Chapter 5

Marine Ecological Disasters and Their Physical Controlling Mechanisms in Jiangsu Coastal Area

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Additional information is available at the end of the chapter

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Abstract

The studies in this chapter are focused on marine ecological disasters in Jiangsu coastal area. Three kinds of algal blooms occurred in this region, namely, red tide associated with *Dinoflagellate*, green tide associated with *Ulvaprolifera* and golden tide associated with *Sargassum*. Numerical model results demonstrated that red tides in Haizhou Bay originated locally, because most of *Dinoflagellates* near Zhoushan Islands would be transported northeastward by the Changjiang diluted water, and even the lucky ones that entered the south of Jiangsu coastal area would die in the Subei Shoal due to high turbidity there. Due to the Changjiang diluted water and the prevailing southerly wind, *Ulvaprolifera* could not drift southward, either. Seawater with high turbidity in the Subei Shoal limited sunlight penetration into deep water column, and further inhibited the growth of *Ulvaprolifera* suspending in the water column. In this chapter, we use drift bottles and satellite-tracked Argos drifters to provide solid direct dynamic evidence that *Ulvaprolifera* could drift from the Subei Shoal to Qingdao coastal area and even further north. The sand ridges limited the traveling path of *Ulvaprolifera* in the Subei Shoal, and wind-driven currents and other baroclinic processes helped *Ulvaprolifera* travel farther to the north.

Keywords: red tide, green tide, golden tide, physical controlling mechanism, Jiangsu coastal area

1. Marine ecological disaster and research contents of this chapter

1.1. Eutrophication

Since the end of the last century, marine environmental quality has become worse and worse as local economy developed rapidly in Jiangsu [1]. Chinese national water quality distribution showed that the pollution problems in China were especially serious in the Changjiang estuary and Jiangsu coastal area. Water pollutions have a series of negative effects on inshore cultivation, wetland protection, among others. Similar as water quality situation, eutrophication problems along the Jiangsu coast were conspicuous. Seawater pollution in China was mainly caused by the discharge of land-sourced pollutants, and coastal cities including Nantong city, Yancheng city and Lianyungang city were affected mostly. The most polluted coastal waters were near estuaries, sewage outlets and their adjacent seas. It was obvious that the seawater near the coast was much more polluted than that of farther offshore. The main pollutants were inorganic nitrogen, active phosphate and petroleum. As the equation of eutrophication index showed [2], the most polluted seawaters were the most eutrophic seawaters. Increment of inorganic nitrogen and active phosphate caused eutrophication in the coastal waters, and this situation has been going on for a long time. There was no obvious inter-annual variation of the polluted sea area in Jiangsu, with the largest area of seriously polluted waters to be 14,371 km^2 in 2012. Generally, eutrophication gradually worsened from spring to autumn during a year. In spring, the seawaters were in the critical state of eutrophication; eutrophication gradually accelerated during summer and finally seawaters became seriously polluted along the Jiangsu coast [1]. Nutrients were sufficient for algal growth in the Jiangsu coastal region. Some algae can produce toxin poisoning shellfish, fish and other marine organisms. Even for nontoxic algal blooms, the excessive reproduction of algae can also cause blockage or damage to gills, and marine organisms can be asphyxiated in the poor oxygen waters [3]. At present, the major marine disasters suffered in the Jiangsu coast were red tide and green tide; but in 2017, golden tide seemed to join in.

1. Red tide

Red tide is a kind of algal bloom with a red or brown color caused by some species of *dinoflagellates* [4]. According to the records of red tides in the Jiangsu Marine Environment Quality Bulletins and National Marine Disaster Bulletins (**Figure 1**), Jiangsu coastal area was not a region with frequent red tides. Nevertheless, they happened nearly every year in the area; especially in 2005, breaking out four times in the Jiangsu coast with a total size of 1274 m^2 (**Figure 2**). Among them, the red tide from September 23 to September 27 was the largest since the red-tide-monitoring area was established in 2005, with a single size of 1000 m^2. According to the statistical data, this kind of tides in this region usually happened from April to September, especially in May and June. The frequency was the lowest in August. In Jiangsu coast, they mainly occurred in the waters of Haizhou Bay and Nantong offshore area, with 78% in Haizhou Bay. The dominant species of red tides in this region was *Skeletone macostatum* (**Table 1**). The red tides in Haizhou Bay were mostly poisonous dinoflagellate, and those in Nantong offshore area were often diatom. Since poisonous blooms were very harmful, the State Oceanic Administration set up a red-tide-monitoring area in Haizhou Bay

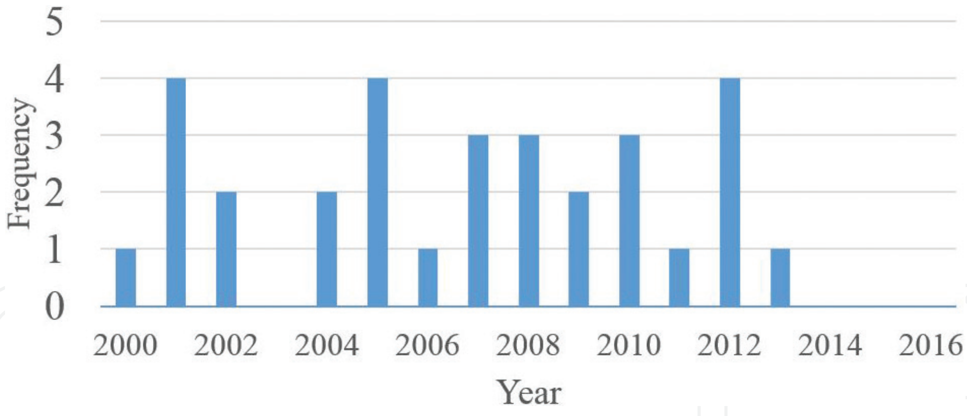

Figure 1. Frequency of red tides in Jiangsu coastal area from 2000 to 2016.

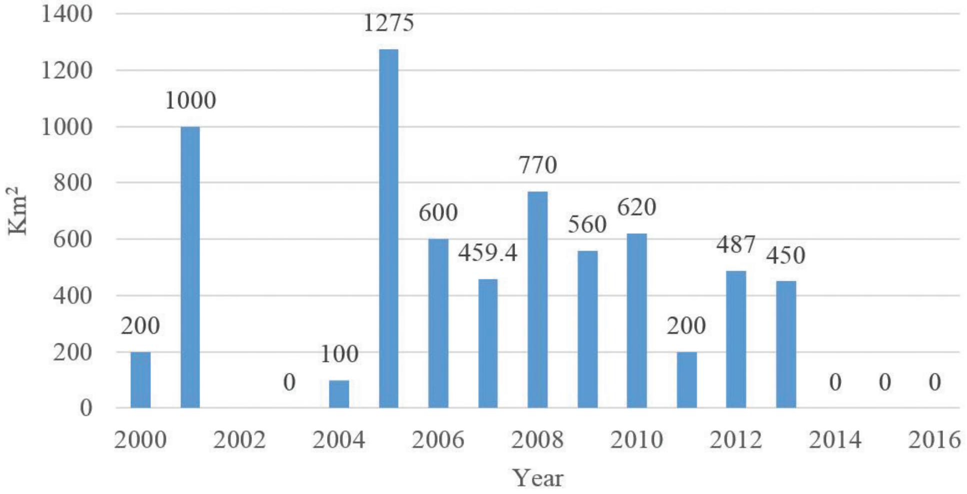

Figure 2. Area variation of red tide in Jiangsu coastal area from 2000 to 2016.

(119°31′E-119°35′E, 34°44′N-34°48′N), where high-frequency monitoring was carried out. Note that although the Jiangsu coastal water was still in a state of eutrophication and has potential risk of red tide, red tide never happened after 2014.

2. Green tide

Algal blooms caused by excessive growth of green algae, such as *Ulvaprolifera*, and their gathering in high density are referred to as green tide [5]. *Ulvaprolifera* is nontoxic and edible with high protein, high dietary fiber, low fat, low energy, rich minerals and rich vitamins. However, massive gathering of *Ulvaprolifera* is regarded as a kind of marine disaster, because green tide blocks sunlight penetration into the water column below the surface, which will affect the growth of other kinds of algae. Anoxia during the demise of green tide causes other marine organisms to be asphyxiated in the poor oxygen waters. Green tide can seriously interfere with human activities along the coast.

Since 2007, green tide erupted in 11 consecutive years and has become a common marine disaster in Jiangsu and Shandong coastal seas. According to some studies [6, 7], *Ulvaprolifera*

Dominant species of red tide	Frequency	Year
Gonyaulax polygramma	1	2004
Noctiluca scientillans	1	2004
Skeletone macostatum	5	2001, 2005, 2010, 2011, 2012
Eucampia zodiacus	2	2006, 2008
Gymnodinium catenatum	3	2005, 2006, 2010
Heterosigma akashiwo	3	2007, 2008, 2013
Thalassiosira sp.	1	2007
Asterionella japonica	1	2008
Karenia mikimotoi	1	2009

Table 1. Dominant species of red tide in Jiangsu coastal area from 2000 to 2016.

originated from the Subei Shoal, which was usually attached to the rafts of *Porphyra* aquaculture facilities (**Figure 3a**). During the harvest season, *Ulvaprolifera* was peeled off from the rafts and moved with tidal currents into the seawater with high turbidity (**Figure 3b**). At the beginning, *Ulvaprolifera* was suspended in the water column (**Figure 3c**); after drifting into clear water, band-shaped green tide was generated with excessive growth (**Figure 3d**). Green tides usually occur from March to August. Sporadic *Ulvaprolifera* could be detected around the Jiangsu coastal sea in late-March. Massive greed tides often arrived at the Qingdao coast in early to mid-June. The demise of green tide started from July and ended in August. Green tide in the Jiangsu coastal area was much smaller in size than that in Shandong. In the Jiangsu coastal sea, green tide usually gathered in the north, with less in the southern region. Only sporadic *Ulvaprolifera* could be found in the Subei Shoal, while in the offshore seas of Yancheng and Haizhou Bay band-shaped green tides with different sizes have been observed. Green tides either landed on the coast or gathered near shore to the north of Jiangsu during different years. According to the data, both the largest distribution area and the largest affected area both reached maxima in 2009, being 58,000 km^2 and 2100 km^2, respectively. In 2016, the largest distribution area was 57,500 km^2, but the largest affected area was only 554 km^2. Generally, green tides off Jiangsu accounted for one-third of the whole *Ulvaprolifera*, and most *Ulvaprolifera* in this region floated in the offshore sea, with a small amount landed in the northern coast of Jiangsu province.

3. Golden tide

Sargassum is a genus of brown macroalgae, so *Sargassum* blooms are commonly referred to as "Golden tides" [8]. Golden tide is new as a marine disaster in the Jiangsu coastal sea (**Figure 4**). The *Porphyra* aquaculture in the Jiangsu coast will be destroyed since there is a competitive growth between *Porphyra* and *Sargassum*. *Sargassum* was believed to originate in the open sea. In the previous years, green tides were often mixed with a small amount of *Sargassum*. For instance, R/V "KeXue #3" detected that the mixing ratio of *Ulvaprolifera* to *Sargassum* was 95:5 on June 8, 2016. As the China Ocean News reported, in late-December of 2016, golden tide suddenly appeared in the Jiangsu coastal area and lasted until late-February

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Figure 3. *Ulvaprolifera* (a) attached on the rafts of Porphyra aquaculture facilities, (b) on the tidal flats, (c) in the water with high turbidity and (d) in clean water.

Figure 4. *Sargassum* in the offshore area of Dafeng in Jiangsu.

of 2017. A lot of *Porphyra* aquaculture facilities collapsed due to this golden tide event. The satellite image in late April of 2017 showed that massive *Sargassum* floated in the open sea and moved landward gradually. The mixing ratio of *Ulvaprolifera* to *Sargassum* detected on June 9, 2017 was 60:40. In future, the Jiangsu coastal sea may face a situation when three kinds of macroalgae occur at the same time.

1.2. Research contents in this chapter

Though being the two main kinds of algal blooms in Jiangsu province, red tide and green tide rarely caused related algal blooms in Zhejiang province, especially in the north of Zhejiang coastal area, which is adjacent to the southern Jiangsu coastal area. Red tides of Zhejiang coast, a province with the most frequent red tides in the country, usually happened around Zhoushan Islands near the Changjiang estuary, while Haizhou Bay in the northern Jiangsu province was a place with frequent red tides. These two provinces are close to each other, but their algal bloom distribution patterns are so different. What separates these red tides is the first question we want to answer in this chapter.

Another emphasis in this chapter is on *Ulvaprolifera* in the Jiangsu coastal area. Previous studies have shown that *Ulvaprolifera* originated from the *Porphyra* aquaculture area in the Subei Shoal in the western Yellow Sea. But little direct dynamic evidence was provided to support this. The Subei Shoal is characterized by complex topography, with a lot of radial sand ridges and broad tidal flats. *Porphyra* aquaculture facilities were placed over the tidal flats, which were believed to be the source of *Ulvaprolifera*. Therefore, it can be summarized as three questions as follows. (1) Could algae in the Subei Shoal move out of this region into the deep waters? (2) If so, could algae subsequently travel northward the Qingdao coast or even further north? (3) Why did green tides break out in Qingdao coast and its adjacent seas, but not in the source region of the Subei Shoal? What was the physical mechanism behind this?

In the following subsections, we will answer these questions and reveal the physical mechanisms for the drifting and development of *Ulvaprolifera*.

2. Observation and research plans

2.1. Hydrological and meteorological data collection

Data used in this study were from field observations and satellite remote sensing products. The data of temperature, salinity, currents, transparency, suspended particulate matter (SPM) and photosynthetically available radiation (PAR) were collected from the field observations. Conductivity-temperature-depth (CTD) instruments deployed at two mooring stations collected long time series of temperature and salinity data. Current data were obtained using the acoustic Doppler current profilers (ADCPs) installed at two anchored and two moored stations. *In-situ* temperature, salinity and PAR data were collected during the four field surveys. We collected transparency values using the Secchi disk, which will be used to calculate *in-situ* SPM concentration.

MODIS-Aqua images from April to June 2012 were used to retrieve monthly averaged SPM data [9]. The wind data were from a blended sea wind data product supported by the US National Oceanic and Atmospheric Administration (http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html).

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2.2. Drift bottles and satellite-tracked Argos drifters

The Subei Shoal is too shallow to deploy satellite-tracked Argos drifters. As a result, house-made drift bottles were used, and 80 were released at 33°13.3′N, 121°10.2′E in 2012 (**Figure 5**). Half of the bottles were empty, to insure that they can float near the surface, and the rest were filled with sand to make them submersed under the surface as some *Ulvaprolifera* suspends in the water column.

Outside the Subei Shoal, four satellite-tracked Argos drifters were deployed in June 2011 in the deep waters, and six were released in June 2011 (**Figure 5**). Location information collected hourly was transmitted to the laboratory via satellite.

2.3. Numerical model

The Regional Oceanic Modeling System (ROMS; citations needed) was used to build the 3D hydrodynamic model for the East China Sea with three-layer nested grids. **Table 2** shows the domains and related information of the three-layer nested models. After being validated, the model can reproduce main currents and their annual variation in the East China Sea,

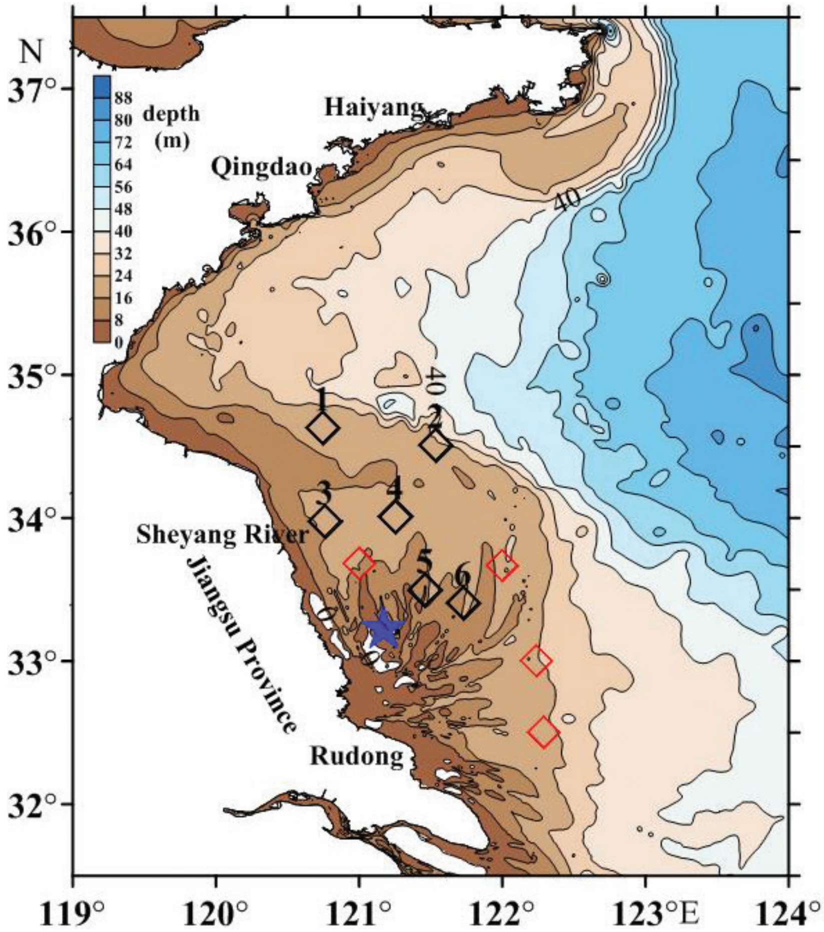

Figure 5. Topography of the southwestern Yellow Sea with release location of drift bottles (blue ★) and satellite-tracked surface Argos drifters released in 2011 (red ◇) and 2012 (red ◇).

Model	Domain	Resolution (°)	Depth (m)	Vertical layers
I	18°S-63°N, 99°E-165°E	1/6	5–5500	20
II	15°N-47.5°N, 105.5°E-139°E	1/12	5–5500	20
III	22.75°N-41°N, 115.75°E-131°E	1/24	5–5500	20

Table 2. Related information for three-layer nested models.

including the Kuroshio current, the Taiwan warm current, the Min-Zhe coastal currents, and so on. In addition, a coastal numerical model built for the Subei Shoal will be described in the following paragraphs.

An unstructured grid, finite-volume, primitive equation community ocean model (FVCOM) was used to build the Subei Shoal coastal numerical model. The model domain was large enough to ensure that the open boundary was far from the Subei Shoal. The resolution in the ridge area was refined to be ~140 m, while the grid was 15,000 m near the open boundary. The model included 56,548 elements and 28,456 nodes in the horizontal direction and 11 sigma levels in the vertical direction. Tidal forcing along the open boundaries was added hourly, which was derived from the Oregon State University Tidal Inversion Software (OTIS) Regional Tidal Solutions and included tidal constituents of M_2, S_2, N_2, K_2, K_1, P_1, O_1 and Q_1. Time step was 1 s for the external mode, and the time split was 10. Finally, the results from this model were validated by observations [10].

3. Main results

3.1. Controlling effects of Changjiang diluted water on the algal distribution in the East China Sea and the Yellow Sea

The Changjiang is the largest river in China; its average annual sediment discharge of 4.86 tons and runoff of 924 billion cubic meters ranked the third and fourth, respectively, in the world. Such large amounts of sediment and runoff will inevitably have important impacts on the physical environment of the East China Sea. The Changjiang River is also a main source of nutrients for our study domain. The Changjiang diluted water also plays an important role on nutrient distribution and its variation trend and affects distribution pattern of algal disaster.

Based on the observation data, the ROMS numerical model was applied to study the extension of the Changjiang diluted water and its effect on nutrient distribution pattern. The results in **Figure 6** show that the Subei coastal current, the Changjiang diluted water and the Min-Zhe coastal current flow southward under the strong northeast winter monsoon; furthermore, the Changjiang diluted water and the Min-Zhe coastal current flow close to the shore. The Subei coastal current appeared to invade the northern part of the East China Sea, and the Min-Zhe coastal current still tended to move northward but was obviously slowed down. In summer, the Changjiang diluted water turned toward northeast, heading to Jeju Island. Both the Min-Zhe coastal current and Taiwan warm current moved northeastward with speeds larger than those in the other months. The Subei coastal current had an obvious tendency to move northward along

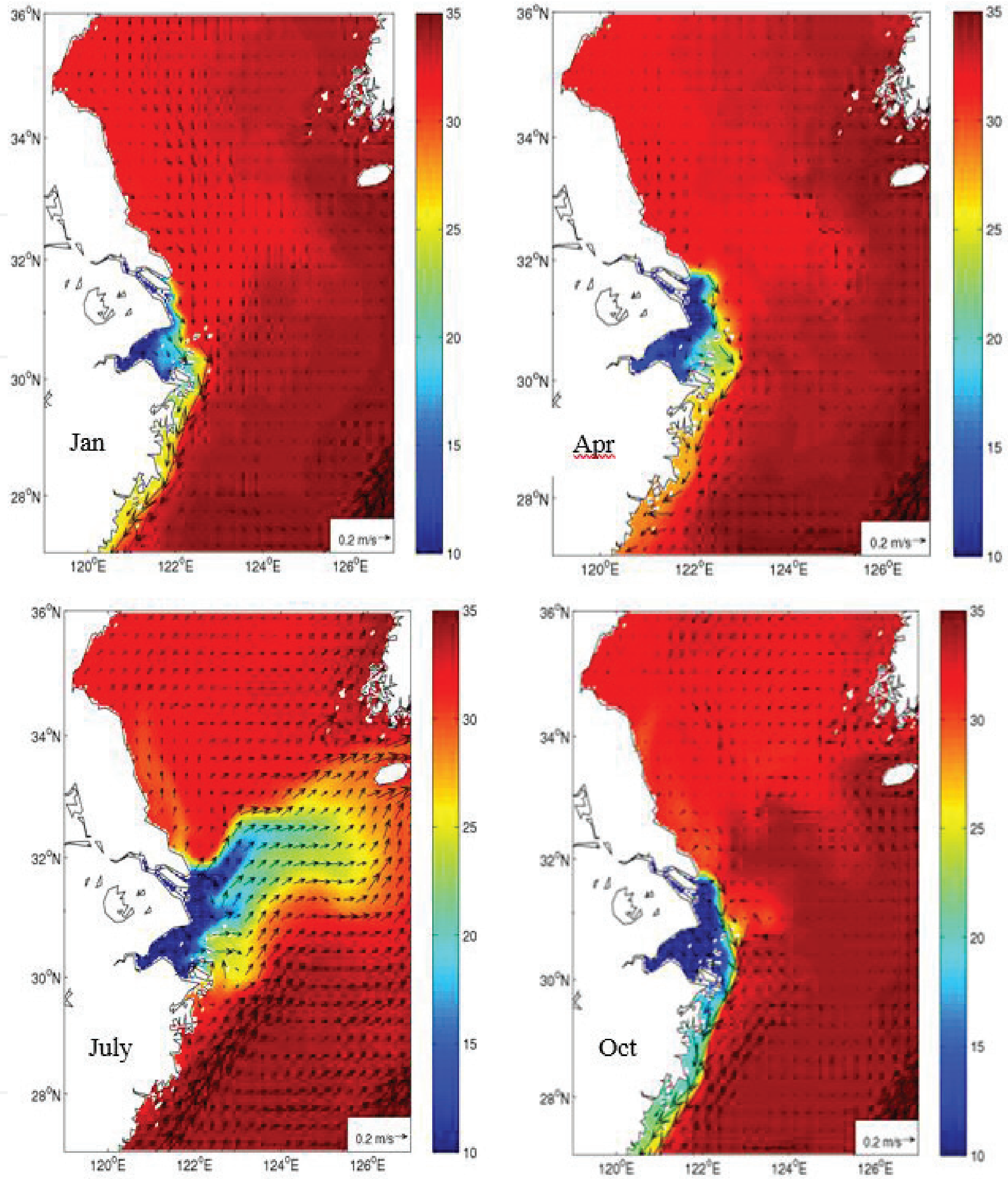

Figure 6. Current and salinity patterns of the 1-m layer in the Changjiang estuary and its adjacent region.

the coast. Spring and summer were transition seasons. The diluted water in the offshore area was limited in the surface layer, and basically there was no evidence of diluted water in the 20-m layer. This was consistent with the characteristics of observed diluted water distribution pattern.

In addition, algal migration paths in the red tide were studied. Assuming that at the end of April, red tide appeared constantly in the Zhoushan coastal area. Simulation through September 1st showed the algal drifting as neutral particles. The trajectories of all particles are shown in **Figure 7**. Most (~89%) of them moved to the Changjiang estuary and the Kuroshio region, and a few (6%) of them were transported to the Tsushima Strait. Satellite images and *in-situ* photos show that the seawater in the Subei Shoal was of high turbidity, but the seawater in the Haizhou Bay was much clearer (**Figure 8**). About 5% of the particles from Zhoushan entered the Yellow

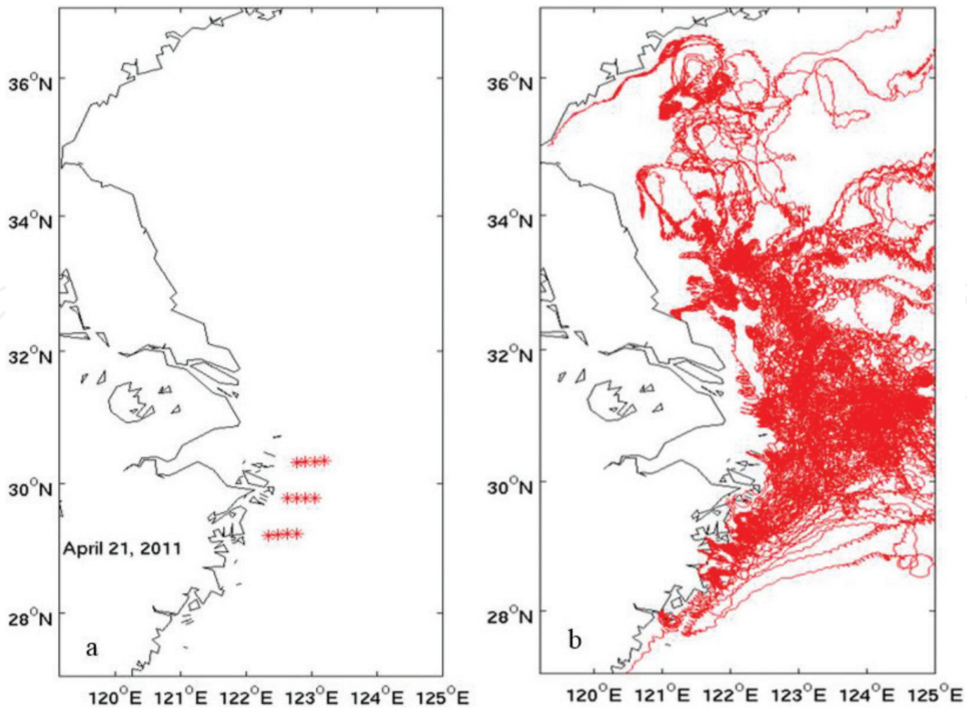

Figure 7. (a) Released locations for all particles and (b) trajectories of all neutral particles released in Zhoushan coastal area in 2011.

Sea, but most of them went through the waters with high suspended sediment concentration in the Subei area for a long time, where they could not grow well and even died in the turbid water. Therefore, it can be concluded that the red tide in the East China Sea can hardly invade the Yellow Sea, and that the red tides happened in Haizhou Bay, Jiangsu province were local events.

For green tides, it is assumed that *Ulvaprolifera* moved like neutral particles, and they appeared continuously in the Subei Shoal for 100 days from April 21, 2011. The trajectories for all particles are shown in **Figure 9**. From late April to early May, green tide moved northward under the prevailing southerly wind. Green tide can transport southward by occasional northerly wind and Subei coastal current outside the 40-m isobath, but they will eventually drift with the northwestward Changjiang diluted water and head toward Korea. They cannot enter the East China Sea. According to the above results, the Changjiang diluted water blocked the way of red tide in the Changjiang estuary and Zhoushan Islands, and it also prevented *Ulva prolifera* in the Subei Shoal from moving to the East China Sea.

3.2. Direct dynamic evidence for *Ulvaprolifera* moving from south to north

Many (~80) drift bottles were deployed on May 2, 2012, and two were retrieved (**Figure 10a**) with one being an empty bottle near the Jiaozhou Bay mouth on May 28, 2012 and the other being sand-filled bottle at 121°15.2′E, 36°30.4′N (near Haiyang) on June 11, 2012. If only looking at the start and the end points, the empty bottle and the sand-filled bottle drifted north by west and east, respectively. They all landed on the coast of Shandong province. This means *Ulvaprolifera* can move out of the Subei Shoal and be further transported to the coastal area of Shandong during spring and summer. Similar as drift bottles but with more details, six satellite-tracked surface-following drifters were released in early June of 2012. The trajectories

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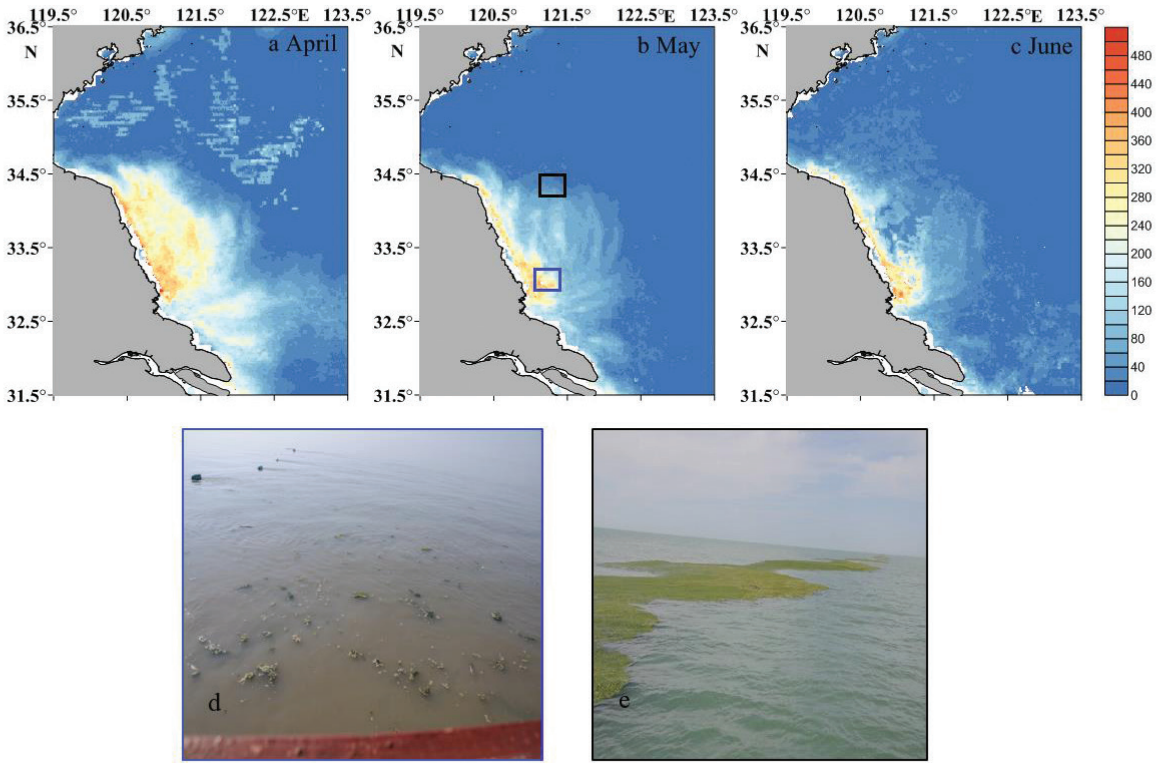

Figure 8. Monthly averaged MODIS-aqua images of surface SPM concentration in April (a), may (b) and June (c) of 2012. *Ulvaprolifera* (d) in the muddy water in the Subei shoal (blue rectangle in (b)) and (e) in clear water outside the Subei shoal (black rectangle in (b)).

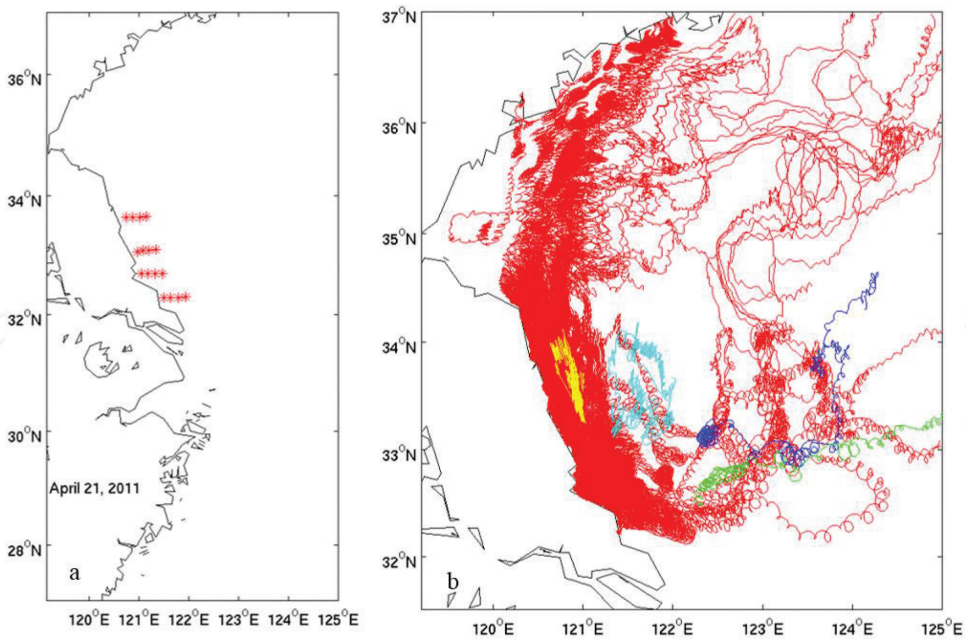

Figure 9. (a) Released locations for all particles, and (b) trajectories of all neutral particles released in the Subei area in 2011 (red) and satellite-tracked Argos drifters (other colors) at the same time.

also indicate that *Ulvaprolifera* can drift from Jiangsu to Shandong coastal area (**Figure 10a**). On average, the drifters drifted at a speed of 11.1 cm s^{-1} (288.8 km $month^{-1}$), which is approximately equal to the speed of floating *Ulvaprolifera* patches.

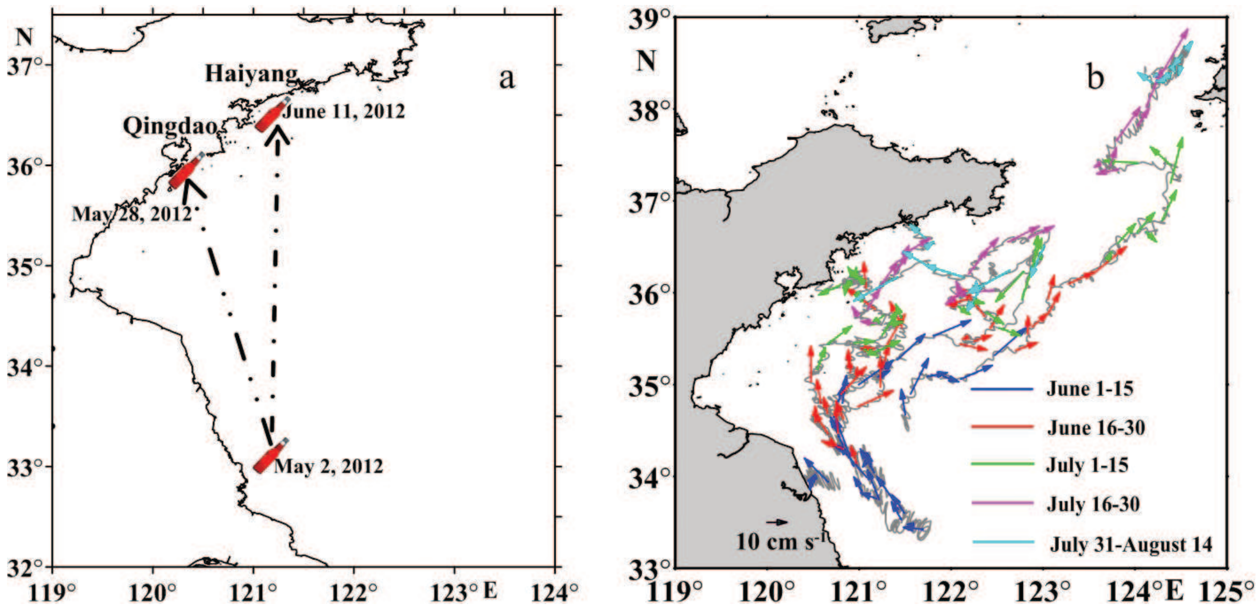

Figure 10. (a) The start and end locations of drifter bottles; (b) the trajectories of six satellite-tracked surface drifters (gray line) and velocity vectors of tide-filtered surface drifter data, with only every other velocity vector being plotted to show the results more clearly.

Numerous small-scale spiral oscillations were observed in the trajectories, indicating strong tidal currents or meso-scale eddies. Net movement of drifters was partly covered by the periodical movements. A low-pass filter at a cutoff period of 25 h was applied to obtain the tide-filtered velocity vectors of the drifters (**Figure 10b**). In the south of 34°30.0′N, most of the vectors nearly kept the same pace as others pointed toward the northwest. This means these vectors are dominated by the same Lagrangian residual current direction. After crossing 34°30.0′N, the consistent pace was broken. The vectors in the north were likely to be affected by complex dynamics there, with the wind being one of the important factors.

To explain the potential relationship with wind, we compared the wind speed data and the clockwise direction deflection angle between wind and drifter velocity (**Figure 11**). Theoretically, in terms of the Ekman theory, the surface current should be 45° to the right of the wind in the Northern Hemisphere. In reality, the angle is less than 45° in the shallow coastal waters. But in our case, the comparison results show only 33% of the angle was between 0 and 45° (**Figure 11a**). It suggests that the trajectories cannot be totally explained by the wind-driven Ekman theory, and other baroclinic processes must also influence the trajectories.

In **Figure 11a**, when wind speeds were larger than 7 m s^{-1}, the wind-driven component dominated the drifter direction, and more data fell within (or close to) 0–45°. For those vectors with angles between 0 and 45°, correlation analysis was done between wind speed and drifter velocity (as a proxy for the wind drift current). The results show that they have significant linear relationship through the origin (n = 49; r^2 = 0.88, slope = 0.023) (**Figure 11b**). This also indicates that in the western Yellow Sea during spring and summer 2012, the wind-driven component of drifter velocity was 2.3% of the wind speed on average.

With the field experiments, we obtained first solid evidence that *Ulvaprolifera* can leave the Subei Shoal and move to the coastal ocean of Shandong province or even further north.

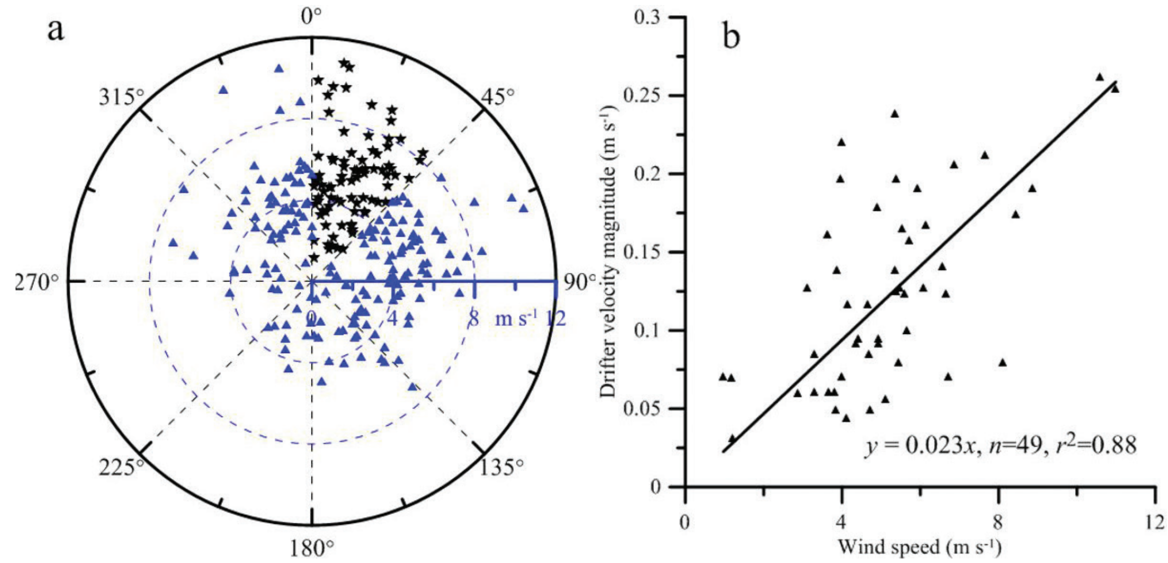

Figure 11. (a) Polar scatterplot of wind speed and clockwise deflection angle between wind direction and drifter velocity direction. The radius axis is the wind speed, while the angle axis is the clockwise deflection angle. Black symbols represent points with deflection angles between 0 and 45°; and blue symbols denote the rest. (b) Scatterplot of wind speed and drifter velocity magnitude for black dots in (a). The black line denotes the linear regression through the origin. n is the number of data points used, and r^2 is the coefficient of determination.

3.3. *Ulvaprolifera* drifting patterns in the Subei area

Figure 12a comes from the comparison of the satellite images related to raft distribution of *Porphyra* aquaculture in the Jiangsu coast between 2004 and 2007. A high-resolution model was built for the Subei coastal ocean to simulate the *Ulvaprolifera* movement after it peeled off from the raft during the *Porphyra* harvest in 2004 and 2007 (**Figure 12a**). Simulation started from May 1st, and neutral particles (representing *Ulvaprolifera*) were released daily every half an hour between 6:00 and 18:00 local time during the harvest season. The harvest duration was supposed to be 5 days, and the drifting simulation lasted half a month. Green dots represent *Ulvaprolifera* peeled off from the rafts added between 2004 and 2007, and red dots were those peeled off from rafts that already existed before 2004. Simulation results illustrated bands of *Ulvaprolifera* and their small bands were generated in the Subei Shoal. These bands were determined by the joint influence of the unique topography, radial tidal currents and wind. Driven by the South-Southeast wind (**Figure 12b**), the red particles traveled more seaward than the green ones. The modeled trajectories using the real wind in 2012 are shown in **Figure 12c**, and less red dots left the Subei Shoal in comparison with the results at the same time in Fig 21b. Why? Looking at **Figure 12a**, *Porphyra* rafts were mainly distributed south of 32.6°N, while the monthly averaged wind (**Figure 13**) appeared primarily as the easterly. Such wind took the *Ulvaprolifera* landward, and it died after being piled up on the coast. The wind direction and the change of the *Porphyra* aquaculture scale were the main reasons for no green tides before 2007.

The FVCOM Subei Shoal coastal numerical model showed that, without wind forcing, *Ulvaprolifera* could not leave the shoal area, which was the same as in the northerly wind case. Under both southerly and southeasterly winds, *Ulvaprolifera* in the study domain could move out of the Subei Shoal and even went further northward. Under the SSE wind condition, when traveling northward, *Ulvaprolifera* north of 32.6°N peeled off from the rafts that existed before

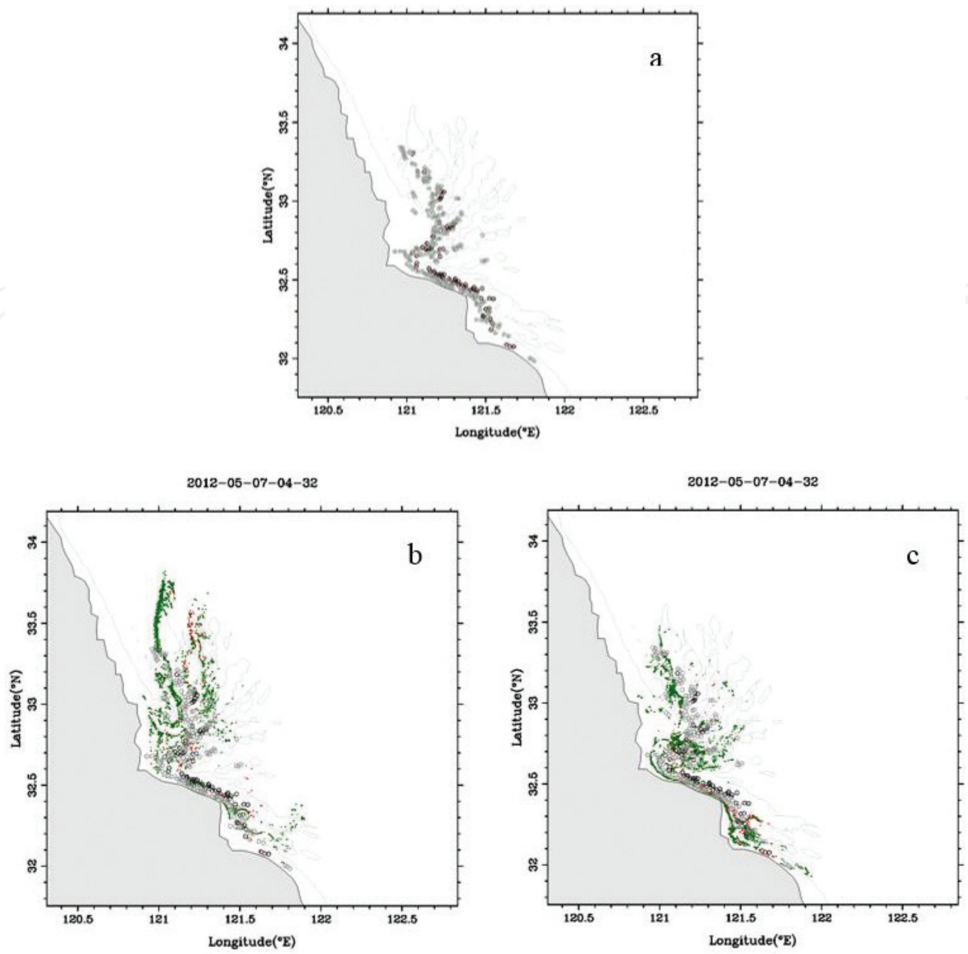

Figure 12. (a) The distribution pattern of *Porphyra* rafts: Red dots for the rafts existed before 2004, green dots for the rafts added between 2004 and 2007. Particles distribution pattern at a moment under the SSE wind (b) and under realistic wind in 2012 (c).

2004 drifted seaward more than that from the rafts added between 2004 and 2007. Wind speed and direction were important during the drifting process. In the case with the southerly wind, *Ulvaprolifera* paths directed northward, while in the latter case, *Ulvaprolifera* generally moved north by west. Particles distributed in different patterns under different wind conditions. This means *Ulvaprolifera* drifting process was influenced by both tidal currents and wind in the Subei Shoal. Tidal currents played the dominant roles within the radial sand ridges, with particles mainly moved along the channels. Outside of the Subei Shoal, wind speed and direction were more important for the trajectories. These findings are consistent with the results of drift bottles and satellite-tracked surface Argos deployed during spring and summer 2012.

3.4. Physical controlling mechanisms of spatial and temporal distribution of *Ulvaprolifera*

Many studies have been carried out in the southwestern Yellow Sea. But specific to the Subei Shoal and its northern waters, field data of physical oceanography were few and precious, not to mention the field data during green tides. In this study, field data were collected in the Subei Shoal and its northern waters during green tides. More importantly, the survey domain

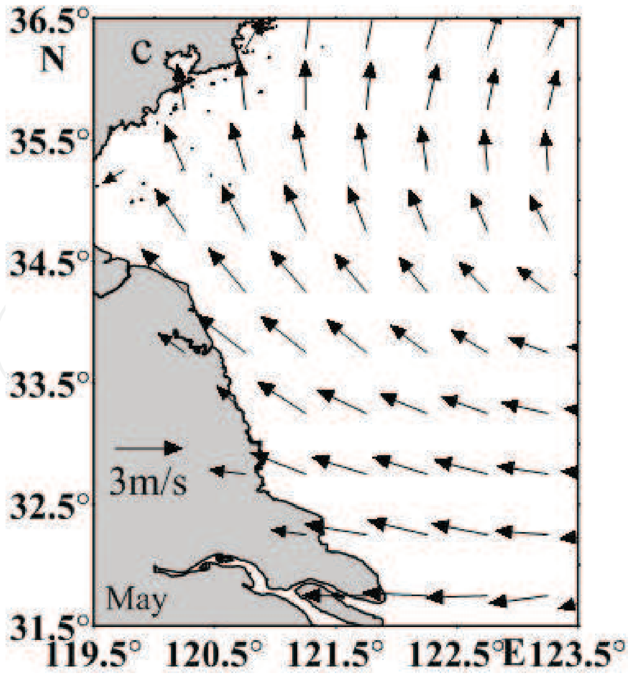

Figure 13. Monthly averaged wind of may 2012.

included the Subei Shoal and the relatively deep waters. The results given in the following paragraphs are about currents, temperature, salinity, SPM and PAR.

The currents in the Subei Shoal were dominated by M_2 tides. The current pattern was significantly limited by the topography, and the back-and-forth current directions were highly consistent with the channel directions. At the four stations, the maximum current speed reached 1.73 m s^{-1}. Harmonic analysis was done for one-month-long current data from Stations M1 and M2. The lengths of the semimajor axes of the surface tidal current ellipses for the M_2 constituent at both stations were about 0.74 m s^{-1}, while the values for the semiminor axes were 0.05 m s^{-1} at Station M1 and 0.32 m s^{-1} at Station M2. This result means that the tidal currents were typical alternating and rotational for Station M1 and Station M2, respectively. The maximum subtidal current speed at Stations M1 and M2 was less than the observed total current by one order of magnitude. The direction of subtidal current was mainly affected by the wind. During spring and summer with the prevailing southerly wind, *Ulvaprolifera* moved back and forth, and the subtidal currents drove *Ulvaprolifera* northward.

The temperature pattern at the two mooring stations shows that temperature was going up from late-April to early June with the increasing rate of 0.15°C/day (**Figure 14**). The diurnal temperature variation was less than 2.21°C. The field observation data during all four periods indicate that a zone with cold surface water existed around the Jiangsu coast between isobaths of 20 m and 30 m (**Figure 15**). These cold zones were speculated to be produced by strong mixing from strong tidal currents and upwelling. The optimum temperature for *Ulvaprolifera* is 15–20°C. From the third survey, temperature in the survey domain was all above 17°C.

The opposite change between salinity and temperature in **Figure 15a** illustrates this station was influenced by the intrusion of Changjiang diluted water. The horizontal salinity pattern shows the intrusion path of Changjiang diluted water (**Figure 15b**). The local diluted water around the

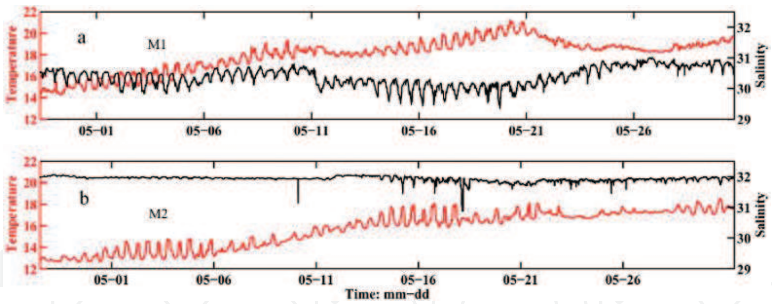

Figure 14. Temporal variations of temperature (red) and salinity (black) at stations M1 (a) and M2 (b).

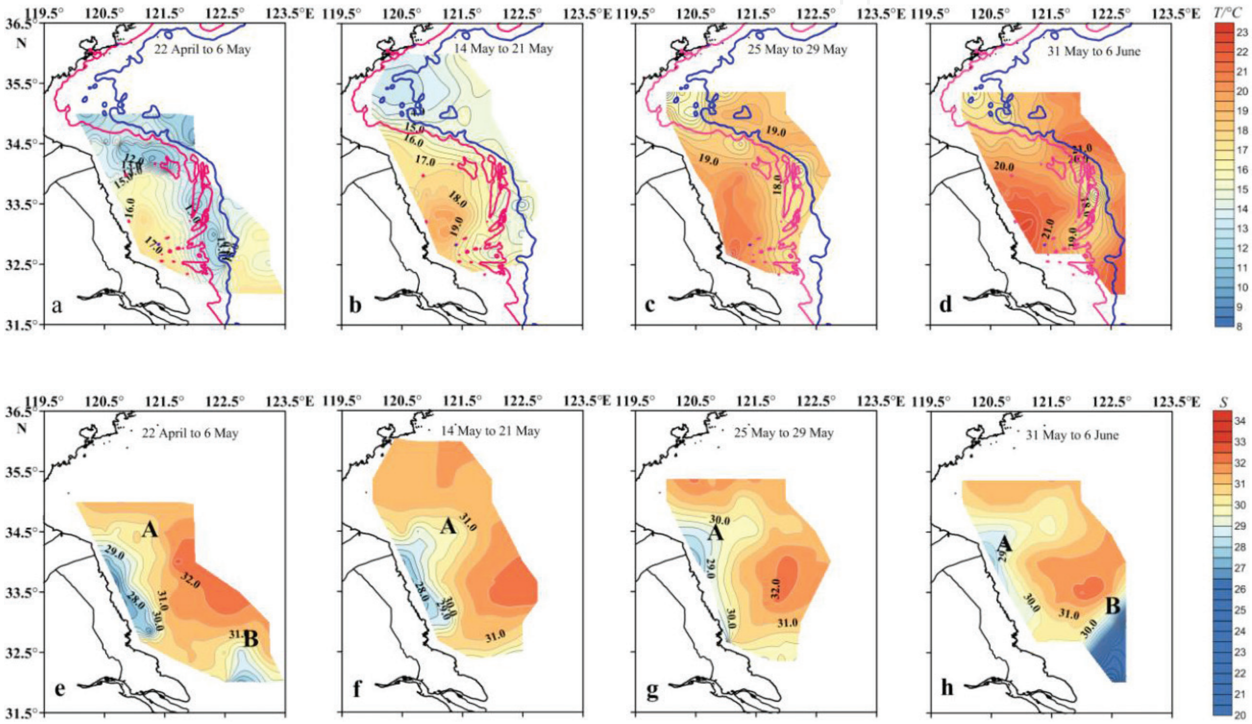

Figure 15. Distribution patterns of surface temperature (°C, upper panels) and salinity (lower panels) from April 22 to may 6 (a, e), from may 14 to may 21 (b, f), from may 25 to may 29 (c, g), and from may 31 to June 6 (d, h) in 2012. The red and blue curves are the 20- and 30-m isobaths, respectively.

Subei Coast was produced by the river discharge in Jiangsu province, which was slowly converging to the north end of Jiangsu coast from late-April to early June with its initial pattern evenly distributed along the coast. From this, we can see that there existed certain kind of relation between Subei diluted water and Changjiang diluted water. When the tongue of Changjiang diluted water went further northward, Subei diluted water was concentrated in the north. Otherwise, Subei diluted water was evenly distributed along the coast. Saline water with salinity more than 5 psu was a hospitable situation for *Ulvaprolifera*, and all coastal seawaters can meet this requirement.

The sea surface SPM concentration determined the penetration of PAR through the seawater column. *Ulvaprolifera* peeled off from the *Porphyra* raft suspended in the water column at first; after growing independently for a certain time, it produced gas inside and was able to float (**Figure 16**). Therefore, before floating, the sea surface SPM concentration would influence the growth of *Ulvaprolifera* (**Figure 16c**). The satellite images of monthly averaged SPM

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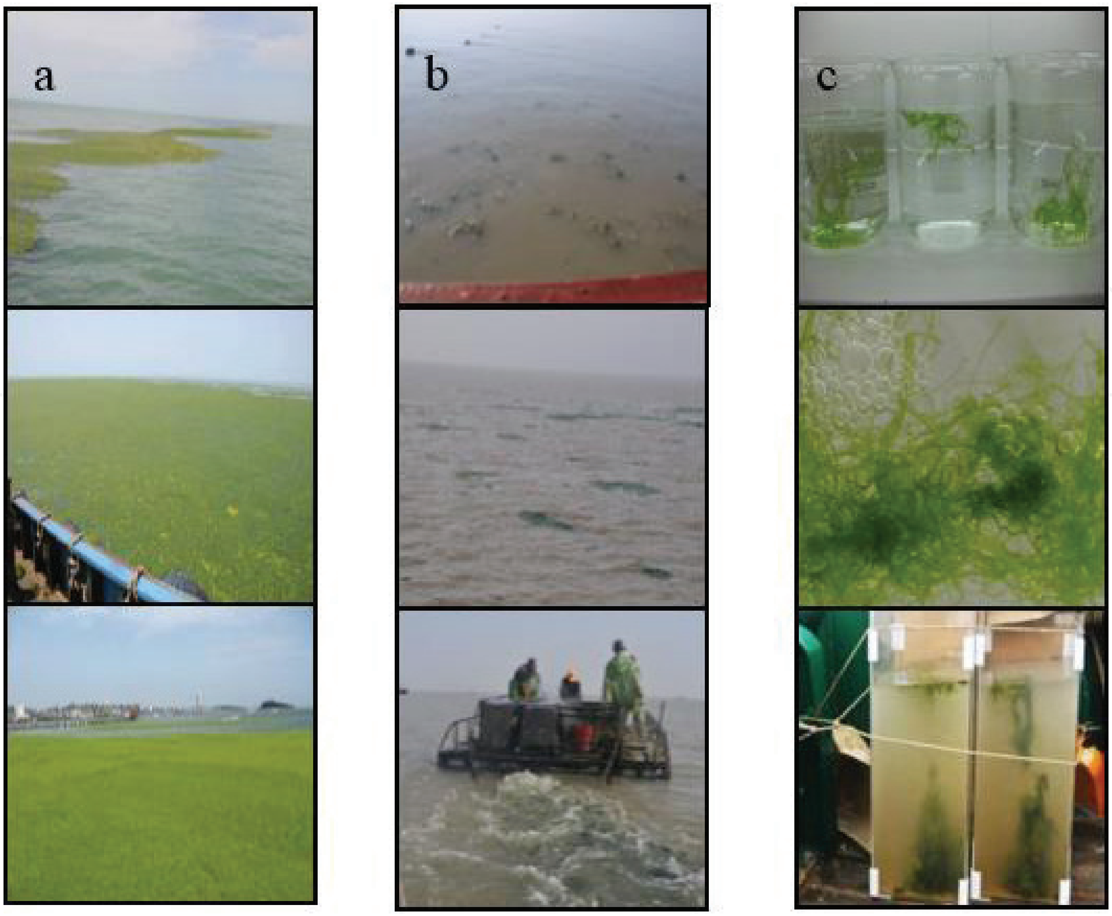

Figure 16. (a) Massive *Ulvaprolifera* and band-shaped green tide, (b) sporadic *Ulvaprolifera* in the Subei shoal with high turbidity and (c) *Ulvaprolifera* suspended in the water column in the laboratory.

concentration in April, May and June (**Figure 8a–c**) illustrate that the SPM decreased month by month as the ocean wave decreased because of the weakening wind. However, the SPM concentration in the Subei Shoal was much larger than that in the other areas. The three-month-averaged SPM concentration was 140.1 mg/dm^3 in the Subei Shoal and 11 mg/dm^3 north of 34.5°N. As shown in **Figure 17**, there was a regression relationship between SPM concentration and transparency, and there existed another exponential relationship between depth and PAR. The quantitative relationship equation could be worked out among SPM, transparency and PAR attenuation coefficient. Based on this equation, the ratio of PAR 10 cm under the water surface to that at the surface could be calculated (**Figure 18a–c**). In the Subei Shoal, the ratio was about 30%; but in the other clear seawater, it could be above 90%.

In short, *Ulvaprolifera* in the Subei Shoal can leave the area due to wind-driven currents and southerly wind. According to the average drifting velocity, *Ulvaprolifera* spent less than 20 days in the region south of 34.6°N. In the Subei Shoal, temperature, salinity and nutrients were suitable for the growth of *Ulvaprolifera*. But the vital disadvantage was the high SPM concentration, which limited light transmission in the water for photosynthesis before floating (**Figure 16b**). As *Ulvaprolifera* traveled northward, temperature in the northern area increased (**Figure 16a**). There, with clear local water and sufficient nutrients, *Ulvaprolifera* grew rapidly. Actually, the seawater near 34.6°N was jointly influenced by cold front and local diluted water, where sufficient nutrients existed.

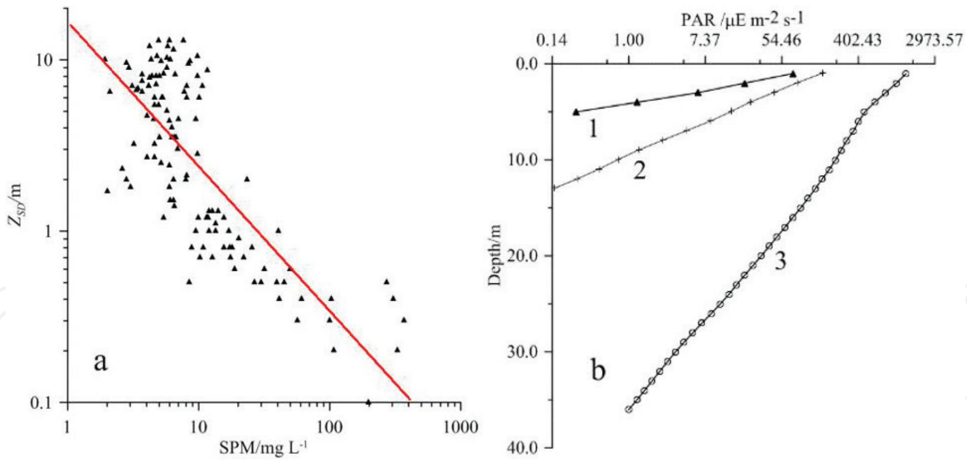

Figure 17. (a) Relation between SPM and Secchi disk depth (Z_{Sd}), as well as least square regression line (red), for the southwestern Yellow Sea during spring 2012. (b) Vertical profiles of the PAR observed in the southwestern Yellow Sea during spring 2012.

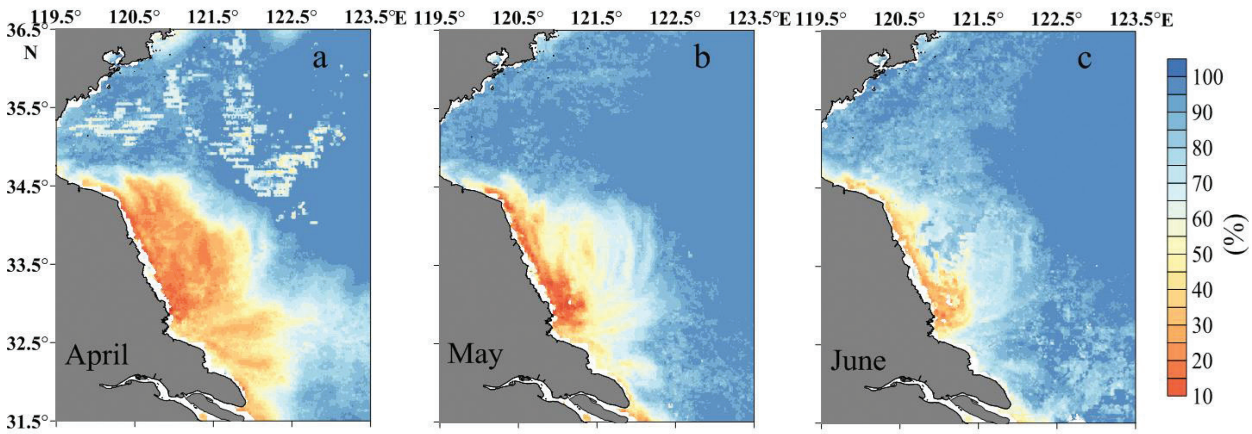

Figure 18. Similar to **Figure 8a–c**, except for the ratio of PAR 10 cm under the water surface to that at the surface.

4. Summary and discussion

Three marine disasters caused by algal blooms in the Jiangsu coastal region were described in detail in this chapter. Red tide was the first kind of algae bloom in the region, green tide has lasted for 11 years since 2007 and golden tide was new but likely to be another common algal bloom. Now, *Sargassum* is considered to originate in the open sea and may be related to global warming (only a hypothesis that needs to be tested). The Jiangsu coastal region now faces a new possibility with three kinds of algal bloom occurring concurrently. Among them, the green tide in the Subei Shoal was the focus of this chapter. With the data from observations and satellite data set, some findings have been obtained.

The Subei Shoal area is seldom affected by red tides in the Changjiang estuary and Zhejiang province where red tides are frequent. This is because the Changjiang diluted water acts like a barrier, which prevents *Dinoflagellates* in the south from moving northward. Even if some manages to reach the shoal, it will die in the water with high turbidity in the Subei Shoal.

Similarly, *Ulvaprolifera* in the Subei Shoal stops moving southward due to the Changjiang diluted water, and the prevailing southerly wind.

Red tides in the Subei area often happened in Haizhou Bay, which was shown to originate locally. Since 2014, red tide has disappeared from Jiangsu province. This may be caused by the growth inhabitation of *Dinoflagellates* when competing with macroalgae like *Ulvaprolifera*.

The study in this chapter also provided solid direct dynamic evidence that *Ulvaprolifera* can drift from the Subei Shoal to the Qingdao coastal area [11]. Drift bottles and satellite-tracked Argos drifters showed that *Ulvaprolifera* in the Subei Shoal can move out of this region and be transported to the Qingdao coast and even further north. The neutral particle-tracking numerical experiment confirmed this viewpoint.

Physical controlling mechanisms were studied here, and answered the question why *Ulvaprolifera* originated in the Subei Shoal broke out in the Shandong coastal region [12]. Seawater in the Subei Shoal (south of 34.6°N) with high turbidity limited photosynthesis to a certain extent for the young *Ulvaprolifera* there. *Ulvaprolifera* cannot grow well in such waters. Wind-driven currents and southerly wind can drive *Ulvaprolifera* northward to the clear water outside of the Subei Shoal. When green tide arrived in the northern region, temperature there gradually rose to be appropriate for the growth of *Ulvaprolifera*. The PAR near surface enhanced in the clear water, and *Ulvaprolifera* can grow rapidly with suitable temperature, salinity and abundant nutrients.

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