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ORIGINAL RESEARCH

Risk of red tide and eutrophication under climate change phenomena in Thailand

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Abstract Climate change events cause changes in seawater quality, subsequently affecting phytoplankton abundance. This study aims to investigate limiting factors for phytoplankton growth, develop a model to simulate the variation of phytoplankton under climate change events, and evaluate the risk of algae blooms during the climate change crisis. The study was conducted in the inner Gulf of Thailand. Phytoplankton and seawater were sampled monthly from January to December 2019. The Pearson correlation and model fitness (linear and non-linear) were employed to investigate limiting factors and simulate the climate change scenarios. Results revealed that the major limiting factors are phosphate and nitrite-nitrate for estuarine and coastal areas, respectively. The model simulations demonstrated that algal blooms in estuarine areas can be observed more frequently in warm and drought-affected regions (rainfall <5 mm/month). Meanwhile, intensive rainfall (>300 mm/month) is a factor influencing the mechanisms of red tide and eutrophication in coastal areas. According to climate change scenarios (IPCC AR5), the model simulation showed that there are risks of red tide and eutrophication in all RCPs. The annual blooms can be found in February and September in estuarine and coastal areas, respectively. These results can enhance the red tide warning system and lead to climate change adaptation practices for aquaculture during extreme weather events in estuarine and coastal areas.

Keywords Red tide . Eutrophication . Phytoplankton blooms . Seawater quality . Climate change . Drought . Flood

Introduction

In estuarine and coastal areas, red tides and eutrophication are natural phenomena of algae blooms or enrichment of phytoplankton that are harmful to marine organisms. There is a small difference between these phenomena. Red tide, including harmful algal blooms (HABs), is characterized by a rapid increase in marine phytoplankton that causes discoloration in surface seawater, depending on the algae's pigments (Zohdi and Abbaspour 2019). Meanwhile, eutrophication is the long-term excessive accumulation of algal growth that can take months or years (Chislock et al. 2013). The occurrences of red tide and eutrophication depend on the increased availability of one or more limiting growth factors needed for photosynthesis, such as sunlight duration, light attenuation, seawater temperature, vitamins, and nutrients, especially nitrogen and phosphorus. The heavy influx of industrial waste, domestic wastewater, agricultural runoff, and fertilizers from intensive animal farming have dramatically contributed to the various pollutants that promote algal blooms, which are transported from land into the sea through river discharge. Consequently, these

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anthropogenic nutrient loads from terrestrial sources cause the frequency of red tides and eutrophication, which have become serious ecological problems worldwide (Johnson et al. 2013; Park et al. 2013; Wang et al. 2008), including Thailand (Chuenniyom et al. 2016; Luang-on et al. 2023; Somsap et al. 2015). The creation of dense algae blooms discolors coastal water and harms water quality. Their formations are often foul-smelling, consisting of phytoplankton or fetid foam with an unpleasant smell. This phenomenon reduces water clarity and limits light penetration, causing severe damage to light-dependent aquatic life (Chislock et al. 2013). Some phytoplankton species are strongly toxic to marine animals and humans. For instance, the blooming of dinoflagellate *Gymnodinium breve* in the Gulf of Mexico caused paralysis of the central nervous system of fish and skin irritation in humans who swim or touch the water through the spray of waves or wind in the beach area (Zohdi and Abbaspour 2019). In addition, the biodegradation of these dense phytoplankton decreases dissolved oxygen in the water column. Subsequently, there is insufficient oxygen for marine organisms, resulting in an anoxic or dead zone, where large-scale mortalities of fish and shellfish can be observed (Anderson et al. 2002; Fu et al. 2012; Zarei and Arjmandi 2014). These studies provide evidence that red tides and eutrophication cause significant damage to marine ecosystems, social harm, and economic loss.

Climate change causes variations in seawater quality (Srisunont et al. 2012), which significantly alter phytoplankton abundance, leading to the occurrence of red tides and eutrophication. The meteorological factors associated with algae blooms in estuarine and coastal areas are known to include air temperature, sunshine, and precipitation (rainfall) (Huang et al. 2018; Meng et al. 2017; Phlips et al. 2020; Xu et al. 2019; Yoon and Kim 2003). High air temperatures corresponding to warm water can induce red tide occurrences (Yoon and Kim 2003). The proper sunlight duration favors algae blooms. However, it depends on the phytoplankton species. For example, dinoflagellate red tide requires only 1 hour of bright sunlight; meanwhile, low cloud cover with 9 hours of sunlight promotes diatom red tide (Huang et al. 2018). Intense rainfall can lead to a significant increase in the magnitude of phytoplankton blooms due to nutrient enrichment from drainage or runoff water from surrounding areas (Meng et al. 2017). In contrast, precipitation inhibits the formation of algae blooms in certain areas (Chen et al. 2023; Trainer et al. 2020). This is because rainfall-runoff adds freshwater to the estuarine and coastal areas, subsequently reducing the salinity of surface seawater, which is unsuitable for phytoplankton growth. In the future, it was forecasted that there would be unstable air temperatures and rainfall patterns. By the end of the 21st century (2081-2100), the global mean surface temperature is expected to increase by 1.5 to 2.0 °C. Extreme precipitation events are becoming more intense (IPCC 2013). The frequency and magnitude of phytoplankton blooms may increase and gradually be affected by rainfall-runoff pollution. Research on model prediction of red tide and eutrophication has been conducted for decades (Jeong et al. 2015; McGillicuddy 2010; Seddigh Marvasti et al. 2012; Yoon and Kim 2003); however, none of these studies have provided information on the variation in phytoplankton quantity during global climate change events. The numerical modeling of this phenomenon must be based on case-based reasoning and examined in different scenarios.

Therefore, this study aims to: 1) investigate limiting factors that affect phytoplankton quantity; 2) develop a mathematical model to simulate the variation of phytoplankton under climate change events; and 3) evaluate the risk of algae blooms (red tide and eutrophication) during extreme weather caused by climate change. Results from the model simulations can forecast the occurrence of red tides and the abundance of phytoplankton, which is the most important primary producer in the marine ecosystem. This information is valuable for critiquing the alternative food chain in the context of climate change and for informing the implementation of adaptation policies, particularly for mariculture assets.

Materials and methods

Study area

As shown in Figure 1, the study was conducted in the inner Gulf of Thailand. Maeklong River Mouth (MK) and Sriracha (SRI) were chosen as sampling sites because these areas are frequently found to have phytoplankton blooms in estuarine and coastal areas, respectively. There are 3 sampling stations in each study area (MK 1-3 and SRI 1-3).

Maeklong River Mouth (MK) is in Samut Songkhram province (UTM unit zone 47P 612675 m E, 1475015 m N). This site has riverine influences. The river discharge was low (118–204 m^3/s) throughout the year (Luang-on et al. 2022). The surface area and volume of seawater are approximately 128.67 km^2 and 0.64 km^3, respectively. Most of this region is shallow, with the depth of seawater 3.0-6.6 m. The Northeast monsoon (November to January) and the Southwest monsoon (May to August) regulate the seawater current at this site (Buranapratheprat 2008).

Sriracha (SRI) is a coastal area in Chonburi province (UTM unit zone 47P 708208 m E, 1458524 m N) (Figure 1). This location is approximately 26 to 35 km south of the Bang Pakong River Mouth, outside the estuarine influence. The surface area and volume of seawater are approximately 16.54 km^2 and 0.75 km^3, respectively. The seawater depth is 3.9–16.5 m. Tidal currents influence the current at this site in the north-south direction, and the seawater velocity was 0.4 m/s (average of high and low tide) (Tharapan and Anongponyoskun 2010).

Sampling and analysis

At each station, phytoplankton and seawater were sampled monthly during the low tide in the spring tide period from January to December 2019. Phytoplankton samples were collected using a plankton net with a pore size of 20 µm. All samples were preserved in 4% formaldehyde liquor and were stored in the dark (closed bottle) at room temperature. Then, phytoplankton species composition and cell densities were determined by the counting chamber method in the laboratory. The Sedgewick-Rafter counting slide method was chosen because it is the standard method for quantifying high-biomass blooms (UNESCO 2010). The slide had a transparent base. It features a centrally mounted chamber (50 mm x 20 mm x 1 mm deep) that can accommodate 1 mL of sample. Then, observations were made under a light compound microscope at a magnification of 100-400. Finally, the phytoplankton abundance was calculated and expressed as cells/L. Seawater parameters such as temperature, pH, salinity, and dissolved oxygen (DO) were measured in situ using a handheld multi-parameter probe (YSI 600QS, USA). Then, the seawater was sampled and filtered

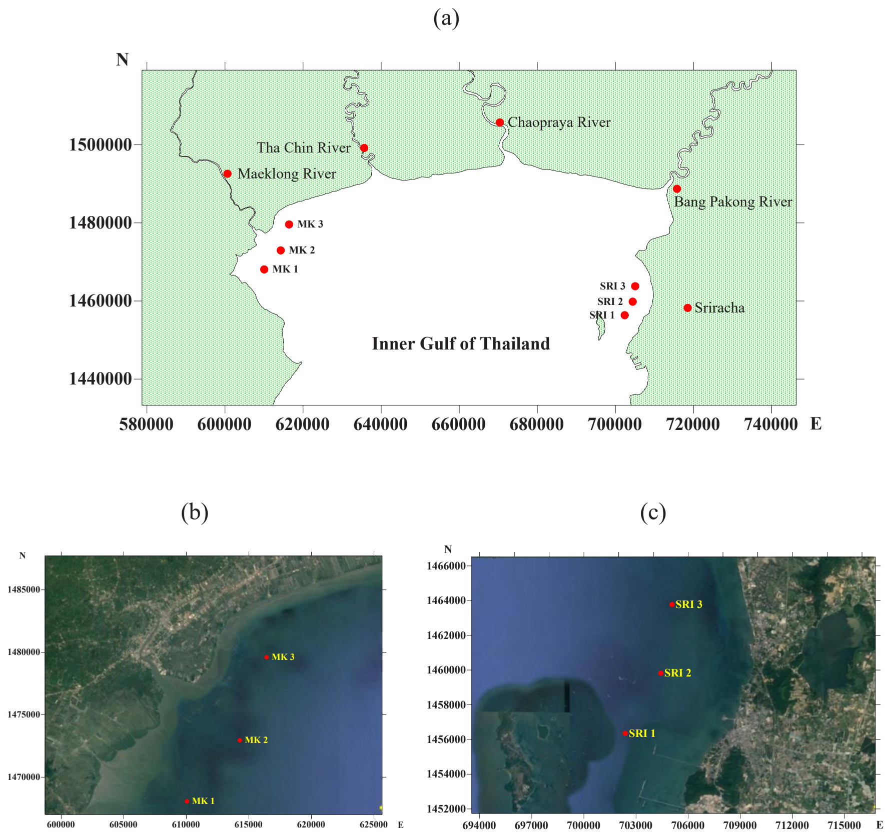

Fig. 1 The study areas and sampling station in (a) the Inner Gulf of Thailand: (b) the Maeklong River mouth (MK), and (c) Sriracha (SRI)

through GF/F filter paper (pore size 0.7 μm) to remove all suspended particles and bacteria and transported to the laboratory. All filtered samples were kept frozen at −20°C for nutrient analysis. Finally, concentrations of ammonium-nitrogen (NH_4^+-N), nitrite and nitrate-nitrogen (NO_2^-+NO_3^--N), phosphate-phosphorus (PO_4^{3-}-P), and silicate-silicon ($Si(OH)_4$-Si) were determined using a TrAAcs 2000 segmented flow analyser (Seal Analytical, USA) (sensitivity ± 0.01 μg L^{-1}).

Data and statistical analysis

The means and standard deviation of phytoplankton quantities and seawater parameters were analyzed using Microsoft Excel 365. Then, the Pearson correlation coefficient (r_{xy}) was used to investigate the limiting factors (seawater parameters) that affect phytoplankton abundance in the study area. All statistical tests were considered significant at the level of P<0.05 and P<0.01. Numerous mathematical models predict phytoplankton growth and abundance, utilizing parameters such as nutrients, seawater temperature, pH, and rainfall (Jeong et al. 2015; McGillicuddy 2010; Seddigh Marvasti et al. 2012; Yoon and Kim 2003). However, there is no direct link between climate variability due to the climate change crisis and the tentative levels of red tides and eutrophication occurrence. In this study, mathematical models to simulate the variation of phytoplankton under climate change events were developed using model fitness (linear and non-linear) in Microsoft Excel 365 software. The model assumes that variations in atmospheric parameters resulting from climate change (air temperature and rainfall) affect seawater quality and impact phytoplankton abundance. This study evaluated the correlations between atmospheric parameters and seawater quality using the numerical models described by Srisunont et al. (2022). Then, the model was combined with the correlation between seawater parameters and phytoplankton quantities from this study, as shown in the following equations.

$$\mathrm{Pl_{MK}} = 3069.4 \times [(-3.099 \ln \mathrm{R}) + 20.821]$$
$$\mathrm{Pl_{SRI}} = 875.78 \times [0.1833\mathrm{R} + 2.2954]$$

Where $\mathrm{Pl_{MK}}$ is phytoplankton quantity in Maeklong River Mouth (cells/L); $\mathrm{Pl_{SRI}}$ is phytoplankton quantity in Sriracha (cells/L);and R is the monthly total rainfall (mm) obtained from the Thai Meteorological Department (TMD). Finally, the coefficient of determination (R^2) was calculated to assess the accuracy of the model prediction.

Climate change scenarios

In this study, we simulated the models under two scenario patterns to estimate phytoplankton quantities during extreme weather due to climate change. The first scenario is flood and drought disasters. These conditions were considered for the model study because the IPCC (2013) forecasted unstable air temperature and rainfall patterns, which would lead to more frequent and severe disasters, especially floods and droughts. In this scenario, the air temperature was fixed, and then the phytoplankton quantities were simulated using the model developed from this study by varying the amount of rainfall. The second scenario is based on future climate projections from the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) (IPCC 2013). The temperature and precipitation changes in the 20-year mean difference for the years 2016–2035, 2046–2065, and 2081–2100 of four climate projection scenarios: a very low forcing level (RCP 2.6); two stabilization scenarios (RCP 4.5 and RCP 6.0); and very high greenhouse gas emissions (RCP 8.5) were input into the models. Results can forecast an abundance of phytoplankton, which shows the risk of algae blooms occurring (red tide and eutrophication) during the climate change crisis. Ultimately, suggestions for adapting to climate change to minimize economic loss in aquaculture can be implemented based on our results.

Results

This study conducted phytoplankton abundance and seawater quality from January to December 2019. Although data on phytoplankton in January and February are absent due to technical errors, the seasonal variation of phytoplankton and seawater in MK and SRI is successfully described, as shown in Figures 2 and 3, respectively.

During the study period, the phytoplankton quantity in the estuary site (MK stations) was 867-7,6870 cells/L. The highest density was found in April. Then, a rapid decrease was observed in the next month (May). The phytoplankton in Division Chromophyta was the most abundant in this study area. Most of the phytoplankton group was diatoms (Class Bacillariophyceae), which accounted for 53.88-99.58% of the total phytoplankton. The dominant species were *Nitzschia* and *Chaetoceros*. Except in November, the dominant species shifted to *Ceratium furca*, a dinoflagellate species in Class Dinophyceae. This species accounted for 80.44% of the total phytoplankton, which reached its highest density at 36,270 cells/L.

The phytoplankton population in a coastal area (SRI stations) differed from that in the estuarine areas. The total phytoplankton was less abundant at 1,806-40,649 cells/L. The highest and lowest cell densities were observed in September and March, respectively (Figure 3). Species composition was similar to MK stations, where diatoms are the most dominant group (73.63-97.48% of total phytoplankton), followed by Class Cyanophyceae in March – June, and Class Dinophyceae in July – December. The common species in this study area were *Chaetoceros*, *Thalassionema*, *Coscinodiscus*, *Pleurosigma,* and *Nitzschia*.

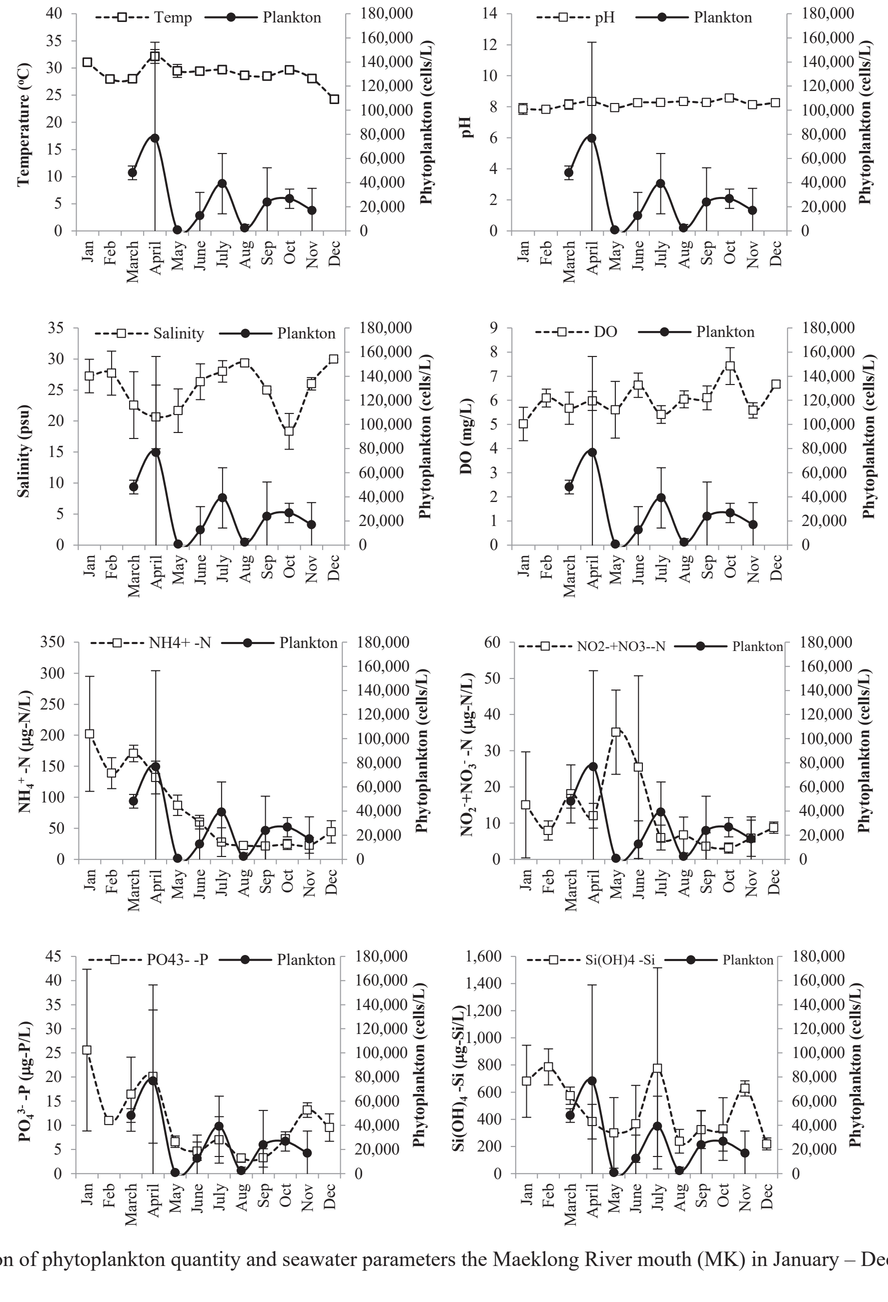

Fig. 2 Variation of phytoplankton quantity and seawater parameters the Maeklong River mouth (MK) in January – December 2019

Seawater qualities in the study period (January – December 2019) were observed (Figure 2 and 3). Seawater temperatures, pH, salinity, and dissolved oxygen (DO) in the estuarine areas (MK) were 28.90±1.93 °C, 8.19±0.22, 25.24±3.66 psu, and 6.02±0.65 mg/L, respectively. Nutrients concentrations were found to be 79.47±65.33 µg-N/L, 12.32±9.72 µg-N/L, 10.64±7.02 µg-P/L, and 466.67±208.59 µg-Si/L for ammonium-nitrogen (NH_4^+-N), nitrite and nitrate-nitrogen (NO_2^-+NO_3^--N), phosphate-phosphorus (PO_4^{3-}-P) and silicate-silicon ($Si(OH)_4$-Si), respectively. In the coastal areas (SRI), seawater temperature, pH, salinity, and DO were similar to those at MK stations, with values of 29.60±1.70 °C, 8.28±0.21, 27.90±3.15 psu, and 6.38±0.48 mg/L, respectively. Whereas nutrients were found to be lower. The concentrations of NH_4^+-N, NO_2^-+NO_3^--N, and PO_4^{3-}-P were 61.57±67.26 µg-N/L, 8.69±12.87 µg-N/L, and 5.41±5.11 µg-P/L, respectively. Expect $Si(OH)_4$-Si concentrations were 654.32±309.89 µg-Si/L, which was slightly higher in SRI.

Results from the Pearson correlation revealed different limiting factors for phytoplankton quantity in the estuarine (MK) and coastal areas (SRI). As shown in Table 1, the abundance of phytoplankton in MK was significantly correlated with seawater temperatures and PO_4^{3-}-P at a significance level of 0.05 and 0.01, respectively. Whereas, in SRI, the pH, salinity, DO, NO_2^-+NO_3^--N, and $Si(OH)_4$-Si were found to significantly affect parameters with P values less than 0.05 and 0.01 (Table 2). Then, these influencing parameters were

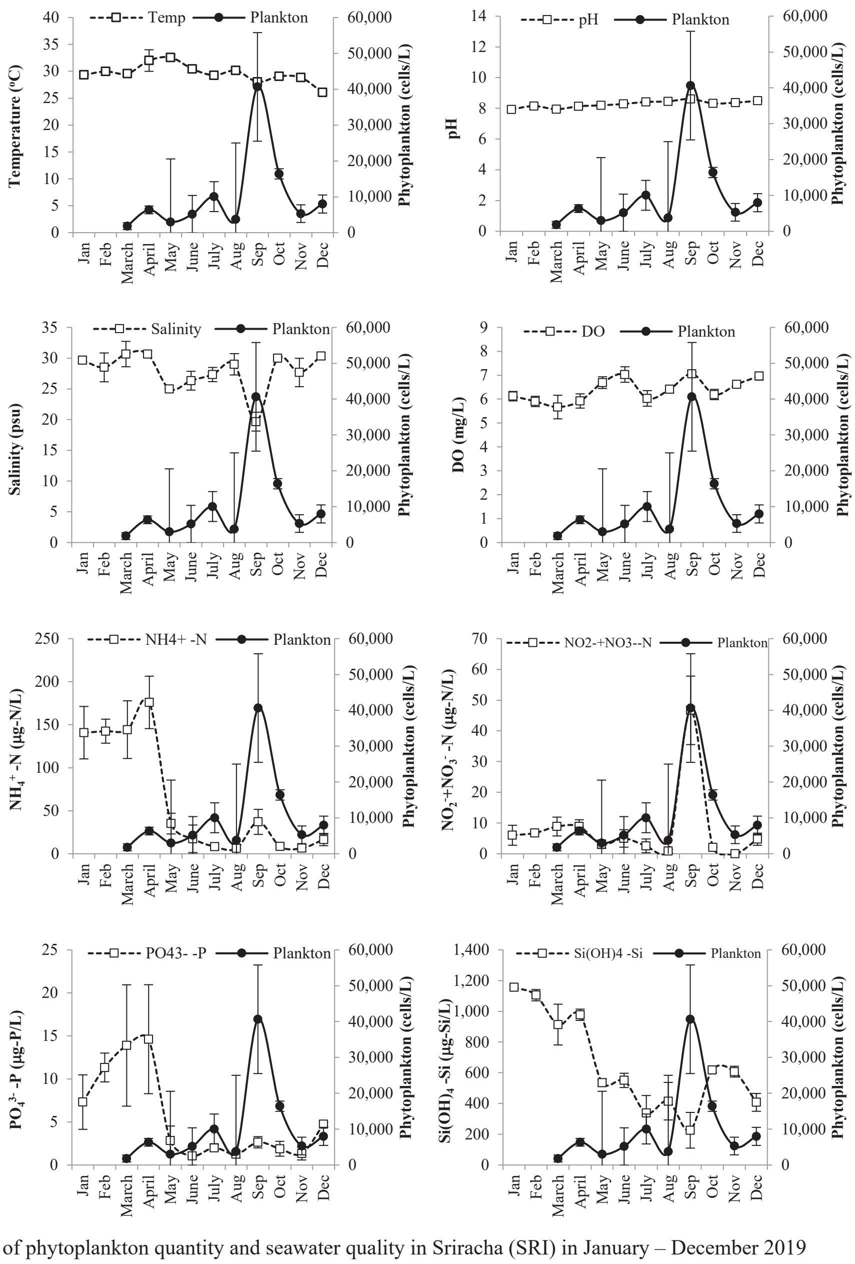

Fig. 3 Variation of phytoplankton quantity and seawater quality in Sriracha (SRI) in January – December 2019

employed to investigate the major limiting factor using a linear regression model. Results demonstrated that the concentration of PO_4^{3-}-P and NO_2^-+NO_3^--N effectively limit the phytoplankton abundance in MK and SRI, respectively, with high levels of the coefficient of determination (R^2) (Figure 4).

To simulate the variation of phytoplankton under climate change events, mathematical models were developed using the limiting factor equation identified in this study. The model simulation of seawater

Table 1 The Pearson correlations between phytoplankton quantity and seawater parameters in the Maeklong River mouth (MK)

	Pl	Temp	pH	Sal	DO	NH_4^+ -N	NO_2^-+NO_3^--N	PO_4^{3-} -P	$Si(OH)_4$-Si
Pl (cells/L)	1								
Temp (ºC)	0.399*	1							
pH	0.229	0.197	1						
Sal (psu)	-0.070	-0.561**	-0.143	1					
DO (mg/L)	-0.062	-0.174	0.380*	-0.206	1				
NH_4^+ -N (µg-N/L)	0.167	0.189	-0.268	0.023	-0.316	1			
NO_2^-+NO_3^--N (µg-N/L)	-0.196	0.128	-0.326	-0.284	-0.274	0.276	1		
PO_4^{3-} -P (µg-P/L)	0.531**	0.060	-0.131	-0.064	-0.253	0.578**	0.117	1	
$Si(OH)_4$-Si (µg-Si/L)	-0.047	0.129	-0.199	0.127	-0.335	0.276	0.011	0.255	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Table 2 The Pearson correlations between phytoplankton quantity and seawater parameters in Sriracha (SRI)

	Pl	Temp	pH	Sal	DO	NH_4^+ -N	NO_2^-+NO_3^--N	PO_4^{3-} -P	$Si(OH)_4$-Si
Pl (cells/L)	1								
Temp (ºC)	0.064	1							
pH	0.426*	-0.464**	1						
Sal (psu)	-0.515**	-0.011	-0.488**	1					
DO (mg/L)	0.371*	-0.320	0.593**	-0.555**	1				
NH_4^+ -N (µg-N/L)	-0.302	0.283	-0.736**	0.292	-0.576**	1			
NO_2^-+NO_3^--N (µg-N/L)	0.446*	-0.210	0.353*	-0.676**	0.302	0.099	1		
PO_4^{3-} -P (µg-P/L)	-0.269	0.282	-0.637**	0.262	-0.557**	0.853**	0.078	1	
$Si(OH)_4$-Si (µg-Si/L)	-0.468**	0.300	-0.879**	0.507**	-0.577**	0.814**	-0.290	0.659**	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

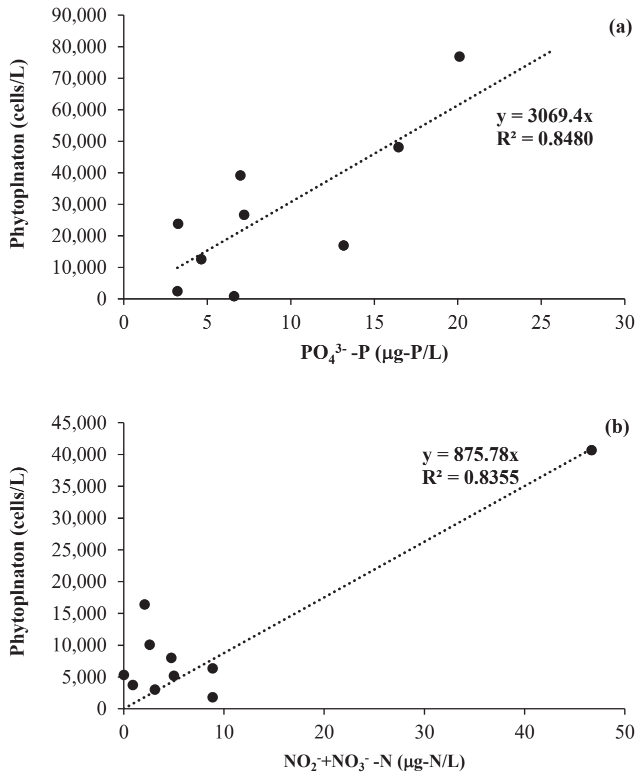

Fig. 4 The model fitness shows limiting factors affecting phytoplankton quantity in (a) the Maeklong River mouth (MK) and (b) Sriracha (SRI)

parameters described by Srisunont et al. (2022) was then input. The coefficient of determination (R^2) for each model simulation was calculated to assess the accuracy of the developed models. As shown in Figure 5, a high level of correlation ($R^2 > 0.7$) indicates that the models are sufficiently precise to simulate the phytoplankton abundance affected by the climate change crisis.

The model simulations revealed alteration patterns of phytoplankton caused by flood and drought disasters in the estuarine (MK) and coastal areas (SRI). As shown in Figure 6, the enrichment of phytoplankton is observed when rainfall amounts decrease in MK (during a drought condition) and significantly increase in SRI (following a flood disaster). According to the red tide monitoring report in Thailand, a phytoplankton cell density of over 50,000 cells/L is the tentative level for the occurrence of red tide and eutrophication (PCD and ARRI 2003). Results from the model simulation revealed that the phytoplankton density reaches the tentative level when rainfall is less than 5 mm and higher than 300 mm in MK and SRI, respectively. In addition, according to climate change scenarios from the IPCC AR5 (IPCC 2013), the model simulation indicates that there are risks of algae blooms (red tide and eutrophication) in all RCPs. As shown in Figure 7, the estuarine (MK) experiences annual blooms in February. This may be because there is rainfall of less than 5 mm/month, accompanied by high phosphate concentrations in seawater. While the coastal areas (SRI) experience algal blooms in September (Figure 7). This may be due to the favorable conditions for phytoplankton growth and proliferation during this period. There is intense rainfall, resulting in a high loading of nitrite-nitrate nitrogen through river runoff. To avoid loss of economic profit, these forecasts of an abundance of phytoplankton can be used to inform the selection of marine culture operations during climate change events.

Discussion

Seasonal variation and influencing factors for phytoplankton abundance

Figure 2 illustrates that the highest phytoplankton density in estuarine areas (MK) occurred in April, with an

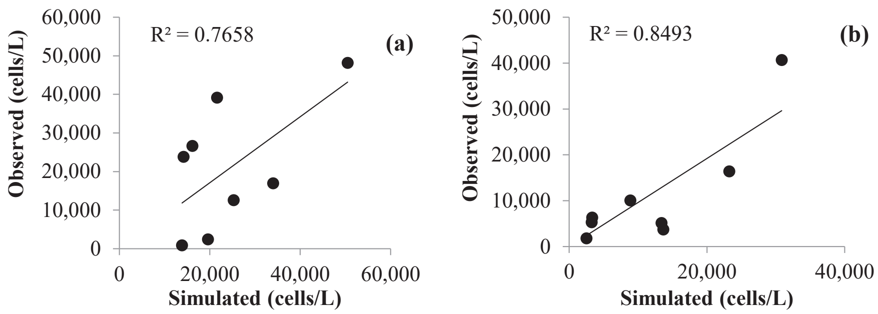

Fig. 5 The coefficient of determination (R^2) of model simulation in (a) the Maeklong River mouth (MK) and (b) Sriracha (SRI)

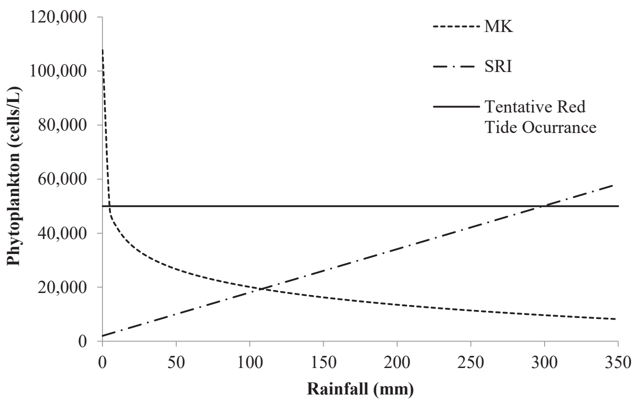

Fig. 6 Simulation of phytoplankton quantity under variation amount of rainfall in the Maeklong River mouth (MK) and Sriracha (SRI)

average of 76,870 cells/L. Then, the phytoplankton population dropped and rose again in July, September, and October, during the rainy season in Thailand. The dominant species were *Nitzschia* and *Chaetoceros,* which are tentative indicators of red tide occurrence (Chuenniyom et al. 2016; Somsap et al. 2015). Two influencing factors can explain this phenomenon. First, seawater temperatures have a significant impact on the growth of phytoplankton. Normally, phytoplankton can grow in seawater temperatures 15-32 ºC (Chen et al. 2023). Increasing temperature can induce phytoplankton growth by intensifying biological activities (Malaei Tavana et al. 2008; Thomas et al. 2012; Zhou et al. 2021). In this study, phytoplankton bloomed in April, during the summer season in Thailand, when the highest seawater temperature reached 32.13±1.27 °C. Our results are consistent with other studies (Gobler et al. 2017; Ho et al. 2019; Hutchins and Fu 2017; Huang et al. 2018; Yin 2003). Marine phytoplankton, particularly diatoms, tend to grow more vigorously in the summer. In addition, light penetration and intensity during this period are higher than in other seasons. This phenomenon can stimulate the growth of marine phytoplankton because light is essential for photosynthesis. Marine phytoplankton, especially diatoms, require at least 13-20 MJ/m²/day of sunlight (Sun 2004), with 9 hours of bright sunlight and low cloud cover (Huang et al. 2018). This period of sunny and warm days can effectively enhance algal blooms, and subsequently, red tides can be observed in estuarine areas (Malaei Tavana et al. 2008).

Second, nutrients, especially nitrogen and phosphorus, are influencing factors for phytoplankton growth. Phytoplankton requires the amount of nutrients as the ratio of C:N:P:Si equal to 106:16:1:1.3 by mole (Ho et al. 2003; Redfield et al. 1963). Results show that in the estuarine areas (MK), there was plenty of silicon for phytoplankton growth. The ratio of Si:P was in the range of 21.07-122.92. However, phosphorus was found to be in limited supply. During the study period, the N:P ratio was most often at a high value, indicating an abundance of nitrogen and a lack of phosphorus available in seawater. High concentrations of dissolved inorganic nitrogen, especially ammonia nitrogen, can inhibit phytoplankton growth (Chen et

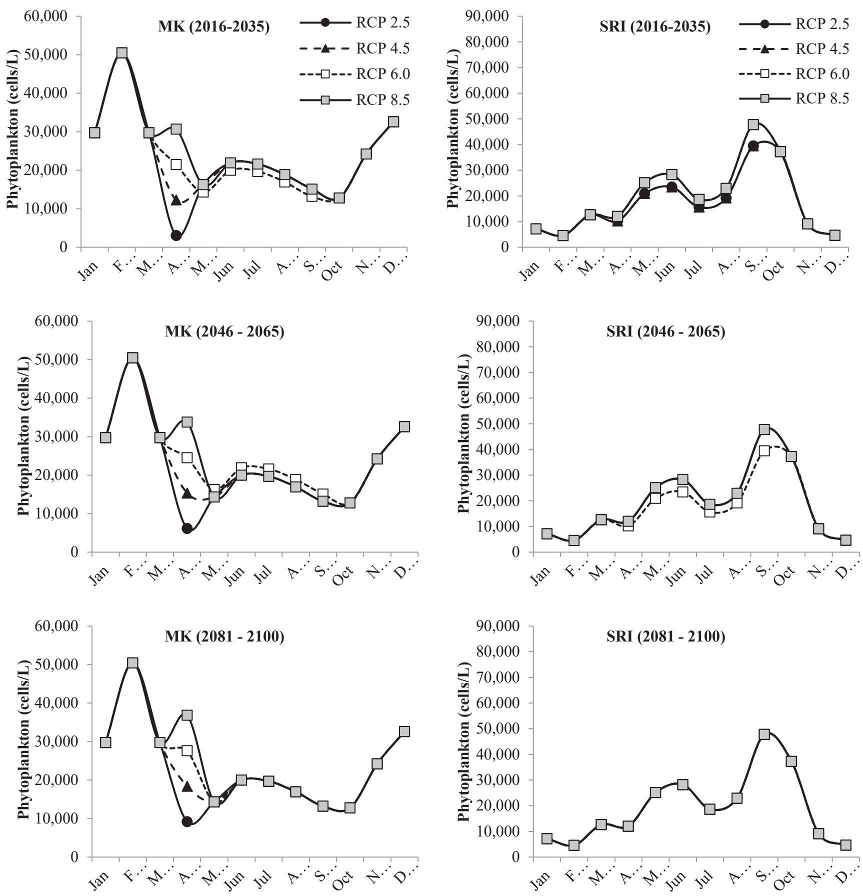

Fig. 7 The phytoplankton simulations in the Maeklong River mouth (MK) and Sriracha (SRI) according to IPCC AR5 change scenarios

al. 2023). Then, the algal bloom was found when the concentration of phosphate phosphorus increased and the N:P ratio was in the range of 8.37-17.08. In concordance with other research, the N:P ratio, which can promote phytoplankton growth, was 9-17 (Chen et al. 2023; Zohdi and Abbaspour 2019; Hao et al. 2011; Quigg et al. 2003). This demonstrates that phosphorus is a limiting factor in estuarine areas, affecting the frequency of red tides and eutrophication occurrences. In addition, results from our study show that the density of phytoplankton was high when the amount of rainfall increased to 85.4-186.2 mm/month in July, September, and October. This is because rainfall and river run-off can enhance phosphorus in seawater columns by the discharge of freshwater and domestic wastewater from land (Horner et al. 1997). Consequently, algal blooms can be observed in the rainy season.

In the coastal areas (SRI), the seasonal variation of phytoplankton differs from that in the estuarine areas (MK). As shown in Figure 3, high phytoplankton density was found only in September. This period coincided with the rainy season, characterized by the highest amount of rainfall (234.7 mm/month). The river discharge via Bang Pakong River conveyed freshwater and organic matter to the study areas. Consequently, the lowest salinity (19.67±1.53 psu) and the highest concentration of nitrite-nitrate nitrogen (46.67±11.14 µg-N/L) were observed. This demonstrates that, although the study area is located on the coast, far from riverine influence, intense precipitation can significantly alter seawater parameters through seawater circulation. In addition, our results reveal a linear correlation between the amount of phytoplankton and the amount of nitrite-nitrate nitrogen. High concentrations of nitrite and nitrate resulted in the enhancement of phytoplankton density (Figure 3 and 4). This finding aligns with other research, which has shown that nitrate is the primary controlling nutrient for algal blooms (Zohdi and Abbaspour 2019). It can be introduced into coastal areas through industrial and urban sewage discharge from land.

Furthermore, monsoons can influence the aggregation of phytoplankton, leading to the occurrence of red tides. During the northeast monsoon from November to April, the seawater circulation in the inner Gulf of Thailand developed a counterclockwise pattern (Buranapratheprat 2008). This results in seawater circulation moving from East to West. All of the organic matter and suspended particles in seawater were carried onto the west side through the water circulation. Consequently, nutrients and domestic wastewater discharge from the Tha Chin River mouth can disperse to the study area (MK) (Figure 1) and cause phytoplankton aggregation in April. Meanwhile, during the southwest monsoon from May to October the seawater circulation in the inner Gulf of Thailand moves from West to East in a clockwise pattern (Buranapratheprat 2008). The southwest wind field causes the intrusion of the main seawater current east of the sea boundary. This results in the dispersion of river run-off from Bang Pakong River to the study areas (SRI) (Figure 1). The quantity of seawater increases the nutrients available for phytoplankton growth. Consequently, the peak of the phytoplankton bloom in SRI was found in September. Our results agree with the research on the algal bloom phenomenon (Luang-on et al. 2022) that red tides and eutrophication usually occur in the inner Gulf of Thailand many times a year in different locations, including the Maeklong River and Sriracha. This demonstrates that the driving forces for algal bloom are not only changes in seawater parameters due to precipitation and river discharge, but also alterations in seawater circulation caused by wind patterns. The cooperation of these factors leads to favorable conditions for phytoplankton growth, which subsequently contributes to harmful algal blooms and eutrophication.

Risk of red tide and eutrophication during climate change

Global climate change alters rainfall patterns, resulting in more intense and frequent floods and drought disasters worldwide. Results from the model simulation reveal that during drought conditions, which are rainfall less than 5 mm/month, red tide and eutrophication are tentatively observed in estuarine areas (MK). As shown in Figure 6, heavy rainfall causes low phytoplankton density. This is because high precipitation may decrease seawater salinity and reduce the residence time of nutrients in the water, resulting in lower nutrient concentrations. Agreeing with other researchers (Chen et al. 2023; Huang et al. 2018; Lee and Qu 2004; Yin 2003; Zhou et al 2021), precipitation can inhibit the formation of red tides and eutrophication in estuarine areas. Tremendous freshwater loading through intense rainfall can reduce the salinity of surface seawater and dilute nutrient concentration (Valiela et al 2012). The freshwater runoff causes strengthened water column stratification. Estuarine circulation: surface water flows outward, and the bottom layer flows inwards, creating a dilution effect (Huang et al. 2018). Moreover, the nutrients brought by surface runoff may not be sufficient to alter the nutrient ratio to the level that can effectively enhance phytoplankton growth (Lee and Qu 2004; Yin 2003). The high volume of freshwater from river runoff during intense rainfall also causes turbidity, which does not favor the growth of marine phytoplankton due to lowered light penetration (Phlips et al. 2020). In contrast, the model simulation from this study demonstrates that the quantity of phytoplankton tends to increase with less rainfall (Figure 6). This is because, during drought conditions, diminished rainfall and high air temperatures lead to an increase in seawater temperature (McCombie 1959). High seawater temperature promotes phytoplankton growth (Chen et al. 2023), leading to algal blooms and the possibility of red tide occurrence. Therefore, our simulations suggest that red tides and eutrophication in estuarine areas can be observed more frequently in warm and drought-affected areas. Meanwhile, intense rainfall limits their occurrences.

In contrast, the model simulations showed that the phytoplankton density in coastal areas (SRI) tends to increase with high rainfall (Figure 6). The phytoplankton density reaches the tentative level of red tide and eutrophication occurrence when rainfall is higher than 300 mm, representing a flood disaster (Pratiwi et al. 2020). In concordance with research by Hao et al. (2011), the algal bloom was observed when rainfall exceeded 200 mm. This is because heavy precipitation brings surface runoff containing nutrients into seawater, leading to favorable conditions for phytoplankton growth. In the coastal areas, the increased rainfall intensity during the rainy season increases stream erosion, uproots stream-edge terrestrial, and damps upwelling of denser nutrient-enrich water (Valiela et al. 2012). Moreover, rain runoff also results in short-term pollution loading from industrial and domestic wastewater into the receiving seawater body, thereby transferring nutrients into the seawater (Meng et al. 2017; Xu et al. 2019). Consequently, nutrient concentration, especially nitrite, nitrate, and phosphate, increased sharply after prolonged rainfall or storm events (Balls et al. 1997). This condition drove the development of algal blooms (Lee 2006; Weise et al. 2002; Yoon and Kim 2003). Consequently, red tides and eutrophication are widespread.

Climate change adaptation under extreme weather events

Results from the model simulation demonstrated that under climate change scenarios (IPCC 2013), by the end of this century (year 2100), red tide and eutrophication can be observed annually in February (MK) and September (SRI) (Figure 7). This forecast can be important information to minimize economic loss by implementing policies for climate change adaptation. According to our results, during drought conditions or the dry season (November to April), red tide and eutrophication were tentatively observed in estuarine areas (MK). Therefore, marine cultures such as green mussel farms, cockle cultivation, shrimp farms, and marine fish farming should avoid cultivation during this period and resume operations in the wet season. Moreover, to reduce production loss, cultivation should be located far from the river mouth. In the riverine influence, freshwater runoff can alter seawater parameters, particularly salinity, turbidity, suspended solids, and nutrients. This fluctuation affects marine organisms, leading to significant mortality. Meanwhile, during flood disasters or the wet season (May to October), red tides and eutrophication tentatively occurred in coastal areas (SRI). Although the coastal areas are far from the river mouth and have less riverine influence, intense rainfall causes red tide occurrence (Figure 6). An increase in frequent storms may worsen coastal water quality. Hence, the marine culture in coastal areas should not operate during the rainy season. The cultivation should start in November and harvest in August, before the tentative red tide occurrence in September (Figure 7). Furthermore, the model simulation indicates that when rainfall is less than 5 mm/month or larger than 300 mm/month, the phytoplankton density will reach the tentative level for red tide and eutrophication. This rainfall level can be used as an indicator to warn fishermen, especially those in aquaculture, in estuarine and coastal areas, to move or harvest marine organisms before the loss of all production. Ultimately, a climate change adaptation policy for marine culture can be developed based on our findings.

Model limitation

The model developed in this study successfully forecasted the possibility of red tides and eutrophication under climate change events and demonstrated the limiting factor for phytoplankton growth in estuarine and coastal areas. However, the model simulations have some limitations. First, the model parameters in this study do not include seawater circulation and light penetration. The relationship between the phytoplankton density and seawater characteristics is complex. Environmental factors, such as weather and hydraulic conditions, may significantly impact seawater quality. In the study areas, seawater circulation is controlled by the monsoon. Wind patterns significantly affect seawater circulation, which causes aggregation of phytoplankton cells, and then the red tide phenomenon can be observed. Light penetration affects the abundance of phytoplankton by influencing the photosynthesis process. Areas with high light penetration exhibit clear seawater, low suspended solids, reduced turbidity, and high transparency. This condition is favorable for the growth of phytoplankton. However, there might not be enough for algal enhancement. Phytoplankton require not only light but also nutrients and vitamins. These elements can be added to seawater through river runoff, beach erosion, upwelling, and domestic discharge, which causes turbidity and reduces light penetration. This indicates that light penetration can suggest a tentative environmental condition for algal blooms, but it may not be a suitable choice for simulating red tides. Although these parameters are not included in the model, the simulation results successfully demonstrate the occurrence of red tide and eutrophication in the inner Gulf of Thailand. Another limitation is site-specific. This research was conducted in Maeklong River Mouth (MK) and Sriracha (SRI), representing estuarine and coastal areas in Thailand. Other places may have different seawater characteristics. The limiting factors for phytoplankton growth differ based on environmental conditions. Consequently, the occurrence of red tides and eutrophication can be altered. Further studies should be conducted in each location to refine the model and enhance its accuracy and reliability. Although each place has specific characteristics, the results from the model simulation developed in this study can be applied to the Indo-Pacific region, where seawater quality and environmental conditions are similar.

Conclusions

The occurrence of red tides and eutrophication during the climate change crisis differs between estuarine and coastal areas. In estuarine areas, the limiting factors affecting algal blooms are seawater temperatures and phosphate phosphorus. High seawater temperatures combined with low rainfall (less than 5 mm/month) lead to a higher frequency of red tides and eutrophication. Meanwhile, in coastal areas, the abundance of phytoplankton is effectively limited by nitrite-nitrate nitrogen. Flooding conditions or intense rainfall (over 300 mm/month) lead to severe red tides and eutrophication. Based on climate change scenarios from the IPCC AR5, red tides and eutrophication are expected to occur in February during drought disasters in estuarine areas and in September during flooding conditions in coastal areas. Therefore, marine cultivation should avoid these periods to minimize the tremendous loss caused by the red tide. Although our study was conducted in Thailand, the results can be applied to the estuarine and coastal areas in the Indo-Pacific region. To implement more reliable simulations of red tide and eutrophication occurrence worldwide, further studies should be conducted in other regions with different seawater characteristics and environmental conditions.

Competing interests There is no competing interest.

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