SPATIOTEMPORAL AND BIOLOGICAL VARIABILITY OF RED TIDE IN TIANJIN COASTAL WATERS DURING THE PAST 15 YEARS

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Abstract. Red tide is a major marine ecological disaster in the coastal area which indicates the change of ecological environment. Bohai Bay is an important platform for the Beijing-Tianjin-Hebei area for regional economic integration, which is an important channel for the marine biology in the Yellow Sea and Bohai Sea. Therefore, in this work, the red tide data from 2002 to 2017 were analyzed to study the spatiotemporal distribution and the changing characteristics of biological groups in this area. In the past 15 years, the occurrence of red tide has been limited from the month of June to August. Spatially, the red tide occurrence was less common in the south than north, and the most frequent red tide event recorded from Tianjin Port channel to the northern area of Jianhe kou. The main red tide biota were *dinoflagellates*, *diatoms* and *Chrysophytae* and the dominant red tide species were *Noctiluca scintillans*, *Skeletonema costatum*, *Phaeocystis globosa* and *Karenia mikimotoi*. Besides, the red tide caused by toxic algae was increasing year by year. However, the high seawater temperature in summer, flood, anthropogenic nutrient influx, and favorable southwest and southeast monsoon wind positively influenced the red tide events.
Keywords: *red tide, spatial-temporal, biological group, coastal waters, Tianjin*

Introduction

The frequency of algal blooms in the marine ecosystem, including Harmful Algal Blooms (HABs), is expanding around the world (Glibert et al., 2005; Guy, 2014; Borowitzka, 2018). HABs are often referred to as ‘red tide’, when it changes the color of the sea to red or almost brown (Zohdi and Abbaspour, 2019). Generally, red tide occurs when the algae like protists and dinoflagellates proliferate extensively in the coastal or marine environment, and within few weeks each cell produces one million daughter cells (Guy, 2014). It is one of the three major coastal pollution types in the world and has

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deleterious effect on the natural resources, coastal and marine life, as well as the human health (Guy, 2014). However, red tide can be harmful or harmless based on the species involved and their physiological and biological features (Zohdi and Abbaspour, 2019). Most of those are non-toxic, but some of the species contributing to the red tide are highly toxic (Guy, 2014). Fish accumulate toxins from the toxic-containing algal cells through the food chain which ultimately come to human contact by consuming those fishes (Borowitzka, 2018). Due to increasing severity on human health, red tide has become the matter of concern all over the world including China (Zhao et al., 2004). Besides, red tide is an important indicator to reflect the change of ecological environment in coastal waters (Cong et al., 2008).

The coastal area is a coupling area of various ecosystems, rich in marine biodiversity, relatively active in material circulation and energy conversion, and plays an important role in maintaining the structural stability and general functioning of the marine ecosystem (Costanza et al., 1997). Bohai Bay, one of the three semi enclosed bays in Bohai Sea, is the spawning ground, fattening ground, feeding ground and important migration channel for marine organisms (Qiao et al., 2018). At the same time, it also carries the regional economic development of Beijing, Tianjin and Hebei. It is one of the most obvious sea areas affected by the coastal man-made disturbance. With the development of coastal urbanization, the pollution of Tianjin coastal waters in Bohai Bay is increasing, and the exchange capacity of semi enclosed bay water is weak. Consequently, the eutrophication of the water body is increasing, and the frequency, area and harm of red tide are increasing year by year. Therefore, the study of red tide in this area is of great significance. Bohai Bay is an early area of red tide research in China (Kang et al., 1982; Zou et al., 1983). In the initial studies, field survey was used to calculate and obtain the data of nutrients and organisms, to evaluate the eutrophication status of water body, and to study the changes of time, space and groups of red tide in combination with the biological and ecological characteristics. This method has been used up to now though the disadvantage of limited space coverage (Li and Lin, 1999; Wei et al., 2004; Huang et al., 2018). With the development of monitoring methods and research technologies, the frequency of red tide monitoring station layout and comprehensive investigation is increasing, and new technologies such as remote sensing and sensors are being applied to red tide analysis (Tan and Shi, 2006; Shi and Wang, 2012). The determination method of red tide also extended the knowledge of the relationship between the distribution characteristics in the sea area and the biological species (Sun et al., 2001; Shi et al., 2012) Plenty of research have been done worldwide to deepen the understanding of the occurrence characteristics and laws of red tide phenomena by new technologies (Song et al., 2016).

However, there are very few researches carried out based on the longer time scale of red tide in Tianjin coastal area of Bohai Bay. In this paper, 15 years long time series (from 2005 to 2017) red tide monitoring data were collected to study the temporal and spatial characteristics of red tide, variability of biological groups, and factors influencing the red tide events and biological groups, which may provide substantial information about the change of biological groups and the mechanism of red tide occurrence in Tianjin coastal area of Bohai Bay.

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Materials and Methods

Study area

Tianjin city is located in the west of the arc shaped coastline of Bohai Bay (*Figure 1*). The total length of this coastline is about 153.67 km and the sea area is about 3000 km^2, including 335.99 km^2 intertidal zone. The sediment of this coast is typical silty sand and muddy. Haihe River system flows through the Beijing, Tianjin and Hebei area of the North China Plain, carrying a large amount of nutrient rich coastal water from the Tianjin into the Bohai Bay (Qiao et al., 2018). As a result of marine development activities and land-based pollution, up to 2017, 34 occasions of red tide experienced in Tianjin sea area of Bohai Bay (*Table 1*). All of these red tides have occurred in coastal waters, and the time was relatively short, particularly from June to August (Qiao et al., 2019).

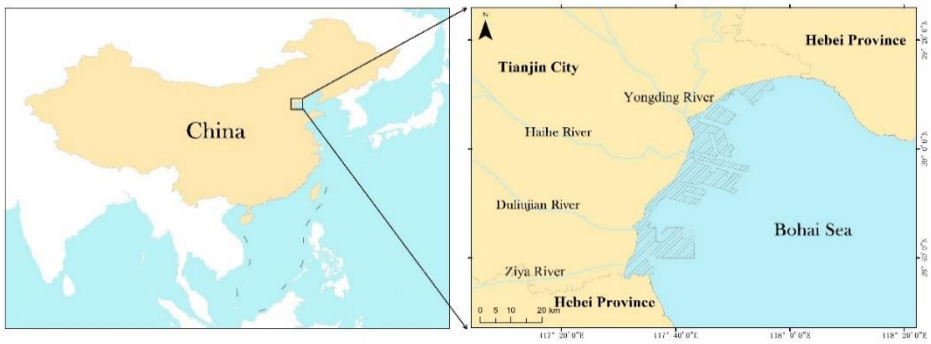

Figure 1. *Location map of Tianjin*

Data acquisition and interpretation

The occurrence time, frequency, area, species of red tide and other relevant information were collected from Tianjin marine environmental quality bulletin (Tianjin Oceanic Administration 2002-2017). The raw dataset of red tide in Tianjin coastal waters from 2002 to 2017 were analyzed by basic statistical method. The frequency of red tide events, causative species, area covering and the annual frequency of algal species were analyzed.

Results and discussion

Spatial variation of red tide

In total 34 red tide were recorded during 2002-2017 in Tianjin coastal waters (*Figure 2*, *Table 1*), with an average of 2.3 events annually. Among them, maximum frequency (six events) of red tide event was found during 2017. In 2002, 2003, 2005, 2008, 2014 and 2015, there was only one red tide event recorded every year. During the recent past five years, the frequency of red tide occurrence increased significantly. Particularly from 2012 to 2017, 17 red tide events recoded in this area which accounted 50% of the total number of red tides recorded during the whole study period. However, this trend was also recorded in the Bohai sea area previously (Song et al., 2016). There were only 3 HAB recorder from the whole Bohai sea area from 1952 to 1989, which has been increased significantly during 2000 to 2014 by occurring 148 HAB events (Song et al., 2016).

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Table 1. *Red tide events in Tianjin coastal area during 2002-2017*

year	Date: Month(occur +,no-)									Frequency of red tide number	Main Species	Distribution Area
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov			
2002	-	-	-	-	+	-	-	-	-	1	*Gymnodinium aerucyinosum Stein*	Tianjin harbor basin
2003	-	-	-	-	+	+	-	-	-	1	*Noctiluca scintillans*	East of Dagu anchorage、Tianjin Port
2004	-	-	-	-	-	+	-	-	-	2	*Karenia mikimotoi*	Tianjin coastal waters
2005	-	-	-	+	-	-	-	-	-	1	*Chattonella marina*	Tianjin coastal waters
2006	-	-	-	+	-	+	-	+	-	3	*Phaeocystis globosa*、*Heterosigma akashiwo*、*Noctiluca scintillans*	Tianjin red tide monitoring area and its adjacent waters
2007	-	-	-	+	+	+	-	+	+	3	*Skeletonema costatum*、*Phaeocystis globosa*、*Eucampia zodiacus*	Tianjin red tide monitoring area and its adjacent waters
2008	-	-	-	+	+	+	-	-	-	1	*Ceratium furca*、*Nitzschia closterium f.minutissima*	Tianjin red tide monitoring area and its adjacent waters
2009	-	-	-	-	+	+	+	-	-	3	*Skeletonema costatum*、*Noctiluca scintillans*	North of the main channel of Tianjin port to Hangu sea area and caijiapu sea area
2010	-	-	+	+	+	-	+	+	+	2	*Noctiluca scintillans*、*Coscinodiscus wailesii*、*Nitzschia pungens*	North of the main channel of Tianjin port to Hangu sea area
2011	-	-	-	-	-	-	-	-	-	-	-	
2012	-	-	-	+	+	+	-	-	-	2	*Leptocylindrus danicus*、*Pseudonitzschia delicatissima*、*Eucampiazoodiacus*、*Thalassiosira nordenskioeldi*、*Chaetoceros curvisetus*、*Skeletonema costatum*	Sea area near Hangu, Hangu to Tanggu offshore
2013	-	-	-	+	+	+	+	-	-	3	*Noctiluca scintillans*、*Pseudo-nitzschia pungens*、*Mesodinium rubrum*、*Skeletonema costatum*、*Thalassiosira nordenskioeldi*、*Chaetoceros affinis*、*P.delicatissima*	East Sea area of Tianjin Port Channel, East of Tianjin Port Economic Zone
2014	-	-	-	-	+	+	+	-	-	1	*Karenia mikimotoi*、*Cochlodinium polykrikoides Margalef*、*Ceratium furca*、*Prorocentrum micans*、*Thalassiosiraezcentrica*	Sea area near Zhongxin ecological city in Binhai New Area

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Date										Frequency of red tide number	Main Species	Distribution Area
year	Month(occur +,no-)											
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov			
2015	-	-	-	-	-	+	+	-	-	1	*Cochlodium polykrikoides*	South Sea area of Tianjin Port
2016	-	-	-	+	+	+	-	-	-	4	*Thalassiosira pacifica*、*Alexandrium catenella*、*Gymnodinium catenatum*、*Cochlodinium polykrikoides Margalef*、*Ceratium furca*、*Gymnodinium impudicum*、*Akashiwo sanguinea*、*Scrippsiella trochoidea*、*Eucampia zodiacus*、*Thalassiosira rotula*	Tianjin red tide monitoring area and its adjacent waters
2017	+	-	-	+	+	+	-	-	-	6	*Thalassiosira pacifica*、*Rhizosolenia delicatula*、*Eucampia cornuta*、*Mosodinium rubrum*、*Thalassiosira rotula* 、 *Ceratium furca*、*Leptocylindrus*、*Nitzschia pungens*、*Lauderia annulata*、*Gymnodinium impudicum*	North of Tianjin Port channel to Hangu sea area、Sea area near Hangu

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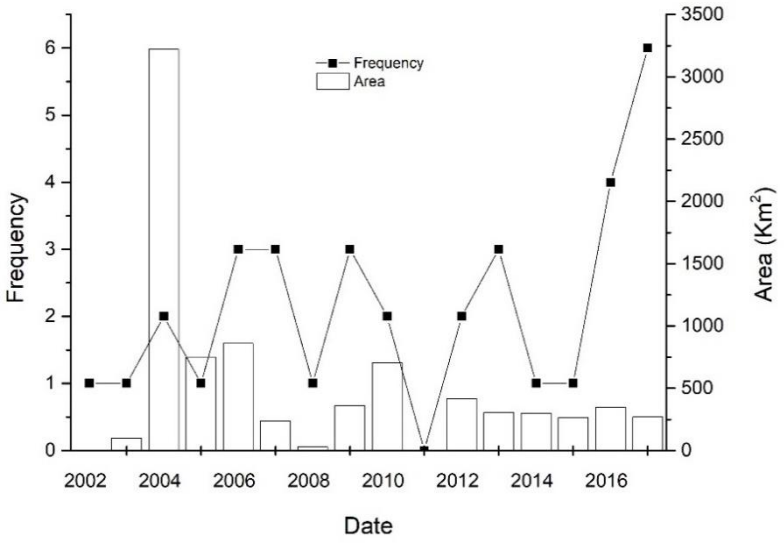

Figure 2. *Statistics of red tide area (histogram) and frequency (line chart) in Tianjin Coastal Area during 2002-2017*

During the study period, red tide covered the overall area of 8168.05 km^2 in Tianjin coastal waters, whereas annually it covered an average area of 544.54 km^2. In 2004, the largest expansion of red tide occurred in tian jin coastal, 3220.00 km^2, followed by 860.00 km^2 in 2006, and the least expansion 0.50 km^2 recorded in 2008. According to previous report, in the whole Bohai sea, areas with the highest concentrations of HAB found in the Bohai Bay, and tend to move from coastal waters to offshore Bohai sea (Song et al., 2016).

Temporal variation of red tide

During 2002-2017, the occurrence period of red tide in Tianjin coastal area was between June and August (*Fig. 3*), which is same as Hebei Province (Mo, 2010; An et al., 2015). In the month of August, the most number of red tide events recorded, which accounting for 27.3% of the total events (*Fig. 3*), July and June followed by comprising 25% and 20% of the total events. Similar kind of results also reported in the whole Bohai sea area where most HAB outbreaks reported in the month of June followed by July and August (Song et al., 2016). Which depicts that the summer season is advantageous for the extensive growth of algal cells and bloom formation. During this time, the Haihe River system intrude largest amount of freshwater into the sea (Zhang et al., 2020). Besides, the land-based domestic sewage, industrial waste water and agricultural non-point source pollution flow into the Bohai Bay. In summer, the prevailing southeast wind transports the nutrients from the lower layer of the coast to the surface of the sea through vertical mixing (Kan et al., 2016). Due to the poor water capacity of Bohai Bay, during the high tide period the content of COD, inorganic nitrogen (IN) and inorganic phosphorius (IP) in the coastal water is higher than that in the normal and low water period (Wu et al., 2007). Therefore, the red tide organisms propagate rapidly, and the seawater surface is seriously eutrophicated (Sun et al., 2004). On the other hand, within a suitable temperature range, the occurrence of red tide is positively correlated with the surface temperature of seawater (Dou et al., 2015). In summer, the variation range of sea water temperature is between 25℃ and 30℃, the surface water temperature is relatively stable,

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and the daily variation of temperature difference is less than 1°C (Wu et al., 2007; Yin et al., 2015). Therefore, the proximal water temperature might assist in the red tide outbreak. In addition, in recent 15 years, the time cycle of red tide event in Tianjin coastal waters has been extended. Particularly, the red tide recorded in March 2017 shows the instance that the duration of red tide is ahead of schedule. Similarly, the red tide recorded in October 2007 and November 2010 revealed the occurrence time of red tide also has a trend of postponements.

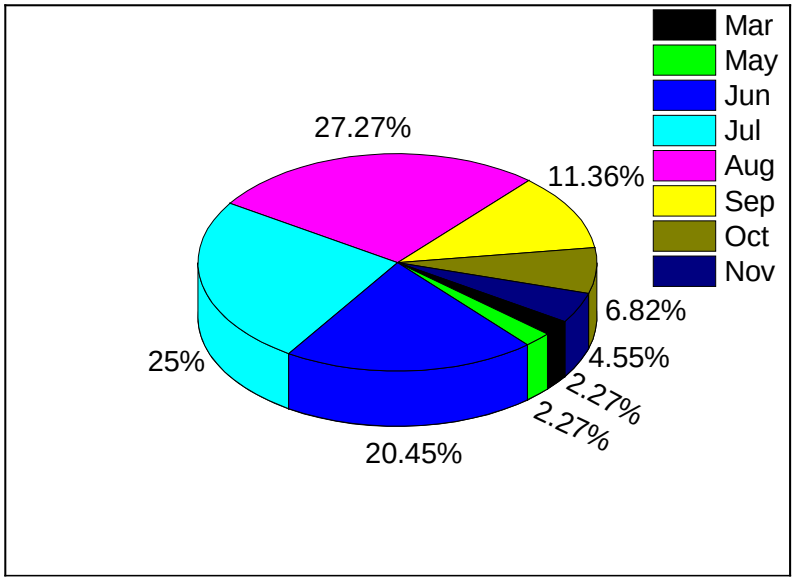

Figure 3. *Temporal variation of Red tide events in the Tianjin coastal area*

Variability of red tide biota

The main red tide causing species are characterized by high carbon content and play a key role in the stability and balance of marine ecosystem (Sun et al., 1999). There are 90 red tide species recorded in the sea area of China and about 30 species in the Bohai Sea area. The main biological groups of red tide in the Bohai Sea include dinoflagellates, diatoms, chromoflagellates, brown flagellates and protozoa. Among them, dinoflagellates, diatoms and chromoflagellates are the dominant red tide causing groups accounting for 75.20% of the total number of red tide in the Bohai Sea and 73.70% of the total area (Guo et al., 2015). It was reported that the dominant red tide species *Noctiluca* and *Chlorella*, accounting for 37.60% and 43.50% of the total red tide events. Before 1990s, the dominant species of red tide in the Bohai Sea mainly included *Noctiluca scientillans* and *Prorocentrum dentatum* (Song et al., 2016). The number of species of red tide biota is increasing year by year, from a single species before 2002 to 10 species in 2017 (*Fig. 4*). After entering into the 21st century, the dominance of red tide species has increased, and the species that can produce toxins, such as *Phaeocystis globosa*, *Gymnodinium catenatum*, *Prorocentrum dentatum*, *Alexandrium catenella*, *Karenia mikimotoi*, and *Skeletonema costatum* were recorded (Lin et al., 2008; Guo et al., 2015). Some species such as *Phaeocystis globosa*, *Karenia mikimotoi* and *Chattonella marina* never caused HAB before 2000 (Song et al., 2016). This change in red tide species composition might be mostly because of dispersal of species through anthropogenic interventions, such as ballast water discharge by worldwide transportation (Richardson, 1997) or by wind from

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seaward open ocean, and in part to the eutrophication around there (Anderson et al., 2008). Besides, the seasonal and annual changes of red tide community also can be the process of species succession (Sun et al., 2002). However, the dominant *N.a scientillans* was responsible for maximum red tide events in this area causing five red tide events (*Fig. 4*). Not only during our study period, but also before 2000 it was reported that most of the HAB events caused by *N. scientillans* (Song et al., 2016). Even the first report of HAB in the Bohai sea during 1952 was caused by *N.a scientillans* (Fei, 1952). Another study reported that, from 1952 to 2014, a total of 57 HAB outbreaks caused by *N.a scientillans* (Song et al., 2016). Besides, *Skeletonema costatum, Phaeocystis globosa* and *Karenia mikimotoi* causes 4,3 and 3 red tide events respectively (*Fig. 4*). The first occurrence of the toxic red tide algae *K. mikimotoi* and *P. globosa* reported in 2006 and 2007, respectively (*Fig. 4*). Later on, the toxic red tide organisms gradually evolved into the dominant species of red tide, and the red tide caused by the toxic algae in the coastal waters showed an increasing trend (*Fig. 4*).

	Gymnodinium aeruginosum	*Noctiluca scintillans*	*Karenia mikimotoi*	*Chattonella marina*	*Phaeocystis globosa*	*Heterosigma akashiwo*	*Skeletonema costatum*	*Eucampia zodiacus*	*Ceratium furca*	*Nitzschia closterium*	*Coscinodiscus wailesii*	*Nitzschia pungens*	*Leptocylindrus danicus*	*Pseudonitzschia delicatissima*	*Thalassiosira nordenskioeldi*	*Chaetoceros curvisetus*	*Pseudo-nitzschia pungens*	*Mesodinium rubrum*	*Chaetoceros affinis*	*Cochlodinium polykrikoides*	*Prorocentrum micans*	*Thalassiosira eccentrica*	*Thalassiosira pacifica*	*Alexandrium catenella*	*Gymnodinium catenatum*	*Gymnodinium impudicum*	*Akashiwo sanguinea*	*Scrippsiella trochoidea*	*Thalassiosira rotula*	*Rhizosolenia delicatula*	*Eucampia cornuta*	*Lauderia annulata*
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Figure 4. *Annual variation of red tide species in Tianjin coastal waters from 2002 to 2017*

The statistical analysis of the past 15 years red tide events shows that the red tide biota has obvious seasonality. With the increase of sea water temperature, the composition and proportion of nitrogen and phosphorus in the coastal water become imbalanced (Liu and Yuan, 2008). As a result, the red tide breaks out and the species and community structure of the red tide biota change. Consequently, the changing red tide biota led to the change of the nutrient concentration and structure of the water body, showing a dynamic relationship of interaction (Liu and Yuan, 2008). Among them, *N. scientillans* is a heterotrophic Dinoflagellata, widely distributed in the coastal areas of China, and able to tolerate high temperature and salinity (Guo et al., 2015). It begins to proliferate in March

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every year and enters into the outbreak period during April to October (Yin et al., 2013). Red tide causing by *N. scientillans* is easy to break out in Tianjin estuary and areas with poor hydrodynamic conditions in the north. It occurred in 2003, 2006, 2009 and 2010 for a short duration (June and August) resulting in changes of physical and chemical factors of water body and impact on water ecological environment. *S. costatum*, a diatom species having a wide range of temperature and salinity tolerance, which is distributed near the shore, a good indicator of pollution. The growth of *S. costatum* cells is limited by nitrogen element. In spring, summer and autumn, red tide can be formed by explosive reproduction of this species (Wang et al., 2006). In 2007, 2009, 2012 and 2013, it happened in the coastal waters during July to September. Besides, in 2004 and 2014, red tide broke out by toxic *K. mikimotoi* in Tianjin coastal waters. *K. mikimotoi* is active on the surface of the water body especially within 2 meters of water depth (Chen et al., 2015). It has obvious diel vertical movement, and its growth has obvious correlation with rainfall, light and trace elements (Chen et al., 2015). However, in 2006 the first occurrence of red tide cause by *P. globosa* observed in Tianjin sea area which evolved into dominant species over time (*Fig. 4*). is a typical toxic and harmful red tide alga, generally in the South Sea area and widely distributed in high water temperature (Qi et al., 2001).

Causative factors of red tide

The cause and mechanism of red tide are different due to the biological groups and species, and closely related to the hydrological and meteorological conditions (Lin et al., 2008; Zou et al., 2015). The natural and geographical environment of the coastal area determines the basic conditions for the outbreak of red tide, such as hydrology, temperature, salinity and nutrients. Therefore, similar red tide biota also shows different bio-ecological characteristics in different sea areas (Zhao et al., 2003).

The temporal and spatial variation of red tide in Tianjin coastal waters is related to the flux of land-based sources into the sea, the pollutants entering into the sea, the surface temperature and the rapid eutrophication of estuarine water. COD, IN, concentration of IP pollutant discharge into the sea is related to the occurrence of red tide, which indicates that the red tide in Tianjin coastal area of Bohai Bay may be greatly affected by land-based emission, which is consistent with the research of Liu Hanlin and Shi Haiming (Shi et al., 2010; Liu et al., 2019). Direct input of land runoff and sewage outfall, the atmospheric deposition flux is also an important source of nitrogen in the marine waters (Ma et al., 2012). Because of the anthropogenic influence, during the last six decades, the concentration of IN increased 7-fold (Xin et al., 2019). Consequently, the phytoplankton biomass increased several folds in recent past and phytoplankton community shifted from diatom dominance to dinoflagellates. Red tide was a rare phenomenon before 1980s but occurring very frequently after 1990s, which changed the Bohai sea area from N-limited to P-limited ecosystem (Xin et al., 2019).

Marine sediment exchange flux is the main source of surface nutrients (Zhang et al., 2009). Tianjin shallow sea beach is a typical accumulation type plain coast. Under the joint action of current and tide, the content of suspended particulate matter in the sediment of the sea area is very high and one of the highest in the world (Mu, 2015). During the past 15 years, human disturbance such as marine exploitation and channel dredging in Tianjin coastal area has increased. Therefore, the concentration of suspended solids has been increased, and the transparency of sea water has been significantly reduced, which directly or indirectly affects the red tide biota (Dou et al., 2015; Guo et al., 2015; Huang et al., 2018).

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In Bohai Bay, most of the red tide broke out in summer season especially from June to August. Summer flood carries tremendous amount of land-based nutrients and pollutants, and the temperature rises from June to August. After reaching at the peak in August, the surface temperature of the sea began to decrease, and the land-based pollutants continued to reduce. Besides, Tianjin has obvious monsoon characteristics. In summer, the coastal wind speed of Tianjin is relatively lower, and the southerly wind prevails in this area (Xu et al., 2018). Analyzed that during the red tide, the wind speed force 3 and 4, and the wind direction was mainly southeast and southwest wind (Zhang et al., 2020). This condition is suitable to raise nutrients from the deep layer of sea water to the surface. Therefore, in summer the surface sea water is under the conditions of high temperature, sufficient light and nutrient rich so as to speed up the growth rate of red tide organisms (Zhang et al., 2020). In addition, low wind speed and waves are conducive to the aggregation of red tide organisms and promote the occurrence of red tide in the coastal waters (Zhang et al., 2020).

However, red tide organisms are a kind of media living in the water body, which has weak or no ability of movement (Mu, 2015). The hydrodynamic condition is closely related to the biomass of red tide organism. Their life cycle, movement and nutrition supply depend on the water current. Therefore, the spatiotemporal and biological changes of red tide contain a series of complex oceanographic and ecological processes, and the research of related fields needs to be further expanded.

Conclusion

Based on the red tide monitoring data of Tianjin marine environmental quality bulletin (2002 to 2017), this paper studies the temporal and spatial changes of red tide in Tianjin coastal area of Bohai Bay. Following are the summary of the red tide event in recent 15 years.

(1) During the past 15 years from 2002 to 2017, 34 red tides were recorded, with an accumulated area of about 8168.05 km^2. The annual average occurrence of red tides was 2.3 events, with an area of 544.54 km^2. The occurrence frequency of red tide increased but the occurrence area of red tide decreased and tends to be stable as a whole, which shows that the prevention and control of land-based water pollution have played an obvious role in the control of pollutants since the 11^{th} five-year plan of China, and the effect of environmental quality improvement in Tianjin coastal waters is obvious.

(2) The occurrence time of the red tide in the coastal waters was mostly in June to August every year, which has obvious seasonal variations. The occurrence of the red tide is sometimes advanced or delayed, which results in the prolongation of the period of the generation and dissipation of the red tide. The spatial distribution of red tide is characterized by less in the south, more in the north, and more in the sea area from the anchorage of Tianjin port to Hangu sea area, showing the change rule of diffusion from the near shore estuary and shoal to the north and east sea areas.

(3) The red tide biota in the coastal area includes Dinoflagellatae, Bacillariophyceae, Chrysophyta, etc. The species of red tide biota increased from 1 to 10. The dominant species of red tide organisms are *Noctiluca scintillans*, *Skeletonema costatum*, *Phaeocystis globosa* and *Karenia mikimotoi*. The number of toxic red tide organisms increased significantly, and harmful red tide in coastal waters showed an increasing trend.

(4) Land source pollutants, sea surface temperature, wind speed and wind direction have an impact on the occurrence of red tide. Land source pollutant flux has a relatively

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large impact on runoff, indicating that the red tide organisms in Tianjin coastal waters may be greatly affected by the input of land source nutrients. In this paper, the analysis of factors affecting the growth of red tide organisms is not comprehensive enough. Other environmental variables such as suspended solids, atmospheric deposition and hydrodynamic forces may also affect the changes of red tide organisms' time and biota. The research work in related fields needs to be further expanded.

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