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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 $\sim 10^4$ 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