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Temporal and spatial distribution of red tide outbreaks in the Yangtze River Estuary and adjacent waters, China

Lusan Liu[a,b], Juan Zhou[a,b], Binghui Zheng[a,b,*], Wenqian Cai[a,b,c], Kuixuan Lin[a,b], Jingliang Tang[d]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[b] State Environmental Protection Key Laboratory of Estuary and Coastal Environmental, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[c] College of Water Sciences, Beijing Normal University, Beijing 100875, China
[d] Zhejiang Provincial Zhoushan Marine Ecological Environmental Monitoring Station, Zhejiang 316000, China

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ABSTRACT

Between 1972 and 2009, evidence of red tide outbreaks in the Yangtze River Estuary and adjacent waters was collected. A geographic information system (GIS) was used to analyze the temporal and spatial distribution of these red tides, and it was subsequently used to map the distribution of these events. The results show that the following findings. (1) There were three red tide-prone areas: outside the Yangtze River Estuary and the eastern coast of Sheshan, the Huaniaoshan–Shengshan–Gouqi waters, and the Zhoushan areas and eastern coast of Zhujiajian. In these areas, red tides occurred 174 total times, 25 of which were larger than 1000 km^2 in areal extent. After 2000, the frequency of red tide outbreaks increased significantly. (2) During the months of May and June, the red tide occurrence in these areas was 51% and 20%, respectively. (3) Outbreaks of the dominant red tide plankton species *Prorocentrum dong-haiense*, *Skeletonema costatum*, *Prorocentrum dantatum*, and *Noctiluca scientillan* occurred 38, 35, 15, and 10 times, respectively, during the study interval.

1. Introduction

A red tide event is a rapid increase or accumulation in the population of algae, protozoa, and/or bacteria in an aquatic system. When the algae are present in high concentrations, the water appears to be discolored or murky and varies in color from purple to almost pink, but it is most commonly red. Additionally, red tides are not typically associated with the tidal movements of the waters, hence the preference among scientists to use the term "algal bloom". Red tide organisms can be divided into toxic and non-toxic organisms, according to their toxicity levels (Gudtaaf, 1992; Su, 2001). Toxic red tide organisms either contain or secrete toxic substances, with the most conspicuous effects being the associated mortality of marine wildlife and coastal species of fish, birds, mammals and other organisms. The poisonous effect of these toxic substances on organisms can be described as paralytic, diarrheic, neurotoxic, amnesic, or ciguatera, shortened to PSP, DSP, NSP, ASP and CFP, respectively (Qi, 2003). The latter can be attributed to the proliferation of red tide organisms, which leads to the excessive consumption of oxygen, thus affecting marine habitats and undermining the structure of the marine ecological system. However, the term "red tide" is misleading because there are many toxic events in which the water shows no discoloration. Likewise, an accumulation of non-toxic, harmless algae can also alter the color of ocean water (Anderson, 1989).

In recent decades and throughout the world, the increasing occurrence of red tides suggests an unsettling trend. However, there are multiple causes of red tides, only some of which relate to pollution or other human activities. Long-term studies at the local or regional level show that red tides are increasing as coastal pollution worsens. Larger areas of the coastal regions are affected, which are subject to an unprecedented variety and frequency of red tide events. To consider PSP as an example, the web of Harmful Algae (http://www.whoi.edu/redtide/) shows the distribution of PSP between 1970 and 2006, during which the human population increased by approximately nine-fold. The many studies or projects that were key to the formulation of many international programs, both bi- and multi-lateral, are examples of how red tide studies along the Atlantic coast have been relatively isolated over the last few decades. To understand the causes, predict the occurrences, and better mitigate the effects, international organizations such as the European Union and the US National Science Foundation have frequently pooled their resources to support joint programs. In China, several large projects were conducted, such as "*Study on ecology, Oceanography mechanism, Prediction Prevention and Treatment of the Red Tide Outbreak in offshore, China*" (2004). However, single-region studies over long periods of time, including examinations of the distribution methods and causes, have not yet been conducted.

* Corresponding author. Tel.: +86 10 8491 5231.
E-mail address: demi_0205@163.com (B. Zheng).

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Based on the three stages of red tide research developed by Su (2001), this article divides the development of China's red tide research into four stages:

- Understanding phase: Before 1977, China only reported the occurrence of red tides through the news media, e.g., where, when, and how. The earliest record of a red tide event, which occurred in Zhejiang-Taizhou, Shipu waters, was published in an issue of the original Zhejiang Provinces Aquatic Experiment Field (Liang and Qian, 1995). During this period, approximately 10 related references were also published (Hua, 1989).
- Exploration phase: From 1977 to 1989, the relevant state ministries gradually paid more attention to studies involving red tides, most of which focused on the physiological ecology and causes of red tides. In this period, 60 papers were published on the topic (Hua, 1989).
- Development phase: From 1989 to 2000, the problems caused by red tides received more extensive attention. Based on studies of physiological ecology, domestic scientists began to consider different approaches in relation to the study of red tides (Hua, 1989). An example of this was the program "The Dynamics and Control Countermeasures Research of the HABs in the Coastal Typical Farming Areas in China", funded by the National Natural Science Foundation of China (NSFC), which was designed for farming areas adjacent to areas in which red tide research was being conducted. In addition, as a result of the wide scope and time-sensitive nature of monitoring using satellite remote sensing (RS) (Wang et al., 2006), some researchers attempted to apply RS to red tide studies, focusing on theories about the feasibility of application.
- Since 2000, RS has been frequently applied in the detection, recognition and analysis of red tides. Domestic scientists have made great efforts to explore this field. Zhou and Fan (2007) summarized the major RS methods by monitoring red tides with MODIS and examined the strengths and weaknesses of this approach, while Jeong (2005) used a sea-color algorithm and spatial analysis technology to detect and analyze red tides using man-made satellite data and GIS. Additionally, risk assessments of red tides have become increasingly important. Zhao (2004) considered three important aspects, i.e., marine ecosystems, marine economy and human health, which should be considered when examining the red tide data obtained before 2001 in all of China's major seas. The degree of harm that red tides cause, including the extent of economic losses and casualties, should be evaluated before dividing the information into the five levels of red tide disasters. Wang and Wu (2009) established the risk assessment model to evaluate the level of harm inflicted by red tides, in which there are four factors: toxin concentration, cell density, red tide area, and the duration of the event.

2. Study area and data sources

2.1. Study area

The Yangtze River Estuary and its adjacent waters are located in the east coastal zone of eastern China, at a longitude of 123°E, and between the latitudes of 29°30′N and 32°00′N. The Estuary covers about 38,010 km^2 and includes the Jiangsu southeast waters, the Shanghai sea, Hangzhou Bay and the Zhoushan waters (Fig. 1). The Yangtze Estuary region has a high incident rate of red tides (Wang, 2002). For many years, diluted water from Changjiang and warm oceanic currents from Taiwan created favorable environmental conditions, including abundant nutrients, sufficient light and correct ambient temperatures, that were beneficial to the seasonal growth of red tide organisms in specific locations (Zhou et al., 2001). Additionally, the region surrounding the Yangtze River Estuary and its adjacent waters is one of the fastest economically developing areas in China; compared to other marine areas, human activities are increasingly frequent in this region, leading to significantly higher concentrations of nitrogen and phosphorus in the seawater (Huang et al., 2003).

2.2. Data sources and treatment

In this study, red tide data were collected and compiled from the earliest record in 1972 through 2009. The data are based on regularly issued reports from the state and relevant provinces and cities, including the Environmental quality of coastal waters of China Annual Report (1986–2000), China Marine Disaster Bulletin (1990–2009), Marine Environment Quality Bulletin of Zhejiang Province (1986–2008) and Marine Environment Quality Bulletin of Shanghai City (1986–2008). Additionally, some of the historical data are sourced from books and papers that focus on red tide research in the Yangtze River Estuary and its adjacent waters (Fu and Huang, 1993; Xu, 1992; Shen et al., 1995; Wang, 2001; Cai et al., 2002; Tang et al., 2005; Fei and Jiang, 2008; Ye et al., 2009). The earliest record of a red tide occurrence in this particular region dates to August–December 1972, when a red tide was detected in the eastern waters of Haijiao. This red tide event, $\sim$24 km^2 in extent, was caused by a bloom of *trichodesmium thiebautii* and resulted in a loss of fish production (Xu et al., 1994). It is important to note that records of red tide events were discontinuous prior to 1985; therefore, we are unsure of the integrity of this historical data.

Currently, scientists in China examine the various aspects of red tide genesis and impacts, focusing on the impact factors and the mechanisms. These factors and mechanisms include climate conditions, e.g., the role of wind velocity; hydrology conditions, e.g., temperature, salinity, DO, and pH; geological conditions, e.g., the species of phytoplankton and its toxicity; and nutrient distribution, e.g., nitrogen, phosphorus, and silicon (Huang et al., 1994; Qi, 2003; Wang, 2002; Zhu et al., 2003). Using ArcGIS technology, the regional and temporal changes of red tides for 1972–2009 are shown.

3. Regional and temporal changes in the Yangtze River estuary and adjacent waters

3.1. The spatial analysis of red tides characteristics

Fig. 2 shows the spatial distribution of red tide occurrences in the Yangtze River estuary and the adjacent waters. There are three regions known to be prone to red tides: outside the Yangtze River Estuary and nearby Sheshan, Huaniaoshan–Shengsi–Gouqi, and Zhoushan and the eastern coast of Zhujiajian. From 1972 to 2009, red tide events occurred 174 times in total. In the affected region, 32 red tide occurrences had no recorded details associated with them, which represents 18.4% of the total number. There were 44 occurrences affecting areas of less than 50 km^2 in areal extent, 41 affecting areas of 50–100 km^2, 41 affecting areas of 100–500 km^2, 24 affecting areas of 500–1000 km^2, and 25 affecting areas of greater than 1000 km^2 (Table 1). From 1987 to 1990, red tides with massive areal extents (an area greater than or equal to 1000 km^2) occurred frequently. From 2000 to 2009, only one year (2007) showed no large occurrence of red tides. Between 1972 and 2009, red tides with the largest areal extent occurred, with some near the Zhoushan waters affecting an area as large as 7000 km^2 during 1990 and 2000.