2016

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-varyingRT of the Chesapeake Bay was conducted over the period from 1980 to 2012. The 33-year simulation results show that themeanRT of the entire Chesapeake Bay systemranges 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 smallerRT 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 correlatedwith 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.

Key words: residence time, Chesapeake Bay, water exchange, estuarine circulation, wind, river discharge

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 bestrongly 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 timescaleshave 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 isregarded 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 RTof 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 transportcould 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.

The water RT of Chesapeake Bay, the largest estuary in the United States, was not welldocumented. 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 mainstemwas initially investigated by Shen and Wang (2007) using the concept of freshwater age. Theyfound 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 remainedlargely 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 Delhezet 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 timeseries 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. Delhezet 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 Delhezet al.(2004), the mean RT,denoted by θas a function of time *t* and location *x*, can be computed using the adjoint equation expressed as,

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

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

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

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 35years (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 RTto reach a stable value in Chesapeake Bay. Therefore, results of RT in the last two years (i.e., 2013 and 2014) were not used and only the RTvalues of 1980-2012were used for analysis.

In this study, we set the boundary of the domain of interest at the mouthof the Bay and computed the RT at any location *x*and time *t*inside the Bay. $\theta(t,x)=T$ denotesthat particles released at location*x* and time *t* will be transported to the mouth of the Bay for a period of*T*. In other words, RTis determined by the hydrodynamics after the release. Notes that the domain of interest in this study included the tributaries (Fig. 1b). As freshwater discharges into estuary at its headwater, which would lead to a non-zero RT value at the headwater due to the fact that water parcelsreleased at the headwater of tributaries will not return and hit theupstream boundary.

2.2 Simulation of the hydrodynamics

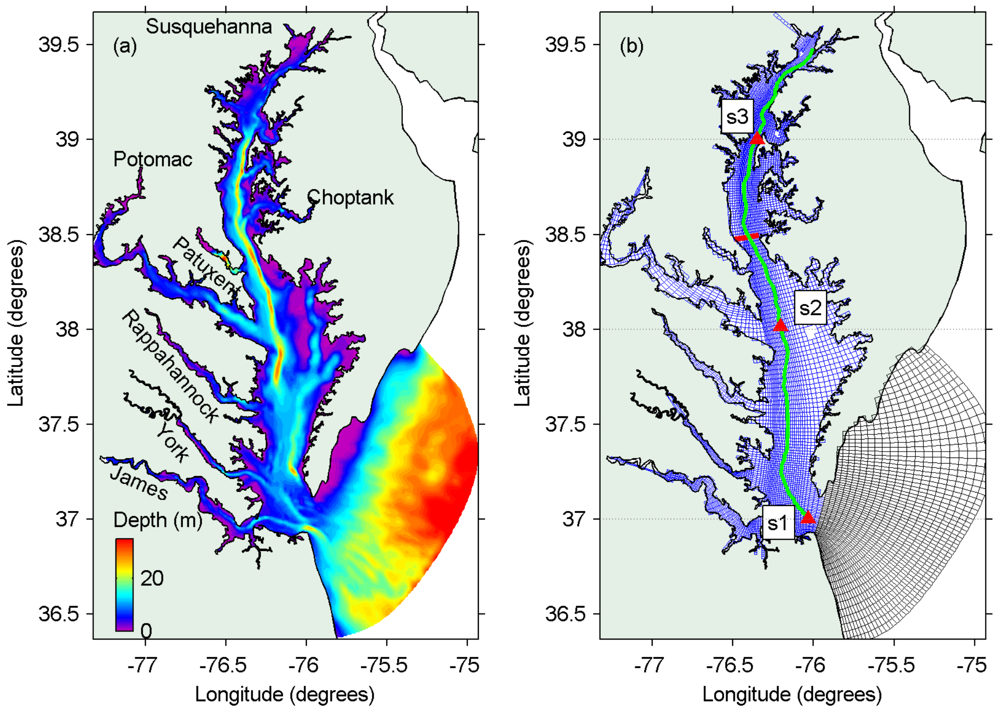


Fig. 1. (a) Bathymetry of the numerical model; (b) domain of interest (blue grid), the deep channel section (green line), middle Bay cross-section (red line), and Station s1, s2 and s3 (red triangle)

A numerical model based on the Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1992) was used to simulate the hydrodynamics. EFDC uses a boundary-fitted curvilinear grid in the horizontal and sigma grids in the vertical. The EFDC model used for the Chesapeake Bay was also referred to as the HEM-3D model (Hong and Shen, 2012, 2013; Du and Shen 2015). The same model was used for this study with the same model configuration and boundary condition.A grid with a horizontal dimension of 112×240 and 20 layers in the vertical was deployed (Fig. 1). The model was forced by interpolated observed tide at the open boundary (http://tidesandcurrents.noaa.gov), freshwater discharges of eight main tributaries (http://waterdata.usgs.gov/nwis/), and wind obtained from the North American Regional Reanalysis (NARR) produced at the National Center for Environmental Prediction (http://www.esrl.noaa.gov/psd/thredds/catalog/Datasets/NARR/pressure/catalog.html).This model has been calibrated for tidal and non-tidal surface elevation, current, and salinity for the Chesapeake Bay from 1999-2008 and it has simulated reliable stratification and destratification responses temporally and spatially in both wet and dry years (Hong and Shen, 2012, 2013).Details of model calibration can be found in Hong and Shen (2012). We ran the model from 1979 to 2014, and saved the half-hourly hydrodynamic results, which were then used to calculate the RT with theadjoint methoddescribed above.

3. Results

3.1 Mean RT of Chesapeake Bay

The mean RT of Chesapeake Bayaveraged over the period from1980 to 2012 is presented in Fig. 2. The spatially and vertically averaged RTvalue of the entire Chesapeake Bay systemfor 1980-2012 was180 days, shorter than 7.6-month reported in Nixon et al. (1996).It was larger than the flushing time estimated by calculating the ratio of freshwater volume to freshwater flow, which ranged from 90 to 140 days (Goodrich, 1988; Kemp et al., 2005; Shen and Wang, 2007). The difference was due to the fact that the flushing time estimationin previous studies was actually the mean renewal time of freshwater while the RT in this study includedrenewal of both the freshwater and saline water. Hong and Shen(2012) estimated the RTby releasing dye at the beginning of the model run and using the e-folder method to determine the RT for a typical mean flow year. Their results suggested that the mean RT in a mean flow year was about 175 days,which is consistent with our results.

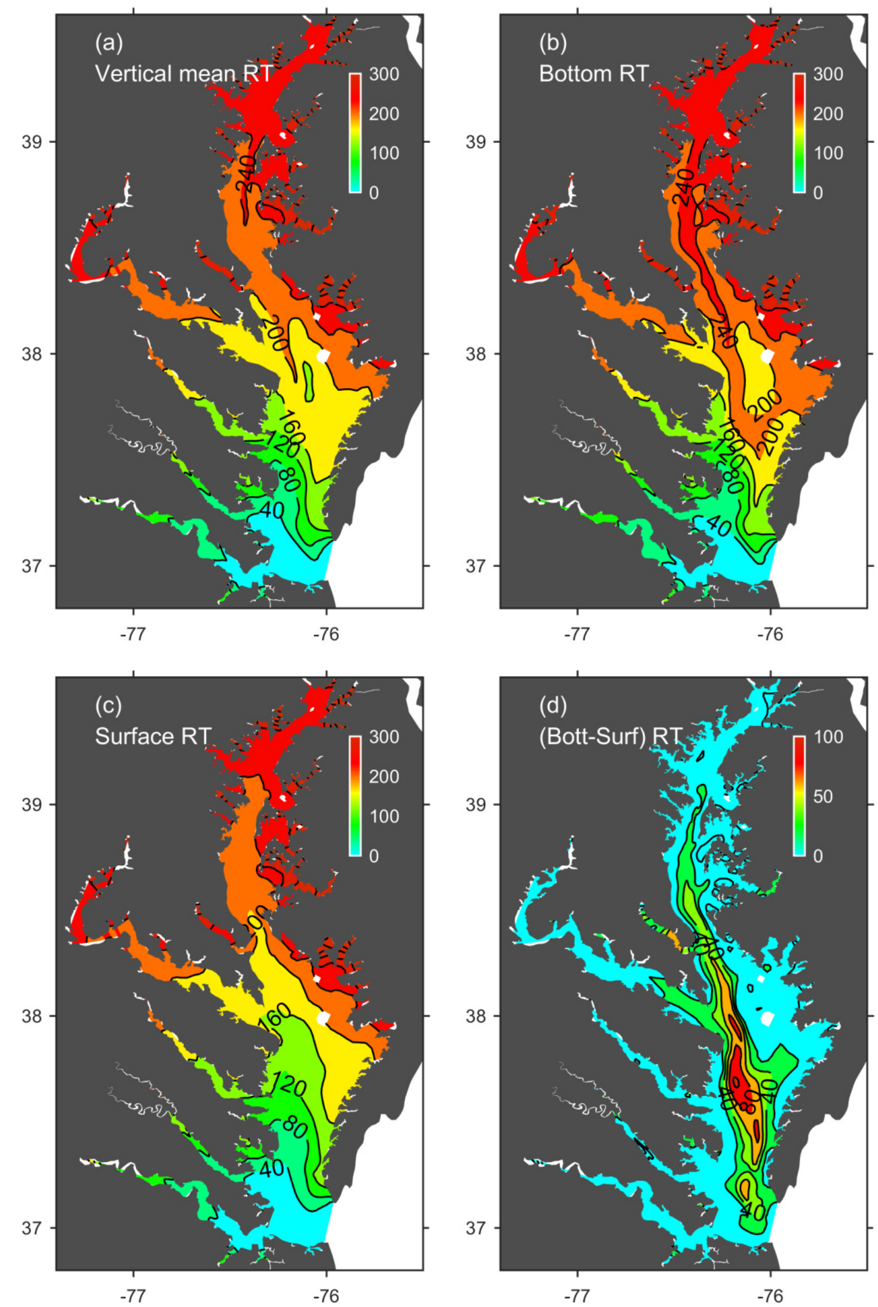


Fig. 2. Vertical mean (a), bottom (b), and surface (c) residence time (days) averaged over 1980-2012; (d) difference between the bottom and surface residence time, positive denoting larger residence time in bottom layers.

Considering the entire Chesapeake Bay as a box, the ratio of total water volume V tothe mean residence time T_R can be regarded as the total effective outflow of the system, Q_{out}. For a steady state condition, the total effective outflow should equal the total influx of "clean" water, which has two sources, river freshwater discharge R and influx of "clean" water from the outside of the Bay Q_{in}. Here the clean water from the outside of the Bay refers to the water that was not transported out of the Bay during the previous ebb tide.

$$Q_{out} = V/T_R = Q_{in} + R \quad (3)$$

Based on the simulation of the past 3 decades, the mean Q_{out} is about 4800 m^3/s, given the volume of the entire Chesapeake Bay system V of $7.5\times10^{10} m^3$ and T_R of 180 days.The total mean freshwater discharge from all the rivers R was about 2200 m^3/s. Therefore, Q_{in} is about 2800 m^3/s, which is of the same order of magnitude as the influx at the Bay mouth measured by Wong and Valle-Levinson (2002).This estimation suggests that the influx of coastal ocean water is as equally important as the freshwater discharge on the water renewal in Chesapeake Bay.

There was a clear longitudinal pattern of the RT. The vertical mean RT ranges from0 to 200 days in the lower Bay (37-38N), 200-240 days in the middle Bay (38-39N), and 240-280 days in the upper Bay(39-39.6N) (Fig. 2a). The gradient of RT was larger in the lower Bay than that in the middle-upper Bay. It took about 200 days to transport a water parcel from the Potomac River mouth (~38N) to the Bay mouth (~37N), while it took only 260 days to transport a parcel from the head of the Bay (~39.5N) to the Bay mouth.

The lateral distribution of vertical mean RT was different in different regions. The lateralasymmetry of the vertical mean RT in the lowerBay was significant, with a much largerRT in the eastern bank than that in the western bank (Fig. 2a). The difference could be as large as 80days. The lateral asymmetries could be attributed to several factors, such as lateral shearing of the gravitational circulation (Valle-Levinson et al., 2003), the largefreshwater dischargefrom the western tributaries(e.g., Potomac River, York River, and James River), and the strengthened ebb flow along the western boundary due to Coriolis force. The lateral pattern was similar in both surface and bottom layers in the lower Bay. In the middle to upper Bay, the vertical mean RT waslarger in the deep area than in the shallow region, which was caused by a larger bottom RT in the deep channel due to the typical gravitational circulation with flow in the deep channel directed to the upstream.

The vertical patternof the RT can be examined by averaging the RT for the surface and the bottom, respectively (Figs. 2b, 2c). The surface RT is the RT averaged over the 5 layers near the surface, and the bottom RT is the RT averaged over the 5 layers near the bottom. The bottom and surface RT, and their difference were presented in Figs. 2b-d, and the vertical profile along the deep channel section was shown in Fig. 3. The gradient of RT was much larger in the bottom layers than in the surface layers, especially in the deep channel section (Figs. 2, 3). The mean bottom RT of the Bay's mainstemwas about 184 days and the mean surface RT was about 145 days. There were minor vertical differencesin the upper Bay and shallow banks, where the water was well-mixed and the vertical difference was less than 10 days (Fig. 2d). Vertical differenceswere significant in the lower to middle Bay, especially in the deep channel where differenceshad a range of 20-100 days. The maximum vertical difference was foundin the deep channel outside of the Rappahannock River mouth (~37.75N).

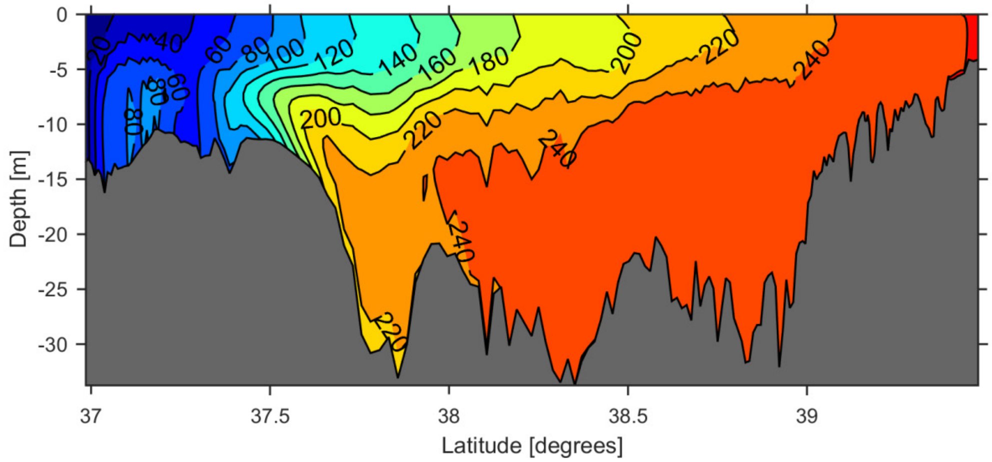


Fig. 3. Vertical profile of residence time (days) along the deep channel section.

3.2 Seasonal cycle of RT

The vertical mean RTof the entire Bayexhibited a clear seasonal cycle, with its largest value in summer (Jun.-Aug.) and smallest value in Nov.-Jan. This seasonal cycle suggested that winter has a short retention time for soluble materials. In contrast, material released in the summer usually has the longest retention time in the Bay. The minimum RT during the winter was mainly due to large freshwater discharge during ensuing months (e.g. Mar. and Apr.), which caused a large downstream residual current during this high-flow period (Fig. 4b-c). TakingSusquehanna River as an example, the river discharge usually peaked in March and troughed in August, which was consistent with the downstream residual current averaged over the Bay's mainstem.

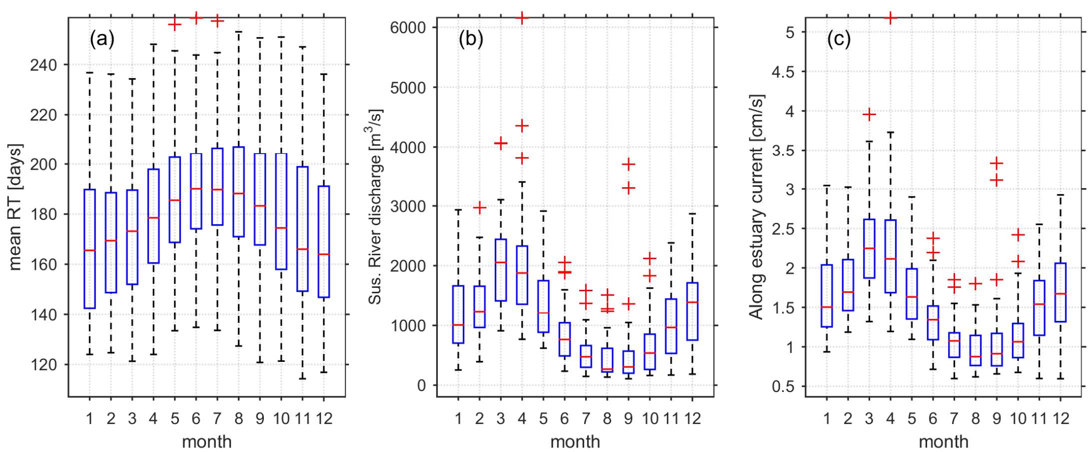


Fig. 4. (a) Seasonal cycle of residence time averaged over the entire Bay; (b) seasonal cycle of Susquehanna River flow; (c) seasonal cycle of vertically mean residual along estuary currentaveraged over the Bay's mainstem. Red lines denote medians of the 33 years of record from 1980 to 2012, blue rectangles denote the first and third quartiles, dashed lines denote the upper and lower whiskers, and red crosses denote the outliers.

RT values during January and Julywereselected to represent the seasonal minimumand maximum RT (Fig. 5a-b). In the middle to upper Bay,a small area had RTvalues larger than 240 days in January (Fig. 5a), while the major area had RT values exceeding 240 days and some areas hadRT even exceeding 280 daysin July (Fig. 5b). The difference between July and JanuaryRT could be larger than 50 days in the upper Bay, 20-40 days in the middle Bay, and 0-40 days in the lower Bay (Fig. 5c). The seasonaldifferencewas highly asymmetrical between the eastern and western banks in the lower Bay (Fig. 5c). The seasonal differencealongthe western bank ofthe lower Bay was usually less than 10 days, but it could be as large as 40 days alongthe eastern bank. A similar pattern of seasonal difference was found for both bottom and surface layers (not shown). Little seasonal difference of the RT in the western bank of the lower Bay was related to the dominating role of frequent tidal exchange in this area. The tidal current (0-100 cm/s) had a much larger magnitude than the residual current (1-2.5cm/s, Fig. 4c) induced by the river discharge.The dominating ebb current and large influence of the tide caused the persistently small RT and little seasonal difference along the western bank near the Bay mouth.The tidal effect decreased in the middle and upper Bay, where the river discharge became more influential on the variation of RT.

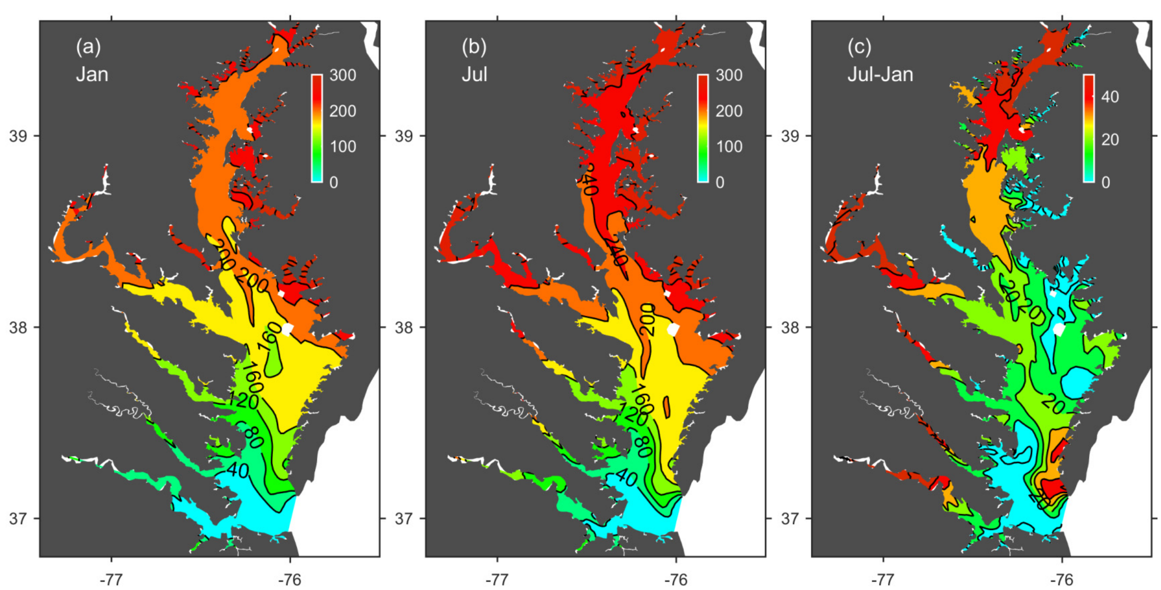


Fig. 5. Vertical mean residence time (days) averaged over 1980-2012 in January (a) and July (b); (c) difference between July and January vertical mean residence time, positive value denoting larger residence time in July.

3.3Interannual variation of RT

There was high interannual variability of the RT. The vertical mean RT of the entire Bay had a standard deviation of 30 days over the period of 1980-2012. The maximum and minimumof the vertical mean RT averaged over the entire Baywere264days and 110days, respectively (Fig. 6). No significant trend of the RT was found during the past 3 decades.There were several particularly high RT years with a yearly mean RT larger than 200 days, e.g., 1980, 1987, 1988, 1991, 1998, 1999, 2000 and 2001 (Fig. 6). The maximum RT occurred in 2001, and the minimum RT occurred in 2003-2004.

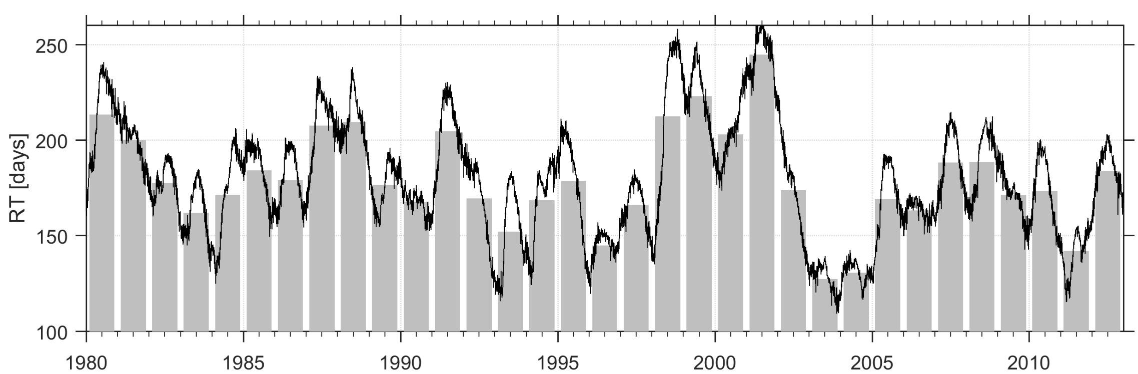


Fig. 6. Time series of vertical mean residence time averaged over the entire Bay for 1980-2012; bar plot indicates the yearly mean.

Sincethe RT highly depends on sub-tidal transport processes, the status of the stratification, and the residual current field, we hypothesized that part of the RT variation was related tothe pre-existing condition. Regressions between the RT of a given season and the RT of the following season were conducted. The regressions demonstrated that the interannualvariation of the previous season accounted for a large portion of interannualvariation of the RT in the following season (Fig. 7). However, the impact of the pre-existing condition varied from season to season. A stronger effect of the pre-existing condition occurred in the fall and winter with an R^2value larger than 0.82, followed by summer with an R^2value of 0.72. The effect of the pre-existing condition was relativelyweaker in the spring, as the winter RT variation accounted for only 68% of spring RT variation. The weaker effect of the pre-existing condition in the spring could be attributed to the high variability of the spring river discharge.

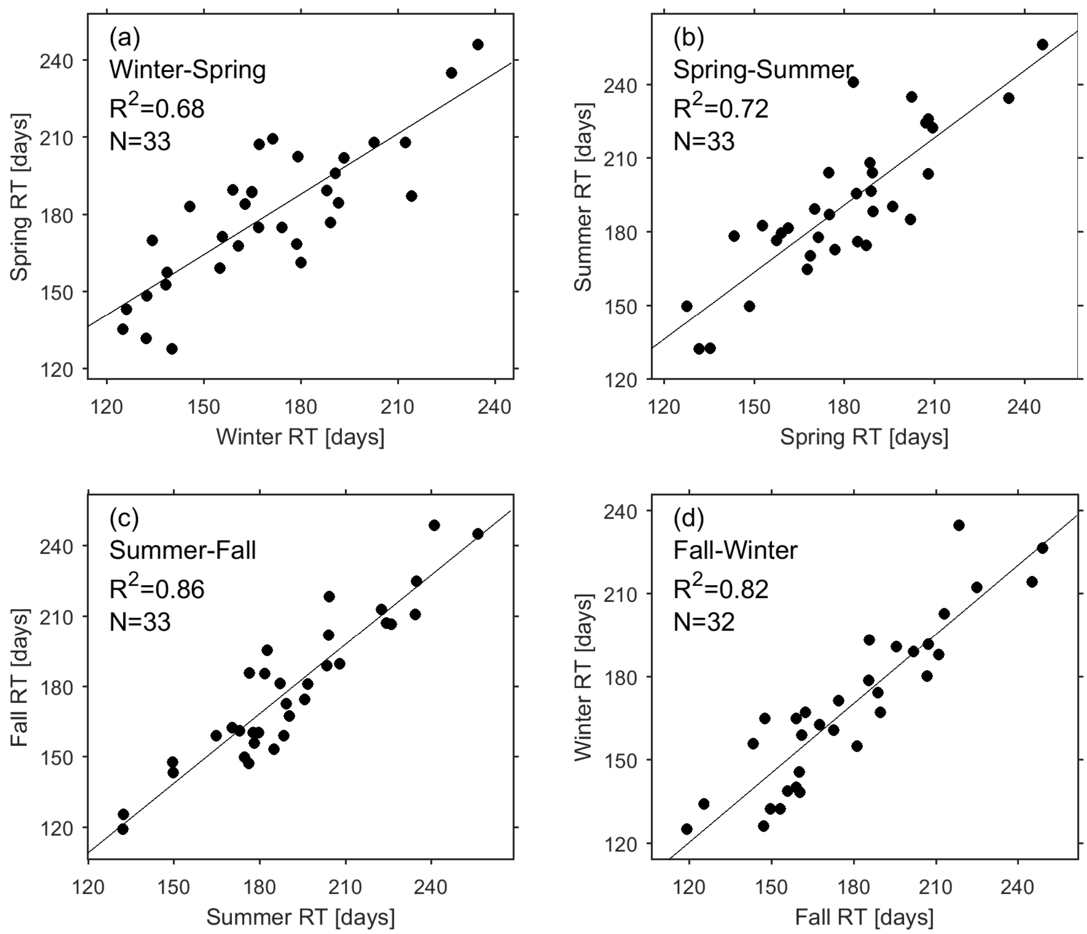


Fig. 7. Regression of the residence time between winter and spring (a), spring and summer (b), summer and fall (c), fall and winter (d). The linear regression coefficient is shown in text.Spring (Mar.-May), summer (Jun.-Aug.), fall (Sep.-Nov.), and winter (Dec.-Feb.).

4. Discussion

4.1 Relationship between RT and river flow

Even though the variation of RT isgenerally believed to behighly controlledby theriverdischarge (Hagy et al., 2000; Shen and Haas, 2004), it is of interest to examine the relative importance of river discharge on the RT over different timescales (e.g. monthly, yearly), and to examine the mean delay between RT and river discharge.We chose the river discharge of Susquehanna River to represent the total river discharge, since the discharge of Susquehanna River accounts for 51% of the total discharge and river discharges from other rivers are usually proportional to it (Guo and Valle-Levinson, 2007). The Susquehanna River daily discharge time series was extracted from the USGS website (http://waterdata.usgs.gov/nwis).The linear regression between the yearly mean RT and the inverse of the yearly mean river flow (without smoothing)has a correlation coefficient R^2 of 0.67 (Fig. 8).

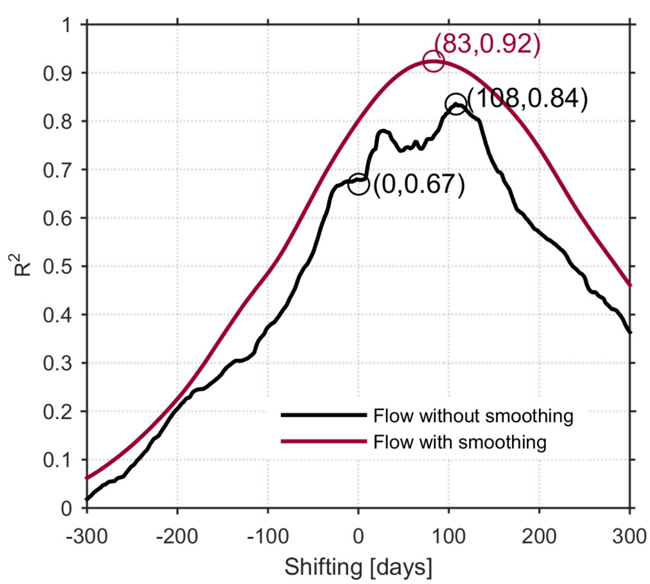


Fig.8. Linear regression coefficient R^2 between the interannualvariation of vertical mean residence time averaged over the entire Bay and the interannual variation of shifted Susquehanna River flow, x-axis denoting the shifting days of flow.

To estimate the delay between river flow and RT, a series of regressions between the yearly mean RT and the inverse of yearly mean flow of the Susquehanna Riverwere conducted, in which the flow (smoothed or unsmoothed) was shifted by different numbers of days. A moving average of 360 days was applied to the flow in order to remove the seasonal frequency.The result showed that the best relation was found when the flow wassmoothed and shifted by83 days, with an R^2value of 0.92 (Fig. 8). Without smoothing, the largest R^2value was 0.84 when the flow was shifted by 108 days (Fig. 8). It should be noted that a shift of 83 days meant that the RT of a given time was determined by the flow condition afterthat given time, instead of prior. For instance, the yearly mean RT for 1980 (t=0-365 days) is determined by the yearly mean river discharge of 83-448 days.

The best relation between yearly mean RT (days) averaged over the entire Bay and the inverse of yearly mean flow (m^3/s) was shown in Eq. 4, where the flow wasmoving averagedby 360 days and shifted by 83 days(Fig. 9a).

$$RT = 118{,}813 / flow + 69.3, R^2 = 0.92, N = 33 \quad (4)$$

This significant relationship suggests that, when itwas averaged yearly, the RT is mainly controlled by river discharge and other factors (e.g. wind, tide) have little impact. However, for a shorter period, the river discharge accounts for a much less percentage of the variation of the RT. Even by shifting the flow by 83 days and applying a moving average of 360 days, the river discharge accounts for 78% of the monthly mean RT variation (Fig. 9b). Without smoothing of the river flow,there is no significant relation between the monthly RT and the monthly flow, withthe largest R^2ofonly 0.22. This can be understood as the variation of RT was between 110-264 days, and the RT depends on the accumulative effect of river flow and other factors (e.g., tide, wind, and the pre-existing condition)for a period of more than 110 days. A short-term pulse of river flow does not necessarily result in a significant change of RT, as the impact of the pulse can be confounded by varied flow conditions in the following days. Even though there were usually multiple pulses of high flow in each year, including short-term pulses (e.g., during storm periods in the summer), there was usually only one peak and one trough of RT in each year (Fig. 6).

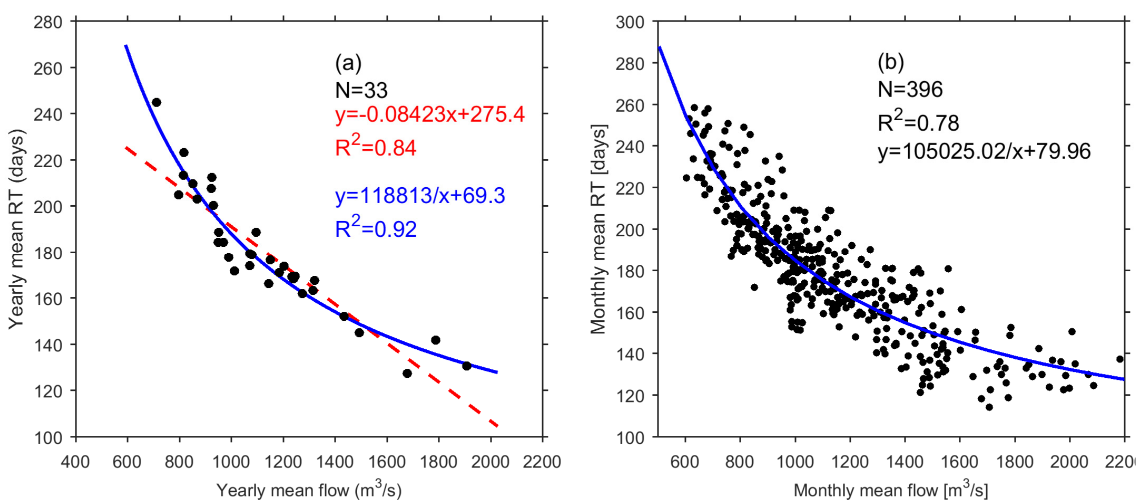


Fig. 9.(a) Regression between interannual variation of yearly mean residence time averaged over the entire Bay and interannual variation of yearly mean Susquehanna River flow shifted by 83 days and moving averaged by 360 days; two kinds of regression were applied and the correlation coefficient is shown in text, where the red dashed line denotes the linear regression between RT and flow, and the blue solid line denotes the linear regression between RT and 1/flow; (b) regression between monthly mean residence time

averaged over the entire Bay and monthly mean flow shifted by 83 days and moving averaged by 360 days.

Based on the significant flow-RT relationship (Eq. 4), a long-term estimation of yearly mean RT back to 1891was conducted and shown in Fig. 10.The 360-day moving average and the 83-day shifting of the flow were applied. Susquehanna River flow datawerethoseobservationscollected at USGS Station 01578310, which had daily discharge data since 1967. The missing discharge data of 1891-1967 were estimated with the data fromanother nearby Station USGS 01570500, located upstream of Station USGS 01578310. Daily discharge values measured at these two stations were highly linearly correlated (R^2=0.997, from a 10-year linear regression). The estimation showed that RT of the past centuryhad a high variability. It seems the interannual variability became larger after the 1970s. The maximum RT occurred in 1930 (RT=248 days) and the minimum RT occurred in 2004 (RT=132 days). No significant trend could be found for the past century.

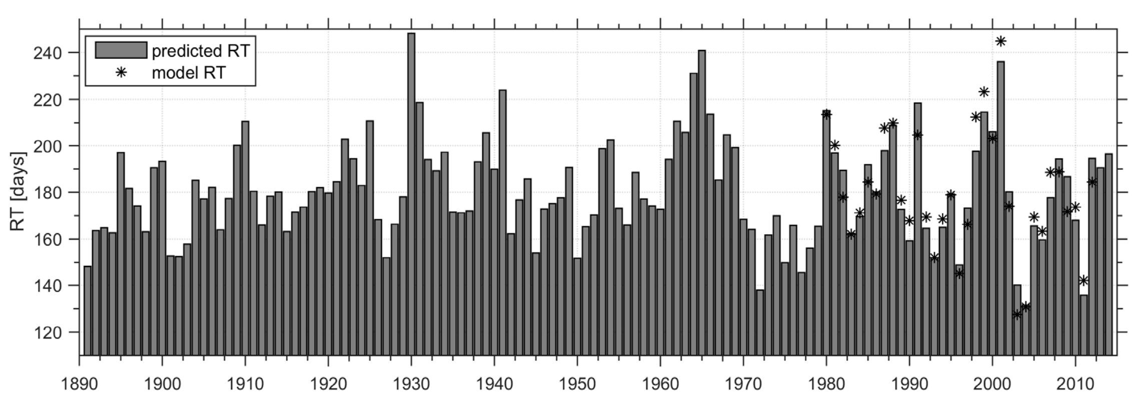


Fig. 10. Estimated mean residence time of the entire Bay since 1891; annual mean residence time from model simulation is shown as a black asterisk.

4.2 Impact of estuarine circulation on RT

Despite the high correlation between the yearly mean RT and yearly mean flow, a large part of the monthly RT variation remained to be explained. Besides the river discharge, tidal exchange and estuarine circulation are two main processes that contribute to the water exchange between an estuary and coastal waters. The relative importance of tidal exchange and estuarine circulation differs in different systems (Hansen and Rattray, 1965; Officer and Kester, 1991). Tide has proven to be important to affect water transport through tidal pumping (Chen et al., 2012) and thus change the pattern of the RT, especially for a small estuary where RT is relatively small (Brye et al., 2012;Andutta et al., 2016). In the Chesapeake Bay, tide contributes to the vertical mixing and the formation of asymmetry of west-east RT distribution and to the gravitational circulation that leads to the huge difference between surface and bottom RT.Consistent with the findings ofBrye et al. (2012), RT varied more significantly over a tidal cycle than over a spring-neap cycle, especially in the area near the mouth boundary (Fig. 11). The semi-diurnal tidal component of the RT weakens toward the upstream. No significant signal of the spring-neap cycle in the RT time-series at selected stations was found.As the residence time of the Bay is on the order of 100 days, the semi-diurnal tidal signal becomes insignificant towards the upstream.

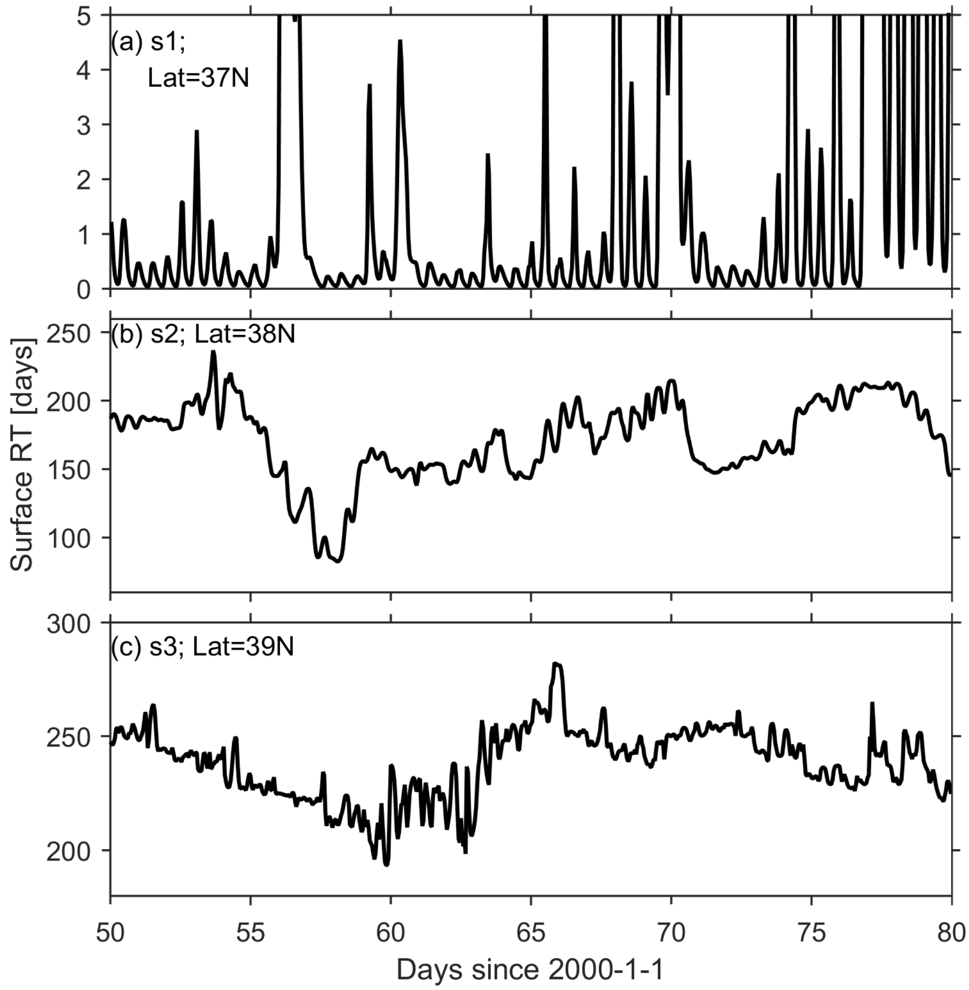


Fig. 11. Time-series of hourly mean surface residence time at 3 selected stations (i.e. s1, s2, s3), whose locationsareshown in Fig. 1b.

The other important process that may havea significant impact on the RT is the estuarine circulation. Hagy et al. (2000) demonstrated the saline influx at the mouth of a partially mixed estuary is important to the water renewal, especially in the area near the mouth. To quantify the variability of estuarine circulation, we calculated the influx for each month at a mid-Bay cross-section (location shown in Fig. 1b with red line) to indicate the strength of the circulation. In order to remove the impact of river discharge on monthly mean RT, the residual value from the monthly RT-flow regression (Fig. 9b) was used to compare with the monthly influx at the mid-Bay cross-section. Similar to the regression between river flow and RT, a delay of 83 days was also considered when conducting the regression between the residual and influx.

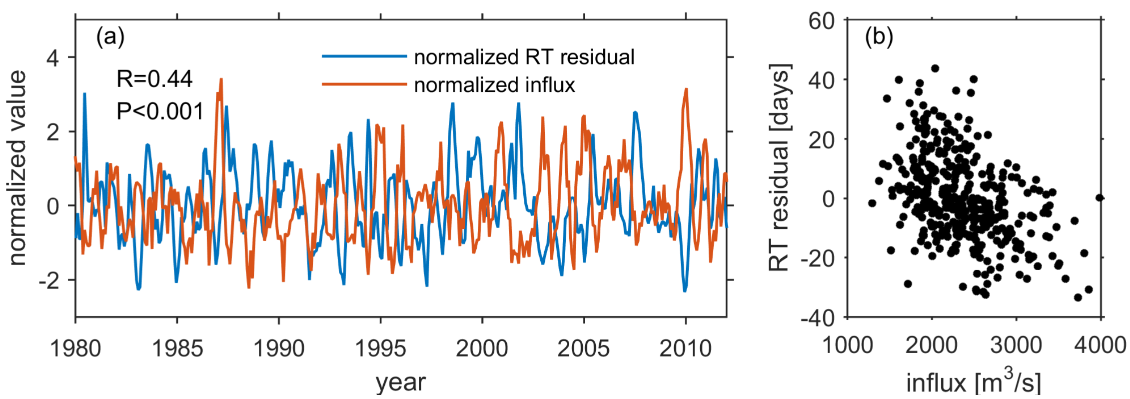
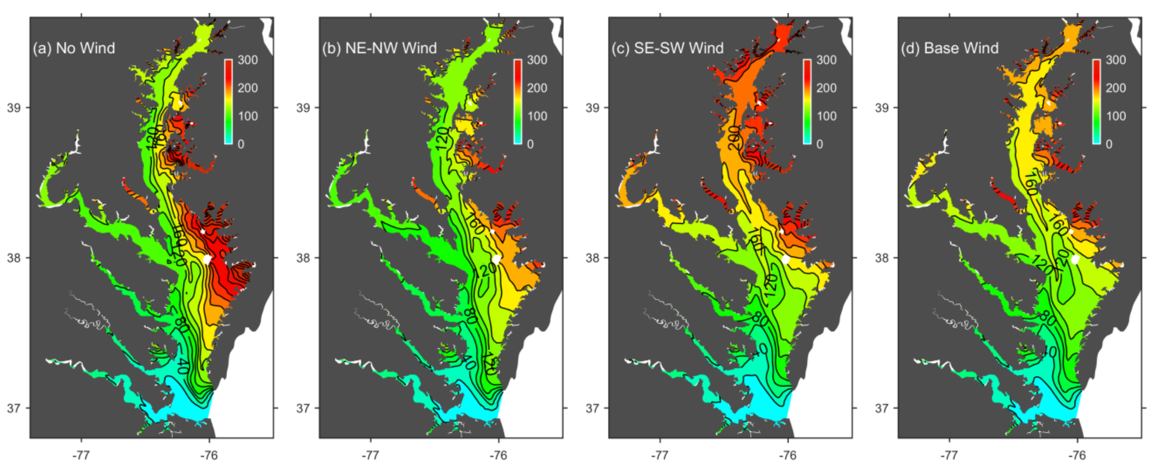


Fig. 12.(a) Time-series of normalized influx at the middle Bay cross section (red line) and normalized residual value from the monthlyRT-Flow regression (blue line). Both time series were normalized by removing the mean and dividingby the standard deviation. A positive value 1.0 of normalized influx denotes the influx is larger than the mean influx by 1.0 standard deviation.(b) Scatter plot of the influx andresidual value from the monthly RT-Flow regression.

The regression between the residual and influx showed that the residual was highly negatively correlated with the influx, with $p<0.001$ (Fig. 12). Even though the R^2 is not high, troughs of the residual RT often coincide with peaks of influx. A larger influx will enhance the outflow and lead to a faster water exchange near the mouth and thus smaller RT. This significant relation also suggests that thosefactors (e.g., wind, tide, river discharge) affecting the estuarine circulation could also have potential impact on the RT, especially on the short-term averaged RT.

4.3Impact of wind

The influence of wind on estuarine circulation has been recognized for many years (Geyer, 1997; Guo and Valle-Levinson, 2008;Scully, 2010; Li and Li, 2011, 2012; Officer, 1976; Scully, 2010; Wang, 1979). To examine the influence of wind on RT, several numerical experiments were conducted (i.e., without wind, with NE-NW wind, with SE-SW wind, base case with all directions of wind). For these simulations, model runs were from 2002 to 2005 and the model configuration was unchanged except the wind forcing. For example, inthe NE-NW wind case, wind was set to be zero when there is the SE or SW wind.The RT value of year 2003 was analyzed and compared.



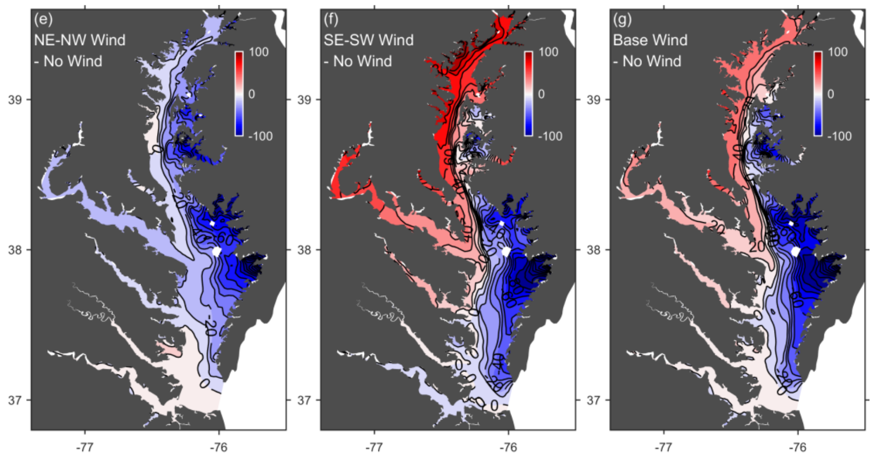


Fig. 13. (a-d) Yearly and vertically averaged RT of 2003 under different wind forcing conditions. (e-f) The impact of wind forcing on the RT, indicated by the differences between model simulations with and without wind forcings.

The comparison between differentcases suggests that wind can have a significant impact on the lateral pattern of RT. With the NE-NW wind forcing, the RT distribution is very similar to the RT distribution without wind forcing, both with large lateral asymmetry between the eastern and western region in the mainstem (Fig.13a-b). The lateral asymmetry is most significant near the mouth of Potomac River (~38N). Southerly wind, however, generates a similar lateral pattern as under base wind condition, in which the asymmetry is highly weakened (Fig.13c-d).

The difference between the no-wind case and the other casesreveals that northerly wind and southerly windshave different impacts in different regions and their impacts are not simply opposite to each other. Both southerly and northerly winds are likely to reduce the RT in the eastern region of the lower-middle Bay (Fig. 13e-f). Southerly wind increase the RT in the middle-upper Bay significantly by up to 100 days (Fig. 13f), while the northerly wind has little impact (<20 days) in the western region of the middle-upper Bay (Fig.13e). It appears that the southerly wind plays a more dominant role in controlling the long-term transport, which is consistent with findings for the impact of wind on freshwater age (Shen and Wang, 2007). The southerly wind causes strong lateral and vertical mixing, reduces the gravitational circulation, and thereby increases the transport time. The influx at the mid-Bay cross-section, indicating the strength of gravitational circulation, was strongly reduced by the SE-SW wind and enhanced by the NE-NW wind (Fig. 14). Compared to NE-NW wind, the influx was reduced by half with SE-SW wind.

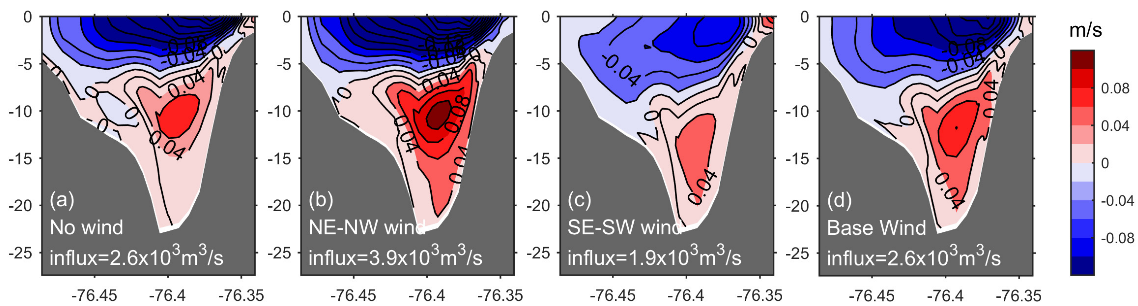


Fig. 14. Along channel residual current at the middle Bay cross section under different wind forcing conditions, with contour level of 0.02 m/s (black lines). Positive value denotes an influx to the upstream. Values of laterally and vertically integrated influx are shown in the text at the bottom.

5. Conclusion

In this study we investigate the water exchange between the Chesapeake Bay and its adjacent coastal sea, using the timescale residence time (RT) thatcan often be used to evaluate the impacts of hydrodynamic conditions on biological and geochemical processes. The long-term simulation of water RT of the Chesapeake Bay was conducted over the period from 1980 to 2012, using an adjoint method, which enables us to compute the time-varying RT in a single model run. The impacts of river discharge, intensity of estuarine circulation, and wind on the RT were discussed. The main conclusions are summarized as follows. (1) The vertically mean RT averaged over the entire Chesapeake Bay system ranges from 110 to 264 days, with a mean of 180 days and a standard deviation of 30 days over the past 3 decades.No clear trend was detected during the past three decades. The bottom RT was larger than that of the surface due to the gravitational circulation, and thevertical differencescould be as large as 100 days. (2) There was a clear seasonal cycle of RT, with high RT occurringin the summer and low RT occurringin the winter, suggesting materials released in winter would be flushed out most quickly. (3) Interannual variability of the RT was significant and was highly correlated with the variability of river discharge. The correlation coefficient between yearly mean RT and yearly mean river dischargecan be as high as0.92, if the river discharge was shifted by 83 days and a moving average of 360 days was applied.(4) 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. (5) Wind exerts a significant impact on the lateral pattern of RT. The upstream wind is more important in controlling the lateral pattern of RT in the mainstem than the downstream wind.

Acknowledgements

We thank Mac Sisson for his assistance in editing the manuscript. We thank Mark Brush, Carl Hershner, Kyeong Park, and Harry Wang for their suggestions. We are grateful to Ya Wang, Qubin Qin and Xin Yu for their assistance in coding of the model and helpful comments. This work is supported by the National Science Foundation (Award #1325518). Additional support is provided by Virginia Institute of Marine Science. This is contribution No. xxxxx of the Virginia Institute of Marine Science, School of Marine Science, College of William and Mary, Virginia.

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