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Effects of meteorological factors on the temporal distribution of red tides in Tolo Harbour, Hong Kong

Jiansheng Huang[a,b,c], Hao Liu[a,b,1], Kedong Yin[a,b,*]

[a] School of Marine Sciences, Sun Yat-sen University, Zhuhai, 519082, China
[b] Key Laboratory of Marine Resources and Coastal Engineering in Guangdong Province, Guangzhou, 510006, China
[c] Dongguan Marine and Fishery Environmental Monitoring Station, Dongguan, 523002, China

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ABSTRACT

Red tides represent a major environmental issue in coastal waters globally. However, few studies have examined the relationship between red tides and meteorological factors. Thus, we used a 32-year time-series of frequent red tide events in Tolo Harbour and Channel, to study their relationship with meteorological factors. Most red tides are dominated by dinoflagellates in March, while most diatom red tides in May. Dinoflagellate and diatom red tides respond differently to different meteorological factors. Warming air temperatures in spring favor the generation of dinoflagellate red tides, while precipitation hinders them. The optimum temperature range is approximately 17–23 °C and 26–29 °C for dinoflagellate and diatom red tides, respectively. Moderate north-easterly winds promote the formation of dinoflagellate red tides. Dinoflagellate red tides are not hindered by cloudy weather and occur in sunlight of varying brightness, whereas diatoms red tides require a certain amount of bright sunlight.

1. Introduction

The term "red tide" refers to the phenomenon of discoloration of seawater caused by the excessive accumulation of marine plankton biomass. Since 1950, red-tide outbreaks have become more frequent in the coastal waters in China (Yan et al., 2001; Zhou et al., 2008) and globally (Anderson, 2003, 2012). In 2003 alone, 119 red-tide events were reported in China (Tang et al., 2006). Red tides often lead to serious economic and ecological problems, causing concern for the safety of seafood caught in these areas because of the harmful toxins associated with algal blooms. Many studies have been conducted on the classification of red-tide-causing organisms (Liu et al., 2013) and the factors affecting red-tide outbreaks in the last three decades (Yin, 2003; Chika, 2016; Wang et al., 2016). Several mechanisms have been proposed to explain the formation of harmful algal blooms (HABs) (Yin et al., 2008; McLeod et al., 2012; Anderson et al., 2015). Among these mechanisms, eutrophication is generally regarded as the major cause of algal bloom formation, as nitrogen and phosphorus are the main limiting nutrients for phytoplankton biomass in marine waters. However, red tides with phytoplankton of high biomass also occur in low-nutrient waters. This phenomenon has been explained by a proposed and model-tested physical-biological coupling-induced aggregation mechanism in low-nutrient environments (Lai and Yin, 2014). Because of the complexity of marine ecosystems, it is often difficult to discern the relationships between marine environmental factors and red tides (Hu et al., 2016); consequently, it remains difficult to predict when and where a red tide will occur. As stated by Wells et al. (2015), data on the fundamental mechanisms driving red tides are lacking. Furthermore, the authors emphasized that climate change pressures will influence marine planktonic systems, leading to an increase in the occurrence of HABs. Therefore, there is a pressing need for the analysis of long time-series datasets of red-tide events.

The frequency of red tides in Hong Kong is one of the highest worldwide (Yin, 2003), resulting in the publication of many studies on red tides. Morton and Twentyman (1971) first reported the occurrence and toxicity of red tides caused by *Noctiluca scintillans* in Hong Kong. The annual red-tide events in Hong Kong waters became frequent during the 1980s (Li et al., 2004), with 27 harmful or potentially harmful dinoflagellate species being identified during 1997–1998 (Lu and Hodgkiss, 2004). Previous studies have found that the red tides in Hong Kong are generally correlated with wind speed and direction (Yin, 2003). However, few studies have examined how other meteorological factors influence the formation of red tides, particularly the red tides of dinoflagellates and diatoms. Thus, the aim of this study was to examine

* Corresponding author at: School of Marine Sciences, Sun Yat-sen University, Zhuhai, 519082, China.
E-mail address: yinkd@mail.sysu.edu.cn (K. Yin).
[1] Joint first author.

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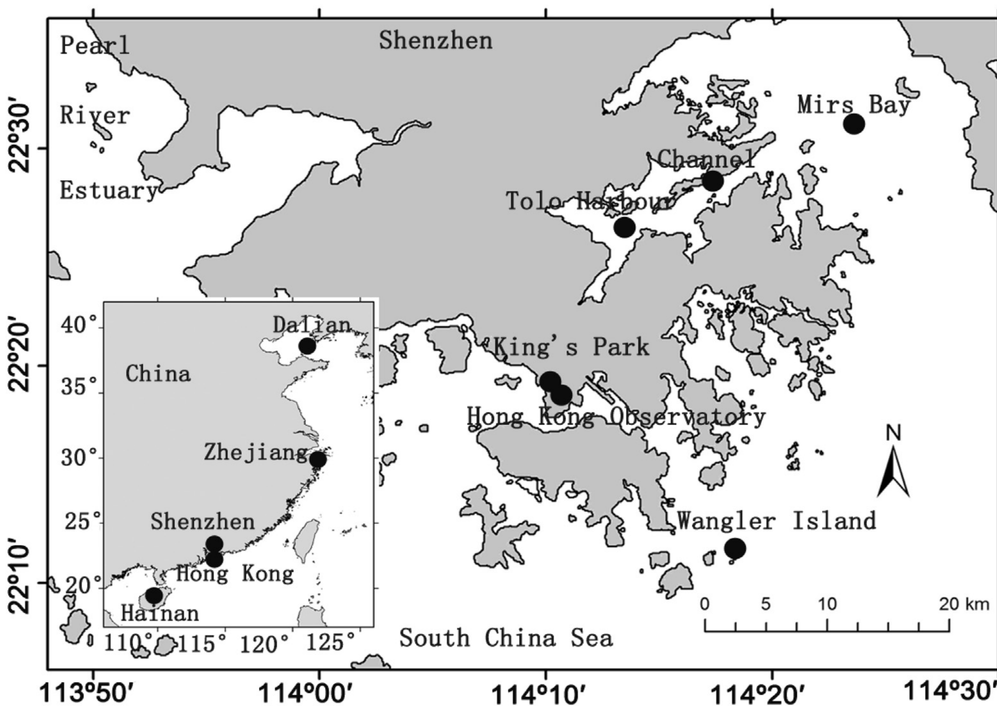

Fig. 1. Map of Tolo Harbour and Channel, Hong Kong and China coasts near Dalian, Zhejiang, Shenzhen and Hainan.

the relationship of total red-tide events, dinoflagellate red tides, and diatom red tides with various meteorological factors, such as air temperature, wind direction, wind speed, rainfall, cloud cover, and hours of bright sunlight.

2. Materials and methods

In this study, a red tide is defined as a patch of discolored water caused by the high biomass of phytoplankton in a marine habitat. Red tides in Hong Kong waters have been monitored by the Agriculture, Fisheries, and Conservation Department (AFCD) of Hong Kong since 1983. This study used the AFCD red-tide time-series data collected in Tolo Harbour and Channel (Tolo) from 1983 to 2014 (Fig. 1). Data on red tides in other regions (including Hainan, Shenzhen, Zhejiang and Dalian) originate from the Red Tide Disasters Law in Typical Chinese Waters (Zhao, 2010) and the Bulletin of Marine Environmental Status of Hainan Province (DOFHP, 2001–2014).

The meteorological factors used in this study include wind direction, wind speed, air temperature, rainfall, cloud cover, and hours of bright sunlight. The data during 1983–2014 originate from the Hong Kong Observatory (http://gb.weather.gov.hk/contentc.htm). Wind direction and wind speed are recorded at Wangler Island. All other meteorological factors are recorded by the Hong Kong Observatory site (Fig. 1). The data for air temperature at the other regions (including Hainan, Shenzhen, Zhejiang and Dalian; Fig. 1) from 1981 to 2010 originate from the National Meteorological Information Center (http://data.cma.cn/); however, temperature data for 2011–2014 are not available. On a red-tide event day, the meteorological factors are referred to as the "red-tide-day meteorological factors". The meteorological factors for all days, including red-tide days, are referred to as regular-day meteorological factors.

The meteorological factor values during 1983–2014 were grouped into eight bins (Table 1). The number of days in a bin of a meteorological factor was counted, and represented the frequency of the meteorological factor in the bin. Thus, each meteorological factor generates eight frequencies from the eight bins. For each bin, we separated the total frequency into the monthly distribution, or divided the total frequency by 32 years to obtain the annual (mean) frequency or we divided the total by 12 months to obtain the monthly (mean) frequency. Similarly, on a red tide event day, we examined values of six meteorological factors and arranged them in eight corresponding bins. The total number of red-tides during 1983–2014 in a bin was counted, which was the frequency of red tides in the bin. The annual frequency or the monthly frequency of red tides was obtained by dividing the total by 32 years or 12 months. Therefore, for each bin (Table 1), there was a pair of the frequencies of red tides (days) and a regular meteorological factor (days), which were used to analyze their relationships.

The software program Sigma Plot version 12.5 was used to perform the statistical analysis.

3. Results

3.1. Monthly distribution of red tides

During 1983–2014, 436 red tides occurred in Tolo, and were caused by dinoflagellates, diatoms, and other taxa. Dinoflagellates are the dominant taxa causing red tides in Tolo (Fig. 2), accounting for 62.6% (273) of tides. Diatoms and other taxa account for 18.6% (81) and 18.8% (82) of red tides, respectively. From 1983 to 2014, the overall frequency of red tides was the highest in March (n = 60) and the lowest in August (n = 14). Dinoflagellate-dominated red tides peak in February–April and have the lowest frequency in August. Diatom red tides peak in May and remain relatively high through August, with the lowest frequency occurring in February. The frequency distribution of the other types of red tides roughly follows the same pattern as the overall pattern of all red tides (Fig. 2A–D). The most frequently occurring red tide dinoflagellate species are *N. scintillans* (73 times), *P. minimum* (44 times), *P. triestinum* (33 times), and *G. polygramma* (23 times) (Table 2). The most frequently occurring diatom species is *S. costatum* (23 times).

3.2. Red tides in relation to monthly changes in meteorological factors

The monthly averages of red-tide-day meteorological factors were compared with those of regular-day meteorological factors (Fig. 3). Red-tide day values of air temperature are similar to those of regular-day values. Red-tide day values of wind speed, wind direction, rainfall, and cloud cover are lower than those of regular-day values. Red-tide-day air temperature (Fig. 3A) and wind direction (Fig. 3D) are similar to