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Estuarine residual flow induced by eddy viscosity-shear covariance: Dependence on axial bottom slope, tidal intensity and constituents

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ABSTRACT

Residual flow generated by Eddy viscosity-Shear Covariance (ESCO) in a narrow estuary is investigated with a numerical model. New aspects concern the dependence of the spatial structure of ESCO flow on (1) longitudinal depth variation for fixed semi-diurnal tidal forcing, (2) varying amplitude of the semi-diurnal tidal forcing, and (3) mixed tidal forcing for fixed stratification at the mouth. Regarding (1) and (2), it appears that ESCO flow merely involves the components due to the semi-diurnal tide (u_{τ,M_2}) and quarter-diurnal tide (u_{τ,M_4}). For a periodically stratified estuary, u_{τ,M_2} is stronger than u_{τ,M_4} in the middle reach, and weaker in the other reaches, while both show a two-layer structure with seaward flow near the surface. For weak stratification, u_{τ,M_2} has a three-layer structure with seaward flow in the middle layer, while u_{τ,M_4} has a two-layer structure and contributes significantly to the total residual flow in the upper and lower reach. For a highly stratified estuary, u_{τ,M_2} dominates the ESCO flow (being weak compared to the total residual flow), and it has a reversed two-layer structure (seaward flow near the bottom). Regarding (3), if diurnal and semi-diurnal tides are of similar order, the ESCO flow due to diurnal tides dominates and it has a two-layer structure. If diurnal tides prevail, the ESCO flow induced by the long-periodic tide (due to joint action of two diurnal tides) is the main contributor to the total residual flow in the upper and lower reach of the estuary.

1. Introduction

It has been noted in many studies that residual flow, driven by a shear stress that is due to the covariance between tidally varying eddy viscosity and the vertical gradient of tidal velocity, is a significant component of the estuarine circulation (Jay and Musiak, 1994; Stacey et al., 2001, 2008, 2010; Burchard and Hetland, 2010; Burchard and Schuttelaars, 2012; Cheng et al., 2010; Geyer and MacCready, 2014). Following Dijkstra et al. (2017), this covariance is referred to as 'Eddy viscosity Shear COvariance' (ESCO). Clearly, eddy viscosity varies during the tidal cycle, e.g. it peaks at both maximum flood and maximum ebb. Besides, another type of temporal variation of eddy viscosity results from the advection of the density field by horizontal currents that have vertical shear (de Ruijter, 1983; van Aken, 1986; Simpson et al., 1990). In the case of tidal currents, during flood, salt oceanic water is strained over fresher water, causing stratification to decrease, thereby resulting in increased turbulence. In contrast, during ebb, relatively light water is advected over salt water, the stratification is enhanced and this suppresses turbulence. In tidally energetic estuaries, this so-called tidal straining mechanism results in variation of eddy viscosity at the period of the primary tide, which is often the semi-diurnal M_2 tide (Burchard and Baumert, 1998; Geyer et al., 2000; Stacey et al., 2001; Simpson et al., 2002, 2005; Pein et al., 2014).

The background stratification of the water column has a strong impact on the temporal variation of turbulent eddy viscosity that results from the straining process, and thereby on the structure of the residual flow that is driven by ESCO. Using a 1D numerical model, Stacey et al. (2008) found that in a periodically stratified water column, the ESCO flow always shows a two-layer structure in the vertical direction, with the flow direction in the layers depending on the tidal phase at which a perturbation in the density field is externally imposed. The onset of stratification during the ebb phase results in landward flow near the bottom and seaward flow near the surface. This is referred to as a 'classical' two-layer structure, because it is identical to that of the estuarine circulation driven by horizontal density gradients. However, if stratification is imposed during the flood phase, the ESCO flow has a 'reversed' two-layer structure (landward directed in the upper layer and seaward below it). Similar findings were reported by Cheng et al. (2010), who investigated the ESCO flow in weakly stratified to highly stratified estuaries by using a 3D numerical model (Cheng et al., 2011,

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2013), in which the variation in stratification was computed internally, rather than being imposed. The degree of stratification in the estuary is controlled by a varying amplitude of a single externally forced tide, i.e., the semi-diurnal tide. Their results show that under periodically stratified conditions the residual flow due to ESCO has a classical two-layer structure. If stratification increases, first a transition to a three-layer structure occurs, and for highly stratified conditions a reversed two-layer structure is obtained. Note that the tidal mean stratification not only affects the temporal evolution of turbulent eddy viscosity, but also the vertical shear of the semi-diurnal tidal current (Chen and de Swart, 2016), which is also a part of ESCO.

Apart from tidal straining, the covariance between eddy viscosity and tidal velocity shear could also result from, e.g., tidal variation of eddy viscosity induced by wind (Verspecht et al., 2009). Recently, Dijkstra et al. (2017) showed with 1D and 2D numerical models that at a specific location in the (partially stratified and M_2 dominated) Scheldt River Estuary, the covariance between M_4 eddy viscosity and M_4 tidal velocity shear contributes about 8% to the total residual flow (other drivers of residual flow are horizontal density gradients, Stokes transport, etc.). Sources of M_4 tidal velocity are, e.g., nonlinear advection of the M_2 tidal momentum by M_2 tidal currents and depth dependent friction (e.g. Ianniello, 1977). The M_4 eddy viscosity component is generated by the friction velocity of the M_2 tide, and by intratidal variations of the density stratification (Simpson et al., 2005).

So far, the studies on ESCO mainly considered estuaries of constant depth with the M_2 being the dominant tide and the ESCO flow was analysed at fixed locations. These observations motivate three research aims of the present study. First (RA.1), to investigate the effect of longitudinal depth variation on the structure of ESCO flow for fixed tidal forcing that consists of a single semi-diurnal constituent. Second (RA.2), to quantify the effect of tidal mean stratification on the ESCO flow at all locations in the estuary. Third (RA.3), to investigate the ESCO-induced residual flow in the case that the externally forced tide contains multiple constituents with frequencies that do not have an integer ratio and stratification at the mouth is kept fixed. The latter is relevant because tidal forces generate not only M_2, but also e.g. diurnal constituents P_1, K_1 and O_1 and a semi-diurnal constituent S_2. As highlighted by Geyer and MacCready (2014), systematic investigation of dynamics of estuaries in which the tidal motion is forced by multiple constituents is "surprisingly" late. One consequence of including diurnal tide is that the straining of isohaline in tidal cycles causes a diurnal component in eddy viscosity. Another important consequence of the joint action of tidal constituents with different frequencies is that nonlinear interactions between any two single tidal constituents will influence other tidal constituents and generate new constituents, in particular a long-periodic tide, which also contribute to the ESCO residual flow.

To address these objectives, the numerical model Delft3D-FLOW (Lesser et al., 2004) is applied to explicitly resolve the temporal and spatial structure of vertical eddy viscosity and tidal flow at different locations. The focus of this work is on the longitudinal dynamics driven by tides. Hence, the estuary is assumed to be straight and narrow, without lateral variations in depth. Moreover, effects of wind and the Coriolis force are not considered. The latter conditions imply a weak lateral flow, which also causes straining of the density field (e.g. Lacy et al., 2003; Burchard and Schuttelaars, 2012; Basdurak et al., 2013).

In Section 2, the numerical model and the design of the experiments are presented. Furthermore, the methods to calculate residual flow induced by ESCO, and to decompose the ESCO forcing into contributions due to different tidal constituents are described. Model results are presented in Section 3, followed by a discussion in Section 4. Finally, Section 5 contains the conclusions.

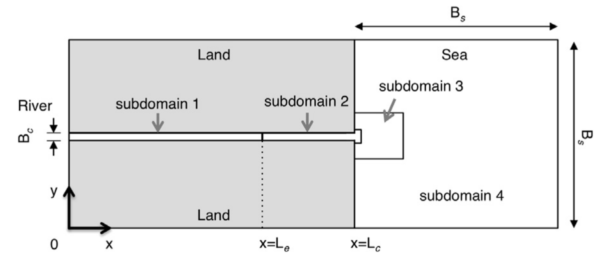

Fig. 1. Geometry of the idealised estuary-shelf sea system. The subdomains are introduced for reasons of numerical efficiency (see text for details).

2. Material and methods

2.1. Model

The numerical hydrodynamic model Delft3D-FLOW (for a description, see (Delft, 2006)) is used to simulate currents, salinity and turbulence in an idealised estuary-shelf system (Fig. 1). Temperature is kept constant so that density variations are due to salinity variations only. An x, y, σ-coordinate system is adopted, in which $\sigma = (z - \eta)/D$, with $z = \eta$ being the vertical level of the free-surface, D being the distance from free-surface to the bottom and x, y, z are Cartesian coordinates. The straight channel is located between river head $x = 0$ and estuary mouth $x = L_c$. It has an undisturbed depth $H(x)$ and a constant width B_c. The adjacent sea has straight open boundaries that are positioned at a distance B_s from the estuary mouth and it has a depth that increases linearly from the coast to the eastern boundary. Freshwater is prescribed at the estuary head $x = 0$ with a constant discharge Q. At the three open boundaries of the sea, tidal sea surface elevations with given amplitudes and frequencies are imposed. Moreover, fixed values of salinity are imposed at these boundaries. A two-equation $k - \varepsilon$ turbulence scheme is used to compute vertical eddy viscosity and eddy diffusivity. Horizontal eddy viscosity and diffusivity are assumed to be constant.

2.2. Setup of experiments

First, a setting of experiments is designed to address the first research aim (RA.1). For this, a fixed river discharge is prescribed at the landward side, while at the seaward boundaries a tide is imposed with a single frequency that in each boundary point has the same amplitude and phase. Furthermore, the bottom is flat from river head to the location $x = L_e$, which is inside the estuary (see Fig. 1), whilst seaward of this location water depth linearly increases to the estuary mouth ($x = L_c$) with different values of the bottom slope. Three different series of experiments are considered. In the first series, the depth $H_e = H(x = L_e)$ is kept fixed and $H_c = H(x = L_c)$ increases with increasing bottom slope. In series 2, The depth in the middle of the estuary ($x = (L_e + L_c)/2$) is fixed, H_e decreases and H_c increases such that the volume of the estuary is kept fixed. Finally, in series 3, H_e decreases and H_c is kept fixed.

The fourth series of experiments is designed to address the second research aim (RA.2). To focus on the effect of varying tidal mean stratification on the spatial structure of the ESCO flow, a constant depth is used between river head and estuary mouth. The forcing is identical to that of the previous series, but now the amplitude of the tide at the open boundaries is varied, such that a different degree of stratification is obtained in the estuary.

Finally, the fifth series of experiments addresses the third research aim (RA.3), i.e., to assess the spatial structure of the ESCO flow in an estuary in which tidal motion is driven by tides imposed at the seaward boundaries that contain multiple constituents with different amplitudes. The constituents that are considered are a semi-diurnal tide with radian frequency ω and two diurnal tidal constituents with frequencies