

Spatiotemporal Patterns of Harmful Blooms in Coastal China and Their Relationship with Sea Surface Temperature

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Abstract. There are serious ecological problems of harmful algal blooms (HABs) in the coastal areas of China. Based on the China Marine Disaster Bulletin (2014-2023) and concurrent sea surface temperature (SST) data, this paper studies the interannual fluctuations and spatial distributions of harmful algal bloom (HAB) frequency and cumulative area, and investigates their relationship with SST. Based on the above results, HABs have been relatively frequent over the past decade and have shown two peaks in 2016 and 2021. The East China Sea is the main hotspot, with the highest proportion in both occurrence (52.2%) and affected area (69.3% in 2023). The Bohai Sea, Yellow Sea and South China Sea have lower HAB activity due to different nutrient loads and hydrodynamic conditions. Correlation analysis shows that HAB indicators are weakly and insignificantly correlated with the annual mean SST (frequency: $r=0.241$, $p=0.503$; area: $r=0.390$, $p=0.265$). Therefore, SST is not a leading statistical factor for interannual variability of HABs in China's coastal waters.

Keywords: Harmful Algal Bloom; Coastal Waters of China; Spatiotemporal Distribution; Sea Surface Temperature; Correlation Analysis.

1. Introduction

Red tides are abnormal blooms of marine microorganisms that damage marine ecosystems and the economy of coastal areas. China is one of the most affected countries; red tides have been occurring more frequently and intensely in recent years. Most studies so far have been localised or single-incident research and have lacked systematic, large-scale, and long-term studies. Specifically, there has been a lack of research on the spatial heterogeneity of HABs across China's four main sea areas, namely the Bohai Sea, Yellow Sea, East China Sea (ECS) and South China Sea, and the corresponding environmental drivers of nutrient input, river runoff and water exchange. Additionally, the connection among sea surface temperature (SST), a general index of change around the world, and yearly variations in red tides in China's coastal areas has not been established.

Based on the above deficiencies, this study collects red tide records from 2014 to 2023 from the China Marine Disaster Bulletin and satellite-derived SST data from the NOAA OISST v2 dataset. Time series, spatial statistics and Pearson correlation analysis are used to (1) show the spatiotemporal evolution patterns of HABs; (2) compare the characteristics and environmental conditions of HABs in the four sea areas; and (3) quantify the statistical relationship between HAB parameters (frequency and cumulative area) and annual mean SST. Based on the above results, an early warning system for changes in the marine environment will be built.

2. Data and Method

2.1. Study area

This study takes China's offshore waters as the study area, covering the four major sea areas: the Bohai Sea, the Yellow Sea, the East China Sea, and the South China Sea. The geographical location of the study area is 105°E-130°E, 15°N-45°N. This region is the most concentrated area of marine economic activities and the most frequent area for red tide disasters in China.

2.2. Data Sources

2.2.1. Red tide data

Red tide data were obtained from the China Marine Disaster Bulletin (2014–2023) issued by the Ministry of Natural Resources. The extracted data includes the annual frequency and cumulative area of red tide nationwide and by sea area. Table 1 summarizes the frequency and cumulative area of red tides in China's offshore waters from 2014 to 2023.

Table 1. Frequency and cumulative area of red tides in China's offshore waters (2014–2023).

Year	Frequency of red tides (times)	Cumulative area of red tides (km ²)
2014	56	7290
2015	35	2890
2016	68	7484
2017	68	3679
2018	36	1406
2019	38	1991
2020	31	1748
2021	58	23277
2022	67	3328
2023	46	1466
Average	50	5448

2.2.2. Sea surface temperature data

SST data were obtained from the NOAA OISST (Optimum Interpolation Sea Surface Temperature) V2 high-resolution dataset. This dataset provides global monthly mean SST data with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. Monthly mean SST data for China's offshore waters (105°E – 130°E , 15°N – 45°N) from 2014 to 2023 were extracted, and the annual mean SST for each year was calculated.

2.3. Methods

The following are the analysis methods in this paper. A Time-Series Model will be used for trend analysis. By drawing graphs of the interannual fluctuations in red tide frequency and cumulative area, the high-incidence years and general temporal development features of red tide disasters were systematically identified. For the analysis of spatial distribution, proportions of red tide frequency and cumulative area in China's four major sea areas were statistically calculated to reveal the pattern and regional differences in the distribution of red tide disasters. Pearson's correlation coefficient was used to examine how often and how widely distributed the areas of severe algal blooms correlated with changes in mean annual sea surface temperature (SST). Pearson's coefficient of correlation (r) is between -1 and 1; it is relatively close to 1 or -1 when the data show a close linear relationship. A p -value of 0.05 is considered to have significant differences at the 0.05 level. All correlation coefficient calculations were done in MATLAB R2023b.

3. Results

3.1. Temporal changes in red tide frequency and area

From 2014 to 2023, red tide frequency fluctuated without a significant trend [1], peaking in 2016–2017 (68 events/yr) and reaching a low in 2020 (31 events) (Figure 1). Cumulative area showed more pronounced variation, with an extreme outbreak in 2021 (23,277 km², 4.3 times the decadal average), mainly due to large-scale blooms in the East China Sea.

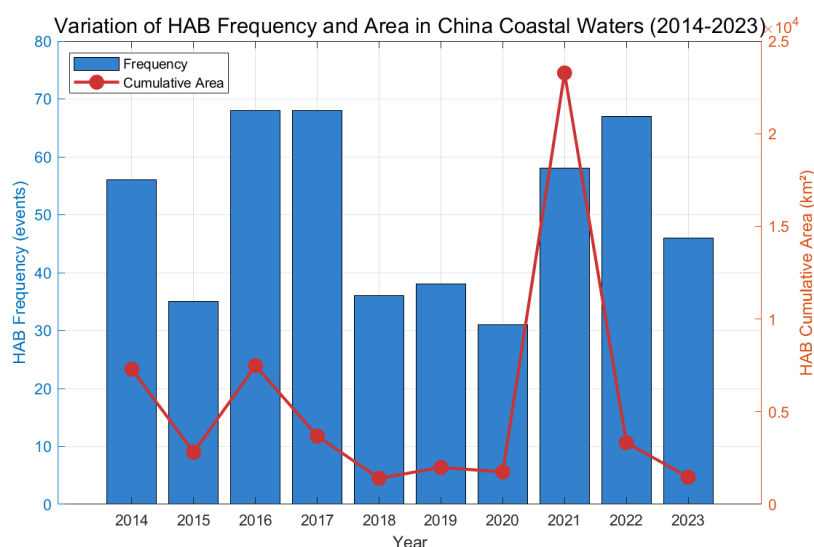


Figure 1. Changes in red tide frequency and area in China's offshore waters from 2014 to 2023.

3.2. Spatial distribution characteristics of red tides

For example, in 2023, the areas of the sea exhibited various spatial distributions of red tides (Table 2). The East China Sea was the sea area with the highest frequency and largest cumulative area of red tides, recording 24 events (accounting for 52.2% of the national total) and a cumulative area of 1,016 km² (accounting for 69.3% of the national total). The Bohai Sea and the Yellow Sea were next, and the South China Sea had the lowest values.

Table 2. Red tide occurrence in China's major sea areas in 2023.

Sea Area	Frequency of red tides (times)	Proportion (%)	Cumulative area (km ²)	Proportion (%)
Bohai Sea	9	19.6	304	20.7
Yellow Sea	6	13	12	8.3
East China Sea	24	52.2	1016	69.3
South China Sea	7	15.2	24	1.6
Total	46	100	1466	100

This distribution pattern is closely related to spatial differences in nutrient concentrations, coastal runoff input, and marine dynamic conditions. Specifically, the Bohai Sea, as a semi-enclosed basin, accumulates nutrients but experiences lower SST and weaker stratification, limiting HAB scale. The Yellow Sea is influenced by cold water masses and strong tidal mixing, which disrupt stratification and suppress bloom formation. The South China Sea, despite its vast area, receives limited large-river nutrient inputs and maintains strong water exchange with the open ocean, resulting in the lowest HAB frequency. In contrast, the East China Sea receives massive nutrient discharges from the Yangtze and Qiantang Rivers, combined with frontal systems and upwelling that concentrate algae and transport nutrients, making it the national HAB hotspot.

3.3. Correlation between red tides and sea surface temperature

From 2014 to 2023, the annual mean SST in China's offshore waters fluctuated between 20.95°C and 21.39°C, showing a slight increasing trend overall. The Pearson correlation analysis showed (Figure 2, Figure 3):

(1) The correlation coefficient between red tide frequency and annual mean SST was $r=0.241$, indicating a weak positive correlation. However, the corresponding p-value was $0.503 > 0.05$, failing the significance test.

(2) The correlation coefficient between red tide cumulative area and annual mean SST was $r=0.390$, showing a slightly stronger correlation than that of frequency. Nevertheless, its p -value was $0.265 > 0.05$, also failing to reach statistical significance.

These results indicate that, on an interannual scale, changes in annual mean SST alone are not a decisive factor in explaining the fluctuations in red tide frequency and impact range in China's offshore waters over the past decade. Red tide occurrence is a complex process involving the synergistic effects of multiple factors. Its response to SST changes may exhibit characteristics such as non-linearity, seasonal dependence, and regional heterogeneity, rather than a simple linear relationship.

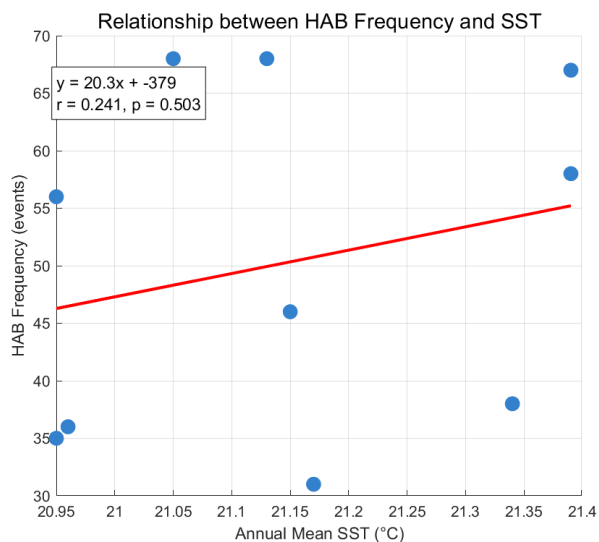


Figure 2. Relationship between red tide frequency and annual mean sea surface temperature.

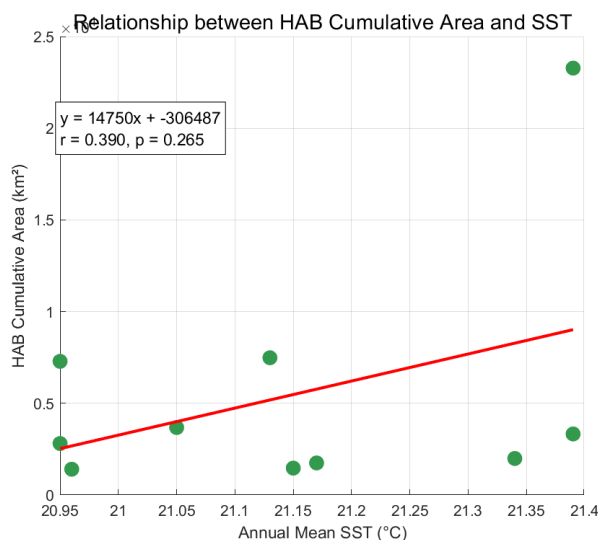


Figure 3. Relationship between HAB Cumulative Area and SST.

4. Discussion

4.1. Drivers of Interannual HAB Variability

HABs in China's coastal waters (2014–2023) showed "phased oscillations" rather than an increase in a single direction: a high-incidence period (2014–2017), a low-incidence period (2018–2020), a resurgence (2021–2022), and a decline in 2023. Therefore, HABs did not increase linearly with anthropogenic disturbance or warming in the climate system.

In 2021, a particular case occurred. The total area covered was 23,277 km², approximately 4.3 times the average for a decade, but it did not have the highest number of occurrences (58 events). Therefore, the severe spatial expansion of single blossoms was responsible for the rise. In the summer of 2021, there were persistently high temperatures, low precipitation and calm winds, and an increase in nutrients from the Yangtze and Qiantang Rivers; thus, a bloom of *Prorocentrum donghaiense* occurred. Dinoflagellate blooms are the most common type of HABs in China's coastal waters [1]. This extreme case shows that HABs are the result of the resonance of multiple factors, and no single reason can explain such a large fluctuation.

4.2. Stability of the Spatial Pattern and Its Ecological Implications.

The ECS has continuously been a hot topic for HAB disasters in China due to frequent outbreaks, large-scale damage and serious economic losses [2], attracting widespread attention from the public. This is the result of the long-term, combined effects of various marine ecological mechanisms. The area of the sea is next to the economically developed and densely populated Yangtze River Delta. The Yangtze River, Qiantang River and Min River are large rivers that discharge a large amount of nitrogen and phosphorus into the ECS each year; thus, the water body is in a state of chronic eutrophication and provides ample material for the growth of HAB algae. The South China Sea is also very large; however, its coastal areas lack significant terrestrial nutrient supply, have strong water exchange capabilities, and maintain relatively low nutrient concentrations, thus exhibiting a much lower frequency of HABs compared to the ECS.

The convergence of the Changjiang Diluted Water and the Taiwan Strait upwelling creates various frontal systems and eddies in the ECS. Hydrodynamic structures have accumulated dispersed algal cells in some places and, by transporting bottom nutrients to the surface euphotic zone through vertical mixing, promoted further growth of algae. Heavy rainfall will also accelerate the nearshore eutrophication process by increasing the inflow of nutrients from land and thus raise the risk of HABs and green tides in inner bays and urban waters [3, 4]. The connection among physical and biogeochemical factors provides an ideal environment for the development of harmful algal blooms in the ECS.

Prolonged, frequent occurrences of HABs have also promoted adaptive succession in the microalgal community structure within the ECS. Some opportunistic HABs, such as *Prorocentrum donghaiense*, have established a stable dominant population in this area over time. Dinoflagellate blooms made up 50.0% of all harmful algal blooms (HABs) in China's coastal waters between 1995 and 2014 [5]. These species have large seed banks and are in favourable ecological conditions; under favourable conditions for the external environment, they can reproduce rapidly and form large-scale blooms. Therefore, the ECS is a major cause of HAB disasters in China and should be a focus area for the optimised construction of future HAB monitoring networks and the first-priority location for prevention and control efforts. The high-incidence pattern of the ECS is mainly due to its prolonged eutrophic conditions, and thus, we cannot determine why sea surface temperature did not emerge as a significant cause for change.

4.3. In-depth Analysis of the Non-significant Sea Surface Temperature–HAB Relationship

4.3.1. Smoothing of Seasonal Signals by Annual Mean Temperature

HABs are typical of spring and summer. The speed of warming in the spring and when biological thresholds are crossed are often more significant than the mean annual temperature. Warming of the world is accelerating the decline of marine living resources globally [6, 7]. The annual mean SST is the average of the twelve monthly values and therefore does not fluctuate seasonally. By not recording these process-based signals, the annual mean SST will be significantly lower than the actual temperature increase.

4.3.2. Non-linearity and Threshold Effects

The Impact of SST on HAB occurrence may be nonlinear. The Optimal Temperature Range for Growth of HAB Algae. If SST is below the lower bound, algal metabolism will decrease; if it is above the upper bound, growth will also be inhibited. There was a slight change in temperature at that time; therefore, there was no significant flowering. Therefore, no significant correlation does not exclude the existence of non-linear SST effects.

4.3.3. Eutrophication as the Dominant Driver of Interannual HAB Variability

The coastal waters of China are a typical nutrient-limited system. The flux of land-sourced nutrient inputs has been relatively high for a long time, and they provide an essential external supply of nutrients for the marine nutrient budget and cycle [8], forming the material basis of HAB occurrence. Given the environment above, fluctuations in river discharge flux have led to non-steady-state features of nutrient budget and cycling over the Chinese continental shelf, and phenomena such as nitrogen accumulation and phosphorus depletion have been observed in some sea areas [9, 10], which are significant drivers for the accumulation of phytoplankton biomass. Interannual fluctuations in SST are relatively weak regulators of HABs; that is, under conditions of abundant nutrients, their impact on the scale of HABs is far less significant than that of nutrient limitations.

Nutrients determine the possible risk and upper bound for HABs at a mechanistic level, and SST mainly affects metabolic rate, growth cycle and population competition. When nutrients are persistently high, annual fluctuations in SST can only modestly alter the timing and species composition of blooms; thus, they are not the main reason for interannual variability in HAB frequency and area.

The data also supports the above analysis. Although SST in China's coastal waters has been rising from 2014 to 2023, there has been no corresponding increase in HABs. Year-on-year changes in these are relatively sensitive to fluctuations in nutrient supply and climate, for example, changes in precipitation, wind and radiation. Given the high-nutrient conditions, the regulation of nutrient supply in HAB control needs to be strengthened in conjunction with all-around monitoring of the environment.

5. Conclusion

Using the HAB disaster dataset and sea surface temperature data for China's coastal waters over the past decade, this paper has systematically investigated the spatio-temporal development features of HABs and their statistical relationships with SST. The first few of the conclusions are as follows:

Strong interannual fluctuations of HABs without a one-way decline. From 2014 to 2023, HABs in China's coastal waters showed a gradual decline, with an average of 50.3 events per year and a mean affected area of 5,447.8 km². The HAB area did not increase steadily each year, but the extremely large-scale event in 2021 (23,277 km²) showed that a combination of extreme weather and eutrophication posed a considerable risk.

The East China Sea is the core area of the absolute HAB disaster. The Space distribution of HABs is uneven, and the East China Sea has always been the most affected area at the national level in 2023, accounting for 52.2% of the frequency of occurrences and 69.3% of the affected area. It is close to a highly eutrophic area with strong hydrodynamic convergence and a rich seed bank of HAB algae in this sea area.

Annual mean Sea Surface Temperature is not the primary statistical factor. Both HAB occurrence frequency ($r=0.241$, $p=0.503$) and cumulative areal extent ($r=0.390$, $p=0.265$) showed a weak positive correlation with annual mean SST, but neither reached statistical significance. Therefore, it can be assumed that the combined effect of eutrophication and other hydrometeorological factors on a multi-year basis is probably much larger than that caused by fluctuations in SST alone. SST is likely to have a non-linear impact on processes such as the speed of spring warming and threshold triggering, and a simple linear average effect will not occur.

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