# The age of Yellow River water in the Bohai Sea

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[1] To quantitatively understand the transport timescales of dissolved material discharged from large rivers into a semienclosed sea, the age of Yellow River water in the Bohai Sea was calculated with the constituent-oriented age and residence time theory (CART) and particle-tracking method. Yellow River water has a mean age of 3.0 years for the entire Bohai Sea. The spatial variation of the water age is significant: 1.2 years near the Yellow River estuary but 3.9 years in the Liaodong Bay. However, the temporal variation in water age is insignificant. The water particles released at the river mouth need only several days to reach the estuary area. The great water age (1.2 years) near the Yellow River estuary is caused by the presence of old water particles that initially left this area but returned to this area again. Without the reentry of Yellow River water from the Yellow Sea to the Bohai Sea, the mean age of Yellow River water in the entire Bohai Sea decreases to 1.2 years. Calculations without tidal forcing give a reduction in water age by more than 50%, suggesting that tidal forcing plays the most dominant role in controlling the age of Yellow River water in the Bohai Sea. Calculations without winds give an increase in water age by 20–30%, suggesting that wind forcing is secondary factor to the age of Yellow River water. Changes in discharge of the Yellow River and in thermal stratification have limited influence on the age of Yellow River water.

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## 1. Introduction

[2] Advection and diffusion are two important processes controlling material transport in coastal water. Because of the complex spatiotemporal structure of these processes, it is helpful to define auxiliary variables, such as water exchange timescale and water age, to quantify their environmental function in coastal water [*Zimmerman*, 1976; *Takeoka*, 1984; *Deleersnijder et al.*, 2001; *Monsen et al.*, 2002; *Delhez et al.*, 2004].

[3] Water age is defined as the time elapsed since the departure of a water parcel from an area, where its age is prescribed to be 0, to its arrival at a water body of interest [*Bolin and Rodhe*, 1973; *Takeoka*, 1984]. Transit time is the age of a water parcel at the outlet of a water body [*Bolin and Rodhe*, 1973]. Transit time may be considered as a special case of water age.

[4] Previous studies [*Meier*, 2007; *Shen and Wang*, 2007; *Gong et al.*, 2009; *Zhang et al.*, 2010a] on water age have typically used the concept of mean water age, which is defined as the mass-weighted arithmetic average of the ages of all of the water parcels within a target domain. In principle, diffusion results in the complexity of water age structure. Without diffusion, the water particles inside a parcel are isolated from the outside environment and therefore have the same age. However, diffusion induces the exchange of particles inside and outside of the water parcel and consequently results in the coexistence of water particles with different ages in a water parcel. In practice, the size of the grid points in a numerical model cannot be infinitely small, and commonly, water parcels of different ages are found at one grid point together. In this study, we also used the concept of mean water age. Additionally, to better understand water age distribution, we also present a water age frequency/spectrum for a target domain.

[5] Water age can be studied by field observations, theoretical analysis, and numerical simulation. Observational techniques, including the isotope-tracer decaying method and the lag time method, are widely used to measure mean water age [e.g., *Adkins and Boyle*, 1997; *Peeters et al.*, 2000; *Hansell et al.*, 2004; *Kershaw et al.*, 2004; *Anderson et al.*, 2010]. However, these methods may underestimate the true mean water age if diffusion is considered [*Deleersnijder et al.*, 2001; *Delhez et al.*, 2003; *Delhez and Deleersnijder*, 2008]. Theoretical analysis is helpful for understanding mean water age [e.g., *Wunsch*, 2002] because instructive analytical solutions may be obtained. However, theoretical analysis is typically not sufficiently powerful when realistic topography or nonlinear terms are considered. Compared to

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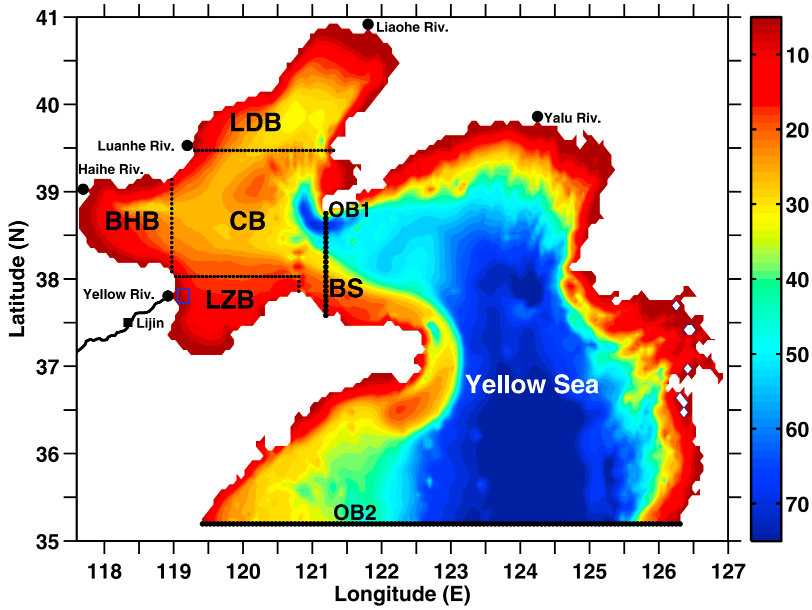


**Figure 1.** Bathymetry of the Bohai Sea and the Yellow Sea (unit: meter). The Bohai Sea is divided into 5 subregions: Laizhou Bay (LZB), Bohai Bay (BHB), Liaodong Bay (LDB), the central basin (CB), and Bohai Strait (BS). The black dots represent the locations of the river mouths of the Yellow River, Haihe River, Luanhe River, Liaohe River, and Yalu River. The black squares represent the location of Lijin Station, where the Yellow River discharge is recorded. The Yellow River estuary (3 × 3 grids) is defined as the area surrounded by the blue line close to the Yellow River mouth. The black lines labeled with OB1 and OB2 are two open boundaries.

the aforementioned methods, numerical simulation includes advection and diffusion processes in addition to realistic topography and forcing conditions [*Chen*, 2007; *Liu et al.*, 2008; *Gong et al.*, 2009; *Hong et al.*, 2010; *Liu et al.*, 2011; *de Brye et al.*, 2012].

[6] There are two widely used numerical methods for calculating mean water age. One method is the particle-tracking method (PTM) [*Chen*, 2007; *Liu et al.*, 2011], and the other method is the constituent-oriented age and residence time theory (CART, see www.climate.be/cart) [*Deleersnijder et al.*, 2001; *Gong et al.*, 2009; *de Brye et al.*, 2012]. These two methods are essentially equivalent, although their simulation results are not identical in practice. PTM is a Lagrangian method and has the advantage of obtaining a spectrum of water age and the pathway of water parcels. However, the computational cost of PTM is high because a large amount of particles must be released to simulate the random walk due to diffusion. CART is a Eulerian method and has the advantage of directly calculating mean water age without needing to know the spectrum of water age in advance, although it is possible to use CART to obtain a spectrum of water age [*Delhez and Deleersnijder*, 2002; *Zhang et al.*, 2010a; *Cornaton*, 2012]. However, the CART method cannot provide information on the pathway of target water mass.

[7] The Yellow River is the largest river that feeds into the Bohai Sea (Figure 1). The river brings freshwater, sediment [*Fan and Huang*, 2008], nutrients [*Yang et al.*, 2009], and persistent organic pollutants (POPs) [*Sha et al.*, 2006] into the sea. The Bohai Sea has an average depth of 18 m and is usually divided into 5 subregions, namely Laizhou Bay, Bohai Bay, Liaodong Bay, the central basin, and the Bohai Strait (Figure 1). Many studies have investigated the water exchange between the Bohai Sea and the Yellow Sea through the Bohai Strait [e.g., *Lin et al.*, 2002; *Wei et al.*, 2003; *Zhang et al.*, 2010b]. The half-life time, which is defined as the necessary time for the concentration of passive matter reducing to 50% of its initial value [*Luff and Pohlmann*, 1996], was used as an index to evaluate the water exchange capacity of the Bohai Sea [*Wei et al.*, 2002]. However, no study has considered the age of Yellow River water in the Bohai Sea.

[8] In this study, the age of Yellow River water is defined as the time elapsed since the river water leaves the river mouth, and the transit time of Yellow River water is water age at the Bohai Strait, which is the sole outlet of Yellow River water into the Yellow Sea. We use CART to obtain the mean age of Yellow River water and to examine the processes controlling the mean water age; we use PTM to calculate the pathway of Yellow River water and the spectrum of water age.

[9] Mean water age in a target domain is influenced by the return of water parcels that once left the target domain and stayed outside the target domain for a significant amount of time. To consider the contribution of returned water parcels to mean water age, we set open boundary for water age calculations far from the target domain. Furthermore, we compare the results of two calculations with and without return of water parcels to the target domain for a quantitative demonstration on the role of returned water parcels.

[10] The paper is organized as follows. Section 2 describes the configuration of the hydrodynamic model and the calculation of water age. In section 3, we present the water age, transit time, age spectrum, and particle pathway results. In section 4, we discuss the effects of nonreturning water and

of several dynamic factors on water age. In section 5, we summarize the entire study.

## 2. Model Description

### 2.1. Hydrodynamic Model

[11] The hydrodynamic model used in this study is based on the Princeton Ocean Model [*Mellor*, 2004]. This model was initially developed by *Guo et al.* [2003] and has been applied by *Wang et al.* [2008] to study the Yellow River plume. The horizontal resolution was 1/18 degree in both the zonal and meridional directions. In the vertical direction, 21 sigma levels were distributed. The time step was 9 s for the external mode and 360 s for the internal mode.

[12] The hydrodynamic model was designed to reproduce the climatological state with seasonal variations and was therefore driven by monthly winds, monthly heat flux, monthly precipitation and evaporation rates, monthly river discharges from all of the rivers inside the model domain (Figure 1), monthly volume transports, and tidal forcing along all of the open boundaries. The monthly mean is defined at middle of each month and a linear interpolation from two monthly mean values was used to obtain the value at a given time step between them. A full description and validation of the hydrodynamic model has been presented by *Wang et al.* [2008]. For subsequent use in CART and PTM calculations, we saved data regarding the sea level, the three velocity components, and the horizontal and vertical diffusivity coefficients for 1 year at an interval of 30 min.

### 2.2. Mean Water Age Calculation by CART

[13] To calculate water age using CART [*Deleersnijder et al.*, 2001], two equations were solved for the concentration of Yellow River water, which is treated as a passive tracer and whose concentration ranges from 0 to unity in the domain of interest, and age concentration of Yellow River water $\alpha(t, x, y, z)$. The concentration of Yellow River water $C(t, x, y, z)$ was controlled by equation (1).

$$\frac{\partial C}{\partial t} + \nabla_H \cdot \left(\vec{u}C\right) + \frac{\partial (wC)}{\partial z} - \nabla_H \cdot (K_H \nabla C) - \frac{\partial}{\partial z}\left(K_V \frac{\partial C}{\partial z}\right) = 0. \tag{1}$$

[14] In this equation, $t$ is time; $x$, $y$, $z$ are three coordinates in space; $\vec{u}$ is the vector for two horizontal velocities; $w$ is the vertical velocity; $K_H$ is the horizontal diffusivity coefficient; $K_V$ is the vertical diffusivity coefficient; and $\nabla_H = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y}$.

[15] The age concentration of Yellow River $\alpha(t, x, y, z)$ was calculated by equation (2); the right-hand side of the equation consists of the concentration of Yellow River water $C(t, x, y, z)$.

$$\frac{\partial \alpha}{\partial t} + \nabla_H \cdot \left(\vec{u}\alpha\right) + \frac{\partial (w\alpha)}{\partial z} - \nabla_H \cdot (K_H \nabla \alpha) - \frac{\partial}{\partial z}\left(K_V \frac{\partial \alpha}{\partial z}\right) = C. \tag{2}$$

[16] The age of Yellow River water $a(t, x, y, z)$ was calculated as the ratio of the age concentration $\alpha$ and the concentration $C$ of Yellow River water [*Deleersnijder et al.*, 2001].

$$a = \alpha / C. \tag{3}$$

[17] A conversion from the $z$ coordinate to the sigma coordinate system used in Princeton Ocean Model (POM) is necessary for the above equations. Because the conversion is exactly the same as equations for water temperature and salinity, which can be found in *Mellor* [2004], we do not present them here.

[18] We developed new modules to solve equations (1) and (2) by referring to those for water temperature and salinity in the POM. Because it is difficult to directly measure water age in an ocean to verify the calculated water age, we used three analytical solutions for water age to check our modules that solve for equations (1) and (2). The first solution is for a spatially homogeneous, steady flow in a one-dimensional channel. According to *Deleersnijder et al.* [2001], the horizontal distribution of age in such a channel can be described by $x/u$ in which $x$ is the distance to the source of the target water and $u$ is the flow speed. This solution should check the module that solves for advection process. A second solution is designed to check the module that solves for the vertical diffusion process. The analytical solution for vertical distribution of age in the water column of a material from the sea surface is given by equation (A11) in Appendix A. A third solution is for water age in presence of both horizontal advection and horizontal diffusion in an one-dimensional space [*Deleersnijder and Delhez*, 2004]. This solution is used to check the module that solves for the horizontal diffusion. As shown in Figures A1 and A2 in Appendix A, the numerical solutions from our modules agree well with their corresponding analytical solutions. Hence, we concluded that the new modules used in this study for solving equations (1) and (2) are reliable.

[19] The model domain (Figure 1) for water age covers the control volume (Bohai Sea) and its outer sea (Yellow Sea). We set two open boundaries (OB1 and OB2 in Figure 1) in the model domain. OB1 is at the Bohai Strait and is designed for only one sensitivity simulation in which Yellow River water outside the Bohai Sea is not allowed to return to the Bohai Sea across OB1. OB2 is for normal simulations in which Yellow River water outside the Bohai Sea is allowed to return to the Bohai Sea, but water outside the model domain was never allowed to return to the model domain. The exact treatments of the open boundary are as follows. If there is an outflow at the interior gird point next to the open boundary, the concentration $C$ and age concentration of Yellow River water $\alpha$ at the open boundary were set to those at the interior gird point. If there is an inflow at the interior gird point next to the open boundary, the concentration $C$ and age concentration of Yellow River water $\alpha$ at the open boundary were set to 0.

[20] The concentration $C$ and age concentration of Yellow River water $\alpha$ at a grid point at a river mouth was set to 1 and 0, respectively, throughout the calculation of CART. The initial values of the concentration $C$ and age concentration of Yellow River water $\alpha$ inside the model domain were set to 0. The time step for solving equations (1) and (2) was 30 min, which is the same as the time interval for saving velocity and diffusivity coefficient data from the hydrodynamic model. The integration time for the CART calculation was 31 years, during which the saved velocities and diffusivity coefficients were repeated at the same time each year.

### 2.3. PTM Model

[21] To study the frequency distribution of water age, the PTM module [*Zhang*, 1995] in the estuarine and coastal ocean

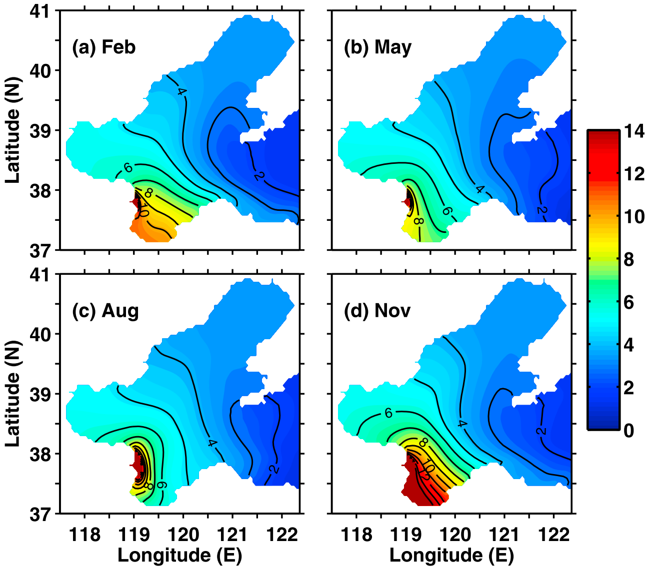


**Figure 2.** Vertically averaged concentration of Yellow River water (equals 1 at the river mouth) in (a) February, (b) May, (c) August, and (d) November. The concentration inside each panel has been multiplied by a factor of 100. The contour interval is 1.

model coupled with a sediment transport module (ECOMSED) [*Blumberg*, 2002] was implemented. The position of a particle in this module is determined by two parts: a component representing advection and a random component representing diffusion. The calculation domain for the PTM module is the same as that for water age (Figure 1). When a particle attempts to cross a land boundary, sea surface, or sea bottom, it is set to reflect back into the calculation domain. Consequently, a particle disappears from the model domain only when it flows out from the open boundary (OB2).

[22] A new group of particles was released at the Yellow River mouth every 30 min for only the first year of the PTM calculation. The total time for the PTM calculation was 31 years. One particle was set to represent a volume of $3.6 \times 10^4$ $m^3$ of Yellow River freshwater, and the total number of particles released in 1 day was determined by the daily Yellow River discharge for that day. When a particle was released, its age was set to 0. Subsequently, the particle age was updated at every time step until it reached OB2, where the particle was discarded. Consequently, the particle can freely pass through the Bohai Strait regardless of which direction it moved.

[23] Given a target region, the age frequency distribution function or age spectrum $\varphi(\tau, t)$ is defined by equation (4) [*Bolin and Rodhe*, 1973].

$$\varphi(\tau, t) = \frac{1}{M_0(t)} \frac{dM(\tau, t)}{d\tau}, \quad (4)$$

where $M_0(t)$ is the total number of particles at time $t$ in a target region; $M(\tau, t)$ is the total number of the particles less than or equal to an age $\tau$ at time $t$ in the target region. Notably, the original definition of the age frequency distribution function by *Bolin and Rodhe* [1973] applies to a steady case and is not a function of time $t$. Here, we applied the same idea to a field with seasonal variations and therefore assumed the age frequency distribution as a function of time $t$.

[24] We recorded the position of all of the particles released in the first year at each time step during the 31 years of calculation. For calculating the age frequency distribution function, we need the pathways of the particles released not only in the first year, but also those in the second year and succeeding years. Based on the fact that the velocity field and diffusivity coefficients used for the PTM calculation were repeated at the same time every year, we assumed that the particles released in the second year and succeeding years have the same pathways as those released in the first year. The only difference is in the ages of the particles. In this manner, we obtained the pathways of the particles released after the second year without additional PTM calculations. By counting the particle number defined by equation (4), we obtained the age frequency distribution function of Yellow River water in the target region.

## 3. Results

### 3.1. Age of Yellow River Water in the Bohai Sea

[25] The horizontal distribution of vertically averaged concentration of Yellow River water $C$ demonstrates a decreasing trend throughout the year in the following order: Laizhou Bay, Bohai Bay, the central basin, Liaodong Bay, and Bohai Strait (Figure 2). Inside the Laizhou Bay, the concentration is higher in the western side than in the eastern side, which reveals an inverse correlation with salinity described by *Wang et al.* [2008]. A concentration front forms along the western coast of the Laizhou Bay where a salinity front also forms [*Wang et al.*, 2008]. The inverse relationship exists because most freshwater in the Laizhou Bay originates from the Yellow River. In contrast, the concentration $C$ does not demonstrate an inverse relationship with salinity in the Liaodong Bay, where freshwater primarily originates from the Liaohe River, not from the Yellow River.

[26] The seasonal variation in the distribution of concentration of Yellow River water is mostly found in the Laizhou Bay and the central basin of the Bohai Sea. In the offshore area of the Yellow River mouth, a northeastward spreading area of high concentration occurs in August, which is consistent with low-salinity water movement due to southeasterly winds [*Wang et al.*, 2008]. In November, the high concentration area moves to the southwestern area of the Laizhou Bay, corresponding again to low-salinity area movement that is caused by the wind-driven current along the coast of the Laizhou Bay [*Wang et al.*, 2008].

[27] The age of Yellow River water is small at the offshore area of the Yellow River and increases in proportion to the distance away from the Yellow River mouth (Figure 3). The volume-averaged annual age is 615 days for the Laizhou Bay, 969 days for the Bohai Bay, 1101 days for the central basin, and 1427 days for the Liaodong Bay (Table 1a). In general, there is an inverse relationship between age (Figure 3) and concentration of Yellow River water (Figure 2). The exception is at the Bohai Strait where the concentration is lowest (Figure 2) but the age is not greatest (Figure 3). Water

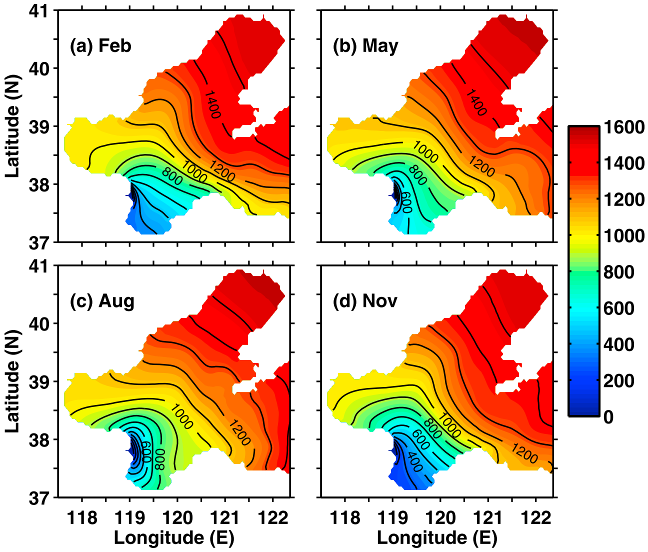


**Figure 3.** Vertically averaged age of Yellow River water (unit: days) in (a) February, (b) May, (c) August, and (d) November. The contour interval is 100 days.

exchange with the Yellow Sea likely affects the age of Yellow River water in that area.

[28] A front of water age is found offshore of the Yellow River mouth and presents an apparent seasonal variation (Figure 3). This variation induces a relatively large seasonal variation in volume-averaged ages of the Laizhou Bay (Table 1a). According to Table 1a, the range of seasonal variation for volume-averaged age is 232 days for the Laizhou Bay, 83 days for the Bohai Bay, 49 days for the central basin, and 29 days for the Liaodong Bay. The ratio of seasonal variation range to annual age is 0.38, 0.09, 0.04, and 0.02 for the Laizhou Bay, Bohai Bay, central basin, and Liaodong bay, respectively. If we treat the Bohai Sea as one water body, its volume-averaged age is 1082 days with a seasonal variation range of 101 days (Table 1a), which indicates weak seasonal variation (101/1082 = 0.09).

[29] The vertical variation in the concentration and age of Yellow River water is small except for the area close to the Yellow River mouth (figure not shown). As presented in Figure 3 and Table 1a, the age of Yellow River water is on the order of more than 1 year. With such time scale, tidal mixing and wind mixing (especially in winter) easily produce a vertically homogenous distribution in concentration and water age in the Bohai Sea.

### 3.2. Budget and Transit Time of Yellow River Water in the Bohai Sea

[30] Because the Bohai Sea has only one outlet (the Bohai Strait) connecting with another water body (the Yellow Sea), the freshwater and water age budget associated with water exchange through the Bohai Strait is one of the key factors to understanding the mean age of Yellow River water in the Bohai Sea (Figure 4).

[31] The annually averaged volume of Yellow River water inside the Bohai Sea ($V_{YR}$), the annually averaged inflow ($F_{YR}^{IN}(x_0)$) and outflow ($F_{YR}^{OUT}(x_0)$) volume transports of Yellow River water through the Bohai Strait ($x = x_0$) were calculated from the conservative matter concentration $C$.

$$V_{YR} = \frac{1}{T}\int_0^T \iiint_{Vol} C(x,y,z,t)dxdydzdt, \tag{5}$$

$$\begin{cases} F_{YR}^{IN}(x_0) = \iint_A f_{YR}^{-}(x_0,y,z)dydz \\ F_{YR}^{OUT}(x_0) = \iint_A f_{YR}^{+}(x_0,y,z)dydz \end{cases}, \tag{6}$$

$$\begin{cases} f_{YR}^{-}(x_0,y,z) = f_{YR}(x_0,y,z) \ \text{if} \ f_{YR}(x_0,y,z) < 0 \\ f_{YR}^{+}(x_0,y,z) = f_{YR}(x_0,y,z) \ \text{if} \ f_{YR}(x_0,y,z) > 0 \end{cases}, \tag{7}$$

$$f_{YR}(x_0,y,z) = \int_0^T \overline{u(x_0,y,z,t)C(x_0,y,z,t)}dt. \tag{8}$$

[32] Here, $T$ denotes the integral time (set to 1 year in this case); $Vol$ the volume integral over the entire Bohai Sea; $A$ the area integral over the entire section across the Bohai Strait; $f_{YR}(x_0, y, z)$ the annually averaged Yellow River flux at a grid point in which negative $f_{YR}(x_0, y, z)$ contributes to inflow transport $F_{YR}^{IN}$, whereas positive $f_{YR}(x_0, y, z)$ contributes to outflow transport $F_{YR}^{OUT}$. The bar $^{-}$ in equation (8) denotes the procedure of detiding.

[33] The annually averaged volume of Yellow River water inside the Bohai Sea ($V_{YR}$) is 6.3 × $10^{10}$ $m^3$ (Figure 4a), which occupies 4.3% of the total water volume in the Bohai Sea (= a mean conservative matter concentration of 0.043 for the entire Bohai Sea). Every year, approximately 2.0 × $10^{10}$ $m^3$ of Yellow River water is discharged into the Bohai

**Table 1a.** Volume-Averaged Age of Yellow River Water in the Bohai Sea and Subregions From Calculation With Boundary OB2[a]

| Subregions | February | May | August | November | Annual |
|---|---|---|---|---|---|
| Bohai Sea | 1079 | 1125 | 1101 | 1024 | 1082 |
| Laizhou Bay | 571 | 731 | 732 | 500 | 615 |
| Bohai Bay | 997 | 984 | 986 | 914 | 969 |
| Central Basin | 1114 | 1124 | 1082 | 1075 | 1101 |
| Liaodong Bay | 1427 | 1444 | 1422 | 1415 | 1427 |
| Bohai Strait | 1236 | 1238 | 1207 | 1273 | 1240 |

[a]Units are days.

**Table 1b.** Volume-Averaged Age of Yellow River Water in the Bohai Sea and Subregions From Calculation With Boundary OB1[a]

| Subregions | February | May | August | November | Annual |
|---|---|---|---|---|---|
| Bohai Sea | 420 | 463 | 441 | 378 | 424 |
| Laizhou Bay | 214 | 284 | 250 | 166 | 218 |
| Bohai Bay | 450 | 447 | 445 | 398 | 434 |
| Central Basin | 427 | 451 | 420 | 399 | 426 |
| Liaodong Bay | 708 | 723 | 706 | 702 | 710 |
| Bohai Strait | 348 | 457 | 411 | 421 | 393 |

[a]Units are days.

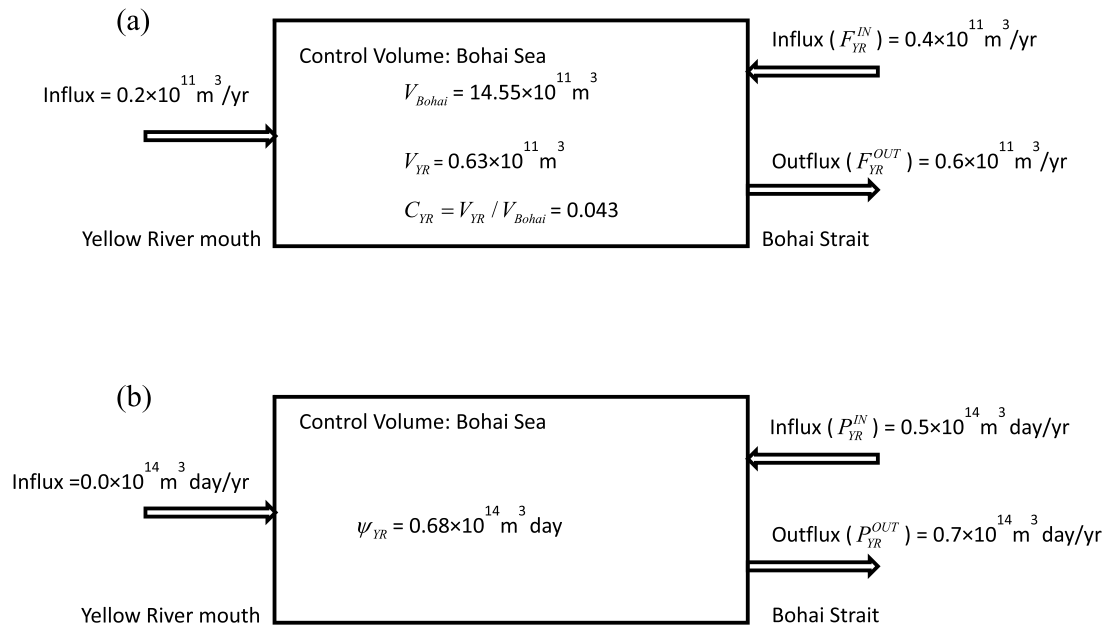


**Figure 4.** Budgets of (a) the Yellow River water and (b) its age concentration in the Bohai Sea. $V_{Bohai}$ is volume of the Bohai Sea. See section 3.2 for the definition and calculation methods of the other variables.

Sea from the river. However, approximately $6.0 \times 10^{10}$ m$^3$ of Yellow River water is transported out of the Bohai Sea through the Bohai Strait, while approximately $4.0 \times 10^{10}$ m$^3$ of Yellow River water is transported into the Bohai Sea through the strait. Therefore, the amount of returned old Yellow River water from the Yellow Sea to the Bohai Sea is twice that of the newly discharged river water from the Yellow River mouth to the Bohai Sea. As shown later, such returned old river water has an apparent influence on mean water age of Yellow River water in the Bohai Sea.

[34] Similarly, we calculated the annually averaged age concentration of Yellow River water inside the Bohai Sea ($\psi_{YR}$), annually averaged Yellow River water inflow transport ($P_{YR}^{IN}(x_0)$) and outflow transport ($P_{YR}^{OUT}(x_0)$) through the Bohai Strait by the following equations.

$$\psi_{YR} = \frac{1}{T}\int_0^T \iiint_{Vol} \alpha(x,y,z,t)dxdydzdt, \tag{9}$$

$$\begin{cases} P_{YR}^{IN}(x_0) = \iint_A p_{YR}^{-}(x_0,y,z)dydz \\ P_{YR}^{OUT}(x_0) = \iint_A p_{YR}^{+}(x_0,y,z)dydz \end{cases}, \tag{10}$$

$$\begin{cases} p_{YR}^{-}(x_0,y,z) = p_{YR}(x_0,y,z) \text{ if } p_{YR}(x_0,y,z) < 0 \\ p_{YR}^{+}(x_0,y,z) = p_{YR}(x_0,y,z) \text{ if } p_{YR}(x_0,y,z) > 0 \end{cases}, \tag{11}$$

$$p_{YR}(x_0,y,z) = \int_0^T \overline{u(x_0,y,z,t)\alpha(x_0,y,z,t)}dt. \tag{12}$$

[35] The transport of age concentration from the Yellow River to the Bohai Sea is 0 because the age of Yellow River water inside the river is 0 (Figure 4b). The annual transport of age concentration through the Bohai Strait into the Bohai Sea is approximately $5.0 \times 10^{13}$ m$^3$ d and that out of the Bohai Sea is approximately $7.0 \times 10^{13}$ m$^3$ d. The difference between the two flows (approximately $2.0 \times 10^{13}$ m$^3$ d) indicates an export of age concentration from the Bohai Sea to the Yellow Sea. Clearly, Yellow River water inside the Bohai Sea naturally increases by 1 year after a duration of 1 year. The net export of age concentration through the Bohai Strait to the Yellow Sea is nearly balanced with the increased 1 year of age concentration inside the Bohai Sea (approximately $2.3 \times 10^{13}$ m$^3$ d = multiplying 365 days by the volume of Yellow River water inside the Bohai Sea [$6.3 \times 10^{10}$ m$^3$]).

[36] The annual volume-integrated age concentration of Yellow River water inside the Bohai Sea ($\psi_{YR}$) is $6.8 \times 10^{13}$ m$^3$ d. Dividing this concentration by the volume of Yellow River water inside the Bohai Sea ($6.3 \times 10^{10}$ m$^3$) gives a mean age of Yellow River water of 1079 days, which is close to the 1082 days given in Table 1a.

[37] As stated in section 1, the age at the outlet of a control volume is regarded as transit time. The calculated transit time at the Bohai Strait is lower at the southern side than at the northern side throughout a year (Figure 5). A general understanding of the current patterns through the Bohai Strait consists of an inflow in the northern area and an outflow in the southern area [*Miao and Liu*, 1988; *Huang et al.*, 1998; *Zhao and Cao*, 1998; *Huang et al.*, 1999; *Wei et al.*, 2003]. According to Figure 5, the inflow carries old river water, but the outflow carries young river water.

[38] The difference of water age from north to south at the Bohai Strait depends on the season (Figure 5). The difference reaches a maximum (approximately 430 days) in winter when the minimum water age (approximately 960 days) and

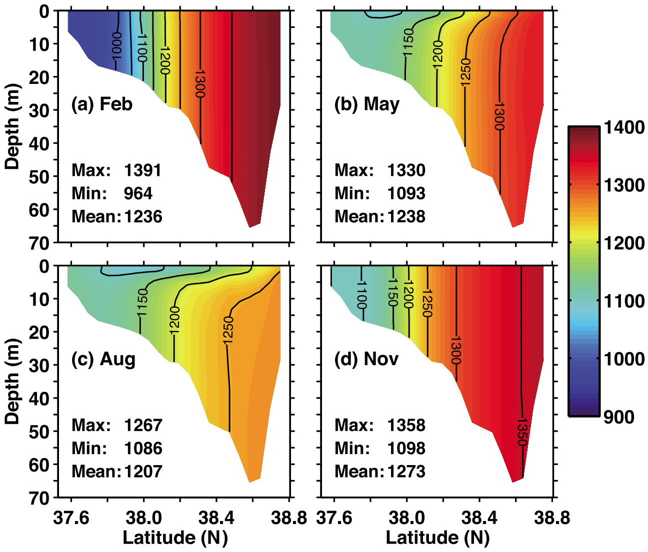


**Figure 5.** Vertical distribution of the age of Yellow River water (unit: days) in the Bohai Strait in (a) February, (b) May, (c) August, and (d) November. The contour interval is 50 days. Maximum value, minimum value, and mean value at the section are given in each panel.

maximum water age (approximately 1390 days) in a year appear in the southern area and northern areas, respectively. Yellow River water is transported out of the Bohai Strait in winter by the wind-driven coastal current along the Laizhou Bay [*Wang et al.*, 2008]. The age difference across the strait is at a minimum (approximately 180 days) in summer when the age in the southern area increases to approximately 1090 day and that in the northern area decreases to approximately 1270 days. Yellow River water is transported northeastward from the river mouth to the central basin in summer and cannot reach the strait [*Wang et al.*, 2008].

### 3.3. Movement of Particles

[39] Because the daily number of particles released at the river mouth in the PTM calculation was proportional to river discharge, its seasonal variation is apparent (Figure 6a). The total number of particles released in a year is $5.5 \times 10^5$ (Figure 6a), most of which stays inside the Bohai Sea in the first year (black line in Figure 6b). The total particle number inside the Bohai Sea (Figure 6b) reaches a maximum at the end of the first year, decreases sharply in the winter and spring, and keeps nearly stable in the next summer and autumn. The sharp reduction in total particle number inside the Bohai Sea in the winter and spring was resulted from the flowing out of numerous particles through the Bohai Strait that is the only exit of particles leaving the Bohai Sea.

[40] To confirm the reentry of particles, we flagged each particle and counted the number of times that the particle reentered the Bohai Sea. According to Figure 6b, the portion of particles not reentering (N = 0 in Figure 6b) decreases with time after the first year. In contrast, the particles reentering once (N = 1 in Figure 6b) or more than once (N > 1 in Figure 6b) increases with time in the first several years and decreases again after get its peak. The stable total particle number in summer and autumn (black line in Figure 6b) was resulted from combined effects of the returning of particles to the Bohai Sea from the Yellow Sea (N = 1 in Figure 6b) and the flowing out of particles from the Bohai Sea to the Yellow Sea (N = 0 in Figure 6b).

[41] We present the horizontal distribution of particle number in the water column (= sum of particle number from bottom to surface) at day 46 (Figure 7) and day 228 (Figure 8) of the fourth year of PTM calculation. Day 46 was chosen because it represents a typical situation when particles flow out of the Bohai Sea. Day 228 was chosen because it represents a typical situation when particles flow into the Bohai Sea again. At day 46 (Figure 7), many particles distribute closely to the Bohai Strait (Figure 7a) and easily flow out of the Bohai Strait. The pathway of outflow is located on the southern side of the strait, as demonstrated by the distribution of particles with 0 times of reentry (Figures 7b). At day 228 (Figure 8), in addition to amount of particles in the area close to river mouth, a large number of particles distribute in the northern part of the Bohai Strait and Liaodong Bay (Figure 8a). The particles in the northern part of the Bohai Strait and Liaodong Bay are those reentering the Bohai Sea (Figures 8c and 8d).

### 3.4. Age Frequency Distribution

[42] As shown in Figures 7 and 8, the particles inside the Bohai Sea have different trajectory histories. Consequently, the particles located at one grid point at a given time may have different water age. An age spectrum (age frequency distribution) defined by equation (4) may be used to describe the age composition at a given area. Here, we focus on the Yellow River estuary (see Figure 1 for the area definition) and the Bohai Strait. The first area is where Yellow River water enters and concentrates in the Bohai Sea, and the latter area is where Yellow River water leaves the Bohai Sea. As an example, we present the age spectrum at day 46 at the estuary (Figure 9a) and at the Bohai Strait (Figure 10a) that were calculated by equation (4) from the results of the PTM calculation in the last year when the composition of particles is annually repeatable. We also present the age spectrums, daily ages, and particle number during 1 year at the estuary (Figures 9c and 9e) and at the Bohai Strait (Figures 10c and 10e).

[43] There is one major peak of frequency at approximately 0 in the age spectrum for the Yellow River estuary at day 46 (Figure 9a). This peak corresponds to the young freshwater that spreads into this area from the Yellow River mouth after several days. In addition to these young particles, we can also identify the presence of old particles that have an age more than half year and even several years (Figure 9a). The frequency of old particles is low but the total number of old particles is not low because they have a wide distribution of age.

[44] Figure 9c is the extension of results at day 46 to 1 year. The presence of young water with an age of approximately 0 can be confirmed throughout the year (Figure 9c). The percentage of this young water keeps large from day ~80 to day ~130, becomes much smaller from day ~140 to day ~200, and becomes larger again from day ~210 to day ~330 (Figure 9c).

[45] The daily particle number and water age in the estuary changes largely during a year (Figure 9e). The increasing of particle number before day 90 and before day 210 are accompanied by decreasing of water age, indicating coming of

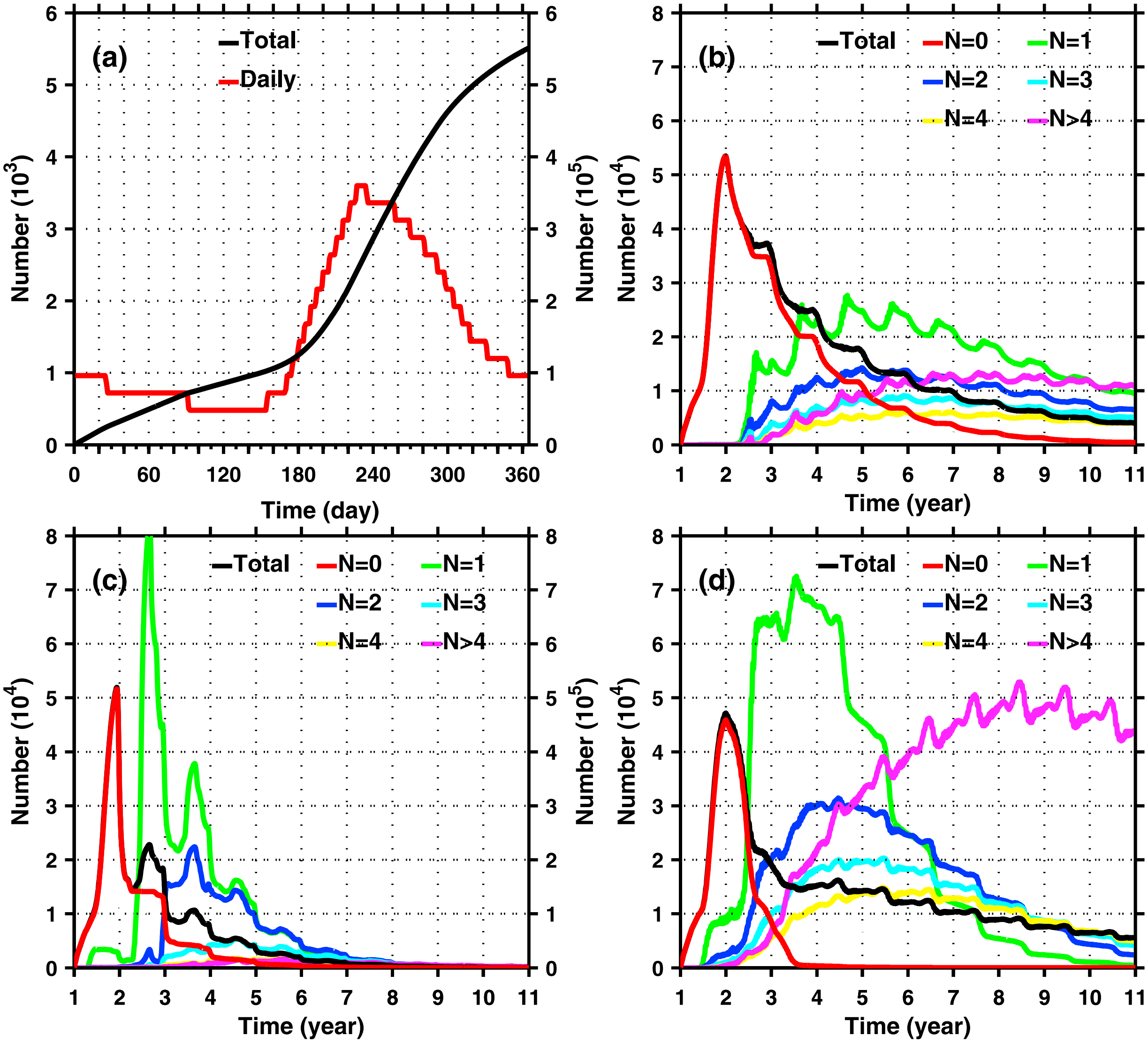


**Figure 6.** (a) Daily number (red line) and accumulative number (black line) of particles released at the river mouth in the first year. The range for daily number is given at left axis while that for accumulative number is at right axis. (b) Number of all particles (black line) inside the Bohai Sea and that of particles (color lines) experiencing reentry process into the Bohai Sea during the first 10 years of the PTM calculation. N represents the reentry times. The ranges for N = 1, N = 2, N = 3, N = 4, and N > 4 are given at left axis while the ranges for total number and N = 0 are at right axis. (c) The same as Figure 6b but for the case without tidal forcing (Case 1). (d) The same as Figure 6b but for the case without winds (Case 4).

newly released particles from the river mouth. However, the peaks of particle number around day 160 and day 280 are accompanied by increasing of water age, indicating little influence of newly released particles from the river mouth but great influence of particles returned to the estuary from area outside the estuary. The daily particle number and water age at the estuary (Figure 9e) gives an annual mean age of Yellow River water as 445 days. Apparently, this great age is a result of coexistence of newly released particles from the river mouth and the returned particles from the area outside the estuary.

[46] The age spectrum at the Bohai Strait at day 46 (Figure 10a) presents multi peaks. The first peak is at approximately half year and the subsequent ones appear with an interval of nearly 1 year (Figure 10a). According to Figure 7, we know that day 46 is the time when the river water particles flow out from the Bohai Sea through the Bohai Strait. The first age spectrum peak is due to the river water that leaves the river mouth in summer and autumn, moves into and stays the Laizhou Bay in autumn, and passes through the southern part of Bohai Strait in winter and spring. The subsequent peaks are due to the river water that leaves the river mouth in summer and autumn, moves inside or outside the Bohai Sea for several years, and finally passes through the southern part of Bohai Strait in winter and spring. The large river discharge in summer and autumn and its exiting through the Bohai Strait in winter and spring determine these age spectrum peaks.

[47] The extension of spectrum at day 46 to 1 year demonstrates the presence of multi peaks in age spectrum throughout a year (Figure 10c). The age of these peaks shows a naturally

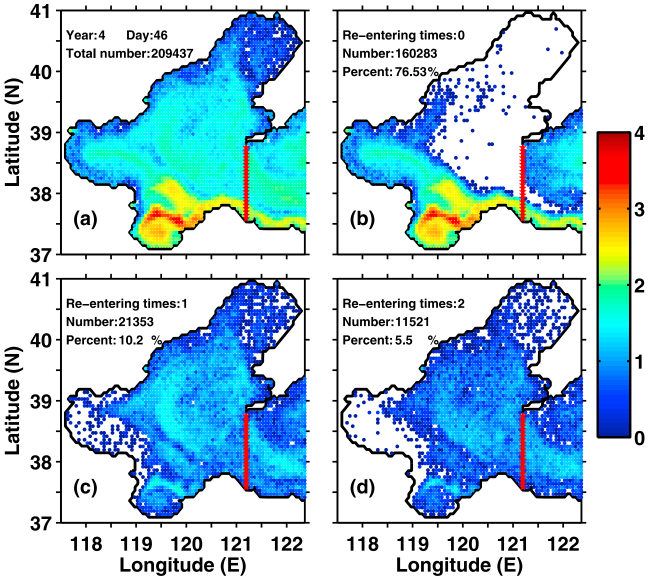


**Figure 7.** Distributions of (a) all particles, (b) particles never reentering the Bohai Sea from the Yellow Sea across the Bohai Strait (red line), (c) particles reentering once, and (d) particles reentering twice, at day 46 of the fourth year of the PTM calculation (day 1141 from the beginning). Colors represent the logarithm (based on 10) of the particle number.

increasing with time during a year, suggesting that the particles passing the Bohai Strait moves freely inside the model domain. This situation is different from the estuary area where the coming of newly released particles has a constant water age (Figure 9c). The daily particle number and age show less variation at the Bohai Strait (Figure 10e) than at the estuary (Figure 9e). The daily age at the Bohai Strait is small (~1000 days) from ~day 140 to ~day 200 and large (~1500 days) from ~day 240 to ~day 340. As shown in section 4.1, if we do not allow the reentry of particles into the Bohai Sea, the age spectrum at the Bohai Strait significantly changes (Figure 10d).

## 4. Discussion

[48] As we presented in section 3.3, reentering particles occupy a portion of Yellow River water inside the Bohai Sea and therefore affect the water age of Yellow River water in the sea. Additionally, because the water age is determined by the current field, any change in the driving forces of the current field, such as river discharge, winds, tide, and heating, may also affect water age. We therefore present water age without the reentry process through the Bohai Strait in section 4.1 and water age calculated by the current field obtained with artificially modified driving forces in section 4.2. These results and the discussion of them will help to understand the process related to the age of Yellow River water inside the Bohai Sea.

### 4.1. Water Age Without the Reentry Process

[49] Setting an open boundary at OB1 (Figure 1), we repeated the water age calculation using CART and PTM. Without the reentry process, the water age decreases by more than 50% in all of the subregions in the Bohai Sea (Figure 11 and Table 1c). A comparison of Figure 11 with Figure 3 indicates that the water age decreases from approximately 1400 days to 700 days in the Liaodong Bay, from 1100 days to 400 days in the central basin, and from 600 days to 200 days in the Laizhou Bay. Although the reduction in the absolute value of water age is great, the exclusion of the reentry process does not change the spatial distribution of water age for the four seasons. Therefore, seasonal variation in the spatial distribution of water age is primarily attributed to the movement of newly discharged Yellow River water.

[50] Without the reentry process, the water age at the Bohai Strait decreases from approximately 1200 days (Figure 5) to 400 days (Figure 12), but the spatial pattern with low water age at the southern side and high water age at the northern side remains (Figure 12). The magnitude of the reduction is greater at the northern side than at the southern side (Figures 12 and 5). In this case, the age of Yellow River water at the Bohai Strait is determined only by the outflow of tracer concentration inside the Bohai Sea and therefore reflects the transit time of the newly discharged Yellow River water in the Bohai Sea.

[51] The influence of the reentry process also appears in the spectrum of water age at the estuary and at the Bohai Strait (Figures 9 and 10). If the particles are not allowed to return to the Bohai Sea in the PTM calculation, the particles with an age longer than 5 years almost disappear at the estuary (Figure 9b); the daily age at the estuary apparently decrease (Figure 9f) and its annual mean is only 294 days, much less than 445 days in the case with reentry process (Figure 9e). Without reentry process, the particle number at the Bohai Strait decrease significantly (Figure 10f). In particular, the particle number after day 230 approaches to 0 and such small number of particle makes the water age spectrum to be hardly defined (Figure 10d). Since the particles returned to the Bohai Sea from the Yellow Sea have relatively large water age, the young particles at the Bohai Strait increases its ratio in the case without the reentry

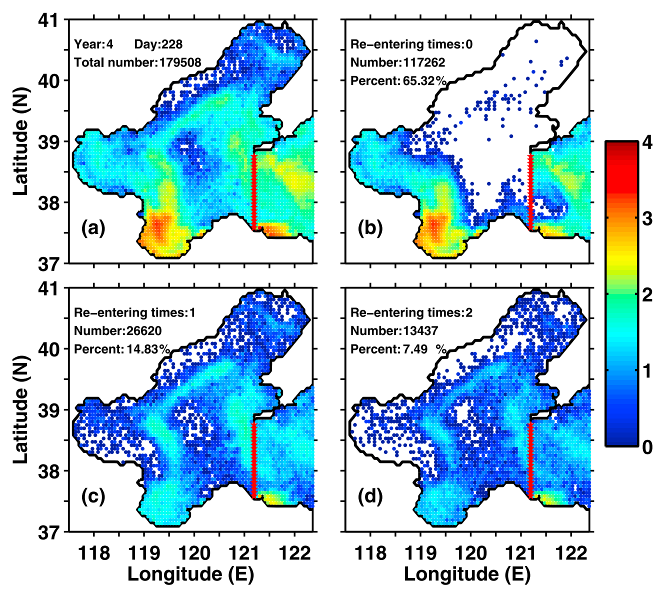


**Figure 8.** The same as Figure 7 but with data for day 228 of the fourth year (day 1323 from the beginning of the PTM calculation).

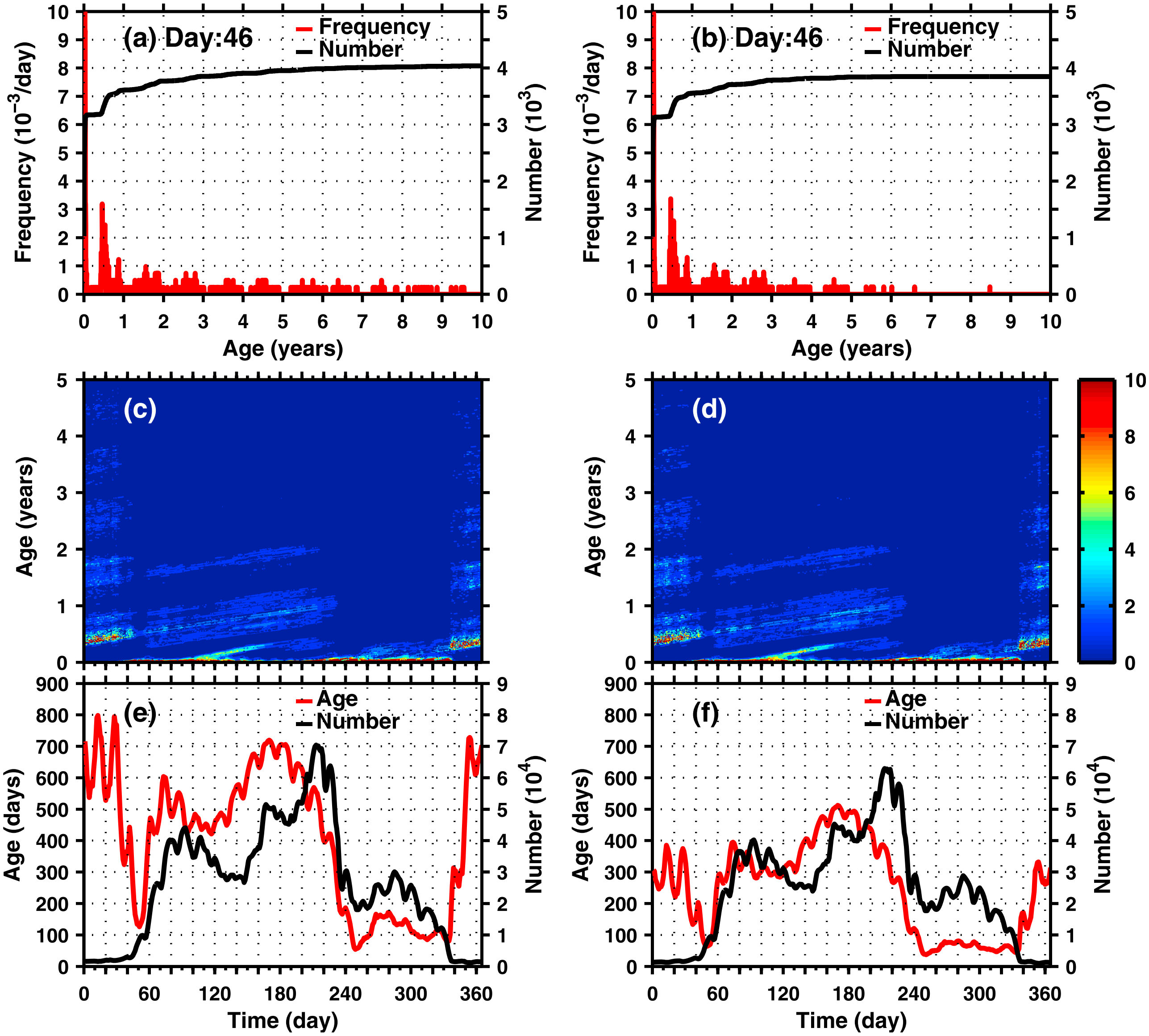


**Figure 9.** (a) Total number (black line, $M(\tau, t)$ in equation (4)) of the particles with ages less than or equal to an age ($\tau$) at day 46 ($t$ = day 46); age spectrum (red line, $\varphi(\tau, t)$ in equation (4)) of Yellow River water at the estuary (see Figure 1 for the position) from calculations using boundary OB2. (b) The same as Figure 9a but from calculations using boundary OB1. (c) The age spectrum $\varphi(\tau, t)$ (unit: $10^{-3}$/d) of Yellow River water at the estuary during a year ($t$ = day 1 to day 365) from calculations using boundary OB2. The age range ($\tau$) is limited to 5 year since the frequency of particles with age larger than 5 years is too small to be identified. (d) The same as Figure 9c but from calculations using boundary OB1. (e) Daily number of particles (black line) and their mean age (red line) of Yellow River water at the estuary from calculations using boundary OB2. (f) The same as Figure 9e but from calculations using boundary OB1.

process (Figure 10b). Consequently, the daily age at the Bohai Strait significantly decreases in the case without the reentry process (Figure 10f).

## 4.2. Influences of Dynamic Factors on Water Ages

[52] We designed 7 cases (Table 2) for examining the control of dynamic factors on water age. In each of these cases, we change only one physical process from the control case (hereafter referred to as Case 0), for which the results were given in section 3, and rerun the hydrodynamic model and CART module to obtain a new water age. The open boundary for water age in these cases is at OB2; therefore, the reentry process was allowed in all of these cases.

[53] The exclusion of tidal forcing (Case 1, removing tidal oscillation at open boundaries) significantly reduces the age of Yellow River water in the Bohai Sea (Table 3a and Figure 13b). Without tidal forcing, the annual mean age of Yellow River water decreases by 57%, 34%, 43%, 50%, 52%, and 46% in the Laizhou Bay, Bohai Bay, central basin, Liaodong Bay, Bohai Strait, and the entire Bohai Sea, respectively (Table 3b). The reduction in water age is small

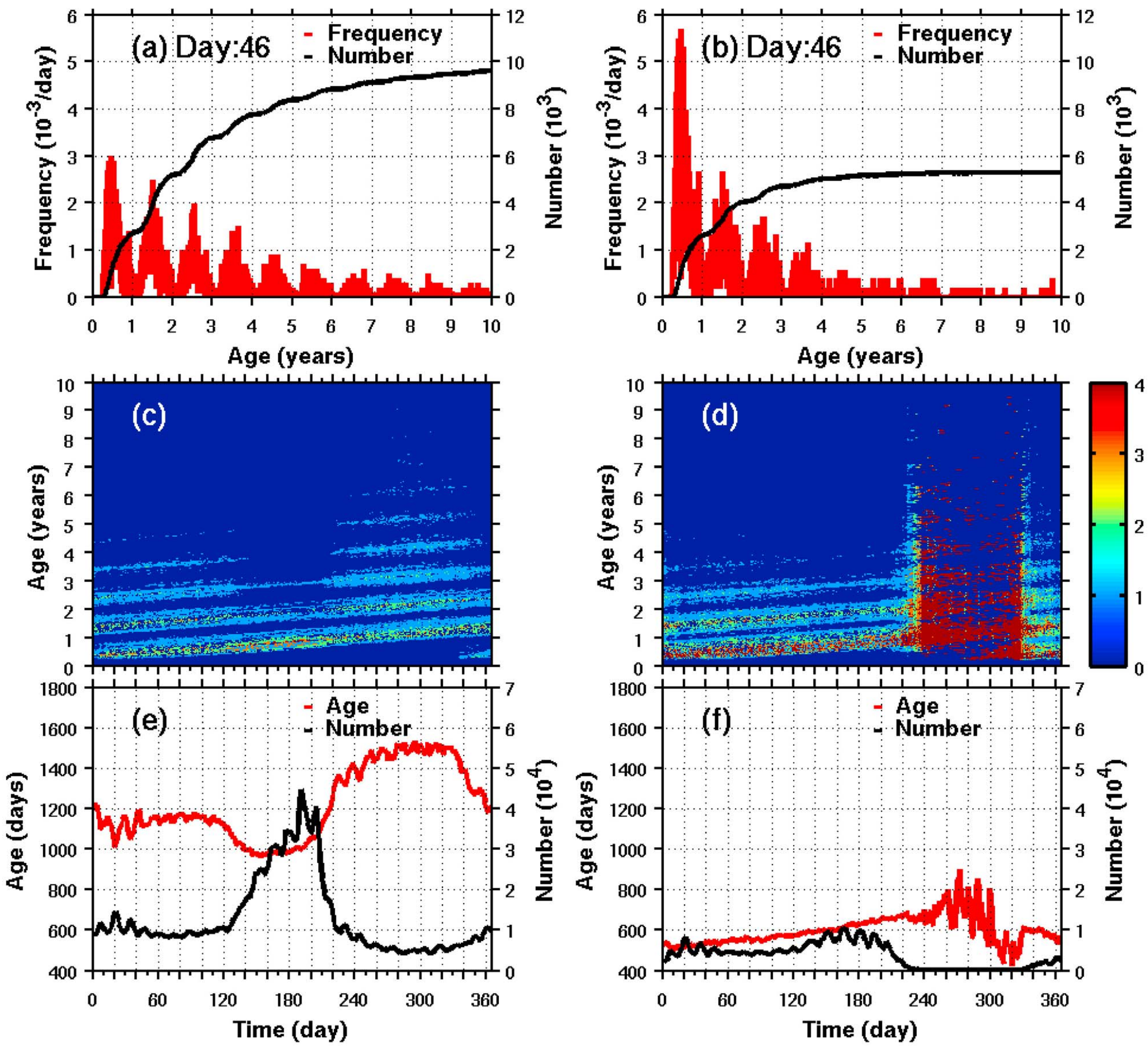


**Figure 10.** The same as Figure 9 but for the Bohai Strait. The particle number in Figure 10f from day 230 to day 330 is very small and the spectrum during this period is essentially meaningless.

near the river mouth and gradually becomes larger with distance from the river mouth (Figure 13b).

[54] The tidal forcing has two major hydrodynamic functions, which are tide-induced change in vertical mixing and tide-induced change in current field. To clarify which function is more important to the reduction of water age, we designed Case 2 and Case 3 (Table 2). Both cases are the same as Case 0 except that the vertical eddy diffusivity coefficient for tracer and age concentrations in Case 2 were replaced by those in Case 1, and the three components of velocity and sea level for tracer and age concentrations in Case 3 were replaced by those in Case 1. Therefore, the tide-induced change in vertical mixing was ignored in the water age calculation in Case 2, whereas the tide-induced change in current field was ignored in the water age calculation in Case 3.

[55] The reduction of water age in Case 1 compared to Case 0 (Figure 13b) is attributed primarily to the tide-induced change in current field (Figure 13d) and not to the tide-induced change in vertical mixing (Figure 13c). The small change in water age in Case 2 (Figure 13c) suggested that tide-induced change in vertical mixing has a negligible role in the age of Yellow River water in the Bohai Sea.

[56] The tide-induced change in current field affects the movement of particle of Yellow River water through the Bohai Strait. Compared to Case 0 (black line in Figure 6b), the total particle number of Yellow River water inside the Bohai Sea decreases sharply from the end of first year in Case 1 (black line in Figure 6c), indicating more particles leaving the Bohai Sea in Case 1 than in Case 0. At the end of second year, the total particle number inside the Bohai Sea is $3.5 \times 10^5$ in Case 0 but $1.3 \times 10^5$ in Case 1. In the summer of second and third years of Case 1, a large number of

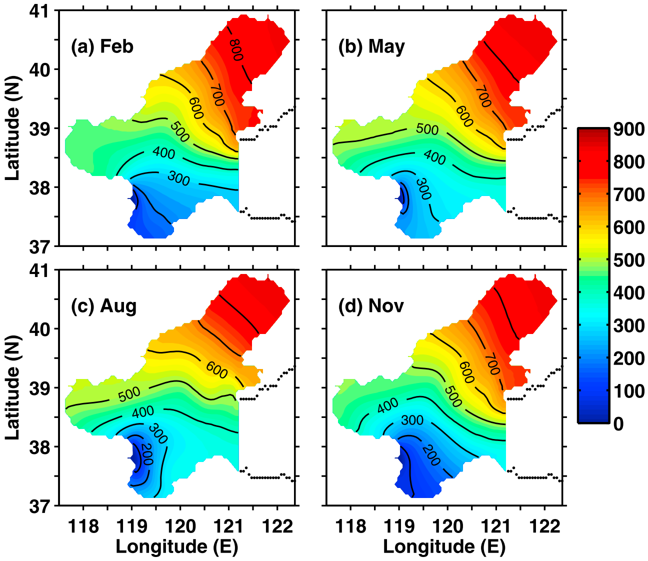

Figure 11. Vertically averaged age of Yellow River water (unit: days) in the Bohai Sea from calculation using boundary OB1 in (a) February, (b) May, (c) August, and (d) November. The contour interval is 100 days.

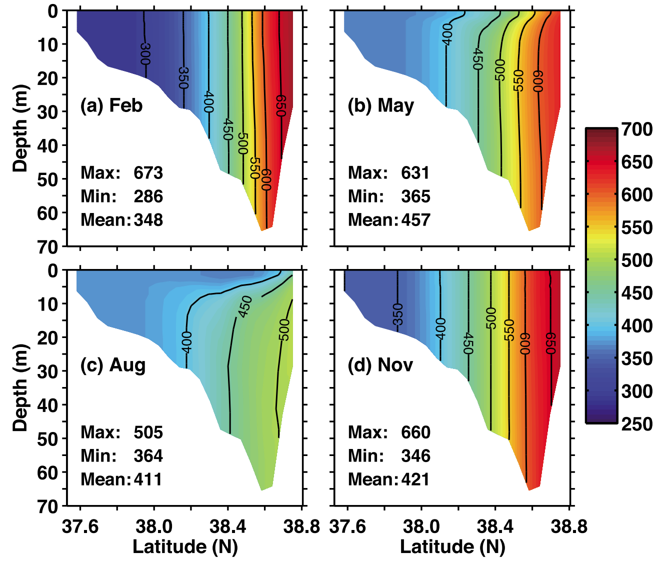

Figure 12. Vertical distribution of age of Yellow River water (unit: days) in the Bohai Strait from calculation using boundary OB1 in (a) February, (b) May, (c) August, and (d) November. The contour interval is 50 days. Maximum value, minimum value, and mean value at the section are given in each panel.

particles return into the Bohai Sea (green line of N = 1 in Figure 6c). However, the returned particles are much less than the particles leaving at the end of first year. Furthermore, they leave the Bohai Sea very soon, inducing another reduction in total particle number before the winter when the major reduction due to leaving of the particles with N = 0 occurs.

[57] The reduction in total particle number due to returned particles from late summer to early winter occurs only in Case 1 (Figure 6c). To understand the reason for this, we present the horizontal distribution of particles at day 167, 228, 320 in second year of Case 1 (Figure 14). At day 167, the particles with N = 0 distribute along the southern coast of Bohai Bay and Laizhou Bay. As suggested by the disconnection of particles with N = 0 around the Bohai Strait (Figure 14a), they already starts to move to the Laizhou Bay from the strait. Following them, the particles with N = 1 distribute from the Bohai Strait to the southern coast of Laizhou Bay (Figure 14b) and the particles with N = 0 accumulate outside the Bohai Strait (Figure 14a). With time passing, the particles with N = 0 outside the Bohai Strait enters the Bohai Sea and becomes the particles with N = 1 inside the Bohai Sea. At day 228, the particles with N = 0 distributes mainly in the Bohai Bay (Figure 14c) while the particles with N = 1 distributes mainly in the Laizhou Bay (Figure 14d) and its total number reaches the maxima (>80000) (Figure 6c and Figure 14d). After that, the particles start to move to the Bohai Strait and then leave the Bohai Sea. At day 320, the particles with N = 0 come back the Laizhou Bay from the Bohai Bay but does not reach the Bohai Strait (Figure 14e). The particles with N = 1 distribute from the Laizhou Bay to the Bohai Strait (Figure 14f). The large number of particles with N = 1 outside the Bohai Strait (Figure 14f) indicate the exiting of particles through the Bohai Strait up to day 320.

[58] According to Figure 14, the different pathway of returned particles in Case 1 from Case 0 is the cause of the reduction in total particle number from late summer to early winter in Case 1. The exiting pathway of particles is from the southeastern coast of Laizhou Bay to the Bohai Strait in both Case 0 and Case1. With tidal forcing (Case 0), the particles return to the Bohai Sea from northern side of the Bohai Strait and distribute from the Bohai Strait to the Liaodong Bay (Figure 8c). These particles have to return to the Laizhou Bay before exiting the Bohai Sea again. Without tidal

Table 1c. Relative Difference of Volume-Averaged Age of Yellow River Water Between Calculations With Boundary OB1 and OB2[a]

| Subregions | February | May | August | November | Annual |
|---|---|---|---|---|---|
| Bohai Sea | −61 | −59 | −60 | −63 | −61 |
| Laizhou Bay | −63 | −61 | −66 | −67 | −65 |
| Bohai Bay | −55 | −55 | −55 | −56 | −55 |
| Central Basin | −62 | −60 | −61 | −63 | −61 |
| Liaodong Bay | −50 | −50 | −50 | −50 | −50 |
| Bohai Strait | −72 | −63 | −66 | −67 | −68 |

[a]Units are percent.

Table 2. Conditions Used in Sensitive Experiments for Case 1 to Case 7

| Case | Yellow River Discharge | Tidal Current | Tidal Mixing | Winds | Thermal Stratification |
|---|---|---|---|---|---|
| 1 | Yes | No | No | Yes | Yes |
| 2 | Yes | Yes | No | Yes | Yes |
| 3 | Yes | No | Yes | Yes | Yes |
| 4 | Yes | Yes | Yes | No | Yes |
| 5 | Yes | Yes | Yes | Yes | No (10°C) |
| 6 | 0.5 times | Yes | Yes | Yes | Yes |
| 7 | 2.0 times | Yes | Yes | Yes | Yes |

**Table 3a.** Volume- and Annually Averaged Age of Yellow River Water in the Bohai Sea and Subregions From Sensitive Experiments[a]

| Subregions | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 |
|---|---|---|---|---|---|---|---|
| Bohai Sea | 586 | 1076 | 580 | 1383 | 1127 | 1097 | 1080 |
| Laizhou Bay | 264 | 609 | 250 | 841 | 628 | 631 | 614 |
| Bohai Bay | 641 | 996 | 449 | 1194 | 979 | 976 | 975 |
| Central Basin | 630 | 1093 | 648 | 1409 | 1153 | 1117 | 1096 |
| Liaodong Bay | 708 | 1401 | 802 | 1778 | 1513 | 1450 | 1413 |
| Bohai Strait | 591 | 1213 | 617 | 1548 | 1308 | 1282 | 1209 |

[a]The results of control case are given in Table 1a. The sensitive experiments are Case 1 to Case 7. Volume-averaged and annually averaged age units is in days.

**Table 3b.** Relative Difference of Volume- and Annually Averaged Age of Yellow River Between Sensitive Experiments and Control Case[a]

| Subregions | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 |
|---|---|---|---|---|---|---|---|
| Bohai Sea | −46 | −1 | −46 | 28 | 4 | 1 | 0 |
| Laizhou Bay | −57 | −1 | −59 | 37 | 2 | 3 | 0 |
| Bohai Bay | −34 | 3 | −54 | 23 | 1 | 1 | 1 |
| Central Basin | −43 | −1 | −41 | 28 | 5 | 1 | 0 |
| Liaodong Bay | −50 | −2 | −44 | 25 | 6 | 2 | −1 |
| Bohai Strait | −52 | −2 | −50 | 25 | 5 | 3 | −3 |

[a]The results of control case are given in Table 1a. The sensitive experiments are Case 1 to Case 7. Relative difference is given in percent.

forcing (Case 1), the particles returns to the Bohai Sea from southern side of the Bohai Strait and distribute from the Bohai Strait to the southern coast of Laizhou Bay (Figure 14d). Since they are already at the exiting pathway of particles, the returned particles in Case 1 can easily reach

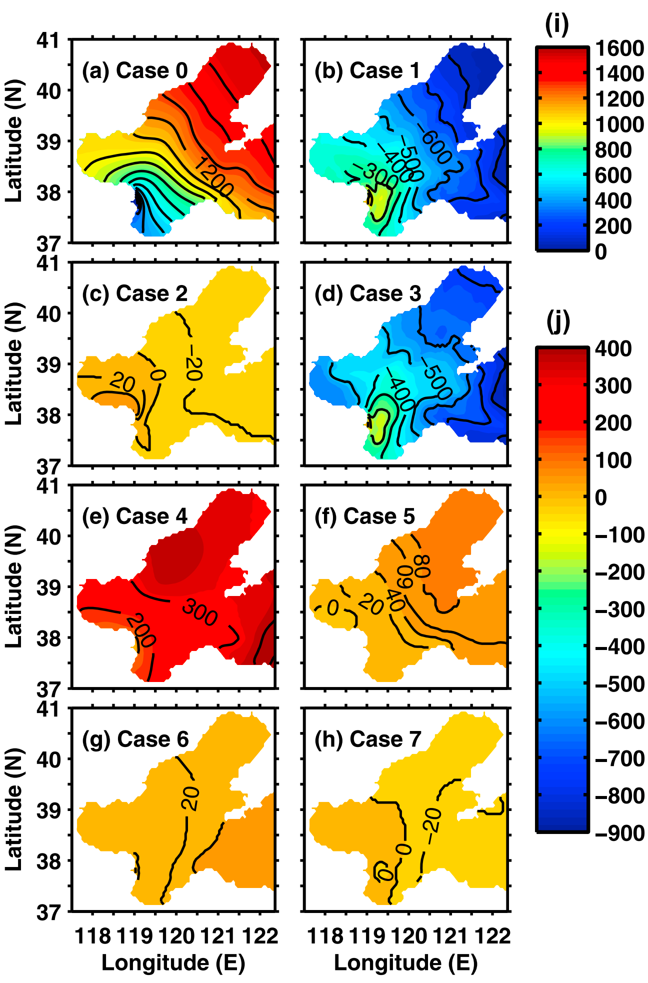


**Figure 13.** (a) Vertically and annually averaged age of Yellow River water (unit: days) in the Bohai Sea calculated for a control case (Case 0). (b–h) The same as Figure 13a but for the differences between the Case denoted inside the panel and Case 0. (i) The color bar shows the color range for Figure 13a, and (j) the color bar shows the color range for Figures 13b–13 h. The contour interval for Figures 13a, 13b, 13d, and 13e is 100 days, and the interval for Figures 13c, 13f, 13 g, and 13 h is 20 days.

the Bohai Strait. Consequently, it is easier for the returned particles to leave the Bohai Sea in Case 1 than in Case 0. This is the cause why the water age of Yellow River water is lower in Case 1 than in Case 0.

[59] The tide-induced change in current field includes three major components. The tide-induced residual current due to the asymmetry in the tidal currents generally acts to prevent Yellow River water from flowing out along the coast of the Laizhou Bay to the Bohai Strait [see *Wang et al.*, 2008, Figure 11]. In addition, the presence or absence of tidal forcing also changes the response of Bohai Sea to the wind-forcing and buoyancy forcing and changes the wind-driven current and density-driven current. All of them should contribute to the tide-induced change in the current field as well as the pathway of particles.

[60] Local winds are also important to the age of Yellow River water in the Bohai Sea. Without local winds (Case 4; Table 2), the age of Yellow River water in the entire Bohai Sea and its subregions increased by 20–30% (Tables 3a and 3b and Figure 13e), which indicates that local winds rank second among all of the dynamic processes discussed here.

[61] The particles of Yellow River water with N = 0 are easier to leave the Bohai Sea in Case 4 (Figure 6d) than in Case 0 (Figure 6b). The timescale for the total number of particles with N = 0 inside the Bohai Sea to decrease to 0 is approximately two and half years in Case 4 (Figure 6d) but 10 years in Case 0 (Figure 6b). Therefore, the particles with N = 0 do not contribute to the increasing of water age in Case 4. On the other hand, the returned particles (N > 0) are more difficult to leave the Bohai Sea in Case 4 (Figure 6d) than in Case 0 (Figure 6b). Apparently, it is the returned particles that increase the water age in the case without winds.

[62] To know the movements of particles, we present the horizontal distribution of particles at day 167, 228, 320 in second year of Case 4 (Figure 15). From day 167 to day 320, the particles with N = 0 continuously move from the Laizhou Bay toward the Bohai Strait and subsequently leave the Bohai Sea (Figures 15a, 15c, and 15e). The movement of particles with N = 0 in opposite direction, which occurs in Case 0 (Figures 7a and 8a) from spring to summer when southerly or southeasterly winds prevails, does not occur in Case 4. Therefore, without winds, the particles with N = 0 lose the driving forcing for them to return the Laizhou Bay and are kept in a one-way movement, i.e., leaving the Bohai Sea. On the other hand, the returned particles in Case 4 enter the Bohai Sea from northern part of Bohai Strait (Figures 15b, 15d, and 15f) and accumulate there to the

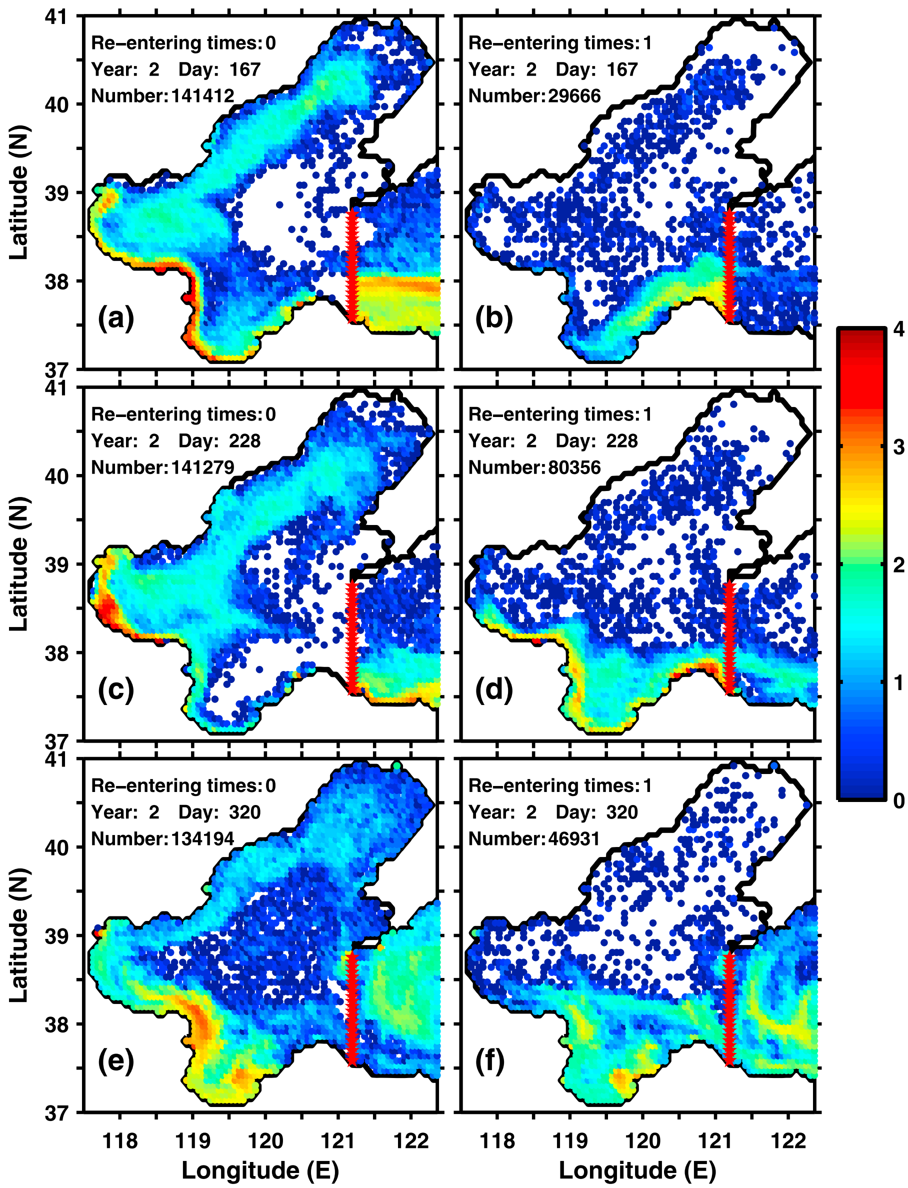


**Figure 14.** Distributions of particles never reentering the Bohai Sea from the Yellow Sea across the Bohai Strait (red line) at (a) day 167, (c) day 228, and (e) day 320 as well as particles reentering once at (b) day 167, (d) day 228, and (f) day 320 of the second year of the PTM calculation in the case without tidal forcing (Case 1). Colors represent the logarithm (based on 10) of the particle number.

Liaodong Bay. Without wind, it is difficult for them to move to the southern coast of Laizhou Bay and therefore need more time to leave the Bohai Sea again.

[63] Thermal stratification due to heating has been known to influence the behavior of the Yellow River plume [*Wang et al.*, 2008]. Without heating, the offshore spreading of the river plume in spring and summer decreased, and surface currents were weakened [*Wang et al.*, 2008]. These changes, however, have limited influences on the age of Yellow River water (Case 5). Without heating, the water age increased by only 0–80 days (Figure 13f), which is only a small percentage of the water age in Case 0 (Table 3).

[64] The changes in Yellow River discharge have slight influence on its water age (Table 3 and Figures 13g and 13h). Halving (Case 6) or doubling (Case 7) Yellow River discharges modified the water age on the order of 20–40 days (Figures 13g and 13h), which is less than 5% of the water age in Case 0 (Table 3).

## 5. Summary

[65] The age of Yellow River water in the Bohai Sea was evaluated by a three-dimensional model that was driven by monthly forcing (wind stresses, heat flux, river discharge, and ocean currents at the open boundary) and tidal forcing. Two methods were used to calculate the water age. One method is based on the constituent-oriented age and residence time theory [*Deleersnijder et al.*, 2001], and the other method is a classic particle-tracking method [*Zhang*, 1995]. The former method presents the spatial distribution of water

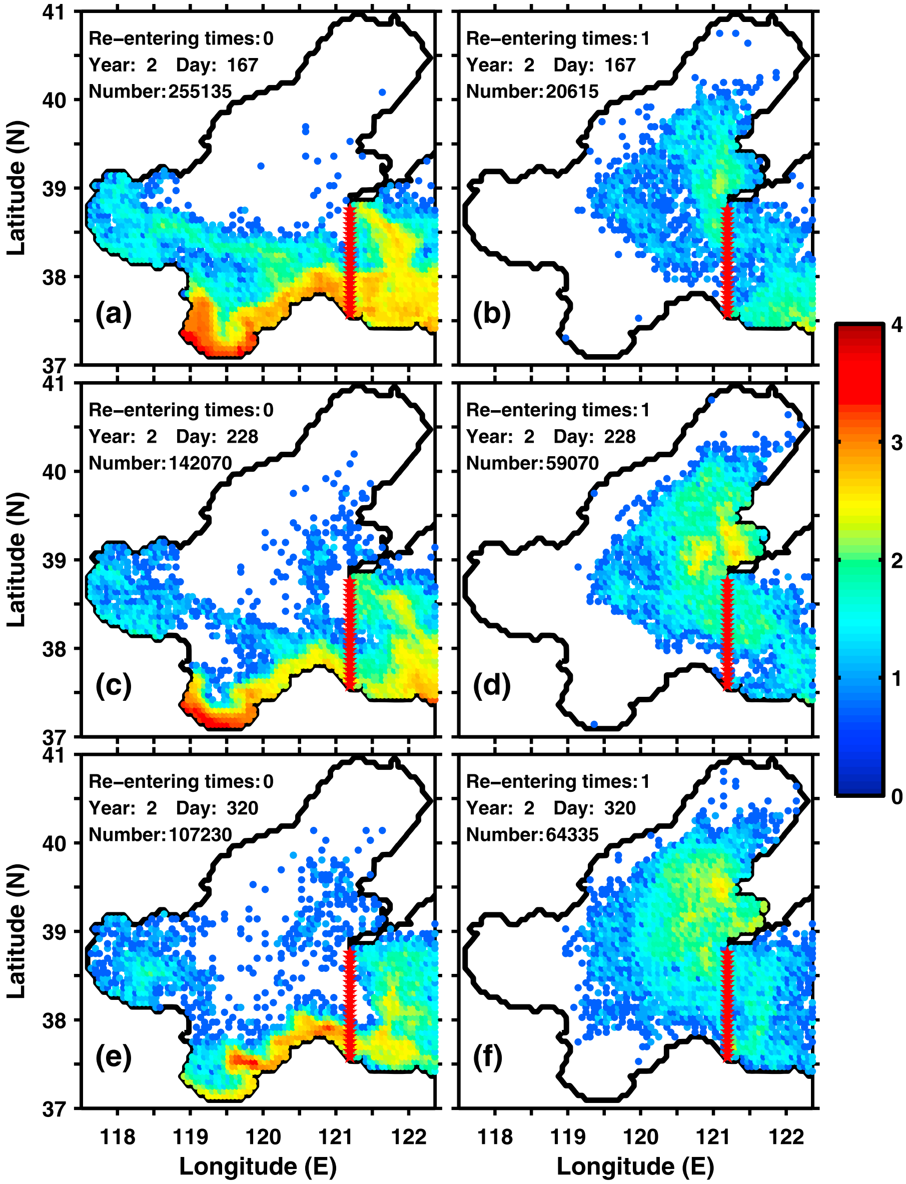


**Figure 15.** The same as Figure 14 but for the case without winds (Case 4).

age and a budget of tracer and age concentrations, whereas the latter method reveals the trajectory and age spectrum of river water particles.

[66] Yellow River water has a mean age of 3.0 years for the entire Bohai Sea. The water age varies significantly in the horizontal direction but varies insignificantly in the vertical direction and in the temporal dimension. The water age is approximately 1.2 years near the Yellow River estuary but 3.9 years in the Liaodong Bay. The great water age (>1 year) induces a nearly homogeneous distribution in the vertical direction and a small temporal variation in spatially averaged water age (a minimum value of 2.8 years in autumn and a maximum value of 3.1 years in spring).

[67] The mean age of Yellow River water reported in this study is much greater than the mean age of river water in estuaries [*Shen and Haas*, 2004; *Shen and Lin*, 2006] and the shelf sea [*Zhang et al.*, 2010a]. The greater water age of Yellow River water may be attributed to the large range of Bohai Sea (approximately 300–400 km from the river mouth) and the weak current speed (0.05 m $s^{-1}$) in the Bohai Sea. However, these factors are not the primary causes for the greater age of Yellow River water found in this study. For example, in an estuary in which the length is assumed to be 400 km and the current is assumed to be a constant (0.05 m $s^{-1}$), the maximum age is approximately 90 days without considering diffusion. This value is far less than that we obtained.

[68] The return of old river water to the target area is the primary cause for the greater age of Yellow River water in the Bohai Sea found in this study. The target area of this study is the entire Bohai Sea. The return of Yellow River water from the area outside of the target area (i.e., the Yellow Sea) has been demonstrated to increase the water age from 424 days (Table 1b) to 1082 days (Table 1a). The trajectory of water particles released at the river mouth further proved the role of returned old Yellow River water. Most of Yellow

River water particles need only several days to reach the estuary area. This result is consistent with previous reports of a short age of river water in an estuary [*Chen*, 2007; *Liu et al.*, 2011]. However, the presence of old water particles in the estuary area results in a mean river water age on the order of 1 year. This fact, i.e., the composition of particles with different ages, was demonstrated by the age spectrum.

[69] The large spatial scale of the target domain (i.e., the Bohai Sea) and the circulations there are the secondary causes for the great water age because the combination of these two factors maintains the river water inside the target domain for more than 1 year. If the target domain was limited to the Yellow River estuary or even to the Laizhou Bay, we can obtain a shorter water age for Yellow River water.

[70] Among all of the dynamic processes associated with circulations, the tide is the most dominant factor to affect the age of Yellow River water. Without tidal forcing, the mean age of Yellow River water was reduced by more than 50%. The tide-induced change in current field, not the tide-induced change in vertical mixing, was shown to be responsible for the reduction in water age. The particles of river water return to the Bohai Sea from northern side of the Bohai Strait in the presence of tide but from southern side of the Bohai Strait in the absence of tide. Consequently, the returned particles are easier to leave the Bohai Sea again in the absence of tide than in the presence of tide because the southern side of the Bohai Strait is the exit for Yellow River water to leave the Bohai Sea. The winds are a secondary factor in controlling the age of Yellow River water. Without winds, the mean age of Yellow River water increases by 20–30%. The particles of river water return to the Bohai Sea from northern side of the Bohai Strait in the absence of winds. Without winds, the returned particles are difficult to move to the southern coast of Laizhou Bay and the southern side of Bohai Strait and therefore stay inside the Bohai Sea for a long time. Changes in Yellow River discharge and in thermal stratification have only slight influences on the age of Yellow River water.

[71] As shown in this study, the return of old river water to the target region is an important factor in the mean age of river water. Both the water age with reentry process and the water age without the reentry process have possible applications. The water age with the reentry process may be applied to materials such as persistent organic pollutants (POPs) that move with water and stay in the sea with a time scale of several years or decades. The water age without the reentry process may be applied to materials such as nutrients that are rapidly used by phytoplankton and have a life span of less than 1 year. Nevertheless, the link between river water age and terrigenous material transport and cycling in the sea must be explored in our future studies.

## Appendix A: Comparison of Numerical Results With Analytical Solutions

[72] According to *Deleersnijder et al.* [2001], the horizontal distribution of age in the channel can be described by $x/u$ in which $x$ is the distance to the source of the target water and $u$ is the speed of steady flow. This solution was used to check our numerical module that solves for the advection process. Figure A1a presents the relationship between water age and distance in the analytical solution and in the module results. With a constant velocity (0.01 m s$^{-1}$), the age increases by 11.57 days with every 10 km leaving the source. This feature is almost exactly given by the module (Figure A1a).

[73] The second analytical solution is for newly formed passive dissolved conservative matter at the sea surface. Assuming that only vertical diffusion applies here and denoting time by $t$, vertical coordinate by $z$, water depth by $H$, and a constant vertical diffusivity coefficient by $K$, the concentration of conservative matter $C(z, t)$, and its age concentration $\alpha(z, t)$ are controlled by the following equations.

$$\frac{\partial C}{\partial t} = K\frac{\partial^2 C}{\partial z^2} \quad \text{(A1)}$$

$$\frac{\partial \alpha}{\partial t} = K\frac{\partial^2 \alpha}{\partial z^2} + C(z,t) \quad \text{(A2)}$$

[74] The initial conditions for $C$ and $\alpha$ are as follows.

$$C(z,0) = 0 \quad \text{(A3)}$$

$$\alpha(z,0) = 0 \quad \text{(A4)}$$

[75] The boundary conditions for $C$ and $\alpha$ at the sea surface ($z$ = 0) and sea bottom ($z$ = $H$) are as follows.

$$C(0,t) = 1 \quad \text{(A5)}$$

$$\alpha(0,t) = 0 \quad \text{(A6)}$$

$$C(H,t) = 0 \quad \text{(A7)}$$

$$\alpha(H,t) = 0 \quad \text{(A8)}$$

[76] By neglecting solution for transient period, the analytical solution for the concentration of conservative matter $C(z, \infty)$ at a steady state is

$$C(z,\infty) = 1 - \frac{z}{H}, \quad \text{(A9)}$$

and the age concentration $\alpha(z, \infty)$ at a steady state is

$$\alpha(z,\infty) = \frac{Hz}{6K}\left(1 - \frac{z}{H}\right)\left(2 - \frac{z}{H}\right). \quad \text{(A10)}$$

[77] The analytical solution for water age $\alpha(z, \infty)$ at a steady state is

$$a(z,\infty) = \frac{\alpha(z,\infty)}{C(z,\infty)} = \frac{Hz}{6K}\left(2 - \frac{z}{H}\right). \quad \text{(A11)}$$

[78] According to equation (A11), the age is inversely proportional to the vertical diffusivity coefficient but is proportional to water depth.

[79] We present vertical distribution of $C(z, \infty)$, $\alpha(z, \infty)$, and $\alpha(z, \infty)$ in the case with a water depth of 60 m and a vertical diffusivity coefficient of 0.001 m$^2$ s$^{-1}$ in Figures A1b, A1c, and A1d, respectively. With the same parameters, we used the numerical module for vertical diffusion to solve the above problem defined by equations (A1)–(A8). The corresponding

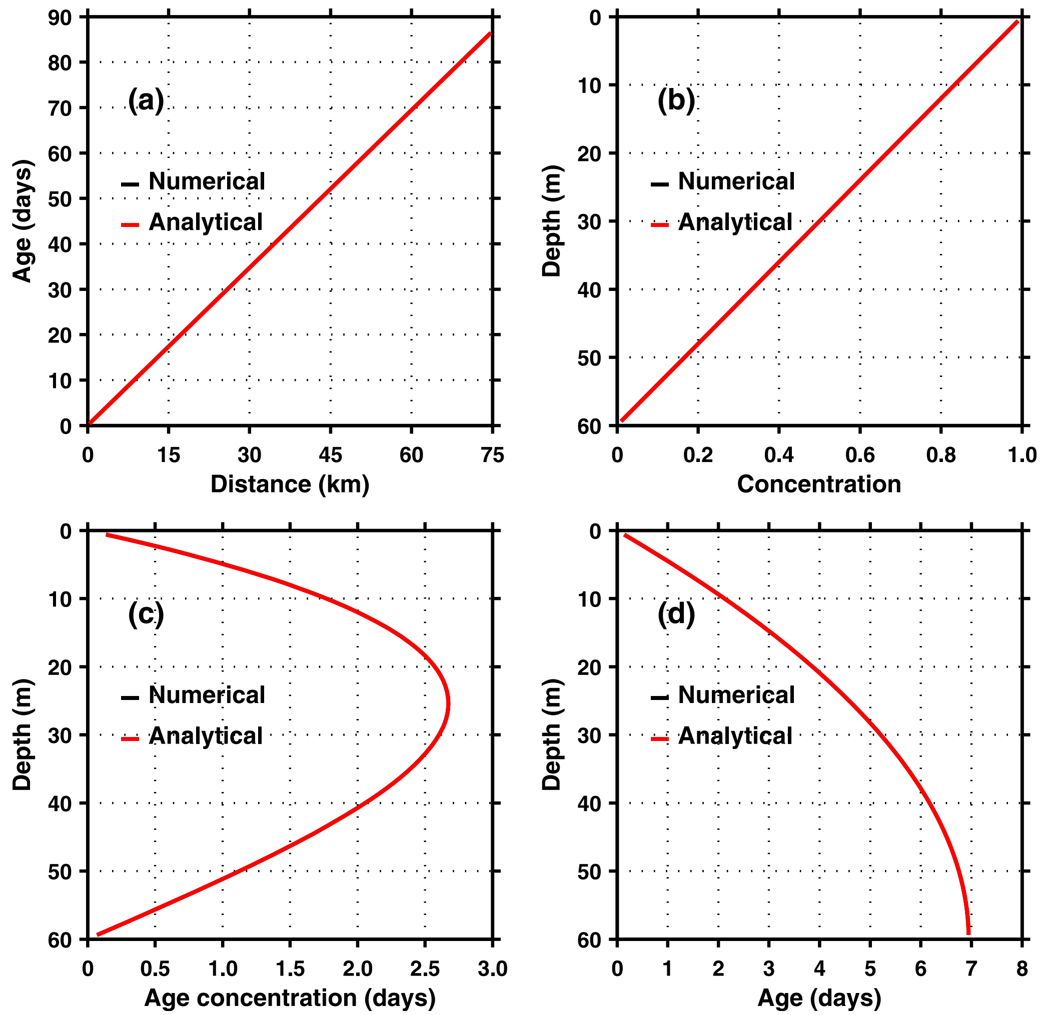


**Figure A1.** Comparison of the numerical results and analytical solutions for water age in (a) a case with a constant current (0.01 m $s^{-1}$) and (b–d) a case with constant vertical diffusion coefficient (0.001 $m^2$ $s^{-1}$). See Appendix A for a description of each case.

numerical solutions at a steady state are also presented in Figures A1b, A1c, and A1d. Again, a good agreement between numerical results and analytical solutions is evidenced in the figures.

[80] Finally, we consider the water age in a one-dimensional flow with constant velocity $u(>0)$ and horizontal diffusivity $K$ in a domain $-\infty < x < \infty$. Differing from first problem, this problem considers horizontal diffusion and therefore can be used to check the numerical module for horizontal diffusion. According to *Deleersnijder and Delhez* [2004], the analytical solution for water age $a(x, t)$ whose age is prescribed to 0 at x = 0 is

$$a(t,x) = t\left(1 - e^{2x} I_{3/2}\right) + e^{2x} I_{1/2}, \tag{A12}$$

where,

$$I_\beta(t,x) = \frac{|x|}{\pi^{1/2}} \int_0^t \theta^{-\beta} e^{-\theta - x^2/\theta} d\theta. \tag{A13}$$

[81] In equations (A12) and (A13), $t$, $a$ and $x$ are dimensionless variables that are defined by dividing original time and space variables by $4K/u^2$ and $4K/u$, respectively.

[82] Assuming $u$ = 0.01 m $s^{-1}$, $K$ = 15 $m^2$ $s^{-1}$, we numerically solved the equations for water age in a one-dimensional flow. Figure A2 presents the horizontal distribution of water age ($a$) along one-dimensional space ($x$) at different time ($t$) from both numerical module and analytical solution (equation (A12)). Again, a good agreement between numerical results and analytical solutions is obtained. At time $t$ = 1/3, low water age is concentrated at $x$ = 0 (Figure A2a). As time increases, the maximum water age increases (see ordinate of each panel in Figure A2). Meanwhile, the low water age propagates in positive direction of $x$ with speed larger than $u$. This occurs in the transition region where the slope of age to $x$ is less than 1. However, in the region upstream of the transition region (i.e., region close to $x$ = 0), the slope of age to $x$ is equal to 1, indicating the propagation speed of $u$. The distribution of low water age in region of $x < 0$ is due to horizontal diffusion.

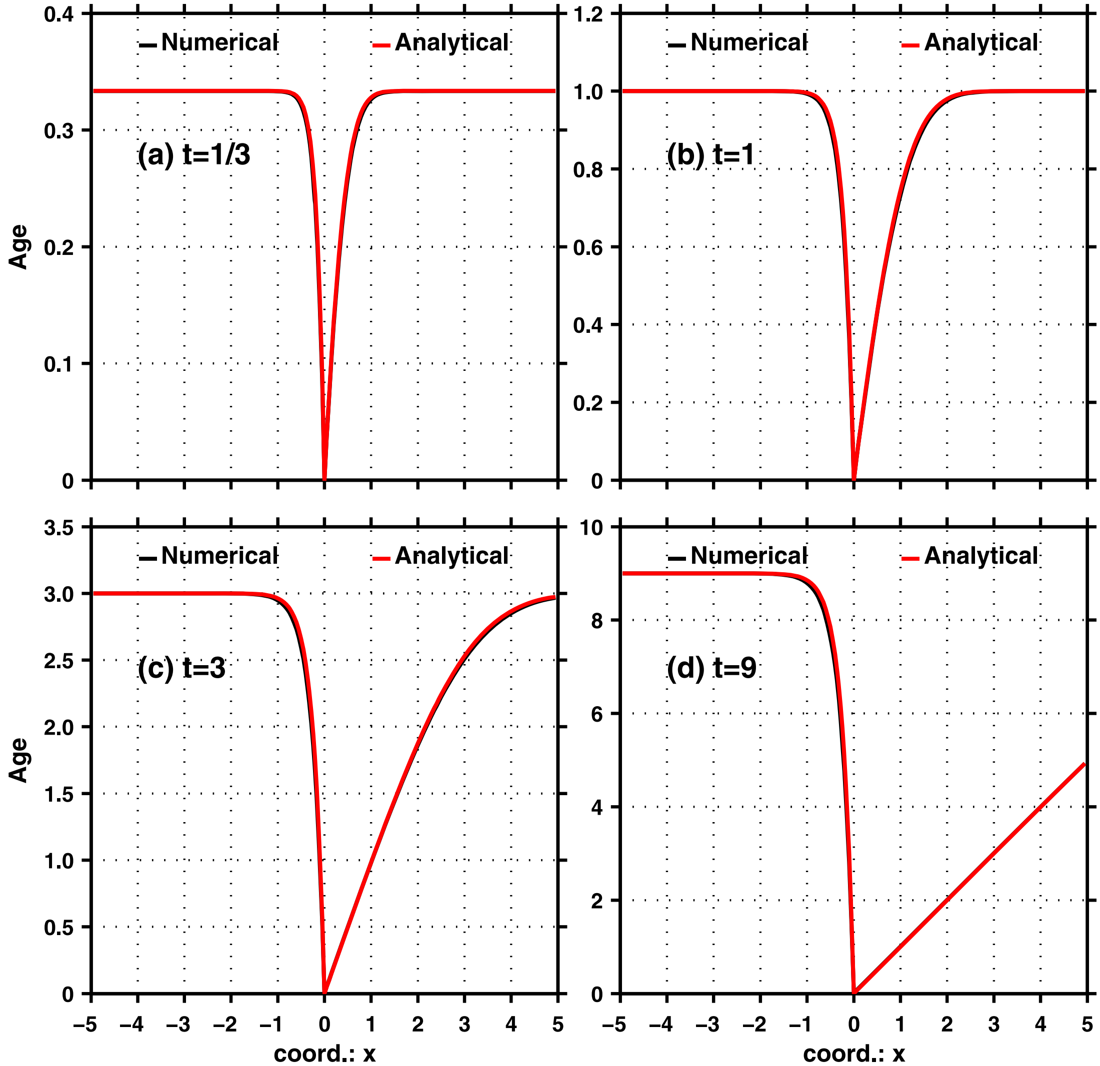


**Figure A2.** Comparison of the numerical results and analytical solutions for the water age at time (a) $t = 1/3$, (b) $t = 1$, (c) $t = 3$, and (d) $t = 9$ in a case with a constant current ($u = 0.01$ m $s^{-1}$) and constant horizontal diffusion coefficient ($K = 15$ $m^2$ $s^{-1}$). The age *a*, time *t*, and coordinate *x* are dimensionless variables. See Appendix A for a description on the problem and solution.

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