Chapter 1

Coastal Upwelling Off the China Coasts

Jianyu Hu, X. San Liang and Hongyang Lin

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80738

Abstract

Upwelling is an important oceanographic phenomenon that brings cooler and nutrient-rich water upward to the surface, facilitating the growth of phytoplankton and other primary producers, which results in high levels of primary productivity and hence fishery production. This chapter presents a review of recent studies on six major upwelling regions along the China coasts, with a focus on the eastern and southeastern coasts of mainland China, based on in situ measurements, satellite observations and numerical simulations. These upwelling regions result primarily from the summer monsoon winds, though other mechanisms, such as river discharge, baroclinicity, topography, tides, and the presence of mean current, may also be in play. In this review, their impacts on local biogeochemical processes are briefly summarized. Also discussed are their possible responses to the globally changing climate.

Keywords: coastal upwelling, off the China coasts, characteristics, mechanism, impact

1. Introduction

Upwelling is an important oceanographic phenomenon that refers to an upward movement of seawater, with a typical speed of order 10^{-6}~10^{-4} m/s. Accompanied by the upwelling process, the subsurface/deep cooler, and normally nutrient-rich, water rises toward the ocean surface, leading to a background with high biological productivity that is beneficial for the growth of phytoplankton and other primary producers. Therefore, good fishing grounds are commonly found in the vicinity of upwelling regions. From the dynamical point of view, major mechanisms for the generation of the coastal upwelling include the alongshore wind and wind stress curl, although other factors (e.g., tides, topography, and river discharge) also play considerable roles depending on the regions under investigation [1].
The coastal upwelling of cold and nutrient-rich waters off the China coasts is significant not only for the regional fishing industry, but also for the global carbon cycle and thus for the Earth’s climate. Therefore, the coastal upwelling becomes a research hotspot of coastal oceanography in China, which has attracted great attention for recent decades. For example, Miao and Hu [2] analyzed the characteristics of wind-driven coastal upwelling off the southeastern China coast using coastal upwelling index (CUI) data, which are calculated online the Pacific Fisheries Environmental Laboratory (PFEL) website (http://www.pfeg.noaa.gov/products/las/docs/global_upwell.html) using the method of Bakun [3]. It is indicated that there exist wind-driven coastal upwelling regions in summer off the eastern Hainan Island and the Leizhou Peninsula, and along the coast from Shantou to Zhejiang (Figure 1). The wind-driven coastal upwelling off the eastern Hainan Island is stronger than that in other regions, and the upwelling is stronger from June to August compared to other months. Wind-driven coastal upwelling off Zhejiang appears earlier than that off the eastern Hainan Island. The wind-driven coastal upwelling experiences different variation periods along the central and southern Fujian coast, Guangdong coast, eastern Hainan Island coast, northern Fujian coast and Zhejiang coast.

Hu and Wang [1] reviewed the progress of upwelling studies in the China seas since 2000 and summarized 12 major upwelling regions in the China seas, including the South China Sea (SCS), the Taiwan Strait (TWS), the East China Sea (ECS), the Yellow Sea, and the Bohai Sea (Figure 2). Half of these upwelling regions are located along the southeastern coast of mainland China, that is, the upwelling off the Yangtze River Estuary, the upwelling along Zhejiang coast, the upwelling regions along the northwestern and southwestern coasts of Taiwan Strait, the upwelling along the eastern Guangdong coast, and the upwelling around

Figure 1. Monthly mean coastal upwelling index (b) off the southeastern China coast (the station locations for calculating the coastal upwelling index are shown in panel (a)). Redrawn from Miao and Hu [2].
the eastern Hainan Island. It is concluded that these coastal upwellings are principally wind-driven, and are hence strongly related to the seasonal variability of monsoon winds.

In this chapter, we describe six major coastal upwelling regions off the southeastern coast of mainland China and discuss the influence factors for these coastal upwelling regions.

2. Major characteristics of coastal upwelling off the southeastern coast of mainland China

2.1. Upwelling in the northern continental shelf of the South China Sea

Published about 15 years ago, Wu and Li [4] and Li et al. [5] overviewed studies of upwelling in the SCS over four decades among 1964–2003, focusing primarily on the spatiotemporal variability of upwelling in the continental shelf of the northern SCS. They pointed out that
in summer upwelling occurs over almost the entire continental shelf of the northern SCS. Figure 3 presents the locations of some upwelling regions, investigated by several representative studies [6–10]. Most of these upwellings have been demonstrated to be induced by the prevailing southwesterly monsoon. Since then, much progress on the coastal upwelling study has been intensively made in the northern SCS using cruise observations, satellite observations, and numerical modelling.

2.1.1. Cruise observations

Over the past two decades, a number of hydrography-oriented cruises have been conducted in the continental shelf of the northern SCS. These data further evidenced the upwelling and its variability. Using underway measurements of sea surface temperature and salinity collected during July–August 2000, Zhuang et al. [11] observed an evident upwelling-related, low-temperature, and high-salinity area along the coast between Dongshan and Huilai (see locations in Figure 2 or 3). Based on the hydrological data from a cruise during July–August 2002, Xu et al. [12] analyzed the upwelled cold water along the eastern coast of Guangdong, and found that cold cores were distributed near the Daya Bay and the Huilai coast. Upwellings off the Pearl River (also called the Zhumjiang River) Estuary were examined during different monsoon periods in July 2000 by Zeng et al. [13], and in May 2001 and November 2002 by Zhu et al. [14], respectively. Zhang et al. [15] investigated hydrological (including upwelling) characteristics off the Pearl River Estuary using data from two cruises in summer and winter 2006. Cai et al. [16] and Wan et al. [17] analyzed the characteristics of upwelling in the eastern Guangdong and southern Fujian coastal waters using the comprehensive cruise data; their results illustrated the coastal upwelling between Shantou and Dongshan undergoing an alternating strong-weak-strong stage during July–August 2006. Based on the conductivity-temperature-depth (CTD) data from the summer cruises of 2001,
2002, 2006, and 2009, Xu et al. [18] revealed the interannual variation in the spatial structure and intensity of upwelling in the eastern Guangdong and southern Fujian coastal seas. The abovementioned cruise data confirmed that the summertime coastal upwelling is conspicuous along the coasts of eastern Guangdong and southern Fujian, with the former occurring earlier and stronger than the latter.

2.1.2. Satellite observations

Using satellite remote sensing data, combined with shipboard measurements conducted in July 2000, Zhuang et al. [19] analyzed upwelling phenomena off the Fujian and Guangdong coasts. Qiao and Lü [20] applied satellite sea surface temperature (SST) and chlorophyll-a (Chl-a) data from different sources to summarize some basic characteristics of the coastal upwelling in the SCS. Applying the Quick Scatterometer (QuikSCAT) wind data, Wang et al. [21] examined relative roles of Ekman transport and Ekman pumping in driving summer upwelling. These results indicated that the coastal upwelling often occurs in the coastal area around the eastern Hainan Island and in the waters along eastern Guangdong and southern Fujian coasts in summer, which may be resulted from multiple dynamic factors such as wind forcing, tidal mixing, and the interactions between local circulation and topography. However, the coastal upwelling in the eastern Guangdong is primarily driven by Ekman transport.

2.1.3. Numerical modelling

Several numerical models have been applied to study the upwelling and its mechanism in the northern SCS since 2000. For example, Chai et al. [22] simulated several upwelling regions in the SCS using the Princeton Ocean Model (POM), and explained their mechanisms. Jing et al. [23, 24] studied the summer upwelling system in the northern continental shelf of the SCS using a three-dimensional (3D) baroclinic nonlinear model. Zhang and Jiang [25] studied the mechanism of cross-shelf transport of the cold bottom water (upwelling water) on the coastal shelf off Shanwei using the Regional Ocean Modeling System (ROMS). These model results showed that the summertime upwelling is a common phenomenon during June–September east of the Hainan Island and the Leizhou Peninsula, and in the coastal areas from Shantou to Nanri. Both southwesterly wind and wind stress curl are responsible for generating the coastal upwelling east of Hainan, while the wind-driven cross-shelf Ekman transport is a significant dynamic factor to the coastal upwelling off the eastern Guangdong and southern Fujian coasts.

2.1.4. Intensive studies

The upwelling off the eastern coast of Hainan Island is strong in summer, which has attracted a lot of intensive studies for recent years [26]. Specifically, Chai et al. [27] simulated the upwelling using the POM; Su and Pohlmann [28] applied a 3D high-resolution model to study the upwelling mechanism; Li et al. [29] investigated the spatial structure and variation of the summertime upwelling in the waters east and northeast of Hainan Island during 2000–2007 by using a nested high-resolution POM forced by QuikSCAT winds; Wang et al. [21] estimated
the mean Ekman transport and Ekman pumping in the coastal waters east and southeast of the Hainan Island; Lin et al. [30, 31] compared the upwelling patterns in the eastern and northeastern Hainan Island using a combination of cruise observations, reanalysis data and satellite data, and studied the mechanism for the upwelling off the northeastern coast of Hainan Island with a numerical model. These results suggested that the coastal upwelling off the eastern coast of Hainan Island usually exists from April to September, with the strongest intensity in summer; the upwelling is mainly induced by summer monsoon wind. By contrast, Jing et al. [24] proposed that the Ekman pumping associated with the local wind stress curl is a key factor modulating the generation of the coastal upwelling off eastern Hainan Island and eastern Leizhou Peninsula. Based on the cruise data in summer 2006, together with the QuikSCAT winds, Xu et al. [32] pointed out that the coastal upwelling regions are merged below 10 m layer in the waters off eastern Hainan and western Guangdong, and that the coastal upwelling off eastern Hainan Island is intermittent and modulated by the alongshore wind while that off the western Guangdong is mainly induced by the wind stress curl.

On upwelling variability, Liu et al. [33] studied the variability of summer coastal upwelling in the northern SCS during the last 100 years. Jing et al. [34] identified that the coastal upwelling in the northern SCS was closely linked to the modulation of El Niño events; they found that during the summer of 1998 (a La Niño year), the coastal upwelling was greatly strengthened associated with an abnormally intensive alongshore wind stress blowing over the region. Su et al. [35] studied the variation of coastal upwelling off the eastern Hainan coast over 50 years of 1960–2006 using an “SST upwelling index”. By using an SST record (AD 1876–1996) derived from coral Porites Sr/Ca, Liu et al. [36] revealed that upwelling in the northern SCS underwent a distinct multidecadal variability, which was proved to be caused by the Asian summer monsoon with an abrupt shift in 1930 from a relatively warm to cold condition, and then back to the warm condition after 1960. These results showed a general intensifying of coastal upwelling off eastern Hainan Island subject to prominent interannual and decadal variations; the intensifying trend was also consistent with the global warming in the twentieth century.

2.2. Coastal upwelling in the Taiwan Strait and its adjacent sea areas

Xiao et al. [37] and Hu et al. [38] collected many papers and comprehensively reviewed the upwelling studies in the TWS mostly before 2000, and also proposed suggestions for upcoming investigators. The reviews showed that the main coastal upwelling regions (Figure 4) in the western TWS are located near Dongshan and Pingtan. Over the past two decades, some progress has been made in studying the TWS upwelling, especially on its variability, mechanism and responses to the El Niño-Southern Oscillation (ENSO), and local environmental variation.

2.2.1. Variability of the coastal upwelling in the western TWS

Strong coastal upwelling usually appears in the western TWS during the summer southwest-erly monsoon period, which has been confirmed by a number of hydrological and satellite
observations in the last decades (e.g., [39–45]). These studies showed that the intensity of coastal upwelling is affected by many factors, such as the northward or northeastward current, southwesterly monsoon, and bottom topography. Recently, more attention has been paid to the variability of the coastal upwelling in the western TWS. Three examples are given next.

Hong et al. [46] studied the interannual variability of summer coastal upwelling in the TWS using a long time series of SST data from 1985 to 2005. It is shown that in some years, the coastal waters near Pingtan or Dongshan had clear upwelling signatures at the sea surface with a negative temperature anomaly and positive salinity anomaly. The alongshore wind stress was demonstrated to be responsible for such interannual variations.

Hu et al. [47] studied the variable hydrographical structure in the southwestern TWS using measurements from four summer cruises in 2004–2007, and revealed that the coastal upwelling near Dongshan occurred with different scales, locations, and intensities. Evident coastal upwelling was seen in the southwestern TWS during each July of 2005 and 2007, and was largely associated with local wind condition as confirmed by numerical modeling results.

Zhang et al. [48] investigated the evolution of a coastal upwelling event in the southern TWS using intensive cruise data and satellite data in summer 2004; the upwelling-related surface cold water was observed near Dongshan in early July, which then reduced its size by half with a decreased Chl-a concentration after half a month, and eventually vanished by the end of July.
2.2.2. TWS upwelling and its responses to ENSO and local environmental variation

As reviewed by Hong and Wang [49], Shang et al. [50], and Hong et al. [51], the TWS upwelling exhibits clear connections to the ENSO, global climate change, and local environmental variation.

Hu et al. [52] showed that two upwelling-related low temperature (high salinity) regions in the western TWS have clear interannual and intermonthly variability in summer. Combining SST and Chl-a data, Shang et al. [53–55] proposed that the ENSO events can potentially have significant impacts on the upwelling in the TWS. Tang et al. [56] revealed interannual variation of two upwelling zones (one near Dongshan) in the southern TWS. These studies indicated that the coastal upwelling in the western TWS has evident connections to the ENSO events. The local wind is much weaker in the TWS during the 1997 El Niño year than that during the 1998 La Niña year [57], suggesting that the ENSO event can affect the wind pattern over the TWS and thus modulate the surface ocean currents, SST, and coastal upwelling in an interannual scale. Hong et al. [46] further revealed that, for the entire western TWS, the summer coastal upwelling was strong in 1987, 1993, and 1998 (Figure 5), during which periods three peaks of the SST Empirical Orthogonal Function Mode 1 (EOF_1) time series matched well, with a time lag of 3 months, with those of the multivariate ENSO index (MEI).

By comparing remote sensing SST with in situ chemical and biological data collected since 1985, Hong et al. [58] obtained evidence of upwelling variation in response to interannual environmental variability in the TWS. According to these observations, the coastal upwelling was weakened in summer of 1997, resulting in an apparent anomaly in nutrient distribution, phytoplankton and zooplankton abundances, and community structure. Hong et al. [51] further summarized the hydrographical features with an emphasis on upwelling, which is the key driver of biogeochemical processes and ecosystem dynamics in the TWS. Hydrographic and satellite data revealed evident teleconnections between the TWS upwelling and the ENSO variability. Besides, Wang et al. [59] estimated the physical (i.e., coastal upwelling) and biological

![Figure 5](image_url). Variation of the eigenvector of SST EOF Mode 1 (EOF_1) in the TWS (black dots) and monthly multivariate ENSO index (MEI; shaded areas) 3 months ahead of the SST EOF_1 eigenvector during 1985–2005. The SST EOF_1 eigenvector is normalized by its maximum for the period 1985–2005. Redrawn from Hong et al. [46].
effects on the nutrient transport in the TWS during summer through a coupled physical-biological numerical ocean model. These studies concluded that the TWS upwelling has a profound impact on biogeochemical processes, biological productivity, and ecosystem structure.

2.2.3. Further understanding of mechanism for the coastal upwelling in the TWS

Several numerical models, such as a 3D nonlinear baroclinic shallow water model [60–62], the Coupled Hydrodynamical-Ecological Model for Regional and Shelf Seas (COHERENS; [63]) model [64], and a 3D nonlinear Estuarine, Coastal and Ocean Modeling System with Sediment (ECOMSED) model [65], have been used to study the mechanism of upwelling along the coasts of Fujian and Zhejiang in summer and winter. These numerical modeling results indicated that the wind stress, the Taiwan Warm Current, tidal nonlinear effect, and bottom topography are the main mechanisms for the upwelling in the coastal waters of Fujian and Zhejiang in both winter and summer. Specifically, the southwesterly or southerly wind induces the coastal upwelling in summer.

Furthermore, Jiang et al. [66] investigated the mechanisms of coastal upwelling in the southern TWS using a nested circulation model based on the POM. It is indicated that the upslope current over a distinctly widened shelf transports the cold water toward the shore in the lower layer, while the southwesterly monsoon wind drives the cold water away from the shore in the surface layer, thus generating the upwelling along the southwestern coast of the TWS.

2.3. Coastal upwelling in the East China Sea

The studies of coastal upwelling in the ECS have been conducted using hydrographic measurements, satellite observations, and numerical modelling. For recent decades, much progress of the upwelling study has been made particularly in the quick developments of numerical modelling technology and remote sensing approach.

2.3.1. Hydrographic measurements

Zhao et al. [67] reported an upwelling north of the Yangtze River (or the Changjiang River) Estuary, covering an area of roughly 1° by 1° centered at (31°30′N, 122°40′E). Several cruise measurements, such as the China-Korea joint investigation in the Yellow Sea and its adjacent sea area [68] and the marine flux investigation in the ECS in July 1998 [69], confirmed the existence of this upwelling in the Yangtze River Estuary. Zhu et al. [70] analyzed the hydrological characteristics in the outer Yangtze River Estuary and showed that the upwelling usually occurs near the first turning point of the Yangtze River Diluted Water. Zhu et al. [71] conducted comprehensive observations in August 2000 and indicated that the coastal upwelling appears along the Zhejiang coast, in the west of the submarine river valley and along the Lüsi coast. Lü et al. [72] presented signals of low-temperature and high-salinity upwelling water in the Yangtze River Estuary using three sections of temperature and salinity distributions (Figure 6) obtained from a cruise in August 2000. There is evidence that in the Yangtze River Estuary the subsurface high-salinity water can rise toward the 5–10 m layer from beneath.
2.3.2 Satellite observations

Hu and Zhao [73] studied the long-term variation of coastal upwelling off northeastern Zhejiang in summer using SST (1987–2005), Chl-a (2002–2006), and wind (1992–2006) data-sets; their results showed that the upwelling, with high Chl-a concentration, has seasonal, annual, and interannual variations. Hu and Zhao [74] investigated the short-term variation of upwelling in the Zhejiang coastal areas during May–October 2004 and indicated that the upwelling has a close relation to the along-shore wind variation. Lou et al. [75] depicted the evolution of the upwelling along Zhejiang coast, which appears in June, peaks
in July and August, and then diminishes until disappears in late September. The mean SST in the upwelling region is about 25-28°C in summer, with a temperature difference of approximately 2–4°C from the ambient nonupwelling waters. Cao et al. [76] investigated the upwelling phenomena in the Yangtze River Estuary.

Zhao et al. [79] used the POM model to study the upwelling mechanism in the Yangtze River Estuary.

Zhu [77] employed a 3D numerical model to analyze the baroclinic (barotropic) effect as the main factor for inducing upwelling in the north (south) of the submarine river valley off the Yangtze River Estuary.

Bai and Wang [80] used the POM model to investigate upwelling occurrences around 10 km away from the coastline in the Yangtze River Estuary.

Liu et al. [81] and Liu et al. [82] used 3D baroclinic ocean models to study the seasonal variation of the vertical circulation and temperature and salinity features associated with upwelling or downwelling.

Zhu et al. [83] used the ECOM-si model (ECOM with semi implicit scheme) to investigate how upwelling is mainly the baroclinic effect induced by mixing between the fresh water from the Yangtze River and the saline water offshore.

Qiao et al. [84] used the MASNUM model to study the baroclinic pressure gradient force near the frontal zone, which elicits an upwelling branch along the topographic slope.

Lü et al. [72] used the MASNUM model to study how upwelling is induced as a branch of the secondary circulation. Topography, Yangtze River discharge, and the Taiwan Warm Current all affect the upwelling.

Jing et al. [85] used the ECOMSED model to study how upwelling occurs along the coasts of Zhejiang and Fujian throughout the year, which is strong in summer and relatively weak in winter.

Lü et al. [86] used the MASNUM model to study how tides (barotropic and baroclinic processes) are key to the upwelling off the Yangtze River Estuary.

Bai et al. [87] used the ECOMSED model to study how upwelling is mainly induced by the Ekman effect and affected by the Taiwan Warm Current and continental slope rising.

Yang et al. [88] used the ROMS model to study how a branch current bifurcates from the subsurface of the Kuroshio northeast of Taiwan, upwells northwestward, then turns to northeast around (27.5°N, 122°E), and finally reaches 31°N off the Yangtze River mouth.

Cao et al. [76] used the ROMS model to study how wind primarily influences the short-term evolution of upwelling, while the topographic variation determines the upwelling center off the Yangtze River Estuary.

Liu and Gan [89] used a 3D high-resolution numerical model to study how intensified upwelling is formed by a strengthened shoreward transport downstream of the promontory coastline.

Yang et al. [90] used the ROMS coupled with phosphate model to study how the transported phosphate-rich water is further upwelled to the surface due to the upwelling just off the Zhejiang coast.

### Table 1. Numerical models used in studying the upwelling in the ECS.

| Authors          | Model                                | Features                                                                                                                                 |
|------------------|--------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Li and Zhao [78] | POM                                  | Upwelling phenomena in the Yangtze River Estuary.                                                                                         |
| Zhao et al. [79] | POM                                  | Upwelling mechanism in the Yangtze River Estuary.                                                                                         |
| Zhu [77]         | 3D numerical model                   | Baroclinic (barotropic) effect is the main factor for inducing upwelling in the north (south) of the submarine river valley off the Yangtze River Estuary. |
| Bai and Wang [80]| POM                                  | Upwelling occurs around 10 km away from the coastline in the Yangtze River Estuary.                                                       |
| Liu et al. [81]  | 3D baroclinic ocean model            | Seasonal variation of the vertical circulation in the ECS.                                                                                 |
| Liu et al. [82]  | 3D baroclinic ocean model            | Temperature and salinity features are associated with upwelling or downwelling.                                                            |
| Zhu et al. [83]  | ECOM-si model (ECOM with semi implicit scheme) | Upwelling is mainly the baroclinic effect induced by mixing between the fresh water from the Yangtze River and the saline water offshore. |
| Qiao et al. [84] | MASNUM                               | Owing to a strong density gradient, the baroclinic pressure gradient force is large near the frontal zone, which elicits an upwelling branch along the topographic slope. |
| Lü et al. [72]   | MASNUM                               | Upwelling is induced as a branch of the secondary circulation. Topography, Yangtze River discharge, and the Taiwan Warm Current all affect the upwelling. |
| Jing et al. [85] | ECOMSED model                        | Upwelling occurs along the coasts of Zhejiang and Fujian throughout the year, which is strong in summer and relatively weak in winter. |
| Lü et al. [86]   | MASNUM                               | Tides (barotropic and baroclinic processes) are key to the upwelling off the Yangtze River Estuary.                                      |
| Bai et al. [87]  | ECOMSED model                        | Upwelling is mainly induced by the Ekman effect and affected by the Taiwan Warm Current and continental slope rising.                      |
| Yang et al. [88] | ROMS                                 | A branch current bifurcates from the subsurface of the Kuroshio northeast of Taiwan, upwells northwestward, then turns to northeast around (27.5°N, 122°E), and finally reaches 31°N off the Yangtze River mouth. |
| Cao et al. [76]  | ROMS                                 | Wind primarily influences the short-term evolution of upwelling, while the topographic variation determines the upwelling center off the Yangtze River Estuary. |
| Liu and Gan [89] | 3D high-resolution numerical model   | Intensified upwelling is formed by a strengthened shoreward transport downstream of the promontory coastline.                              |
| Yang et al. [90] | ROMS coupled with phosphate model    | The transported phosphate-rich water is further upwelled to the surface due to the upwelling just off the Zhejiang coast.                 |

Note: MASNUM is a model established by the Laboratory of MArine Sciences and NUmerical Modeling, the State Oceanic Administration, China.
summertime upwelling off the Yangtze River Estuary using satellite data and proposed that along-shore wind stress and wind stress curl play similar important roles on the upwelling evolution.

2.3.3. Numerical modeling

Numerical models have been developed or applied for studying the characteristics of coastal upwelling and its dynamics in the ECS (Table 1). These simulations suggested that the coastal upwelling usually appears off the Yangtze River Estuary and along the Zhejiang coast, mostly in summer. The continental slope, wind speed, and the angle between the wind direction and the coastline control the coastal upwelling intensity. Topography, Yangtze River discharge, the Taiwan Warm Current, and the branch current bifurcating from the subsurface of the Kuroshio all affect the upwelling. In addition, baroclinic (barotropic) effect is the main factor for inducing upwelling in the north (south) of submarine river valley off the Yangtze River Estuary [77]. However, in the coastal waters near the Zhoushan Islands (located off the northeastern coast of Zhejiang), wind forcing may sometimes exert negative influences on the generation of coastal upwelling by weakening the intrusion of the Taiwan Warm Current onto the continental shelf [72].

3. Discussion

3.1. Influence of topography on upwelling

As mentioned above, the influence of topography on the generation and modulation of coastal upwelling has been observed in the ECS, TWS, and the northern SCS; so it is worthy of being separately discussed here as an important upwelling-related factor. A 3D modelling study by Gan et al. [91] revealed that the widened shelf off Shantou plays an important role in intensifying the local upwelling. The strongest advection occurs over the converging isobaths near Shanwei, i.e., the head of the widened shelf (Figure 7) where a negative pressure gradient also exists at the lee of the coastal cape over the inner shelf and locally amplifies shoreward motion. In addition, Chen [92] discussed the effects of cape and canyon on wind-driven coastal upwelling in the western TWS, suggesting that the positive vertical velocity is produced by changes in the relative vorticity downstream of the cape or canyon, which becomes a dominant upwelling mechanism there. Topography also exerts influences on upwelling by steering bottom currents upward. Upwelling can even be intensified by a strengthened shoreward transport downstream of a promontory coastline [89]. Recently, Wang et al. [93] investigated relative contributions of the local wind and topography to the coastal upwelling intensity in the northern SCS in the case when the upwelling-favorable wind retreats, using a high-resolution version of the POM. It is indicated that the topographically induced upwelling is comparable with the wind-driven upwelling at surface; while at bottom, topography has a stronger contribution than the local wind in controlling the upwelling intensity in the inner shelf of the northern SCS [93].
3.2. Influence of river on upwelling

For the upwelling near the Pearl River Estuary, the interaction between upwelling and river plume should be considered [94–96]. The enhanced stratification due to the presence of plume thins the surface frictional layer and strengthens the cross-shelf circulation in the upper water column. As a result, the surface Ekman current and the compensating flow beneath the plume are amplified, while the shoaling of the deeper dense water minimally changes in the upwelling region. The pressure gradient generated between the buoyant plume and the ambient sea water accelerates the wind-driven current along the inshore edge of the plume, but retards it along the offshore edge [95]. The buoyancy in the plume considerably modulates the alongshore and cross-shelf upwelling circulation in the upper water column [95], and that the upwelling initially occurs to the east of the Pearl River Estuary, intensifies eastward, and reaches its maximum near Shantou [96]. For the upwelling off the Yangtze River Estuary area, upwelling is associated with a strong salt-induced horizontal density gradient. The plume fronts separate the diluted and saline water, and this density structure elicits upwelling as a branch of the density-driven secondary circulation [72].

3.3. Influence of circulation on upwelling

The density (or salinity) front, which separates the inshore low-salinity coastal water from the offshore Taiwan Warm Current Water, is one of the primary inducing factors for the upwelling along the western coast of ECS. Using a numerical model, Yang et al. [88] revealed that the upwelling off the Zhejiang coast comes from the subsurface water of the Kuroshio northeast of Taiwan in summer (Figure 8). The phosphate-rich upwelling water off the coast of Zhejiang is mainly originated from the deep sea water in a special area (122.1°E–122.5°E, 130 m–300 m deep) northeast of Taiwan, as the nearshore Kuroshio branch current continuously transports the phosphate-rich deep sea water to the bottom area off the coast of Zhejiang [90].
As for the northern SCS, Wang et al. [97] investigated the subsurface upwelling signals off the coasts of Fujian and Guangdong provinces in summer 2000, using a combination of hydrographical, tide-gauge and mooring data, satellite observations, and numerical circulation model output. It is suggested that the subsurface upwelling is closely related to the coastal sea level fluctuation and is evidently modulated by both local wind-forcing and large-scale SCS circulation.

3.4. Influence of tide on upwelling

Lü et al. [98] studied the summertime upwelling off the western coast of Hainan Island using satellite SST data and numerical modeling. The presence of the tidal mixing front [99] was believed to play a profound role in stimulating the upwelling near the southwestern coast of Hainan Island. This upwelling was also evidenced by comprehensive cruise data collected in the summer of 2006 [100]. On the other hand, the southwesterly monsoon induces downwelling that competes with the front-induced upwelling off the western coast of Hainan Island.

In the TWS and the ECS, Hong et al. [101] also indicated that tidal mixing plays important roles in enhancing the upwelling in the TWS. In addition, tides contribute to the upwelling generation because tidal mixing facilitates the expansion of the Yangtze River Diluted Water, and strong tidal mixing results in considerable horizontal density gradient across a tidal front and thus induces upwelling [72, 86].

Internal tides may also affect the upwelling intensity [102, 103]. These studies used satellite multisensor data such as the moderate resolution imaging spectroradiometer (MODIS) SST, QuikSCAT ocean surface winds, and sea surface dynamic height, and suggested that
the interaction between upwelling and internal tides enhances the uplifting of lower-layer water; thus, the summertime upwelling pattern and intensity tend to be altered on the shelf off Guangdong.

4. Summary

There are six major coastal upwelling regions off the southeastern coast of mainland China, as shown in Figure 2. The main features of these coastal upwelling regions are summarized below.

In the northern SCS, coastal upwelling regions are distributed primarily off the eastern coast of Hainan Island and off the coasts of eastern Guangdong. The southwesterly monsoonal winds are the most prominent factor controlling the upwelling generation. Besides the alongshore wind stress, wind stress curl, distinct topographic features, frontal eddies, and local circulations are among the mechanisms for the coastal upwelling in the northern SCS.

In the TWS, two main coastal upwelling regions are identified, i.e., along the southwestern and northwestern coasts of the TWS. The former appears between Xiamen and Shantou, while the latter occurs from the east of Pingtan to Meizhou. Both upwellings are regarded as wind-driven, which occur during the southwesterly monsoon period with a relatively strong intensity in July. In addition, the bottom topography and the ascending of the northward current also affect the upwelling. With respect to the time-varying features, the coastal upwelling in the western TWS shows short-term variations caused by winds, and has evident responses to ENSO or local environmental variations.

In the ECS, coastal upwellings are observed in the Yangtze River Estuary and along the coast off Zhejiang. The alongshore wind, topography, tides, and local circulation are among the significant factors in determining the generation of coastal upwellings.

Upwelling in the coastal waters of China seas is complex, in terms of the spatial distribution, time-varying characteristics, generation mechanisms, and factors affecting its evolution and dynamics. It covers a wide range of temporal variability, including interannual and multidecadal timescales associated with the ENSO events and global climate change, as well as shorter timescales associated with fluctuations caused by winds or internal tides. Consequently, observations based solely on limited cruise measurements would not be able to provide in-depth knowledge of the upwelling dynamics or its associated biogeochemical processes. A number of dedicated offshore surveys covering all seasons have been conducted in the China seas over 2005–2011, aiming with a constant goal of collecting more hydrographic data as well as biogeochemical parameters. A much better understanding of the main characteristics and dynamics of upwelling in the China seas has been gained, based on these in situ measurements, multisources of satellite remote sensing data and outputs from global/regional ocean circulation models (some with biogeochemical modules) [104, 105]. Nevertheless, there are still certain issues related to coastal upwelling, which remain to be addressed in the near future, for example, the possible changes of upwelling under global climate change, the influences of submesoscale processes on the upper-ocean upwelling, etc.
Acknowledgements

This work is jointly supported by the National Basic Research Program of China (2015CB954004) and the National Natural Science Foundation of China (41776027, 41606009 and U1405233).

Author details

Jianyu Hu*, X. San Liang² and Hongyang Lin¹

*Address all correspondence to: hujy@xmu.edu.cn

1 State Key Laboratory of Marine Environmental Science, College of Ocean and Earth Sciences, Xiamen University, Xiamen, China

2 School of Marine Sciences, Nanjing University of Information Science and Technology, Nanjing, China

References

[1] Hu JY, Wang XH. Progress on upwelling studies in the China seas. Reviews of Geophysics. 2016;54(3):653-673

[2] Miao X, Hu JY. Analysis on characteristics of wind-driven coastal upwelling off the southeastern China coast using coastal upwelling index. Marine Science Bulletin. 2011;30(3):258-265 (in Chinese with English abstract)

[3] Bakun A. Coastal upwelling indices, west coast of North America, 1946-71. U.S. Dept. of Commerce, NOAA Tech. Rep, 1973, NMFS SSRF-671

[4] Wu RS, Li L. Summarization of study on upwelling system in the South China Sea. Journal of Oceanography in Taiwan Strait. 2003;22(2):269-276 (in Chinese with English abstract)

[5] Li L et al. Upwelling in the South China Sea. In: Su JL, Yuan YL, editors. Hydrography near the China Seas. Beijing: China Ocean Press; 2005. p. 272-278 (in Chinese)

[6] Guan BX, Chen SJ. The current systems in the near-sea area of China Seas. Qingdao: Technical Report, Institute of Oceanology, Chinese Academy of Sciences; 1964. 85pp (in Chinese)

[7] Chen JQ et al. A study on upwelling in Minnan-Taiwan Shoal fishing ground. Taiwan Strait. 1982;1(2):5-13 (in Chinese with English abstract)

[8] Zeng LM. A preliminary analysis of indicators of offshore upwelling off eastern Guangdong. Tropic Oceanology. 1986;5:68-73 (in Chinese with English abstract)

[9] Deng S. Analysis on upwelling in the south of Qizhou Islands. Technical Report, South China Sea Branch of State Oceanic Administration; 1987 (in Chinese)
[10] Han WY, Ma KM. A study of coastal upwelling off eastern Guangdong. Acta Oceanologia Sinica. 1988;10(1):52-59 (in Chinese with English abstract)

[11] Zhuang W et al. An analysis on surface temperature and salinity from southern Taiwan Strait to Zhujiang River estuary during July-August, 2000. Journal of Tropical Oceanography. 2003;22(4):68-76 (in Chinese with English abstract)

[12] Xu JD et al. Hydrology features in outer sea of eastern Guangdong in summer 2002. Journal of Oceanography in Taiwan Strait. 2003;22(2):218-228 (in Chinese with English abstract)

[13] Zeng GN et al. Analysis of hydrologic section off Zhujiang River estuary in northern South China Sea during various southwest monsoon phases. Journal of Tropical Oceanography. 2005;25(3):10-17 (in Chinese with English abstract)

[14] Zhu J et al. Analysis on sectional characteristics of temperature and salinity off the Zhujiang River estuary—during the cruises of May 2001 and November 2002. Journal of Xiamen University (Natural Science). 2005;44(5):680-683 (in Chinese with English abstract)

[15] Zhang Y et al. Analysis on hydrological characteristics off the Pearl River Estuary in summer and winter of 2006. Journal of Tropical Oceanography. 2011;30(1):20-28 (in Chinese with English abstract)

[16] Cai SZ et al. Characteristics of upwelling in eastern Guangdong and southern Fujian coastal waters during 2006 summer. Journal of Oceanography in Taiwan Strait. 2011;30(4):489-497 (in Chinese with English abstract)

[17] Wan XF et al. Seasonal variation features of the hydrodynamic environment in the western Taiwan Strait. Journal of Applied Oceanography. 2013;32(2):156-163 (in Chinese with English abstract)

[18] Xu JD et al. Observational study on summertime upwelling in coastal seas between eastern Guangdong and southern Fujian. Journal of Tropical Oceanography. 2014;33(2):1-9 (in Chinese with English abstract)

[19] Zhuang W et al. Coastal upwelling off eastern Fujian-Guangdong detected by remote sensing. Chinese Journal of Atmospheric Sciences. 2005;29(3):438-444 (in Chinese with English abstract)

[20] Qiao FL, Lü XG. Coastal upwelling in the South China Sea. In: Liu AK, Ho CR, Liu CT, editors. Satellite Remote Sensing of South China Sea. Taiwan: Tingmao Publish Company; 2008. p. 135-158

[21] Wang DK et al. Role of Ekman transport versus Ekman pumping in driving summer upwelling in the South China Sea. Journal of Ocean University of China. 2013;12(3):355-365

[22] Chai F et al. Formation and distribution of upwelling and downwelling in the South China Sea. In: Xue HJ et al, editors. Oceanography in China, Vol. 13. Beijing: Ocean Press; 2001. p. 117-128 (in Chinese with English abstract)
[23] Jing ZY et al. Numerical study on summer upwelling over northern continental shelf of South China Sea. Journal of Tropical Oceanography. 2008;27(3):1-8 (in Chinese with English abstract)

[24] Jing ZY et al. Numerical study on the summer upwelling system in the northern continental shelf of the South China Sea. Continental Shelf Research. 2009;29(2):467-478

[25] Zhang YY, Jiang YW. The mechanism of cold water cross-shelf transport in the continental shelf off Shanwei. Journal of Xiamen University (Natural Science). 2012;51(4):746-752 (in Chinese with English abstract)

[26] Xie LL et al. Overview of studies on Qiongdong upwelling. Journal of Tropical Oceanography. 2012;31(4):35-41 (in Chinese with English abstract)

[27] Chai F et al. Upwelling east of Hainan Island. In : Hue HJ et al, editors. Oceanography in China. Vol. 13. Beijing: Ocean Press; 2001. p. 129-137 (in Chinese with English abstract)

[28] Su J, Pohlmann T. Wind and topography influence on an upwelling system at the eastern Hainan coast. Journal of Geophysical Research-Oceans. 2009;114(C6):C06017

[29] Li YN et al. Numerical simulation of the structure and variation of upwelling off the east coast of Hainan Island using QuikSCAT winds. Chinese Journal of Oceanology and Limnology. 2012;30(6):1068-1081

[30] Lin PG et al. Observation of summertime upwelling off the eastern and northeastern coasts of Hainan Island, China. Ocean Dynamics. 2016;66(3):387-399

[31] Lin PG et al. Dynamics of wind-driven upwelling off the northeastern coast of Hainan Island. Journal of Geophysical Research–Oceans. 2016;121:1160-1173

[32] Xu JD et al. Study on coastal upwelling in eastern Hainan Island and western Guangdong in summer, 2006. Acta Oceanologica Sinica. 2013;35(4):11-18 (in Chinese with English abstract)

[33] Liu Y et al. Variation of summer coastal upwelling at northern South China Sea during the last 100 years. Geoichimica. 2009;38(4):317-322 (in Chinese with English abstract)

[34] Jing ZY et al. Upwelling in the continental shelf of northern South China Sea associated with 1997-1998 El Niño. Journal of Geophysical Research-Oceans. 2011;116(C2):C02033

[35] Su J et al. A western boundary upwelling system response to recent climate variation (1960-2006). Continental Shelf Research. 2013;57(SI):3-9

[36] Liu Y et al. Recent 121-year variability of western boundary upwelling in the northern South China Sea. Geophysical Research Letters. 2013;40(12):3180-3183

[37] Xiao H et al. Summarization of studies on hydrographic characteristics in Taiwan Strait. Journal of Oceanography in Taiwan Strait. 2002;21(1):126-138 (in Chinese with English abstract)
[38] Hu JY et al. A review of research on the upwelling in the Taiwan Strait. Bulletin Marine Science. 2003;73(3):605-628

[39] Hu JY et al. Analysis on sea surface temperature and salinity in the Taiwan Strait during August 1998. Tropic Oceanology. 2000;19:15-22 (in Chinese with English abstract)

[40] Tang DL et al. Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements. Remote Sensing of Environment. 2002;83(3):457-471

[41] Chen H et al. Underway measurement of sea surface temperature and salinity in the Taiwan Straits in August, 1999. Marine Science Bulletin. 2002;4:11-18

[42] Chen ZZ et al. Observation of upwelling and diluted water in southern Taiwan Strait during July, 2005. Journal of Tropical Oceanography. 2008;27(4):19-22 (in Chinese with English abstract)

[43] Chen XH et al. Densely underway measurement of surface temperature and salinity in Xiamen-Quanzhou near-shore area. Advances in Earth Science. 2009;24(6):629-635 (in Chinese with English abstract)

[44] Lin PG et al. Variation characteristics of upwelling in Taiwan Strait and its relationship with wind in summer 2011. Journal of Oceanography in Taiwan Strait. 2012;31(3):307-316 (in Chinese with English abstract)

[45] Zhu J et al. On summer stratification and tidal mixing in the Taiwan Strait. Frontiers of Earth Science. 2013;7(2):141-150

[46] Hong HS et al. Interannual variability of summer coastal upwelling in the Taiwan Strait. Continental Shelf Research. 2009;29:479-484

[47] Hu JY et al. Variable temperature, salinity and water mass structures in the southwestern Taiwan Strait in summer. Continental Shelf Research. 2011;31:S13-S23

[48] Zhang CY et al. Evolution of a coastal upwelling event during summer 2004 in the southern Taiwan Strait. Acta Oceanologia Sinica. 2011;30(1):1-6

[49] Hong HS, Wang DZ. Studies on biogeochemical process of biogenic elements in the Taiwan Strait. Journal of Xiamen University (Natural Science). 2001;40(2):535-544 (in Chinese with English abstract)

[50] Shang SL et al. An overview of the marine ecosystem response to climate-ocean variability. Journal of Marine Sciences. 2005;23(3):14-22 (in Chinese with English abstract)

[51] Hong HS et al. An overview of physical and biogeochemical processes and ecosystem dynamics in the Taiwan Strait. Continental Shelf Research. 2011;31:S3-S12

[52] Hu JY et al. Hydrographic and satellite observations of summertime upwelling in the Taiwan Strait: A preliminary description. Terrestrial Atmospheric and Oceanic Sciences. 2001;12(2):415-430
[53] Shang SL et al. Upwelling induced variability of Chlorophyll in the Taiwan Strait as observed by SeaWiFS and AVHRR. In: RJ Frouin et al., editors. Proceedings of SPIE Vol. 4892 Ocean Remote Sensing and Applications. Bellingham, WA: SPIE; 2003

[54] Shang SL et al. Short-term variability of chlorophyll associated with upwelling events in the Taiwan Strait during the southwest monsoon of 1998. Deep-Sea Research II. 2004; 51(10-11):1113-1127

[55] Shang SL et al. Hydrographic and biological changes in the Taiwan Strait during the 1997-1998 El Nino winter. Geophysical Research Letters. 2005(32):L11601

[56] Tang DL et al. Long-time observation of annual variation of Taiwan Strait upwelling in summer season. Advances in Space Research. 2004;33(3):307-312

[57] Kuo N-J, Ho C-R. ENSO effect on the sea surface wind and sea surface temperature in the Taiwan Strait. Geophysical Research Letters. 2004;31(13):L13309

[58] Hong HS et al. Evidence of ecosystem response to the interannual environmental variability in the Taiwan Strait. Acta Oceanologia Sinica. 2005;27(2):63-69 (in Chinese with English abstract)

[59] Wang J et al. Summer nitrogenous nutrient transport and its fate in the Taiwan Strait: A coupled physical-biological modeling approach. Journal of Geophysical Research-Oceans. 2013;118(9):4184-4200

[60] Pan YP, Sha WY. Numerical study on winter coastal upwelling off Fujian and Zhejiang coast. Oceanologia et Limnologia Sinica. 2004;35(3):193-201 (in Chinese with English abstract)

[61] Pan YP, Sha WY. Numerical study on the summer coastal upwelling off Fujian and Zhejiang. Marine Science Bulletin. 2004;23(3):1-11 (in Chinese with English abstract)

[62] Pan YP, Sha WY. Numerical study on the coastal upwelling off Fujian and Zhejiang. Marine Forecasts. 2004;21(2):86-95 (in Chinese with English abstract)

[63] Luyten PJ et al. COHERENS–A coupled hydrodynamical-ecological model for regional and shelf seas: User documentation. Management Unit of the Mathematical Models of the North Sea. 1999:1-914

[64] Zeng GN. Application of COHERENS model on environmental dynamics of the Taiwan Strait. Ph.D thesis of Xiamen University, Xiamen; 2006. 154pp (in Chinese with English abstract)

[65] Jing ZY et al. Numerical study on the coastal upwelling and its seasonal variation along Fujian and Zhejiang coast. Journal of Hohai University. 2007;35(4):464-470 (in Chinese with English abstract)

[66] Jiang YW et al. Characteristics and mechanisms of the upwelling in the southern Taiwan Strait: A three-dimensional numerical model study. Journal of Oceanography. 2011; 67:699-708
[67] Zhao BR et al. Characteristics of the ecological environment in upwelling area adjacent to the Changjiang River estuary. Oceanologia et Limnologia Sinica. 2001;32(3):327-333 (in Chinese with English abstract)

[68] Zou EM et al. An analysis of summer hydrographic features and circulation in the southern Yellow Sea and the northern East China Sea. Oceanologia et Limnologia Sinica. 2001;32(3):340-348 (in Chinese with English abstract)

[69] Bai H et al. Light transmission in summer and its relation to sediment transportation in the East China Sea. Marine Sciences. 2002;26(5):45-48 (in Chinese with English abstract)

[70] Zhu DD et al. Hydrologic distribution characteristics of HAB frequent occurrence area in the outer Changjiang River estuary. Chinese Journal of Applied Ecology. 2003;14(7):1131-1134 (in Chinese with English abstract)

[71] Zhu JR et al. Observation of the diluted water and plume front off the Changjiang River estuary during August 2000. Oceanologia et Limnologia Sinica. 2003;34(3):249-255 (in Chinese with English abstract)

[72] Lü XG et al. Upwelling off Yangtze River estuary in summer. Journal of Geophysical Research-Oceans. 2006;111:C11S08

[73] Hu MN, Zhao CF. Long-time observation of upwelling in the Zhoushan Islands and adjacent seas during the summer season. Periodical of Ocean University of China. 2007;51:235-240 (in Chinese with English abstract)

[74] Hu MN, Zhao CF. Upwelling in Zhejiang coastal areas during summer detected by satellite observations. Journal of Remote Sensing. 2008;12(2):297-304 (in Chinese with English abstract)

[75] Lou XL et al. Satellite observation of the Zhejiang coastal upwelling in the East China Sea during 2007-2009. Proceedings of SPIE. 2011:8175

[76] Cao GP et al. Mechanism of upwelling evolvement in the Yangtze River Estuary adjacent waters in summer, 2007. Marine Sciences. 2013;37(1):102-112 (in Chinese with English abstract)

[77] Zhu JR. Dynamic mechanism of the upwelling on the west side of the submerged river valley off the Changjiang mouth in summertime. Chinese Science Bulletin. 2003;48(24):2754-2758

[78] Li HF, Zhao BR. Simulation of the three-dimensional circulation of the East China Sea in summer. Studia Marina Sinica. 2003;45:48-63 (in Chinese with English abstract)

[79] Zhao BR et al. Numerical simulation of upwelling in the Changjiang River mouth area. Studia Marina Sinica. 2003;45:64-76 (in Chinese with English abstract)

[80] Bai XZ, Wang F. Numerical study on the mechanism of the expansion of the Changjiang River diluted water in summer. Oceanologia et Limnologia Sinica. 2003;34(6):593-603 (in Chinese with English abstract)
[81] Liu XQ et al. Dynamic process of vertical circulation and temperature-salinity structure in coastal area of East China Sea, I. Basic characteristics of the circulation. Oceanologia et Limnologia Sinica. 2004;35(5):393-403 (in Chinese with English abstract)

[82] Liu XQ et al. Dynamic process of vertical circulation and temperature-salinity structure in coastal area of East China Sea, II. Temperature and salinity structure. Oceanologia et Limnologia Sinica. 2004;35(6):497-506 (in Chinese with English abstract)

[83] Zhu JR et al. Observation and modeling analysis of dynamic mechanism of the upwelling at Lüsi. Journal of East China Normal University. 2004;2:87-91 (in Chinese with English abstract)

[84] Qiao FL et al. Coastal upwelling in the East China Sea in winter. Journal of Geophysical Research-Oceans. 2006;111(C11):C11S06

[85] Jing ZY et al. Numerical study on the coastal upwelling and its seasonal variation in the East China Sea. Journal of Coastal Research. 2007;50:555-563

[86] Lü XG et al. Tidally induced upwelling off Yangtze River estuary and in Zhejiang coastal waters in summer. Science in China (Series D): Earth Sciences. 2007;50(3):462-473

[87] Bai T et al. Numerical study of upwelling of the Changjiang River Estuary and its adjacent sea area in summer. Marine Sciences. 2009;33(11):65-72 (in Chinese with English abstract)

[88] Yang DZ et al. Numerical study of the ocean circulation on the East China Sea shelf and a Kuroshio bottom branch northeast of Taiwan in summer. Journal of Geophysical Research-Oceans. 2011;116(C5):C05015

[89] Liu ZQ, Gan JP. Modeling study of variable upwelling circulation in the East China Sea: Response to a coastal promontory. Journal of Physical Oceanography. 2013;44:1078-1094

[90] Yang DZ et al. Numerical study on the origins and the forcing mechanism of the phosphate in upwelling areas off the coast of Zhejiang Province, China in summer. Journal of Marine Systems. 2013;123:1-18

[91] Gan JP et al. Intensified upwelling over a widened shelf in the northeastern South China Sea. Journal of Geophysical Research-Oceans. 2009;114(C9):C09019

[92] Chen ZY. Coastal upwelling study: Observation, dynamic analysis and modelling. Ph.D thesis of Xiamen University, Xiamen; 2013. 145 pp. (in English with Chinese abstract)

[93] Wang DX et al. Relative contributions of local wind and topography to the coastal upwelling in the northern South China Sea. Journal of Geophysical Research-Oceans. 2014;119(C4):2550-2567

[94] Wong LA et al. A model study of the circulation in the Pearl River Estuary (PRE) and its adjacent coastal waters: I. Simulations and comparison with observations. Journal of Geophysical Research-Oceans. 2003;108(C5):3156

[95] Gan JP et al. Interaction of a river plume with coastal upwelling in the northeastern South China Sea. Continental Shelf Research. 2009;29(4):728-740
[96] Shu YQ et al. The 4-D structure of upwelling and Pearl River plume in the northern South China Sea during summer 2008 revealed by a data assimilation model. Ocean Modelling. 2011;36(3-4):228-241

[97] Wang DX et al. Coastal upwelling in summer 2000 in the northeastern South China Sea. Journal of Geophysical Research-Oceans. 2012;117:C04009

[98] Lü XG et al. Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. Geophysical Research Letters. 2008;35(2):L02604

[99] Hu JY et al. Tidal front around the Hainan Island, northwest of the South China Sea. Journal of Geophysical Research-Oceans. 2003;108(C11):3342

[100] Sun ZY et al. Horizontal distribution of temperature and salinity in eastern Beibu Gulf in summer 2006. In: Hu JY, Yang SY, editors. A Collection of Research Papers on Marine Science in the Beibu Gulf (Vol. 1). Beijing: China Ocean Press; 2008. p. 73-78 (in Chinese with English abstract)

[101] Hong HS et al. Source water of two-pronged northward flow in the southern Taiwan Strait in summer. Journal of Oceanography. 2011;67(4):385-393

[102] Gu YZ et al. Remote sensing observation and numerical modeling of an upwelling jet in Guangdong coastal water. Journal of Geophysical Research-Oceans. 2012;117:C08019

[103] Pan AJ et al. A preliminary study of the internal tide in the summertime upwelling regime off the Guangdong shelf edge in 2002 and its local feedback. Journal of Oceanography in Taiwan Strait. 2012;31(2):151-159 (in Chinese with English abstract)

[104] Qiao FL. Regional Oceanography of the China Seas: Physical Oceanography. Beijing: Ocean Press; 2012. 300 pp (in Chinese)

[105] Xiong XJ et al. China Coastal Ocean: Physical Oceanography and Marine Meteorology. Beijing: Ocean Press; 2012. 280 pp (in Chinese)
