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Influence of a Water Regulation Event on the Age of Yellow River Water in the Bohai

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Abstract Abrupt changes in freshwater inputs from large rivers usually imply regime shifts in coastal water environments. The influence of a water regulation event on the age of the Yellow River water in the Bohai was modeled using constituent-oriented age and residence time theory to better understand the change in the environmental function of the hydrodynamic field owing to human activities. The water ages in Laizhou Bay, the central basin, and the Bohai strait are sensitive to water regulation. The surface ages in those areas can decrease by about 300 days, particularly in July, and the age stratification is also strengthened. A water regulation event can result in declines in the water age in early July ahead of declines in the water age under climatological conditions (without the regulation event) by about 1 and 5 months in the central basin and Laizhou Bay, respectively. The change in the coastal circulation due to the water regulation event is the primary reason for the change in the Yellow River water age. The high Yellow River flow rate can enhance the density flow and, therefore, reduce the age of the Yellow River water. The subsequent impact of a single water regulation event can last about 1.0 to 4.0 years in different subregions.

Key words water regulation event; water age; constituent-oriented age and residence time theory; Yellow River; Bohai

1 Introduction

A quantitative evaluation of river water transport processes in coastal waters will benefit the understanding of marine environmental issues (*e.g.*, eutrophication). The water age is a useful auxiliary variable to describe water transport timescale (Bolin and Rodhe, 1973; Takeoka, 1984; Delhez *et al.*, 2014), which is defined as the time elapsed from the departure of a water parcel from a source to its arrival at a location of interest (Bolin and Rodhe, 1973; Takeoka, 1984; Delhez *et al.*, 2014). Constituent-oriented age and residence time theory (CART, see www.Climate.be/cart) (Deleersnijder *et al.*, 2001) has been widely used to calculate the water ages in coastal sea areas (*e.g.*, Shen and Haas, 2004; Shen and Lin, 2006; Meier, 2007; Shen and Wang, 2007; Liu *et al.*, 2008; Gong *et al.*, 2009; Hong *et al.*, 2010; Wang *et al.*, 2010; Hong and Shen, 2012; Liu *et al.*, 2012; de Brye *et al.*, 2013; Wang *et al.*, 2013; Ren *et al.*, 2014; Wang *et al.*, 2015; Yuan *et al.*, 2016).

Located in the northwestern Pacific Ocean, the Bohai is a shallow semi-enclosed sea and is connected to the Yellow Sea through the Bohai Strait (Fig.1). It covers a surface area of 7.7×10^4 km^2 (117˚35´–122˚25´E, 37˚07´–41˚00´N) and has an average depth of about 18 m. The Bohai can be geographically divided into five major subregions: Laizhou Bay, the central basin, Bohai Bay, Liaodong Bay, and Bohai Strait. The Yellow River, which is one of the largest rivers in East Asia, discharges a substantial amount of fresh water with sediments and nutrients into the Bohai. Liu *et al.* (2012) investigated the spatial and temporal distributions of the age of Yellow River water in the Bohai under climatological conditions. Since 2002, the Yellow River Conservancy Commission has carried out water regulation events, typically in June and July, to create a balance between water and sediment (*e.g.*, Li, 2002; Wu *et al.*, 2015). It is important to know how water regulation events affect the transport timescale of Yellow River water in the Bohai. In this study, the age of Yellow River water in the Bohai was simulated over a

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water regulation event.

This study is organized as follows. The hydrodynamic model and the age model are described in Section 2. Section 3 presents the spatial and temporal changes in the age of Yellow River water due to the water regulation event. In Section 4, the influencing dynamic factors are identified, and the impact of a single water regulation event is also discussed. The results of this study are summarized in Section 5.

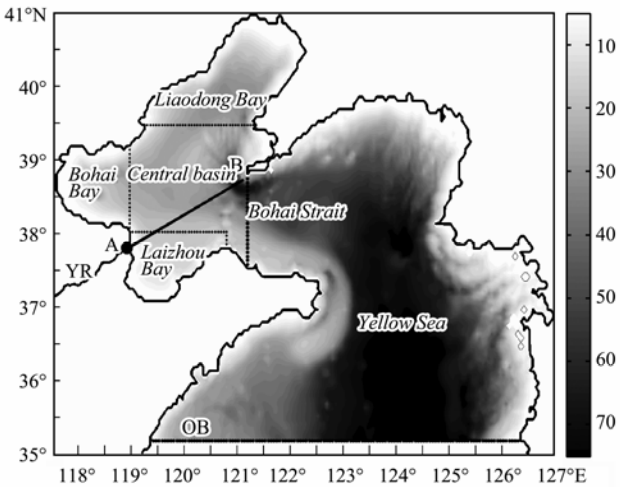

Fig.1 Model domain and bathymetry (units: m). The black dot designates the position of the Yellow River mouth. The solid line denotes Transect AB. The dashed lines demarcate the subregions of the Bohai. The line labeled OB indicates the location of the model open boundary.

2 Model Description

The Princeton Ocean Model (POM) used in this study is from Wang *et al.* (2008). The horizontal grid resolution is 1/18˚ in both the zonal and meridian directions and there are 21 sigma levels in the vertical direction. Detailed descriptions of the hydrodynamic model are provided in Mellor (2004) and Wang *et al.* (2008). The Yellow River discharge data during the water regulation event were recorded at Lijin Station in 2010. It should be noted that the water regulation event mainly changed the seasonal variation in river discharges. However, there was difference between climatological annual discharges and the year 2010 discharges. To eliminate the difference, the 2010 discharge data were multiplied by R1/R2, where R1 and R2 are the climatological and 2010 annual discharges of the Yellow River, respectively. The Yellow River discharges with and without the water regulation event are shown in Fig.2. It should be noted that the hydrodynamic field was calibrated in Wang *et al.* (2008). The simulation results of the harmonic constants of four major tidal constituents (M_2, S_2, K_1, and O_1) at 29 stations and the distributions of water temperature and salinity in the Bohai were in good agreement with the observations (see Figs. 4–7 in Wang *et al.*, 2008).

The water age module used in this study is based on CART (Deleersnijder *et al.*, 2001) and from Liu *et al.* (2012). According to CART, the mean age of a water parcel can be calculated using the concentration C and the age concentration β transport equations:

$$\frac{\partial C}{\partial t} + \nabla(\boldsymbol{u}C - \boldsymbol{K}\nabla C) = 0 \ , \tag{1}$$

$$\frac{\partial \beta}{\partial t} + \nabla(\boldsymbol{u}\beta - \boldsymbol{K}\nabla \beta) = C \ , \tag{2}$$

where $\boldsymbol{u}$ is the velocity vector and $\boldsymbol{K}$ is the diffusivity tensor. The mean age a of the water parcel then can be calculated as follows:

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

The concentration of Yellow River water in a given grid C is the ratio of the volume of Yellow River water to the total water volume within the grid domain. The values of C therefore range from 0 to 1. The open boundary of the outer sea was set along the line labeled OB in the southern part of the Yellow Sea (Fig.1), allowing water exchange between the Bohai and the Yellow Sea through the Bohai Strait. Liu *et al.* (2012) verified the age module by comparing numerical results with three typical analytical solutions. The same three solutions were used to check the present numerical module, which is used to solve 1) the advection process only, 2) the diffusion process only, and 3) the combined processes of advection and diffusion.

Table 1 shows the numerical experiments in this study. The models without and with the water regulation event

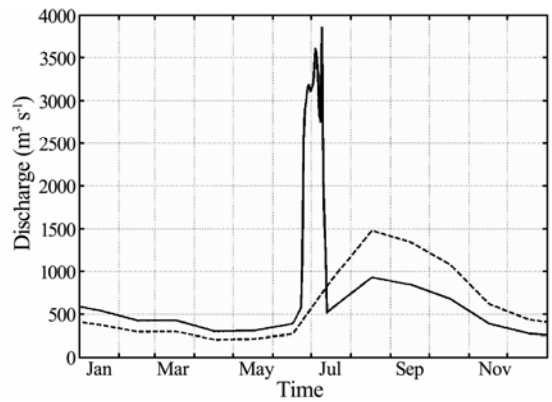

Fig.2 Yellow River discharges (units: $m^3 s^{-1}$) for the control case (dashed line) and Case 2 (solid line).

Table 1 Numerical experiments

Case	Hydrodynamic model	Age model	Note/usage
1	Climatological hydrodynamic field	Climatological river discharge	The control case; without considering the water regulation event
2	With the water regulation event	With the water regulation event	To study the influence of the water regulation event on water age
3	With the water regulation event	Climatological river discharge	To reveal the different roles of the hydrodynamic field and river
4	Climatological hydrodynamic field	With the water regulation event	discharges

are denoted as the control case (*i.e.*, the climatological state, or Case 1) and Case 2, respectively. The modeling results for the control case are from Liu *et al.* (2012). In addition, two other cases (Case 3 and Case 4) were designed to determine governing dynamic factors, which are described in Section 4.1.

3 Response of the Yellow River Water Age to the Water Regulation Event

3.1 The Horizontal Distribution

We mainly focused on the horizontal distribution of the surface water age as well as the concentration of the Yellow River water in the Bohai because freshwater is lighter than seawater. In the north temperate zone, February, May, August, and November are usually regarded as the typical months of winter, spring, summer, and autumn, respectively. Because the water regulation event lasted from June to July (Fig.2), the ages and the concentrations of the Yellow River water in June and July are shown together with those in February, May, August, and November (Fig.3). The surface age of the Yellow River water was low in the vicinity of the Yellow River mouth and increased with distance from the Yellow River mouth under Case 2, while the surface concentration of the Yellow River water was high at the river mouth and decreased with distance from the river mouth (Fig.3). There were more significant seasonal variations in the horizontal distribution of the age and the concentration of the Yellow River water in Laizhou Bay, south of the central basin, and in the Bohai Strait than in other areas of the Bohai (*i.e.*, the northern central basin, Bohai Bay, and Liaodong Bay). A notable spread of the Yellow River water was found towards the northeast offshore from the Yellow River mouth in July and a southward spread in Laizhou Bay in November, which was consistent with the results for the control case (Wang *et al.*, 2008; Liu *et al.*, 2012).

The difference between Case 2 and the control case for the surface water ages and concentrations are shown in

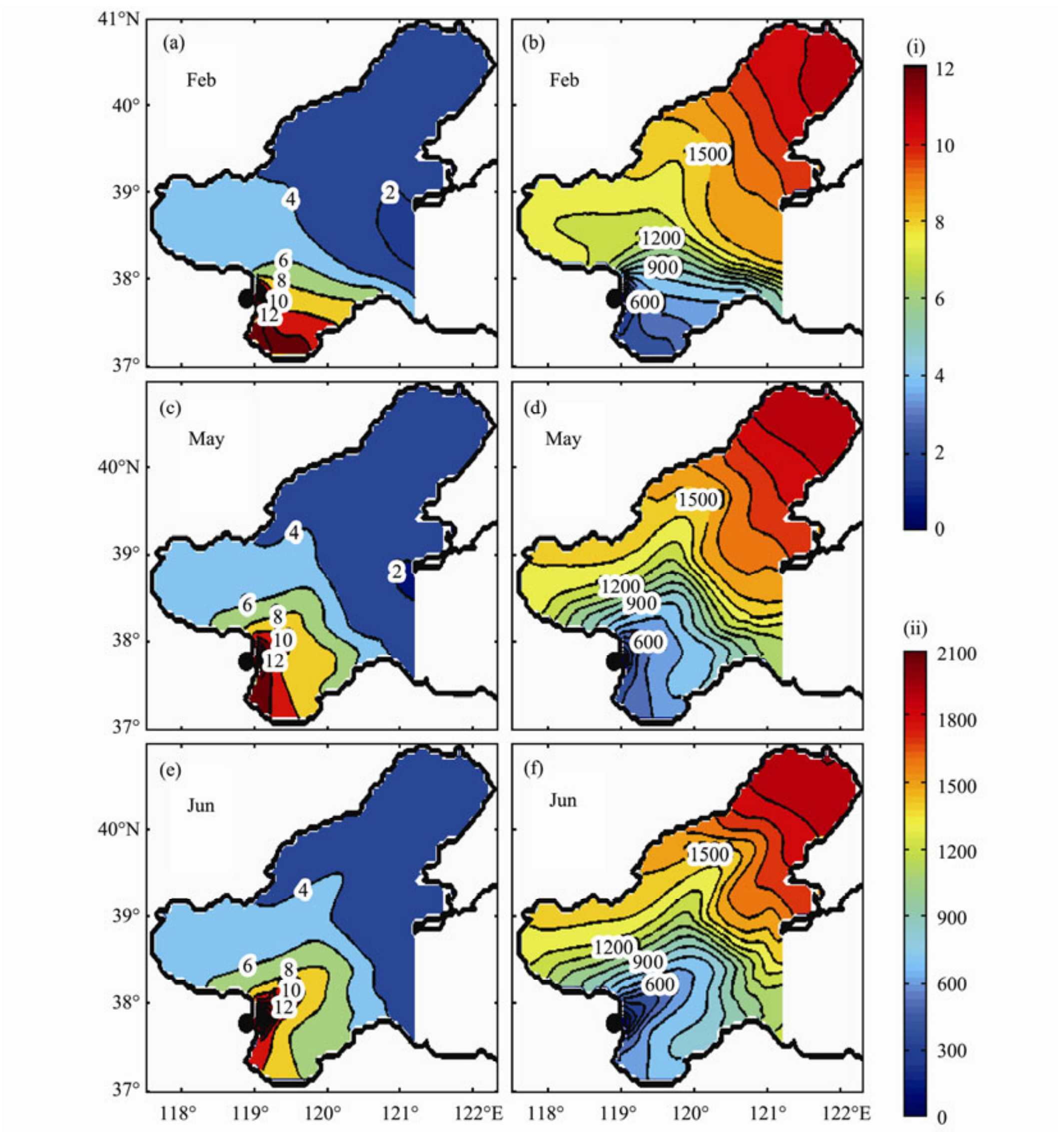

Fig.3 (a)–(f) Horizontal distributions of the surface concentration (left panels, unit: %) and age (right panels, units: d) of the Yellow River water for Case 2 in (a, b) February, (c, d) May, (e, f) June. The color legend shows the range of (i) concentration and (ii) age, respectively. The contour interval for concentration is 2% and that for age is 100 days.

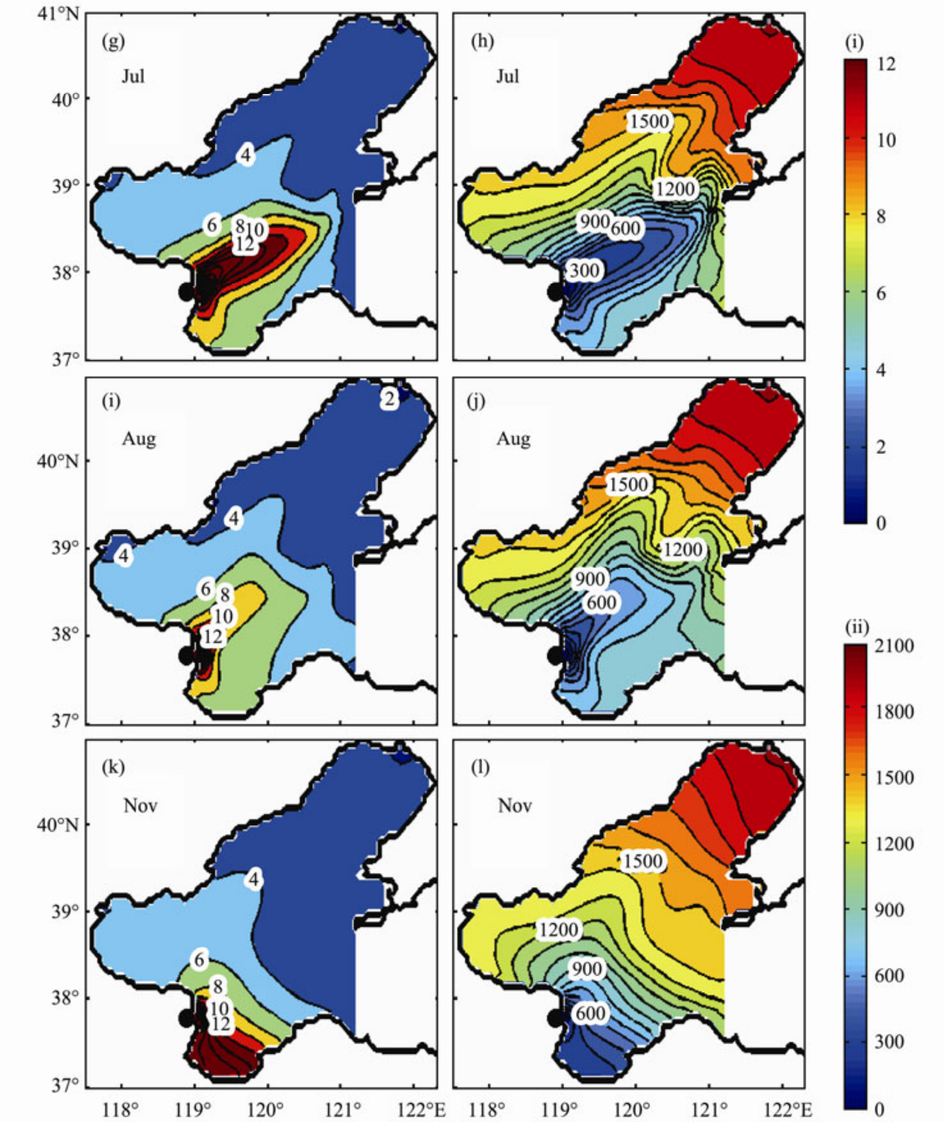

Fig.3 (g)–(l) Horizontal distributions of the surface concentration (left panels, unit: %) and age (right panels, units: d) of the Yellow River water for Case 2 in (g, h) July, (i, j) August, and (k, l) November. The color legend shows the range of (i) concentration and (ii) age, respectively. The contour interval for concentration is 2% and that for age is 100 days.

Fig.4, which illustrates that the influence of the water regulation event on the surface age and concentration of the Yellow River water has a distinct seasonal pattern (Fig. 4). In February, the most notable decrease in the Yellow River water age (about 50 days) and increase in the Yellow River water concentration occurred near the Yellow River mouth. The water age also decreased and the concentration increased along the west coast of Laizhou Bay. Nevertheless, the ages and the concentrations in the middle and eastern part of Laizhou Bay, the central basin, Bohai Bay, and south of the Bohai Strait increased and decreased, respectively. The most notable increase in the water age (about 100 days) occurred in the eastern part of Laizhou Bay (Figs.4a and 4b). In May, the areas where the age decreased spread to the middle of Laizhou Bay, the central basin, and southern part of Bohai Bay, while the concentration increased in these areas. The most notable increase in age (about 50 days) occurred near the Bohai Strait (Figs.4c and 4d). The Yellow River discharge abruptly increased from about 400 $m^3 s^{-1}$ on 16 June to >2700 $m^3 s^{-1}$ on 25 June due to the water regulation event (Fig.2). The artificial flood lasted approximately half a month (Fig.2) and contributed about 20% of the total annual Yellow River water that was discharged to the Bohai Sea. In June, the Yellow River water decreased in age and increased in concentration in the areas of the Bohai, except in the eastern part of Laizhou Bay, the northern part of Bohai Bay, and in Bohai Strait. It is noteworthy that the age decreased by about 150 days near the river mouth (Figs.4e and 4f). In the following month (*i.e.*, July), the age of the Yellow River water decreased throughout almost all of the Bohai; however, the concentration of the Yellow River water increased. The substantial decrease in age and increase in concentration occurred in Laizhou Bay, followed by the central basin and even the Bohai Strait, with a maximum decrease of about 300 days in water age (Figs.4g and 4h). Unlike the previous months, the Case 2 results in August indicated that the Yellow River water in the vicinity of the river mouth became less concentrated and older than that of the control case. The increase in water age and the decrease in concentration gradually weakened with increasing distance from the river mouth. In contrast, the water in the eastern part of Bohai remained more concentrated and younger than the control case; however, the age difference decreased to about 150 days near the Bohai Strait (Figs.4i and 4j). In November, the older water area extended from the vicinity of the river mouth to the entire Laizhou Bay, the southern part of the central basin, and the southern part of Bohai Bay, because of less Yellow River water in these areas. The younger water area remained smaller, with a maximum decrease of only about 50 days in water age in the northern part of the Bohai Strait (Figs.4k and 4l).

3.2 The Vertical Distribution

Located on the main axis of the diluted water, Transect AB (see the location in Fig.1) was selected to study the impact of the water regulation event on the vertical distribution of the Yellow River water age (*e.g.*, Wang *et al.*, 2008). The water age was always lower near the Yellow River mouth than that near the Bohai Strait regardless of the water regulation event (Fig.5). The age of the Yellow River water was nearly homogeneous vertically in the autumn and winter (figure not shown) but was stratified in the spring and summer (Fig.5). The stratification in May occurred from the mouth of the Yellow River to the middle of the central basin and was about 5 m beneath the surface. It spread northeastward in June. By July and August, the front of the younger water dominated all of Transect AB and the mixed layer deepened.

However, the water regulation event changed the vertical distribution of the stratification in the spring and summer. In May, the stratification of the water age near the river mouth strengthened (Fig.5b) compared with the control case (Fig.5a). Because of the water regulation event in June, the increasing stratification area spread to

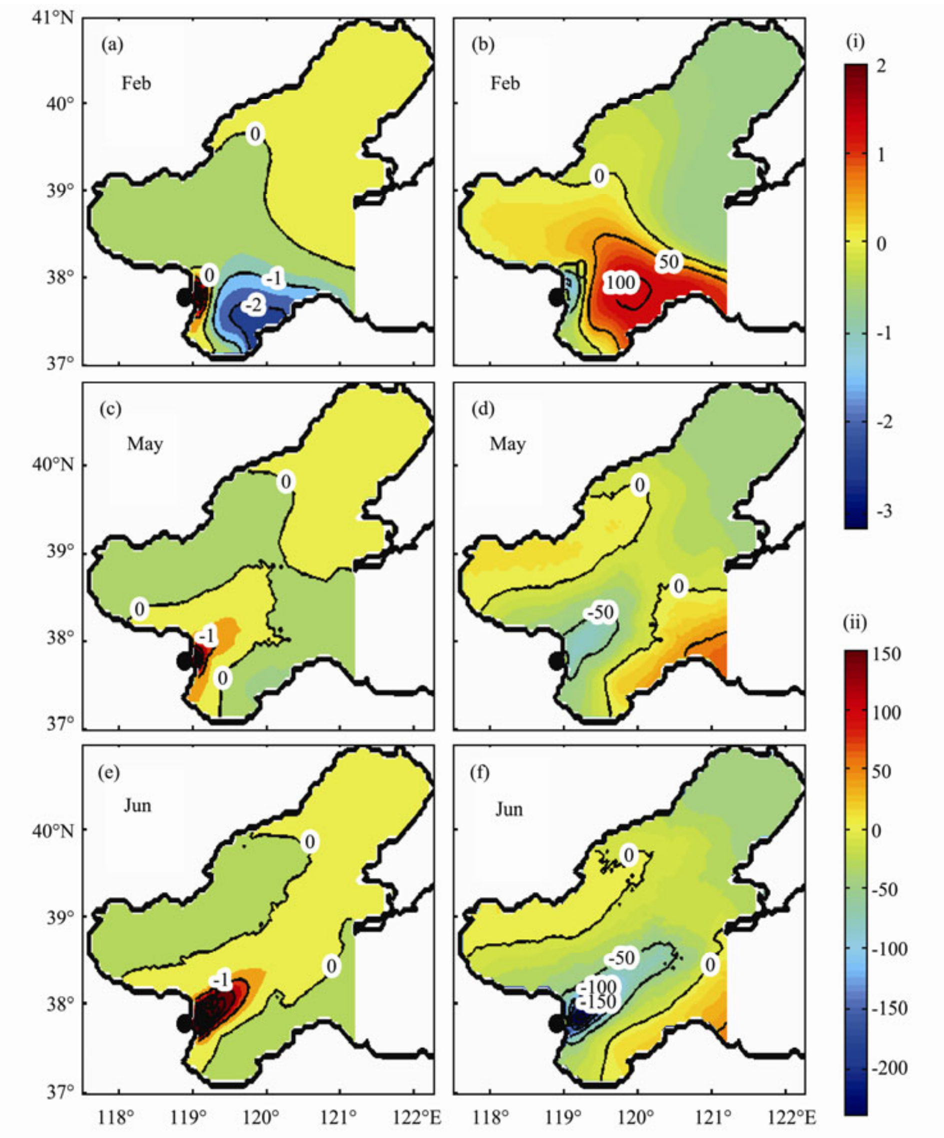

Fig.4 (a)–(f) Differences in surface concentration (left panels, unit: %) and age (right panels, units: d) of the Yellow River water between Case 2 and the control case in (a, b) February, (c, d) May, (e, f) June. The color legend shows the range of (i) concentration and (ii) age, respectively. The contour interval for concentration is 1%, and for age is 50 days.

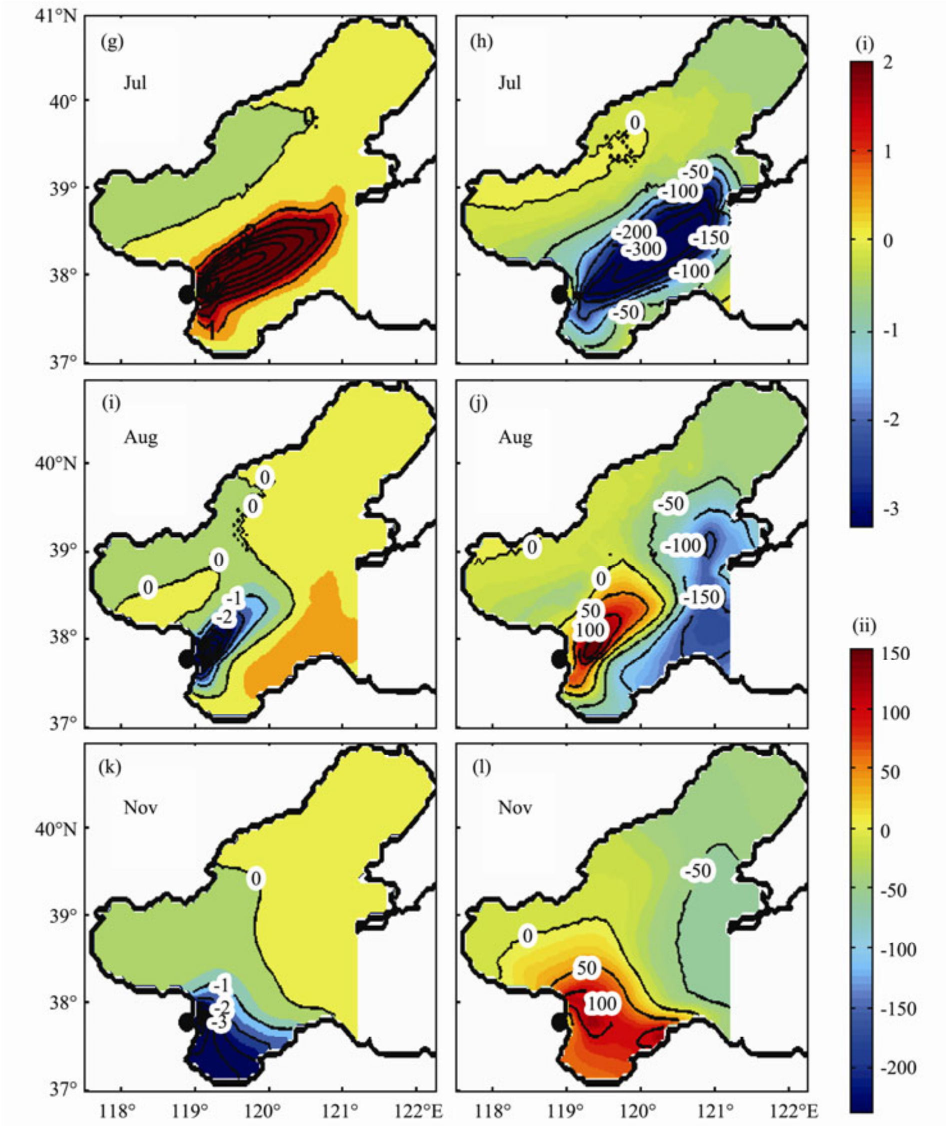

Fig.4 (g)–(l) Differences in surface concentration (left panels, unit: %) and age (right panels, units: d) of the Yellow River water between Case 2 and the control case in (g, h) July, (i, j) August, and (k, l) November. The color legend shows the range of (i) concentration and (ii) age, respectively. The contour interval for concentration is 1%, and for age is 50 days.

Laizhou Bay and the southern part of the central basin. For example, in the western part of Laizhou Bay, the water age difference between the bottom and surface layers (WADBS) increased from about 260 days (Fig.5c) in the control case to about 410 days in Case 2 (Fig.5d). In July, the stratification along the entire Transect AB was stronger than that of the control case. In the western part of Laizhou Bay, the WADBS increased from about 420 days in the control case to about 620 days in Case 2 and from about 520 days to about 760 days in the central basin (Figs.5e and f). In August, the age became less stratified because of the less Yellow River discharge from the regulation event. For example, the WADBS in the western part of Laizhou Bay recovered from about 480 days in the control case (Fig.5g) to about 260 days in Case 2 (Fig.5h).

3.3 The Average Surface Water Ages in Subregions

Freshwater from the Yellow River is mainly transported in the upper layer. Thus, the average ages at the surface were our primary concerns for the five Bohai subregions (*i.e.*, Laizhou Bay, the central basin, Bohai Bay, Liaodong Bay, and the Bohai Strait). Unlike the other subregions, Laizhou Bay and the central basin were sensitive to the water regulation event (Fig.6).

In comparison with the control case, the water regulation event reshaped the annual cycle of the Yellow River discharge by adding an artificial flood peak (>2700 $m^3 s^{-1}$) from late June to early July to the natural discharge peak (about 930 $m^3 s^{-1}$) in mid-August (Fig.2). Consequently, the lowest age (<450 days) was identified approximately on 9 July in Laizhou Bay, which responded to the artificial flood peak almost instantaneously, with a time lag of about 2 days (solid lines in Figs.2 and 6a). This first low-age period occurred ahead of that in the control case by about 5 months (Fig.6a). Similar to the control case, the other low-age period in Case 2 appeared in early December, with a time lag of approximately about 110 days to

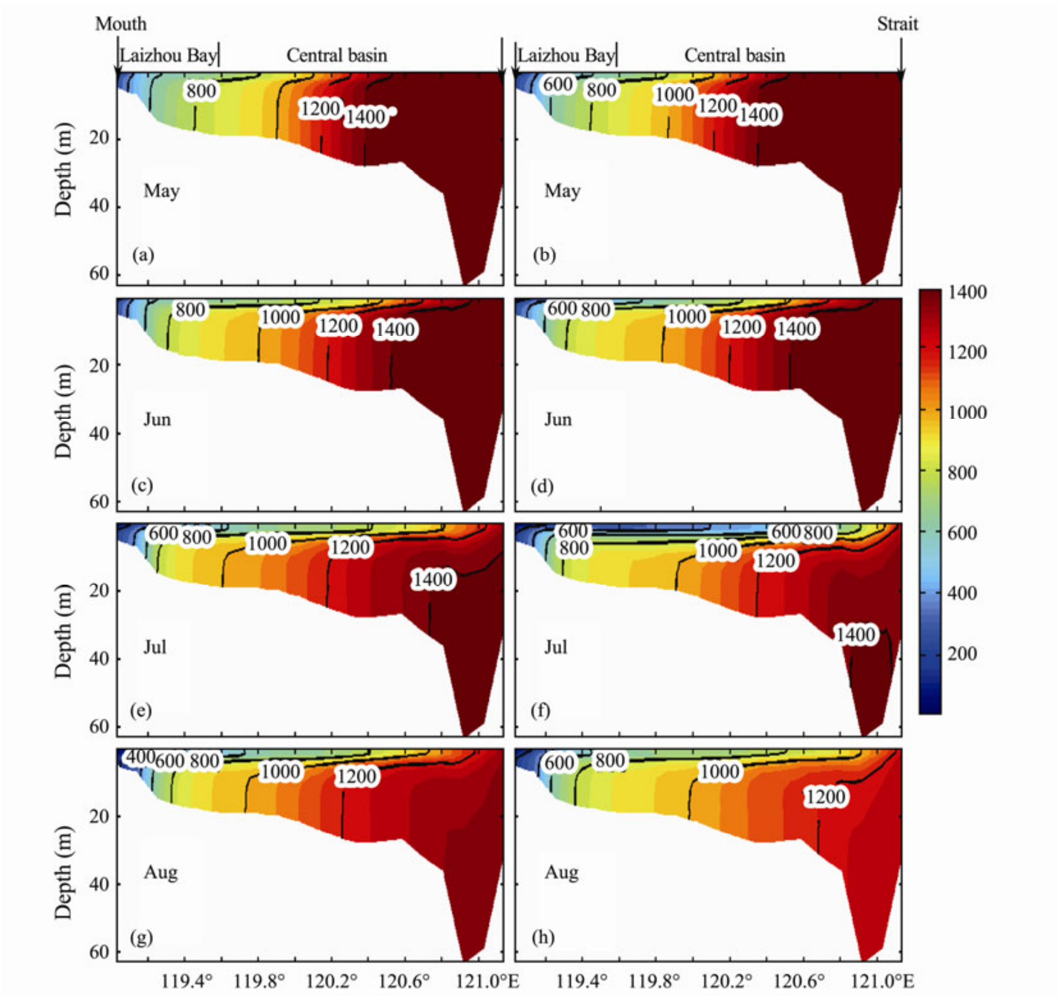

Fig.5 Vertical distributions of the Yellow River water age (units: d) along Transect AB for the control case (left panels) and Case 2 (right panels) in (a, b) May, (c, d) June, (e, f) July, and (g, h) August. The contour interval is 200 days.

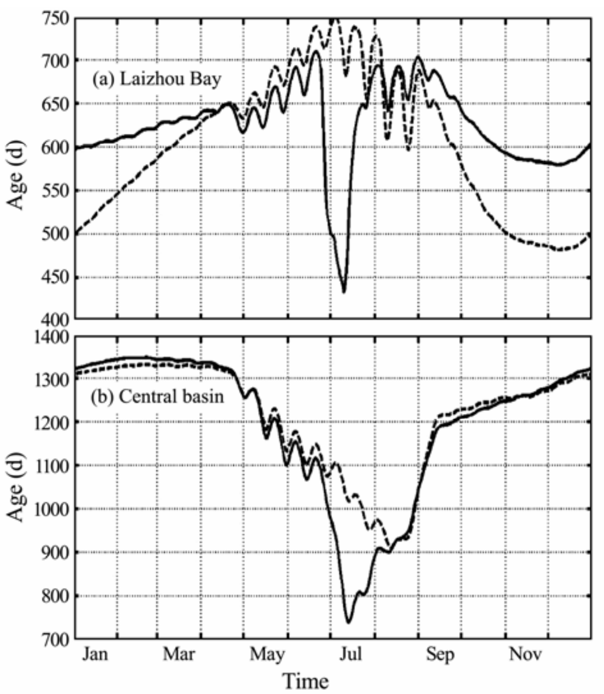

Fig.6 Average surface ages of the Yellow River water (units: d) in (a) Laizhou Bay and (b) the central basin. The dashed and solid lines represent the control case and Case 2, respectively.

the natural discharge peak in mid-August. There was a distinct decrease in lag time with increased discharge. This indicates that the abrupt increase in freshwater input from the Yellow River accelerates its transport timescale substantially.

When Yellow River water discharges into the Bohai, the orientation of the main axis of the diluted water is northeastward. The central basin receives the highest amount of the Yellow River freshwater first. Hence, the age of the Yellow River water in the central basin responds to the change in the Yellow River discharge synchronously. Compared with the control case, the low-age period occurred in early July, an advance of about 1 month, and the marked decrease in the age of the Yellow River discharge was about 170 days (Fig.6b).

4 Discussion

4.1 Dynamic Factors

The water regulation event abruptly and substantially altered the temporal variation of the Yellow River discharge (Fig.2) and also changed the hydrodynamic field in the Bohai. Therefore, Cases 3 and 4 were conducted (Table 1) to determine which dynamic factor (*i.e.*, hydrodynamic field or riverine input) governed the difference in the water age between Case 2 and the control case (Figs.4 and 5). Case 3 used the regulated flow, whereas the Yellow River open boundary in the age module remained unchanged (*i.e.*, the same as that in the control case). Case 4 took into account the river discharge in the age module as in Case 2, whereas the hydrodynamic model was the same as that in the control case. Compared with the control case, Case 3 (Fig.7), resulted in an age difference that was notably close to that in Case 2 (Fig.4), but Case 4 did not show the similarity in the age difference (Fig.8). Hence, the change in hydrodynamic field was an important factor for interpreting the influence of the water regulation event on the Yellow River water age relative to the river open boundary condition in the age module. The circulation differences between Case 2 and the control case at the surface and in Transect AB are shown in Figs.9 and 10, respectively, which explain the influence of the hydrodynamic field on water age.

In February, the increase in riverine freshwater input (Fig.2) resulted in slightly stronger surface density current in the offshore direction off the river mouth (see the red arrow in Fig.9a), and, therefore, the slightly younger

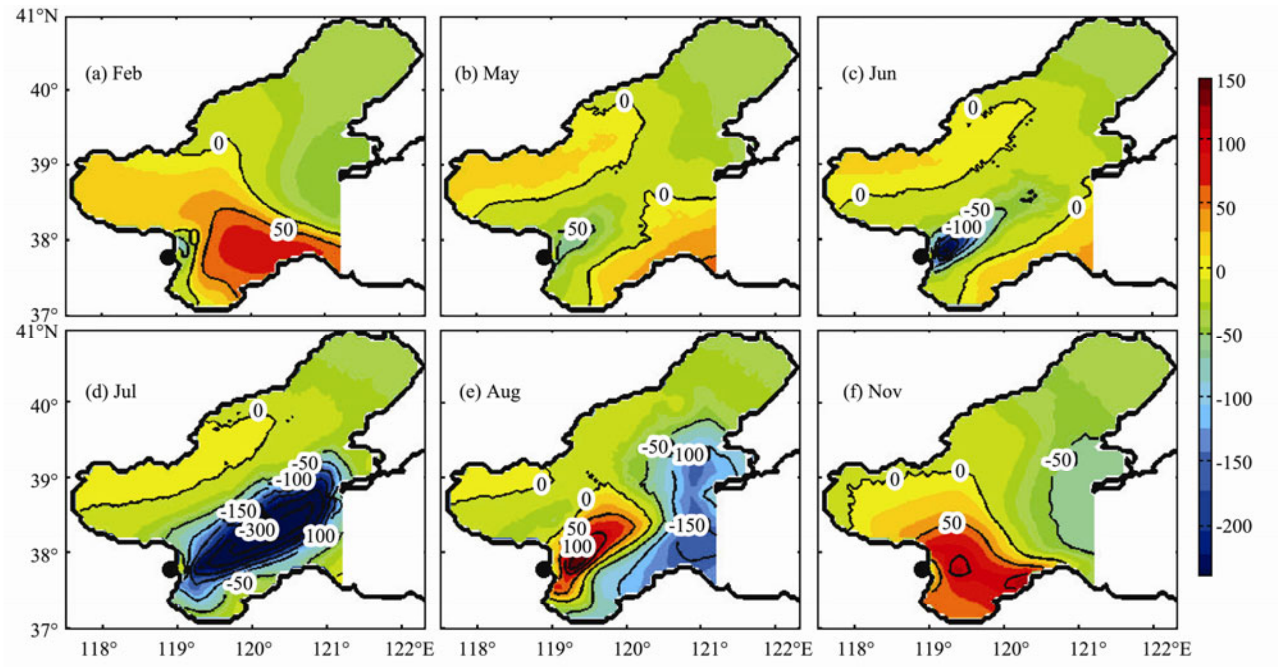

Fig.7 Differences in the surface ages of the Yellow River water (units: d) between Case 3 and the control case in (a) February, (b) May, (c) June, (d) July, (e) August, and (f) November. The contour interval is 50 days.

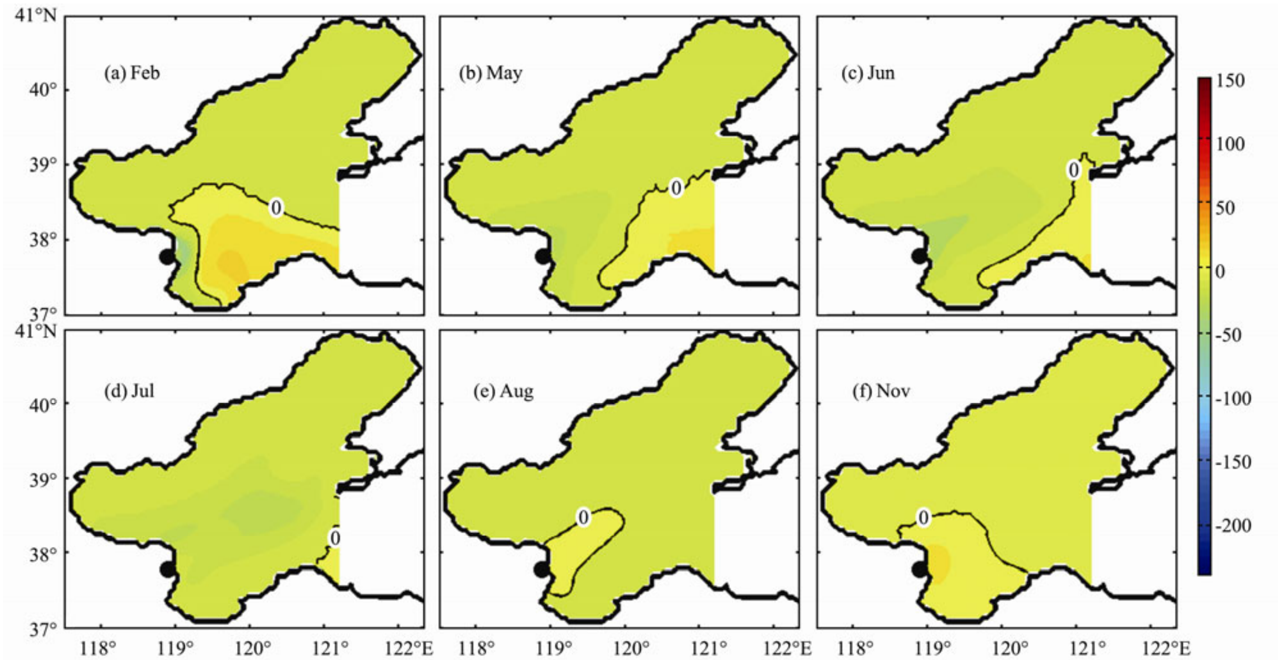

Fig.8 Differences in the surface ages of the Yellow River water (units: d) between Case 4 and the control case in (a) February, (b) May, (c) June, (d) July, (e) August, and (f) November. The contour interval is 50 days.

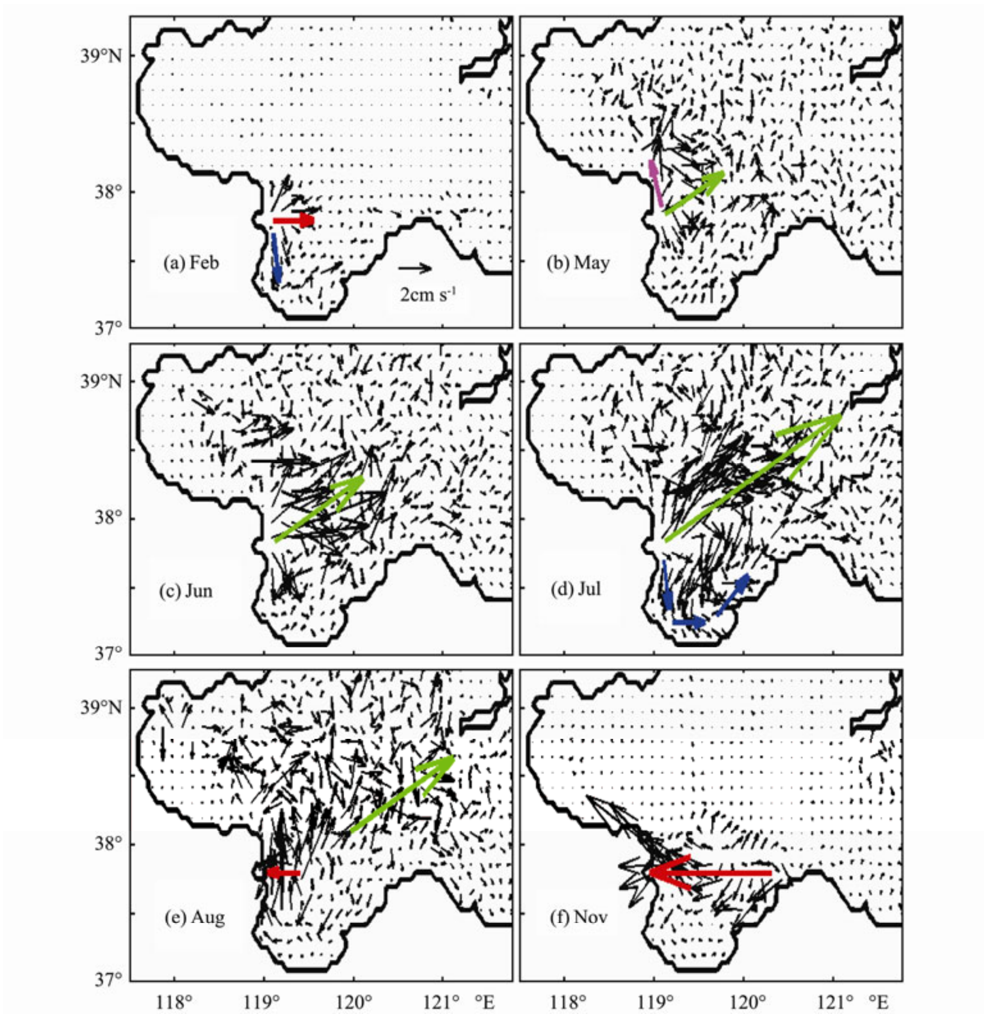

Fig. 9 Differences in the surface circulation between Case 2 and the control case in (a) February, (b) May, (c) June, (d) July, (e) August, and (f) November. The color arrows indicate the direction of water transport.

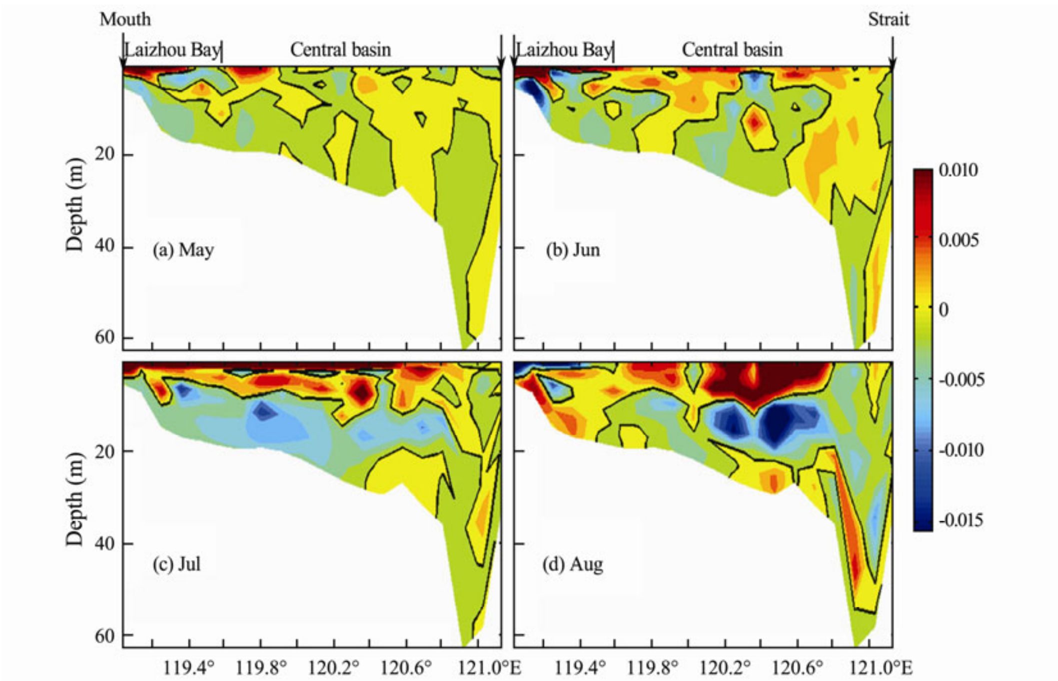

Fig.10 Vertical differences in circulation component projected onto Transect AB (units: $\mathrm{m\,s^{-1}}$) between Case 2 and the control case in (a) May, (b) June, (c) July, and (d) August. The positive values denote the flow direction from A to B, whereas the negative values denote from B to A.

water in the vicinity of the river mouth (Figs.4b and 7a). The southward current (see the blue arrow in Fig.9a) along the west coast of Laizhou Bay also induced the low-age water (Figs.4b and 7a). In May, another low-age water area was identified in the central basin and the southern part of Bohai Bay, except for the areas in the vicinity of the river mouth and the western part of Laizhou Bay (Figs.4d and 7b). This low-age water area was due to the plume of the Yellow River water discharging towards the central basin and Bohai Bay (see the purple and green arrows in Fig.9b). The current shear in vertical was enhanced in the vicinity of the river mouth (Fig.10a), resulting in a stronger age stratification (Figs.5a and 5b). In June, the water regulation event produced a stronger surface current flowing towards the central basin (see the green arrow in Fig.9c, and Fig.10b), resulting in a decrease in the surface water age and an increase in the age stratification in Laizhou Bay and the central basin (Figs.4f and 7c; Figs.5c and 5d). In July, the stronger surface current covered the central basin and even reached the Bohai Strait (see the green arrow in Fig.9d, and Fig. 10c). In addition, starting from the river mouth, a current flows along the shoreline in Laizhou Bay, and then to the eastern part of the Bay (see the blue arrow in Fig.9d). Those changes in the hydrodynamic field induced the substantial decrease in the water ages in Laizhou Bay, the central basin, and the Bohai Strait (Figs.4h and 7d) and enhanced the age stratifications in those areas (Figs.5e and 5f). In August, the riverine discharge in Case 2 was lower than the control case (Fig.2). As a result, the surface circulation turned shoreward in the vicinity of the river mouth (see the red arrow in Fig.9e, and Fig.10d), which was opposite to that in the previous months (*e.g.*, Figs. 9a–d and 10a–c). Accordingly, the surface water age increased (Figs.4j and 7e) and the age stratification decreased (Figs.5g and 5h) near the river mouth. The surface current in the eastern part of the central basin continued to flow toward the Bohai Strait (see the green arrow in Fig.9e, and Fig.10d), which reduced the water age (Figs.4j and 7e). In November, there was a strong surface current that moved from the eastern coast of Laizhou Bay to the river mouth (see the red arrow in Fig.9f), which prevented the Yellow River water from leaving Laizhou Bay and consequently increased the water age (Figs.4l and 7f).

In general, as the riverine freshwater input increased, the density current increased and the water age decreased. This phenomenon was noted in the spring, summer, and autumn. In the winter, the density current also occurred in the vicinity of the river mouth, while water columns were well mixed by strong wind in the other areas (Wang *et al.*, 2008).

4.2 Residence Time of the Yellow River Water Under the Influence of the Water Regulation Event

The residence time was calculated to further evaluate the influence of the water regulation event on the transport processes of Yellow River water in the Bohai using the approach proposed by Takeoka (1984):

$$\theta = \int_0^{\infty} \frac{C(t)}{C(t_0)} \mathrm{d}t , \tag{4}$$

where θ is the average residence time, t_0 denotes the initial time, t is the time afterward ($t-t_0>0$), and $C(t)$ is the concentration of Yellow River water. The average residence time of the Yellow River water throughout the surface of the entire Bohai was 883 days under the influence of the water regulation event. It varied spatially as follows: 270 days in Laizhou Bay, 612 days in the central basin, 1110 days in Bohai Bay, and 1515 days in Liaodong Bay (Fig.11). Compared with the residence time without the influence of the water regulation event, the average residence time of the Yellow River water in the central basin decreased by about 17%, while the residence time in the other subregions was less sensitive to the influence by the event. The average residence time represents the transport timescales of the Yellow River water throughout the Bohai and its subregions and is an indication of the how long a water regulation event can influence the environment in the Bohai.

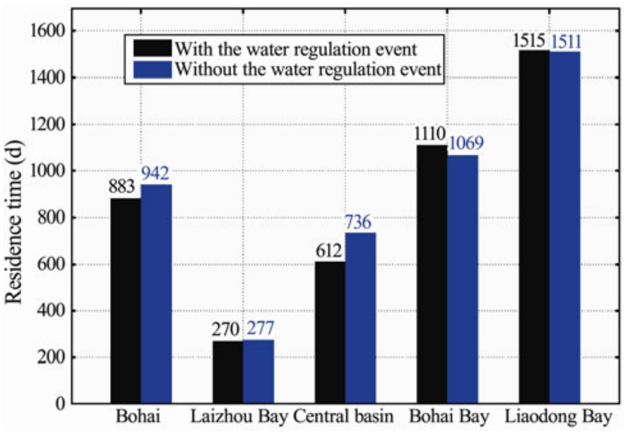

Fig.11 Average residence times (unit: d) of the Yellow River water in the surface of the Bohai and its subregions. The black and blue bars show the average residence time of the Yellow River water with and without the water regulation event, respectively.

5 Summary

The influence of the Yellow River water regulation event on the Yellow River water age in the Bohai was studied using CART. The water regulation event primarily affected the Yellow River water age in Laizhou Bay, and then in the central basin and Bohai strait. These three subregions were characterized by a lower age of the Yellow River water at the surface, with a maximum age decrease of about 300 days, and notable age stratification, especially in July. The artificial flood peak caused by the water regulation event produced the youngest water in Laizhou Bay and the central basin in early July. In comparison with the climatological condition without the regulation event, the first time period with the lowest age occurred about 1 and 5 months earlier for the central basin and Laizhou Bay, respectively, as the water regulation event was triggered. The change in the hydrodynamic field due to the water regulation event primarily affected the Yellow River water age. The higher Yellow River flow rate enhanced the density current and therefore reduced the age of the Yellow River water. Under the water regulation event, the duration change because of the Yellow River water ranged from about 1.0 to 4.0 years in the Bohai Sea and its subregions.

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