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Impacts of freshwater discharges from the Mekong river system on the oceanic variability off Southern Vietnam

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ABSTRACT

In recent years, the primary concern in the downstream region of the Mekong River system has been changes in river discharge due to climate change and the construction of upstream hydropower dams. This change might affect the salinity and productivity in the southern waters of the Mekong Delta. This study used measured water discharges, satellite ocean color, and a gridded salinity dataset from 2010 to 2020 to investigate these variations. The spatial and temporal distributions of sea surface salinity and chlorophyll a concentration have been discussed based on statistical analysis. It has been confirmed that the salinity in the Gulf of Thailand is consistently lower than that in the East Vietnam Sea. In the Mekong plume area, salinity is strongly correlated with variations in freshwater discharge. The main reasons for these distributions were discussed in this paper. It is noted that the time lag between freshwater discharges and salinity and chlorophyll a concentrations in the Mekong plume region was 1 month. In contrast, they were 5 months and 2 months in the Gulf of Thailand, respectively. It can be confirmed that Mekong River water did not play a significant role in the productivity of the Gulf of Thailand, but it is the main source of the lower salinity. In the offshore area of the Mekong plume, the impact of freshwater discharges was small in magnitude but quite apparent in phase, with a 2-month time lag between salinity and ocean color.

Keywords: Gulf of Thailand, Mekong River, salinity, freshwater, chlorophyll-a.

1. Introduction

The Mekong River is the third-longest in Asia, at about 4,900 km, flowing through six countries (China, Myanmar, Laos, Thailand, Cambodia, and Vietnam) (Liu et al., 2009). The river flows into the East Vietnam Sea (or East Sea - hereafter EVS) via nine estuaries in southern Vietnam. The freshwater from the Mekong River provides a significant source of nutrients, sediment, and other contaminants to the sea. Xue et al. (2012) revealed the mechanisms of sediment and freshwater in the Vietnamese estuarine region. Large amounts of freshwater and sediment were delivered near the mouths during the southwest monsoon. In the northeast winds, the coastal

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current pushes the sediment and freshwater southward into the Gulf of Thailand. Buranapratheprat et al. (2016) also confirmed that the northeast wind significantly contributed to freshwater accumulation by generating surface water flow into the Gulf of Thailand during the northeast monsoon. Hence, the Mekong River affects human lives not only on the mainland but also indirectly through the marine environment of southern Vietnamese waters.

The southern Vietnamese waters are characterized by rich biodiversity, strategic importance, and economic significance. These waters include the Gulf of Thailand (hereafter, the Gulf), the Mekong River plume (hereafter, the plume), and the offshore area of the Mekong estuary (hereafter, the East) (Fig. 1), which play vital roles in the country's ecology and economy. Renowned for their rich marine life, these waters support a diverse array of species, including fish, corals, and other aquatic organisms. The vibrant coral reefs and mangrove forests are not only ecological treasures but also crucial for maintaining the health of the marine ecosystem. These ecosystems provide breeding grounds and habitats for numerous species, contributing to the region's high biological productivity. The Mekong River strongly impacts the Plume region (Zeng et al., 2022). This plume plays a crucial role in the marine ecosystem by delivering sediments, organic matter, and nutrients that support a diverse range of aquatic life. It influences regional oceanography, impacting coastal currents, water quality, and biological productivity (Loisel et al., 2014). The plume's dynamics are subject to seasonal variations driven by monsoon cycles (Tang et al., 2023). In the estuarine region of the Mekong River, the current flows southwestward in the NE monsoon season while it flows northeastward in the SW monsoon season (Wyrtki 1961; Kelly et al., 2007). This region is relatively shallow but has complex tides, with a maximum tidal range of about 3.5 m (Phan et al., 2019). Therefore, the hydrodynamics here are complex due to the impacts of waves, currents, tides, and river discharges. The Gulf is a shallow basin located between 6° and 13.5°N and 99° and 104°E. Vietnam, Cambodia, Thailand, and Malaysia surround it. The average depth in the Gulf is about 40 m, with a maximum of about 80 m at the center (Yanagi and Takao, 1998). The Gulf is one of over sixty Large Marine Ecosystems (LME) worldwide (Duda and Sherman, 2002). It provides fisheries and resources for large populations of surrounding countries.

Many rivers flow into the Gulf, such as the Kelantan River (Malaysia), the Bang Nara River, the Pattam River, the Tapi River, the Klong River, the Tha Chin River, the Chao Phraya River, the Bang Pakong River, the Rayong River (Thailand), and the Mekong Tributaries in Cambodia and Vietnam. Among those rivers, the Mekong River system is a significant and vital source of freshwater to the Gulf (Stansfield and Garret, 1997). Monsoons, on seasonal and interannual scales, strongly influence Gulf dynamics. From May to August, southwest monsoon winds prevail, while from November to February, the northeast monsoon dominates. Circulation in the Gulf is strongly influenced by the monsoon winds (Aschariyaphota et al., 2008; Saramul, 2017; Anutaliya, 2023). At the entrance of the Gulf, in the northeast monsoon, the surface current is southward, while it is northward in the southwest monsoon. Inside the Gulf, the circulation appears cyclonic in the northeast wind and anticyclonic in the southwest wind season (Buranapratheprat and Bunpapong, 1998). Anutaliya (2023) used satellite altimetry and confirmed that about 50% of the surface current variability is geostrophic, set up by wind stress curl.

In recent years, amid rapid economic and population growth in the Mekong watershed, the number of dams has increased rapidly to meet demand for hydropower (Xue et al., 2010). More than 160 dams have been operating in the Mekong River Basin. Consequently, freshwater discharges to the ocean will be reduced in amount (Tang et al., 2023) or phase-lagged. These changes will negatively impact the environment or ecosystem (Grumbine and Xu, 2011). Lauri et al. (2012) predicted that the operation would have a greater impact than that of climate change. Rasanen et al. (2017) noted that hydropower operations have significantly modified discharges since 2011. In recent years, the saline intrusion in the Mekong River system has become more severe due to changes in freshwater discharges and climate change (Rasanen et al., 2017; Binh et al., 2020). Eslami et al. (2019) found that the lack of sediment sources makes the channels deeper, which is one of the reasons causing the rapid intrusion. However, if the salinity in the estuarine region increases with lower upstream discharges, saline intrusion will occur more strongly and intrude farther landward. One motivation for this investigation is to examine how changes in salinity are driven by variations in freshwater discharges from the Mekong system. Is the severe saline intrusion in the Mekong River due to the saltier water in the sea?.

In addition, river discharges carry large amounts of freshwater and nutrients that support ocean productivity and the ecosystem (Auricht et al., 2022), so it is necessary to estimate the time lag between the measured station for water discharges and salinity and productivity. The time lags between river discharges and chlorophyll-a (hereafter, Chla) have been investigated in some important river systems, such as: in the adjacent sea area due to the Yangtze River discharges (Wang et al., 2015); in the Gulf of Manfredonia with freshwater discharges from the Po River (Babagolimatikolaei, 2024); in the Kenyan coastal waters driven by Tana River discharge (Mutia et al., 2021); in the equatorial East Sea (Sun, 2017); etc. However, the time lags between freshwater discharges from the Mekong River and salinity or chlorophyll a in the adjacent waters remain unclear.

This paper analyzes freshwater discharges, satellite-measured salinity, and Chla datasets to examine how Mekong River discharges have varied in recent years and their relationships to salinity and Chla distributions in southern Vietnam. In addition, the time lag in the Mekong River system will affect the salinity and productivity of the adjacent waters, as discussed. This will provide an overview and may serve as a basis for further investigation and near-future predictions.

Figure 1 shows the monthly satellite sea surface salinity (SSS) standard deviation in the selected study areas based on the standard deviations of SSS. We first discuss the variation in satellite SSS distribution in EVS (99−121°E, 1−25°N) and then further investigate the changes in SSS and Chla in three selected study areas: the Gulf of Thailand (Gulf: 99−105°E, 6.5−13°N), the Mekong Plume area (Plume: 102.5−109°E, 7.5−11°N), and the East of Plume (East: 109.5−115.5°E, 7.5−11°N). We selected the limitations of each area based on the SSS standard deviation and its variations (Fig. 1).

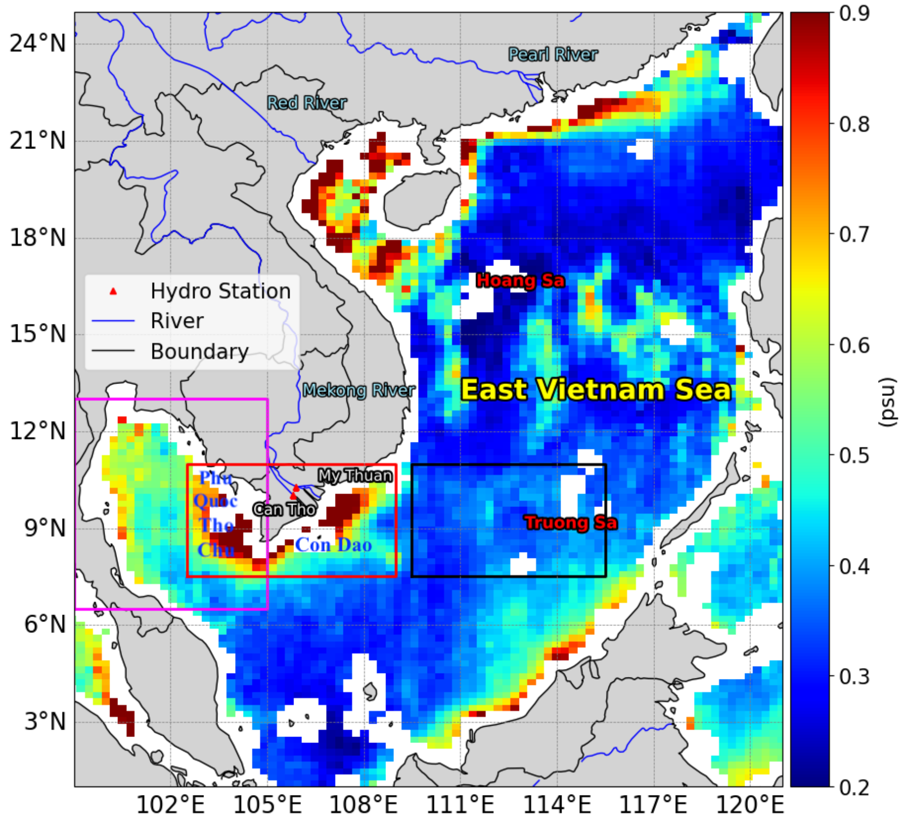


Figure 1. Monthly satellite SSS standard deviation (psu) in the EVS and three study domains: Gulf of Thailand (Gulf-pink box), Mekong plume (Plume-red box), and East Mekong plume water (East- black box)

2. Data and methodology

2.1. Data sources

2.1.1. Sea Surface Salinity

This study uses SSS from the Climate Change Initiative (CCI) project, which has been planning to generate improved SSS fields since 2010. This dataset was created by assembling the Soil Moisture and Ocean Salinity (SMOS), Soil Moisture Active Passive (SMAP), and AQUARIUS satellite products (Boutin et al. 2021). The monthly SSS CCI dataset v04.41, with a 25 km grid, for the period 2010−2020, was used. Wang et al. (2023) validated this dataset against in situ-gridded data. They confirmed that CCI is the best dataset on a monthly timescale compared to other products such as SMOS, Aquarius, or SMAP.

2.1.2. Chlorophyll-a

Chla indicates the quality of the environment because it provides information about the concentration of algae in seawater. High Chla concentrations are usually found in estuarine, upwelling, or polluted areas. When the river flows into the coastal region, it carries nutrients and freshwater. Therefore, this study examines how the Chla fields responded to changes in total discharges from the Mekong River over the last 10 years. The Chla data can be retrieved from the NOAA ERDDAP (Castaneda-Guzman et al. 2021). The monthly dataset titled "Chla, Aqua MODIS, NPP, L3SMI, Global, 4 km, Science

Quality" for 2010 to 2020 was used for three study regions: The Gulf, the Plume, and the East domains. The Chla concentration in this dataset was highly reliable when compared with in situ data from 57 synchronized sites in Vietnamese coastal waters (Tuan and Ha 2021).

2.1.3. Freshwater discharges (FD)

Freshwater discharges from the Mekong River system were measured at the My Thuan (105°54'45.5"E; 10°16'42.4"N) and Can Tho (105°47'39.0"E; 10°03'21.7"N) stations in Vietnam. At these stations, freshwater discharges are estimated hourly using the measured results of a current meter at six representative depths from the bottom (at the bottom, 0.8*H, 0.6*H, 0.4*H, 0.2*H, and at the surface, where H is the depth). In addition, ADCP is also used to measure the discharges 4 times a year for checking and validation. The cross-sectional area of the river is normally measured every 2 months during the dry season and monthly during the flood season. When using ADCP or when the banks are significantly eroded, they measure the cross-sectional area more frequently; for example, in 2024, they measured it up to 10 times. The Viet Nam Meteorological and Hydrological Administration provided the dataset. To consider the impact of the Mekong River discharges, the total discharge was computed as the sum of discharge data at two stations for the period of 2010−2020. These stations are about 100 km from the sea and cover all tributaries flowing to the coastal region (Fig. 1).

2.1.4. Surface current fields

The surface current fields were downloaded and processed from the Hybrid Coordinate Ocean Model (HYCOM) dataset for a similar period. The HYCOM is an advanced numerical modeling system designed to simulate three-dimensional ocean circulation and thermodynamic processes. By employing a hybrid vertical coordinate framework that dynamically combines isopycnal, terrain-following, and fixed-depth coordinates, HYCOM effectively represents ocean dynamics across a wide range of spatial and temporal scales. The model is widely applied in oceanographic research and operational forecasting to analyze currents, water mass transformation, air-sea interactions, and marine environmental variability in both coastal and open-ocean regions. In this study, we use surface residual currents from HYCOM to examine how the current climatology in the study areas varies and how these fields change over the period under discussion.

2.2. Analysis method

This study's approach is to analyze the monthly, seasonal, and interannual variations using statistical analyses. Monthly SSS and Chla distributions and anomalies were computed and compared with the variations of total freshwater discharge. The monthly mean data are long-term averages over the entire area, while the anomaly values are calculated by subtracting the long-term mean from the observed values. Seasonal variations were also considered: winter (December to February), spring (March to May), summer (June to August), and autumn (September to November). The correlations and cross-correlations were estimated to assess how freshwater discharges affect the variability of SSS and Chla. Some basic formulas were used to compute climatology, anomaly, coefficient of determination, and cross-correlation coefficient.

3. Results

3.1. Variability of sea surface salinity due to the changes in freshwater discharges

Figure 2 depicts the SSS climatology in the EVS from an 11-year dataset (2010−2020), while Fig. 1 shows the SSS standard deviation based on the same dataset. SSS in most of the sea ranges from 33 psu to 34 psu. It should be noted that in the northern part, SSS levels are higher from December to April than in other months. It results from the intrusion of the Kuroshio current in the winter and early spring. During the year, the standard deviation offshore EVS is only about 0.3 psu, while it varies much in the Gulf of Tonkin, the Gulf, the southern China coast, and the northwest of Borneo Island due to the impact of the large rivers, such as the Pearl River, Red River, and Mekong River.

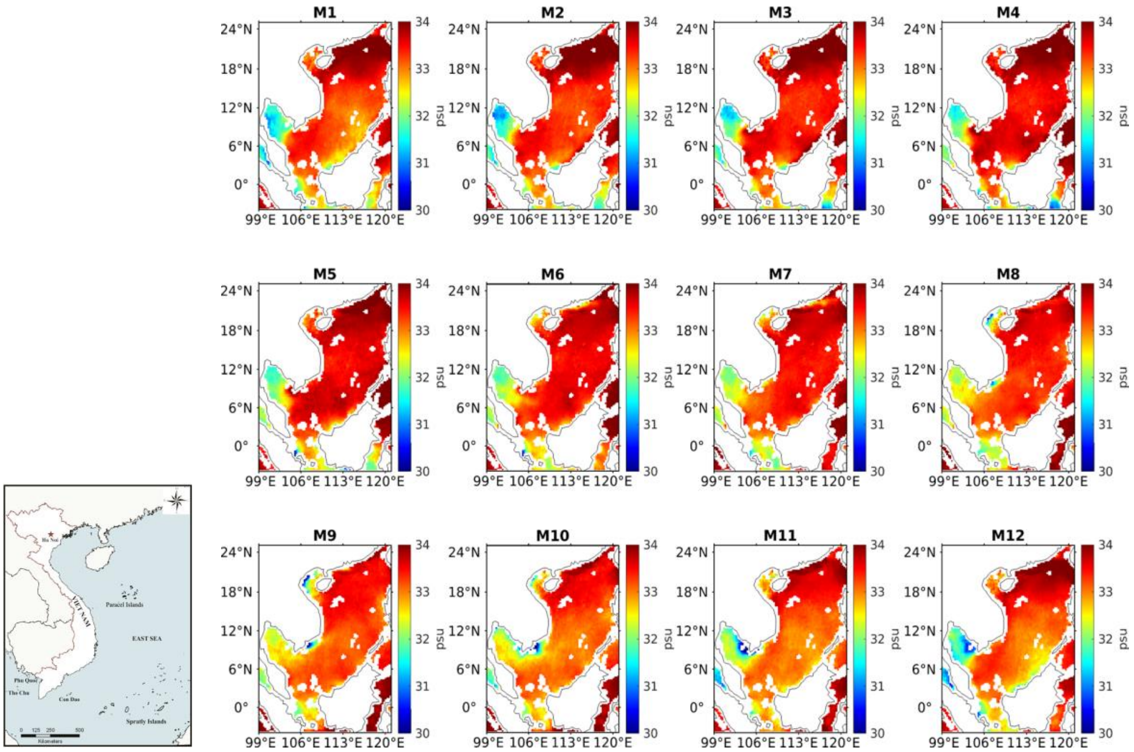
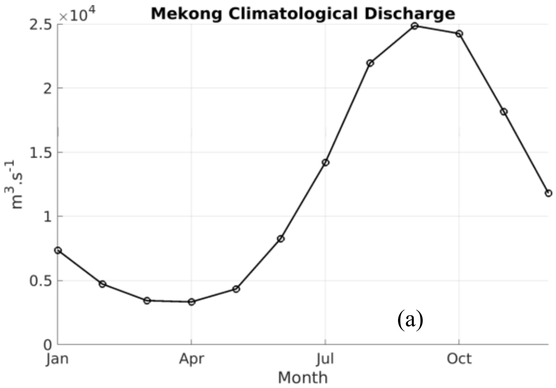


Figure 2. Monthly SSS mean in the EVS computed from satellite data

The Gulf's SSS is always lower than that in other parts of the EVS, ranging from 31 to 32.5 psu. This is because the Gulf is quite enclosed, and its entrance is parallel to the dominant monsoon wind direction. Therefore, water exchange between the Gulf and EVS is limited. The Mekong River system controls the Gulf's SSS, the Chao Phraya River, and other smaller rivers. These rivers have very different total discharges. While the total Mekong River's discharges are about 4,000 to 25,000 m^3s^{-1} (Fig. 3), the Chao Phraya River's discharges reach the maximum value in October at only 2,000 m^3s^{-1} (Samural and Ezer, 2014). Other rivers contribute much smaller freshwater discharges, on the order of ~300 m^3s^{-1} (Samural and Ezer, 2014). Although the mainstream of the Mekong River does not flow into the Gulf, the Mekong's impact on the Gulf's SSS is significant. In the surface current fields, it should be noted that the inverse of the current along the Vietnamese coast is due to monsoon winds (Appendix 1). In the winter, the current was mostly southwestward, and in the summer, it was in the opposite direction. In the Gulf of Thailand, the surface current was clockwise in the summer and anticlockwise in the winter. On a large scale, the impact of the monsoon on surface currents and on water transport to the offshore or the Gulf of Thailand was clearly observed.

To consider the temporal distributions of SSS from the Mekong River to the Plume and Gulf domains, the long-term mean SSS was computed. In the Plume domain, SSS appears to be highest in April, before the rainy season begins in May. From June to October, freshwater from the Mekong River flows into the coastal waters, reducing salinity and generally moving northeastward under the influence of the SW monsoon. From November to December, during the NE monsoon, lower-salinity water reverses its flow and is pushed into the Gulf. Consequently, mixing between the inner Gulf water and lower-salinity water reduces salinity throughout the Gulf. This mechanism explains why the SSS in the Gulf is much smaller than that in the EVS. The low-salinity water mass intrudes deeper into the Gulf from January to April (Fig. 2). In January, it moves westward and northward; in February and March, it moves westward and northward. It takes several months until July to homogenize SSS in the Gulf. In August and September, the SSS in the Gulf is relatively uniform until the low-salinity water mass begins to intrude in the following winter.



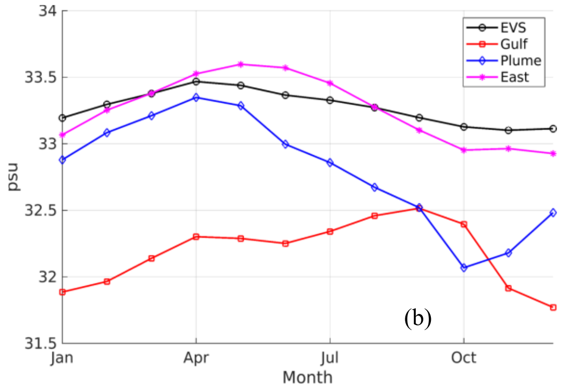


Figure 3. Monthly climatology of Mekong River's freshwater discharge (a) and mean SSS of different domains: EVS, Gulf, Plume, and East areas (b) from 2010 to 2020

In the Mekong River system, seasonal variation in water discharge is apparent, with a dry season from January to May and a wet season beginning in mid-May. At the My Thuan and Can Tho stations, the total discharge reaches its maximum in September and gradually decreases through the end of the year. SSS is very closely linked to freshwater discharges from rivers. In the EVS, the average SSS reaches its maximum value in April, about 33.5 psu. Although many large rivers flow into the sea, the tendency of SSS in EVS is slightly inverted compared to the Mekong River discharges. The EVS trend is similar to it in the East domain. In the Plume area, the relationship with the Mekong River discharges is most apparent because it connects directly with the Mekong River system. From May, the SSS decreases from 33.4 psu to 32.1 psu in October due to increased freshwater inflow. In the Gulf, the effect of river discharges occurs later than that in the plume. Gulf's SSS peaks in September and drops to 31.7 psu in December. It means that it takes some months for the freshwater to reach the Gulf. The lag time will be discussed in the next section.

Interannual variations of discharges and SSS were also considered for four seasons, as in Figs. 4−6. From 2010 to 2020, the Mekong River discharge anomaly changed little in spring and varied widely in summer. 2015 was the year with the fewest discharges, while 2017−2018 received more water overall. It can be confirmed that, from 2018 through 2020, the river's discharge decreased the most. This period also saw hydropower plants bloom in Mekong-shared countries. In addition, atmosphere-ocean interaction also plays an important role, in addition to FD from estuaries. It can be seen as an unusual SSS increase in 2020 with a similar change in FD as in 2015 because 2020 was known as the worst drought ever (Khoa, 2020). 2016 was also a drought year, but not as severe as 2020. 2016 and 2020 were considered the hottest years (NASA GISS and NOAA NCEI 2024), so evaporation was enhanced, another reason for changes in SSS. Consequently, the SSS anomaly increased in the Plume and Gulf domains in all seasons. From 2017 to 2020, the SSS anomaly increased from -0.2 to over 0.5 psu. These sharp increases have never occurred with such a large amount in previous years, even during 2015−2016. This is a very noticeable tendency of SSS in the Plume and the Gulf.

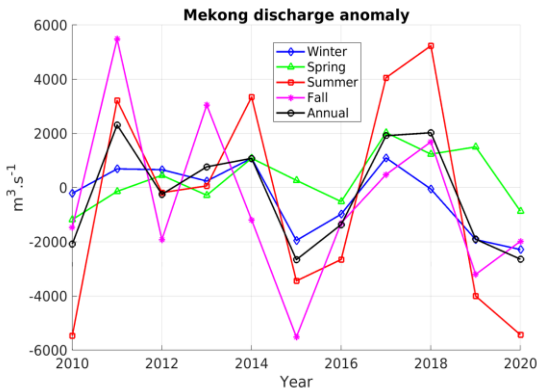


Figure 4. Annual variations of Mekong discharge anomaly from 2010 to 2020

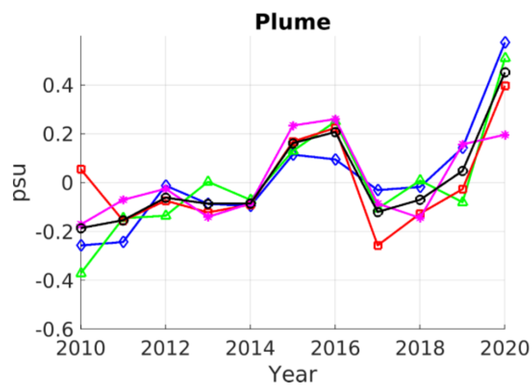


Figure 5. Seasonal variations of SSS anomaly in the Plume area from 2010 to 2020

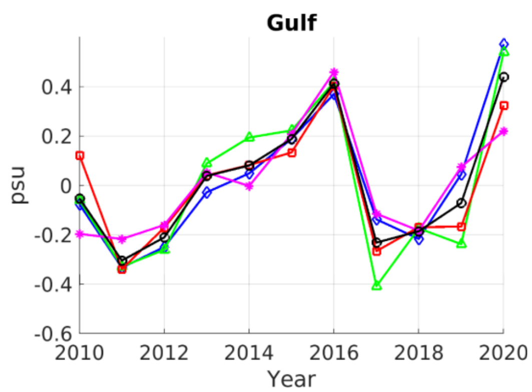


Figure 6. Seasonal variations of SSS anomaly in the Gulf area from 2010 to 2020

3.2. Chlorophyll-a distribution and impact of the Mekong River's discharge

The Chla distribution represents the impact of the river and freshwater behavior. In the Plume domain, high Chla concentrations are found near the coastlines and decrease gradually offshore. Chla concentration develops southwestward from November to February due to the prevailing NE monsoon. Since June, the footprint of river discharges has been evident in the Mekong estuarine region, as seen in the increasing Chla concentration. As shown in Fig. 3a, river discharge peaks in September and October; the high Chla concentration zone also expands near the coastline (Fig. 7).

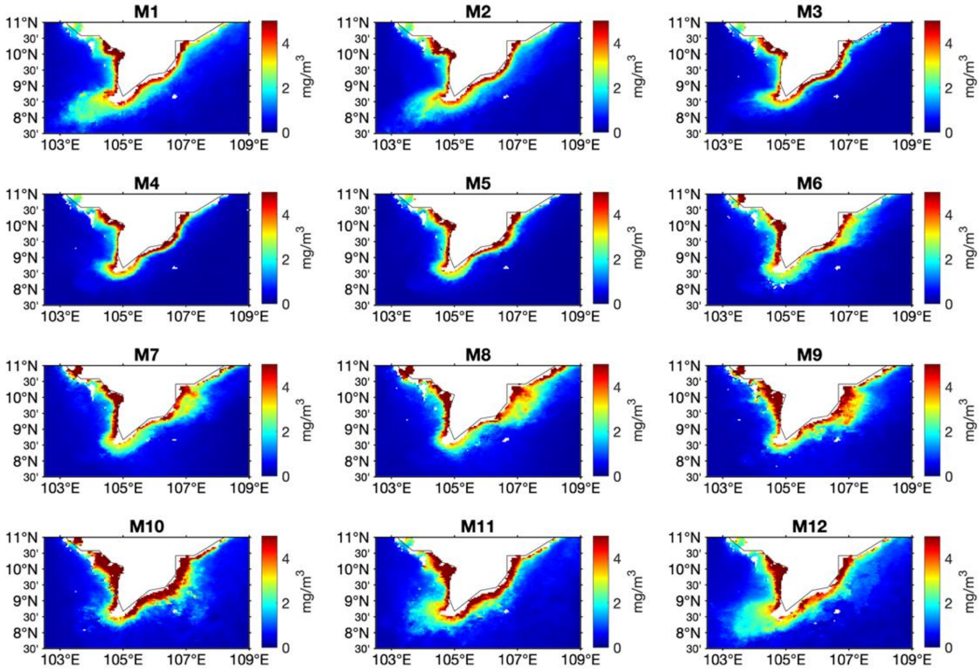


Figure 7. Long-term mean monthly Chla distribution (2010-2020) in the Plume

In the Gulf, seasonal variation and spatial distribution of Chla concentration are less apparent than in SSS (Fig. 8). Due to the movement of low-salinity water masses from the Mekong River, as discussed in Fig. 3, Chla concentration also increases along the Eastern coast of Thailand from October to February. The high concentration of Chla is limited to the near-coastal zone in the Gulf, while it remains below 1 mg/m^3 in most of the Gulf. Comparing the monthly variation in the Gulf, the plume, and the East regions (Fig. 9), it can be confirmed that the Plume domain has the highest Chla concentration due to its proximity to the river discharge. The Gulf shows a similar tendency for variation in Chla concentration to that of the plume. However, the East domain shows no significant variation because it is the offshore region. The two-seasonal mode (wet and dry seasons) is quite apparent in the Plume and the Gulf due to the freshwater discharges from the Mekong River. Fig. 10 depicts Chla concentration anomalies in different seasons and annual variations from 2010 to 2020. In the East domain, Chla concentration has decreased slightly over the past few years. In the Gulf and Plume domains, the annual Chla concentration anomaly is not very strong but varies significantly across seasons. In autumn, Chla concentration increases in both domains regardless of decreasing freshwater discharges (Fig. 4). However, in summer, while total freshwater discharges decrease, the Chla concentration also decreases (Figs. 4 and 10). This raises the question of the time lag between the freshwater discharges from two stations and the Chla concentration or SSS in each domain. This question will be discussed in Section 4.

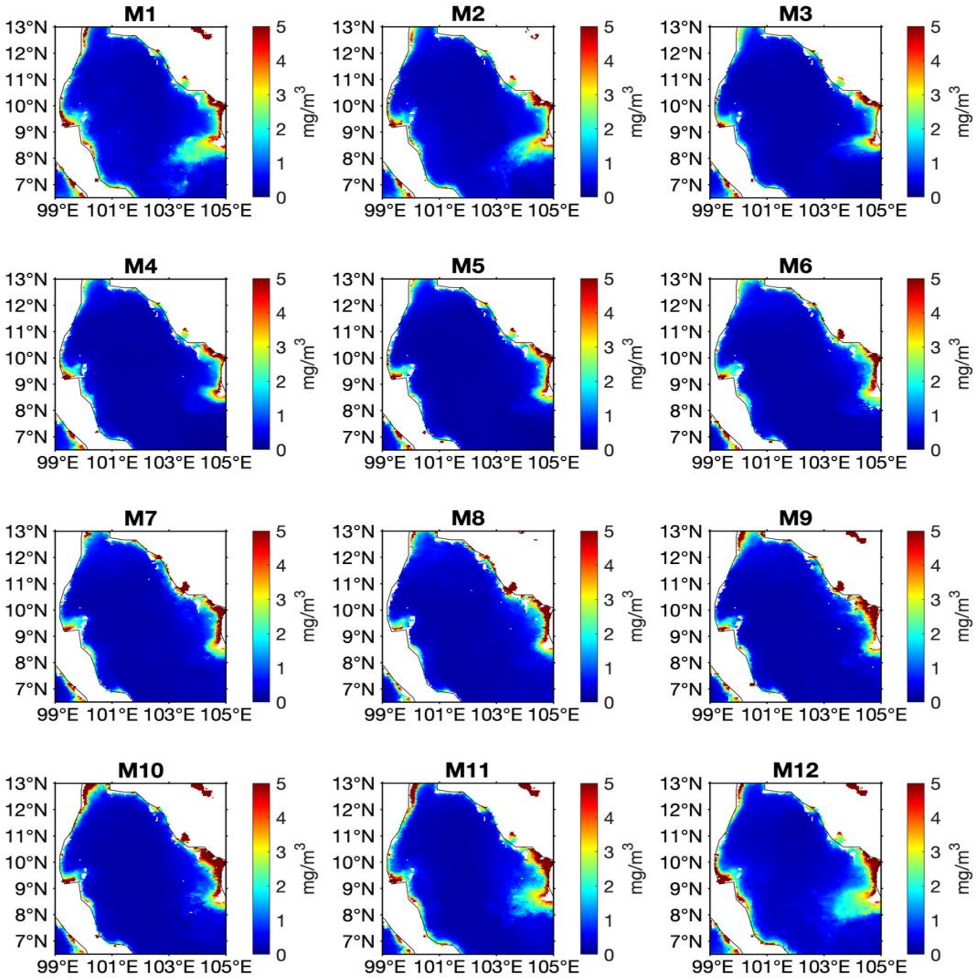


Figure 8. Long-term mean monthly Chla distribution (2010−2020) in the Gulf area

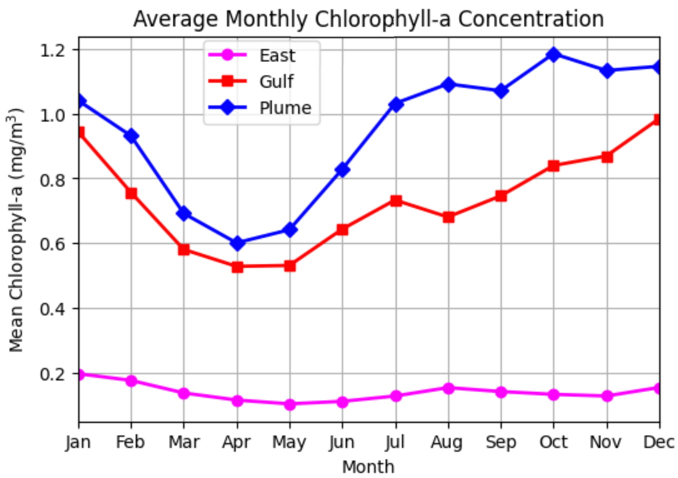


Figure 9. Monthly climatology of Chla concentration in the Gulf, Plume, and East areas

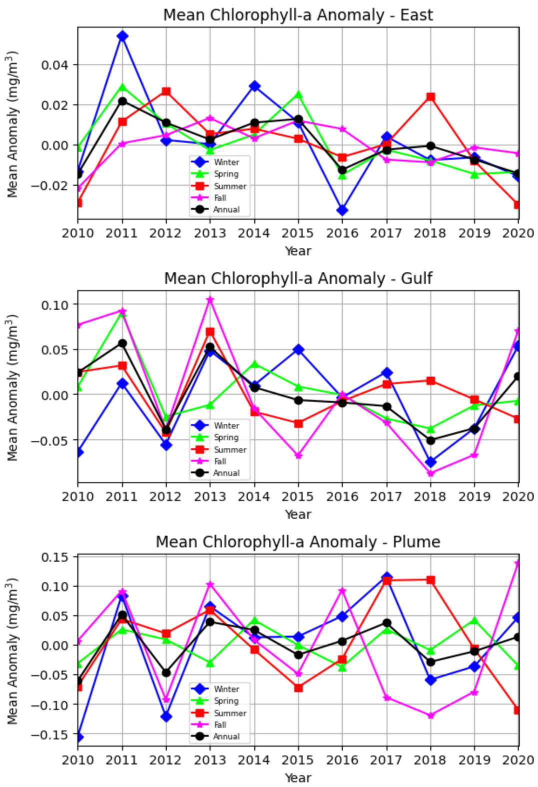


Figure 10. Seasonal variations of the averaged Chla concentration anomaly in the Gulf, Plume and East areas

4. Discussion on the responses of the Gulf and Plume domains to the changes in the Mekong freshwater discharges

The coefficient of determination (R^2) and the regression equations were computed to assess the relationships among SSS, Chla concentrations, and freshwater discharges. The relationship between SSS or Chla with FD in the Plume domain is relatively straightforward, with a high coefficient (Fig. 11). In other domains, the coefficients are smaller than 0.3 (figures not shown here), but the tendency is quite strongly related to the FD of the Mekong River, especially in the Gulf. Figure 12 shows the cross-correlation between FD and SSS or Chla for three regions. In the Gulf and the East domains, SSS decreases when FD increases. The lag between SSS and FD in the plume is 1 month, and in the East it is 2 months. In the Gulf, it takes 5 months for the highest correlation between SSS and FD from the Mekong River. This five-month lag could be explained by the seasonal monsoon and transport (Xue et al., 2012). In Fig. 12, it can be seen that almost all cross-correlation computations have very small p-values ($p < 0.01$), except for the correlation between Chla and FD in the East area. It confirmed that the results are statistically significant at the 1% significance level. In the East area, because it is offshore and outside the Mekong River, the correlation between Chla and FD is weak. It might depend on the nutrient transport and dispersal processes in the coastal zone (Lu et al., 2020).

Unlike SSS, Chla concentration has a similar trend to FD. Chla increases when FD increases. Getting the highest correlation between Chla and FD in the Plume also takes one month. The time lags to reach the highest correlation between Chla and FD in the Gulf and the East areas are two months, respectively. It shows that the Chla maximum in the Gulf area is not caused by Mekong River water but rather by direct local runoff into the Gulf during the summer monsoon or by other forcings, such as biogeochemical cycles, precipitation, or local hydrodynamics. In addition, the two-month lag in Chla concentration might be attributed to the transit time of nutrient-rich freshwater, while the lack of a five-month peak could result from nutrient consumption or sinking during transport. Huynh et al. (2020) investigated the relationships among surface Chla, sea surface temperature, and wind. They confirmed the role of the Mekong FD in Chla distribution, but its relationship in the Gulf remains poorly understood. The mechanisms underlying these time lags remain an open question requiring further study. Still, they are very important for forecasting environmental variables based on measurements of freshwater discharge from two stations on the Mekong mainstream.

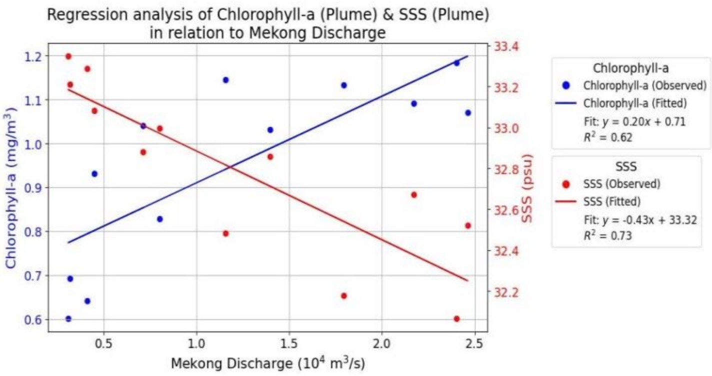


Figure 11. Relationships between SSS, Chla, and the Mekong freshwater discharge in the Plume area

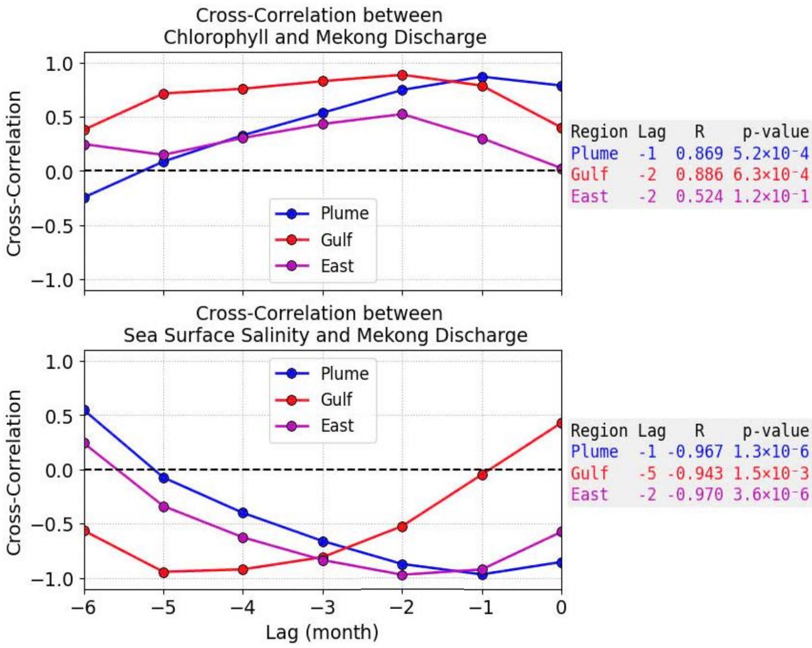


Figure 12. Cross-correlations between Chla concentration (upper), SSS (lower), and the Mekong freshwater discharges

5. Conclusions

Based on analyses of measured discharges from two hydrological stations in Vietnam, satellite datasets of SSS and Chla concentrations, and monthly and annual variations in river discharges, SSS, and Chla, the following was described: Freshwater discharge strongly affected oceanic fields, including SSS and ocean color, in Vietnam's southern waters. It can be confirmed that the SSS in the Gulf is always smaller than that in the EVS. The movement of low-salinity water mass due to the NE monsoon is the main reason for this distribution. Since 2018, salinity in the Plume and the Gulf has varied, with higher anomalies from 2010 to 2020. It can be concluded that the southern water is saltier, even though the decrease is the same as in 2015. The maximum SSS anomaly in the Plume and Gulf domains occurred in winter, exceeding 0.5 psu. This increase in SSS may be a factor in the more severe saline intrusion observed in recent years. The relationship between Chla concentration and freshwater discharge was not identical to that with SSS because algae required time to grow in response to riverine nutrients. The cross-correlation showed that the time lag between the Plume region in SSS and Chla concentration is 1 month, whereas it is 2 months in the East domain. In the Gulf, the time lag for SSS is 5 months, but it is only 2 months for ocean color. However, the primary causes of the time lag between freshwater discharges, SSS, and Chl-a concentration, as well as the assessment of their magnitudes under different impacts, remain open questions for future studies. In addition, a numerical ocean model should be used to study the mechanisms of freshwater discharge transport and the oceanic field responses to it, as well as to other forcings, such as monsoon winds, ENSO, and air-sea interaction processes.

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Conflict of interest

The authors declare that the research was conducted without commercial or financial relationships that could create a conflict of interest.

Data Availability Statement

The CCI salinity data can be downloaded at https://climate.esa.int/en/projects/sea-surface-salinity/. The ERDDAP Chlorophyll-a data are available to the public at https://coastwatch.pfeg.noaa.gov/erddap/griddap/, while the HYCOM data are available at https://www.hycom.org.

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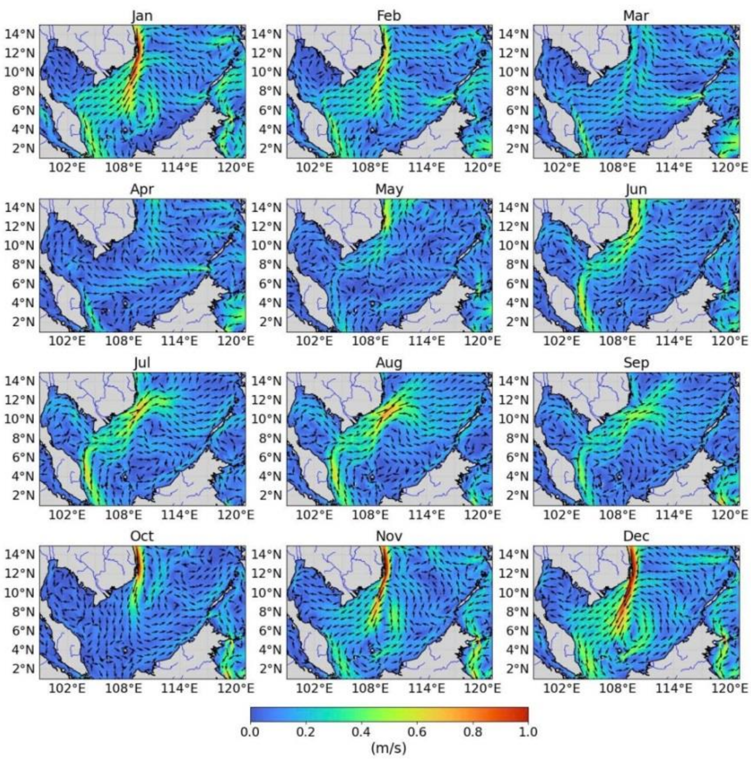
APPENDIX



Appendix 1. Monthly surface current fields in the period of 2010-2020