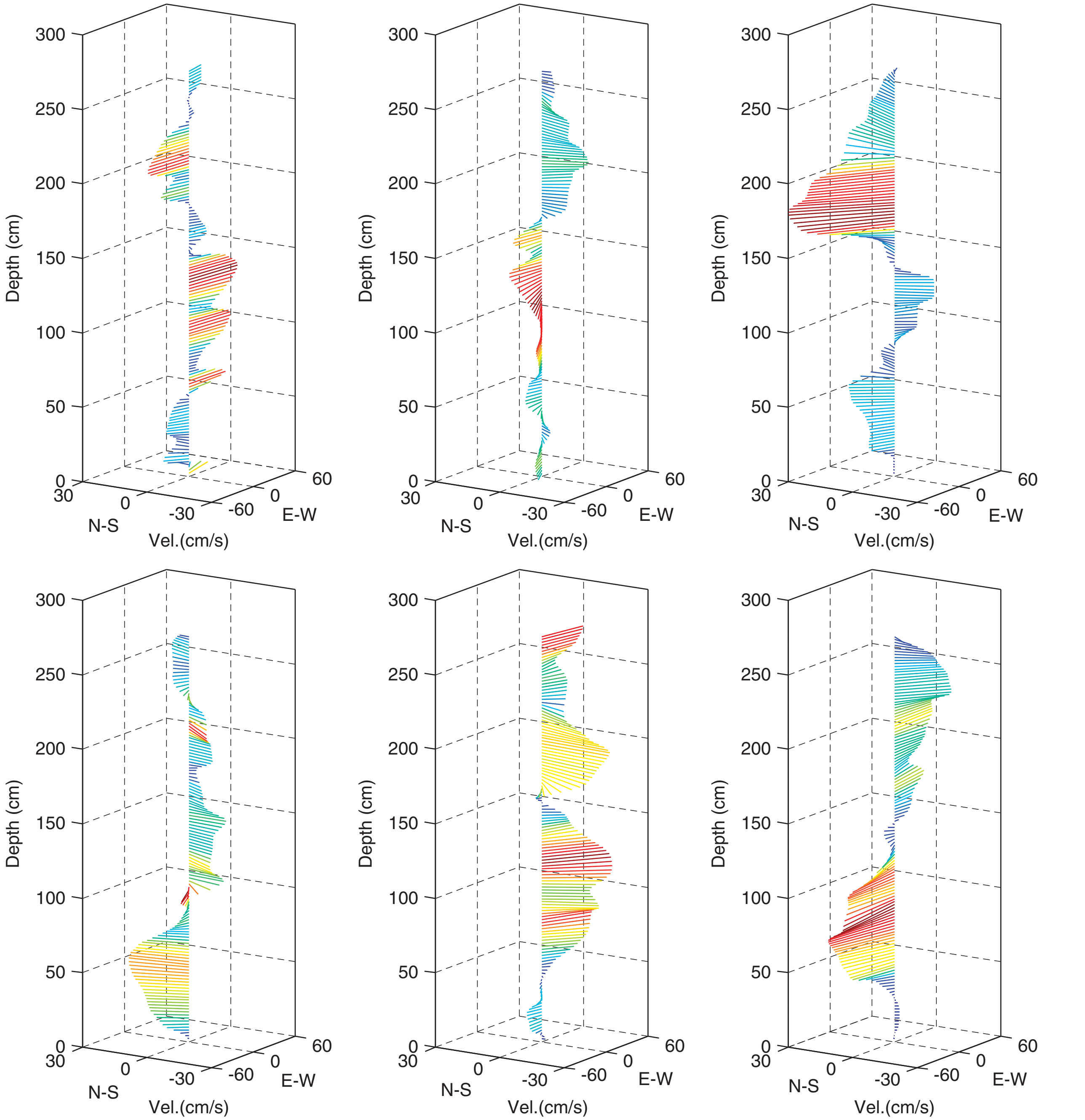


Fig. 3. Study 0828_1—Left to right, top to bottom; 3D vector plots taken at successive 3-min time intervals showing evolution of shear-current structure. The plots are scaled according to velocity vector magnitude and direction, red being maximum-positive (northerly) direction and blue being minimum-negative (southerly) direction.

These results which are summarized in Table 3 show that the East–West characteristic velocities has a mean of ~40 cm/s with standard deviation ~12 cm/s while the North–South characteristic velocities show a mean of ~20 cm/s and standard deviation ~5 cm/s. The quantities from Eqs. (5) and (6) used in the computation of shear diffusivities (dimensionless integral, I_i and initialization time, T_n) are presented in Table 3 along with the statistics on the distribution of the characteristic velocity. The

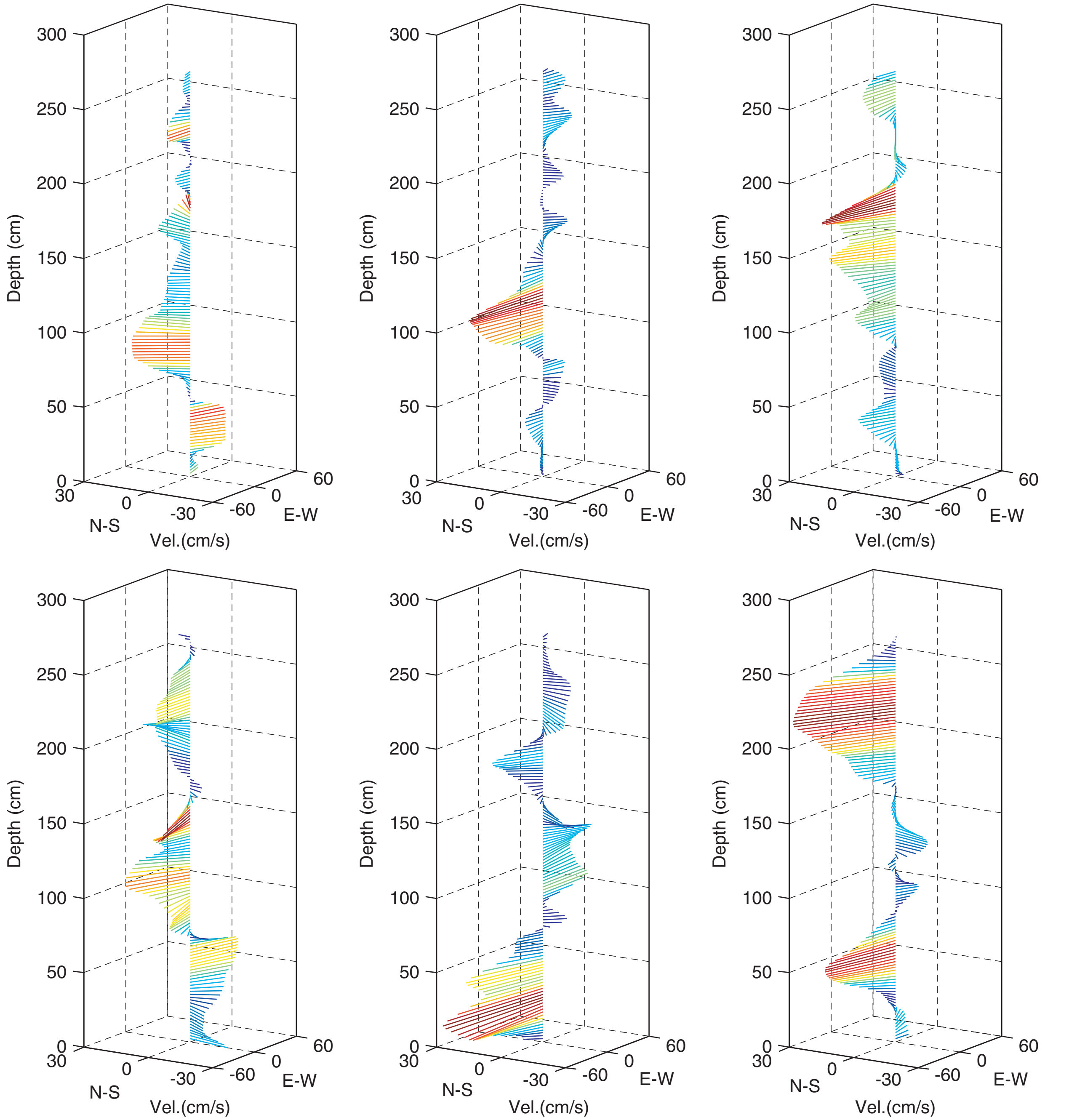


Fig. 4. Study 0828_2—Left to right, top to bottom; 3D vector plots taken at successive 3-min time intervals showing evolution of shear-current structure. The plots are scaled according to velocity vector magnitude and direction, red being maximum-positive (northerly) direction and blue being minimum-negative (southerly) direction.

numerically determined values for I_i were found to be in the range 0.06–0.24 (mean ~0.12) and these figures were found to be in agreement with the values recommended by Fisher as previously stated. The T_n values were determined using Ψ values of 0.1 and 0.4 giving a lower bound of 85 s and upper bound of 709 s. These values for T_n implies that the constituent of interest, in this case a pulse discharge of tracer at the surface would become fully mixed into the water column within minutes following application.

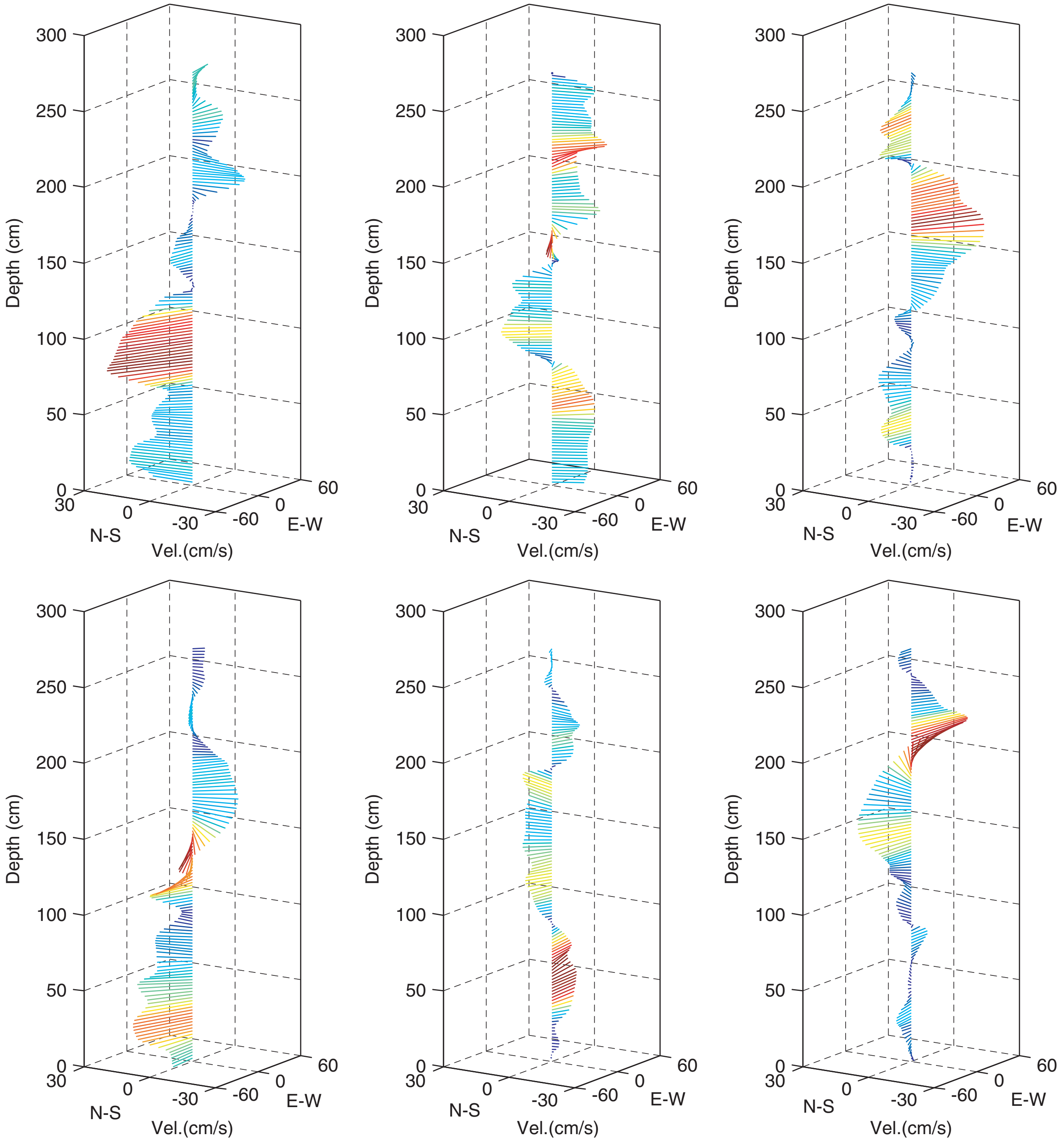


Fig. 5. Study 1007—Left to right, top to bottom; 3D vector plots taken at successive 3-min time intervals showing evolution of shear-current structure. The plots are scaled according to velocity vector magnitude and direction, red being maximum-positive (northerly) direction and blue being minimum-negative (southerly) direction.

3.2. Shear diffusivity

The discretized Eq. (8) formed the basis of an algorithm fro evaluating shear (effective) diffusivity. The numerically computed diffusivity values were $\sim$2–4 $\times 10^5$ cm^2/s along the x-coordinate direction and $\sim$4–7 $\times 10^4$ cm^2/s along the y-coordinate direction. In all the studies, the E–W shear-diffusivity was found to be about one order of magnitude higher than the N–S diffusivities. These values are in line with the observation of the evolution of the dye-patch and within order of magnitude estimates of

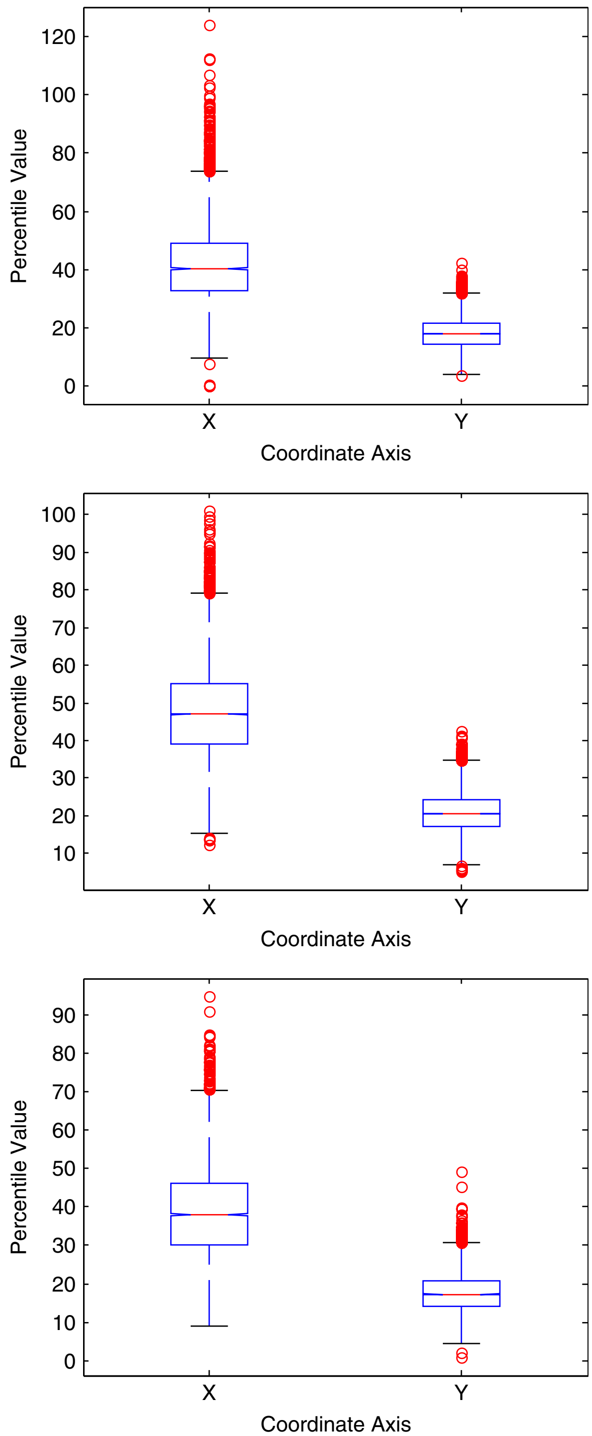


Fig. 6. Statistical summary of characteristic velocities. Top—study 0828_1; middle—study 0828_2; bottom—study 1007. ○, outliers within dataset.

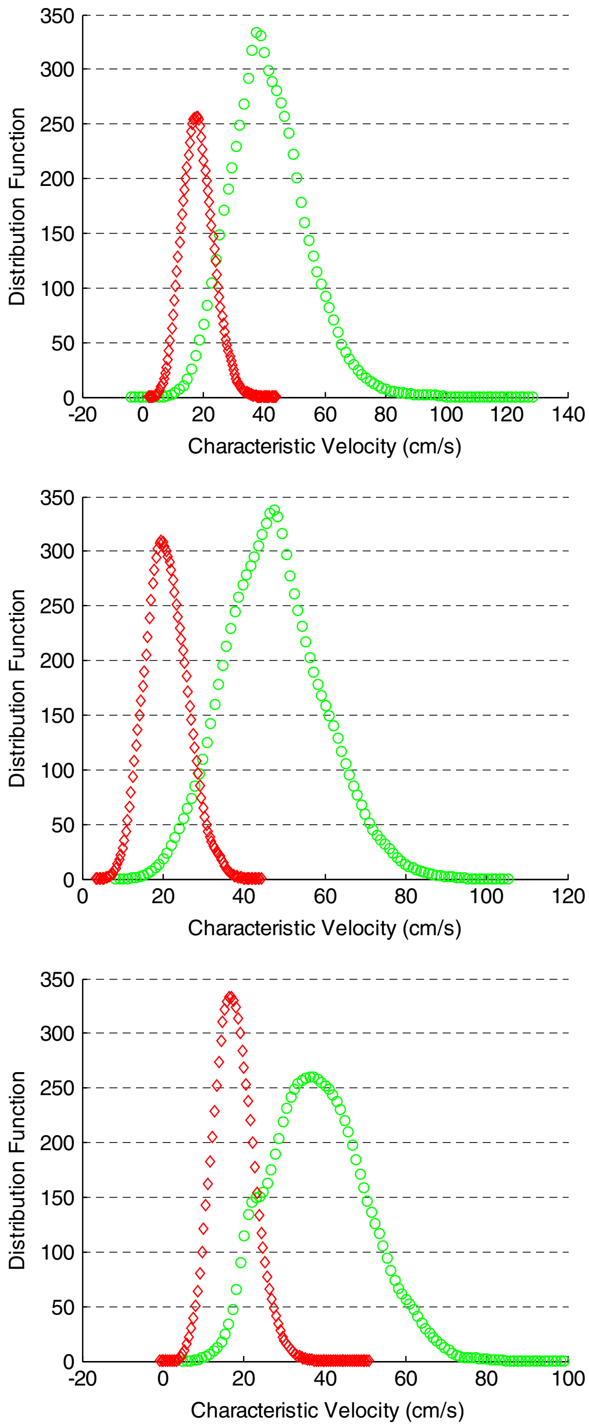


Fig. 7. Density distribution function of characteristic velocity computed from shear-current. Top—study 0828_1; middle—study 0828_2; bottom—study 1007 (○, East–West; ◇, North–South).

the diffusivities from concentration profiles of the diffusing dye-patch. Using the numerical estimates of the diffusivities, the variance σ_i^2 ($i = x, y$) of an evolving dye cloud over the duration of the experiments were obtained. Taking 68% of the dye to be within $2\sigma_i$, ($\sigma_i{}^2 = 2K_{ie}t$) this leads to a size estimate of ~500–600 m along the x-coordinate axis and ~200–300 m along the y-coordinate axis. The numerical size estimates of the diffusing cloud approximated very closely (~100%) the size of an observed dye patch from the dye release in study 1007. Given the lower detection limits of fluorometric instruments, combined with relatively high background fluorescence levels in the body of water, there are inherent uncertainties associated with mass-balance computations in such natural systems.

This implies that size estimates based on fluorescence measurements tend to be lower than actual. In fact, other researchers have noted these uncertainties and Okubo suggested that 50–75% accuracy would be acceptable for most experiments involving dye releases (Okubo, 1971). Similar estimates of the spatial extent using turbulent diffusivity values were found to be 3–5 times lower. Fig. 8 presents the above size estimates in graphical form, outlining numerical estimates of a diffusing cloud based on turbulence and shear diffusion viewed against the actual observed dye patch size obtained several minutes after release.

4. Discussion

The order of magnitude difference in the estimated values of diffusivity from experiment 1007 suggests that shear diffusivity dominated over turbulent diffusivity within the study area. The diffusive process can be characterized by shear diffusivity values obtained from the numerical scheme as described. The explanation for the shearing effect being observed in one study and not in others may be due to the marked difference in meteorological conditions (Fig. 9) encountered in study 1007 compared to study 0828_1 and 0828_2. The wind pattern observed during study 1007 was considerably more variable (in both magnitude and direction) when compared to the pattern observed during the other two studies. This might have contributed to the shearing effect being more pronounced in this particular study1007 compared to the other two. The effect of wind stress on the evolution of surface currents is well known and a functional relationship, $\boldsymbol{u}(x,y) = f(\boldsymbol{w})$ between the current vector $\boldsymbol{u}$ and wind speed $\boldsymbol{w}$ can be found in the literature. Given the long period variability in observed wind speed, one would expect a corresponding variability in surface current propagating through the water column and producing shear as a result. By the same token, short period variability in wind events as observed for both studies 0828_1 and 0828_2 appears as turbulence in the water column.

Through this series of studies, the onset of shear-augmented diffusion was observed for this wind-driven bay and found to be influenced by the variability with depth and time of the magnitude and direction of the current as well as the vertical turbulent diffusivity. The studies were localized both temporally and spatially in order to separate the effects of spatially variable currents on the estimates of the dimensionless integral, I and initialization time, T_n. Algorithms were developed for characterizing the diffusive processes and for the evaluation of diffusivity values using the 3D currents field that was obtained with a vessel-mount ADCP. In the initial stages following the introduction of a constituent into the bay (on the order of seconds) and for times less than T_n, the diffusion process will be governed by turbulence. Following this, and for times greater than T_n (which is of the order of minutes) depending on the bathymetry, turbulence intensity and shear structure of the currents field, the diffusion process will be governed by vertical shear. It is imperative to note that the initialization time is dependent on the distance to the diffusion floor (bottom boundary) which could be a physical boundary for instance in this study, the benthic boundary layer or could be a virtual boundary within the water column such as a thermocline or pycnocline. The diffusion floor effectively limits the further vertical transport of the constituent and ultimately affects the time for complete vertical mixing or initialization time, T_n. In addition to this is the issue of water column stability as it affects the eventual mixing, on which the mechanism of shear-augmentation of the diffusion process depends (Bowden, 1965; Okubo and Carter, 1966).

Using the numerical estimates of shear diffusivities, the estimated variance and therefore the spatial extent of a dye patch after a time period following initial release were obtained. The estimates obtained from using the numerical analyses of direct observation of currents were compared with observations of a dye-patch from the tracer experiments. The estimated spatial extent of a

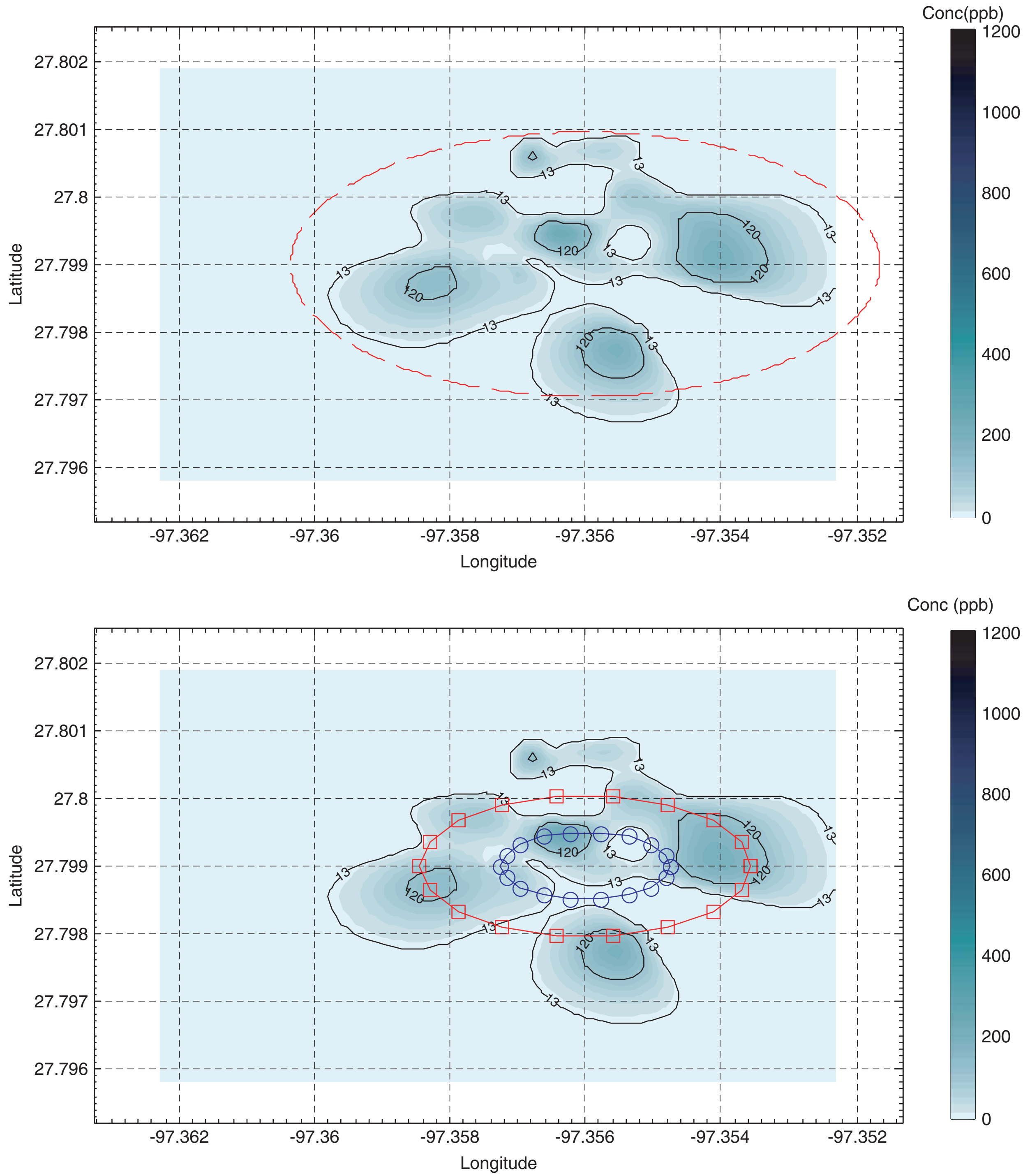


Fig. 8. Top; observed dye patch, 5557 s after instantaneous release. Outlined (- - -) is the 68% numerical estimate of spread with 2σ based on shear ($K_x = 2.09 \times 10^5$, $K_y = 0.43 \times 10^5$). Bottom; same dye patch outlined open circles (○) is the 68% numerical estimate of spread with 2σ based on turbulence and open squares, the 99% numerical estimate also based on turbulence ($K_x = 1.69 \times 10^4$, $K_y = 0.30 \times 10^4$). The estimates based on turbulence presents an underestimation of the concentration distribution.

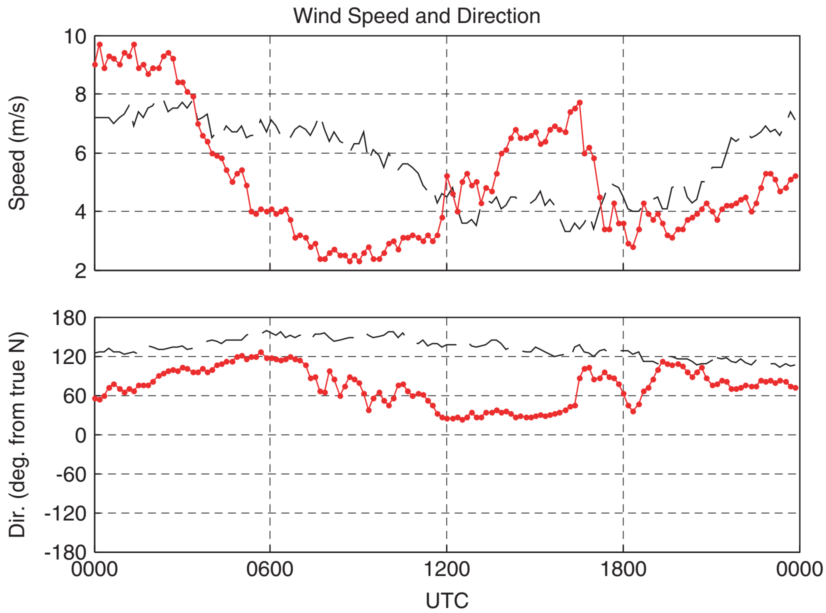


Fig. 9. Wind speed (top panel) and direction (bottom panel) over a 24 h period taken during the experiments. Broken lines (- - -) study 0828_1 and 0828_2. Solid lines (-●-) study 1007. Wind strength is comparable during the three studies but conditions reported during study 1007 is highly variable revealing long period events.

diffusing cloud undergoing shear diffusion was found to be ~3–5 times higher than those predicted for a similar patch undergoing turbulent diffusion. This was in close agreement with actual observations of the dye patch from study 1007 being ~3 times greater in size than the size observed from study 0828_1 and 0828_2 supporting the argument that shear diffusion was the dominant process in study 1007.

It is imperative to note that the application of rigorous analytical techniques to the characterization of shear diffusion processes in natural systems such as the one described in this study will be predicated on the fulfillment of conditions beyond those prescribed earlier. Recall a sufficiently low T_n relative to the vertical extent of the water column and vertical turbulent diffusivity K_z in the presence of a shear current structure. This study indicates that even where T_n is sufficiently low which will be nearly always true for shallow bodies of water the shear current may not always lead to diffusion augmentation. Particularly in bays and estuaries where flow reversal and stratification is common, it will be necessary to be able to qualify or categorize those prevailing conditions when in concert with T_n and the shear coefficient, I_i produce shear diffusion in natural systems as observed in study 1007.

5. Conclusion

Noting that the diffusion process was enhanced up to 10–20 times and if one were to attribute this to an increase in turbulence, this would require 3–5 times increase in the turbulence intensity of the flow field. The meteorological conditions and geomorphology of the study area did not vary to the extent of being able to justify this level of increase in turbulence. The fact that the current in this bay is forced predominantly by the wind allowed us to examine the effect of varying meteorological conditions on the diffusive process. Current and wind measurements did indicate that the turbulence field in study 0828_1 and 0828_2 were comparable (if not slightly higher) in intensity relative to study 1007 yet we observed a higher degree of diffusion in study 1007. The long-period wind events during study 1007 would appear to force a predominant shear structure leading to the conclusion that shear-current rather than increasing turbulence intensity produced the diffusion augmentation in this shallow body of water observed in study 1007.

Through this study, we characterized the flow field in terms of shear current and estimated the time taken to complete vertical mixing or initialization time, T_n. Estimates were also made for the shear coefficient, I_i from which the shear diffusivity values were determined using a numerical algorithm that was developed as part of this study. This was in line with the overarching objectives within our research group of developing integrated environmental assessment schemes for the coastal and nearshore environment.

5.1. Future work

The ability to characterize diffusion processes from hydrodynamic information is important as it can be applied to different bodies of water especially when viewed against the backdrop of the logistical challenge and expense associated with conducting dye-tracer experiments. Given the state of the art in currents measurements in surface waters, this ability will form a logical extension of existing instrumentation for oceanographic and environmental assessments.

In order to be able to apply this comprehensively, the role of wind stress and water column stability will have to be examined in order to develop the set of meteorological and oceanographic conditions under which the shear augmentation of the diffusion process will prevail subject to T_n and I_i. This will result in a classification similar to the development of atmospheric stability classes in meteorological and air quality studies necessary for the application of the Pasquill-Gifford (Pasquill, 1962) dispersion model. The development of parameterization schemes that constituent transport models for environmental assessments in coastal and surface waters depend upon will be significantly enhanced.

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