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Water residence time in Chesapeake Bay for 1980–2012

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ABSTRACT

Concerns have grown over the increase of nutrients and pollutants discharged into the estuaries and coastal seas. The retention and export of these materials inside a system depends on the residence time (RT). A long-term simulation of time-varying RT of the Chesapeake Bay was conducted over the period from 1980 to 2012. The 33-year simulation results show that the mean RT of the entire Chesapeake Bay system ranges from 110 to 264 days, with an average value of 180 days. The RT was larger in the bottom layers than in the surface layers due to the persistent stratification and estuarine circulation. A clear seasonal cycle of RT was found, with a much smaller RT in winter than in summer, indicating materials discharged in winter would be quickly transported out of the estuary due to the winter-spring high flow. Large interannual variability of the RT was highly correlated with the variability of river discharge ($R^2 = 0.92$). The monthly variability of RT can be partially attributed to the variability of estuarine circulation. A strengthened estuarine circulation results in a larger bottom influx and thus reduces the RT. Wind exerts a significant impact on the RT. The upstream wind is more important in controlling the lateral pattern of RT in the mainstem.

1. Introduction

Concerns have grown over the increase of nutrients and other pollutants discharged into the estuaries and coastal seas (Nixon, 1995; Paerl et al., 2006; Smith et al., 1999). These substances have deleterious effects on aquatic organisms and human health through the food chain (Kennish, 1997). Due to the increase of anthropogenic nutrient input, many estuaries and coastal seas have become more eutrophic over the past few decades (Carpenter et al., 1998; Kemp et al., 2005; Murphy et al., 2011; Nixon, 1995). The ecological responses of a waterbody to increased nutrient loads have been widely linked to the flushing capability of the system (Boynton et al., 1995; Josefson and Rasmussen, 2000; Monbet, 1992). The available nutrient supply for algae growth and bloom is determined not only by the nutrient loads, but also by the retention of nutrients, which is related to the residence time (RT) of a system (Nixon et al., 1996). For example, coastal eutrophication has been built up in Koljo Fjords because of slow water exchange, even though there are no significant nutrient loads (Lindahl et al., 1998; Nordberg et al., 2001; Rosenberg, 1990). The export rate of nutrients proved to be strongly negatively related with the RT (Dettmann, 2001; Nixon et al., 1996). The RT is thus a key parameter in quantifying the impact of hydrodynamics on biochemical processes in an estuary (Boynton et al., 1995; Cerco and Cole, 1992). In addition, from a management perspective, it is essential to know the timescale for a pollutant discharged into a water body to exit the system. Therefore, it is of importance to study the flushing capacity and water exchange for an estuary.

To quantify the flushing capacity, several transport timescales have been used. Among them, flushing time, RT, and water age are the three fundamental concepts of transport time (Alber and Sheldon, 1999; Bolin and Rodhe, 1973; Hagy et al., 2000; Huang et al., 2010; Liu et al., 2004; Liu et al., 2008; Shen and Haas, 2004; Shen and Wang, 2007). Flushing time is regarded as a bulk or integrative property that describes the overall exchange or renewal capability of a waterbody (Dyer, 1973; Geyer et al., 2000; Officer, 1976; Oliveira and Baptista, 1997). The age of a water parcel is defined as the time elapsed since the parcel departed the region in which its age is defined to be zero (Deleersnijder et al., 2001; Takeoka, 1984; Zimmerman, 1976). The RT of a water parcel is defined as the time needed for the water parcel to reach the outlet (Zimmerman, 1976) and thus can be regarded as the remainder of the lifetime of a water parcel in a waterbody (Takeoka, 1984). Age and RT can be applied not only to steady-state cases, but also to time-varying cases (Deleersnijder et al., 2001; Delhez, 2005; Takeoka, 1984). Although flushing time can be used to estimate the overall flushing capability of a waterbody, the steady-state approach does not provide spatial and temporal variations in a large estuary, especially in a partially mixed estuary (e.g., Chesapeake Bay), where the transport could vary substantially in different regions and different vertical layers. The transport process for a substance in an estuary has large variability due to the time-varying estuarine dynamics. It is desirable to know the spatial pattern of the RT and its temporal variation, which can be applied to determine the impact of hydrodynamics on biogeochemical processes and be used for environmental assessment.

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The water RT of Chesapeake Bay, the largest estuary in the United States, was not well documented. The RT of the Bay's tributaries was calculated using box model or e-folder time (e.g., Hagy et al., 2000; Shen and Haas, 2004). Hagy et al. (2000) calculated the RT in Patuxent River, one main tributary of Chesapeake Bay, using a box model and found the control of residence time from the head to its mouth changed from primarily river flow to the intensity of gravitational circulation. The spatially averaged RT of 7.6 months in Chesapeake Bay was estimated in a numerical model using e-folder time (Nixon et al., 1996). The spatial pattern of transport time in the Bay's mainstem was initially investigated by Shen and Wang (2007) using the concept of freshwater age. They found that it requires 120–300 days for a marked change in the characteristics of the pollutant source discharged into the Bay from the Susquehanna River to affect significantly the conditions near the Bay mouth for selected wet and dry years. However, the spatial variation and long-term temporal variation of the RT still remained largely unknown.

Here we aim to investigate the spatial pattern and long-term temporal variability of the RT in Chesapeake Bay. A long-term numerical simulation of the RT from 1980 to 2012 in Chesapeake Bay was conducted for the first time using a robust algorithm developed by Delhez et al. (2004). The seasonality and interannual variability of RT will be examined. Finally, the main factors controlling the variation of RT will be discussed, including river discharge, estuarine circulation and wind.

2. Methods

2.1. RT calculation

The RT is often computed using a particle tracking method by injecting some particles at a fixed time, following the path of these particles, and registering the time when they leave the domain of interest (Gong et al., 2008; Monsen et al., 2002). Another method to calculate the RT is to use the remnant function approach proposed by Takeoka (1984), by integrating the model-calculated tracer concentration time series to give a mean RT (Wang et al., 2004; Wang and Yang, 2015). With both approaches, the RT depends on the release time and different values of RT will be obtained if particles or tracers are released at different times, such as high tide or low tide (Brye et al., 2012). In order to obtain a mean RT for a period, many releases are required with regard to the changing current condition (Monsen et al., 2002). They are not computationally efficient, and therefore it is difficult to evaluate the long-term temporal variation of RT. Delhez et al. (2004) proposes an adjoint method to compute the RT. The method provides variations of RT in space and time with a single model run. The method does not require any Lagrangian module. It is based on an Eulerian algorithm that makes it more appropriate for long-term and large-scale simulations than the straightforward Lagrangian approach (Delhez, 2005).

According to the approach of Delhez et al. (2004), the mean RT, denoted by θ as a function of time t and location x, can be computed using the adjoint equation expressed as,

$$\frac{\partial\overline{\theta(t,x)}}{\partial t} + \delta_\omega(x) + \nu \cdot \nabla\overline{\theta(t,x)} + \nabla \cdot \left[\kappa \cdot \nabla\overline{\theta(t,x)}\right] = 0 \tag{1}$$

where v is the velocity vector, κ is the symmetric diffusion tensor and

$$\delta_\omega(x) = \begin{cases} 1 & if \quad x \in \omega \\ 0 & if \quad x \notin \omega \end{cases} \tag{2}$$

where ω is the domain of interest. At the boundary of the domain of interest $\theta = 0$ is used, which ensures the residence time to vanish at the boundary for the first time the water parcel hits the boundary and the computed residence time is the same as the residence time computed using Lagrangian method (Delhez and Deleersnijder, 2006; Blaise et al., 2010). For stability reasons, the adjoint equation must be integrated backward in time with the reversed flow, i.e. velocity vector v changed to $-v$. The backward procedure is also necessary because one does not know in advance the fate of the particles (Delhez, 2005). In order to calculate the mean RT, two steps were required. In the first step, the hydrodynamic model was used to generate the velocity and turbulence fields, and the intermediate results were saved every half-hour. We ran a hydrodynamic model from 1979 to 2014 and obtained 35 years (1980–2014) of hydrodynamic fields. The first year of 1979 was used to spin-up the model and not used to calculate the RT. In the second step, Eq. 1 was integrated backward with the interpolated hydrodynamic field at each time step based on the hydrodynamic field saved in the first step, running from the end of 2014 to the beginning of 1980. The model experiments showed that it takes about 1.5 years for the RT to reach a stable value in Chesapeake Bay. Therefore, results of RT in the

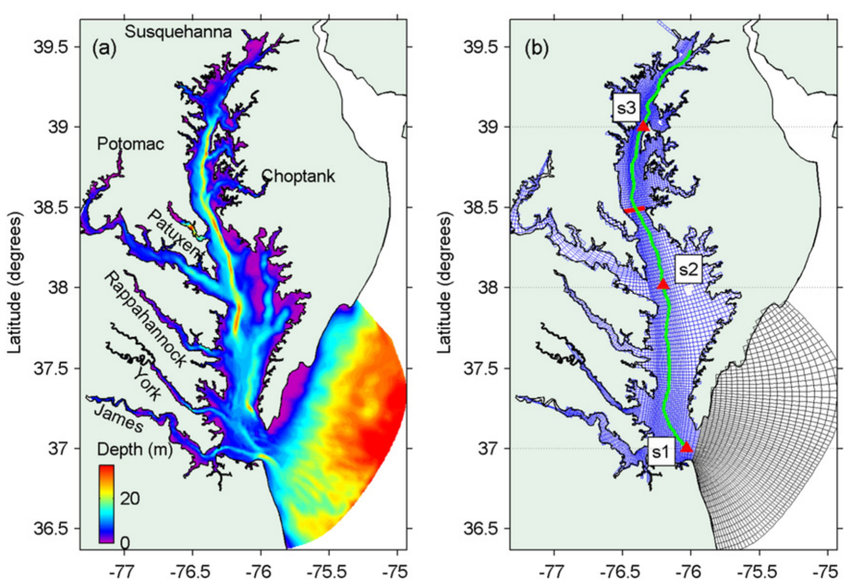

Fig. 1. (a) Bathymetry of the numerical model; (b) domain of interest (blue grid), the deep channel section (green line), middle Bay cross-section (red line), and Station s1, s2 and s3 (red triangle).