Coastal upwelling in the East China Sea in winter

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[1] The dynamic mechanisms of the upwelling off the East China Sea (ECS) coast in wintertime are studied. First, the upwelling signals off the ECS coast are identified by the observed temperature, salinity, nutrients, and dissolved oxygen data obtained during the cruises in January 1999. The MASNUM wave-tide-circulation coupled model is then employed to simulate the hydrography of the ECS. Comparisons between the simulations and observations show that the model performance is satisfactory. On the basis of successful simulation, four numerical experiments are conducted to investigate the upwelling mechanisms. The results suggest that the density (or salinity) front, which separates the inshore Low Salinity Coastal Water and the offshore Taiwan Warm Current (TWC), is the primary inducement for the upwelling. Owing to strong density gradient, the baroclinic pressure gradient force (PGF) is quite large near the frontal zone, and this PGF elicits an upwelling branch along the topography slope. Wind, TWC, and tide affect the density front in extension and intensity, thus exerting subsidiary influences on the upwelling. According to Ekman’s theory, the northerly monsoon is downwelling favorable. However, the net effects of wind on the upwelling off the ECS coast in winter are positive because it drives the Changjiang River Diluted Water (CDW) flowing southward and forms the density front. Similarly, the resultant effects of TWC on the upwelling are negative for obstructing the pathway of CDW. Tide contributes to the upwelling because tidal mixing facilitates the expansion of CDW.


1. Introduction

[2] Despite its small magnitude in velocity, upwelling plays an important role in the nutrient transport and larval dispersal in the ocean, and has significant impacts on fishery and biogeochemical processes such as harmful algal blooms. The coastal waters of the East China Sea (ECS) are believed to be a typical upwelling region, and have been attracting many investigations in the past 30 years [e.g., Hu et al., 1980; Pan et al., 1985; Zhu, 2003; Lü et al., 2006]. However, most studies on the upwelling in this area have been focused on summertime because, at least partially, the upwelling signals are pronounced in summertime; and thus can be easily identified by the distribution of physical and biochemical elements such as the sea surface temperature (SST), the sea surface salinity (SSS), and the dissolved oxygen (DO). There have been only limited studies on the upwelling in the ECS coastal waters in winter. Hu et al. [1980] proposed that the interaction between the Taiwan Warm Current (TWC) and topography is the primary cause of the upwelling off Zhejiang coast in summer. They speculated that the upwelling could exist also in winter because TWC also influences the Zhejiang coastal waters. Huang [1996] believed that the intrusion of TWC onto continental shelf would result in upwelling in winter. However, no more experimental evidences were provided to substantiate these claims.

[3] Guo et al. [2004] suggested that the shelf current system off the ECS coast comprises three components (Figure 6a): the TWC, the Changjiang River Diluted Water (CDW), and the Zhejiang and Fujian Coastal Current (ZFCC). Besides TWC, the latter two components could also exert influences on the upwelling, but their exact contributions are rarely evaluated quantitatively by previous researchers.

[4] In winter, the hydrographic circumstances of the coastal waters in the ECS are complex. The TWC carries water of high salinity northward, while the CDW and the coastal currents hug the coast of Zhejiang and Fujian southwestward within a narrow band when the northerly monsoon winds is predominant in winter [Chang and Isobe, 2003]. The CDW and coastal currents are characterized by very low salinity. For convenience, we name these two waters as Low Salinity Coastal Waters (LSCW). The movements and properties of the TWC and LSCW are totally different. These two water masses may interact with each other and affect the vertical circulation in the study region.
During the period from November 1997 to January 2000, which included 13 transects (A–M). Dots represent the survey stations. Dashed lines represent isobaths in meters.

The aims of this paper are to: (1) analyze the upwelling structure in the ECS coastal waters based on the field data obtained by the R/V Xiangyanghong No. 9 during the cruises in January 1999; (2) numerically simulate the circulation system of the ECS by using the MASNUM (Laboratory of MARine Sciences and NUMerical Modeling) wave-tide-circulation coupled model; and (3) investigate the dynamic mechanisms responsible for the upwelling off the Zhejiang coast in winter using four numerical experiments.

The paper is organized as follows. After the introduction given in section 1, section 2 presents observation data on the in situ temperature, salinity, DO and nutrients, together with the numerical model and its configurations. The observations are discussed in section 3. In section 4, the model validation is given first, followed by an analysis of the results of the numerical experiments. The conclusion is given in the last section.

2. Methods

2.1. Data

Cruises covering the Yellow Sea (YS) and the shelf of the ECS were conducted in four seasons by the R/V Xiangyanghong No. 9 during the period from November 1997 to January 1999. They were: spring cruise in May 1997, which included 13 transects (A–M). Dots represent the survey stations. Dashed lines represent isobaths in meters.

The local observations of the Changjiang River discharge are available as climatological monthly means. The discharges from January to December were (11008, 11903, 16825, 25254, 33345, 40432, 52183, 44065, 39315, 32952, 21817, 13413) in m$^3$/s. These data are used in the numerical model to assess the river effects on upwelling.
Table 1. Summary of Numerical Experiments Schemes

<table>
<thead>
<tr>
<th>Exp</th>
<th>CDW</th>
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<td>NoW</td>
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<td>NoT</td>
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“Y” means that the effects are considered in the model, and ‘N’ means that the effects are excluded from the model.

[13] The initial temperature and salinity fields are prescribed using the annual mean Levitus climatology [Levitus, 1982]. The initial sea level, the velocity, and the lateral boundary conditions (temperature, salinity, sea level and velocity) are interpolated from the global 0.5° by 0.5° model results [Xia et al., 2004]. The Changjiang River discharge is included as a boundary condition [Qiao et al., 2004a] by using the climatological monthly means described in section 2.1. The salinity boundary condition of the Changjiang River is set to 1.0 psu. The model is integrated for 6 years and the results of the last year are used in this study.

2.2.2. Numerical Experiment Schemes

[14] The possible factors affecting the ECS coastal upwelling are: the CDW, the TWC, the wind, and the tidal current. Therefore four experiments are set up to investigate the influence of each factor upon the upwelling (Table 1).

[15] The basic model simulation is referred to as the Control Run. In each experiment, a single physical process is closed, and the model is integrated to a quasi-steady state. The effects of this factor are examined by comparing the results of the experiment with that of the Control Run. To eliminate the effects of the CDW, the salinity of the whole model domain excluding the CDW area is set to 35.0 psu. This test is called Exp. EvenS. For the other three cases, the effects of TWC, wind forcing, and tides are removed, respectively, while keeping other physical processes intact. These three cases are called Exp. NoTWC, NoW, and NoT, respectively. In the Exp. NoTWC, we remove the TWC by closing the two entrances of TWC, i.e., the Taiwan Strait and the Kuroshio branching northeast to Taiwan. Along 124°E, the line between 24°N and 32°N is also set to land to avoid the intrusion of the Kuroshio onto the continental shelf and generates new “TWC”.

[16] A restart field on December 1 of the Control Run is stored at the end of the 6th year. The four experiments continue to integrate from the restart file for 15 months. Then the monthly averaged fields of the last February are used for analysis.

3. Evidences of the Upwelling

[17] Generally, when upwelling event occurs, the colder, more salted, and nutrient-richer water will rise from the deep layers to replace the surface water. The concentrated nutrients lead to the higher phytoplankton and lower DO values. Therefore the vertical distributions of temperature, salinity, DO, and nitrate serve as the indirect indicators of upwelling [Gong et al., 2003]. Figure 2 shows the observed vertical distributions of temperature, salinity, DO, and nitrate along transects H, K, and M in January 1999. The strong doming structure of the distributions of DO in Figure 2c provides an indirect evidence of the possible upwelling off the Changjiang River mouth. The similar structures of the temperature and the salinity in Figures 2i and 2j also imply that there may have existed upwelling along the transect M.

[18] The vertical profiles of the temperature, salinity, nutrient, and DO along the transect K do not show the similar doming structure from bottom to the sea surface. But Figures 2e–2h show an interesting structure in which the colder, the fresher, the lower DO, and the nutrient-richer water are confined only in the upper 20 meters layer at the westernmost three stations, whereas the vertical distributions of the fields are homogeneous at the other stations along the transect K. There are two possible reasons responsible for the formation of these structures. The first is that the CDW flows southward off the Zhejiang coast in winter due to the winter monsoon over the ECS, leading to the surface lower salinity belt along the Zhejiang coast [Chen et al., 2006, Figure 6]. The existence of the lower salinity layer inhibits the vertical convective mixing so that the fresher and colder water remain at the upper layer. The other possible reason is the existence of upwelling which blocks the vertical mixing between the upper and bottom layer. This results in the formation of the vertical distributions of temperature and salinity similar to those shown in Figures 2e and 2f.

[19] In order to gain better understanding on the relationship between the vertical distributions of the nutrients and DO with upwelling along the transect K, the horizontal distributions of the surface nitrate and Chl_a in winter are shown in Figure 3. Figure 3a illustrates the distribution of the surface nutrients in January 1999, which is obtained by objective mapping the observations at all stations shown in Figure 1 onto 0.25° by 0.25° grids. The strong nutrients front can be detected along the Zhejiang coast, reaching 12 μM/100 km. The satellite-observed Chl_a in winter (Figure 3b) also shows a high-concentrate belt along the Zhejiang coast. Since the surface water has high-concentrate nutrient and Chl_a along the transect K, the deep water should also have high corresponding values due to the strong vertical convective mixing in winter. But the observations along the transect K do not coincide well with this proposition; on the contrary, the nutrient-richer water exists only at the upper 20 meters layer. This implies the possible existence of upwelling, which inhibits the mixing of the surface nutrient-richer water with the deep water.

[20] Obviously, due to difficulties in making direct observation of the vertical velocity, the analyses above can only serve as a deduction of possible upwelling from the observed vertical distributions of temperature, salinity, DO, and nutrient values. Numerical experiments are required to confirm the hypothesis drawn from indirect evidences, and to provide better understanding on the formation mechanisms of upwelling in winter.

4. Model Results

4.1. Model Validation

4.1.1. Temperature and Salinity

[21] The simulated horizontal distributions of the surface temperature and salinity in the ECS and YS are compared with the climatological observations collected in the surveys
during 1958~1999 [Guo et al., 2004]. All the data are under strict quality control and interpolated to the grid of 20’ by 20’ for analysis.

The simulated and observed surface temperatures in winter are shown in Figures 4a and 4b, respectively. The patterns of the simulated and observed temperature agree well. The main pattern of the SST in the ECS is that the temperature drops from south to north and from the outer sea to the coastal sea. There is an obvious temperature front along the coast of Zhejiang and Fujian with higher temperature in the outer sea and lower temperature in the inner side of the front. The cold water from the outer sea of Jiangsu extends to the southeast along the Changjiang River bank and a cold tongue is formed in the northern ECS. The isotherm is intense near the Kuroshio area which flows along the continental slope, and the temperature ranges from
The temperature to the right of the Kuroshio is somewhat uniform, ranging from 22 to 25°C. The warm tongue of the Yellow Sea Warm Current stretches into the YS from the area south to the Cheju Island.

Due to the strong convective mixing, the temperature is vertically uniform from surface to a depth of about 75 m in the ECS and YS. So the simulated and observed temperatures at 50 m depth also agree well (not shown).

The simulated and observed surface salinity fields in winter are shown in Figures 5a and 5b, respectively. The distribution pattern of the simulated salinity agrees in general with that of the observation. In winter, the CDW
flows southward along the Zhejiang coast, and a strong salinity front is formed in the Zhejiang and Fujian coastal areas. The water with low salinity from the outer area of Jiangsu extends to the southeast along the Changjiang River bank and a low salinity tongue is formed in the northern ECS. The high salinity tongue of the Yellow Sea Warm Current stretches into the Yellow Sea from the area south to the Cheju Island.

4.1.2. Upper Layer Circulation

The diagram of circulation pattern in winter based on observation [Guo et al., 2004] is shown in Figure 6a, while the simulated circulation field at the depth 10m is given in Figure 6b. Compared with the observation the main current system in the ECS and YS are well reproduced by the model. The main stream of the Kuroshio flows northeast between 200–1000 m isobath along the steep ECS continental slope. The simulated Kuroshio turning point is near 31°N while the observed one is 30°N. The small deviation is mainly due to the coarse horizontal resolution of the model [Guo et al., 2003]. Driven by the northerly winter monsoon, the CDW flows southward along the Zhejiang coast.

4.2. Upwelling Mechanism Analysis

In this part, the model experimental results are compared with those of the Control Run to examine the effects of the corresponding dynamical factor. All the results of upwelling are the monthly mean of February.

The results of Control Run show a very conspicuous feature of the salinity field in ECS in winter; the strong salinity and temperature front along the coast of the Zhejiang and Fujian as shown in Figures 4a and 5a, respectively. This front is also clear in density field (not shown). The synthesized analysis of the numerical results suggests that this density front and the associated frontal circulation are the dominant mechanism for the upwelling.

4.2.1. Model Responses From Exp. EvenS

Figure 7a shows the upwelling at 10 m of the Control Run. The upwelling area is in the shape of a long and narrow belt clinging to Zhejiang and Fujian coastline. The upwelling belt extends southwest for more than 500 km from the Hangzhou Bay offshore waters. The peak value of upwelling velocity exceeds $4 \times 10^{-5} \text{ m s}^{-1}$ off the Zhejiang coast.

The model responses of the upwelling area from Exp. EvenS exhibit a dramatic change in contrast with the Control Run (Figure 7b). The upwelling belt almost disappears and the magnitude of vertical velocity is less than $0.5 \times 10^{-5} \text{ m s}^{-1}$ in most upwelling area. This indicates that the CDW has the direct and primary effects on the vertical circulation in the ECS coastal waters.

In winter, the salinity front between the LSCW and TWC is so strong (Figure 5) that a remarkable baroclinic pressure gradient sets up. This baroclinic force dominates the vertical circulation near the frontal area, which would drive the upwelling. Figures along cross sections are helpful to elucidate the mechanism described above (Figure 7c). The density field of Control Run shown in Figure 7c has a typical winter front structure. The front extends from surface to bottom because of the strong mixing in winter. The density increases offshore, and the sea water driven by the baroclinic force moves onshore and upward from the deep layer. The upwelling arises as a branch of the cross-isopycnic secondary circulation. The originally vertical isopycnic lines are distorted by the upwelling and become upward at 5–10 m depth. This structure is quite similar to the observed transects of temperature, salinity, and DO along Transect K (Figures 2e–2g).
The prevailing winter monsoon is from north (Figure 8a). The averaged wind stress is $0.11 \text{ N m}^{-2}$, much larger than that in summer ($0.02 \text{ N m}^{-2}$). In accordance with Ekman’s classic theory, the northerly wind is downwelling favorable. It is imaginable that removing of the winter monsoon forcing from the model will suppress downwelling and therefore, enhancing upwelling in the study region. However, Exp. NoW presents the totally opposite results: the upwelling belt does not intensify. To the contrary, it diminishes dramatically (Figure 8b).

In fact, this interesting result reflects the same mechanism as explained in section 4.2.1. The LSCW flows southward steadily in winter and the driving force is ascribed to the strong northerly wind [Su and Yuan, 2005]. If the 31 psu isohaline is taken as a division, the LSCW almost disappears and the TWC becomes the dominant water mass in ECS coastal waters, in case the wind forcing is set to zero (Figure 8c). Consequently, the salinity front, which separates the LSCW and TWC, also disappears if the surface winds are removed. Without the density-driven mechanism, there would be no frontal circulation and upwelling branch (Figure 8d).

4.2.3. Model Responses From Exp. NoTWC

The TWC is one of the major currents in the ECS shelf circulation system. Originating from the Taiwan Strait and the shelf-intrusion waters from Kuroshio, the TWC flows along the coast of the Zhejiang and Fujian year round [Su and Yuan, 2005; Guan, 2002]. Previous studies have shown that the TWC is a very important inducement of the summer upwelling off the ECS coast [e.g., Hu et al., 1980; Pan et al., 1985; Liu and Su, 1991; Lü et al., 2006]. It is believed that the TWC also contributes to the upwelling off the ECS coast in winter because its main stream is quite steady in both summer and winter, although the surface TWC water is influenced by monsoon [Hu et al., 1980; Xu, 1986; Huang, 1996].

Exp. NoTWC suggests that the TWC may exert dual influences on the ECS coastal upwelling in winter. For one thing, the encroachment of TWC onto the continental shelf results in upwelling in a three-dimensional interaction process between the cross-isobath flow and sloping bottom topography. For another, TWC exerts a negative effect on upwelling, as revealed in Figure 9a. In Exp. NoTWC, the TWC is basically eliminated by closing its two inflow entrances. Without the resisting and blocking of the TWC, the southward LSCW intensifies remarkably (Figure 9b). In the Control Run, the speed of the main LSCW stream is $8–20 \text{ cm s}^{-1}$, while in the Exp. NoTWC, the speed increment is $4–8 \text{ cm s}^{-1}$. The absence of TWC also reinforces the horizontal salinity gradient in the frontal zone (Figure 9c), namely, the density front intensifies. In comparison with the Control Run, the density variation between $120^\circ$E and $122.5^\circ$E increases about 50% on the transect along $29^\circ$N (from 2.4 to 3.6 kg m$^{-3}$, Figures 7c and 9c). Subsequently, the intensification in density front brings about considerable increase of upwelling under the control of density-driven mechanism.
4.2.4. Model Responses From Exp. NoT

Tides are believed to be one of the mechanisms driving upwelling [Tee et al., 1993; Luo et al., 1998; Lü et al., 2006, 2007]. By contrast with Figure 7a, the vertical velocity of Exp. NoT shows a similar distribution pattern (Figure 10a), with a small shrinkage in upwelling extension. This indicates that tide has only limited effects on the upwelling off ECS coast in winter.

The effects of tide on upwelling are also related to the distribution of the CDW. Tidal mixing is helpful to the diffusing process and enlarges the expansion of CDW [Zhu et al., 1999]. Turning off the tidal process, the modeled scope of CDW expansion shrinks (Figure 10b). Consequently, the upwelling changes with the variation of CDW expansion and density front.

5. Discussions and Conclusions

The observed in situ temperature, salinity, DO, and the nutrients data are combined with the numerical model simulations to study the upwelling off ECS coast in winter. The impacts of wind, the CDW, the TWC, and tide on the formation of the upwelling are analyzed.

The analyses of the observations show that there probably exists upwelling in the study area in winter. The doming structures of the vertical distributions of temperature, salinity, DO, and nutrients along the hydrographic transects in the ECS denotes that there exists an upward movement of the water in winter. The structures of DO and nutrients along the transect K show an interesting feature in which the nutrient-richer water are confined in the upper 20 m. While in winter, the strong convection mixing should mix the whole column of the water homogeneously. This implies the possible existence of upwelling, which blocks the vertical mixing between the upper and the bottom layers.

The results of the numerical experiments suggest that the upwelling off the ECS coast in winter is induced primarily by the strong density (or salinity) front separating the inshore LSCW and the offshore TWC. Driven by the
intense baroclinic pressure gradient near frontal zone, the deep water is forced inshore and upward. This mechanism is verified by a simplified and analytical model [Dong et al., 2004, Figure 2b], which exhibit a clockwise cross-frontal cell generated by the density field near winter front. In this study, the cross section circulation pattern shown in Figure 7c is qualitatively consistent with the two-dimensional calculation of Dong et al. [2004]. In fact, not only the winter front, the summer front is also associated with the secondary circulation and the upwelling branch [James, 1978; Garrett and Loder, 1981; Loder et al., 1993; Dong et al., 2004]. In the study region, the summertime front-related density gradient is suggested as the primary mechanism for coastal upwelling [Lü et al., 2006]. However, the formation mechanism of density fronts in winter and summer is different. In summer, the fronts form a boundary between the well-mixed and the stratified water. Generally, the density differences between the two waters stem from temperature disparity; namely, the higher temperature of the well-mixed water and the colder temperature of the water under the thermocline. This front structure is controlled primarily by tidal mixing [Simpson and Hunter, 1974]. Therefore tidal mixing is the virtual causation for the upwelling off Zhejiang coast in summer [Lü et al., 2006]. In winter, the mixing processes are mainly attributed to strong wind and surface cooling. Winter cooling of the sea surface causes vertical penetrative convection. The contribution of tidal mixing is relatively minor. As far as the ECS offshore waters are concerned, the density front in winter is due to the salinity, rather than temperature. Without the LSCW or, the CDW, mixing alone is insufficient to generate the density front. In this connection, the CDW can be regarded as the fundamental inducement for the winter upwelling off the ECS coast.

Involved in the interaction with the CDW, both the wind forcing and TWC exert dual effects on the upwelling off ECS coast in winter. Driving the upper water to accumulate onshore, the dominant northerly winter monsoon over the ECS is downwelling favorable. Nevertheless, wind also serves as the main propeller for the southward
Figure 9. Numerical results of the Exp. NoTWC. (a) Upwelling \((10^{-5} \text{ m s}^{-1})\) distribution at 10 m depth. (b) Horizontal current vectors \((\text{m s}^{-1})\) and SSS contours (psu) at 10 m depth. The salinity contour interval is 1 psu. (c) Same as Figure 7c, but for the Exp. NoTWC.

Figure 10. Numerical results of the Exp. NoT. (a) Upwelling \((10^{-5} \text{ m s}^{-1})\) distribution at 10 m depth. (b) SSS distribution at 10 m depth in psu. The salinity contour interval is 0.5 psu.
movement of CDW. The LSCW will not flow southward without the wind forcing (Figure 7b). Therefore the net effect of wind is positive for upwelling.

[41] Similarly, the TWC itself is a producer for the coastal upwelling through its encroachment and ascending onto the topography slope, especially in summer [e.g., Hu et al., 1980; Pan et al., 1985; Liu and Su, 1991; Li et al., 2006]. In winter, another role of TWC is the obstructing of the LSCW from flowing southward. The resultant net effect of TWC on upwelling depends upon the relative importance of TWC itself and that of CDW. As the above analyses illustrate, the latter factor is likely to weigh more. Accordingly, TWC may weaken the upwelling in winter. This conclusion is different from the previous understanding about the TWC’s enhancement to the upwelling in the ECS as reported in the literatures [Xu, 1986; Huang, 1996].

[42] Numerical experiment indicates that the limited influences of tides on upwelling are also associated with the CDW and the density front. Tidal mixing is a favorable dynamic factor for the diffusion process in the ocean, and promotes the expansion of the CDW. Thus, the upwelling area in Control Run is slightly larger than that in Exp. NoT. In addition, Lü et al. [2007] suggested that the tide-inducing mechanism for summer upwelling off Zhejiang coast involves both the barotropic and baroclinic processes. The barotropic tidal residual currents converge near the seabed and induce an upwelling band, which is similar to that shown in Figure 7a, to maintain mass conservation. The barotropic tidal currents are unrelated to season, so the barotropic mechanism should be also applicable to explain the upwelling in winter.

[43] In summary, the density front between the LSCW and TWC is the kernel inducement for winter upwelling off the ECS coast. Relative to the TWC, the LSCW is more sensitive to external dynamic forcing such as wind. The wind forcing, the TWC, and the tide have subsidiary influences on the upwelling off the ECS coast in winter through their effects on the distribution of LSCW.

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