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Spatial variations of flow structure over estuarine hollows

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ABSTRACT

Observations of the flow field over an elongated hollow (bathymetric depression) in the lower Chesapeake Bay showed tidally asymmetric distributions. Current speed increased over the landward side of the hole during flood tides and decreased in the deepest part of the hollow during ebb tides. A simple conceptual analysis indicated that the presence of a horizontal density gradient can generate the asymmetric spatial variations of flow structure depending on the sign of the horizontal density gradient. When water density decreases downstream, the velocity increases over the downstream edge of the hollow. Conversely when water density increases downstream, the flow decreases over the hollow more than a case without a horizontal density gradient. The conceptual analysis is confirmed by numerical experiments of simplified hollows in steady open channel flows and of an idealized tidal estuary. These hollows also alter the local current field of tidally averaged estuarine exchange flows. The residual depth-averaged currents over a hollow show a two-cell circulation when Coriolis forcing is neglected and an asymmetric two-cell circulation, with a stronger cyclonic eddy, when Coriolis forcing is included.

1. Introduction

Natural pits or scour holes (hereafter called hollows), which are bathymetric depressions in the shape of elongated holes, are widely observed morphological features in coastal embayments and estuaries. Large hollows have significant impacts on local currents and wave patterns. According to Bernoulli dynamics, when a homogeneous current passes a hollow, the current velocities decrease due to the increase of the water depths in the hollow. Numerical studies of a prototypical mining pit off the Dutch Coast showed that the velocity decreases by about 10% in the pit compared to the reference case (without pit). The influence areas are of the order of 50% of the pit length (van Rijn et al., 2005). The reduction of current speed over a hollow was shown to depend on hollow dimensions. Davies and Brown (2007) carried out a series of idealized numerical experiments and showed that current velocities are reduced more in a deep than in a shallow hollow, while elliptical hollows exhibit less reduction of velocity than circular hollows. The topographic rectification of tidal currents over a hollow, under a homogeneous water column, generates spatial variations of vorticity and effects tidal residuals. Park and Wang (1991) found that two counter-rotating transient vorticities of tidal flows are generated over a simple Gaussian hollow and the advection of two transient vorticities leads to a cyclonic residual vorticity. The residual transport showed an anti-clockwise deflection of flow around the hollow. Roos et al. (2008) developed an analytical model and investigated the evolution of large-scale sandpits in a tidally dominated offshore environment. The results showed that flow contraction is strongest for large and elongated pits, with an orientation parallel to the flow direction.

In the direct vicinity of hollows, the flow structures can exhibit significant spatial variation. Field observations in the hole located at Dyfi Estuary showed that the flow increased over the landward side of the hole during flood and over the seaward side of the hole, during the ebb. This flow enhancement was considered as a result from flow convergence at the upstream end of the hole, which was partly caused by a nearby topographic feature (Davies and Brown, 2007). A different temporal variation of flow structure over a tidal cycle has been observed in the hollow off Cape Charles in the lower Chesapeake Bay (Salas-Monreal, 2006). During flood tides, currents were stronger in the landward side than in the seaward side of the hollow. During ebb tides, velocities were reduced in the deepest part of the hollow. These flow patterns were unlikely caused by nearby coastline morphology (Fig. 1) nor could they be interpreted with Bernoulli-type dynamics, which consider a momentum balance mainly between advection and barotropic pressure gradient. In estuaries, the baroclinic pressure gradient plays a crucial hydrodynamics role because of the horizontal density gradient arising from the salinity difference between ocean water and freshwater. The objective of the present study is to investigate the cause of the tidally asymmetric spatial distributions of flow over an estuarine hollow. This objective is addressed with numerical simulations that show that the baroclinic pressure gradient is a modifier of Bernoulli-type

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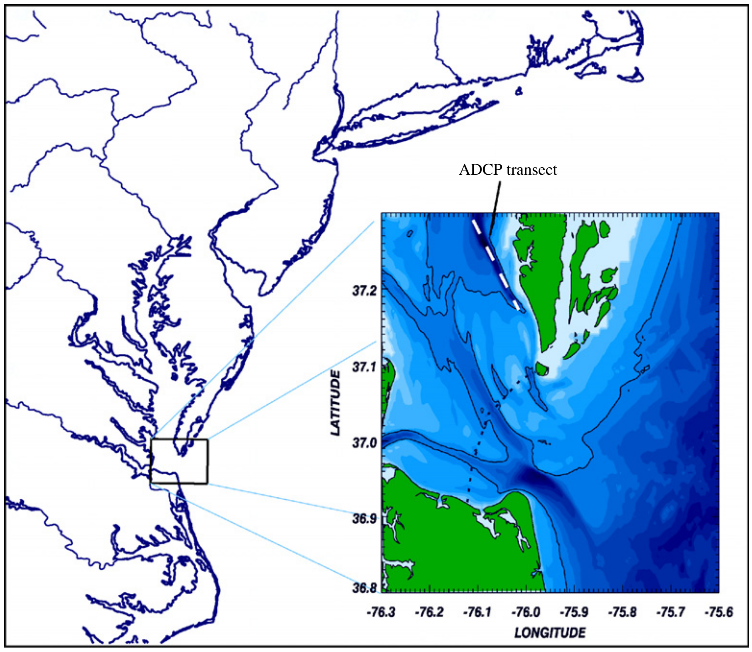

Fig. 1. Study area in the Chesapeake Bay and the ship track during the observations of May 28–30th, 2002.

dynamics and can produce the observed tidally asymmetric flow structure over estuarine hollows. Also, the effects of these hollows on estuarine residual flows are examined.

The paper is organized as follows. In Section 2, field observations in the lower Chesapeake Bay are described to motivate a conceptual analysis and a series of numerical simulations. A simple conceptual analysis is presented in Section 3 to show the effect of the horizontal density gradient on flow dynamics. In Section 4, a group of numerical experiments is carried out to model a steady open channel flow in order to demonstrate the conceptual analysis. Also, effects of hollow's geometry on flow dynamics are presented. In Section 5, a second group of experiments is designed to depict hydrodynamics, in an estuarine hollow, in order to compare them to those observed in the lower Chesapeake Bay. Finally, we present the conclusions in Section 6.

2. Observations

Filed observations were collected along the hollow off Cape Charles in the lower Chesapeake Bay (Fig. 1). The hollow is approximately 15 km long, 3 km wide and 45 m deep, forming an asymmetric elliptical shape. All data were collected onboard the National Ocean and Atmospheric Administration (NOAA) ship *R/V Ferrel*. Current velocity data were obtained using a towed acoustic Doppler current profiler (ADCP), during four semidiurnal tidal cycles from May 28th to May 30th, 2002. A total of 23 transect repetitions were sampled over 49 h. Sampling started 3 h before the high tide under local winds below $2\,m\,s^{-1}$, and after one month of high river discharge. The density structure had a continuously stratified water column, ranging from 1014 to $1022\,kg\,m^{-3}$ (Salas-Monreal, 2006). During the observation period, the tidal range was about 1 m at nearby Kiptopeke station (# 8632200 of the National Oceanic and Atmospheric administration and ~10 km away from the sampling site).

During flood tides, the flow speed increased as it moved over the deepest part of the hollow. Fig. 2a shows a typical snapshot of the flow along the main axis of the hollow. The speed increased from ~70 cm/s from the southern edge of the hollow (left side of the figure) to ~80 cm/s over the north slope (right side of the figure) of the hollow. The velocity enhancement was pronounced on the landward side of the hollow. During ebb tides, the current speed was reduced as the flow entered the deepest parts of the hollow. Fig. 2b shows a typical snapshot of flow structure during ebb tides. The maximum current speed was about 0.8 m/s and located near the deepest part of the hollow.

In Bernoulli-type dynamics, the flow is expected to decelerate as it moves through an increasing water column. It appears that Bernoulli-type dynamics can explain the flow structure during ebb tides, but it cannot explain the flow enhancement during flood tides. Salas-Monreal (2006) suggested, in agreement with Davies and Brown (2007), a three-dimensional (3D) flow dynamics where the flow converges as it enters the hollow and diverges as it leaves the hollow. According to this idea, the flow accelerates as it moves towards the deepest part of the hollow, which seems consistent with the flow structure during flood tides. However, this idea cannot explain the flow structure during ebb tides. On the basis of the following conceptual analysis, it appears that the horizontal density gradient is an essential ingredient for the flow acceleration during flood and deceleration, during ebb.

3. Conceptual analysis

In an attempt to explain the observed tidally asymmetric flow patterns, a flat channel with a simple hollow of sinusoidal shape is considered. The longitudinal bathymetric distribution of the hollow can be represented as

$$H = h_1 + h_2 \sin\left(\frac{\pi x}{L}\right), \quad 0 \leqslant x \leqslant L \tag{1}$$

where H is the total depth of the hollow as a function of the along-hollow distance x, h_1 is the depth outside the hollow, h_2 is the maximum depth of the hollow measured from h_1, and L is the length of the hollow. Neglecting friction, just for the sake of argument, the depth-integrated one-dimensional (1D) momentum equation under steady state is

$$u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} - \frac{g}{\rho_0}\frac{\partial \rho}{\partial x}h, \quad h = H + \eta, \quad \eta \ll H \tag{2}$$