Spatial-temporal distribution of red tide in coastal China

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Abstract. The frequent occurrence of red tides in China's coastal areas has caused huge losses to society and economy, and seriously threatened the coastal marine environment and ecological security. Based on the data of 30 years from 1990 to 2019, this paper analyzes spatial-temporal distribution characteristics of red tide in China's coastal areas. Our results show that 1557 red tides occurred in China's coastal areas from 1990 to 2019. (1) There were 961 red tides from 2001 to 2012, which was the high red tide period in offshore China, accounting for 62.00% of the total number of red tides. The number of red tides in the Bohai Sea, Yellow Sea, East China Sea and South China Sea were 117, 103, 588 and 153, respectively. Seasonally, 536 red tides occurred from April to September, accounting for 87.00% of the total number of red tides. (2) In space, according to the kernel density estimation, red tides are mainly concentrated in Bohai Bay, Yangtze River Delta, Pearl River Delta and other regions with relatively dense population and relatively developed economy, especially in Zhejiang Province and the estuary of the Yangtze River. The research in this paper is of great significance to the monitoring and prevention of red tides and water environment management.

1. Introduction

Red tide is an ecological anomaly caused by the discoloration of marine water due to the explosive reproduction or aggregation of some planktonic algae, protozoa or bacteria in the ocean under certain environmental conditions [1]. As early as 1831 to 1836, Darwin recorded the red tide events caused by Trichophyta in Brazil and Chile in the "Beagle" nautical records. With the development of economy and society, the increasingly frequent interaction between human beings and the ocean and the intensification of industrialization and urbanization have led to frequent red tide events, which have caused increasingly serious harm to the ecological environment and human health, and have a trend of globalization. Nowadays, red tide has become one of the marine environmental disasters commonly faced by coastal countries in the world, which seriously affects the sustainable development of coastal countries.

In recent years, many scholars have studied the spatial-temporal distribution characteristics of red tides in China's coastal areas, analyzed and summarized the overall spatial-temporal characteristics of red tides in China's coastal areas, and proposed some countermeasures, such as: Luo Hao et al. (2013) studied the spatial-temporal characteristics of red tides in China and put forward some mitigation countermeasures [1]; by analyzing the red tides data from 1995 to 2014 for a total of 20 years, Guo Hao et al. (2015) found that the occurrence of red tides in China has the characteristics of year-round, entire
sea area, multiple types, and high hazards [2]; Yu Rencheng and Liu Dongyan (2016) analyzed the current status and evolution trend of harmful algal bloom disasters in China’s coastal areas [3].

Many scholars have paid attention to the spatial-temporal distribution characteristics and types of red tides in China’s coastal areas, providing valuable reference materials for red tide monitoring. However, previous studies often focus on some key areas in China’s coastal areas, and lack of comprehensive research and analysis on the occurrence of red tide in China’s coastal areas. Based on 30 years of red tide data from 1990 to 2019, we analyze the spatial-temporal distribution characteristics of red tide in offshore China. This study can provide technical support for red tide monitoring, forecasting and early warning, and is of great significance for preventing and controlling red tide disasters, protecting the marine environment and resources, and ensuring social and economic security [4].

2. Study area
The sea area of China includes the Bohai Sea, Yellow Sea, East China Sea and South China Sea. There are mainly 14 coastal provinces and cities in China, including Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, Hainan, Taiwan, Hong Kong and Macao, etc., as shown in Fig. 1.

3. Data and Methods

3.1 Data
The data used in this study social statistics recorded the occurrence time, scale and other information of red tide in China's coastal areas, as shown in Table 1.

| Data Elements      | Source(Data type)                  | Time     |
|-------------------|------------------------------------|----------|
| Social statistics  | Historical records of red tides    | 1990~2019|
|                   | China Marine Disaster Bulletin and  |          |
|                   | Statistical Annual Report(Text data)|          |

Social statistics record information about the time, location and scale of red tides in China from 1990 to 2019, mainly including China Marine Environmental Quality Bulletin (1998~2019), China Marine Disaster Bulletin (1998~2019), and China’s coastal provinces and cities Marine Environmental Quality Bulletin and related research papers.

3.2 Methods
This paper analyzes the red tide data in recent 30 years from 1990 to 2019 in China's coastal areas. On the one hand, we count the occurrence frequency of red tides in each sea area; on the other hand, we study the spatial distribution characteristics based on kernel density analysis. The technical flowchart is shown in Fig 2.
4. Spatial-temporal characteristics of red tide disaster in coastal China

This paper analyzes the temporal and spatial characteristics of red tides in China's coastal areas. On the one hand, from the two scales of the year and the month, the frequency of red tides in China's coastal areas has been counted, and its characteristics have been analyzed; On the other hand, based on the kernel density estimation, the spatial distribution characteristics of red tides in China's coastal areas have been analyzed.

4.1 Time distribution characteristics

From 1990 to 2019, a total of 1,557 red tides occurred in China's coastal areas and the number of red tides each year is shown in Fig 3. It can be seen from Fig. 3 that the annual average number of red tides is 52, and the overall trend is increasing, with an average annual increase rate of 0.3%. The early 1990s was a period of frequent occurrence of red tides in China's coastal areas, but they were all below 50. The period from 1993 to 2000 was a stable low-incidence period with an average annual frequency of 30, and the inter-annual changes were small [5]. The number of red tides occurred in 2001 with a leap, with an average annual number of 77, and the inter-year changes were quite drastic, with a large increase in 2003. A total of 961 red tides occurred from 2001 to 2012, which was the peak period of red tides and 4 times the sum of 1990 to 2000. After 2012, it showed a downward trend, but there was still a slight increase.

From 1998 to 2019, the number of red tides in China's coastal areas is shown in Fig 4. From Fig 4, it can be seen that there were 813 red tides in the East China Sea, which is the sea area most affected by red tides. The South China Sea and the Bohai Sea are the second most affected by red tides, with 249 and 198 occurrences respectively, and the Yellow Sea has the least number of occurrences at 133. (For the Bohai Sea, the total number of red tide occurrences was 198, with an average of 22 times per year, of which 20 were the highest in 2001, and the least was 1 in 2008; for the Yellow Sea, the total number of occurrences of red tides is 133, an average of 6 times per year, of which the highest in 2004 and 2005 were 13 times, and the least was 1 time in 2018; for the East China Sea, the total number of occurrences of red tides is 813, an average of 37 times per year, of which 86 were the highest in 2003, and the least in 1998 was 5; for the South China Sea, the total number of red tide occurrences is 249, an average of 11 times per year, of which 18 were the highest in 2004, and the least in 2019 was 3.) Since 1998, the occurrence of red tides in the four sea areas has been decreasing.

The monthly frequency of red tides in China from 2009 to 2019 is shown in Fig 5. As can be seen from Fig 5, April to September are the peak period of red tides, in which the number of red tides occur most in May (182 times), accounting for 30% of the total number of red tides, followed by June (120 times), accounting for 20% of the total number of red tides, and December (0 times) is the least. There are also differences in the months of red tides in different sea areas [6]. In the coastal areas of Guangdong, red tides began to occur in February or March, the peak season is in May, and the latest month is in December, with only one occurrence. Red tides mainly occur in autumn along the coast of Fujian, mostly from September to October, and December is the latest month. In the coastal areas of Zhejiang and the Yangtze River estuary, red tides occur from May to September, mainly from May to July, with the maximum in May.
4.2 Spatial distribution characteristics

The occurrence locations of red tides in each area of China's offshore waters are shown in Fig 6. As can be seen from Fig 6, red tides mainly occurred in the Bohai Bay of Yellow Sea, the waters around the Yangtze River Estuary and Zhejiang of the East China Sea, and the Pearl River Estuary of the South China Sea from 1990 to 1999. Red tides mainly occurred in the Bohai Sea, East China Sea and the coastal area of Guangdong Province from 2000 to 2009. From 2010 to 2019, red tides mainly occurred in Hebei, Tianjin, Yangtze River Estuary, Zhejiang, Fujian and Guangdong coastal areas, among which Zhejiang coastal areas were the worst-hit areas.

For the Bohai Sea, red tides mainly occurred in the Bohai Bay and the west of Liaodong Bay from 1990 to 1999, and increased explosively after 2000, expanding to the north of Bohai Bay, the north of Liaodong Bay and the Laizhou Bay. For the Yellow Sea, red tides mainly occurred in Jiaozhou Bay before 2000. After 2000, red tides occurred frequently in many estuaries such as Jiaozhou Bay, Rizhao East Port near the coast, and the mouth of the Yalu River. Among them, the Yalu River Estuary broke out in 2011 for a 20-day red tide disaster with an area of 4000 km² [7]. Red tides along the coast of Jiangsu mainly occurred in the Haizhou Bay and Nantong offshore and offshore waters, which may be related to the rich nutrients in these two seas. For the East China Sea, the red tide-prone areas are mainly the areas near Zhoushan, Zhejiang, Pingtan, Xiamen, and the mouth of the Yangtze River. Among them, the coastal area of Zhejiang is the hardest hit area, due to the rapid development of shipping and aquaculture industries [9]. For the South China Sea, the occurrence area of red tide is mainly concentrated in the Shenzhen Bay area of the Pearl River Estuary. After 2000, the duration of disasters has been on the rise, with a large impact range.

The spatial distribution of red tide in different areas of China's coastal waters is shown in Fig. 7. It can be seen from Fig. 7 that 39 red tides had an area of more than 1000 km², which mainly occurred in Bohai Bay, Liaodong Bay, Yangtze River Estuary and the coastal area of Zhejiang from 2000 to 2014. There were 26 red tides with an area of 500~1000 km², 201 red tides with an area of 100~500 km², 511 red tides with an area of 50~100 km², and 780 red tides with an area less than 50 km². According to the statistics of the occurrence time of red tides in different periods, it is found that during the 10 years from 1990 to 1999, the area of red tide exceeded 1000 km² only 3 times. During the 14 years from 2000 to 2014, 36 red tides with an area of more than 1000 km² occurred. This indicates that the occurrence scale of red tide is larger and larger, and the frequency is higher and higher.

In order to identify the areas where red tides occur frequently, this study used the kernel density estimation (KDE) method to analyze the spatial density of 30a red tides data (Fig. 8). As can be seen from Fig 8, the East China Sea is the region with the highest occurrence frequency of red tide, mainly distributed in the Yangtze Estuary, Zhejiang Province and the coastal areas of Fujian Province. The worst-hit areas include the Yangtze Estuary, Zhejiang Zhoushan, Taizhou and other coastal areas. Red tides in the Bohai Sea are mainly distributed in coastal waters, and the most frequent areas are the northern part of Bohai Bay, the western and eastern parts of Liaodong Bay. The occurrence of red tide in the Yellow Sea is rare and mainly distributed in the waters of Meizhou Bay, Jiangsu Province. The area of the South China Sea is large, and the red tide mainly concentrates on the Pearl River Estuary and other coastal waters.
5. Conclusions

The occurrence of red tide is a very complex phenomenon, which is the result of the interaction of internal factors such as red tide organisms and external factors such as environmental factors and human activities. Taking the coastal red tides of China as the research object, this paper analyzes the temporal and spatial distribution characteristics of 1557 red tides from 1990 to 2019.

(1) In terms of time, the total number of red tides from 2001 to 2012 is 961, accounting for 62% of the total number of red tides, which is the peak period of red tides in offshore China, and 4 times of the total number of red tides from 1990 to 2000. The red tides occurred mainly from April to September. Among them, May occur the most, 182 times, accounting for 30% of the total number of red tides. In December, the number of red tides was the least, 0.

(2) In terms of space, red tides mainly occurred in the Bohai Bay of Yellow Sea, Yangtze River Estuary and adjacent waters of Zhejiang Province of East China Sea, and Pearl River Estuary of South China Sea from 1990 to 1999, red tides increased explosively in the Bohai Sea, East China Sea and the coastal areas of Guangdong Province from 2000 to 2009, red tides mainly occurred in Hebei, Tianjin, Yangtze River Estuary, Zhejiang, Fujian and Guangdong coastal areas from 2010 to 2019, and Zhejiang coastal areas were the most affected areas; according to the area statistics, more than 1000 km² of red tides mainly occurred in the Bohai Sea, the Yangtze River Estuary, Zhejiang coastal area.

Red tide threatens mariculture and Marine fishery resources, damages Marine ecological environment, damages coastal tourism, and seriously affects human health and social sustainable development. It is one of the following research contents to carry out research on the characteristics of red tides by using Marine water products with higher spatial resolution. It is also necessary to pay attention to the correlation between the occurrence and extinction of red tides and ocean color and temperature.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (41701447), and the Training Program of Excellent Master Thesis of Zhejiang Ocean University.

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