



Advances on Coastal and Estuarine Circulations Around the Changjiang Estuary in the Recent Decades (2000–2020)

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Advances on the circulation in the Changjiang Estuary and adjacent East China Sea (ECS) and Yellow Sea (YS) coastal waters in the recent decades (2000–2020) are synthesized in this review. The circulation over the complicated bathymetry in the region is locally driven by winds, tides, as well as riverine discharge, and is remotely influenced by shelf currents between the 50 and 100-m isobaths through the cross-shelf exchanges. The interchange of the momentum and the freshwater pathway inside the Changjiang Estuary are jointly determined by tides and seasonally varying discharge and winds over the shelf. The buoyant waters are trapped inside the bulge that forms and expands over the shelf to the west of the 30-m isobath in the vicinity of Hangzhou Bay and the Changjiang Estuary. These buoyant waters are exported offshore by the shelf current, tidal mixing, and variations of wind patterns, forming the Changjiang River plume, which shows notable seasonality due to the reversal of both winds and shelf currents in the ECS and YS. Extensive spatial irregularities in the form of freshwater patches are present along its pathway to the Tsushima Strait in summer and to the Taiwan Strait in winter, respectively. Tides and the bathymetry irregularity have recently been found to play critical roles in determining the cross-shelf exchanges of water mass and momentum along the pathway of the ECS coastal current, and along this pathway, a year-round upslope intrusion of shelf waters appears in both summer and winter. Tides also play an important role in altering the expansion of the Changjiang River plume, cross-shelf extrusion of waters, and variation in the Yellow Sea Coastal Current over the shallow Subei Shoal.

Keywords: Changjiang (Yangtze river) estuary, coastal circulation, East China Sea, river plume, bulge

INTRODUCTION

The coastal waters in the East China Sea (ECS) and southern Yellow Sea (YS) are found over their respective shelves to the west of the 50-m isobath, which extends northward from $\sim 25^{\circ}\text{N}$ to $\sim 37^{\circ}\text{N}$ (Figure 1A). These coastal waters are bordered by the southern coast of the Shandong and the coastlines of the Jiangsu, Shanghai, Zhejiang, and Fujian. In the southern ECS, the interlinked

coastal waters mainly extend southwestward, running parallel to the Fujian and Zhejiang coasts to the south of the Changjiang Estuary. The complicated coastlines are composed by many islands, bays, and channels, such as those in the vicinity of the Zhoushan Islands and Changjiang Estuary. Coastal waters in the southern ECS are generally shallower than 50 m, except in some deep channels with depths >100 m among the Zhoushan Islands. The Hangzhou Bay and the Changjiang Estuary widen toward the east and the ECS. The bathymetry of the coastal waters in the southwestern YS is generally characterized by the Subei Shoal (a.k.a. the Yangtze Bank), which extends to the southeast and over which the nearshore waters are generally shallower than 10 m. A northwestward incising submerged valley is surrounded by the 50-m isobath in the northwestern ECS to the southwest of the Subei Shoal. The northwestward extending YS Trough characterizes the bathymetry of the southern YS.

The Changjiang River is the largest river in the East Asia and exports buoyant waters with an averaged discharge rate of $\sim 26,400 \text{ m}^3/\text{s}$ into the ECS and YS (Mei et al., 2015). The water depth in this long estuary is generally shallower than 20 m, and riverine waters rush into the ECS shelf through its complicated passages and channels (**Figure 1B**). The Changjiang Estuary is divided into the North and South Branches by the Chongming Island. In the mid-estuary, the Changxing Island separates the South Branch into the North and South Channels. The anthropogenic underwater infrastructure and the navigation channel in the vicinity of Hengsha Island further divide the South Channel into the North and South Passages. This complicated bathymetry, which will be explored in the following sections, greatly alters the characteristics of the circulation and freshwater as well as the interaction between the estuarine circulation and the coastal circulation at the mouth of the Changjiang Estuary. Coastal circulations over the complicated nearshore bathymetry to the west of the 50-m isobath in the ECS and southern YS are jointly forced by variable multiscale local forcing, including tides, winds, and river discharge. Coastal and estuarine circulations also interact with shelf circulations, for example, the Taiwan Warm Current (TWWC), Yellow Sea Warm Current (YSWC, in winter), and Yellow Sea Cold Water Mass (YSCM, in summer) as well as the Kuroshio in the Okinawa Trough and the Taiwan Strait Current (TSC).

The Kuroshio and the intrinsic characteristics of the ECS shelf current act as the major external factors that influence coastal and estuarine circulation. The annually average volume transport of the Kuroshio is $\sim 24.37 \text{ Sv}$ in the central ECS (Liu et al., 2021), and a stronger/weaker Kuroshio is usually present in the warm/cold half of the year in the northern hemisphere (Yang et al., 2018). Observations based on the conservation of the total water volume over the shelf reveal that the integrated volume transport by the Kuroshio intrusion into the ECS is $\sim 1.3\text{--}1.4 \text{ Sv}$ (Isobe, 2008). The shelf currents, which originate from the southern ECS, interact with the circulation between the 100 and 200-m isobaths and flow into the Tsushima Strait, exiting into the southern Japan Sea further north (Gan et al., 2016; Lie and Cho, 2016; Li et al., 2016). The northward penetrating warm waters in the ECS are from the TSC and those that originated from the Kuroshio intrusion over the shelf to the northeast of Taiwan

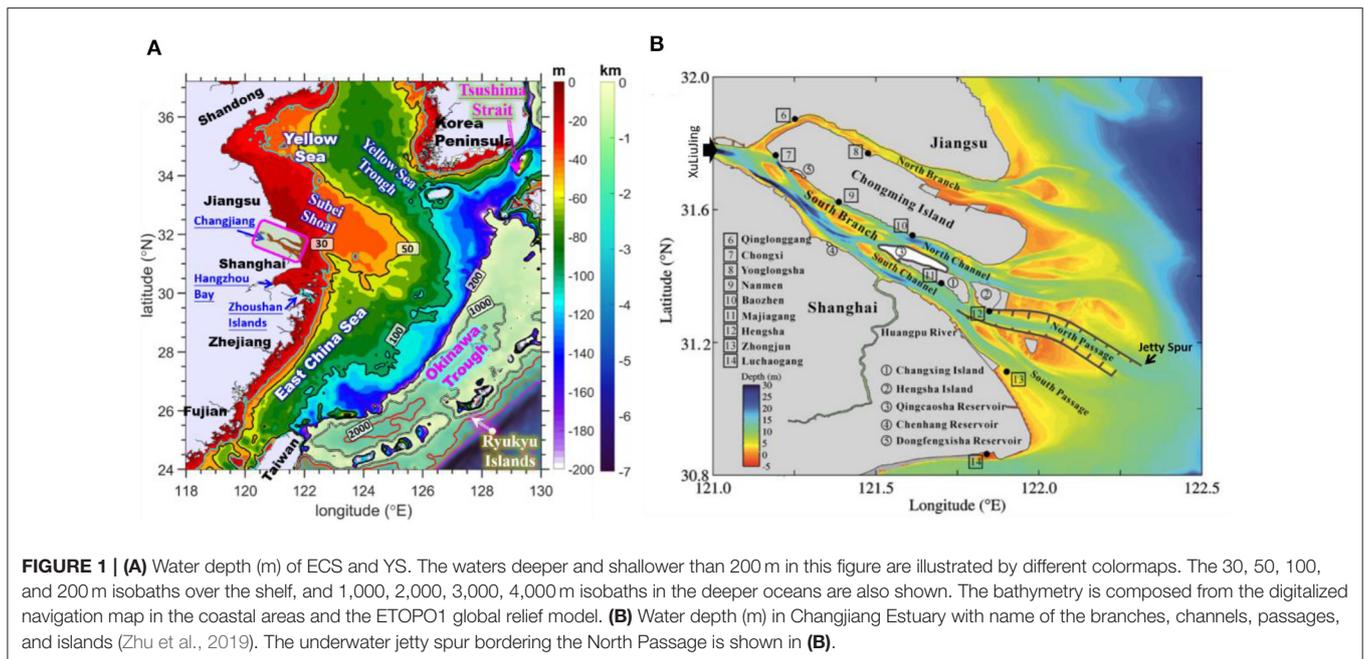
[synthesized by Hu and Wang (2016) and simulated by Yang et al. (2013), among others]. They form the northward flowing TWWC, which greatly modulates the shoreward intrusion of shelf waters toward the coastal seas off the Zhejiang and Fujian coasts in summer. This northward current has also been found to be largely regulated by the southwestward flowing Zhe-Min Coastal Current (ZMCC), which carries buoyant waters from the Changjiang River to the Taiwan Strait in winter. The TSC and the interactions between the TWWC and ZMCC are also greatly regulated by synoptic wind variability, which establishes downshelf propagating coastally trapped waves that alter the respective intensity of these currents (Li and Huang, 2019).

In the southern YS, a notable northward penetration of warm waters, indicative of YSWC, is observed in the Yellow Sea Trough in winter. Previous studies have recognized that the YSWC mainstream shifts westward toward the eastern flank of the shallower Subei Shoal (Lin and Yang, 2011; Lin et al., 2011), where tides have been suggested to play important roles in regulating the regional circulation. The circulation in summer is mainly governed by the monsoonal winds, tides, Changjiang River Plume and the YSCM, which resides from the YSWC in winter and is sealed in the lower layers of the Yellow Sea Trough in summer. The expansion of the Changjiang River Plume, whose underlying dynamics will be further explored in the following sections, shows notable spatial variations in its pathways in the ECS and southern YS.

We revisit recent understandings on estuarine circulation in the Changjiang River Estuary and coastal circulations in the ECS and southern YS, and pay more attention on the circulation dynamics than the recent comparative reviews, which focus more on the seasonal (Guan and Fang, 2006; Lie and Cho, 2016) and interannual (Matsuno, 2020) variabilities of the shelf waters and biogeochemical processes (Chen J. et al., 2020) to the further seaward of the studied area. The rest of this manuscript is arranged as follow. In Section Changjiang estuarine circulation, we synthesize the characteristics of the circulation in the Changjiang Estuary. The expansion of the Changjiang river plume is synthesized in Section Changjiang River plume. Section Coastal Currents in the ECS and southern YS summarizes recent advances on the coastal currents in the ECS and southern YS, and the impact of circulation dynamics on hypoxia off the Changjiang Estuary is synthesized in Section Impacts of Circulation on Hypoxia off the Changjiang Estuary. The summary and prospects are given in Section Summary and Prospects.

CHANGJIANG ESTUARINE CIRCULATION

The Changjiang River is the largest river in the East Asia and the fifth largest river worldwide in terms of riverine discharge. The maximum/minimum discharge rate of Changjiang River appears in summer/winter ($\sim 40,000/\sim 13,000 \text{ m}^3/\text{s}$) (Luan et al., 2016). The buoyant waters that flow through the complicated passages and channels of the Changjiang Estuary (**Figure 1B**) form the interactive estuarine circulation, and its underlying mechanisms have often been investigated in studies of the general flow pattern [e.g., Xue et al. (2009) and the references therein]. Majority of the



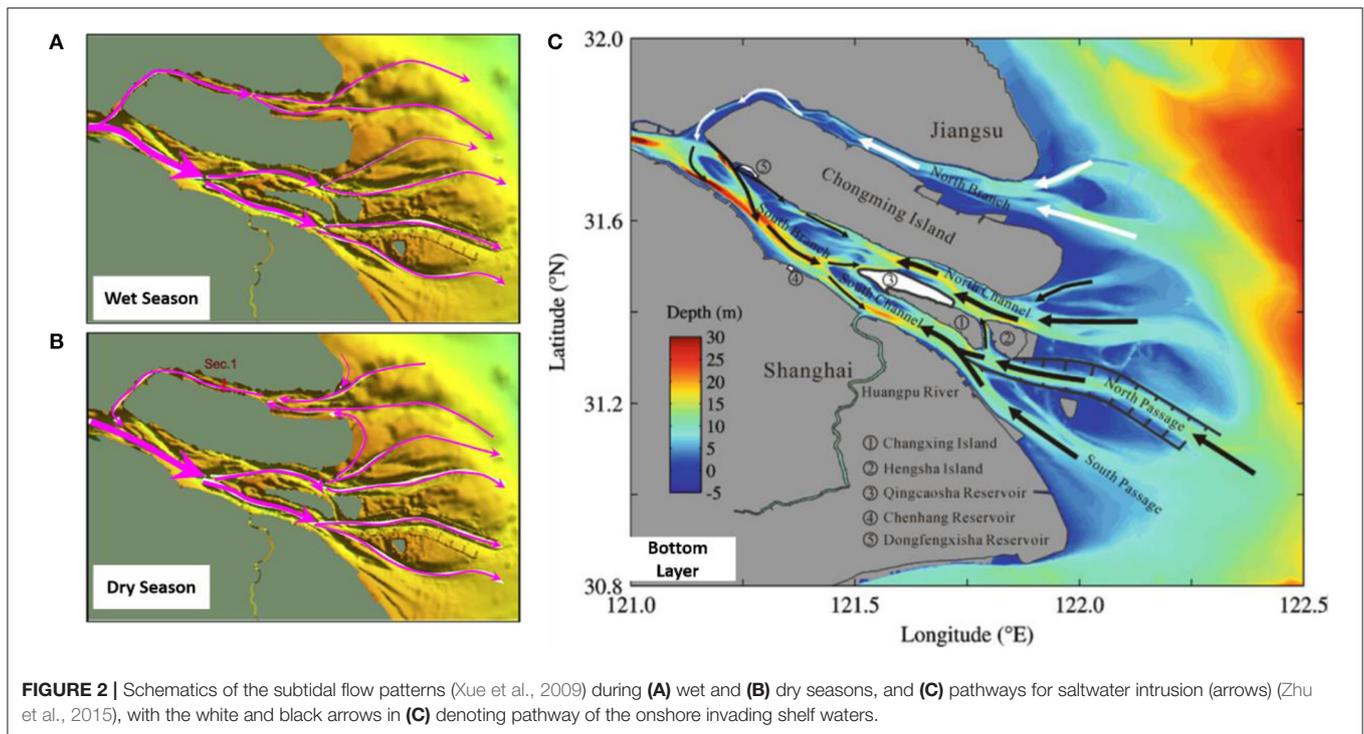
riverine runoff rushes into the ECS through the South Branch, which, in winter, counts for over 95% of the discharges (Li et al., 2010). The partitioning of buoyant waters toward the North Branch (<5%) oscillates with flood and ebb tides and varies in the spring and neap tidal cycles. The main features of Changjiang estuarine circulation are an onshore intrusion of shelf waters and the extrusion of buoyant waters, which are also modulated by anthropogenic activities. It should be noted that although we, respectively, reviewed the characteristics of the intrusion of shelf waters and the extrusion of riverine waters, the exchange flow in the Changjiang Estuary is composition of these bidirectional circulations with the general circulation pattern is shown in the **Figure 2**, and the underlying dynamics are synthesized in the follow contents.

Intrusion of Shelf Waters

The Changjiang estuarine circulation is generally stronger in summer (**Figure 2A**) than that in winter (**Figure 2B**). In addition to the intrusion of the shelf waters from the lower layer at the mouth of the estuary (**Figure 2C**), there is a long-distance intrusion of saltwater from the North Branch to the South Branch (white arrows in North Branch and the black arrows in South Branch in **Figure 2C**). This intrusion, due to its notable threat on freshwater supply of the neighboring cities, is the focus of the previous studies in the recent decades and it is reported to occasionally inject saltwater into the mainstream freshwater of the South Branch (Xu et al., 2018). This intrusion is regulated by the intensity of upstream riverine runoff and the tidal range over the shelf neighboring the North Branch in the lower estuary (Wu et al., 2006), as well as winds over the shelf off the Changjiang Estuary (Zhang et al., 2017; Lyu and Zhu, 2018; Zhu et al.,

2018a; Zhu et al., 2019). The respective responses of the estuarine circulation in those complicated branches and channels to those forces will be further synthesized in the following contents.

The intrusion of salt waters from the North Branch to the South Branch is greatly altered by the tidal and wind forcings. The non-linearity of the tidally induced momentum flux and bottom friction over the abrupt topography induce tidal rectification (Xue et al., 2009). The invasion of shelf waters through the North Branch then occurs when the intensity of the freshwater flow in this branch is weaker than that of the tidally rectified current. The influence of non-linear tidal rectification in modulating the exchanges among the channels and passages in the Changjiang Estuary network was also described in detail by Alebregtse and de Swart (2016), which further emphasized the attenuation of the semi-diurnal tide by extensive riverine discharge in summer. The associated non-linear river-tide interactions diminish the semi-diurnal variation of the surface-elevation amplitude and thus have minimal effects on the tidal velocity amplitude and phase of tidal waves. The numerical experiments in Qiu et al. (2012) showed that the water exchanges between the North Branch and South Branch are much stronger during spring tides than during neap tides. The intrusion of shelf waters from the North Branch toward the South Branch also shows notable seasonality. In winter, the tidally rectified current is intensified to strengthen the intrusion of shelf waters from the North Branch toward the South Branch, when the seaward surface elevation gradient (i.e., barotropic pressure gradient) is reduced by northerly winds (Xue et al., 2009). The estuary-ward Ekman transport by the northerly winds strengthens the intrusion of saltwater toward the South Branch (Li et al., 2010, 2012), and this intrusion is greatly intensified since 1999, possibly due to the more frequent



outbreaks of northerly and northeasterly wind event (Zhang et al., 2019a). Water exchange between the South Channel and North Channel is greatly affected by the variation in wind direction (Li et al., 2012). When the northeasterly wind prevails, saltwater intrusions in the North Channel have been found to be weaker than those imposed by the northerly winds. Li L. et al. (2014) found that the shelf water intrusions in the North Channel are amplified due to the deepening topography mid-channel and to the east of Chongming Island.

In the further downstream, circulations in the South Passage and North Passage are also greatly influenced by tides and winds. The numerical simulations by Wu and Zhu (2010) and Wu et al. (2010) suggested that tidally induced subtidal circulation plays an important role, and Stokes transport due to the propagation of tidal waves has been found to amplify the onshore invasion of shelf waters in the South Passage. This process makes the South Passage the most saline outlet besides the North Branch. The circulation in the North Channel and North Passage is primarily dominated by the extensive seaward export of riverine buoyant waters. Passive tracers deployed in a simulation have further revealed a significant intrusion of saltwater in the South Passage toward the North Passage, and this intrusion has been found to be diminished by northerly winds.

Extrusion of Riverine Waters

The riverine waters mainly extrude out of the Changjiang Estuary through the South Branch. The transport time required for the buoyant waters to travel from the river entrance (XuLiuJing in Figure 1B) to the estuary exit ($\sim 122.5^\circ\text{E}$) is

approximately 23 and 35 days for high and low discharge conditions, respectively (Wang et al., 2010). The time required for the buoyant waters to exit the estuary increases from the North Channel to the South Channel and from the North Passage to the South Passage due to the diversion of freshwater discharge and the increase in bottom friction. The gravitational exchange flow at the exit of the estuary accelerates the seaward export of the buoyant waters from the river entrance further downstream.

This transport time experiences notable seasonality and spring-neap variation (Wang Y. et al., 2015). It is greater in winter compared to that in summer, and the seaward export of freshwater is stronger during the neap-tide period than during the spring-tide period. Similarly, field observations have shown that the residual current in the North Passage is stronger in summer than that in winter, and it is more influential during spring tides than during neap tides (Pu et al., 2015). Tidal stirring, longitudinal and lateral depth-mean straining act as the principal mechanism determining the contrasting mixing intensity observed during spring and neap tides (Pu et al., 2016). The tidal effect is more important in winter, when the discharge rate is greatly reduced, compared to that in summer (Zhang et al., 2017). Tidal waves invade further upstream toward the South Branch in winter (Zhang et al., 2018a). Surface elevation at the upstream of the South Branch is higher in summer than that in winter, while variations of surface elevation is minimal at the estuary exit. In the down-estuary section, a higher barotropic pressure gradient is thereafter established in summer. The lateral circulation in the cross-branch direction is generated by the

barotropic pressure gradient to enhance the intrusion of shelf waters in the North Channel (Zhu et al., 2018b).

Anthropogenic Impacts

Anthropogenic impacts on the Changjiang estuarine circulation are represented by the Three Gorges Dam in the further upstream of the river (not shown), the progressive narrowing of the North Branch and the underwater infrastructure in the North Passage (**Figure 2B**). The impoundment of Three Gorges Dam was considered to greatly alter the streamflow (Zhang et al., 2019b; Wang et al., 2020; Yu et al., 2020a) and nutrient discharges of Changjiang river and thereby have a great potential in altering the hydrographic properties (Yan et al., 2008), sediments (Dai et al., 2016) and biogeochemical processes (Chai et al., 2009) in the estuary and thereafter the coastal seas. The increased discharge rate in the dry season, due to impoundment of Three Gorges Dam could be favorable for ensuring the freshwater supplement (Cai et al., 2019) and has potentials to suppress the injection of saltwater from the North Branch to the South Branch. The incremental anthropogenic impacts, such as the narrowing and shallowing of the North Branch, also progressively reduced the saltwater intrusions from the North Branch to the South Branch, and the topographic changes in the North Channel from 2007 to 2017 strengthened/weakened the intrusion of shelf waters during spring/neap tides (Chen et al., 2019). However, the role of Three Gorges Dam in changing the estuarine and coastal circulations is considered to be secondary referring to the underwater infrastructure in the North Passage (Wu et al., 2018c). The large-scale underwater construction (**Figure 1B**) in the vicinity of Hengsha Island greatly strengthens the tidal current (Zhang et al., 2018a), direction of rotation and vertical structure of the tidal ellipse (Pu et al., 2017) and thereby stability of the inside waters (Wan and Zhao, 2017), thus altering the stratification in the North Passage (Ma et al., 2011; Wan et al., 2014; Chen et al., 2020b). This underwater construction diminishes the freshwater partition in the South Channel while amplifies the onshore intrusion of saltwater in the South and North Passages, and alleviates the invasion of shelf waters in the North Channel by reducing/increasing the partition of riverine waters in the South/North Channel (Zhu et al., 2018a; Zhu et al., 2019). From the North to the South Channel, an anticlockwise circulation anomaly is thereby established (Li et al., 2020). The built underwater jetty spur (**Figure 1B**) has greatly increased the transport time by 50% (Wang et al., 2010). This underwater infrastructure has also been observed to strengthen the southward motion of the Changjiang River plume over the shelf by eliminating the lateral circulation at the estuary exit, where the northeastward extension of the buoyant plume begins (Wu et al., 2018c).

CHANGJIANG RIVER PLUME

The Changjiang River plume is formed by the massive amount of freshwater extruding through the Changjiang Estuary and plays a critical role in determining the regional circulation in the coastal seas. For example, the recent synthesis of previous observations and numerical simulations showed the seasonality of the coastal

circulation over the shelf to the west of the 50-m isobath (Wu and Wu, 2018), and a year-round persisting bottom-trapped plume off the Zhejiang and Fujian coasts is proposed (Zhang et al., 2020). This bottom-trapped plume is critically sustained by extensive tidal mixing, and it imposes an unexpected counterwind southwestward coastal current off Zhejiang in the summers of 2006 and 2009 (Li et al., 2014b).

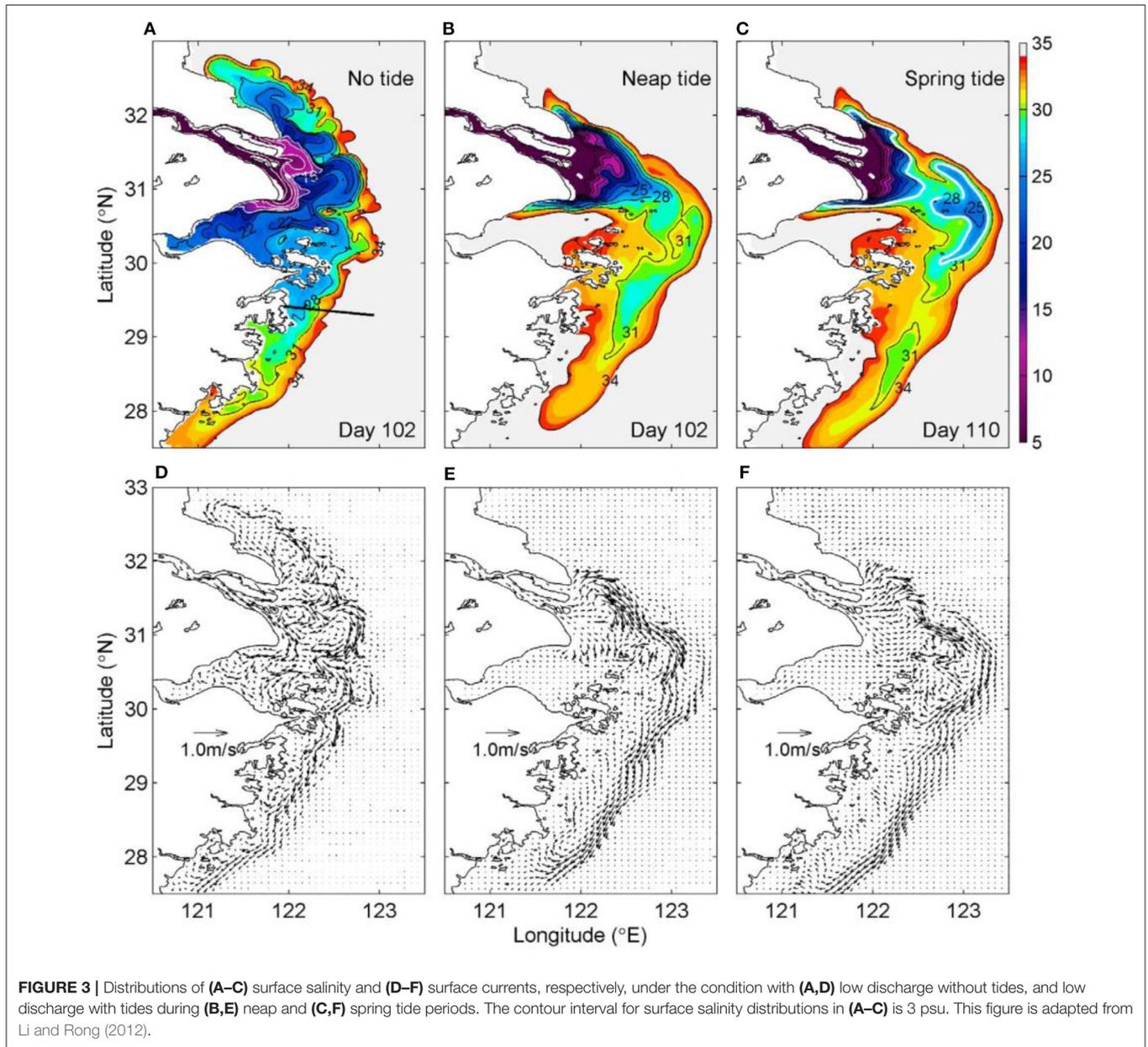
The Changjiang River Plume also interacts with the TWWC in the central ECS shelf, the TSWC in the Tsushima Strait (Isobe et al., 2002), and TSC in the Taiwan Strait (Lie and Cho, 2016), and shows notable seasonality and remarkable spatial variation, which is characterized by distinct flow patterns over the shelf of the coastal sea off the Changjiang Estuary. These freshwaters can also greatly impact the connectivity between the Japan Sea and the northern ECS by altering the baroclinicity of the water in the Tsushima Strait in summer (Isobe et al., 2002; Senjyu et al., 2006). For example, the numerical tracer experiments conducted by Chang and Isobe (2003) showed that 68% of the Changjiang River plume is transported into the Tsushima Strait and the extension of these buoyant waters is strongly constrained by the TWWC. In the following contents, we will further synthesize the spatial characteristics and driving mechanisms of the Changjiang River plume in summer and winter, respectively.

Changjiang River Plume in Summer

The freshwater that rushes out of the Changjiang estuary is arrested by the northward coastal current and northeastward flowing TWWC and widely broadened to the southeast, east, and northeast over the shelf region in the surface layer (Hwang et al., 2014). There is weak bidirectional southwestward and northwestward extrusion of these buoyant waters observed over the coastal seas off Zhejiang and over the Subei Shoal (Kim et al., 2009; Bai et al., 2013; Zhu et al., 2015; Zhang et al., 2020). However, this southwestward branch of the plume cannot travel further southward into the Taiwan Strait (Wu et al., 2018b). The entirety of the plume, which widely spreads over the central and northern ECS and southern YS shelves (Lie et al., 2003), turns northeastward over the shelf to the east of the 50-m isobath and flows toward Cheju Island (Chen et al., 2008). The behavior of the plume in the coastal seas to the west of the 50-m isobath is different from that over the shelf in depths >50 m since the coastal waters are better mixed than those offshore, which is further described below.

Bulge Circulation

Numerous numerical simulations and observations have clearly shown that the buoyant waters from the Changjiang River plume are partially mixed with the saltwater being stored in a bulge over the shelf to the west of the 50-m isobath (Chang and Isobe, 2003; Shan et al., 2009). This bulge, which is enveloped by sharp density fronts (Lu and Shi, 2007), usually bifurcates at the head of the submerged valley that is delineated by the 50-m isobath over the shelf to the southeast of the Changjiang Estuary and then extends northward into the Subei Shoal, southwestward to Hangzhou Bay and then the coastal seas off Zhejiang (Du et al., 2011) (**Figure 3**).



The majority of these plume waters then extend northeastward toward the central ECS shelf and interact with the TWWC.

The characteristics of the circulation of this bidirectional extruding bulge is critically determined by tides (Wu et al., 2018b). The Changjiang River plume in the coastal areas off the estuary disperses eastward and southeastward in the form of “cloudy patches” and that the dispersion direction varies coherently with tides, when steady winds force estuarine and coastal circulations (Shi and Lu, 2011). The strong tidal mixing over the shallow Subei Shoal suppressed the northward extrusion of Changjiang River plume (Wu et al., 2011). The bulge also considerably varies with the spring-neap tide transition (Figure 3), and is mainly limited in the coastal seas to the west of the 30-m isobath during spring tides and extends

further eastward during neap tides when tidal rectification and tidal asymmetry are weak. Tidal asymmetry has been found to establish high pressure at the head of the submerged valley, and the plume is thus guided to extend northeastward at $\sim 122.5^\circ$ E. Although its magnitude is much weaker than that in the southward and northeastward branches, tidally induced Stokes drift transports a small portion of the shallow Subei Shoal in winter (Wu et al., 2014), and the wind can only affect this northward extrusion during the neap-tide period.

Tides also increase the amount of freshwater trapped by the bulge (Figure 3; Li and Rong, 2012; Rong and Li, 2012). The bulge circulation is stabilized and its ballooning is suppressed with time (Figures 3B,C,E,F). Detachment of buoyant waters from the plume occurs during the transition period from

neap to spring tides, when the stratification of the partially mixed plume waters is destroyed and buoyant water patches form, while variation of the Changjiang River discharge rate cannot greatly influence this process of detachment. However, the numerical simulation by Yuan et al. (2016) showed that although the buoyant plume neighboring the Changjiang Estuary instantly (within 1 day) responds to variation in Changjiang River discharge, it takes ~ 15 days for the offshore branches of this plume to respond in summer. Thereby, the response of the detachment of buoyant plume to the changing discharge rate should be further investigated.

Winds may also play a crucial role in detaching buoyant waters during the growth of the bulge (Xuan et al., 2012). Wind-induced mixing and upwelling along the edge of the bulge causes saltwater to detach the buoyant waters over the 30-m isobath. This detachment mainly occurs during the period when the speed of southwesterly winds exceeds 8 m s^{-1} . Thus, the characteristics of the complicated bulge circulation and its dynamics also necessitate further study (Wu et al., 2018b).

Far-Field Plume

Over the ECS shelf to the east of the 50-m isobath, the interaction between the Changjiang River plume and shelf currents is associated with the complicated wind and tidal patterns and the remote influence of previously introduced shelf currents, which alter the pathway of the plume (Figure 4). For example, the long-term satellite observations (Kim et al., 2009, 2014) of Chlorophyll-*a* indicated that the eastward motion of the Changjiang River plume lags behind the variations in river discharge by about 1 to 2 months. Bai et al. (2015) adapted and validated the advanced satellite-derived salinity algorithm in Bai et al. (2013) and reported strong interannual variability in the distribution of the Changjiang River plume (Figure 4), which was partially identified in some earlier satellite observations (Ahn et al., 2008). In addition to the most frequently observed northward and northeastward pathways, Bai et al. (2015) identified two unusual pathways of the Changjiang River plume, which flows into the Cheju and Tsushima Straits without residing over the shelf and flows southeastward in the central ECS (Types 2 and 3 in Figure 4). The plume area estimated in that study is regulated by the intensity of river discharge and winds over the shelf. The arrival of typhoons may also play an important role in altering the variability of the pathways of this plume. For example, Oh et al. (2014) and Hong et al. (2016) proposed an extensive northward extrusion of the Changjiang River plume into the YS in 2012. The velocity records of July 2015 further showed that typhoons could even bend the Changjiang River plume to flow southwestward along the Zhejiang coast (Zhang et al., 2018c).

Changjiang River plume extends eastward in the form of patches of low-salinity water instead of as a tongue-shaped plume extending toward Cheju Island (Lie et al., 2003), and it intensifies the TWWC and TSWC (Chen et al., 2008). The baroclinic instability associated with the extensive density fronts enveloping these massive buoyant waters facilitates the eastward transmission of the Changjiang River plume through buoyant eddies that detach from its edge, while the southerly summer

monsoon enhances this detachment. The strong tides over the ECS shelf suppress this baroclinic instability, while the detachments of low-salinity water patches are primarily caused by the spatially non-uniform southeasterly wind (Ge et al., 2015). However, the extensive tide-induced vertical mixing in the northern ECS shelf tends to enhance the meandering of buoyant waters off the Subei Shoal and displaces the plume to the north toward the YS (Type 2 in Figure 4). The formation of low-salinity water patches of the plume is induced by increased vertical mixing, especially during the spring-tide period (Moon et al., 2010). The freshwater content of these patches is highly dependent on the intensity of winds, which contributes to the variation of the motion of the plume by altering wind-driven Ekman transport, and a synoptically weakened southerly summer monsoon facilitates the southeastward displacement of the buoyant plume (Moon et al., 2012; Chang et al., 2014). There is not close correlation between the changes in the Changjiang River discharge and the pathway of the Changjiang River plume in the central ECS, although the area of the buoyant plume in the central ECS has been observed to vary closely with the discharge rate (Bai et al., 2015).

Changjiang River Plume in Winter

When flushing out of the estuary, the cold and buoyant waters from the Changjiang estuary are constrained in the coastal seas to the west of the 30-m isobath and advected southwestward in form of the Zhe-Mini Coastal Current (ZMCC) toward the Taiwan Strait (Guan and Fang, 2006). This extensive coastal current, which may be identified by surface temperature and salinity (Gao et al., 2009; Wu et al., 2018b), and the mud belt (Bian et al., 2013; Li et al., 2013) off Zhejiang and Fujian coasts, can be seen in winter. The intensity of the ZMCC in February 2012 was quantified to be $\sim 0.215 \text{ Sv}$ by Wu et al. (2013) using phase-averaging technology. The tidally induced residual current roughly contributes $\sim 0.12 \text{ Sv}$ to the transport of ZMCC (Li and Rong, 2012).

Along its path to the Taiwan Strait, the baroclinicity induced by this extensive buoyant plume stimulates the upshelf motion of shelf waters beneath the TWWC and alters the connectivity between the northern SCS and southern ECS (Hu et al., 2010). The baroclinicity from this plume facilitates the formation of the upshelf motion of waters beneath the TWWC, even when downwelling-favorable winter monsoon prevails (Qiao et al., 2006). It has also been reported that a portion of these buoyant waters extrudes northwestward along the coastline of the Subei Shoal in the southern YS to form Subei Coastal Waters (Wu et al., 2018a), whose underlying dynamics will be synthesized below.

Although the buoyant waters from the Changjiang River can be seen off the Zhejiang and Fujian coasts, its southward pathway with the ZMCC showed an extensive meandering that excites synoptic cross-shelf water exchanges (Yuan et al., 2008; He et al., 2010; Bai et al., 2013). The concurrent transport of the northward Kuroshio intrusion from the shelf to the northeast of Taiwan and the TWWC establish water-column stratification over the shelf to the east of the 50-m isobath off the Zhejiang and Fujian coasts, where the tidal wave diverges (Wu, 2015). The tidal current and associated mixing are minimized in the coastal

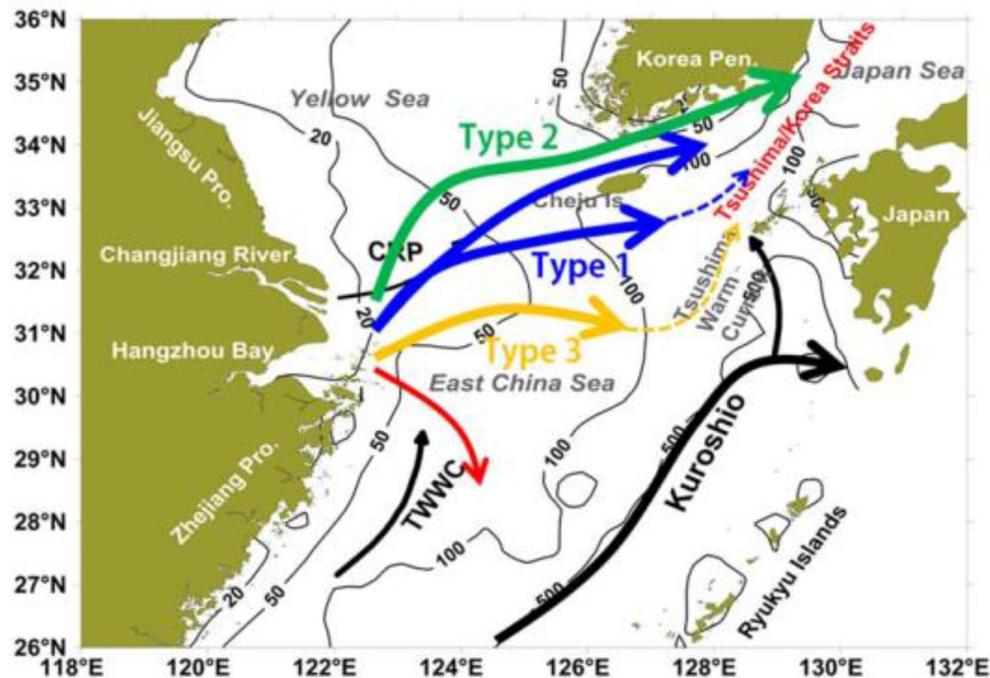


FIGURE 4 | Schematic pathways (colored arrows) of the three types of Changjiang River Plume identified from the 31 psu isohalines. The dashed arrows in blue and yellow signify plume water higher than the 31 psu would have advected by the Tsushima Warm Current to the Tsushima-Korea Straits. The red arrow shows the occasional movement triggered by typhoons. This figure is adapted from Bai et al. (2015), and Type 1 stands for the most frequently observed pathway of the plume, while Type 2 shows the pathway of buoyant waters when the buoyant waters are extensively advected toward Tsushima Strait, without residing over the shelf. Type 3 is rarely observed southeastward motion of the buoyant plume.

areas where a divergence occurs, which stimulates the cross-shelf penetration of two cold-water tongues. The penetration of these shelf waters then induces the offshore export of coastal waters carried by the ZMCC through the joint effect of baroclinicity and relief (JEBAR). This scheme explains the quasi-stationary or less-propagational cross-shelf water exchanges along the Zhejiang and Fujian coasts (Yuan et al., 2010). This cross-shelf meandering of the coastal current seems not to be governed by frontal instability, and interestingly, fluctuations in temperature but not salinity are a prerequisite for extensive cross-shelf water exchanges, although the appearance of the buoyant plume was found to play an essential role in maintaining the extensive southwestward flow of the ZMCC (Wu et al., 2013).

COASTAL CURRENTS IN THE ECS AND SOUTHERN YS

East China Sea Coastal Current (ECSCC)

The variations of coastal circulation in the ECS are jointly driven by monsoons, tides, and the buoyancy forcing from the extensive Changjiang River discharge (Lie and Cho, 2016; Wu et al., 2018b). In general, coastal circulation over the shelf shallower than 50 m generally flows northeastward in summer and southwestward in winter (Lee and Chao, 2003; Ge et al., 2013; Gan et al., 2016), although extensive synoptic variation has also been observed (Xuan et al., 2016a). The instabilities associated with this current

may stimulate notable cross-shelf water exchange in both seasons (Yuan et al., 2005, 2008; He et al., 2010).

The northeastward coastal circulation has been found to generate the upshelf intrusion of shelf waters from the bottom layers of the TWWC, forming a distinct and extensive cold water belt off the Zhejiang and Fujian coasts in summer (Hu and Wang, 2016). In winter, the ZMCC carries ~90% of the Changjiang River discharge (Wu et al., 2013) into the Taiwan Strait (Shen et al., 2017), which modulate the intensity of the TSC through the formation of a zonal density front in the strait (Chen and Sheu, 2006). Along its path, these cold and buoyant waters are vertically well mixed and form a sharp density front with the northeastward flowing TWWC over the outer shelf in winter (Huang et al., 2010).

The characteristics of coastal currents in the ECS are partially synthesized in Guan and Fang (2006) and Hu and Wang (2016), which were important references in our review, especially for studies prior to 2010. In this section, we focus more on the detailed dynamics that govern the cross-isobath transport, and pay more attention on the coastal circulations specifically in the ECS, instead of the entire China Seas.

It has long been recognized in 1990s (Liu and Su, 1991) that the possible forcing mechanisms driving the summer upwelling off the Zhejiang coast include the upwelling favorable southerly monsoon, upward lifting of the shoreward intrusion of the Kuroshio Current from the shelf to the northeast of Taiwan,

shoreward and upward movements of the TWWC induced by bottom friction, and the response of the TWWC to the regionally diverging isobaths. It was also suggested that upwelling could be divided into inshore and offshore segments (roughly divided by the 70-m isobath), with wind forcing dominating the upwelling process of the inshore area and the TWWC driving the upwelling in the offshore region. Subsequent numerical simulations and observations in the 2000s further confirmed the importance of winds and TWWC in generating the upwelling along the ECS coast (Jing et al., 2007; Wei et al., 2007).

These previous studies have proposed that upwelling does not uniformly occur along the ECS coast, and the detailed dynamics underlying this upwelling circulation are progressively revealed in the recent decades. The upshelf intrusion of shelf waters is intensified on the lee side of coastal promontories along the Zhejiang and Fujian coasts (Chen et al., 2014; Liu and Gan, 2014) as well as at the head of the submerged valley in the central ECS shelf and to the southeast of the Changjiang Estuary (Liu and Gan, 2015; Yuan et al., 2017), where a cold water center with high primary productivity is frequently observed (Shi and Wang, 2012). That upwelling in that submerged valley is strengthened by the baroclinicity of waters imposed by the extensive presence of buoyant waters from the Changjiang River discharge (Zhu, 2003), and it is considered to be the onshore branch of the TWWC over the shelf to the east of the 50 m isobath (Wang et al., 2019a). This spatially irregular distribution of upwelling circulation has been frequently reported in recent decades, and we have now recognized the importance of topography as well as tidally induced mixing in generating upwelling in the ECS. For example, field observations and numerical simulations by Lü et al. (2006) have shown that the upslope intrusion of shelf waters in the vicinity of the Changjiang Estuary is mainly induced by a cross-frontal density gradient that is compensated by extensive tidal mixing. Liu and Gan (2014, 2015) proposed that the onshore intrusion of shelf waters on the lee-side of Zhoushan Islands and at the head of the submerged valley is not merely induced by bottom Ekman transport but is generated by the along-shore variation of the meridional pressure gradient, which is exerted by the response of the coastal current to the variation in bottom topography.

Interestingly, although we have recognized that it is mainly the northeasterly wind that prevails in the ECS and that a strong southwestward flowing ZMCC characterizes the coastal circulation in winter (Wu et al., 2013), the downslope export of coastal waters due to coastal Ekman dynamics has rarely been reported. For example, previous studies like those of Qiao et al. (2006), Jing et al. (2007), and references therein have suggested that although both the wind and ZMCC favor the downwelling of shelf waters, it is mainly the upshelf intrusion of shelf waters due to the northeastward flowing TWWC that is observed (Hu, 1994).

Some previous studies have focused on the dynamics governing the formation of this upwelling circulation in winter, and tides, as well as the buoyant nature of the coastal currents, have been found to play predominant roles. For example, the numerical simulation and field observations by Qiao et al. (2006) revealed that the sharp density front between the ZMCC

and TWWC, due to extensive buoyant discharge from the Changjiang Estuary, facilitates the formation of an extensive cross-front baroclinic pressure gradient that drove upwelling off the Zhejiang coast. Tidal currents extend the river plume further to the southwest and contribute to the formation of upwelling. The northeastward flowing TWWC obstructs the pathway of the ZMCC, the associated density front, and the upwelling of deep shelf waters. Upwelling in the coastal area of the ECS is thereby a year-round phenomenon, with maximum and minimum upward velocities in summer ($\sim 10^{-2} \text{ ms}^{-1}$) and winter ($\sim 10^{-3} \text{ ms}^{-1}$), respectively (Jing et al., 2007). The recent long-term observations by Huang et al. (2016) over the shelf to the east of Zhejiang in the central ECS have clearly shown that the cross-isobath transport of shelf waters varies coherently with the along-shore velocities of the ZMCC. More importantly, that study proposed that shelf velocities also present extensive synoptic and intra-seasonal variability and suggested that the along-shore geostrophic current may play a more important role in generating the cross-shore water exchange than the role of bottom friction.

Yellow Sea Coastal Current (YSCC)

The coastal current in the southwestern YS over the shallow Subei Shoal was named as the Yellow Sea Coastal Current (YSCC), which, together with the ECSCC, comprises the China Coastal Current system (Guan and Fang, 2006). In the water column, it is recently proposed that the observed current profiles demonstrate a clockwise rotation, probably due to the “horizontal diffusion of geostrophic vortex stretching” (Song et al., 2019). The YSCC was considered to be a year-round southward flow (Lie and Cho, 1994), and the southward YSCC in winter is generated by the baroclinicity of the fresher waters carried by the Lubei Coastal Current (Wei et al., 2016) or Bohai Sea Coastal Current (Sun et al., 2018) from further north of the Shandong Peninsula. In summer, it is formed by the baroclinicity from the YSCM in the Yellow Sea Trough (Xia et al., 2006) to flow southeastward along the eastern flank of the Subei Shoal (Lie and Cho, 2016).

Yuan et al. (2008) questioned the conclusions of the flow pattern of the YSCC and suggested that the YSCC could be reversed to flow northwestward along the coastline of the Subei Shoal in summer, as also revealed by some simulations in the recent decades (Qiao et al., 2011; Wang et al., 2013b; Shi et al., 2016). A northward extending buoyant plume associated with upwelling in the summers of 2008 and 2009 was observed over the Subei Shoal (Yuan et al., 2017). This northwestward YSCC in summer, accompanied with the southeastward flow in winter, indicates a seasonal reversal of the flow direction, and this seasonal reversal is proven by the *in-situ* hydrography observations (Wei et al., 2016) and some recent numerical simulations (Gan et al., 2016).

Tides have recently been considered to be another important driving force that alters the circulation over the Subei Shoal. The density front, which is established by extensive tidal mixing over the shelf surrounding the shallow Subei Shoal, generates upwelling of shelf waters along its eastern flank in summer (Lü et al., 2010; Liu and Gan, 2016). This upwelling may result in cold surface waters that are most frequently observed when southerly

winds prevail (Zhu et al., 2018c). The formation of these cold surface waters is also impacted by the spring-neap tides (Liang et al., 2018). The water column is stratified during neap tides, while during the spring tides, sea surface temperature is at a minimum, which implies strong vertical mixing. YSCC along the eastern flank of the Subei shoal flows southeastward along the 30-m isobath (Xia et al., 2006; Wang et al., 2013a). However, the Lagrangian drifters released over the Subei Shoal clearly showed a northeastward floating trajectory, which is generally perpendicular to the southeastward Eulerian residual current, given that the impact of the southerly summer monsoon exceeds that of the residual current due to increased bottom friction from the extensive tidal currents.

The high-resolution numerical simulation by Xuan et al. (2016b) showed that the tidally induced residual current flows northwestward along the coastline of the Subei Shoal and reverses to the southeastward along the 50-m isobath over the eastern flank of the Subei Shoal (Figure 5A). The authors considered the offshore branch of this current as the YSCC, which exhibits clear seasonal variability. The inshore branch is named as the Tide-Induced Coastal Current (TICC), and it was considered to be a year-round northwestward current. The observations and numerical simulation (Wu et al., 2018a) for the circulation in December 2016 and January 2017 also clearly showed a northwestward current flowing against the northerly wind along the coastline of the Subei Shoal (Figure 5B). The tidal stress induced by the propagation of a Poincaré wave, together with the rotation of the earth, forces the northwestward current along the coastline of Jianguo, while tidally strengthened bottom friction suppresses the wind-forced current. The standing wave imposed by the collapsing of tidal waves from the YS and ECS modulate this coastal current, resulting in an eastward flow in the cross-shore direction. This northward current is generated by the Stokes drift due to the propagation of tidal waves (Wu et al., 2014).

The numerical simulation by Wang et al. (2017b) exhibited a different winter flow pattern from that of Xuan et al. (2016b) and Wu et al. (2018a) by taking those buoyant waters from the minor rivers along the coastline of Jianguo. Although the tidally induced residual current was still suggested to play a critical role in modulating the interactions between the YSWC and YSCC in winter, Wang et al. (2017b) considered that the currents over the Subei Shoal mainly flow southeastward in winter and that these freshwaters are merely from the rivers with minimal discharge along the Subei coast, instead of the Changjiang River plume, since the variations of salinity is insensitive to the discharges of Changjiang River. This finding contradicts those of Wu et al. (2014), Oh et al. (2014), and Xuan et al. (2016b), in which the Changjiang River plume was considered to be the major source of these freshwaters. The recent numerical simulation using water ages indicated that the minimum salinity of these fresher coastal waters lags behind the peak in Changjiang river discharge by about 2 months in summer, and these waters reside over the shallow Subei Shoal in winter (Zhu and Wu, 2018). Taking this lagged response of the circulations over the Subei Shoal to the river discharge from Changjiang river into consideration, the

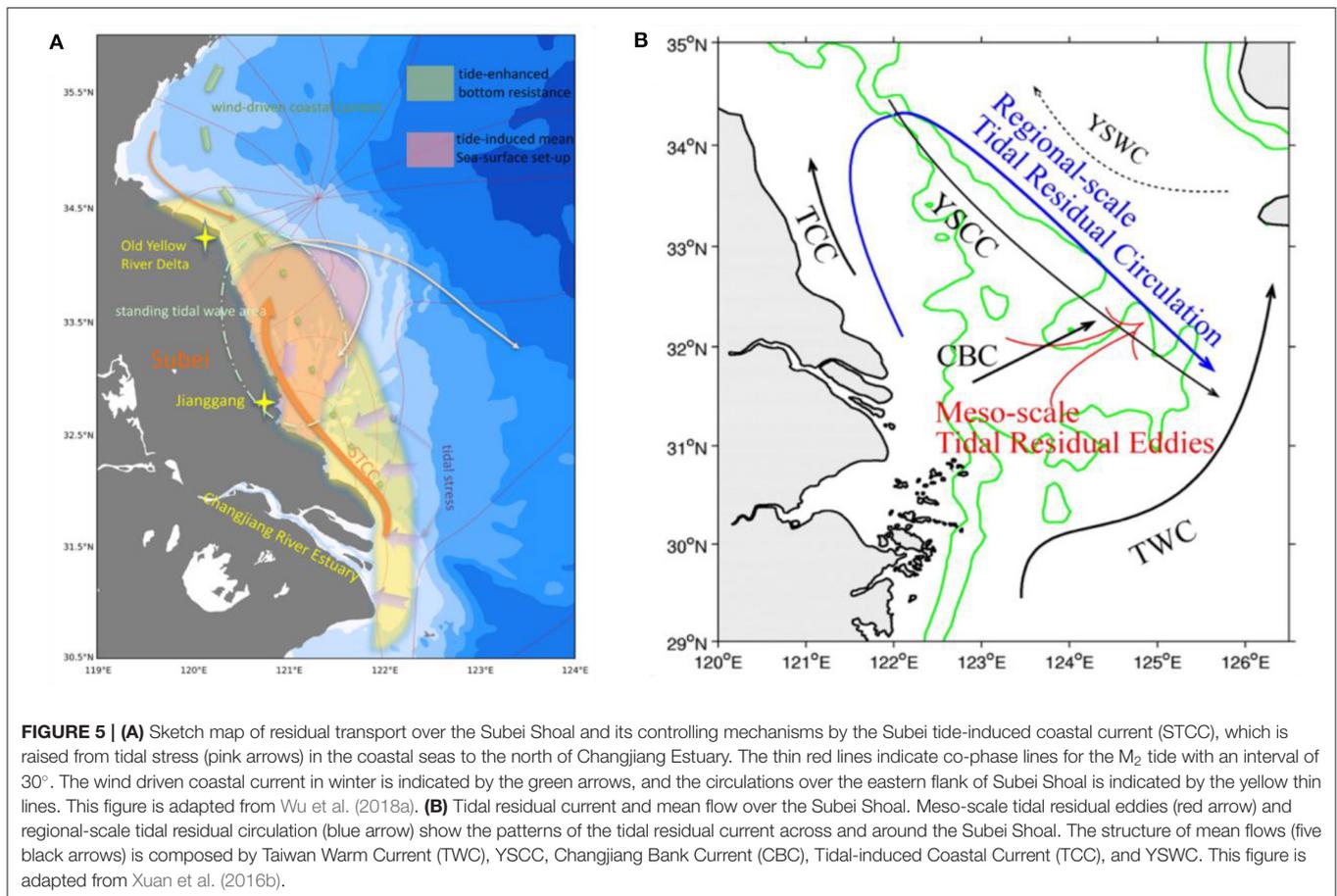
roles of buoyancy forcing in altering the YSCC are worth to be further explored.

It can be summarized that the flow pattern of the YSCC, which is the result of complicated forcing conditions associated with the shallow shelf of the Subei Shoal, should be further investigated. According to the contrasting flow patterns of the shallow coastal waters in the vicinity of its eastern flank and the submerged valley to the south, it becomes necessary to further evaluate the YSCC by examining its coastal and offshore branches (Wei et al., 2016; Xuan et al., 2016b; Wu et al., 2018a). The former branch is characterized as Subei Coastal Water (SCW), while the latter is characterized as the YSCC in Xuan et al. (2016b), which interacts with the YSWC/YSCM and the offshore branch of TWWC to the east of the 50-m isobath.

IMPACTS OF CIRCULATION ON HYPOXIA OFF THE CHANGJIANG ESTUARY

The buoyant plume from Changjiang exports huge amounts of dissolved inorganic nitrogen ($\sim 5,896$ Gg N/yr), phosphate (~ 381 Gg P/yr) (Gao et al., 2008, 2012; Tong et al., 2017; Liu et al., 2018) and sediments (~ 250 million tons/year) (Yang et al., 2006, 2015) into the ECS. As shown in Figure 6, the nutrients from Changjiang discharge, together with those intruding into the ECS through the Taiwan Strait (Huang et al., 2019) and from the Kuroshio (Chen et al., 1995; Chen, 1996; Lui et al., 2015; Qian et al., 2017; Zhang et al., 2019c; Zuo et al., 2019), played critical roles in stimulating the phytoplankton bloom (Li et al., 2014a; Yu et al., 2018), eutrophication and hypoxia in the coastal water. Chen et al. (2017) proposed that hypoxia usually occurs in the bottom waters in the eutrophication area with the concentration of surface chlorophyll-*a* exceeds 3.0 mg L^{-1} . The formed hypoxia are destructive to the marine ecosystem (Xu et al., 2015; Zhu et al., 2016b) in ECS (Chen et al., 2003; Wang et al., 2012; Qian et al., 2017; Wei et al., 2017a; Zhou et al., 2017; Zhang et al., 2018b; Wang et al., 2019c; Wang et al., 2019b; Zhang et al., 2019c; Chen et al., 2020a) and the YS (Zhai et al., 2020). It is generally considered that during the recent decades from 1980s to 2010s, there is an accelerated anthropogenic nutrient loading, and occurrence of eutrophication (Wang J. et al., 2015; Wang et al., 2016, 2018) and hypoxia (Wu et al., 2020) in the coastal waters (Liu et al., 2018; Chen J. et al., 2020). The recent overview by Chen J. et al. (2020) is recommended as an important reference that comprehensively synthesized the nutrient dynamics and biogeochemical processes, and here we focus on the impact of circulation dynamics to the changing hypoxia condition in the coastal seas of the ECS. The impact of circulation on the biogeochemical processes, not only revealed by its redistribution (Wang et al., 2019b; Wei et al., 2020) of nutrients and the elevated Redfield ratio (Wang J. et al., 2015; Chen et al., 2017; Liu et al., 2018), but also its changes on the stratification, residence time and ventilation of the shelf waters (Rabouille et al., 2008; Zhu et al., 2016a; Luo et al., 2018; Zhang et al., 2019c) will be overviewed in this section.

Hypoxia, usually with acidification of the seawaters (Wei et al., 2017b, 2020), generally occurs in the coastal seas neighboring

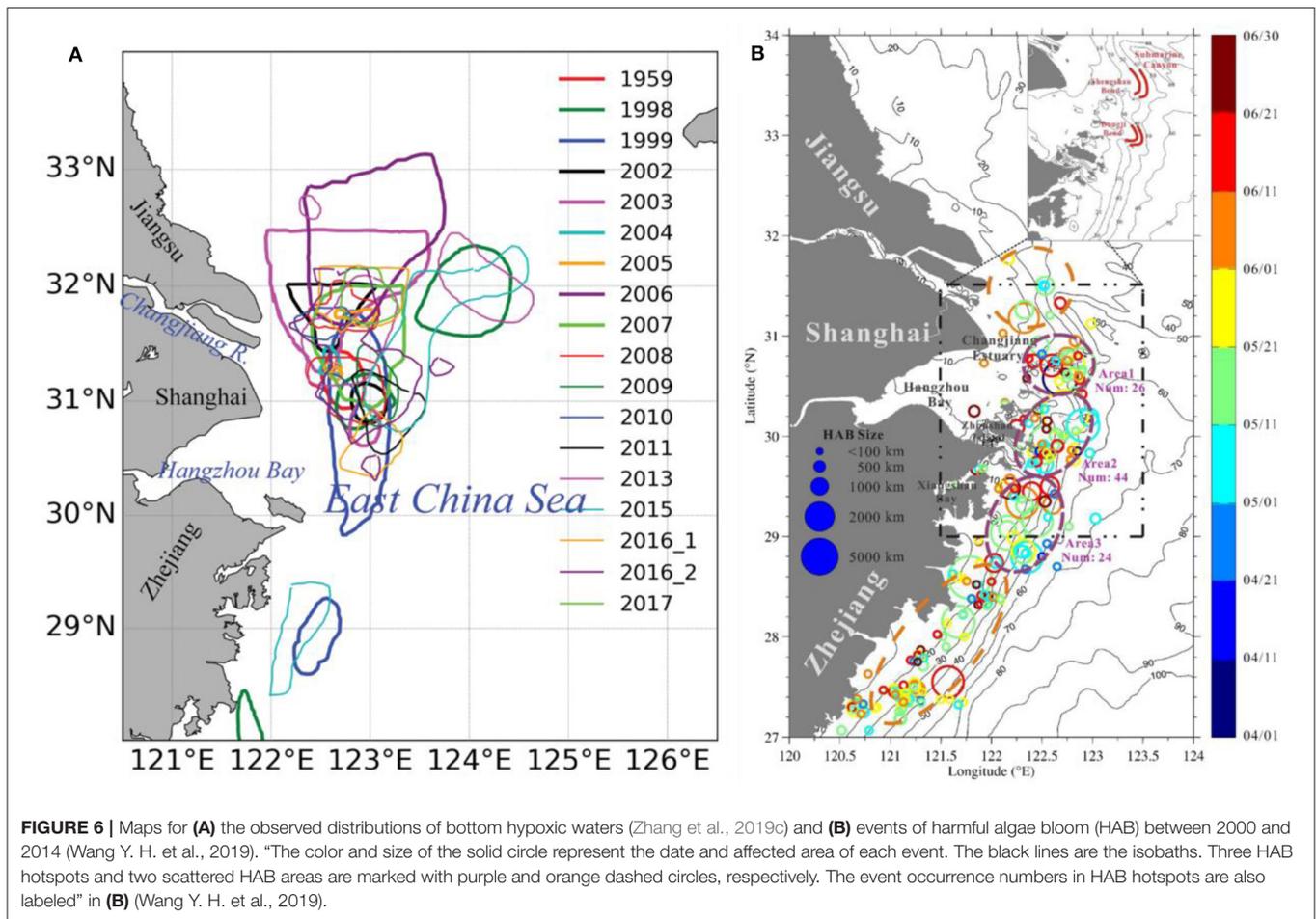


the 30 m isobath over the shelf. It strengthens from the late spring to summer (Zuo et al., 2019) and peaks in August (Zhu et al., 2011, 2017). There are also observations showing that the hypoxia can occasionally last longer to the mid-autumn (Wang et al., 2012; Chen C. C. et al., 2020). In winter, the buoyant waters are well-ventilated and hypoxia is thereby prevented (Zheng et al., 2016; Liblik et al., 2020). It is considered that the physical environment favors the development of hypoxia in summer, when the Changjiang river discharge maximizes (section Changjiang estuarine circulation), an intensified northeastward TWWC appears (Wang et al., 2012), upwelling of the shelf waters is established and the coastal waters are more stratified (Zheng et al., 2016; Chen et al., 2017). From June to August, the hypoxic waters mainly expand northeastward from the coastal seas to the east of Zhejiang and where mud-belt is observed (Zhang et al., 2019c). This hypoxia is mainly established by the Changjiang buoyant plume and intrusion of Kuroshio subsurface water (Zhang et al., 2019c), while the northeastward expansion is largely related to the strengthening of the northeastward TWWC and advances of upwelling circulation (Wei et al., 2011). Stratification of the coastal waters responses to circulation/discharges within ~ 35 hr (Ni et al., 2016), followed by an response of the bottom dissolved oxygen to changes of stratification is generally ~ 6 to ~ 50 h (Zhang et al., 2018b). The

stratification is also sensitive to changes in the wind intensity and direction (Chen et al., 2015; Zheng et al., 2016; Zhou et al., 2017), which jointly regulate the stratification, coastal current and pathway of the buoyant plume.

Kuroshio intrusion mainly regulates the hypoxia by increasing the residence time of the bottom coastal waters (from ~ 11 to ~ 40 days) in summer (Zhang et al., 2019c). However, the intrusion also alleviates the hypoxia through carrying shelf waters with a higher concentration of dissolved oxygen (Luo et al., 2018; Zuo et al., 2019). It is also found that the incoming Kuroshio waters is deoxygenating and acidifying (Lui et al., 2015). The overall effect of the Kuroshio intrusion is to increase the intrusion of nutrients and strengthen the stratification intensity over the shelf. Thus, the summer hypoxia have a tendency of being worsened under the influence of the Kuroshio intrusion (Lui et al., 2014).

In the synoptic timescale, the increment of Changjiang river discharge is believed to stimulate the expansion of hypoxia (Zheng et al., 2016; Zhou et al., 2017), although there are also studies suggested that the changes in hypoxia are not response to the changes in the river discharge instantly (Chen et al., 2015). The offshore detachment of buoyant waters in form of “cloudy patches” synthesized in the section 3.1, played critical roles in regulating the hypoxia condition (Liblik et al., 2020;



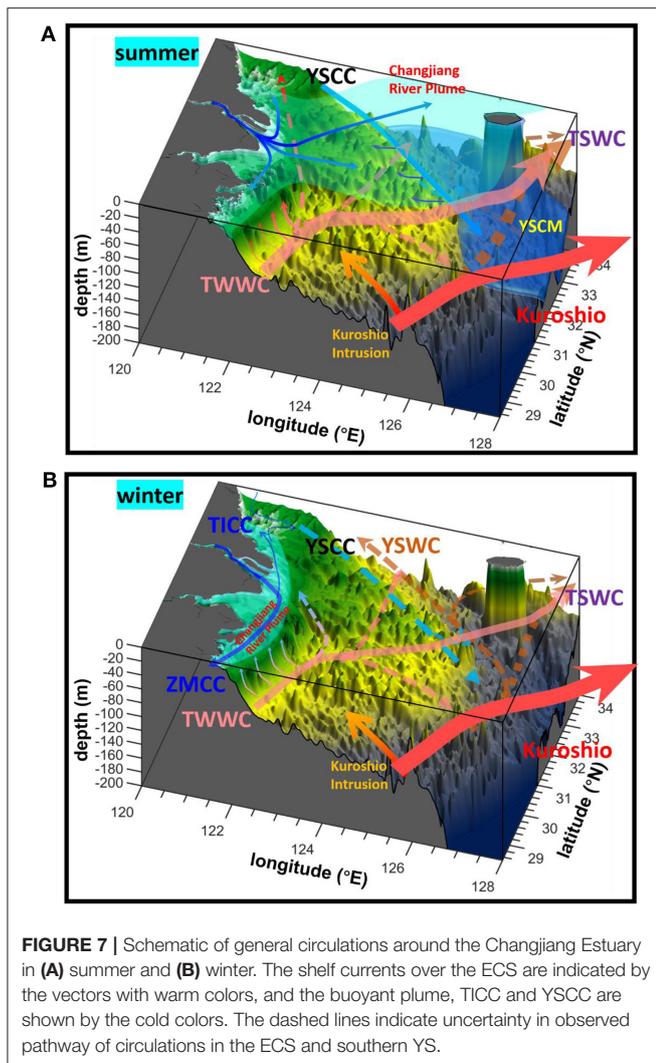
Wei et al., 2020). The phytoplankton bloom sealed inside these patches with relatively stable environment and the organic debris favor the formation of hypoxia. This offshore detachment of buoyant plume is also found to play critical roles in regulating the algal bloom and formation of high chlorophyll-*a* centers (Figure 6B) in the coastal seas (Wang Y. H. et al., 2019). In summer, the hypoxia off the Changjiang Estuary is dissipated by the arriving typhoon (Wu et al., 2005), which greatly alters the pathway of buoyant plume from Changjiang and strengthens vertical mixing (Zhu et al., 2016a). However, the extensive vertical mixing and the excessive nutrient loading due to the increased river discharge during the typhoon period greatly stimulate the establishment of phytoplankton bloom after typhoon. This process boosts the restoration of hypoxia within several days after typhoon landing and the waters are re-stratified (Wang et al., 2017a). This timescale is shorter than the formation of hypoxia due to moderate changes in winds (Ni et al., 2016). The changes of hypoxia condition, in a shorter timescale, is also found to vary in a semi-diurnal tidal period, e.g., ~12h, due to the combined effect of the bottom topography and spatial irregularity of the tidal extrusion distance off the Changjiang estuary (Zhu et al., 2017; Zhang et al., 2019c).

SUMMARY AND PROSPECTS

Summary

This manuscript synthesizes the recent studies on the circulation in the Changjiang Estuary and the neighboring circulation in the coastal East China Sea and southern Yellow Sea (Figure 7). The exchange flows among the branches, channels, and passages in the Changjiang Estuary have been found to be greatly influenced by seasonal variation in riverine discharge while also being regulated by the tides. It has been found that over 95% of the riverine runoff rushes into the East China Sea through the South Branch, while the greatly diminished discharge rate in winter (i.e., dry season) facilitates the extrusion of saltwater and the injection of saltwater from the North Branch to the South Branch. This upstream extrusion oscillates with the flood and ebb tides and its amplitude increases during the spring-tide period, while the byproducts of these propagating tidal waves have been recently recognized to play important roles in regulating the estuaryward extrusion of shelf waters. The northerly wind facilitates the injection of saltwater from the North Branch to the South Branch.

The buoyant waters from the South Branch have been found to be evenly partitioned toward the South and North Channels. Gravitational circulation, forced by the density gradient between



the buoyant waters from riverine discharge and the denser shelf waters, intensifies the exchange of these flows. The jetty spur that borders the North Passage acts to extensively redistribute the freshwaters in the lower estuary, resulting in great circulation complexity. It is generally understood that this construction substantially increases the transport time required for the buoyant waters to travel from the river entrance to the estuary mouth.

In the coastal waters off the estuary, bulge circulation delineated by an extensive density front traps a considerable portion of riverine buoyant waters and mixes them with the waters from the ECS shelf. This bulge broadly expands southwestward toward Hangzhou Bay, southeastward toward the submerged valley, eastward, and northeastward toward the central ECS shelf, and northwestward toward the shallow waters over the Subei Shoal. Thus, the Changjiang River plume plays an important role in regulating the general circulation in the ECS and southern YS. Tides also play important roles in regulating the formation of this bulge. It has been shown that along the

edge of the bulge, buoyant waters are shed in the form of “cloudy patches” in response to the variability in tidal and wind forcing and variations in the TWWC. The baroclinicity associated with these shed buoyant waters and the spatial variations of the tides facilitate the cross-shelf export of freshwaters in the coastal seas to the southwest of the Changjiang Estuary.

When southerly winds prevail, the Changjiang River plume generally travels to the northeast and is exported toward the southern YS and Tsushima Strait further to the north. This northward and northeastward motion of the buoyant plume shows extensive spatial variability in the form of notable patches of buoyant waters. The southward motion of the Changjiang River plume is diminished by the northeastward coastal current, which facilitates the formation of the extensive upwelling in the coastal seas off the Fujian and Zhejiang coasts, where the upslope intrusion of colder shelf waters is regulated by the along-shore irregularity of the bathymetry. A northwestward extrusion of buoyant waters from the Changjiang River plume is also observed in the nearshore regions of the shallow Subei Shoal.

In winter, the Changjiang River plume is carried by the ZMCC to flow southwestward in the coastal seas off the Zhejiang and Fujian coasts. Along its pathway, the cold water from the bottom-advected buoyant plume exerts an extensive shoreward pressure gradient, which is balanced by extensive tidal mixing, and stimulates upwelling in the coastal seas off the Zhejiang and Fujian coasts. A minimal portion of these buoyant waters (~10%) also extrude northwestward toward the nearshore regions of the shallow Subei Shoal and alter the YSCC, which was recently found to be regulated by the southeastward coastal current from the Shandong Peninsula, the intrusion of the YSWC, and tidal mixing along the eastern flank of the Subei Shoal.

The general circulation associated with the YSCC to the west of the 50-m isobath in the southern YS has been frequently debated in recent decades. A year-round southeastward current over the shallow Subei Shoal has been observed, and the details of its flow pattern have been progressively evaluated, although the underlying dynamics remain unclear. A series of recent observations and high-resolution numerical simulations have suggested that tides play important roles in regulating the YSCC by increasing turbulent mixing and establishing a cross-isobath pressure gradient that facilitates the seasonal reversal of its mainstream flow, and the cross-shore exchanges between the waters in the Subei Shoal and Yellow Sea Trough.

It is considered that the physical environment favors the development of hypoxia, particularly in summer, when the river discharge maximizes, an intensified northeastward TWWC appears (Wang et al., 2012), upwelling of the shelf waters is established and the coastal waters are more stratified. Those physical processes redistribute nutrients, elevate Redfield ratio (Wang J. et al., 2015; Chen et al., 2017; Liu et al., 2018), and further affect the stratification, residence time and ventilation of the shelf waters. Thus, could largely modulate the biogeochemical processes and hypoxia off the Changjiang Estuary.

Prospects

Although the recent observations and numerical simulations have greatly enriched our understanding of the details of the

coastal circulation in the ECS and YS as well as circulation in the Changjiang Estuary, it should be noted that the interactions and circulation dynamics governing the estuarine-coastal-shelf-slope-Kuroshio current system are still not thoroughly understood due to the complex bathymetry, regional and remote forcing factors, and the wide-spectrum temporal variabilities in this circulation system. These wide-spectrum variabilities are transmitted to the current system over the ECS and southern YS through cross-scale interactive exchange flows, which should be further investigated. Our prospects of future studies on the coastal and estuarine circulations around of the Changjiang Estuary are as follow:

- The detailed mechanisms of, for example, tides in determining the exchange flows in the branches and channels in the Changjiang Estuary are worthy to be further investigated to better reveal the cross-scale interactions (Lu et al., 2015) of the wind-driven shelf circulation and the tidally-modulated estuarine circulations. The roles of tidal-straining, asymmetric tidal mixing (Lu et al., 2019), wind-straining and buoyancy run-offs could be investigated in details (Zhu et al., 2018b) to complete the mechanisms governing this multichannel estuary. The coastal, shelf and estuarine circulations must be systematically coupled in a quasi-seamless way, instead of, respectively, taking the coastal and estuarine circulations as the lateral boundary of each other. The synoptic fluctuations in not only the winds around the estuary, but also their remote impacts arriving with the downshelf propagating of, for example, coastally trapped waves (Ding et al., 2018), should be included.
- Given the nutrients carried by the buoyant waters from Changjiang are largely trapped inside the bulge off the estuary, we should further investigate its behavior, includes the residence time of the sealed waters, the processes governing its growth, as well as the dynamical role of bulge in communicating the circulations in Hangzhou Bay and Changjiang Estuarine. The synoptic fluctuation and fate of the far-field plume should be better investigated through measuring the surface salinity in fine-scales by satellite remote sensing and high-frequency profiles by the moored buoy array observations.
- The dynamical role of the TWWC, including the variations of its intensity and meanders in the mainstream should be better observed by a series of multi-functional buoys or regularly performing field cruises by using the phase-averaged method.

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We should also further clarify the general flow pattern of the YSCC and TICC/SCW, and investigate the impact of the diurnal variations of forces, including not only heat flux but also land-sea breeze, which is recently considered to non-negligibly modulate the long-term variation of ECS circulation (Yu et al., 2020b).

- The contribution of the various physical processes to the biogeochemical process like hypoxia need to be further clarified and quantified. The interactive multi-scale physical processes should be considered to provide comprehensive understanding on the marine environmental issues in the region.

The accumulation of information based on multiple long-term observations from bottom- or surface-moored instruments, as well as high-resolution numerical simulations, is essential. These high-resolution numerical simulations and accompanying field observations will facilitate the formation of a comprehensive understanding of the exchange flows and their underlying dynamics and mechanisms. Moreover, cautious is required to interpretate the interannual or decadal variabilities of estuarine and coastal circulations over this shallow shelf sea. The rapid changes of forces, including, for example, strong winds (Chai et al., 2020), and the associated near inertial oscillation (Meng et al., 2020) or riverine discharges (Lee et al., 2017; Moon et al., 2019), potentially have the long-lasting influences to overtake the responses of the coastal and estuarine circulations in the lower-frequency.

AUTHOR CONTRIBUTIONS

ZL writes the manuscript by integrating the comments and suggestions from JH, HW, JG, ZC, and YD. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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