Detecting chlorophyll-a concentration and bloom patterns in the coastal area around Indonesia's new capital city (Nusantara) using ocean color reanalysis data

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Abstract. The concentration of chlorophyll-a is crucial in assessing marine productivity and harmful algal blooms. This study utilized ocean color reanalysis data from 1 January 2019 to 31 December 2021. The distribution of chlorophyll-a concentration and its relationship to various environmental parameters is analyzed with Principal Component Analysis (PCA). The PCA results demonstrate that chlorophyll-a concentration is significantly influenced by nitrate, phosphate, silicate, sea surface salinity (SSS), dissolved oxygen (DO), solar radiation, river discharge, rainfall, and sea surface temperature (SST), with a variance of 90.07%. Different parameters dominate at different times of the year. From February to April, it was affected by nitrate, silicate, DO, and solar radiation, while phosphates and SSS had a significant influence from July to November. River discharge and rainfall were the most predominant factors from June to January, while SST mainly influenced chlorophyll-a concentration in May and December. This study also identified the occurrence of two algal blooms in Balikpapan Bay. Concentration of up to 40 mg m^3 were found in November 2019 and June 2020, lasting for an average of five days with a bloom period peak of one day. The November 2019 event was triggered by an intensive increase in phosphates concentration within five days, while the June 2020 event resulted from unusually high rainfall followed by an increase in nutrients.

Key Words: chlorophyll-a variability, harmful algal blooms, Balikpapan Bay, Nusantara City.

Introduction. The current plans of the Indonesian government to relocate the national capital from Jakarta to Nusantara City (SETKAB 2022), situated in East Kalimantan province, with Balikpapan Bay as the new capital's coastal location (Putri et al 2021), have highlighted the significance of understanding the water mass dynamics in Balikpapan Bay (Nurjaya et al 2018; Anwar et al 2021; Fauzah et al 2021; Putri et al 2021; Hermansyah et al 2020; Nur et al 2018; Nur et al 2021). This bay is affected by various environmental factors, such as the ocean dynamics of Makassar Strait and river runoff that vary seasonally due to diurnal and seasonal rainfall variations. Seasonal rainfall is characterized by wet seasons that last from November to December and March to April, while the dry season occurs from August to October (Nurdiati et al 2021; Ramadhan et al 2022). These water mass dynamics have been shown to impact the water quality, phytoplankton abundance, chlorophyll-a concentration, and other marine bio-geophysical parameters (Effendi et al 2016; Zainol et al 2020). Prevailing semidiurnal tide types in Balikpapan Bay increase phytoplankton abundance and nutrients within the water column (Zhang et al 2020; Ho 2022). However, human-induced pollution, such as oil spills (Gade et al 2017; Setiani & Ramdani 2018; Nur et al 2020), domestic, industrial waste, and agricultural activities negatively affect the bay, causing ecological and environmental damage, possibly through the occurrence of harmful algal blooms (GEOHAB 2010; Zainol et al 2020; Li et al 2021). The harmful algal blooms (HAB) produce toxins harming marine life and humans or cause oxygen depletion, emphasizing better management strategies to reduce nutrient enrichment (GEOHAB 2010). Chlorophyll-a concentration has been identified as a proxy for estimating phytoplankton biomass (Kunarso et al 2023), including those types that can cause HAB in coastal waters (Nababan et al 2016; Tarigan & Wiadnyana 2013; Sidabutar et al 2022). High chlorophyll-a concentrations are frequently associated with HAB in coastal waters, indicating the growth of harmful algae fueled by nutrients in the water. Thus, long-term monitoring of chlorophyll-a levels and other environmental variables, such as nutrient concentration and oceanographic conditions, can aid in predicting the occurrence of HAB and contributing to the development of effective risk management strategies (Maslukah et al 2019; Mahmudi et al 2020; Badriana et al 2023).

Despite the extensive research on HAB in several Indonesian bays such as Jakarta Bay (Tarigan & Wiadnyana 2013; Sidabutar et al 2020; Sidabutar et al 2021), Lampung Bay (Aditya et al 2015; Thoha et al 2019), and Ambon Bay (Mahmudi et al 2020; Likumahua et al 2020; Likumahua et al 2021), research in Balikpapan Bay is limited. However, there is suspected evidence of the occurrence of algal bloom (Iswinarto 2020; Almutoif 2023) and other types of phytoplankton causing them (Budiarsa & Rafii 2013). Given that a portion of the coast of Balikpapan Bay is within the territory of the country's capital city, there is a substantial risk of increased nutrient enrichment originating from domestic and industrial waste (Zhang et al 2016). Therefore, it is critical to investigate the variability of chlorophyll-a concentration and potential occurrence of HAB as well as analyze the environmental parameters potentially affecting them in Balikpapan Bay. This study utilizes data from daily ocean color reanalysis (E.U. Copernicus Marine Service Information 2023b), temperature and salinity from hydrodynamic models (Anwar et al 2021), nutrients from ecosystem models (E.U. Copernicus Marine Service Information 2023a), river discharge (Harrigan et al 2020), and atmospheric parameters (Pusat Database BMKG 2023).

This study aimed to detect algal bloom occurrences using chlorophyll-a concentration and explore its variability and correlation with environmental parameters. The results of this research are expected to contribute to a better understanding of Balikpapan Bay's ecological and environmental dynamics and develop effective management strategies to prevent HAB and mitigate their harmful effects on marine ecosystems and human health.

Material and Method

Description of the study sites. Balikpapan Bay is a semi-enclosed water area located in Kalimantan Timur, between the coast of Nusantara City, in the head part of the bay, and Balikpapan City and Penajam Paseur Utara Regency, in the mouth part of the bay. Balikpapan Bay oriented on a north-south axis (of approximately 35 km), with the head of the bay in the northern part and the mouth of the bay in the southern part. The width of the bay is around 1–8 km (Nurjaya et al 2018; Putri et al 2021). The Balikpapan Bay receives fresh water from the land through four major rivers: Sepaku, Semoi, Wain and Riko Rivers (Nur et al 2020; Nur et al 2021). In contrast, the saline water comes from the Makassar Strait via the mouth of the bay (Hermansyah et al 2020). The Balikpapan Bay and the surrounding area can be seen in Figure 1.

Material. This study utilizes various data sources, including surface chlorophyll-a concentration, temperature, salinity, nitrate, phosphate, silicate, dissolved oxygen, rainfall, and solar radiation. The ocean color reanalysis data (OCEANCOLOUR_GLO_BGC_L4_MY_009_104), available from the Copernicus Marine Environment Monitoring Service (CMEMS), are used for daily surface chlorophyll-a concentration. This data integrates information from Sea-viewing Wide Field-of-view Sensor (SeaWiFS), MODIS-Aqua, MODIS-Terra, The Medium Resolution Imaging Spectrometer (MERIS), Visible Infrared Imaging Radiometer Suite - Suomi National

Polar-Orbiting Partnership (VIIRS-SNPP), Ocean and Land Color Instrument - Sentinel 3A & Sentinel 3B (OLCI-S3A&S3B), and other satellite data, and has a spatial resolution of 4 km x 4 km (E.U. Copernicus Marine Service Information 2023b).

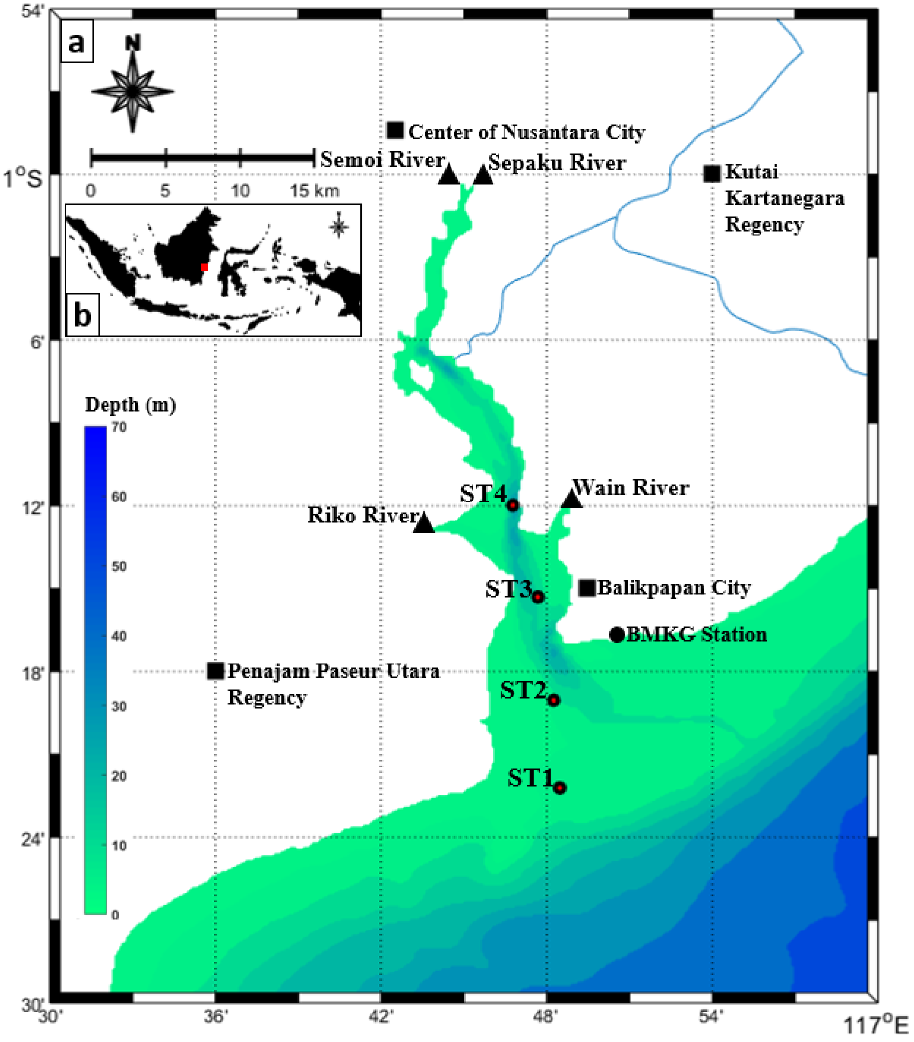

Figure 1. (a). Bathymetry map of Balikpapan Bay and its surrounding area. The chlorophyll-a sampling station shown in red–black dots, Center Nusantara City, Penajam Paseur Utara Regency, Kutai Kartanegara Regency, and Balikpapan City are indicated by solid black boxes, Sepaku, Semoi, Wain, and Riko Rivers are indicated by solid black triangles, BMKG Station in a solid black dot. (b) The inset map is the area of Indonesia, with the study area indicated by a red box.

For daily surface temperature and salinity, simulation results from the Hamburg Shelf Ocean Model (HAMSOM) are used for Balikpapan Bay and surrounding waters, with a spatial resolution of 0.15 x 0.15 km (Anwar et al 2021). Daily river discharge reanalysis data are retrieved from the Global Flood Awareness System (GloFAS-ERA5), with a horizontal resolution of 0.1° x 0.1° (approximately 11.1 km) at a daily time step (Harrigan et al 2020). Discharge data from the Sepaku, Semoi, Wain, and Riko Rivers, the core river systems in Balikpapan Bay, are used in this study. daily nitrate (NO_3), phosphate (PO_4), silicate (Si), and dissolved oxygen (DO) data are obtained from the Global Ocean Biogeochemistry Analysis and Forecast (GLOBAL_ANALYSIS_FORECAST_BIO_001_028), with a spatial resolution of 0.25° x 0.25° (E.U. Copernicus Marine Service Information 2023a). Daily solar radiation data are obtained from hourly of ERA5 data (Hersbach et al 2023) and have a spatial resolution of 0.25° x 0.25° (approximately 27 km). Daily rainfall data are obtained from BMKG Sepinggan, Balikpapan, accessed at Pusat Database BMKG. All spatial data used in this study corresponds to an area located between 1.5S - 1S and 116.5E - 117E (Figure 1) covering years 2019-2021.

Method. Verification is performed using chlorophyll-a concentrations obtained in-situ and from MODIS. The in-situ measurements were conducted twice on 1 June 2021 and 14 October 2021 at eight stations, but only four stations were used for verification. The verification is aimed to evaluate the magnitude and time series pattern of chlorophyll-a concentration, based on the corrected ocean color reanalysis data. Correlation Coefficient (CC) and Root Mean Square Error (RMSE) are applied to calibrate and validate chlorophyll-a concentration from ocean color reanalysis, in-situ, and MODIS data. Principal Components Analysis (PCA) is employed to analyze the correlation and contribution of seawater and atmospheric parameters to the variability of chlorophyll-a concentrations. The monthly means of sea surface temperature, salinity, nitrate, phosphate, silica, dissolved oxygen, total river discharge, rainfall, and solar radiation serve as active variables. In contrast, chlorophyll-a concentration is used as active observation. XLSTAT 2019 is used to perform PCA on this data. The daily and spatial means of chlorophyll-a concentration are used to analyze algal bloom events in Balikpapan Bay. The threshold for algal bloom events is determined by following research conducted using MODIS (Tarigan & Wiadnyana 2013), with modifications of the magnitude following the RMSE between in-situ, MODIS, and ocean color reanalysis data. Then Ocean Data View v.5.1.2 was employed to plot the spatial chlorophyll-a concentration during an algal bloom. Thus, the Data-Interpolating Variational Analysis applied to spatial interpolation in Balikpapan Bay waters.

Results. To ensure the quality of the ocean color reanalysis data, a comparison was made between in-situ and ocean color reanalysis data along with monthly mean MODIS imagery and ocean color reanalysis data, before conducting a comparison of time-series analysis to ocean color reanalysis chlorophyll-a data. Figure 2 shows the comparisons between in-situ and reanalysis data at four stations and Figure 3. exhibits the monthly spatial mean for MODIS satellite imagery data and ocean color reanalysis data from January 2019 to December 2021 in Balikpapan Bay and surrounding water.

Due to the limited spatial range of ocean color reanalysis, only stations 1, 2, 3, and 4 successfully matched the data out of the eight stations observed in the survey. The range of chlorophyll-a concentration values from ocean color reanalysis was found to be 0.8–1.6 mg m^{-3}, while the range from in-situ measurements was 0.35–0.95 mg m^{-3}. In October, the chlorophyll-a value ranged from 0.55–1.4 mg m^{-3} for the ocean color reanalysis and 0.6–0.8 mg m^{-3} for the in-situ data. Figures 2a and 2b show the same pattern found between in-situ data and satellite imagery and is supported by a correlation coefficient of >0.9 with a significance level of 95%. The calculated root mean square error is 0.50 mg m^{-3} in June and 0.52 mg m^{-3} in October, indicating that ocean color reanalysis overestimates the in-situ data average by 0.51 mg m^{-3}. Nonetheless, the spatial pattern generated by the ocean color reanalysis data matches the in-situ data pattern, confirming the effectiveness of ocean color reanalysis data for spatial analysis.

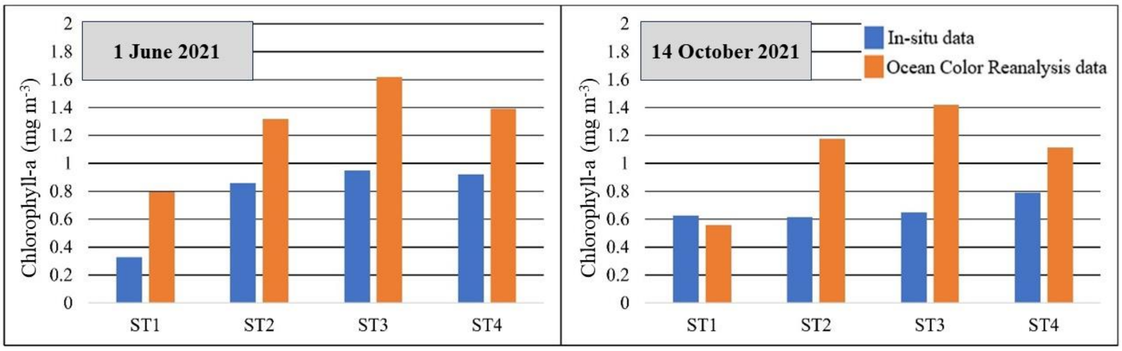

Figure 2. Chlorophyll-a concentration from in-situ and ocean color reanalysis data on 1 June 2021 and 14 October 2021 at four stations (Figure 1) in Balikpapan Bay.

Figure 3 displays the compared monthly means of chlorophyll-a concentrations between MODIS satellite imagery data and ocean color reanalysis data. The monthly mean chlorophyll-a concentration ranges from 1.25–2.13 mg m^{-3} for ocean color reanalysis data and 2.06–4.21 mg m^{-3} for MODIS data. The correlation between the two data sets is 0.7, with a significance level of 95%, indicating a considerable similarity in their time-series patterns. In 2019, the MODIS data pattern displayed a bow shape, while the ocean color reanalysis data exhibited two bows. However, MODIS and ocean color reanalysis data displayed similar patterns in the following two years. Although the correlation coefficient did not have an excellent value (>0.9), the time-series pattern and gap value seem visually and statistically sound. The root means square error between the MODIS and ocean color reanalysis data is 1.49 mg m^{-3}, suggesting that MODIS data overestimates ocean color reanalysis data. This finding is consistent with Khalil et al (2009), who also investigated chlorophyll-a concentration on the East Coast of Kalimantan using in-situ and MODIS data. They found that MODIS overestimated the concentration with an RMSE of 1.12 mg m^{-3}. Blondeau-Patissier et al (2004) also found MODIS to overestimate data in coastal water areas, which is common in turbid coastal waters. Nevertheless, ocean color reanalysis data is still useful for long-term time-series analysis.

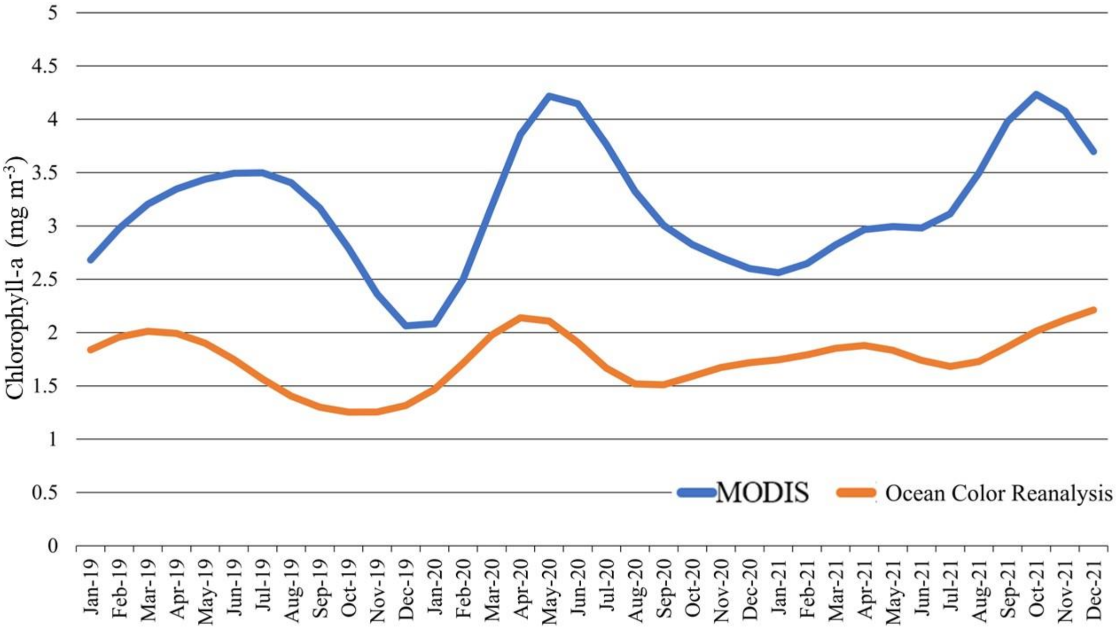

Figure 3. Monthly mean of chlorophyll-a concentration from MODIS satellite data and ocean color reanalysis data during January 2019 – December 2021 at Balikpapan Bay.

Monthly composite of chlorophyll-a concentration and ocean-atmospheric parameters. Figure 4 shows the monthly mean composite of chlorophyll-a concentration, total river discharge, rainfall, solar radiation, sea surface temperature (SST), sea surface salinity (SSS), nitrate (NO_3), phosphate (PO_4), silicate (Si), and dissolved oxygen (DO) during 2019-2021 in Balikpapan Bay. The chlorophyll-a concentration decreased from 1.95 mg m^{-3} to 1.61 mg m^{-3} between January and March, increased to 1.92 mg m^{-3} in April, and decreased to 1.53 mg m^{-3} by July. The concentration increased again in the year's second half, reaching 1.85 mg m^{-3} by December, with an annual mean of 1.75±0.13 mg m^{-3}. This value and pattern are similar to previous research conducted on the east coast of Kalimantan by Khalil et al (2009), who reported a range of chlorophyll-a concentration as around 1-4 mg m^{-3}, with less chlorophyll-a concentration in the dry season than in the wet season. Additionally, Ningsih et al (2021) also found the annual mean of chlorophyll-a concentration to be up to 1.5 mg m^{-3}. The monthly composite of total river discharge is a summation from Sepaku, Semoi, Wain, and Riko Rivers. It shows a seasonal pattern with two peaks a year, which can be separated into two periods: January to June and July to December. The monthly composite of total river discharge in January is around 255 m^3 s^{-1}, decreases to the lowest level in March with a discharge of 203 m^3 s^{-1}, then immediately increases to 262 m^3 s^{-1} in April, the first period. The value then decreases until August, with the lowest discharge of 135 $m^{-3}·s^{-1}$, and increases again till the peak in December, with a total discharge of 220 m^3 s^{-1}. The total discharge from January to June is higher than from July to December. The total river discharge values range is the same as the research conducted by Nur et al (2021). The monthly composite pattern of chlorophyll-a correlates with total river discharge, except for February. The total river discharge increased from 254 m^3 s^{-1} in January to 260 m^3 s^{-1} in February, while the chlorophyll-a concentration decreased from 1.95 mg m^{-3} in January to 1.74 mg m^{-3} in February. Overall, however, the total river discharge has a similar pattern to chlorophyll-a concentration.

The monthly rainfall shows two peaks in a year, but the river discharge shifts the pattern. The peak of rainfall occurs in January with a value of 365.23 mm $month^{-1}$, and the first lowest level is in March with a value of 196.56 mm $month^{-1}$. The second peak is in June, with a value of 379.73 mm $month^{-1}$, while the second lowest level is in November, with a value of 169.26 mm $month^{-1}$. The shifting time of the monthly peak between river discharge and rainfall indicates that the discharge is not generated by local rainfall; instead, it might be generated by the hydroclimate system over Balikpapan Bay, from where the river originates. According to research by Nurdiati et al (2021) and Ramadhan et al (2022), the wet season's peak in the northern area of Balikpapan Bay occurs from November to December and March to April, while the driest period occurs from August to October. These seasonal patterns align with total river discharge. Therefore, the mentioned research studies support the allegation that upstream rainfall generates river discharge.

The monthly solar radiation displays a pronounced seasonal pattern, characterized by two peaks and two valleys in a year, which are inversely related to the monthly rainfall. Based on the available data, it can be inferred that the radiation levels vary from 0.85 MJ m^{-2} to 0.94 MJ m^{-2}. Specifically, the solar radiation for January is observed to have a mean value of 0.88 MJ m^{-2}, which steadily increases towards its first peak in March with a mean value of 0.94 MJ m^{-2}, before declining to its lowest level in June with a mean value of 0.85 MJ m^{-2}. Subsequently, solar radiation shows an increasing trend again, reaching its peak in October with a recorded value of 0.95 MJ m^{-2}. Overall, these findings suggest the importance of considering the impact of seasonal solar radiation variability on oceanographic processes and climate dynamics. This seasonal solar radiation is also like research conducted by Hendrizan et al (2020). Based on the data presented, the monthly SST exhibits a pattern like rainfall, with an exception being the earlier peak for SST. The mean SST value for January is observed to be around 29°C. It then decreases to 28.8°C in February and rises again, attaining its highest value in May with a mean SST reading of 29.7°C. After that, the SST level was significantly reduced again, reaching its lowest value in August, with a mean SST temperature of 28.6°C. In the following months, the SST displays an upward trajectory, culminating in its second peak in November with a recorded value of 29.5°C. These findings suggest the relevance of seasonal SST changes in understanding oceanographic processes and marine ecosystem dynamics. For comparison (Nur et al 2018), using 3-D Regional Ocean Modeling System (ROMS) simulated the changes in water mass characteristics in Balikpapan Bay. Based on their simulation results, the SST of Balikpapan Bay from October 2012 to January 2013, both in the inner and outer bay, ranges between 29°C and 30°C. Moreover, Putri et al (2021) based on an oceanographic survey in Balikpapan Bay in March 2020, obtained an SST range between 29°C and 30°C in the outer bay and between 30°C and 32°C in the inner bay.

The monthly SSS variations exhibit a distinct seasonal pattern that differs from other ocean-atmospheric parameters. Based on the available data, it can be inferred that the SSS value ranges from 28.64 PSU in April to 29.25 PSU in March, between January and July. Subsequently, the SSS value displays a significant increase, with its peak recorded in September at 31.1 PSU. After that, the SSS level significantly reduced again in the following months, reaching a value of 29.8 PSU in December. It is worth noting that Putri et al (2021) study reported an SSS range of 29 to 33 PSU, measured in March 2020. Hence, the SSS value utilized in this study falls within the range of the in-situ values, thereby making the study an appropriate point of reference for subsequent research to understand the dynamics of ocean salinity processes.

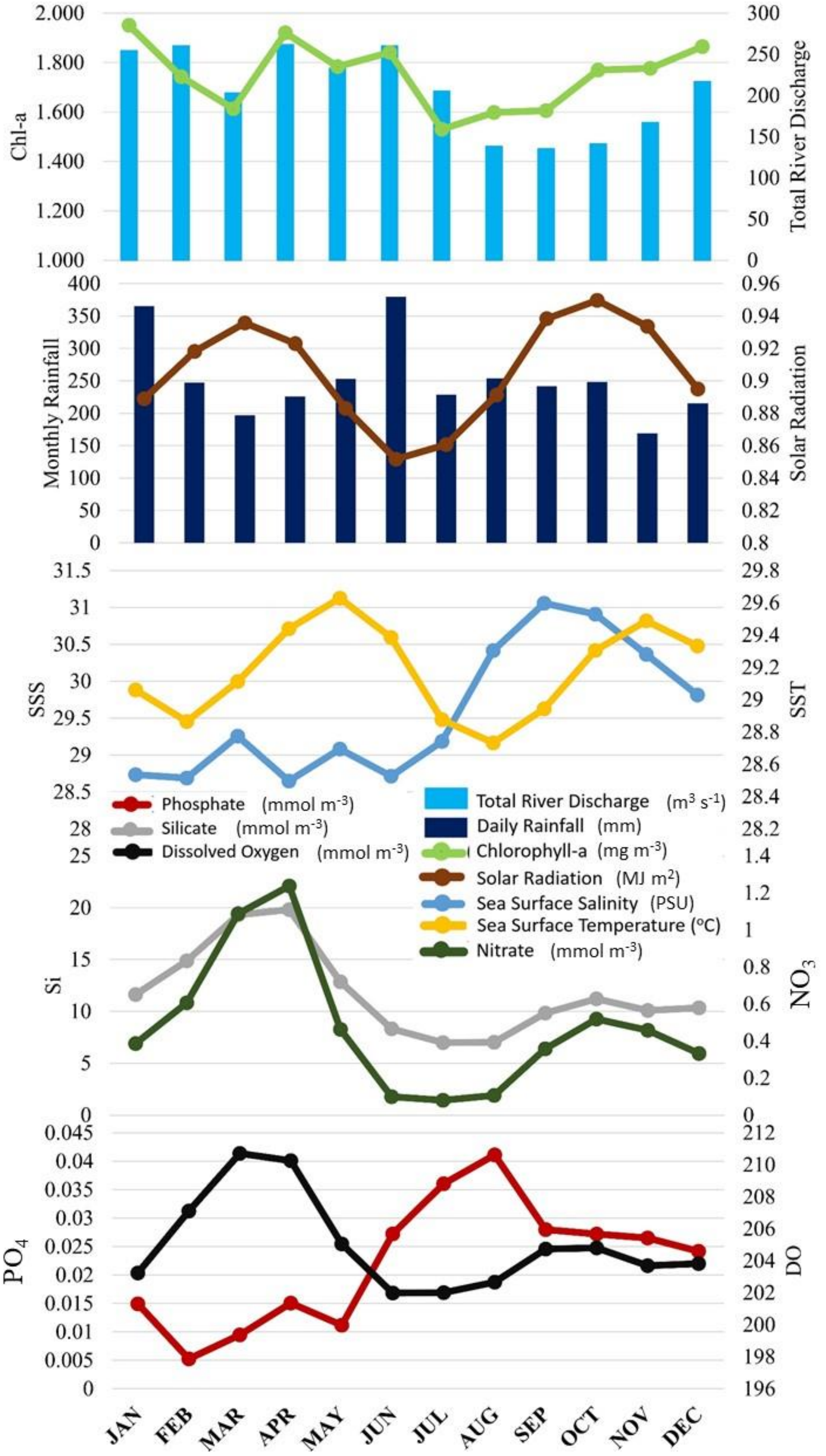

Figure 4. Monthly composite of chlorophyll-a concentration, total river discharge, rainfall, solar radiation, sea surface temperature (SST), sea surface salinity (SSS), nitrate (NO_3), phosphate (PO_4), silicate (Si), and dissolved oxygen (DO) during 2019-2021, at Balikpapan Bay.

This study presents a monthly composite of nutrients using concentrations of nitrate, phosphate, and silicate. The data reveals that nitrate and silicate concentrations exhibit a similar seasonal pattern, with peaks observed in April (1.23 mmol m^{-3} for nitrate and 19.8 mmol m^{-3} for silicate) and October (0.52 mmol m^{-3} for nitrate and 11.2 mmol m^{-3} for silicate). Conversely, nitrate's lowest values were recorded in June (0.009 mmol m^{-3}) and silicate in August (7.02 mmol m^{-3}), respectively. Moreover, the monthly peak average for phosphate was observed in August, with a value of 0.041 mmol m^{-3}, while the lowest value was recorded in February, with a value of 0.0052 mmol m^{-3}. These findings highlight the importance of considering nutrient variations in understanding the biogeochemical processes driving marine productivity and ecosystem dynamics. The study presents monthly data on various oceanographic parameters in Balikpapan Bay from 2019 to 2021. The chlorophyll-a concentration had a mean value of 1.75 ± 0.13 mg m^{-3}, consistent with previous research on the east coast of Kalimantan. Total river discharge exhibited a seasonal pattern, with two yearly peaks, and correlated with chlorophyll-a concentration. Monthly rainfall also had two peaks per year with shifting peaks compared to total river discharge, which may indicate an origin in the hydroclimate system over Balikpapan Bay. Solar radiation had a distinct seasonal pattern, inversely correlated with monthly rainfall. Monthly SST followed a pattern like rainfall, with an earlier peak, while SSS followed a distinctly seasonal pattern. Nutrient variations, namely nitrate, phosphate, and silicate concentrations, showed seasonal patterns crucial in understanding the biogeochemical processes pivotal to marine productivity and ecosystem dynamics. These findings provide valuable insight into the significance of seasonal patterns in understanding oceanographic and climate dynamics.

Principal component analysis of the monthly composite of chlorophyll-a concentration and ocean-atmospheric parameters. As mentioned earlier, there is a seasonal pattern similarity between chlorophyll-a concentration and ocean-atmospheric parameters, which include SST, SSS, solar radiation, total river discharge, rainfall, DO, nitrate, phosphate, and silicate. A PCA analysis was conducted to investigate the relationship between chlorophyll-a concentration and environmental parameters. The analysis identified three significant modes, F1, F2, and F3, with a total variability of 90.07%. However, Figure 5 only displays modes F1 and F2, with a total variability of 79.83%, as mode F3 with cosine2 above 0.5 only comprises SST. Therefore, mode F3 can be represented by its SST variability. Hence, modes F1 and F2 need to be examined in detail to determine the contribution of each parameter to their variability.

Based on Figure 5, three clusters can be observed between the active variables, the environmental parameters, and the active observations, which are the monthly mean of chlorophyll-a concentration. Two clusters are from mode F1 and one from mode F2. The positive mode F1 is circled with a solid line, including the variables solar radiation, DO, nitrate, and silicate. This first cluster is crucial in chlorophyll-a concentration, particularly from February to April. The second cluster, from the negative mode F1, comprises SSS and phosphate. The effect of these two parameters on chlorophyll-a concentration is strong, mainly from July to November, and shown by the dashed line boundary. The third cluster is from the negative mode F2, where rainfall and total river discharge are the influential parameters. Both parameters strongly affect chlorophyll-a concentration in January and June, as shown by the dot-dash line boundary. The detailed contribution of each parameter to each mode is as follows: For cluster one, the contributions are 20.03% for DO, 22.46% for silicate, 20.72% for nitrate, and 4.75% for solar radiation. This event indicates that DO and nutrients dominate more than solar radiation in developing chlorophyll-a. For cluster two, SSS and phosphate contribute 5.03% and 17.12%, respectively. This event suggests that the influence of SSS is not more significant than that of nutrients in the development of chlorophyll-a. Finally, for cluster three, total river discharge and rainfall contribute with 25.28% and 19.21%, respectively. These results show that the roles of river discharge and rainfall are not significantly different in increasing chlorophyll-a concentration.

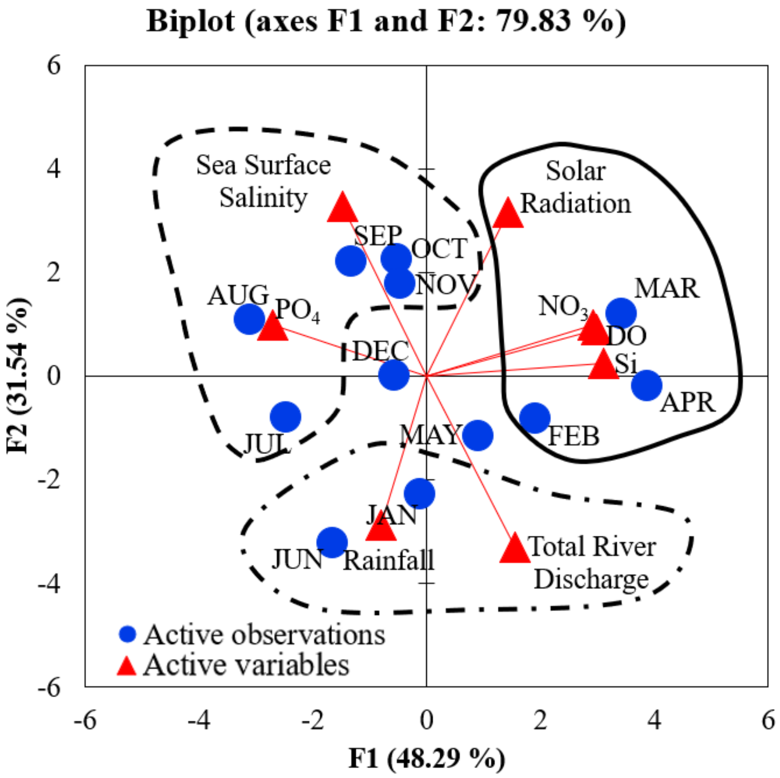

Figure 5. Correlation of monthly chlorophyll-a concentration with total river discharge, rainfall, solar radiation, sea surface temperature (SST), sea surface salinity (SSS), Nitrate (NO_3), Phosphate (PO_4), Silicate (Si), and Dissolved Oxygen (DO) during 2019 – 2021 at Balikpapan Bay.

A study has revealed a seasonal pattern similarity between chlorophyll-a concentration and ocean-atmospheric parameters, including SST, SSS, solar radiation, total river discharge, rainfall, DO, nitrate, phosphate, and silicate. PCA identified three significant modes, F1, F2, and F3, with a total variability of 90.07%. While mode F3 solely comprises SST, modes F1 and F2 must be examined to determine each parameter's contribution to their variability. Additionally, three clusters between environmental parameters and monthly mean of chlorophyll-a concentration were observed, where cluster one (DO, silicate, nitrate, and solar radiation) played a crucial role in chlorophyll-a concentration, mainly from February to April. Meanwhile, cluster two (SSS and phosphate) had a strong influence mainly from July to November. Lastly, cluster three (total river discharge and rainfall) significantly increased chlorophyll-a concentration in January and June. Nutrients and DO were found to be more dominant than solar radiation.

Time series and spatial analysis of algal bloom even based on chlorophyll-a concentration approach. Based on the daily ocean color reanalysis data from 1 January 2019 to 31 December 2021, two instances of algal bloom were identified, marked by a chlorophyll-a concentration above 8.5 mg m^{-3} (Tarigan & Wiadnyana 2013). Figure 6 illustrates algal bloom occurrences in June and November, specifically on 16 June 2020, and 9 November 2019. Algal bloom on 9 November 2019, peaked four days after neap tide or 11 days after spring tide. On the other hand, the algal bloom on 16 June 2020, occurred two days after neap tide or nine days after spring tide. These findings are consistent with previous studies that suggest algal bloom occurs after spring tide and could happen right after or after neap tide before the next spring tide. The intense mixing influences this pattern during spring tide, relatively calm water dynamics after the tide, and the calmest period during neap tide. Algal bloom can occur when the water becomes rich in nutrients during mixing and smaller tidal range. After identifying the algal bloom occurrences during 2019-2021, a detailed daily time series analysis was conducted for the two events. Figure 7 displays the chlorophyll-a concentration with all environmental parameters from 2 November 2019 to 17 November 2019, approximately seven days before and after the peak algal bloom occurrence. Similarly, Figure 8 illustrates the same information for 9 June 2020 to 24 June 2020. Figures 9 and 10 also present the spatial chlorophyll-a concentration during the six-day algal bloom events in November 2019 and June 2020, respectively.

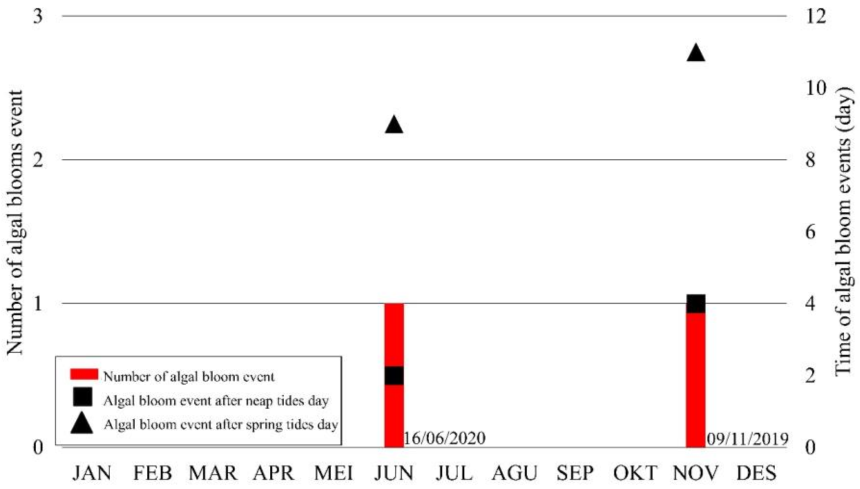

Figure 6. Algal bloom events based on the daily spatial mean of chlorophyll-a concentration during 1 January 2019 – 31 December 2021 at Balikpapan Bay.

Figure 7 shows the daily mean chlorophyll-a concentration and all environmental parameters for the November 2019 algal bloom events. Chlorophyll-a concentration started to increase on 6 November 2019, with a concentration of 2.21 mg m^{-3}, while on the previous day (5 November 2019), the concentration was 0.45 mg m^{-3}. The concentration continued to rise to 2.56 mg m^{-3}, then 6.8 mg m^{-3}, and peaked at 10.43 mg m^{-3} on 9 November 2019. The day after the peak algal bloom occurrence, on 10 November 2019, the chlorophyll-a concentration dropped to 1.15 mg m^{-3}, and for the next seven days, it remained in the range of 1-1.9 mg m^{-3} before returning to pre-algal bloom levels. The November 2019 algal bloom event was characterized by a low-to-high chlorophyll-a development that plummeted instantly, influenced by environmental factors. Phosphate and salinity were previously analyzed, the dominant factor contributing to chlorophyll-a phosphate and salinity, consistent with the PCA analysis shown in Figure 6. Phosphate concentrations began to rise on November 2, peaking on November 6, from 0.00038 mmol m^{-3} to 0.00218 mmol m^{-3}, increasing almost tenfold within five days. However, the phosphate concentration gradually decreased and returned to its initial levels, requiring eleven days. Salinity increased from 33.09 PSU on 4 November 2019 to a peak of 33.46 PSU on 7 November 2019, then gradually decreased and returned to 33.06 PSU after six days. Based on this description, the peak of the algal bloom event and the peak of phosphate and salinity increase had a three-day gap. Additionally, high river discharge was observed from 3 November 2019 until the peak of the algal bloom on 9 November 2019, with a daily discharge ranging from 38-48 $m^3 s^{-1}$. There was also rainfall from 2 November 2019 to 6 November 2019, ranging from 2.0 mm day^{-1} to 16.5 mm day^{-1} during the algal bloom process from 6 November 2019 to 9 November 2019, while solar radiation ranged from 0.93 MJ m^{-2} to 0.94 MJ m^{-2}. After the peak algal bloom event, chlorophyll-a values did not immediately return to pre-event levels, presumably sustained by the increased nitrate and silicate. Nitrate values increased from 5 November 2019 with 0.0079 mmol m^{-3}, peaking on 11 November 2019 with 0.0274 mmol m^{-3}, then remaining in that range for six days. Silicate increases began on 7 November 2019 with a value of 4.43 mmol m^{-3}, peaking on 11 November 2019 with 4.56 mmol m^{-3}. During this algal bloom event, the dissolved oxygen (DO) value increased from 199.32 mmol m^{-3} to 199.23 mmol m^{-3} after the event, suggesting phytoplankton sinking to the bottom of the water and being processed by oxygen-demanding bacteria.

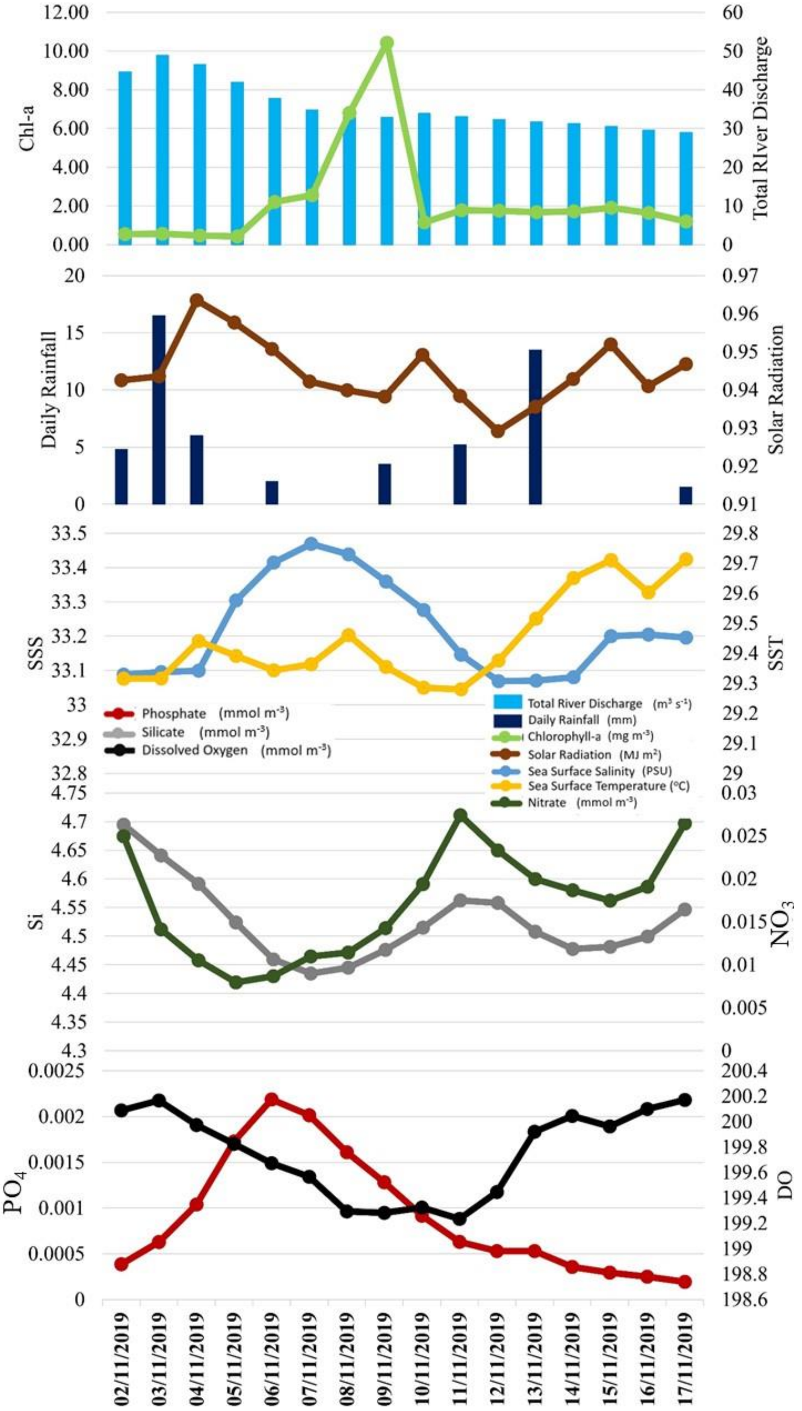

Figure 7. The daily spatial mean of chlorophyll-a concentration, total river discharge, rainfall, solar radiation, sea surface temperature (SST), sea surface salinity (SSS), nitrate (NO_3), phosphate (PO_4), silicate (Si), and dissolved oxygen (DO) during 2 November 2019 – 17 November 2019 at Balikpapan Bay.

Figure 8 presents the average daily concentration of chlorophyll-a along with environmental parameters during the algal bloom event in June 2020. This event differed from the one in November 2019, as the chlorophyll-a concentration spiked within a day.

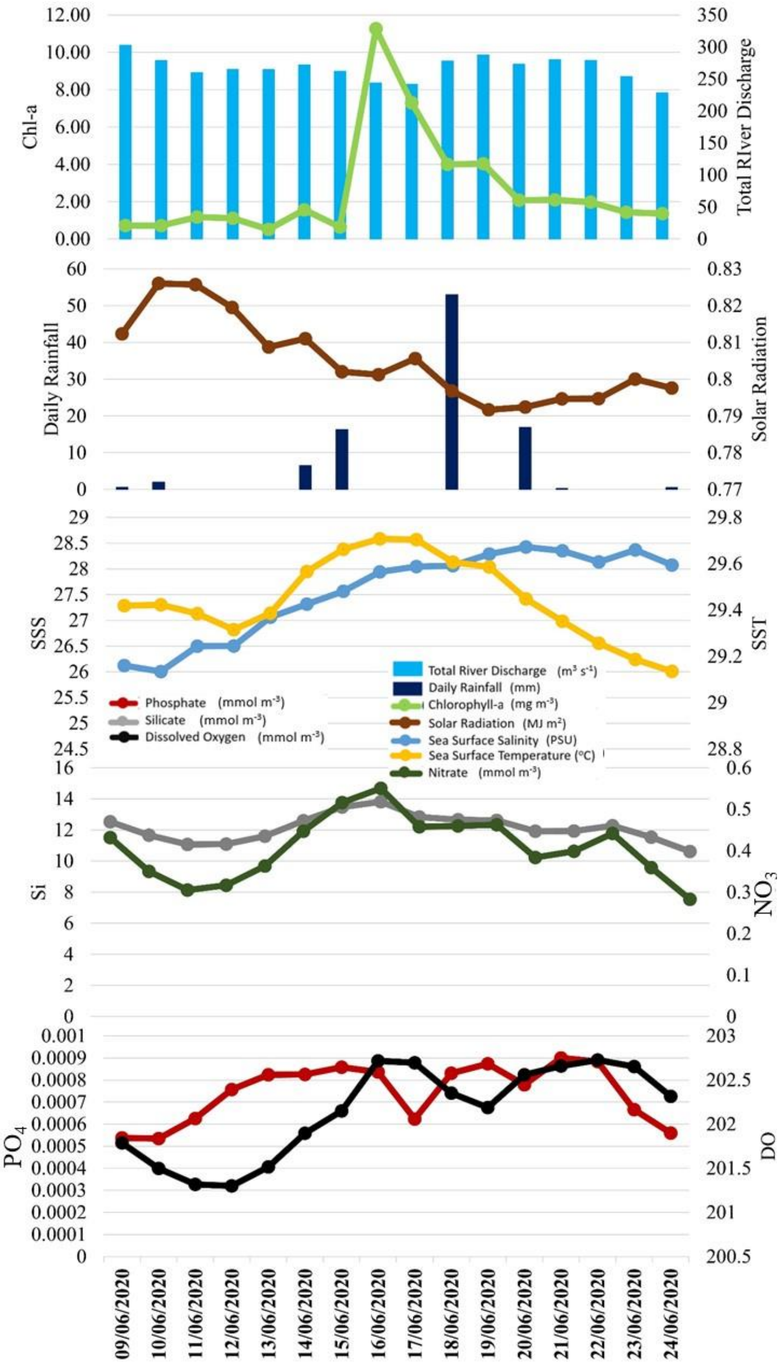

Figure 8. The daily spatial mean of chlorophyll-a concentration, total river discharge, rainfall, solar radiation, sea surface temperature (SST), sea surface salinity (SSS), nitrate (NO_3), phosphate (PO_4), silicate (Si), and dissolved oxygen (DO) during 9 June 2020 – 24 June 2020 at Balikpapan Bay.

On 15 June 2020, the concentration was 0.65 mg m^{-3}, then escalated to 11.27 mg m^{-3} on 16 June 2020. Afterward, the concentration decreased over seven days until it returned to typical values between 1-1.5 mg m^{-3}. Based on June's previous analysis, the most influential monthly composite parameters in June were river discharge and precipitation. As shown in Figure 8, the river discharge was between 260 m^3 s^{-1} and 302 m^3 s^{-1} before the algal bloom event, from 9 June 2020 to 15 June 2020. The river discharge was low, at 243 m^3 s^{-1}, during the event, but it increased again to 287 m^3 s^{-1} on 19 June 2020. Precipitation had occurred for four days before the algal bloom event, ranging from 0.6 to 16.3 mm day^{-1}. The highest daily rainfall occurred one day before the algal bloom event. The solar radiation parameter ranged from 0.79 to 0.8 MJ m^{-2}

during the event and from 0.81 to 0.82 MJ m^{-2} before. Additionally, SSS and SST increased during the event, from 29.4ºC (9 June 2020) to 29.7ºC (16 June 2020) for SST and from 26.12 PSU (9 June 2020) to 28.42 PSU (20 June 2020) for SSS. The nutrient increase before the algal bloom event was less significant than in November 2019, as it only doubled in June 2020. On the other hand, during the November 2019 event, the increase was as much as 10-fold. Moreover, the concentration of phosphates dropped from 0.0008 to 0.0006 mmol m^{-3} one day after the peak of the algal bloom event, indicating that the excess phosphates were consumed by the algae, causing an explosion of chlorophyll-a concentration in the water body. Additionally, DO increases from 201.3 to 202.7 mmol m^{-3} during the event and then decreased to its lowest point four days after, with a 202.1 mmol m^{-3} value. This was most likely due to dead algae being processed by oxygen-producing microbes.

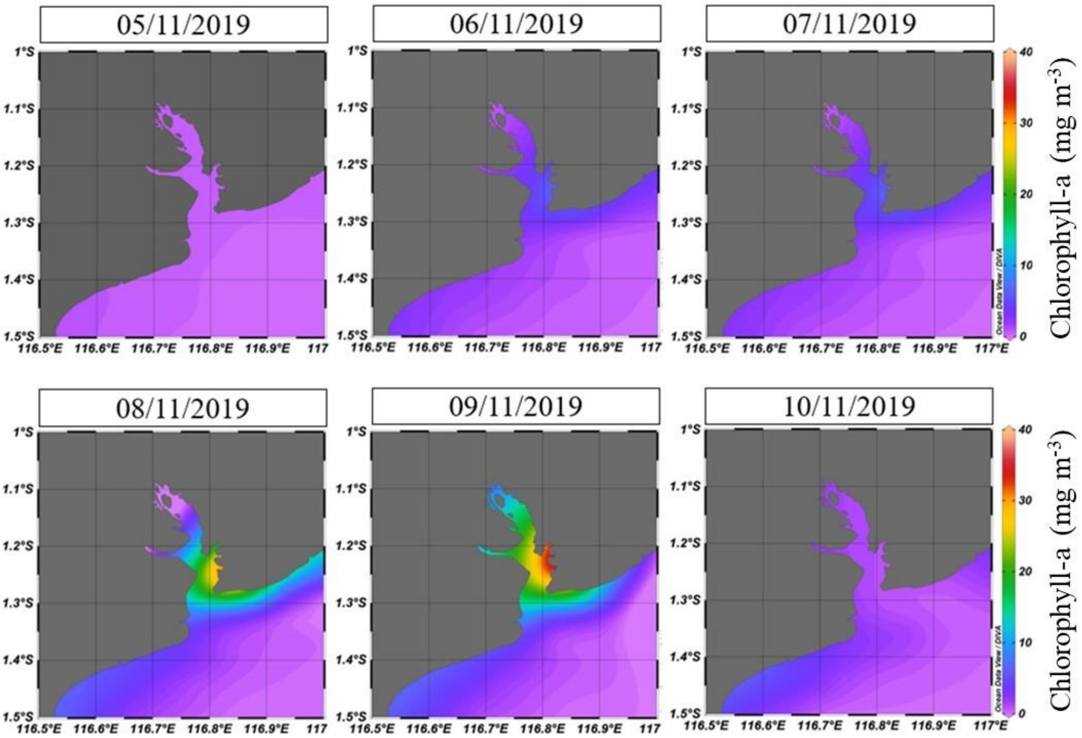

Figure 9. The daily mean of chlorophyll-a concentration during an outbreak of algal bloom on 5 November 2019 – 10 November 2019 at Balikpapan Bay.

Regarding time series analysis, the daily spatial average has indicated two algal bloom events between 2019 and 2021, namely in November 2019 and June 2020. The time series analysis also highlights the different characteristics of these two events. The November 2019 event displayed a gradual increase leading up to its peak, while the June 2020 event exhibited an immediate spike followed by a gradual decline. Figure 9 (November 2019) and Figure 10 (June 2020) present the spatial distribution of chlorophyll-a concentrations during these algal bloom events over six days (5-10 November 2019) and (15-20 June 2020).

In Figure 9, it is apparent that on 5 November 2019, the concentration of chlorophyll-a was below 1 mg m^{-3}. On the following day, 6 – 7 November 2019, it rose to 10 mg m^{-3} along the coast of Kota Balikpapan while remaining below 1 mg m^{-3} in offshore waters and upstream areas. The peak of the algal bloom occurred on November 8-9, with the concentration of chlorophyll-a reaching 40 mg m^{-3} at the Wain River estuary. It then spread to the middle of the bay with a concentration of 30 mg m^{-3} and along Balikpapan in a concentration of 10-15 mg m^{-3}. One day later, on November 10, the chlorophyll-a concentration returned to around 1 mg m^{-3} in the middle of the bay, while remaining between 3 and 5 mg m^{-3} along the coast. Therefore, based on the daily spatial pattern, it can be strongly suggested that the algal bloom originated from the Wain River estuary on the coast of Kota Balikpapan.

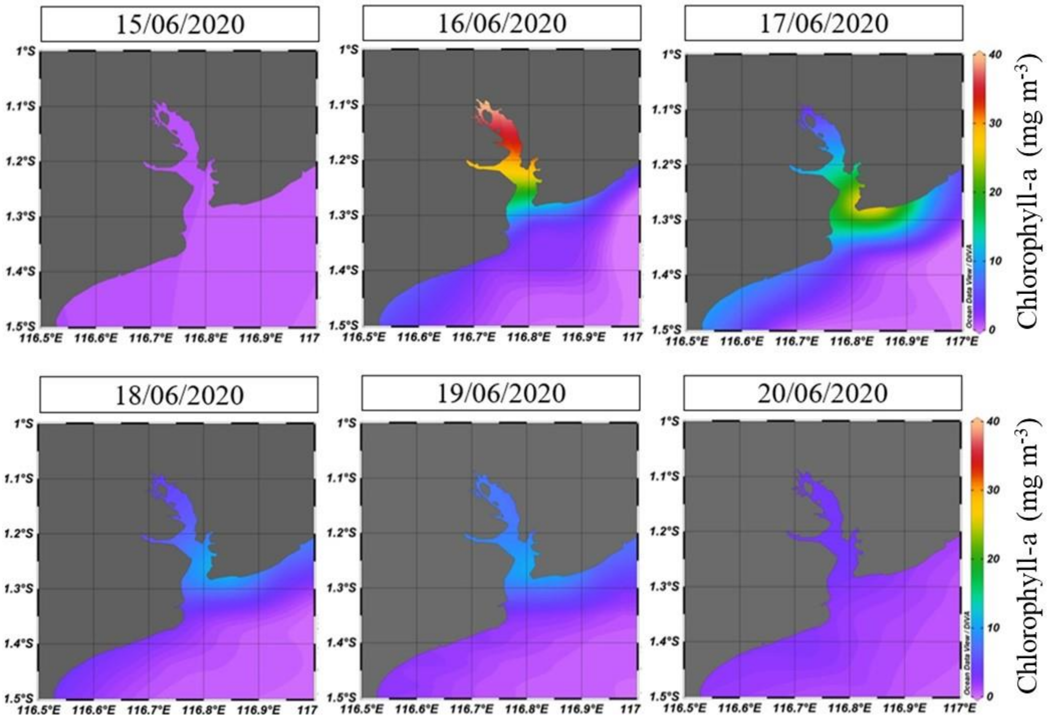

Figure 10. The daily mean of chlorophyll-a concentration during an outbreak of algal bloom on 15 June 2020 – 20 June 2020 at Balikpapan Bay.

The spatial concentration of chlorophyll-a during the algal bloom event in June 2020 is illustrated in Figure 10. On 15 June 2020, the chlorophyll-a concentration in the water ranged between 1-3 mg m^{-3}. However, on the following day (16 June 2020), the concentration of chlorophyll-a spiked to 40 mg m^{-3} in the upstream waters of the bay, 30 mg m^{-3} in the middle of the bay, and 15-20 mg m^{-3} at the mouth of the bay. Then, on 17 June 2020, the concentration declined to 15 mg m^{-3} in upstream waters, 20 mg m^{-3} in the middle of the bay, and 10 mg m^{-3} at the mouth of the bay. Additionally, the high concentrations were observed primarily along the coast of Kota Balikpapan. Over the next three days, the concentration decreased until it returned to normal levels on 20 June 2020, with chlorophyll-a concentrations around 1-3 mg m^{-3}. Based on the spatial pattern, the algal bloom event in June 2020 originated in the bay's upstream waters. After that, the bloom was maintained for two days in the Wain River estuary on the Kota Balikpapan coast, with lower concentrations (around 15 mg m^{-3}). Based on the information discussed above, it is apparent that the spatial increase in chlorophyll-a concentration, or algal bloom, consistently occurs at the river estuary and subsequently spreads to the middle of the bay and along the coast of Balikpapan Bay. This event indicates that the triggering source, such as nutrients and river discharge, always originates from the river. This event aligns with the previous explanations, as both PCA and time series analyses demonstrate consistency with the observed facts and explanations.

Discussion. To ensure data quality, comparisons were made between in-situ measurements, ocean color reanalysis data, and MODIS satellite imagery. The time-series analysis revealed a strong correlation between ocean color reanalysis data and satellite imagery for chlorophyll-a concentrations. However, the ocean color reanalysis data tended to overestimate in-situ data by an root mean square error of 0.51 mg m^{-3}. Despite this, the spatial pattern generated by the ocean color reanalysis data confirmed its effectiveness for spatial analysis (correlation >0.9). The correlation between monthly mean chlorophyll-a concentrations from MODIS and ocean color reanalysis data indicated similar time-series patterns. MODIS consistently showed an overestimation compared to the in-situ data, which aligns with previous studies conducted by Khalil et al (2009) and

Blondeau-Patissier et al (2004) on chlorophyll-a concentration. Nevertheless, ocean color reanalysis data remains a valuable resource for long-term time-series analysis.

The monthly composite of oceanographic parameters in Balikpapan Bay from 2019 to 2021 reveals interesting patterns and correlations. The chlorophyll-a concentration showed a mean value of 1.75±0.13 mg m^{-3}, similar to previous studies in the region (Ningsih et al 2021). The concentration displayed a seasonal variation, with higher values in the second half of the year compared to the first half. This pattern aligns with the findings of other researchers who reported higher chlorophyll-a concentrations during the wet season (Khalil et al 2009). Total river discharge, derived from multiple rivers, exhibited a clear seasonal pattern with two peaks per year. It correlated with the chlorophyll-a concentration, indicating the influence of river inputs on nutrient availability and phytoplankton growth. Monthly rainfall displayed two peaks per year, but the timing of the peaks differed from the total river discharge, suggesting an influence from the hydroclimate system over Balikpapan Bay (Nurdiati et al 2021; Ramadhan et al 2022). Solar radiation exhibited a distinct seasonal pattern, inversely correlated with the rainfall (Hendrizan et al 2020). This highlights the significance of considering seasonal solar radiation variability in understanding oceanographic processes and climate dynamics. The SST displayed a similar pattern to rainfall, with an earlier peak and higher values in the first half of the year. This pattern aligns with other studies and emphasizes the importance of seasonal SST changes in understanding oceanographic processes and marine ecosystems (Nur et al 2018; Putri et al 2021).SSS exhibited a distinct seasonal pattern, differing from other parameters. It showed an increase from January to September before decreasing again in the following months. This pattern provides insights into the dynamics of ocean salinity processes and demonstrates the relevance of considering SSS variations in studying marine ecosystems (Putri et al 2021). Nutrient concentrations, including nitrate, phosphate, and silicate, exhibited seasonal patterns. Nitrate and silicate concentrations peaked in April and October, while phosphate concentrations peaked in August. Understanding these nutrient variations is crucial for understanding biogeochemical processes that drive marine productivity and ecosystem dynamics. Overall, the analysis of monthly composite data provides valuable insights into the seasonal patterns and correlations of various oceanographic parameters in Balikpapan Bay. These findings contribute to our understanding of the complex interactions and dynamics of the marine environment in the region.

A study conducted by Nababan et al (2016), Ningsih et al (2021), and Munandar et al (2023) highlighted the seasonal pattern similarity between chlorophyll-a concentration and ocean-atmospheric parameters, such as SST, SSS, Solar Radiation, Total River Discharge, Rainfall, DO, Nitrate, Phosphate, and Silicate Maslukah et al (2019). Through PCA analysis, three significant modes (F1, F2 and F3) were identified, with a total variability of 90.07%. While mode F3 exclusively comprised SST, modes F1 and F2 revealed three distinct clusters. Cluster one, characterized by strong contributions from DO, silicate, nitrate, and solar radiation, played a crucial role in chlorophyll-a concentration from February to April. Cluster two, influenced primarily by SSS and Phosphate, exhibited pronounced effects on chlorophyll-a concentration from July to November. Lastly, cluster three, driven by total river discharge and rainfall, had significant impacts on chlorophyll-a concentration in January and June. The findings indicate that nutrients and DO dominate the development of chlorophyll-a concentration, surpassing the influence of solar radiation (Rozirwan et al 2021; Sidabutar et al 2021).

The occurrences of algal bloom in Balikpapan Bay between 2019 and 2021 were investigated in the study. Two instances of algal bloom were identified, one in November 2019 and another in June 2020. The study utilized daily ocean color reanalysis data and conducted a detailed time series analysis to examine the characteristics of these events (Sidabutar et al 2021; Tarigan & Wiadnyana 2013). The threshold of chlorophyll-a concentration for identify algal bloom follows (Tarigan & Wiadnyana 2013; Sidabutar et al 2022). The algal bloom in November 2019 exhibited a gradual increase in chlorophyll-a concentration, peaking at 10.43 mg m^{-3} on 9 November 2019, before gradually returning to pre-bloom levels. River discharge and a ten-fold increase in phosphate within five days were identified as influencing factors for this event. The algal bloom in June 2020, on the other hand, demonstrated an immediate spike in chlorophyll-a concentration, reaching 11.27 mg m^{-3} on 16 June 2020, followed by a gradual decline. Precipitation and an increase in nutrients were identified as influencing factors for this event. The spatial distribution analysis revealed that algal bloom originated from the Wain River estuary in both events and spread to the middle of the bay and along the coast of Kota Balikpapan. These findings support previous explanations and provide valuable insights into the triggering sources and patterns of algal bloom in Balikpapan Bay, further reinforcing suspicions of algal bloom occurrences in the area (Iswinarto 2020; Almutoif 2023).

Conclusions. This research examines various oceanographic parameters in Balikpapan Bay from 2019 to 2021, highlighting seasonal patterns and correlations. The monthly composite means of chlorophyll-a concentration displayed a seasonal pattern, with higher concentrations during the wet season (January and April) and lower concentrations during the dry season (March and July), consistently with previous studies. The monthly mean value of chlorophyll-a concentration is about 1.92–1.95 mg m^{-3} during the wet season and 1.53–1.61 mg m^{-3} during the dry season. Total river discharge also exhibited a seasonal pattern with two yearly peaks (January and April) and a strong correlation with chlorophyll-a concentration. Seasonal variations in solar radiation, SST, SSS, rainfall, and nutrient concentrations were emphasized as important factors for understanding the biogeochemical processes driving marine productivity and ecosystem dynamics. The principal component analysis was applied to investigate the relationship between chlorophyll-a concentration and several environmental parameters, identifying three significant modes (F1, F2, and F3) that explained 90.07% of the total variability. The study also identified three clusters of environmental parameters and the monthly mean of chlorophyll-a concentration. The positive mode F1 played a crucial role in chlorophyll-a concentration, particularly from February to April. It includes solar radiation, DO, nitrate, and silicate variables. The second cluster, from the negative mode F1, includes SSS and phosphate variables. The effect of these two parameters on chlorophyll-a concentration is strong from July to November. The third cluster, from the negative mode F2 includes rainfall and total river discharge as the influential parameters. Both parameters strongly affect chlorophyll-a concentration in January and June.

The ocean color reanalysis data are used to examine the daily time series and spatial analysis of chlorophyll-a concentration. It aims to detect algal bloom events during 2019 – 2021. The ocean color reanalysis data has been validated with in-situ and MODIS data. The validation showed a similar spatial and temporal pattern with a coefficient correlation of 0.9 for the spatial in-situ data and 0.6 for the time series MODIS data. Then the RMSE is around 0.54 – 1.49 mg m^{-3} with ocean color underestimate to in-situ and MODIS data. Moreover, two algal bloom occurrences (November 2019 and June 2020) were identified using daily ocean color reanalysis data. It shows the chlorophyll-a concentration daily spatial mean up to 8.5 mg m^{-3} and around 40 mg m^{-3} at the epicenter of algal bloom. Both November 2019 and June 2020 algal bloom events show different characteristics in terms of onset and decline. The algal bloom events originated from the estuary on the coast of Balikpapan Bay. Overall, the research provides valuable insights into the relationship between environmental parameters and chlorophyll-a concentration, and into the temporal and spatial patterns of algal bloom occurrences in Balikpapan Bay.

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tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

Conflict of interest. The authors declare no conflict of interest.

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