Spatiotemporal Distribution and Occurrence of Surface Phytoplankton Blooms Using Spectral Indices Derived from Sentinel-2 Imagery in the Upper Gulf of Thailand

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Abstract: *Phytoplankton blooms are natural phenomena in marine waters, resulting from the rapid growth of phytoplankton. These blooms significantly impact aquatic organisms and their habitats, particularly by reducing the oxygen levels in surrounding waters, which can potentially damage natural aquatic ecosystems and coastal aquaculture zones. Among the various methods used to detect phytoplankton blooms, satellite remote sensing is especially valuable for timely monitoring and large-scale coverage. This approach is particularly important for regions where blooms regularly occur. The Upper Gulf of Thailand is of considerable importance, as it is drained by the tributaries of major rivers. Unfortunately, this region has experienced numerous phytoplankton blooms, which have impacted aquaculture and tourism in the coastal zone. Given these circumstances, our study aimed to utilise spectral indices, including the Maximum Chlorophyll Index (MCI) and the Normalised Difference Chlorophyll Index (NDCI), to detect surface phytoplankton blooms. We derived these indices from Sentinel-2 MSI imagery via Google Earth Engine and analysed the spatiotemporal distribution and occurrence of surface phytoplankton blooms in the Upper Gulf of Thailand. Our findings revealed that areas with intense surface phytoplankton blooms showed high MCI and NDCI values. Analysing the relative frequency of bloom occurrence in each month of 2023 indicated that near-estuarine and coastal areas experienced more frequent bloom occurrences than offshore areas. Overall, the average annual relative frequency of bloom occurrences within a 5 km radius in the estuary where the Tha Chin River was highest at 28.59%, followed by the Bang Pakong River at 16.27%, the Chao Phraya River at 11.30%, and the Mae Klong River at 7.95%. The results indicate that the spectral indices, including the MCI and NDCI, are reliable methods for detecting and monitoring surface phytoplankton blooms. Additionally, understanding the spatiotemporal distribution and occurrence of these blooms is useful for comprehending the phenomenon in the marine environment.*

Keywords: Phytoplankton Blooms, Spectral Indices, Sentinel-2, Google Earth Engine, Gulf of Thailand

1. Introduction

Phytoplankton blooms are natural phenomena in estuarine and coastal ecosystems (Carstensen et al., 2015). These blooms result from the rapid growth of phytoplankton biomass (Cloern, 1996). They significantly impact aquatic organisms and their habitats by reducing oxygen levels in the surrounding waters, limiting the availability of light and nutrients to aquatic plants, and causing hypoxia (Mishra et al., 2022). This can potentially damage natural aquatic ecosystems and coastal aquaculture zones (Department of Marine and Coastal Resources, 2015).

The Upper Gulf of Thailand is of considerable importance, as it is drained by the tributaries of four major rivers: the Bang Pakong, Chao Phraya, Tha Chin, and Mae Klong. Unfortunately, this region has experienced numerous phytoplankton blooms, which have impacted aquaculture and tourism in the coastal zone. Field observations by researchers have documented the phenomenon of phytoplankton blooms throughout the year at the mouths of these rivers and in coastal areas (Chumnantana, 2006; Chuenniyom et al., 2016). Additionally, studies using satellite imagery have also detected phytoplankton blooms in these regions (Suwanlertcharoen and Prukpitikul, 2018; Luang-on et al., 2023).

Among the various methods used to detect phytoplankton blooms, satellite remote sensing is especially valuable for timely monitoring and large-scale coverage. There are several algorithms from satellite remote sensing imagery for detecting phytoplankton blooms, including surface-floating algae blooms. These methods encompass the maximum chlorophyll index (MCI) (Gower et al., 2005; Gower et al., 2008), the floating algae index (FAI) (Hu, 2009), the normalised difference chlorophyll index (NDCI) (Mishra and Mishra, 2012), and the use of routine global false color imagery (Qi et al., 2020). Additionally, the chlorophyll-a (Chl-a) anomaly product is a reliable tool for detecting and monitoring abnormal Chl-a occurrences associated with high algae biomass events across global oceans, coastal regions, and inland waters (Wang, 2021). These techniques are useful for establishing a system for routine production, facilitating the easy evaluation and monitoring of surface phytoplankton blooms in their spatiotemporal distribution across the ocean, coastal, and inland waters.

The red-edge band is essential as phytoplankton exhibit a peak in spectral reflectance near 700 nm, attributed to the minimal combined absorption by both water and phytoplankton (Gurlin et al., 2011). This red-edge band centered around the 705 nm wavelength indicates that the Sentinel-2 MSI could be applicable to a broader spectrum of chlorophyll-a (chl-a) retrieval algorithms than the Landsat 8 OLI (Beck et al., 2016). Both the MCI and the NDCI utilise the 705 nm wavelength spectral band in their algorithms, making them suitable for use with Sentinel-2 MSI imagery. The NDCI uses the red-edge wavelength, which was originally applied in marine and coastal environments (Caballero et al., 2020; Mishra and Mishra, 2012) and also applied in freshwater environments for mapping algal blooms dynamics (Kislik et al., 2022). Additionally, the MCI is an analytical method that utilises spectral band difference algorithms to exploit spectral regions exhibiting significant changes in the reflectance spectrum due to the presence of algal blooms, compared to adjacent bloom-free waters (Blondeau-Patissier et al., 2014a). The index is notably high under 'red tide' conditions, characterized by intense, visible surface plankton blooms (Gower and King, 2011). Elevated MCI values are correlated with high chlorophyll-a levels in oceanic, coastal, and lacustrine waters (Gower et al., 2005; Blondeau-Patissier et al., 2014b). Researchers have applied the MCI in various studies; for instance, Ryan et al. (2008) used MCI images to illustrate synoptic bloom patterns and compute long-term statistics, while Suwanlertcharoen and Prukpitikul (2018) employed the MCI to detect phytoplankton blooms in the Upper Gulf of Thailand. Furthermore, the study by Salls et al. (2024) employed the MCI and the NDCI to estimate chlorophyll-a concentrations under diverse conditions, serving as a monitoring tool for inland lakes over extensive spatial scales.

Google Earth Engine (GEE) is a cloud-based geospatial analysis platform (Gorelick et al., 2017). GEE's cloud computing capabilities facilitate the analysis of large datasets and time series, enhancing the ability to examine the spatial and temporal variability of surface phytoplankton blooms. Recent studies have demonstrated the effectiveness of GEE in monitoring water quality, particularly for detecting phytoplankton blooms (Lobo et al., 2021; Kislik et al., 2022).

Therefore, this study aims to utilise spectral indices, including the MCI and the NDCI, to detect surface phytoplankton blooms. We derive these indices from Sentinel-2 MSI imagery via GEE and analyse the spatiotemporal distribution and occurrence of surface phytoplankton blooms in the Upper Gulf of Thailand.

2. Materials and Methods

2.1 Study Area

The study area is located in the Upper Gulf of Thailand (Figure 1) and is delineated by geographic coordinates from longitude 100° 00' to 101° 00' E and latitude 12° 30' to 13° 30' N. Encompassing an area of 10,000 km², it is bordered by land to the north, east, and west, while opening to the South China Sea to the south and southeast. The Upper Gulf of Thailand is drained by the tributaries of four major rivers: the Bang Pakong, Chao Phraya, Tha Chin, and Mae Klong. The Gulf is shallow, with an average depth of approximately 20 meters and tidal heights ranging from 1 to 3 meters (Buranapratheprat, 2013). Additionally, the Gulf of Thailand is particularly vulnerable to hypertrophic and eutrophic conditions due to significant river discharges along its northern coastline and water circulation patterns affected by northeast and southwest monsoons (Buranapratheprat et al., 2021). During the southwest monsoon, winds from the Indian Ocean generate a clockwise wind-driven current in the upper Gulf. Inside the Gulf, these winds shift to the northeast, causing the wind-driven circulation in the upper Gulf to flow counterclockwise (Chaiongkarn and Sojisuporn, 2013).

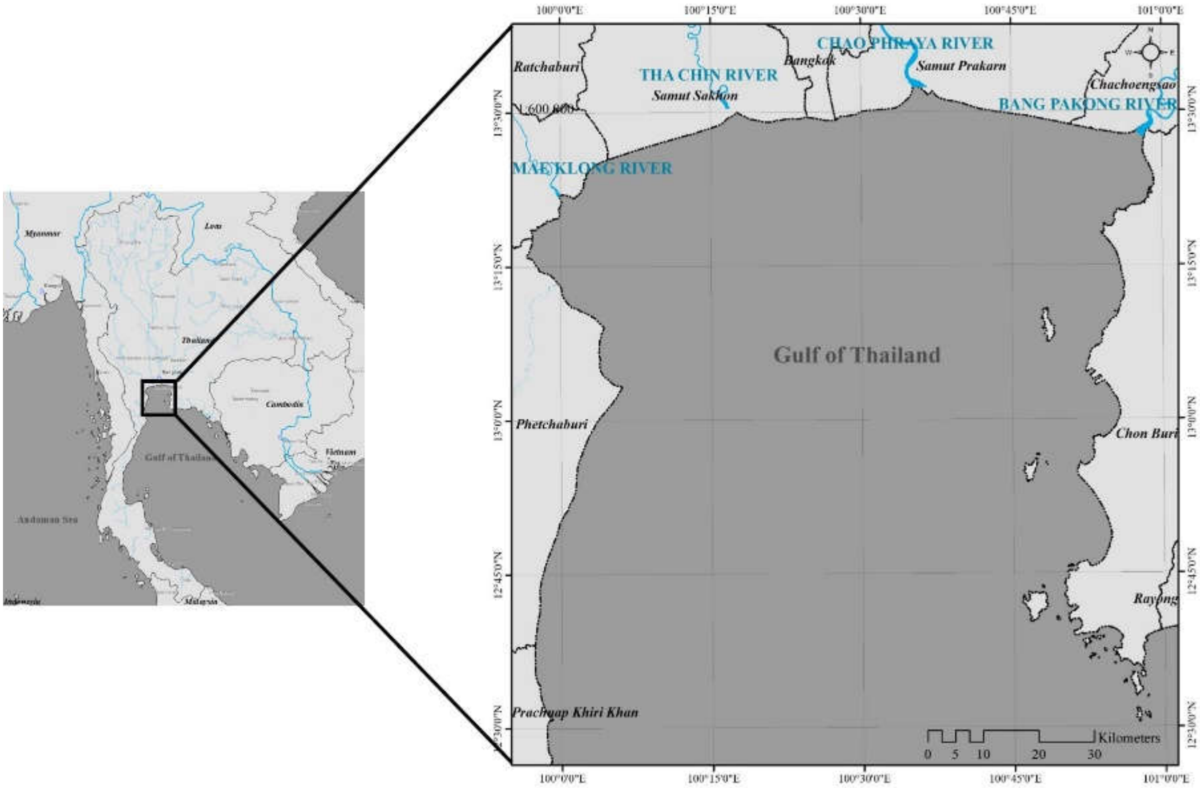


Figure 1: Study area located in the Upper Gulf of Thailand.

2.2 Data Used

2.2.1 Satellite Imagery

This study utilised optical remote sensing data derived from Sentinel-2 MSI for the year 2023. Harmonised Sentinel-2 MSI (MultiSpectral Instrument, Level-2A) data were obtained from GEE, a cloud-based geospatial analysis platform that enables users to visualise and analyse satellite images. Level-2A data were computed by running Sen2Cor, which involves Scene Classification and Atmospheric Correction applied to Top-Of-Atmosphere (TOA) Level-1C orthoimage products. The primary output of Level-2A is an orthoimage with Bottom-Of-Atmosphere (BOA) corrected reflectance. Sentinel-2 MSI has 13 bands with a spatial resolution of 10–60 meters, a wide swath width, and a high revisit time of 5 days with 2 satellites under cloud-free conditions (European Space Agency, 2015). Sentinel-2 MSI imagery was used in the study to detect surface phytoplankton blooms and analyse their spatial distribution and occurrence.

2.2.2 Ancillary Data

In this study, ancillary data included news and situation reports, and ocean condition data, all of which were collected to evaluate surface phytoplankton blooms. Ocean condition data from the time of the incident, including surface currents, were used to analyse the movement and natural phenomena of surface phytoplankton over time. The surface ocean currents were derived from the Global HYbrid Coordinate Ocean Model (HYCOM) data, obtained from the NetCDF Subset Service (NCSS). These currents were used to compute the average velocity and direction of surface current circulation for the monthly spatial distribution in 2023.

2.3 Methods

The processing steps utilised in this study are illustrated in Figure 2. Satellite image pre-processing and image processing for detecting and extracting areas of surface phytoplankton blooms were conducted using GEE. Additionally, the spatiotemporal distribution and occurrence of surface phytoplankton blooms were analysed using Geographic Information System (GIS) software.

2.3.1 Satellite Image Pre-Processing and Image Processing

1) Image Pre-processing

Harmonised Sentinel-2 MSI Level-2A data were processed in GEE, is cloud and land masking process using scene classification (SCL), where the SCL Class Table was selected for cloud and land to remove thick and cirrus clouds and also land area, ensuring that only the water area remained for analysis.

2) Image Processing

The detection of surface phytoplankton blooms was performed using the following steps: (1) Spectral indices calculation, where MCI and NDCI were computed to characterize the reflected light from intense surface phytoplankton blooms; (2) Water turbidity retrieval, where water turbidity was calculated using an algorithm derived from the study by Suwanlertcharoen et al. (2020); and (3) Masking of MCI and NDCI in turbid water, particularly in estuaries, using a criterion of water turbidity greater than 15 nephelometric turbidity units (NTU).

2.3.2 Surface Phytoplankton Blooms Detection and Extraction

Surface phytoplankton blooms detection, where feature extraction of phytoplankton bloom areas was analysed using MCI and NDCI threshold values, with criteria for extracting surface phytoplankton bloom areas involving positive MCI (MCI > 0.01) and NDCI (NDCI > 0.1) values.

2.3.2.1 Maximum Chlorophyll Index (MCI)

The MCI was initially developed by Gower et al. (2005) for the MERIS sensor on the Envisat satellite and has since been adapted for use with the Sentinel-3 OLCI, ensuring continuity in the necessary spectral bands. Originally, the MCI was calculated using water-leaving radiance, but it can also be applied to reflectance (Salls et al., 2024). The MCI algorithm measures the height of a spectral band above a baseline that passes through two other spectral bands. For Sentinel-2 MSI, the optimal band combination for calculating the MCI includes Band 4 (665 nm), Band 5 (705 nm), and Band 6 (740 nm). The MCI is useful for detecting phytoplankton blooms and other types of aquatic vegetation. In this study, we applied the MCI algorithm to Sentinel-2 MSI data as follows:

$$MCI = R_{rs(705)} \quad k \quad \left(R_{rs(665)} + \left(R_{rs(740)} \quad R_{rs(665)} \right) \frac{\lambda_{(705)} \quad \lambda_{(665)}}{\lambda_{(740)} \quad \lambda_{(665)}} \right)$$

where $R_{rs(665)}$, $R_{rs(705)}$ and $R_{rs(740)}$ refer to the surface reflectance values in Band 4 (665 nm), Band 5 (705 nm), and Band 6 (740 nm) of Sentinel-2 imagery, respectively. λ_{665}, λ_{705} and λ_{740} refer to the band wavelength of 665, 705 and 740, respectively. k is cloud correction factor for reducing the effect of thin cloud (this study using k=1.005)

2.3.2.2 Normalised Difference Chlorophyll Index (NDCI)

The NDCI was originally developed to estimate chlorophyll-a concentrations using satellite remote sensing imagery in estuarine and coastal turbid productive waters (Mishra and Mishra, 2012). The NDCI, designed to predict chlorophyll content in these waters, is calculated using the red and red edge spectral bands, focusing on the absorption peak at 665-675 nm and the reflectance peak at approximately 700 nm. It can also be used for detecting phytoplankton blooms (Caballero et al., 2020). The NDCI for Sentinel-2 MSI was calculated as follows ((Mishra and Mishra, 2012); Lobo et al., 2021);

$$NDCI = \frac{[R_{rs(705)} \quad R_{rs(665)}]}{[R_{rs(705)} + R_{rs(665)}]}$$

where $R_{rs(705)}$ and $R_{rs(665)}$ refer to the surface reflectance values in the red edge 1 (Band 5) and red (Band 4) bands of Sentinel-2 imagery, respectively.

2.3.3 Relative Frequency of Bloom Occurrences Analysis

An analysis of the spatiotemporal distribution and occurrence of surface phytoplankton blooms in the study area for 2023, using Sentinel-2 MSI data, was conducted through a relative frequency of bloom occurrences analysis, expressed as a percentage. The bloom frequency for each pixel is defined by Equation 2 (Zhang et al., 2015).

$$F_{i,j} = \frac{C_{i,j}}{TC_j} \times 100 \qquad (2)$$

where $F_{i,j}$ is the relative frequency of bloom occurrence in the i^{th} pixel during time j expressed as a percentage; $C_{i,j}$ is the count of bloom occurrence in same pixel; and TC_j is the total count of MSI images.

2.3.4 Evaluation of Surface Phytoplankton Blooms Detection

The detected areas of phytoplankton blooms were evaluated by comparing their visible appearance with the mapped locations and extents. The incidents of phytoplankton blooms were corroborated using RGB False Color Composite imagery and other relevant data, including news and situation reports.

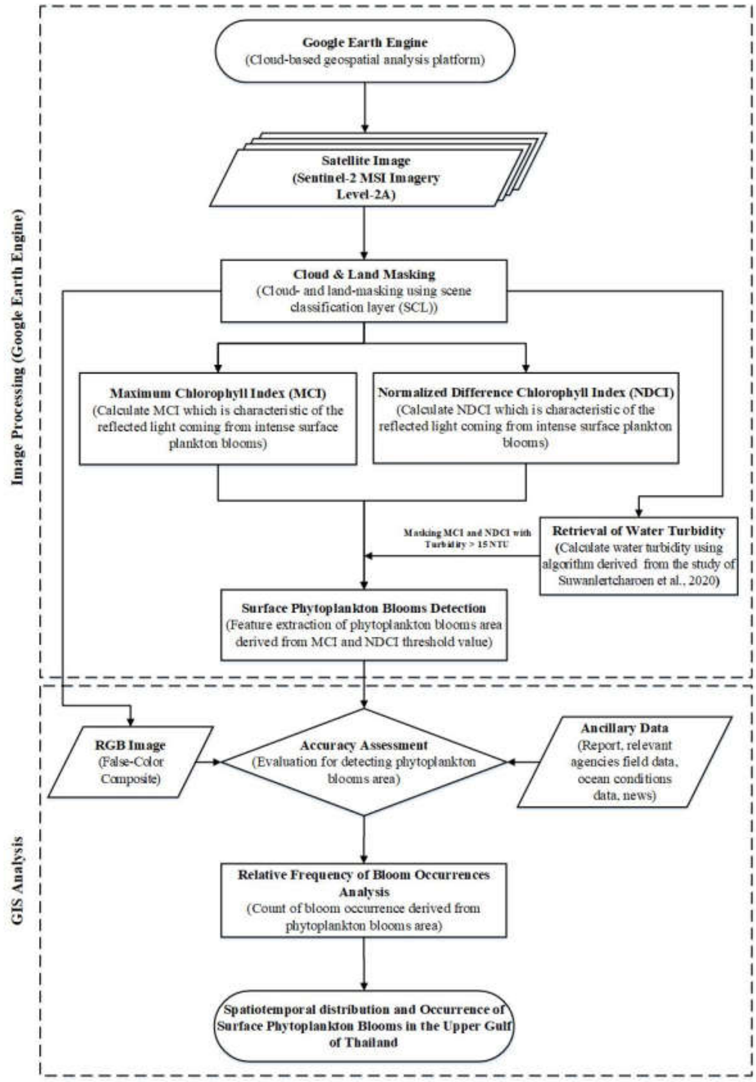


Figure 2: Flowchart of the process in this study.

3. Results and Discussion

3.1 Results

3.1.1 Surface Currents Variations

The characteristics of the average velocity and direction of the surface current circulation in 2023, computed from the HYCOM data in the Upper Gulf of Thailand, the average current velocity ranges between 0.016 and 0.080 m/s. During the northeast monsoon season (November - February), the current pattern flows counter-clockwise to the southwest, with November 2023 having the highest current velocity of about 0.080 m/s. During the first transition monsoon (March - April), the circulation pattern is clockwise to the northeast, but the current velocities are not very high, with March 2023 having the lowest current velocity of about 0.016 m/s. During the southwest monsoon (May - September), the circulation pattern is clockwise, flowing to the east and southeast. During the second transition monsoon (October), the current direction begins to change counter-clockwise to the south, as shown in Figure 3 and Figure 4.

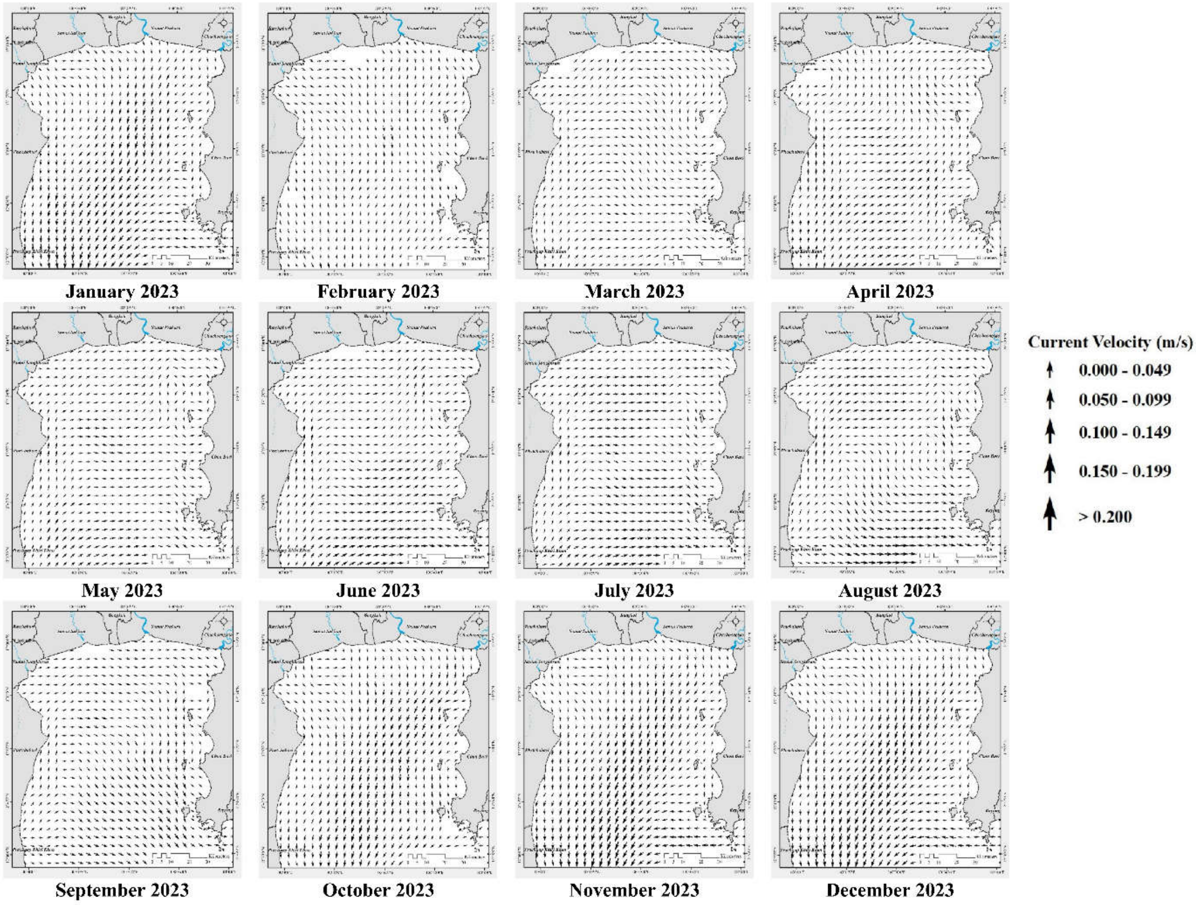


Figure 3: The monthly spatial distribution of residual surface currents from the HYCOM data in the Upper Gulf of Thailand for 2023.

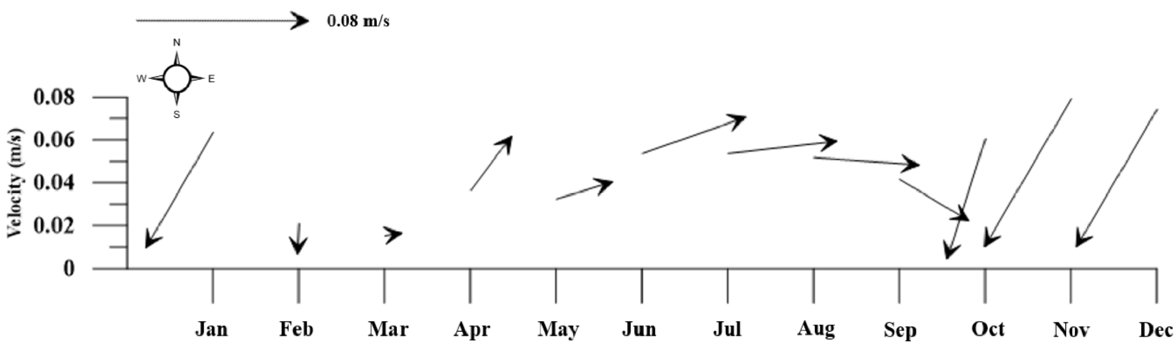
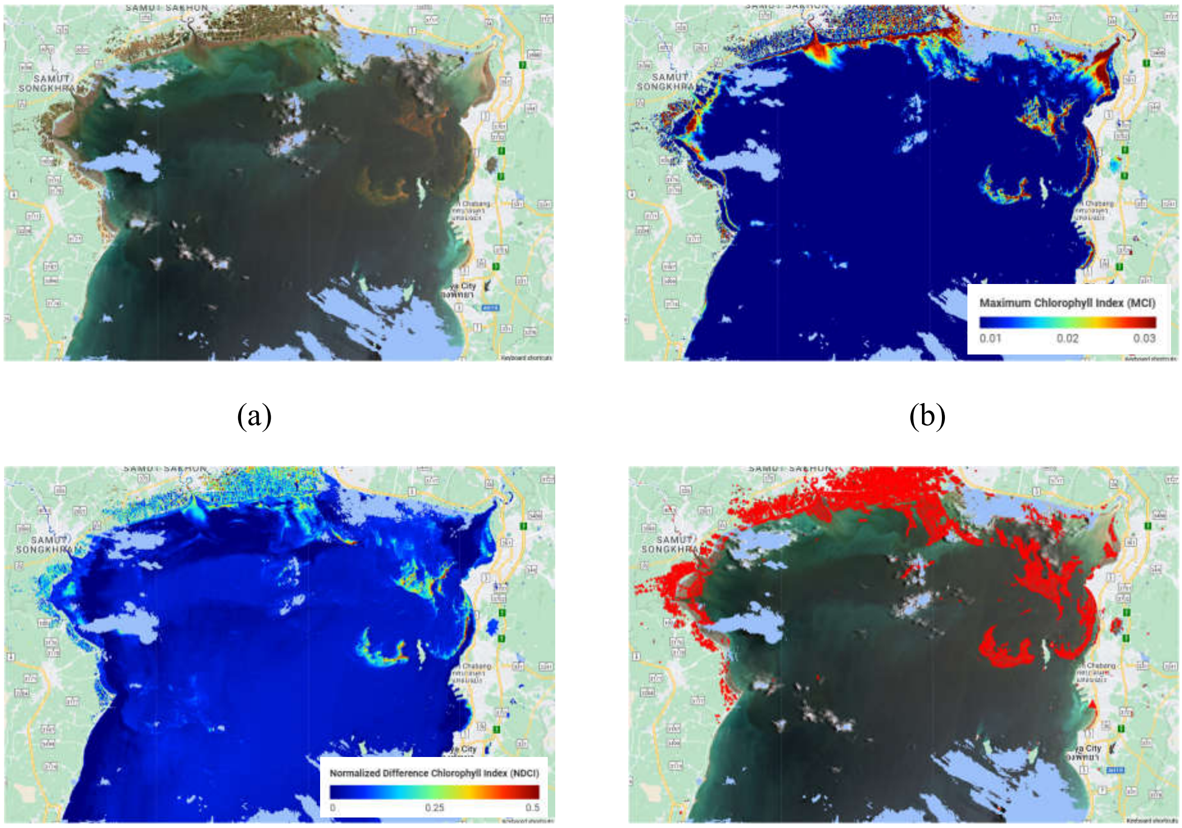


Figure 4: The monthly average current velocity and direction from the HYCOM data in the Upper Gulf of Thailand for 2023.

3.1.2 Surface Phytoplankton Blooms Detection and Extraction

Phytoplankton bloom detection using MCI and NDCI from Sentinel-2 MSI was analysed. The analysis showed that in areas of intense surface activity, phytoplankton blooms exhibited high MCI and NDCI values. The criteria for extracting surface phytoplankton bloom areas in this study involved using positive MCI (MCI > 0.01) and NDCI (NDCI > 0.1) values. An example case of surface phytoplankton bloom detection is illustrated by comparing Sentinel-2 MSI RGB False Color Composite images, spectral indices (MCI and NDCI), and the extraction of surface phytoplankton bloom areas. This example shows a surface phytoplankton bloom on 14 August 2023, comparing (a) Sentinel-2 MSI RGB False Color Composite images in band 5 (705 nm), band 3 (560 nm), and band 2 (490 nm), (b) MCI, (c) NDCI, and (d) the extraction of surface phytoplankton bloom areas, as shown in Figure 5.



(a) (b)

(c) (d)

Figure 5: Comparison of Sentinel-2 MSI showing a surface phytoplankton bloom on 14 August 2023 between (a) Sentinel-2 MSI RGB False Color Composite images in band 5 (705 nm), band 3 (560 nm), and band 2 (490 nm), (b) MCI, (c) NDCI, and (d) the extraction of surface phytoplankton bloom areas (red color).

3.1.3 Spatial Distribution and Occurrence of Surface Phytoplankton Blooms

The spatial distribution and occurrence of phytoplankton blooms in 2023 were analysed using time-series satellite images from the Sentinel-2 MSI. This analysis involved counting the occurrences of blooms and the total number of MSI images to determine the relative frequency of bloom occurrences. Figure 6 shows the monthly count of bloom occurrences in the upper Gulf of Thailand for 2023. Additionally, phytoplankton blooms occur within a radius of 10 km from the estuaries of the Bang Pakong, Chao Phraya, Tha Chin, and Mae Klong rivers, encompassing the entire study area, as shown in Figure 7. It was found that near-estuarine and coastal areas experienced more frequent bloom occurrences than offshore areas. Based on the monthly spatial distribution, it was observed that there was a gradual increase from August to November, followed by a gradual decrease in December.

The annual relative frequency of bloom occurrences in the Upper Gulf of Thailand in 2023 is shown in Figure 8. Figures 8 indicate that the relative frequency of bloom occurrences near estuarine and coastal areas is higher than in other regions, particularly in the Tha Chin estuary. Based on the relative frequency of bloom occurrences within a 5 km radius of the Bang Pakong, Chao Phraya, Tha Chin, and Mae Klong estuaries, it was found that all four river estuaries were affected by phytoplankton blooms in almost every month of 2023. Overall, the average annual frequency of blooms in the four main river estuaries was 18.62%. The Tha Chin estuary had the highest average annual frequency at 28.59%, followed by the Bang Pakong River at 16.27%, the Chao Phraya River at 11.30%, and the Mae Klong River at 7.95 %. Also, the average annual frequency of blooms within a 10 km radius of the four main river estuaries was 13.29%. The Tha Chin estuary had the highest average annual frequency at 15.49%, followed by the Bang Pakong River at 12.97%, the Chao Phraya River at 12.19%, and the Mae Klong River at 10.05%. These blooms have significantly impacted aquaculture and tourism in the coastal zone, especially along the Chonburi coast, which is renowned for its popular tourist beaches.

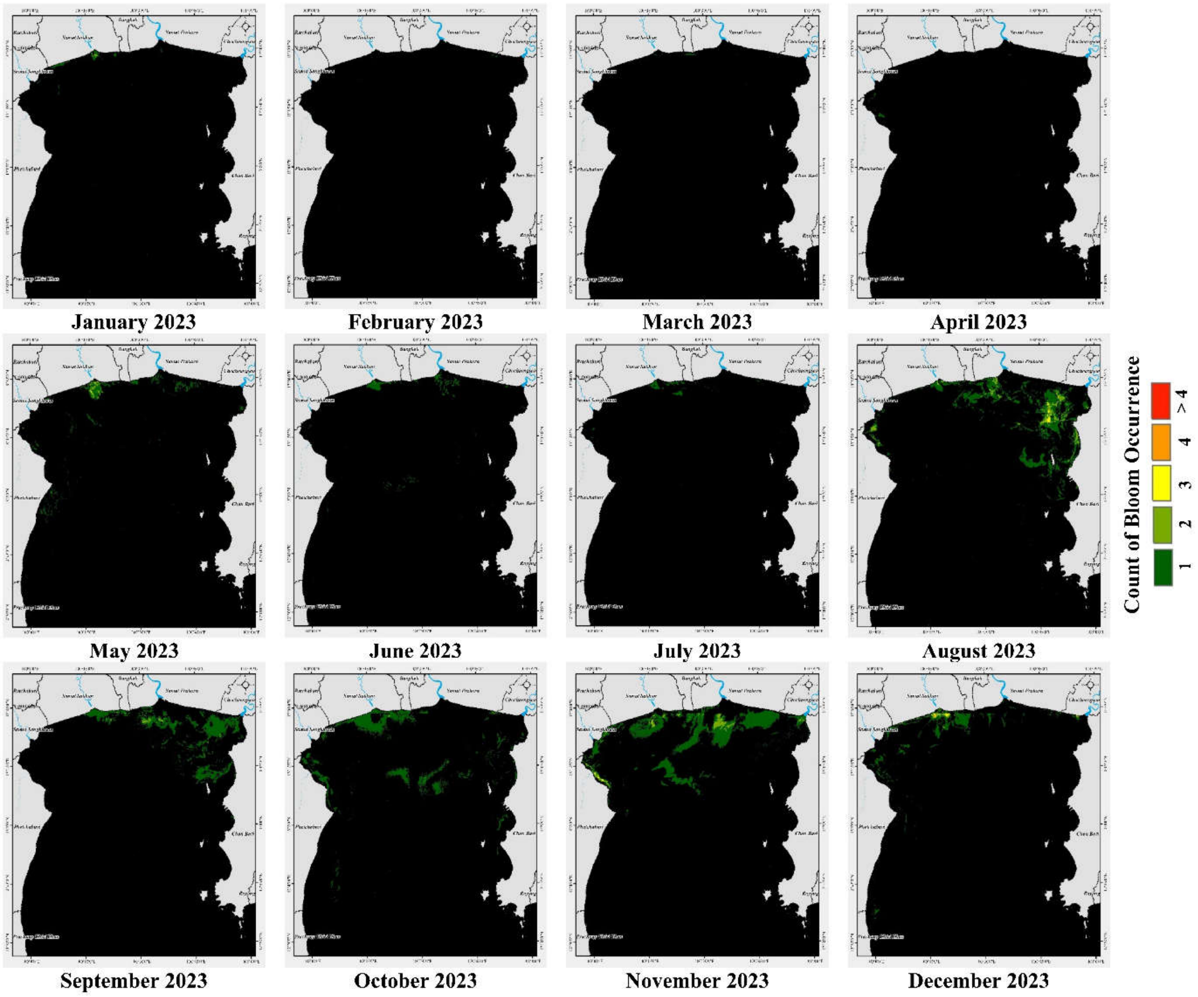
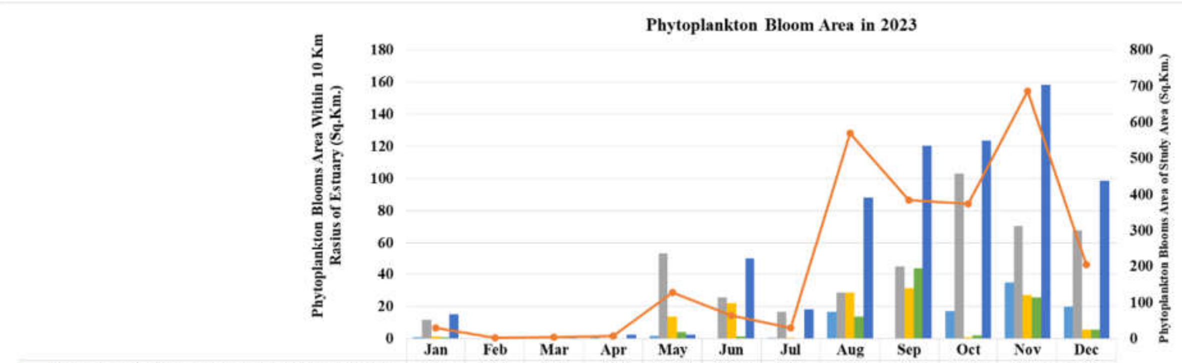


Figure 6: The monthly count of bloom occurrences in the Upper Gulf of Thailand in 2023.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mae Klong River Estuary (Within a 10 km Radius)	0.99	0.02	0.00	1.85	1.72	0.38	0.84	16.74	0.00	17.22	34.86	19.80
Tha Chin River Estuary (Within a 10 km Radius)	11.98	0.18	0.64	0.21	53.16	25.70	16.70	28.75	44.99	103.10	70.35	67.58
Chao Phraya River Estuary (Within a 10 km Radius)	1.44	0.11	0.10	0.58	13.64	22.41	0.57	28.90	31.55	1.12	27.28	5.62
Bang Pakong River Estuary (Within a 10 km Radius)	0.89	0.05	-	0.07	3.95	1.37	0.25	13.71	43.88	2.10	25.65	5.50
Four Main River Estuaries (Within a 10 km Radius)	15.29	0.36	0.75	2.71	2.71	49.86	18.36	88.10	120.42	123.54	158.13	98.50
Phytoplankton Blooms Area (Study Area)	29.55	2.56	4.16	7.50	127.80	64.33	31.17	569.23	385.73	374.64	687.04	205.26

Figure 7: Phytoplankton blooms occur within a radius of 10 km from the estuaries of the Bang Pakong, Chao Phraya, Tha Chin, and Mae Klong rivers, encompassing the entire study area.

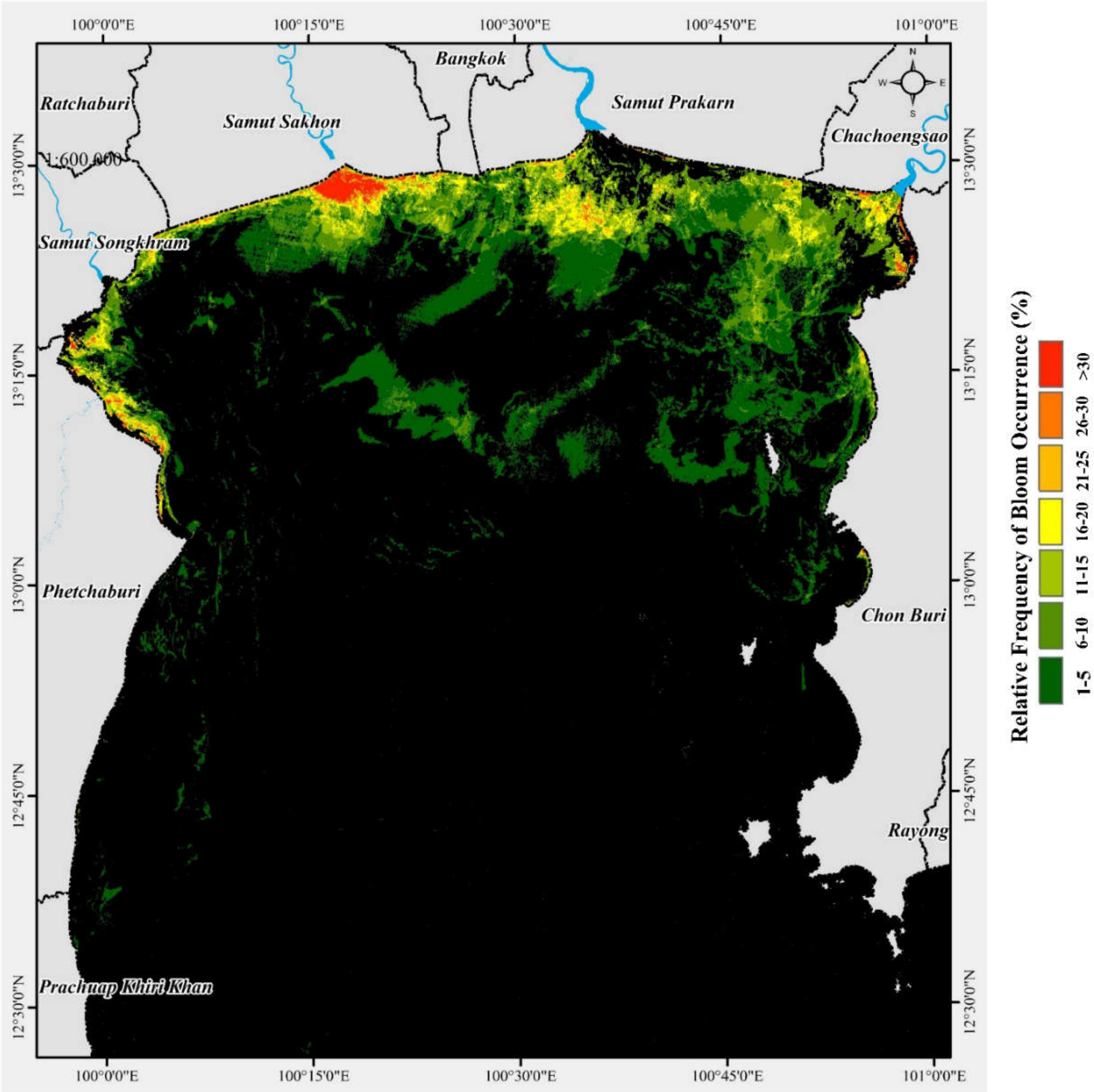


Figure 8: The annual relative frequency of bloom occurrences in the Upper Gulf of Thailand in 2023.

3.1.4 Evaluation of Surface Phytoplankton Blooms Detection

The evaluation for detecting surface phytoplankton blooms utilised criteria for extracting bloom areas from MCI and NDCI. Scatter plots of MCI and NDCI, using the selected intense phytoplankton bloom areas as the area of interest (AOI) on August 14, 2023, are shown in Figure 9. Figure 9 demonstrates that the scatter plots are consistent and show high correlations, especially in the range of MCI > 0.01 and NDCI > 0.1.

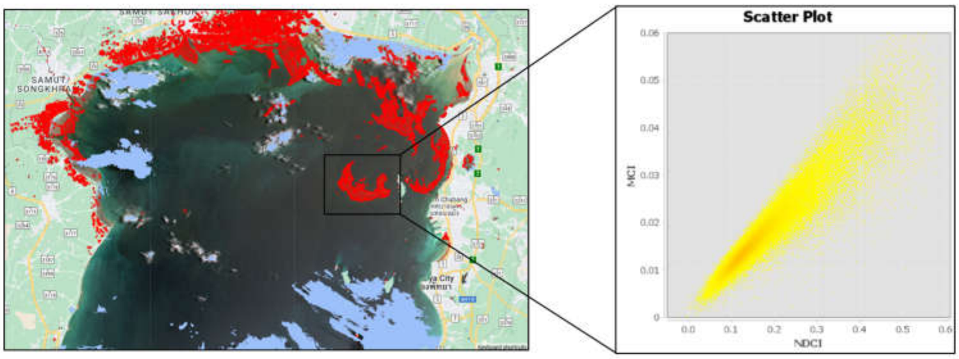


Figure 9: A scatter plot of MCI and NDCI was generated using selected intense phytoplankton bloom areas as the area of interest (AOI) on August 14, 2023.

The results indicate that phytoplankton bloom detection using MCI and NDCI from Sentinel-2 MSI successfully characterized the phytoplankton blooms in both offshore and nearshore areas. Additionally, the data indicate that some of the phytoplankton blooms had reached the shoreline by this date, consistent with field data and news reports, particularly in the case of August 12-19, 2023 (Department of Marine and Coastal Resources, 2023a, Department of Marine and Coastal Resources, 2023b). This phenomenon was caused by the bloom of a dinoflagellate called *Noctiluca scintillans*, a species that does not produce toxins but can cause the death of aquatic animals due to its lack of oxygen, resulting in a large number of dead aquatic animals being found along the coast.

3.2 Discussion

The results of surface phytoplankton bloom detection and extraction using spectral indices, including the MCI and the NDCI, were quite effective and reliable in coastal and offshore waters, especially in estuary areas with high turbidity and optically complex waters, when both indices were used together. A limitation is that the MCI frequently indicates the presence of algae in waters with high sediment concentrations (Wynne et al., 2018). This corresponds with the results of the MCI and NDCI, as shown in Figure 5, which indicate that the Bang Pakong River estuary had higher turbidity and sediment concentrations compared to other river estuaries. The MCI values exhibited high readings, whereas the NDCI values exhibited low readings. The NDCI can also detect surface phytoplankton blooms in coastal turbid productive waters, consistent with the study by Caballero et al. (2020), which applied the NDCI to monitor small blooms more effectively using Sentinel-2 imagery, revealing surface patches and a heterogeneous distribution. Therefore, this method's effectiveness is due to the estuary's relatively turbid water and high sediment content, which affect the characteristics of the plankton bloom phenomenon. These findings are consistent with the study by Wang et al. (2019), which indicated that the surface suspended sediment front played a crucial role in defining the shoreward boundary of the phytoplankton bloom region. High turbidity, causing light attenuation, emerged as a significant factor restricting phytoplankton blooms in turbid nearshore waters.

The 2023 study on the spatial distribution and occurrence of surface phytoplankton blooms revealed that most blooms occurred year-round in estuaries, along the shore, and in offshore areas. This finding aligns with Chumnantana (2006), who reported year-round phytoplankton blooms at major stations. Similarly, Lirdwitayaprasit et al. (2006) documented nine occurrences of blooms caused by *Noctiluca scintillans* and seven by *C. furca* at the Bang Pakong river mouth between June 2003 and November 2004, predominantly during the rainy season and often following heavy rainfall by 1-2 days. Additionally, Luang-on et al. (2023) observed that phytoplankton blooms, specifically Green *Noctiluca scintillans*, were found farther from the shore and estuaries compared to other types such as dinoflagellates and cyanobacteria. The occurrence and distribution of Green *Noctiluca scintillans* blooms, along with other phytoplankton blooms, varied with the monsoon season. These observations confirm the mechanisms of seasonal phytoplankton blooms dynamics in relation to monsoon-induced variables. The intensity of phytoplankton blooms near coasts and river mouths is proportional to nutrient loads, while in offshore areas, vertical water column movement and stability are also crucial (Buranapratheprat et al., 2008). Blooms were not always found in high-nutrient nearshore waters but were observed farther from river mouths (Rungsupa et al., 2003). Suwanlertcharoen and Prukpitikul (2018) also reported occurrences in both coastal and offshore areas.

Furthermore, the surface current patterns during the southwest monsoon season likely facilitate the bloom of cells in the eastern inner Gulf, as the total surface current flows eastward. HYCOM surface current data from 2023 supports this, showing currents flowing east and southeast from May to September. The results indicated that the velocity of the surface current circulation during the northeast monsoon season is higher than during the southwest monsoon season, consistent with the study by Kongprom et al. (2015) on surface current patterns in the Upper Gulf of Thailand using High Frequency Radar in 2013. The circulation characteristics, particularly during the northeast and southwest monsoon, correspond to the spatial distribution characteristics of the phytoplankton bloom area.

4. Conclusions

In this study, spectral indices, including the MCI and NDCI, derived from Sentinel-2 MSI imagery via GEE were utilised to detect surface phytoplankton blooms and to analyse the spatiotemporal distribution and occurrence of these blooms in the Upper Gulf of Thailand.

The results of this study indicated that surface phytoplankton bloom detection and extraction using the MCI and the NDCI were quite effective and reliable in coastal and offshore waters, especially in estuary areas with high turbidity and optically complex waters, when both indices were used together. The 2023 study on the spatial distribution and occurrence of surface phytoplankton blooms revealed that most blooms occurred year-round in estuaries, along the shore, and in offshore areas. Analysing the relative frequency of bloom occurrence in each month of 2023 indicated that near-estuarine and coastal areas experienced more frequent bloom occurrences than offshore areas. Overall, the average annual relative frequency of bloom occurrences within a 5 km radius in the estuary where the Tha Chin River was highest at 28.59%, followed by the Bang Pakong River at 16.27%, the Chao Phraya River at 11.30%, and the Mae Klong River at 7.95%. Additionally, the characteristics of the average velocity and direction of the surface current circulation in 2023, computed from the HYCOM data, showed that the surface current patterns during the southwest monsoon season likely facilitated the bloom of cells in the eastern inner Gulf, as the total surface current flows eastward. Overall, the circulation characteristics, particularly during the northeast and southwest monsoon, correspond to the spatial distribution characteristics of the phytoplankton bloom area.

This study indicates that the spectral indices, including the MCI and NDCI, are reliable methods for routinely detecting and monitoring surface phytoplankton blooms. Additionally, understanding the spatiotemporal distribution and occurrence of these blooms is essential for comprehending the phenomenon in the marine environment. Furthermore, the capabilities of Sentinel-2 provide valuable ecosystem observations for monitoring water quality and the spatiotemporal distribution of blooms, which are critical for ecological and management purposes at a regional scale.

References

Beck, R., Zhan, S., Liu, H., Tong, S., Yang, B., Xu, M., Ye, Z., Huang, Y., Shu, S., Wu, Q., Wang, S., Berling, K., Murray, A., Emery, E., Reif, M., Harwood, J., Young, J., Nietch, C., Macke, D., Martin, M., Stillings, G., Stump, R., Su, H., (2016). Comparison of satellite re ectance algorithms for estimating chlorophyll-a in a temperate reservoir using coincident hyperspectral aircraft imagery and dense coincident surface observations. *Remote Sens. Environ. 178, 15–30.*

Blondeau-Patissier, D., Gower, J.F.R., Dekker, A.G., Phinn, S.R., Brando, V.E., (2014a). A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans. *Progress in Oceanography 2014; 123:123-144.*

Blondeau-Patissier, D., Schroeder, T., Brando, V.E., Maier, S.W., Dekker, A.G., Phinn, S., (2014b). ESA-MERIS 1 0 -year mission reveals contrasting phytoplankton bloom dynamics in two tropical regions of Northern Australia. *Remote Sensing 2014; 6(4): 2963-2988.*

Buranapratheprat, A., Morimoto, A., Phromkot, P., Mino, Y., Gunbua, V., Jintasaeranee, P. (2021). Eutrophication and hypoxia in the upper gulf of Thailand. *J. Oceanogr. 77, 831–841.*

Buranapratheprat, A., (2013) Development of an algorithm based on optical properties of seawater for salinity estimation in the Upper Gulf of Thailand. *Burapha Science Journal 2013; 18(2): 246-54.*

Buranapratheprat, A., Yanagi, T., Niemann, K.O., Matsumura, S., Sojisuporn, P., (2008). Surface Chlorophyll-a Dynamics in the Upper Gulf of Thailand Revealed by a Coupled Hydrodynamic Ecosystem Model. *Journal of Oceanography 2008; 64: 639-656.*

Caballero, I., Fernández, R., Escalante, O.M., Mamán, L., Navarro, G., (2020). New capabilities of Sentinel-2A/B satellites combined with in situ data for monitoring small harmful algal blooms in complex coastal waters. *Sci Rep 10, 8743 (2020).*

Carstensen, J., Klais, R., Cloern, J.E., (2015). Phytoplankton blooms in estuarine and coastal waters: Seasonal patterns and key species. *Estuarine, Coastal and Shelf Science 2015; 162: 98-109.*

Chaiongkarn, P., Sojisuporn, P., (2013). Characteristics of Seasonal Wind and Wind-driven Current in the Gulf of Thailand. *Bulletin of Earth Sciences of Thailand 2013; 5(1): 58-67*.

Chuenniyom, W., Chalermwut, J., Sirichaiseth, T., Wannarangsee, T., (2016). Phytoplankton and red tides in the Samut Sakhon coastal area. *Burapha Science Journal 2016; 21(3): 174-89*.

Chumnantana, R., (2006). Causative phytoplankton of red tide phenomena in the Upper Gulf of Thailand. Marine and Coastal Resources Research Center, Department of Marine and Coastal Resources, Bangkok; 2006.

Cloern, J.E., (1996). Phytoplankton bloom dynamics in coastal ecosystems: A review with some general lessons from sustained investigation of San Francisco Bay, California. *Reviews of Geophysics 1996; 34(2): 127-168.*

Department of Marine and Coastal Resources, (2015). The phenomenon of red tides in Thailand [in Thai]. Marine and Coastal Resources Research and Development Institute, Department of Marine and Coastal Resources, Bangkok; 2015.

Department of Marine and Coastal Resources, (2023a). e-Daily Report: A phenomenon of seawater color change was observed at Bangsaen Beach, Chonburi Province. (in Thai). Retrieved September 4, 2024, from https://edailyreport.dmcr.go.th/milestone/detail/9463.

Department of Marine and Coastal Resources, (2023b). e-Daily Report: A phenomenon of seawater color change was observed in Chonburi Province. (in Thai). Retrieved September 4, 2024, from https://edailyreport.dmcr.go.th/milestone/detail/9524.

European Space Agency, (2015). Sentinel-2 User Handbook. Source: https://sentinel.esa.int/documents/247904/685211/Sentinel-2_User_Handbook.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenkom S., Thau, D., Moore, R., (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment 202 (2017): 18-27*.

Gower, J., King, S., Borstad, G., Brown, L., (2005). Detection of intense plankton blooms using the 709 nm band of the MERIS imaging spectrometer. *Int. J. Remote Sens. 26, 2005–2012*.

Gower, J., King, S., Goncalves, P., (2008). Global monitoring of plankton blooms using MERIS MCI. *Int. J. Remote Sens. 29, 6209–6216.*

Gower, J.F.R., King, S., (2011). A global survey of intense surface plankton blooms and floating vegetation using MERIS MCI. In: Tang D, editor. Remote Sensing of the Changing Oceans. Springer-Verlag Berlin Heidelberg; 2011. p. 99-121.

Gurlin, D., Gitelson, A.A., Moses, W.J., (2011). Remote estimation of chl-a concentration in turbid productive waters - Return to a simple two-band NIR-red model?. *Remote Sens. Environ. Elsevier Science 115 (12), 3479–3490.*

Hu, C., (2009). A novel ocean color index to detect oating algae in the global oceans. *Remote Sens. Environ. 113, 2118–2129.*

Kislik, C., Dronova, I., Grantham, T.E., Kelly, M., (2022). Mapping algal bloom dynamics in small reservoirs using Sentinel-2 imagery in Google Earth Engine. *Ecological Indicators, Volume 140, 2022, 109041*, ISSN 1470- 160X.

Kongprom, A., Prukpitikul, S., Buakaew, V., Kesdech, W., Suwanlertcharoen, T., (2015). Spatial characteristics of the surface circulation and wave climate using high frequency radar. *Proceeding of the 35th Asian conference on Remote Sensing; 2015 Oct 19-22, Manila: Philippines; 2015.*

Lirdwitayaprasit, T., Meksumpun, S., Rungsupa, S., Furuya, K., (2006). Seasonal variations in cell abundance of Noctiluca scintillans in the coastal waters off Chonburi Province, the upper Gulf of Thailand. *Coastal Marine Science 2006; 30(1): 80-84.*

Lobo, F. de L., Nagel, G.W., Maciel, D.A., Carvalho, L.A.S. de, Martins, V.S., Barbosa, C.C. F., Novo, E.M.L. de M., (2021). AlgaeMAp: Algae Bloom Monitoring Application for Inland Waters in Latin America. *Remote Sensing 13, 2874.*

Luang-on, J., Ishizaka, J., Buranapratheprat, A., Phaksopa, J., Goes, J.I., Mau´re, E.R., Siswanto, E., Zhu, Y., Xu, Q., Nakornsantiphap, P., Kobayashi, H., Matsumura, S., (2023). MODIS-derived green Noctiluca blooms in the upper Gulf of Thailand: Algorithm development and seasonal variation mapping. *Front. Mar. Sci. 10:1031901.*

Mishra, S., Mishra, D.R., (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment 117 (2012), 394–406*.

Mishra, P., Naik, S., Babu, P.V., Pradhan, U., Begum, M., Kaviarasan, T., Vashi, A., Bandyopadhyay, D., Ezhilarasan, P., Panda, U.S., Murthy, M.V.R., (2022). Algal bloom, hypoxia, and mass fish kill events in the backwaters of Puducherry, Southeast coast of India. *Oceanologia 2022, 64, 396–403*.

Qi, L., Hu, C., Mikelsons, K., Wang, M., Lance, V., Sun, S., Barnes, B.B., Zhao, J., Zande, D.V., (2020). In search of oating algae and other organisms in global oceans and lakes. *Remote Sens. Environ. 239, 111659*.

Rungsupa, S., Throngroop, C., Piemsomboon, A., Paphawasit, N., Panichphon, A., Sophol, A., (2003). Red tide incidences in the Gulf of Thailand. In: ARRI, editor. Aquatic Resources Research Institute, Chulalongkorn University and Water Quality Management Section, Pollution Control Department, Bangkok; 2003. p. 75–106.

Ryan, J.P., Gower, J.F.R., King, S.A., Bissett, W.P., Fischer, A.M., Kudela, R.M., Kolber, Z., Mazzillo, F., Rienecker, E.V., Chavez, F.P., (2008). A coastal ocean extreme bloom incubator. *Geophysical Research Letters 2008; 35: L12602*.

Salls, W.B., Schaeffer, B.A., Pahlevan, N., Coffer, M.M., Seegers, B.N., Werdell, P.J., Ferriby, H., Stumpf, R.P., Binding, C.E., Keith, D.J., (2024). Expanding the Application of Sentinel-2 Chlorophyll Monitoring across United States Lakes. *Remote Sens. 2024, 16, 1977*.

Suwanlertcharoen, T., Prukpitikul, S., (2018). Detection of Phytoplankton Blooms in the Upper Gulf of Thailand Using Sentinel-3A OLCI Imagery. *Environment and Natural Resources Journal 2018; 16(1): 9-20*.

Suwanlertcharoen, T., Prukpitikul, S., Buakaew, V., (2020). Retrieval of water turbidity using sentinel-2 image time series to enhance water quality assessment for consumption. *Journal of Environmental Management 2020;16:74-93*.

Wang, M., Jiang, L., Mikelsons, K., Liu, X., (2021). Satellite-derived global chlorophyll-a anomaly products. *International Journal of Applied Earth Observation and Geoinformation, Volume 97, 2021, 102288*, ISSN 1569-8432.

Wang, Y., Wu, H., Lin, J., Zhu, J., Zhang, W., & Li, C. (2019). Phytoplankton blooms off a high turbidity estuary: A case study in the Changjiang River Estuary. *Journal of*

Geophysical Research: Oceans, 124, 8036, 8059. https://doi.org/10.1029/2019JC015343.

Wynne, T.T., Meredith, A., Briggs, T., Litaker, W., 2018. Harmful Algal Bloom Forecasting Branch Ocean Color Satellite Imagery Processing Guidelines. NOAA Technical Memorandum NOS NCCOS 296 48 pp.

Zhang, Y., Ma, R., Zhang, M., Duan, H., Loiselle, S., Xu, J., (2015). Fourteen-Year Record (2000–2013) of the Spatial and Temporal Dynamics of Floating Algae Blooms in Lake Chaohu, Observed from Time Series of MODIS Images. *Remote Sensing* 2015; 7: 10523-10542.