Available online at www.sciencedirect.com

ScienceDirect

Continental Shelf Research 27 (2007) 20–42

CONTINENTAL SHELF RESEARCH

www.elsevier.com/locate/csr

Tidal effects on estuarine circulation and outflow plume in the Chesapeake Bay

Xinyu Guo[a,*], Arnoldo Valle-Levinson[b]

[a]*Center for Marine Environmental Studies, Ehime University, 2-5 Bunkyo-Cho, Matsuyama 790-8577, Japan*
[b]*Department of Civil and Coastal Engineering, University of Florida, 365 Weil Hall, P.O. Box 116580, Gainesville, FL 32611, USA*

Received 10 January 2006; received in revised form 17 August 2006; accepted 30 August 2006

Abstract

The response of the Chesapeake Bay to river discharge under the influence and absence of tide is simulated with a numerical model. Four numerical experiments are examined: (1) response to river discharge only; (2) response to river discharge plus an ambient coastal current along the shelf outside the bay; (3) response to river discharge and tidal forcing; and (4) response to river discharge, tidal forcing, and ambient coastal current. The general salinity distribution in the four cases is similar to observations inside the bay. Observed features, such as low salinity in the western side of the bay, are consistent in model results. Also, a typical estuarine circulation with seaward current in the upper layer and landward current in the lower layer is obtained in the four cases. The two cases without tide produce stronger subtidal currents than the cases with tide owing to greater frictional effects in the cases with tide. Differences in salinity distributions among the four cases appear mostly outside the bay in terms of the outflow plume structure. The two cases without tide produce an upstream (as in a Kelvin wave sense) or northward branch of the outflow plume, while the cases with tide produce an expected downstream or southward plume. Increased friction in the cases with tide changes the vertical structure of outflow at the entrance to the bay and induces large horizontal variations in the exchange flow. Consequently, the outflow from the bay is more influenced by the bottom than in the cases without tide. Therefore, a tendency for a bottom-advected plume appears in the cases with tide, rather than a surface-advected plume, which develops in the cases without tide. Further analysis shows that the tidal current favors a salt balance between the horizontal and vertical advection of salinity around the plume and hinders the upstream expansion of the plume outside the bay.

Keywords: Estuarine dynamics; River plume; Tidal effects; Vertical mixing; Mathematical models; Chesapeake bay

---

1. Introduction

Studies on the circulation and salinity distributions in Chesapeake Bay have a long history (Pritchard, 1952). Using observations, (Pritchard, 1954, 1956) constructed a two-dimensional (2D) framework for the dynamics of estuarine circulation, in which the effects of tidal currents on the salt and momentum balances in an estuary were recognized. Boicourt (1973) depicted the nature of the Chesapeake Bay outflow plume and the intruding oceanic flow underneath. Goodrich and Blumberg (1991) demonstrated the presence of an estuarine circulation in the Chesapeake Bay based on 168 current records from 1977 to 1983.

---

*Corresponding author. Tel./fax: +81 89 927 9824.
E-mail address: guoxinyu@dpc.ehime-u.ac.jp (X. Guo).

0278-4343/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2006.08.009

This consisted of a seaward current in the surface layer and a landward current in the lower layer. Observations across the entrance to the Chesapeake Bay showed that the exchange flow varies largely in the transverse direction (Valle-Levinson et al., 1998). An analytical solution illustrated that not only bathymetry variations but also friction is crucial to determine the transverse structure of exchange flows across the entrance to any estuary (Valle-Levinson et al., 2003). Following these observational and theoretical studies, the circulation in the Chesapeake Bay at any time scale should be studied in a 3D framework. Such framework should include a realistic bathymetry and tidal forcing.

Numerical simulations on the estuarine circulation in Chesapeake Bay also have a long history. Using a 3D primitive equation numerical model, Chao and Boicourt (1986) carried out a pioneering simulation of a plume in an idealized estuary with an adjacent shelf ocean. With a very similar model, Chao (1988a, b, 1990) investigated the influences of the bottom slope, winds and tide on the plume. Concentrating on the water exchange at the Chesapeake Bay entrance, Valle-Levinson et al. (1996) studied numerically the dynamics at the transition between an idealized estuary and an adjacent shelf. Wheless and Valle-Levinson (1996) investigated intratidal variations of a plume in an idealized inlet-shelf domain. Several numerical simulations with bathymetries that resemble those of Chesapeake Bay have also been carried out. Spitz and Klinck (1998) simulated the tides in the Chesapeake Bay by assimilating data from tide gauges. Wang and Johnson (2000) developed a 3D hydrodynamic model for the Chesapeake Bay, in which the model was driven by realistic forcing from 1985 to 1994. Xu et al. (2002) demonstrated the improvements of model results by assimilating high-resolution salinity data. Recently, Li et al. (2005) applied Regional Ocean Modeling System (ROMS) to the Chesapeake Bay and examined the sensitivity of model results to turbulence mixing parameterizations. At present, several other 3D numerical models for this estuary are being developed (http://ccmp.chesapeake.org/CCMP/workshops.html).

In this study, a 3D numerical model is used to examine the effects of tidal currents on estuarine circulation in Chesapeake Bay. Because of important effects of bathymetry in the bay (Valle-Levinson et al., 2003), a fine grid size (~400 m) is implemented in the simulations. Fresh water discharge, tidal forcing, and ambient coastal current outside the bay are used to drive the model. By including and excluding tidal forcing and ambient coastal currents, their effects on the subtidal currents are examined inside and outside the bay.

After a description of the numerical model in Section 2, the model results for the four cases are shown in Section 3. Analysis of the dynamics of the plume outside the bay is given in Section 4 along with a comparison with other studies. Finally, a summary is given in Section 5.

2. Numerical model

One of the community ocean models, the Princeton Ocean Model (POM), is used as the basic model. The POM is a 3D primitive equation ocean model that includes full thermodynamics and a level 2.5 Mellor–Yamada turbulence closure model (Blumberg and Mellor, 1987; Mellor, 1998). The model domain and bathymetry are shown in Fig. 1. The horizontal resolution is 1/240° in both the zonal and meridional directions. In the vertical, 11 sigma-levels are evenly arranged. The minimum water depth in the model domain is set to 3 m. The time step is 3 s for the external mode and 120 s for the internal mode. During the calculations, the vertical eddy viscosity and diffusivity are given by the Mellor–Yamada turbulence closure model with a background value of $10^{-5}\,\mathrm{m}^2/\mathrm{s}$. The horizontal eddy viscosity is calculated by the embedded Smagorinsky formula with a proportionality parameter of 0.1, and the horizontal eddy diffusivity is obtained using an inverse Prandtl number of 0.5.

At the surface, no wind stresses are imposed. The bottom stresses (τ_x, τ_y) are calculated using a quadratic friction law:

$$(\tau_x, \tau_y) = \rho C_z(u, v)(u^2 + v^2), \tag{1}$$

where ρ is the water density, u and v are zonal and meridional components of velocity. The bottom drag coefficient is calculated by the embedded formula in POM (Mellor, 1998),

$$C_z = \max\left(0.0025, \frac{\kappa^2}{[\ln(0.05H/z_0)]^2}\right), \tag{2}$$

where $\kappa = 0.4$ is the von Karman constant, H the water depth, and z_0 the roughness parameter that is set to 0.1 cm.

The model is forced with river discharge, ambient coastal current and tides. The water temperature is set as a constant (= 15°) and only the salinity is solved. Instead of using the standard central difference scheme for tracer advection, we used the