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Flood-ebb and spring-neap variations of lateral circulation in the James River estuary

Ming Li[a,*], Wei Liu[a], Robert Chant[b], Arnoldo Valle-Levinson[c]

[a] Horn Point Lab, University of Maryland Center for Environmental Science, 2020 Horn Point Road, P.O. BOX 775, Cambridge, MD 21613, USA
[b] Institute of Marine and Coastal Sciences, Rutgers, the State University of New Jersey, 71 Dudley Road, New Brunswick, NJ 08901, USA
[c] Civil and Coastal Engineering Department, University of Florida, PO Box 116580, Gainesville, FL 32611, USA

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ABSTRACT

Mooring observations in the James River estuary show one-cell lateral circulation that persists from spring to neap tides despite large changes in vertical stratification. The lateral circulation is twice as strong on ebb than on flood during neap tide, but shows little flood-ebb asymmetry during spring tide. A numerical model is developed to simulate the lateral circulation. It captures an observed three-fold change in stratification and reproduces the observed temporal evolution of the lateral circulation. An analysis of the streamwise vorticity equation reveals that the lateral circulation is generated by the tilting of the planetary vorticity by the along-channel flow but opposed by turbulent diffusion and lateral baroclinic forcing due to sloping isopycnals. Tilting of the vertical component of relative vorticity by the along-channel flow is insignificant. Vortex stretching is also weak in the straight segment of the estuary where mooring observations were available. During neap tide, vorticity generation is larger on ebb due to stronger vertical shear in the along-channel current, thereby leading to stronger lateral circulation on ebb. During spring tide, however, turbulent mixing reduces the shear and the flood-ebb asymmetry in the vorticity generation, resulting in little flood-ebb variations in the lateral circulation strength. Such strength is comparable between spring and neap tides because of the compensative changes in the vorticity budget: increased baroclinic forcing and decreased diffusion during neap tides versus decreased baroclinic forcing and increased diffusion during spring tides.

1. Introduction

In a pioneering study, Nunes and Simpson (1985) observed a flood-tide axial surface front in a well-mixed estuary in North Wales, and suggested that this front was produced by a pair of counter-rotating circulation cells in the cross-channel section. They further hypothesized that these lateral circulation cells were generated by the cross-channel density gradients resulting from the non-uniform advection of the along-channel density gradient. This observation has spun off a series of numerical and analytic modeling investigations aimed at illuminating driving mechanisms for the lateral circulation in the estuaries (e.g. Li and Valle-Levinson, 1999; Li, 2001; Lerczack and Geyer, 2004; Chen and Sanford, 2009; Cheng et al., 2009; Scully et al., 2009; Huijts et al., 2009, 2011; Li et al., 2014).

Using a numerical model of an idealized estuarine channel, Lerczak and Geyer (2004) reproduced the two counter-rotating lateral circulation cells and determined that they are indeed driven by differential advection and cross-channel density gradients. Their study showed that the lateral circulation is about 4 times as strong during flood than that during ebb tides and this flood-ebb asymmetry is related to nonlinear advective processes and time-varying stratification over a tidal cycle. In a modeling study of the Hudson River estuary, Scully et al. (2009) showed that one-cell lateral circulation is generated by tidal advection due to lateral Ekman transport. They also reported flood-ebb asymmetry in the lateral circulation strength, and found that the lateral circulation is stronger under weakly stratified spring tide conditions than under strongly stratified neap tide conditions. Lateral flows can also be generated by the interactions between barotropic tidal currents and cross-channel variations in bathymetry (Li and Valle-Levinson, 1999; Li, 2001, 2002). Lateral flow convergence appeared over the edges of deep channels and was produced by the phase lag of the flow in the channel relative to the shoals (Valle-Levinson et al., 2000a). A recent modeling study by Li et al. (2014) showed that the lateral circulation switches from two circulation cells to one cell as Kelvin number, or the estuary width, increases.

A major motivation for studying the lateral circulation in estuaries is that lateral advection may play a role in driving estuarine exchange flows (Lerczak and Geyer, 2004; Scully et al., 2009; Burchard et al.,

* Corresponding author.
E-mail address: mingli@umces.edu (M. Li).

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2011; Geyer and MacCready, 2014). When averaged over a tidal cycle, the lateral circulation tends to force the surface water seaward but bottom water landward, thus augmenting the estuarine exchange flow. This lateral advection mechanism depends critically on the existence of a flood-ebb asymmetry in the lateral circulation strength. Over the spring-neap tidal cycle, Lerczak and Geyer (2004) found similar asymmetry in the strength of the lateral circulation. Increased lateral advection under weakly stratified spring conditions contributes, along with the baroclinic pressure gradient, to driving the exchange flow. In contrast, during stratified neap conditions, lateral flows are shut down and their contribution to driving exchange flow decreases. Consequently, the estuarine exchange flow in the Hudson River estuary changes by a factor of 2–3 over the spring-neap tidal cycle (Geyer et al., 2000), even though eddy viscosity increases by one order of magnitude from neap to spring tides (Peters and Bokhorst, 2001). Therefore, there is a need for increased understanding of the flood-ebb and spring-neap variations of the lateral circulation in estuaries.

Several observational studies have been directed at the lateral circulation in recent years. In a channel in northern San Francisco Bay, Lacy et al. (2003) observed that lateral circulation produced lateral straining to restratify a well-mixed water column. Scully and Geyer (2012) observed that lateral straining by lateral circulation led to stronger stratification on the flood tide than on the ebb tide in the Hudson River estuary. Similar findings were reported for Delaware Bay by Aristizabal and Chant (2014). More recently, Hugeunard et al. (2015) observed enhanced near-surface vertical mixing during the ebb tide that is related to lateral circulation. However, there have been few detailed observations of the temporal variability of the lateral circulation in estuaries over the flood-ebb and spring-neap tidal cycles. One exception was Collignon and Stacey (2012) who documented the temporal variation and spatial structure of lateral circulation. They observed that lateral circulation reverses its sense several times during the ebb tide, featuring intratidal variability that is apparently unrelated to the flood-ebb asymmetry reported in previous modeling studies.

This paper presents one-month long mooring observations of lateral circulation in the James River, the southernmost tributary to Chesapeake Bay (Fig. 1). The mooring arrays at two nearby cross sections provide an unprecedented detailed documentation of the lateral circulation and salinity structure over flood-ebb and spring-neap tidal cycles. It may appear paradoxical that Pritchard (1956) developed his classic theory of estuarine dynamics in the James River and suggested the transverse dynamics in the James River to be essentially geostrophic. However, Pritchard's calculations of various terms in the along-channel momentum balance indicated that frictional terms were comparable to the Coriolis accelerations. Later observations and analyses by Valle-Levinson et al. (2000a, 2000b) clearly showed that the ageostrophic terms such as frictional and advective accelerations were greater than Coriolis accelerations during spring tides and comparable to or smaller than the Coriolis accelerations during neap tides. Therefore, the James River estuary provides a pertinent site to study the lateral circulation. To interpret the observed temporal variability of the lateral circulation, a numerical model of the James River is developed and validated against the mooring observations. A diagnostic analysis of the streamwise vorticity equation is conducted to distill the generation and dissipation mechanisms of the lateral circulation and understand the observed flood-ebb and spring-neap variations of the lateral circulation.

The paper is structured as follows. Section 2 reports observations of the lateral circulation and density structure in the James River estuary. Section 3 describes the configuration and validation of the numerical model. Section 4 presents the diagnostic analysis of the lateral circulation through the streamwise vorticity equation. This is followed by conclusions and discussions in Section 5.

2. Field observations

The James River is the southernmost tributary to Chesapeake Bay (Fig. 1a). It has a channel-shoal bathymetry, consisting of a main channel of maximum depth of 15 m, located approximately between 0 and 2 km from the north coast, and a secondary channel, 5–6 m deep,

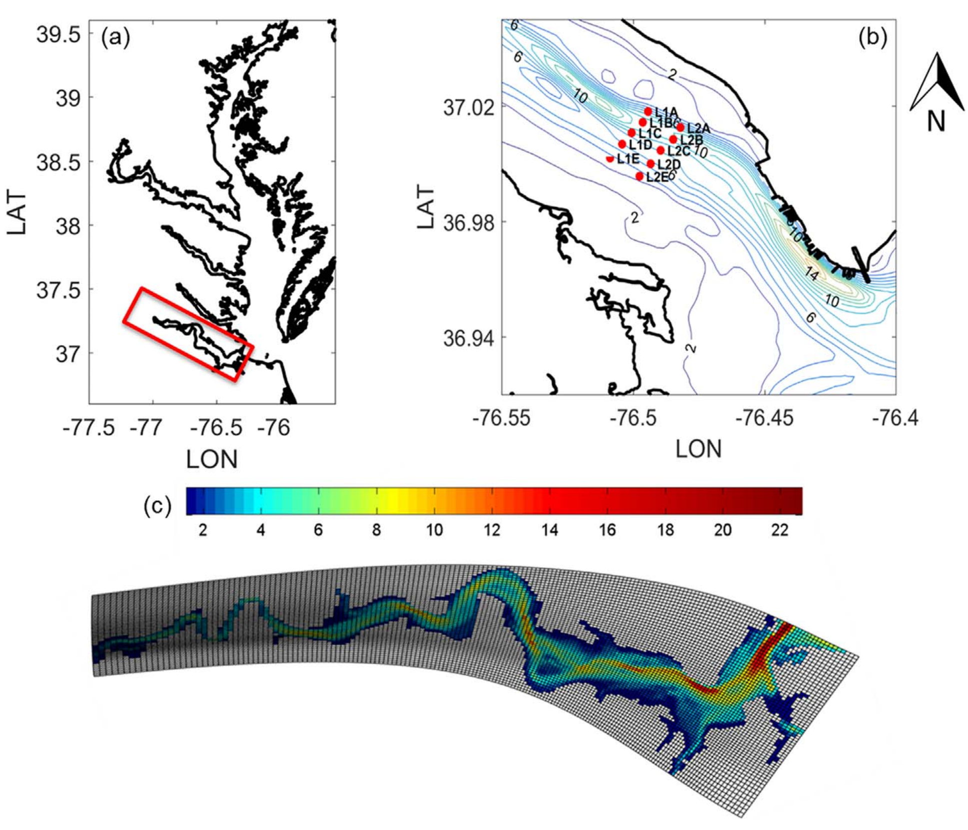

Fig. 1. (a) Map of Chesapeake Bay and its southernmost tributary - the James River (marked by the red rectangle). (b) Zoomed-in view of the observational site with mooring stations marked by red dots. (c) ROMS grid and bathymetry of the James River estuary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)