Continental Shelf Research 28 (2008) 2450–2471

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Wind effects on the lateral structure of density-driven circulation in Chesapeake Bay

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ARTICLE INFO

Article history:
Received 10 August 2007
Received in revised form
25 March 2008
Accepted 20 June 2008
Available online 27 June 2008

Keywords:
Chesapeake Bay
Estuarine circulation
Wind-driven currents
Wind-induced mixing
Transverse structure

ABSTRACT

The response of the density-driven circulation in the Chesapeake Bay to wind forcing was studied with numerical experiments. A model of the bay with realistic bathymetry was first applied to produce the density-driven flow under average river discharge and tidal forcing. Subsequently, four spatially uniform wind fields (northeasterly, northwesterly, southwesterly, and southeasterly) were imposed to examine the resulting cross-estuary structure of salinity and flow fields. In general, northeasterly and northwesterly winds intensified the density-driven circulation in the upper and middle reaches of the bay, whereas southeasterly and southwesterly winds weakened it. The response was different in the lower bay, where downwind flow from the upper and middle reaches of the bay competed with onshore/offshore coastal flows. Wind remote effects were dominant, over local effects, on volume transports through the bay entrance. However, local effects were more influential in establishing the sea-level slopes that drove subtidal flows and salinity fields in most of the bay. The effect of vertical stratification on wind-induced flows was also investigated by switching it off. The absence of stratification allowed development of Ekman layers that reached depths of the same order as the water depth. Consequently, bathymetric effects became influential on the homogeneous flow structure causing the wind-induced flow inside the bay to show a marked transverse structure: downwind over the shallow areas and upwind in the channels. In the presence of stratification, Ekman layers became shallower and the wind-induced currents showed weaker transverse structure than those that developed in the absence of stratification. In essence, the wind-driven flows were horizontally sheared under weak stratification and vertically sheared under stratified conditions.

1. Introduction

The influence of winds on estuarine circulation (gravitational circulation) has been described for several decades. For example, the analytical solution of estuarine circulation given by Hansen and Rattray (1965) included the contribution of winds. According to their solution, a down-estuary wind intensified the estuarine circulation, while an up-estuary wind weakened it. Geyer (1997) applied this solution to explain observations in Waquoit Bay, Massachusetts, in terms of wind forcing. In addition, Weisberg (1976), Elliott (1978) and Wang (1979) also observed predominant wind-driven pulses in currents or sea levels of an estuary.

Recent studies have focused, in addition to the vertical and along-estuary structure of estuarine flows, on their transverse structure. Assuming a balance between pressure gradient and vertical stress divergence in an idealized estuary with a triangular cross-section, Wong (1994) and Friedrichs and Hamrick (1996) obtained an analytical solution for the circulation. The solutions in Wong (1994) are for flows driven by along-estuary density gradients, by local along-estuary winds, and by subtidal sea-level oscillations at the entrance to an estuary, which represent the remote effect of winds. His solutions revealed a marked transverse structure that depended on the bathymetry. In the deep central part of the triangular section, the net flow was in the opposite direction of the density gradient or the local winds. Over the two shallow sides of the cross-section, the net flow was in the direction of the density gradient or of the local winds. The current caused by a subtidal sea-level oscillation at the entrance to an estuary (the remote effect) was in the same direction throughout the cross-section but strongest in the deep central part.

Kasai et al. (2000) introduced rotation effects to the formulation of Wong (1994) and also looked at the transverse dynamics. They used the Ekman number to evaluate the relative importance of friction and rotation in their analytical solution. A large Ekman number meant that most of the water column was occupied by the Ekman depth. In that case, friction dominated the dynamics

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doi:10.1016/j.csr.2008.06.008

and the current structure approached the solution given by Wong (1994), i.e., bathymetry causes a strong transverse structure in the currents. In the case of a small Ekman number, the solution approached the traditional two-layer vertical structure of estuarine circulation. Valle-Levinson et al. (2003) extended the solution of Kasai et al. (2000) to a section with arbitrary bathymetry and applied the solution to explain the transverse structure of observed currents in several estuaries with different Ekman numbers. Following the same dependence on the Ekman number, Winant (2004) and Sanay and Valle-Levinson (2005) characterized the wind-driven flows affected by Coriolis under various bathymetric cross-sections and homogeneous density.

The above theoretical studies have examined current structures inside the estuary and assumed a linear superposition of the wind-induced and density-induced currents. This, of course, differs in a real estuary because winds can change the density field as well as the turbulence field. Winds can change the strength of estuarine currents, while turbulence, according to Kasai et al. (2000) and Valle-Levinson et al. (2003), can change the transverse structure of the current, regardless of whether it is wind induced or buoyancy induced. Chao (1988) investigated the wind effects on a pre-existing estuarine current in an idealized estuary using a three-dimensional model, which included the effects of winds on the density field but neglected wind effects on the turbulence field because he used a constant viscosity.

In this study, the work of Guo and Valle-Levinson (2007) is extended through the inclusion of winds. A uniform wind field from four directions (NW, NE, SE, and SW) as well as the corresponding sea-level change at the bay mouth were prescribed in a numerical model of the Chesapeake Bay to examine the modifications to a pre-existing estuarine circulation inside the bay and at the bay mouth. These modifications were also assessed by determining the wind response in a homogeneous Chesapeake Bay.

2. Numerical model and experiments

The model used in this study is the same as in Guo and Valle-Levinson (2007), the Princeton Ocean Model (POM). The POM is a three-dimensional primitive equation ocean model that includes full thermodynamics and a Mellor-Yamada level 2.5 turbulence closure model (Mellor, 2004). The model domain and bathymetry are shown in Fig. 1. The horizontal resolution was 1/240° in both the zonal and meridional directions, which gave 744 grids in the meridional direction and 420 grids in the zonal direction. In the vertical, 11 sigma-levels were evenly distributed. Calculations with 21 sigma-levels showed qualitatively the same results as those with 11 sigma-levels. The minimum water depth in the model domain was set to 3 m. The time step was 3 s for the external mode and 120 s for the internal mode. During calculations, the vertical eddy viscosity and diffusivity were determined by the Mellor-Yamada turbulence closure model with a background value of $10^{-5}\,\mathrm{m}^2/\mathrm{s}$. At the bottom, a common quadratic friction law was used to calculate bottom stress (see Guo and Valle-Levinson, 2007 for the parameters used). The horizontal eddy viscosity was calculated by the embedded Smagorinsky formula with a proportionality parameter of 0.1, and the horizontal eddy diffusivity was obtained using an inverse Prandtl number of 0.5.

The model was first forced with river discharge, an ambient coastal current and tides to produce the estuarine currents in the Chesapeake Bay. The water temperature was set as a constant (15 °C) throughout all the calculations and only the evolution of salinity was calculated. The contribution of temperature to the density gradient in the horizontal and vertical directions has been suggested to be less than 1/4 relative to salinity (Seitz, 1971; Goodrich et al., 1987). Referring to Hargis (1980), a total of $2200\,\mathrm{m}^3/\mathrm{s}$ of fresh water was introduced to the model domain from the Susquehanna (51% of total), Potomac (18%), James (14%), Rappahannock (4%), York (2%), and other small rivers (11%) (see Fig. 1 for the position of the rivers and see Guo and Valle-Levinson, 2007 for the method of introducing river discharge).

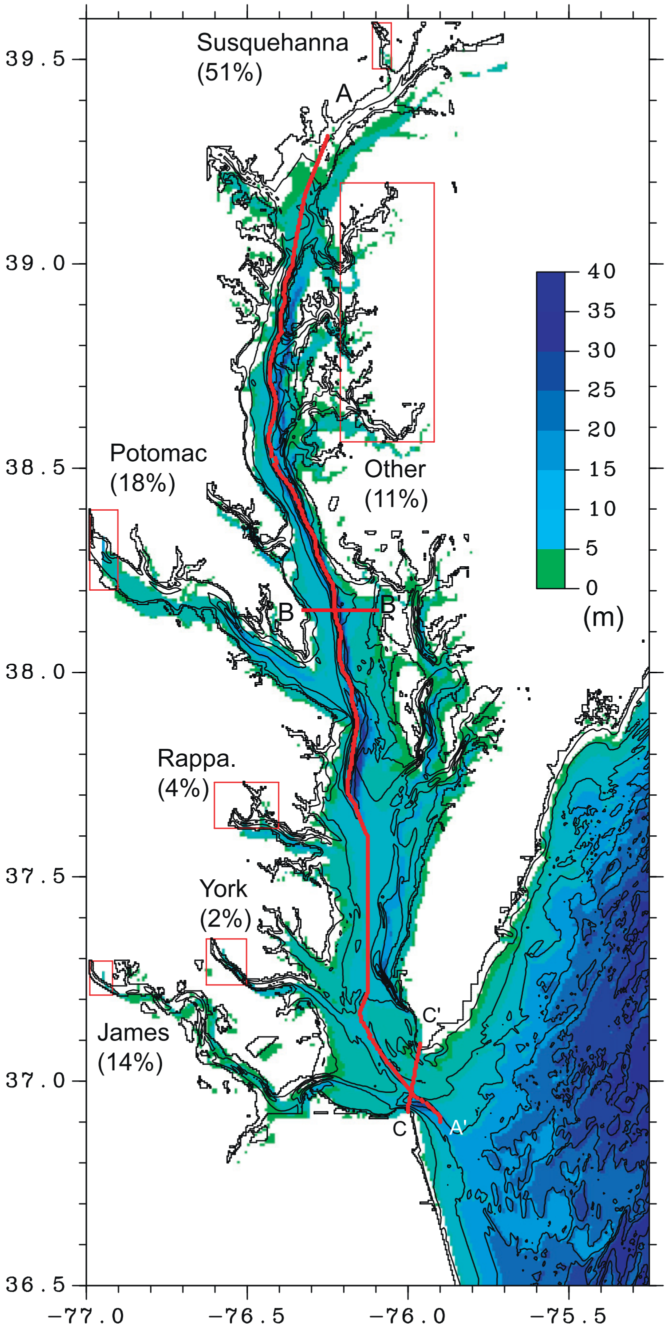

Fig. 1. Model bathymetry: the boxes denote river locations and the numbers inside the parentheses denote the percentage of each river discharge, relative to the total ($2200\,\mathrm{m}^3/\mathrm{s}$), as given by Hargis (1980). The longitudinal cross-section (A–A′) and two lateral cross-sections (B–B′ and C–C′) are referenced in subsequent figures.

Prescription of the southward ambient current in the shelf was motivated by previous studies. Beardsley and Boicourt (1981) reported a southward coastal current in the Middle Atlantic Bight. Epifanio and Garvine (2001) inferred the existence of a southward coastal current outside the Chesapeake Bay. In our simulations, an