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# Lateral structure of tidal asymmetry in vertical mixing and its impact on exchange flow in a coastal plain estuary

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ABSTRACT

Residual currents induced by asymmetries in tidal mixing (ATM) were determined using a series of underway-current velocity profiles and salinity measurements, estimates of vertical mixing, and an analytical expression. Six different 12-hour transect surveys at the mouth of the James River were carried out under typical spring and neap tides and a range of river flows. The ATM-induced flows were found to be of the same order of magnitude as the density-driven flows. These flow profiles showed either a two or a three-layer structure in the channel and a two-layer structure over shoals. More stratification during ebb than flood periods (tidal straining) favored gravitational circulation, whereas reversed straining (more stratification at flood) opposed gravitational flow. The contribution of ATM-induced residuals increased as water column stratification increased. Lateral variations in ATM favored lateral shear in along-channel flow, enhancing the laterally sheared exchange. Observations were in good agreement with previous numerical and analytical model results. In particular, observational validation is presented on reverse tidal straining inducing residuals that act against gravitational circulation. Inconsistencies arise from the assumptions made in the models, namely no Coriolis forcing, no topographic features such as headlands, and simplified nature of stratification.



## 1. Introduction

The dynamics of estuarine circulation have been considered to involve a balance between the pressure gradient, induced by the surface slope and the baroclinic pressure gradient caused by along-channel density gradients, and the stress divergence (Pritchard, 1956; Hansen and Rattray, 1965; Chatwin, 1976). The contribution of tidal processes to such balance is through the stress divergence, which is typically parameterized by the vertically and tidally averaged eddy viscosity. However, spatial and temporal tidal asymmetries in turbulent mixing may influence estuarine exchange by introducing residual currents. Recent studies have shown that these tidal asymmetries can lead to asymmetric mean velocity profiles resulting in a Eulerian subtidal flow (Jay and Musiak, 1996; Stacey et al., 2001, 2008; Cheng et al., 2010).

The interaction between along-channel density gradients and vertical shear in tidal currents (i.e. tidal straining) may produce stratified ebb tides and well-mixed flood tides (Simpson et al., 1990). Jay and Musiak (1996) and Stacey et al. (2001) stated that this tidal asymmetry in vertical mixing enhances surface currents during ebb and enhances bottom currents during flood, resulting in two-layered subtidal circulation (i.e. up-estuary near the bottom, down-estuary near the surface).

Although previous studies are in agreement with regard to the influence of tidal asymmetries on near-surface subtidal currents, there are conflicting views on the degree of near-bed influence. Geyer et al. (2000) stated that near-bed residual circulation is slightly affected by asymmetries in vertical mixing, whereas Scully and Friedrichs (2003) documented enhanced vertical shear in ebbing currents near bed associated with asymmetric vertical mixing. Stacey et al. (2008) pointed out the importance of timing of stratification and its strong impact on subtidal flow. Their numerical model results showed that for flood tide being well mixed and ebb tide being stratified, the subtidal circulation generated by this asymmetry has the same pattern as that of the gravitational circulation. However for the case of reverse asymmetry (i.e. stratified flood, well-mixed ebb), they obtained a subtidal circulation that competed against gravitational circulation (i.e., up-estuary near the surface, down-estuary near the bottom).

Cheng et al. (2010) examined the residual currents induced by asymmetric tidal mixing in a weakly stratified, narrow estuary. They found that the strength of residual currents and tidal asymmetry is

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directly proportional to each other. Consistent with the results of Stacey et al. (2008), they pointed at the impact of stratification phase on residual currents. Burchard and Hetland (2010) analyzed the relative importance of gravitational circulation and residuals created by asymmetric mixing for periodically stratified tidal estuaries. They concluded that without wind straining, asymmetric induced residuals contributed up to twice more than the density-driven flow to estuarine circulation.

Asymmetric tidal mixing (ATM) can be defined as the vertical mixing term in the momentum equation not being sinusoidal over a tidal period. It arises from the covariance between eddy viscosity and vertical shears at intratidal time scales. The degree of asymmetry generally varies in space, thus affecting estuarine exchange. Previous studies showed the impact of lateral variability in bathymetry on flows by using spatially and temporally constant eddy viscosity (Wong, 1994; Kasai et al., 2000; Valle-Levinson et al., 2003; Winant, 2008; Huijts et al., 2006, 2011). Scully and Friedrichs (2007) and Huijts et al. (2009) showed that lateral asymmetries in mixing may induce laterally sheared residual circulation with up-estuary flow over the shoal, and down-estuary flow in the channel.

In this paper, observations carried out at Hampton Roads, at the transition between James River and Chesapeake Bay, are used to investigate the influence of ATM on estuarine exchange flow. Specific objectives include analyzing the vertical pattern and the strength of ATM-induced residual flow. The relative importance of ATM-induced flow with respect to density-driven flow is explored. Moreover the lateral variation of vertical mixing and its influence on subtidal estuarine dynamics is assessed. The study area and data processing are described in Section 2 and the results are presented in Section 3. The results include asymmetries in eddy viscosity and in vertical mixing, and different ATM structures over the cross-section. Sources of the asymmetry are investigated by analyzing values of potential energy anomaly. Last, observations are compared to numerical and analytical results. Implications are discussed in Section 4, and conclusions are presented in Section 5.

## 2. Study area and data processing

Data were collected along a 2 km-long, cross estuary transect at Hampton Roads, Virginia (Fig. 1) under different tidal forcing, wind forcing and river discharge conditions in 2004 and 2005. The transect was sampled onboard the R/V Fay Slover during a successive neap-spring tidal cycle (16–23 May 2005). Three surveys that took place during spring tides (23 February, 30 September 2004, and 23 February 2005) and one during neap tide (4 November 2004) were also included to illustrate seasonal variability.

Continuous velocity measurements and station density profiles were obtained over a period of 12–13 hours, with a 600 kHz RD instruments acoustic Doppler current profiler (ADCP) and a Sea Bird (SBE-25) conductivity-temperature-depth (CTD) recorder, respectively. The towed ADCP collected 1 s pings, which were averaged over 20 ensembles, along transect. This gave a horizontal resolution of ~50 m, cruising at ~2.5 m s$^{-1}$. The vertical bin size was 0.5 m ( $<$ 3 cm s$^{-1}$ standard deviation) for the data set collected in 2004 and 1 m for the rest of the data ( $<$ 1 cm s$^{-1}$ standard deviation). Velocity data were compass-calibrated and corrected by the method of Joyce (1989) using Global Positioning System data. For each data set, 15 trajectory

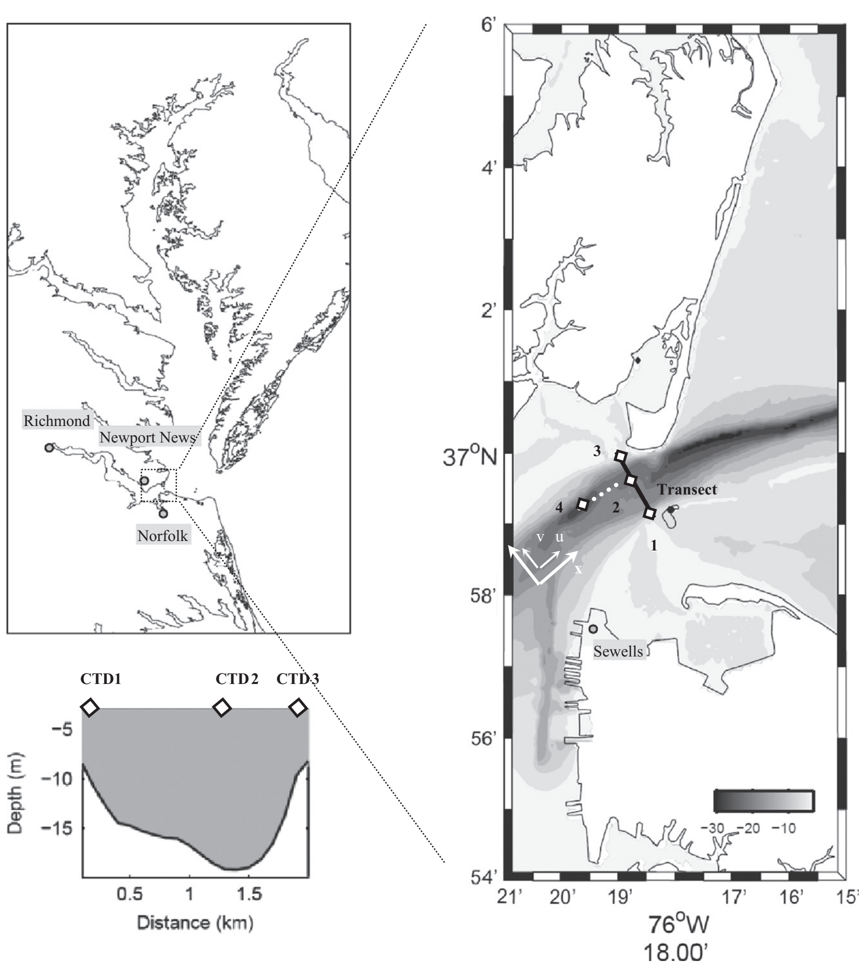


**Fig. 1.** Map of the study area in the lower James River estuary showing the bathymetry, the transects sampled, and four stations where the CTD casts were taken (looking up-estuary).