Chapter 1

Coastal Upwelling Off the China Coasts

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Additional information is available at the end of the chapter

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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

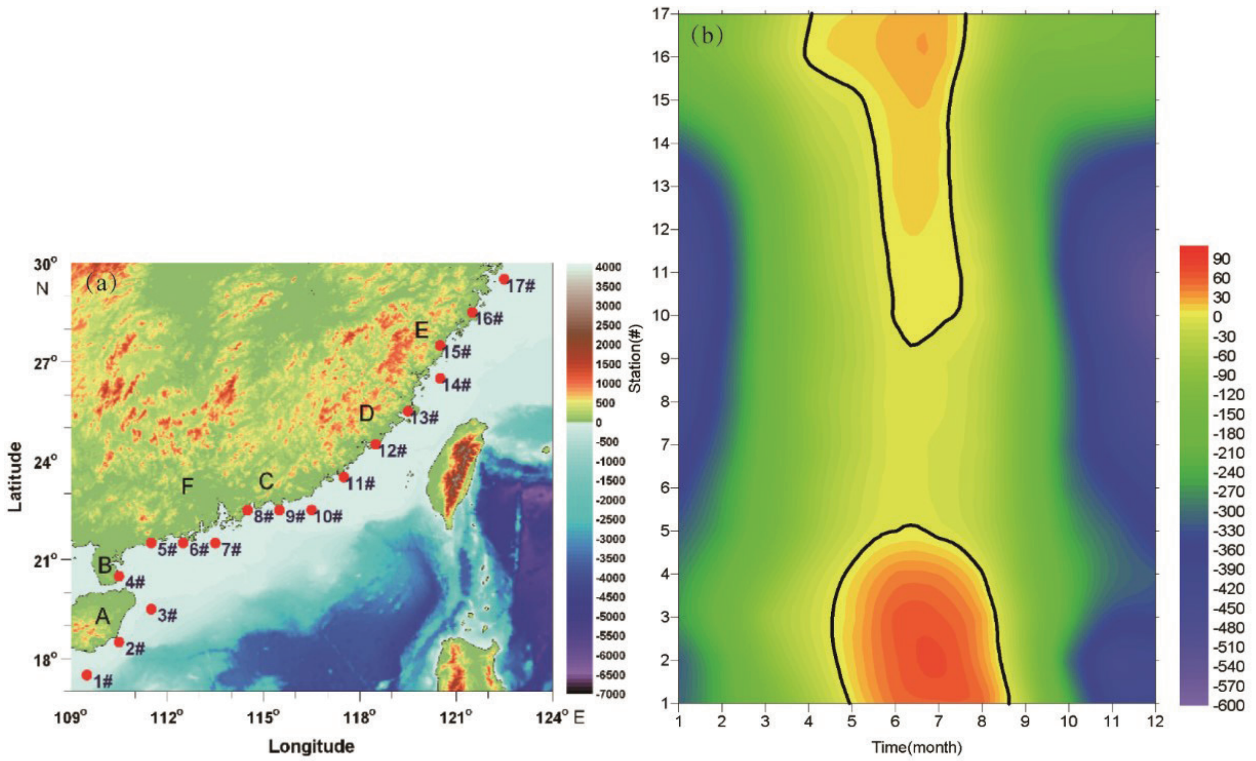

Figure 1. Monthly mean coastal upwelling index (b) off the southeastern China coast (the station locations for calculating the coastal upwelling index are shown in panel (a)). Redrawn from Miao and Hu [2].

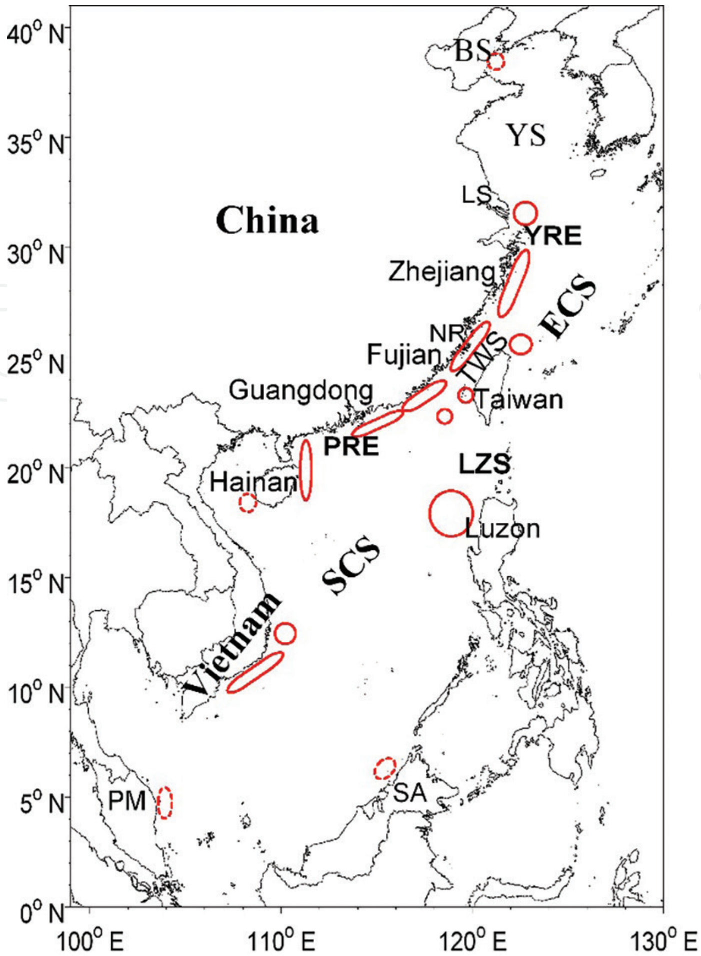

Figure 2. Map of major upwelling regions in the China seas, including the South China Sea (SCS), the Taiwan Strait (TWS), the East China Sea (ECS), the Yellow Sea (YS), and the Bohai Sea (BS). In this figure, the Yangtze River Estuary and the Pearl River Estuary are indicated by YRE and PRE, respectively. PM stands for the Peninsular Malaysia; LZS for Luzon Strait; and LS, NR, and SA for Lüsi, Nanri, and Sabah, respectively. The red ellipses or circles schematically mark locations of the major upwelling regions in the China seas. The ellipses or circles in dashed lines are upwelling regions that are sometimes mentioned. Cited from Hu and Wang [1].

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 Zhujiang 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,

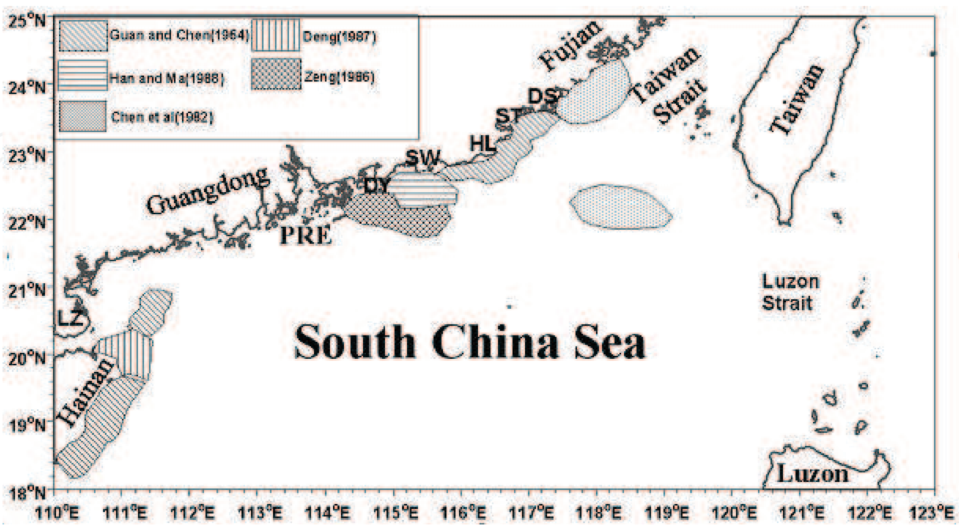

Figure 3. Reported upwelling regions in the continental shelf of the northern SCS. Redrawn from Wu and Li [4]. It summarizes the research included in [6–10]. PRE stands for the Pearl River Estuary; LZ for the Leizhou Peninsula; DS, ST, HL, SW, and DY for Dongshan, Shantou, Huilai, Shanwei, and the Daya Bay, respectively.

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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 southwesterly monsoon period, which has been confirmed by a number of hydrological and satellite

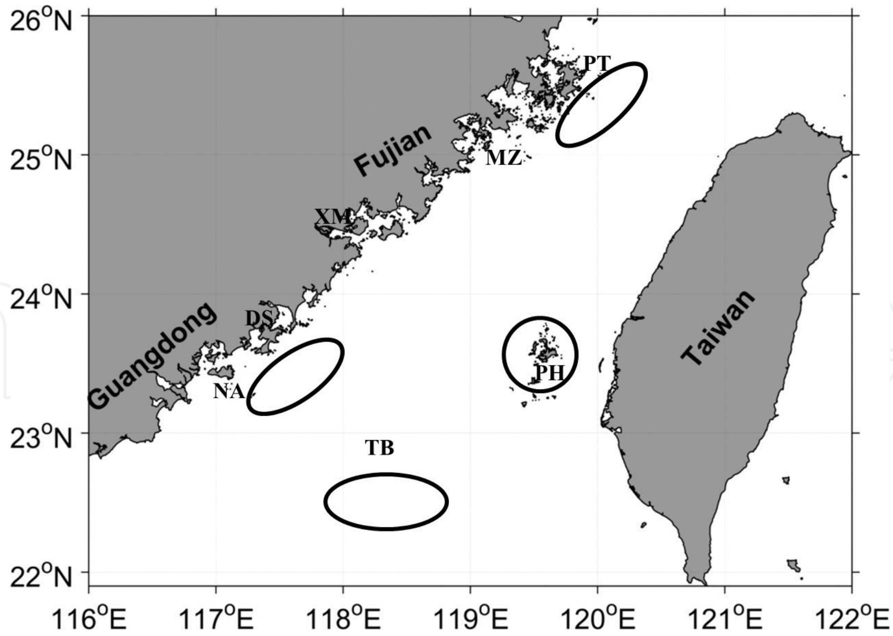

Figure 4. Schematic map of main upwelling regions in the TWS. Redrawn from Hu et al. [38]. DS: Dongshan; MZ: the Meizhou Island; NA: Nan-ao; PH: the Penghu Islands; PT: Pingtan; TB: the Taiwan Bank; XM: Xiamen. Four ellipses and circle schematically indicate the locations of four upwelling regions.

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

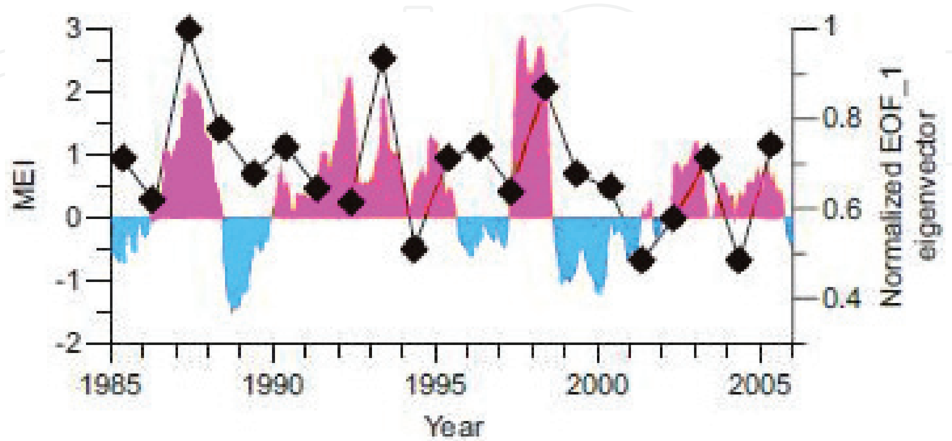

Figure 5. Variation of the eigenvector of SST EOF Mode 1 (EOF_1) in the TWS (black dots) and monthly multivariate ENSO index (MEI; shaded areas) 3 months ahead of the SST EOF_1 eigenvector during 1985–2005. The SST EOF_1 eigenvector is normalized by its maximum for the period 1985–2005. Redrawn from Hong et al. [46].

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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.

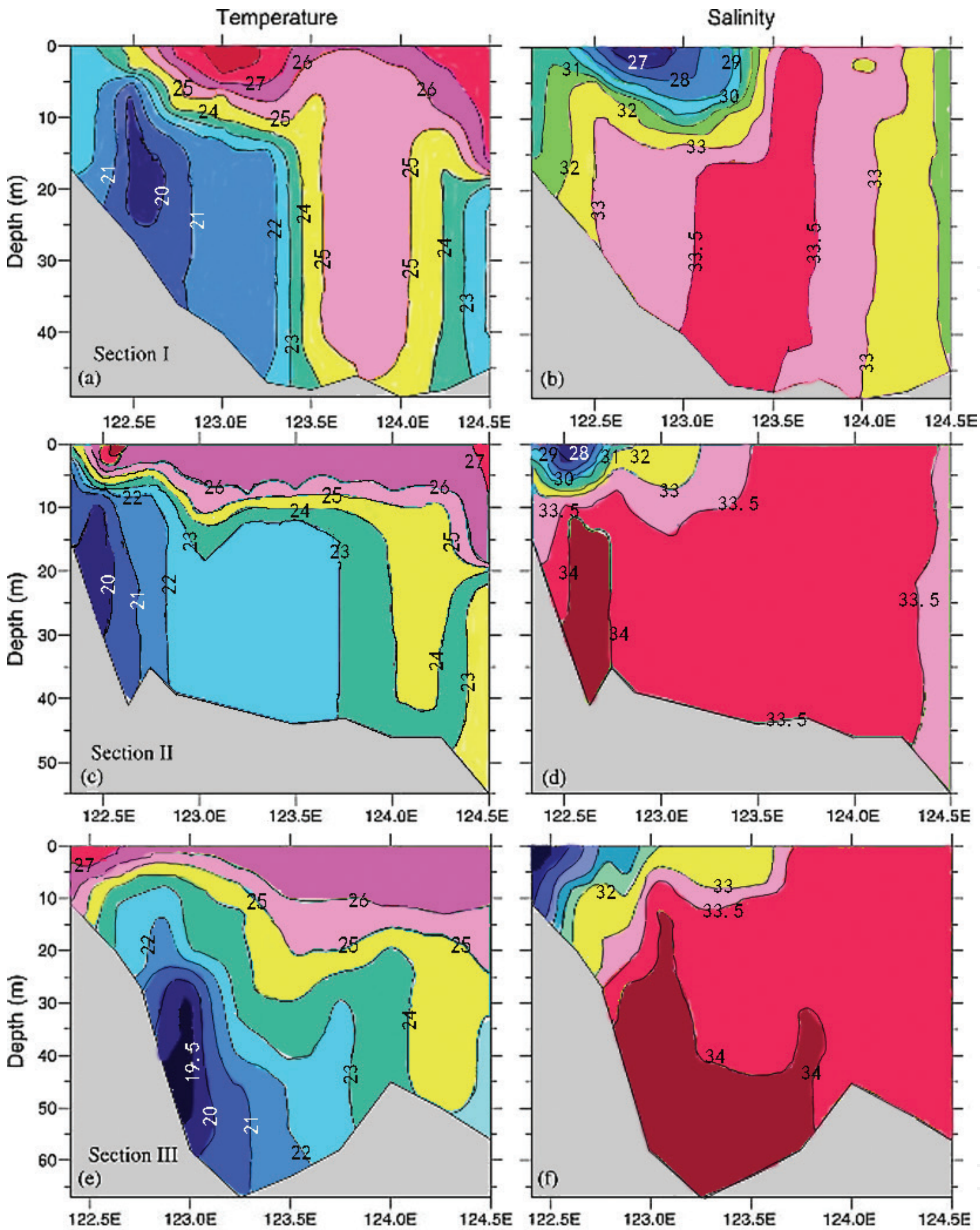

Figure 6. Vertical distributions of temperature (°C; left panels) and salinity (right panels) along Section 32.0°N (top), Section 31.5°N (middle), and Section 31.0°N in the Yangtze River Estuary. Redrawn from Lü et al. [72].

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) datasets; 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

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 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.

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

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 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].

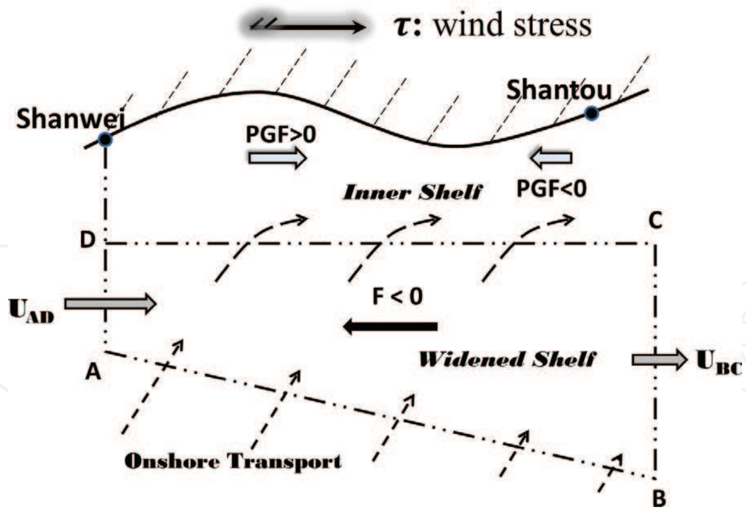

Figure 7. Schematic picture showing the wind-driven upwelling processes and forcing mechanism over the middle and inner shelves of a widened shelf. Redrawn from Gan et al. [91]. PGF denotes pressure gradient force; $\mathbf{U}_{AD}$ and $\mathbf{U}_{BC}$ are mean velocities normal to the two streamlines AD and BC, respectively. The line AD is at the head of the widened shelf (near Shanwei) and BC, downstream of it (near Shantou).

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].

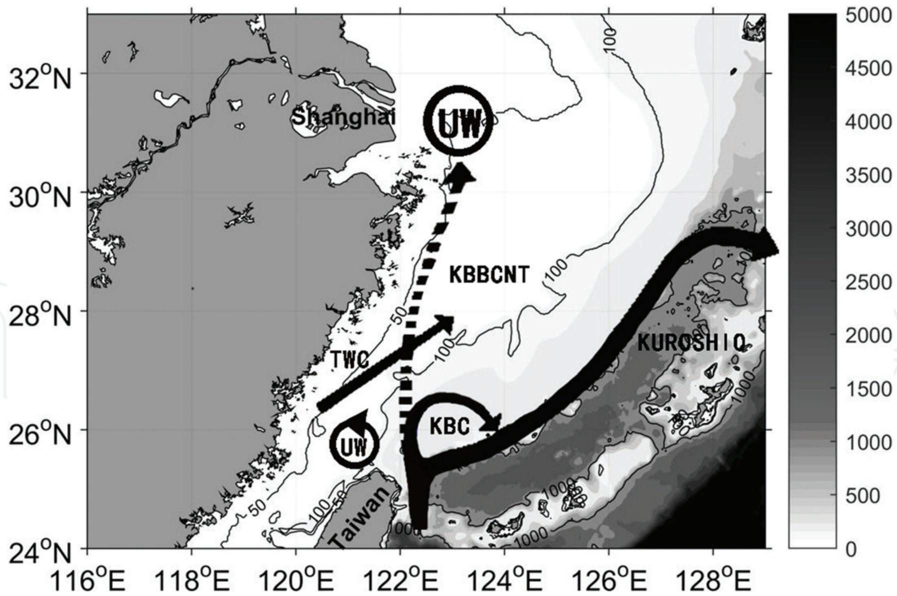

Figure 8. Summer ocean circulation pattern in the ECS. The solid thin lines represent the isobaths of 50, 100, and 1000 m. The bold dashed line represents the possible ocean current of the Kuroshio Bottom Branch Current to the northeast of Taiwan (KBBCNT). The bold solid lines show the Kuroshio, the Kuroshio Branch Current (KBC), and the Taiwan Warm Current (TWC), and UW denotes upwelling. Redrawn from Yang et al. [88].

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.

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