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The Temporal Trends in Chlorophyll-A Concentration along the Southern Coast of Papua over a 25-year Period, from 1998 to 2022

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ABSTRACT

The region situated along the southern coast of Papua Island exhibits a considerable likelihood of upwelling, which is distinguished by higher amounts of chlorophyll-a concentration. The present study examined the variability of upwelling phenomena spanning a period of 25 years (1998-2022) through the utilization of satellite-derived data obtained from the Ocean-Colour Climate Change Initiative (OC-CCI). Apart from the chlorophyll-a concentration, the southern region of Papua exhibits a significant amount of suspended sediment contamination, as indicated by the observations of Rrs 555. Upon conducting EOF analysis during each season, it has been observed that there has been a significant rise in the levels of chlorophyll-a concentrations over the past several years in the northern region of the Arafura Sea. The period spanning from 2016 to 2022 witnessed a rise in precipitation amounts, leading to a greater transportation of nutrients through water discharge and consequently resulting in an increase of chlorophyll-a concentration.

Keywords: chlorophyll-a, EOF, Papua, Arafura Sea.

INTRODUCTION

Chlorophyll-a, the most abundant pigment in phytoplankton, is one of the components that helps determine the overall primary productivity of the ocean (Boyer et al., 2009). Air-sea interaction has a significant impact on the chlorophyll-a distribution, as well as its high and low concentrations (Wirasatriya et al., 2019). Chlorophyll-a concentrations are, on average, higher in coastal waters than they are in the open ocean (Munandar et al., 2023). This is because river flow carries an abundance of nutrients that are derived from land (Wirasatriya et al., 2021). Previous studies have shown, through a number of different investigations, that high chlorophyll-a concentrations and low sea surface temperature (SST) are highly associated with upwelling event. Because of this upwelling event, there is a rise in the total amount of fisheries caught. As a consequence of this, it is essential to have a solid understanding of the variability of chlorophyll-a in a given location (Zainudin et al., 2017; Dabuleviciene et al., 2023).

Because Indonesia is an archipelago, it contains a great number of locations with a high potential for upwelling events to take place. In the past, researchers have conducted a number of studies to investigate the relationship between the presence of chlorophyll-a and the occurrence of upwelling events in specific regions of the seas. These regions include the southern waters of Java Island (Susanto et al., 2001; Susanto et al., 2006; Iskandar et al., 2009; Wirasatriya et al., 2018; Wirasatriya et al., 2020), the northern Maluku Sea (Atmadipoera et al., 2018; Munandar et al., 2023), the Lesser Sunda Islands (Ningsih et al., 2013; Setiawan et al., 2020; Wirasatriya et al., 2021), the Banda Sea (Gordon and Susanto, 2001; Susanto et al., 2006), the Arafura Sea, and others. According to several of these studies, both the distribution and the strength of upwelling are affected by the monsoon winds that blow across the waters of Indonesia. In Indonesia, there are four distinct seasons each year: two monsoon seasons and two transitional seasons. The rainy season in Indonesia from December to February (DJF) is caused by the northwest (NW) monsoon, which is a wind system that moves from the Asian continent to the Australian continent and brings a significant amount of water vapor with it. In contrast, the east monsoon winds that blow from Australia to Asia from June till August (JJA) carry very little water vapor, causing Indonesia to experience a dry season during that time of year (Chang et al., 2005; Chang et al., 2006; Griffiths et al., 2009). The first and second transitional seasons occur, respectively, from March to May (MAM) and September to November (SON).

Several studies have talked about the upwelling event that occurs in the southern waters of Papua, which include the Arafura Sea, Banda Sea, and the waters that surround it (Alongi et al., 2011; Condie, 2011; Kampf, 2015; Kampf, 2016). According to the findings of these studies, the southeast monsoon is the primary driver of the upwelling that occurs in the Arafura Sea and the areas that are nearby. There have been reports of phytoplankton blooms occurring in the northwestern part of the Arafura Sea during the southeast monsoon, more than 80,000 square kilometers in total area (Kampf, 2016). Previous studies have shown that it can take between one and three months for winds coming from the southwest to trigger a widespread bloom of phytoplankton (Kampf, 2015). Strong southeasterly winds in the Gulf of Carpentaria led to the lack of thermal stratification, which allowed surface currents to flow westward and deeper currents to flow eastward, resulting in upwelling and downwelling occurrences on its east and west sides, respectively (Condie, 2011). During the many decades that have passed, the Arafura Sea and the areas surrounding it have not been subjected to any kind of study that examines how the chlorophyll-a distribution in relation to upwelling has changed over time.

This research investigates the varying amounts of chlorophyl-a that can be found in the southern part of Papua Island using satellite measurements. Utilizing data from the years 1998 to 2022, the purpose of the experiment was to identify changes in the concentration and distribution of chlorophyll-a in the region over the past few decades. This paper is organized as follows in order to make the material more comprehensible: Section 2 describes the methodology, Section 3 describes the findings of the data processing, and Sections 4 and 5 independently summarize the study with the discussion and conclusions.

DATA AND METHODS

The chlorophyll-a data utilized in this study was obtained from the Ocean-Colour Climate Change Initiative (OC-CCI) project, which is managed by the European Space Agency. Further information about this project can be found at http://marine.copernicus.eu/. The OC-CCI initiative is a component of a program established by the European Space Agency (ESA) with the aim of generating essential climate variables of "climate-grade" quality utilizing satellite data. The OC-CCI dataset is comprised of data from SeaWiFS, VIIRS, MERIS, MODIS-Aqua, and OLCI-S3A. The data has been processed using the most effective atmospheric correction and chlorophyll algorithms, as outlined by Sathyendranath et al. (2019). According to Garnesson et al. (2022), the OC-CCI data exhibit a high degree of accuracy, as evidenced by the Root-Mean-Square Deviation (RMSD) value of 0.34. The chlorophyll-a concentration underwent an Empirical Orthogonal Function (EOF) analysis in order to isolate the primary modes of variability within each respective season (Björnsson and Venegas, 1997; Hannachi et al., 2007).

The study employed daily level 4 data at a spatial resolution of 0.04º, which was subjected to interpolation techniques to address the issue of missing data values. The study retrieved remote sensing reflectance data at 555 nm and 443 nm wavelengths (Rrs 555 and Rrs 443) from the ocean color database (https://oceancolor.gsfc.nasa.gov/). The purpose of this was to investigate the plausibility of satellite-derived chlorophyll-a concentration being influenced by the presence of murky river water. The observation of a low Rrs 443 nm suggests a pronounced absorption of Rrs 443 nm by phytoplankton, as reported in previous studies (Shi and Wang, 2007; Siswanto et al., 2020; Munandar et al., 2023). Conversely, it has been suggested by Acker et al. (2004), Tan et al. (2006), and Zheng and Tang (2007) that a low Rrs 555 nm value is indicative of a low concentration of suspended sediment.

The ERA5 database provides information on precipitation through the use of monthly averaged data on single levels beginning in January 2000 and continuing through December 2022. The root mean square error (RMSE) value of ERA5 data was found to be 100 mm/month, which is proof that the data possesses a high level of accuracy, as stated by Jiao et al. (2021). The ETOPO model is a comprehensive representation of the earth's surface, encompassing both terrestrial topography and oceanic bathymetry. It is a global relief model with a resolution of 1 arc-minute. Further information on this model can be found at https://www.ncei.noaa.gov/products/etopo-global-relief-model. The bathymetric and topographic data were obtained through the utilization of ETOPO.

RESULT AND DISCUSSION

Spatial distribution of chlorophyll-a, Rrs 443, and Rrs 555

Based on the spatial distribution (Figure 2), it can be seen that the region surrounding the northern Arafura Sea contains a significant amount of chlorophyll-a (>1 mg/m^3).

It was also noticed that the concentrations of chlorophyll-a at the location were considerably variable from one season to the next, with JJA months sees the highest chlorophyll-a concentrations. In the meantime, it was discovered that the month of DJF had the lowest concentration. The monsoon system that blows in Indonesian waters is liable for causing changes in the chlorophyll-a concentration that can be found in the Arafura Sea (Alongi et al., 2011; Condie, 2011; Kampf, 2015; Kampf, 2016). There is another place where there is an abundance of chlorophyll-a, and that is in the Gulf of Papua. Chlorophyll-a concentrations in this area don't appear to fluctuate significantly from season to season. The higher concentrations of chlorophyll-a in both locations may be attributed to the abundance of rivers with expansive estuaries.

First, a qualitative evaluation was carried out to check the precision of the chlorophyll-a measurements in relation to Rrs 443 and Rrs 555. This was done before moving on to more in-depth analysis. Regions characterized by higher amounts of chlorophyll-a in the northern Arafura Sea exhibit

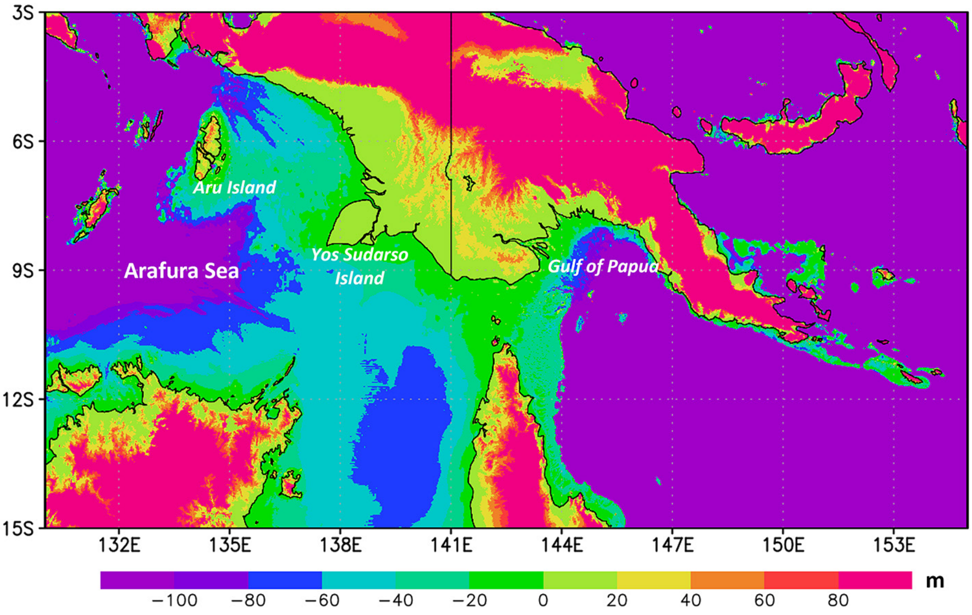

Figure 1. Bathymetry and topography of the studied site

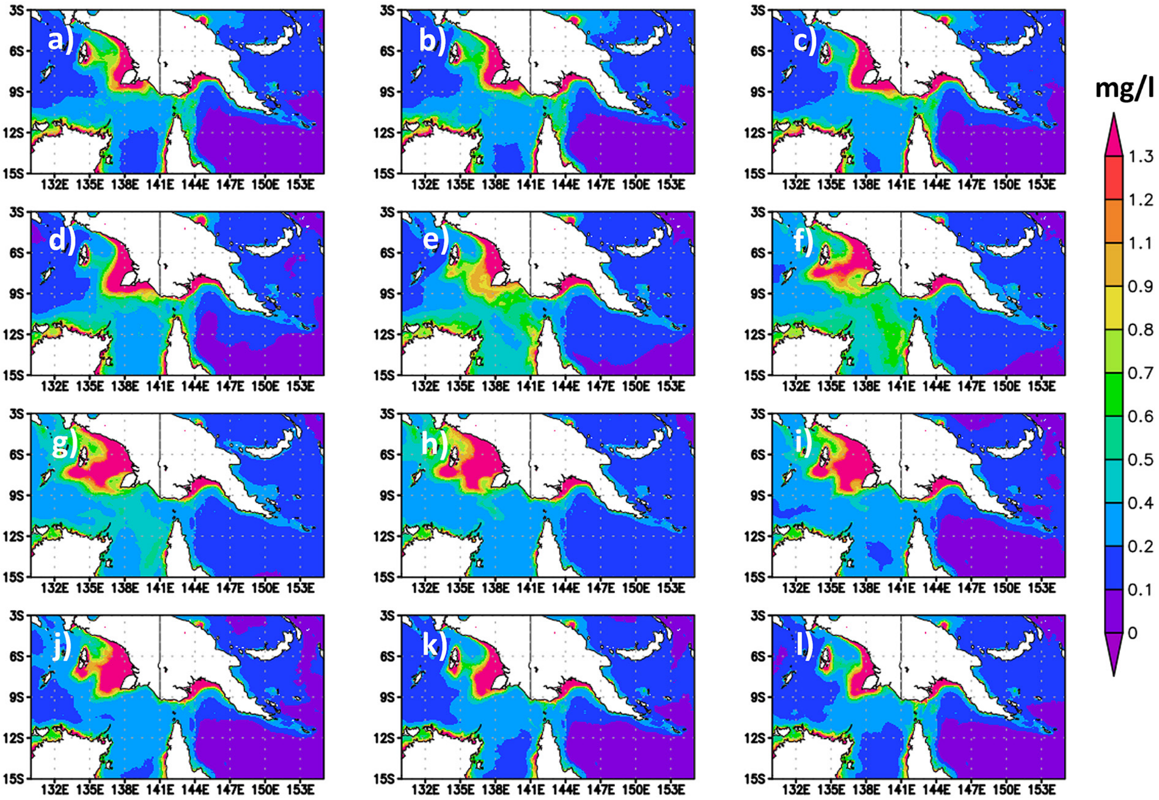

Figure 2. Distribution of chlorophyll-a along the southern coast of Papua in climatology of (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. The dataset utilized for the computation spans from 1998 to 2022

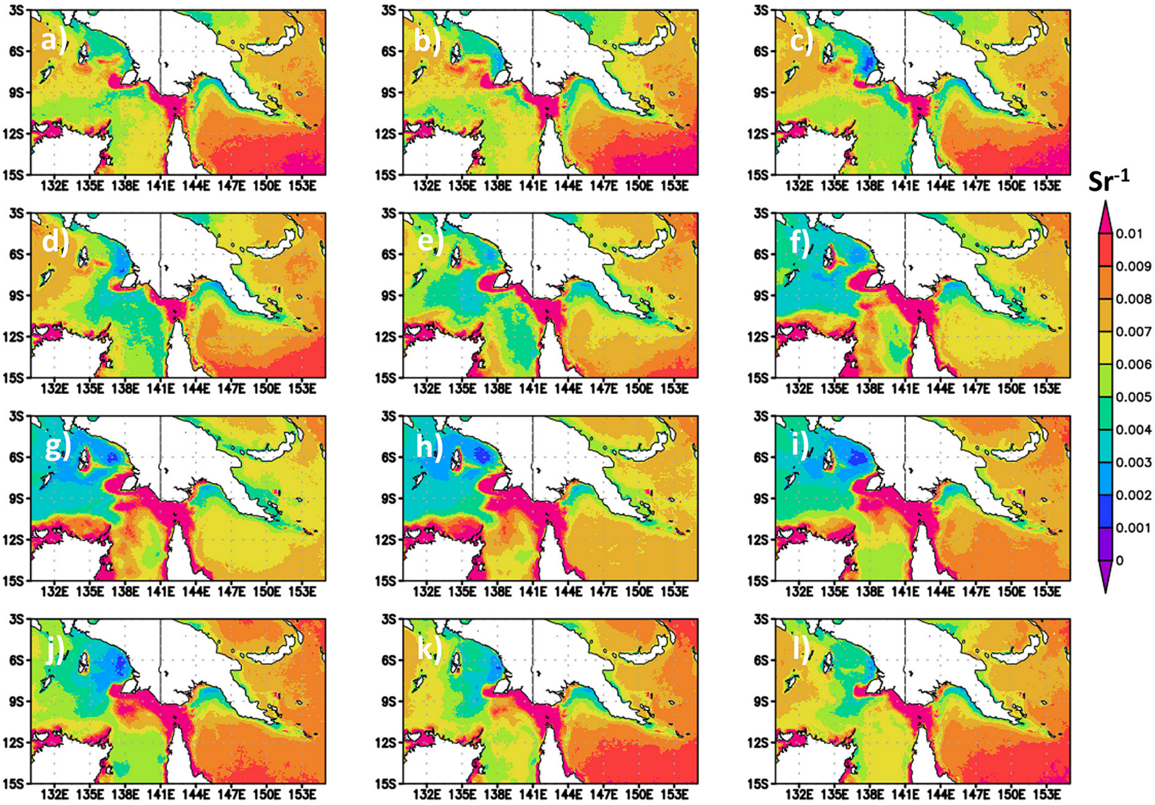

Figure 3. Distribution of Rrs 443 along the southern coast of Papua in climatology of (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. The dataset utilized for the computation spans from 1998 to 2022

diminished values of remote sensing reflectance at wavelengths of 443 and 555 nm. This result indicates the presence of phytoplankton and minimal levels of suspended sediment contamination (Figure 3). The Rrs 443 outcomes also indicate a substantial prevalence of phytoplankton in the Gulf of Papua. Nonetheless, the outcome of Rrs 555 indicates a substantial level of suspended sediment pollution in the aforementioned region and southern region of Papua (Figure 4). To put it differently, the southern area of Papua exhibits a significant degree of suspended sediment pollution. Therefore, the concentration of chlorophyll-a will be specifically targeted in the northern area of the Arafura Sea.

The highest amounts of phytoplankton were seen in the northern Arafura Sea during the months of August and September. During the period of the NW monsoon, specifically in January, the concentrations of phytoplankton were observed to be at their lowest. The findings presented herein exhibit a resemblance to the outcomes depicted in Figure 2, which showcase the climatic patterns of chlorophyll-a. In addition, the SE monsoon season, which runs from July to September, was the time of year in Rrs 555 that displayed the highest amounts of contamination from suspended material.

EOF analysis

We examined the first three EOFs for DJF, MAM, JJA, and DJF and discovered the primary modes for each season in order to gain a better understanding of how chlorophyll-a has evolved over the course of the past 25 years. According to the results of the EOFs for all seasons, the majority of the variable may be accounted for by the high chlorophyll-a gradient that can be found in the southern part of Papua. The initial two EOF modes elucidated over 30% of the entire variance in chlorophyll-a across all seasons. The overall variance was accounted for by the four seasonal periods of DJF, MAM, JJA, and SON in the following proportions: 39%, 33%, 47%, and 43% correspondingly.

The initial mode (EOF1) of the DJF exhibited a variance explanation of 27% in total. Its spatial configuration exhibits a conventional layout of average DJF chlorophyll-a, featuring two positive anomalies located in the Arafura Sea and

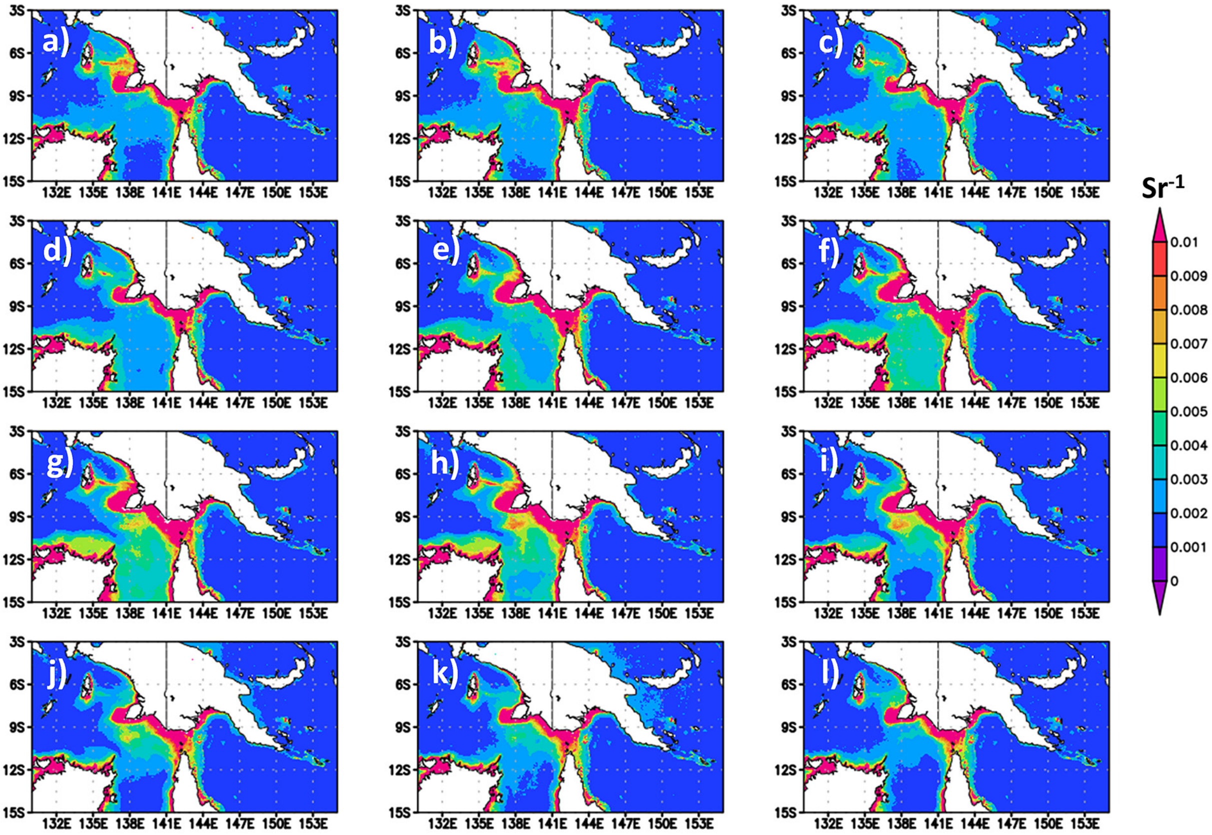

Figure 4. Distribution of Rrs 555 along the southern coast of Papua in climatology of (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. The dataset utilized for the computation spans from 1998 to 2022

Gulf of Papua (Figure 5a). The linked time series demonstrates the interdecadal variability of this trend (Figure 5b). The phase shift from negative to positive (started from 2017) that occurred over the southern Papuan seas during this season suggests an increase in chlorophyll-a during the last six years. The mode 2 of the EOF (EOF2), which accounted for 12.1% of the total variance, exhibits both positive and negative anomalies across the Arafura Sea. A negative anomaly has been identified in close proximity to the Papua coastline, whereas a positive anomaly has been detected in the vicinity of the Aru Islands. This particular pattern is commonly observed during the year of La Nina. A rise in SST brought on by La Nina event, which led to a reduction in chlorophyll-a concentrations along Papua's coastal regions (Dewi et al., 2018). This pattern also exhibits decadal fluctuations, wherein the transition from a negative to positive phase occurred in 2016.

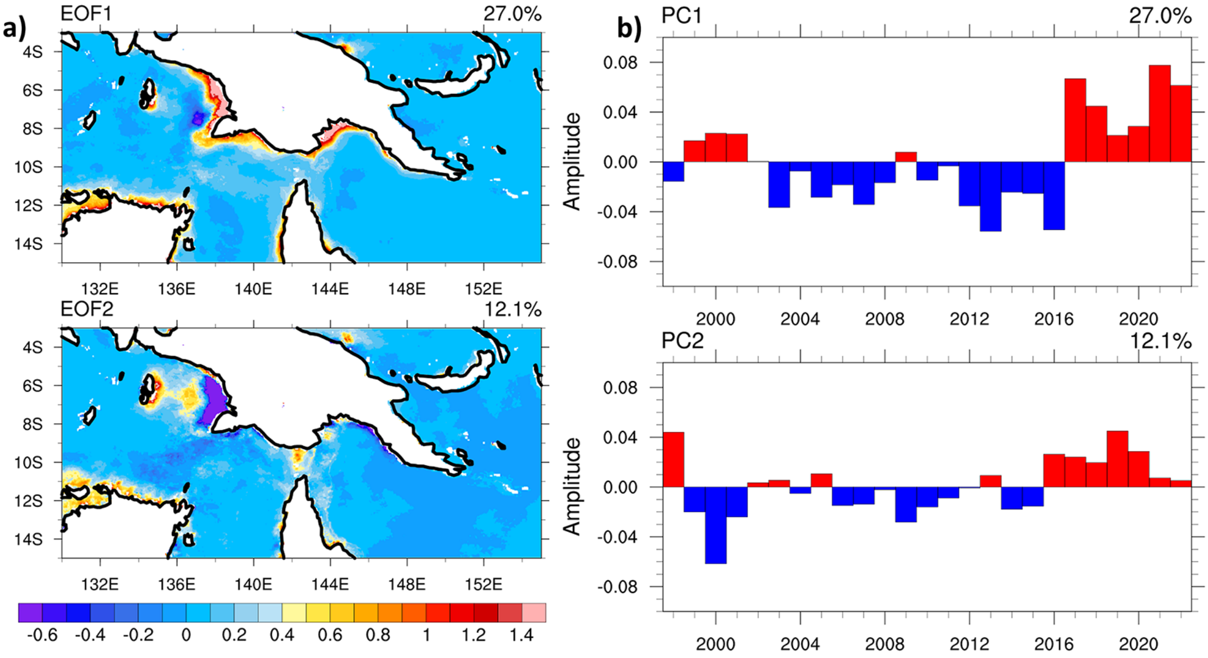

Figure 5. EOF analysis of chlorophyll-a for DJF. (a) its spatial structure and (b) corresponding time series PC

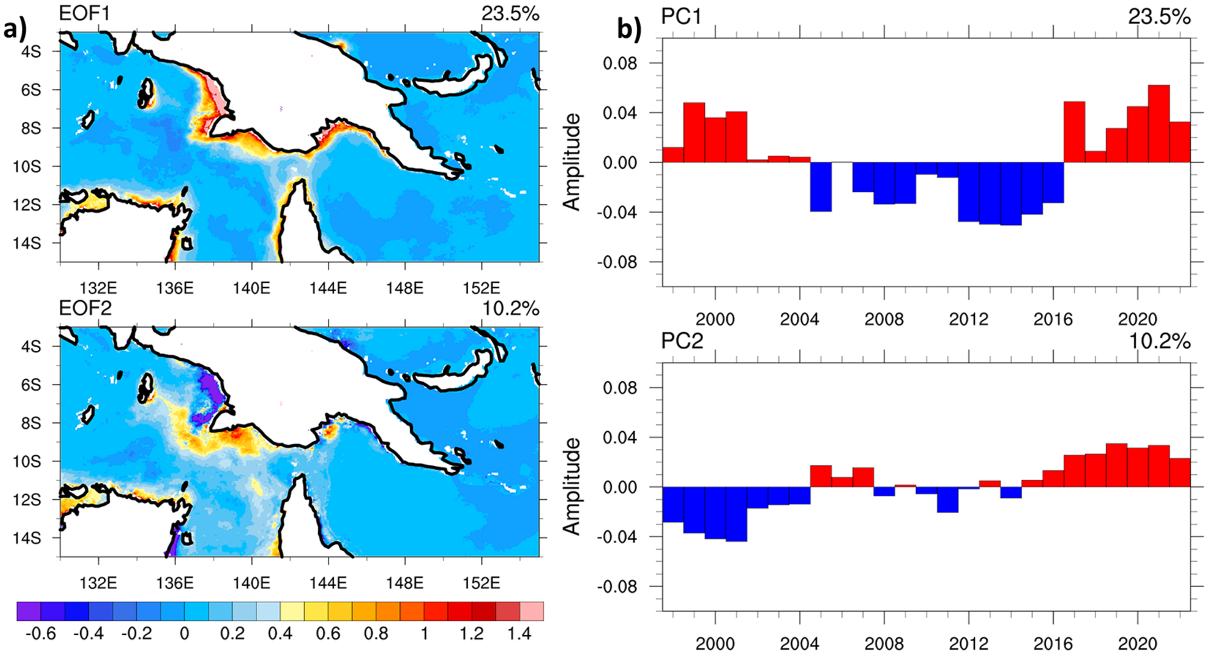

Figure 6. EOF analysis of chlorophyll-a for MAM. (a) its spatial structure and (b) corresponding time series PC

Moreover, it can be observed that the EOF1 pertaining to MAM elucidates 23.5% of the overall variance (Figure 6a). Its spatial structure exhibits certain resemblances with EOF1 during the DJF, which is a characteristic feature of the chlorophyll-a concentration distribution during the period of the NW monsoon (Kämpf, 2016). The EOF2 (10.2%) exhibits a spatial distribution characterized by a positive anomaly located to the south of Yos Sudarso Island, and a negative anomaly present in certain regions of the Arafura Sea. The spatial pattern of EOF2 depicts chlorophyll-a concentrations in Papua Island during periods of extremely heavy precipitation. The current month of MAM is characterized by high amounts of precipitation in certain areas of Papua (Sukri et al., 2003). The lowlands are the predominant feature of the southern region of Papua, characterized by the presence of wide river estuaries. During periods of high

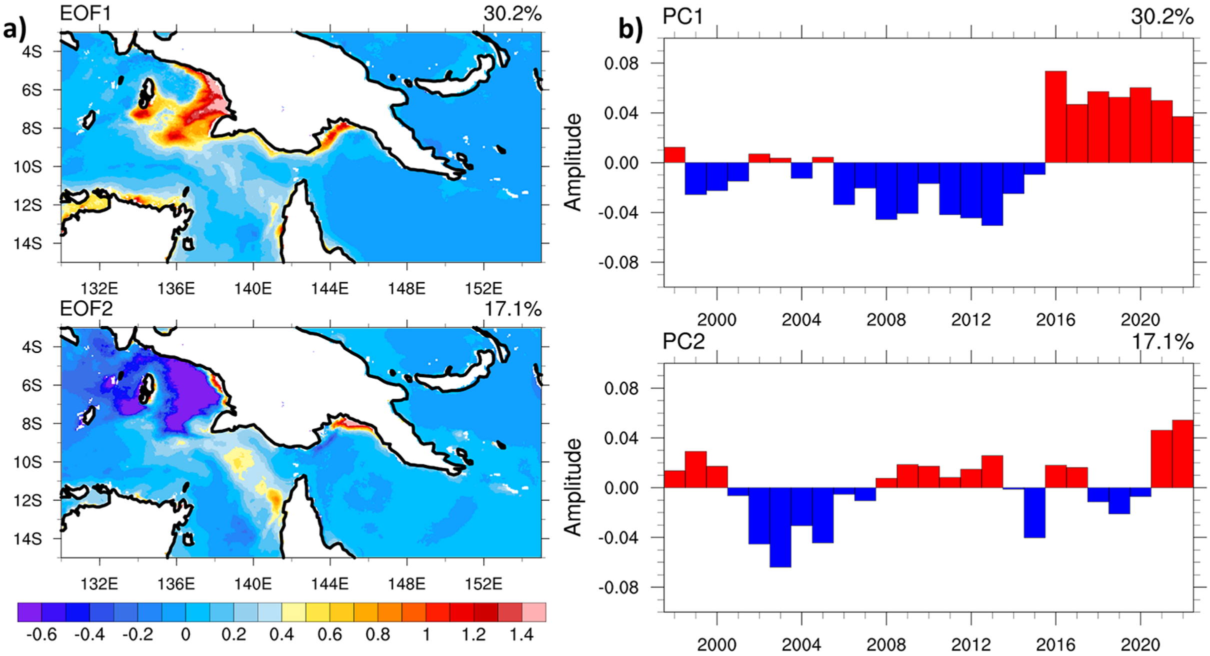

Figure 7. EOF analysis of chlorophyll-a for JJA. (a) its spatial structure and (b) corresponding time series PC

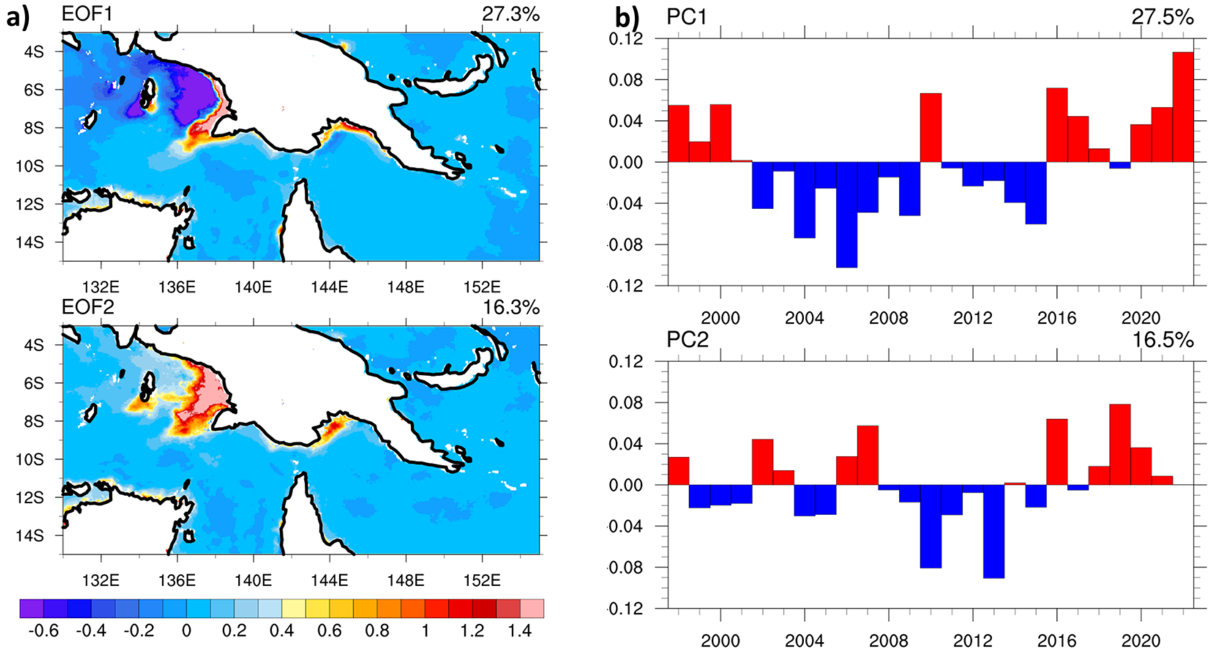

Figure 8. EOF analysis of chlorophyll-a for SON. (a) its spatial structure and (b) corresponding time series PC

precipitation, there is a likelihood that the nutrients present in the soil will be carried away by the river discharge and eventually deposited into the ocean (Zheng and Tang, 2007). Similar to the month of DJF, the temporal progression of PC1 and PC2 exhibits a discernible augmentation in chlorophyll-a concentration during recent years (Figure 6b).

The EOF1 for JJA, which accounts for 30.2% of the total variance, indicates that the majority of the variance is explained by the northern Arafura Sea's high chlorophyll-a gradient (Figure 7a). This observed pattern of chlorophyll-a is commonly associated with the SE monsoon season (Kämpf, 2015). The PC1 of the time series is subject to decadal variations, and in 2016, it switched from being in a negative phase to moving into a positive phase (Figure 7b). Similar to the DJF, the EOF2 (17.1%) shows a notable suppression of chlorophyll-a escalation in the Arafura Sea due to the increase in SST, which occurred mainly during La Nina events (Jourdain et al., 2013). The time series shows an irregular cycle with 6-yearly variation from 2000 to 2013.

In addition, 27.3% of the overall variance was accounted for by the EOF1 that was obtained from the SON period (Figure 8a).

The spatial pattern of the northern Arafura Sea exhibits both negative and positive anomalies, which is intriguing. This phenomenon manifests during the developmental phase of La Nina (Jourdain et al., 2013), wherein SST experiences an increase in warmth within the Indonesian maritime region. Its time series of PC1 shows a transition from negative phase to positive phase in the year 2016, which is consistent with patterns observed in other seasons (Figure 8b). The EOF2 was responsible for 17.1% of the overall variance, displayed considerable similarities with the EOF1 during the months of JJA. Over the past few years, the corresponding PC2 displays positive phase.

Based on the outcomes of the EOF analysis conducted across all seasons, it can be observed that the time series of the PC1 exhibits a rise in the concentration of chlorophyll-a starting from the year 2016. Nevertheless, the causative factors behind this phenomenon remain unknown at present. Significant climatic factors may be responsible for the alteration of oceanographic mechanisms and ecological patterns in the southern region of Papua, specifically in the Arafura Sea.

Distribution of precipitation

The prevalence of expansive river estuaries in the southern lowlands of Papua prompted us to investigate the plausibility of nutrient influx from terrestrial sources via runoff during periods of intense precipitation. According to Kim et al. (2014), the proliferation of chlorophyll-a in coastal regions may be impacted by increased precipitation, which results in the delivery of soil nutrients through river discharge. Thus, a comparison is made between the precipitation patterns observed in the Papua region during the time frame spanning from 2000 to 2015 (Figure 9) and the time frame from 2016 to 2022 (Figure 10).

The purpose of this analysis is to determine whether or not there has been a perceptible shift in the patterns of precipitation that have been occurring over the course of the most recent several years.

When compared to the levels that were shown between 2016 and 2022, the precipitation that was observed between the years 2000 and 2015 showed a significantly lower amount. This occurrence takes place not only during certain months of the year but rather all during the course of the calendar year. In keeping with this finding, according to data that ranges from 1956 to 2016, Sapala et al. (2021), Sekac et al. (2021), and Pereira et al. (2019) also found that there was an increase in the amount of precipitation that occurred in the Papua New Guinea region. The northern land region of Papua, which is characterized by its highlands, is subject to a degree of precipitation that is comparatively high. The most substantial increase in precipitation is seen during the month of April. Additionally, it can be observed from Figures 9 and 10 that the month of November exhibited the lowest amount of precipitation in general. Allen et al. (1989) found that the presence of El Niño-Southern Oscillation (ENSO) events did not have a major impact on the patterns of precipitation that were observed on the island of Papua. According to the findings of the research conducted by Nicolls (1973), there is a connection between the strength of the Walker circulation and the amounts of precipitation that accumulate in Papua. His study indicates that the weakening of the walking circulation is likely to result in below-average precipitation levels in Papua. On the other hand, there has been a reported intensification of the walker circulation in recent years, as noted by Zhao and Allen (2019). It is highly likely that the

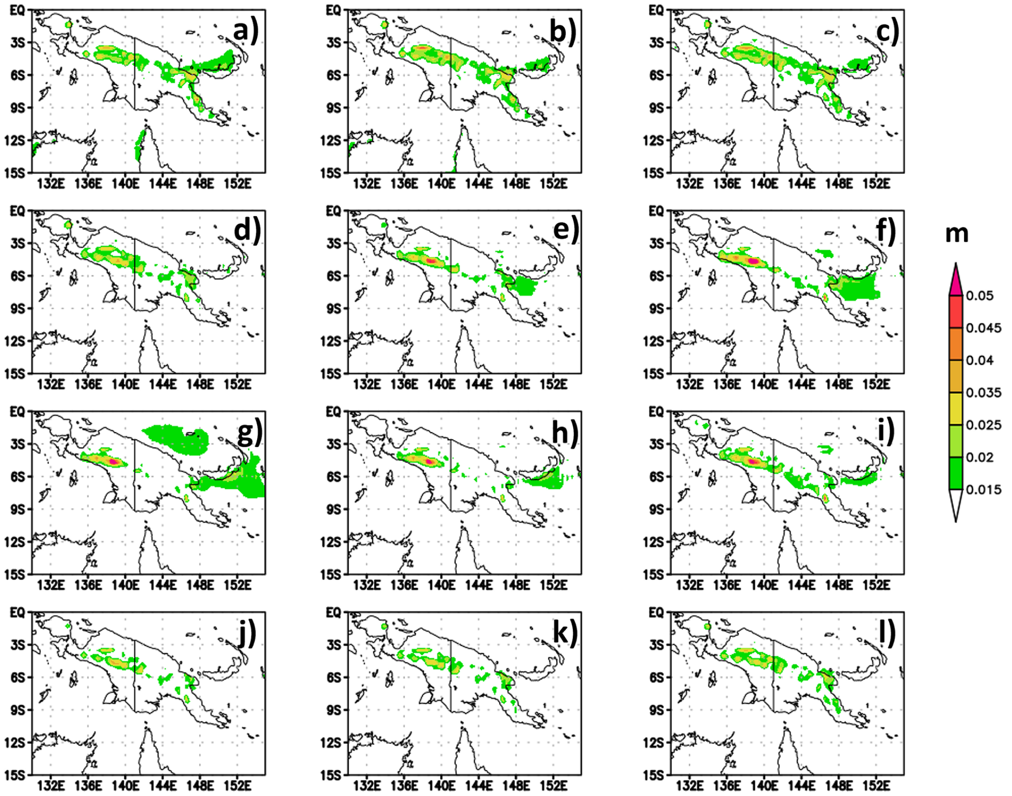

Figure 9. Distribution of total precipitation along the southern coast of Papua in climatology of (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. The dataset utilized for the computation spans from 2000 to 2015

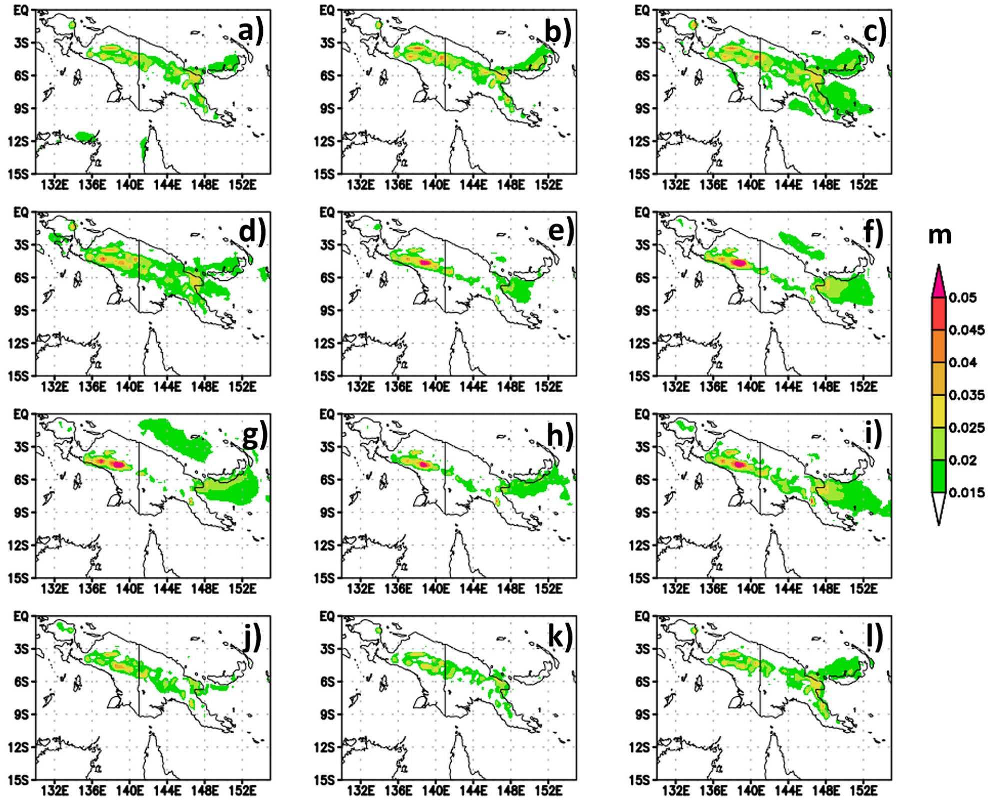

Figure 10. Distribution of total precipitation along the southern coast of Papua in climatology of (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December. The dataset utilized for the computation spans from 2016 to 2022

existence of that phenomenon lead to an increase in the amount of precipitation that occurs on Papua Island. The increase in the amount of precipitation in the Papuan highlands has resulted in an increase in chlorophyll-a concentration over the northern region of Arafura Sea during the timeframe spanning from 2016 to 2022.

CONCLUSION

The southern lowlands of Papua exhibit the features of a river system with a substantial estuarine region, resulting in a significantly higher level of chlorophyll-a concentration within said locale. Nevertheless, the abundant presence of rivers also results in significant levels of suspended sediment pollution in these aquatic bodies. The analysis of remote sensing reflectance at a wavelength of 443 nm revealed that the abundance of phytoplankton exhibited monthly fluctuations in the northern region of the Arafura Sea. Consequently, our attention was directed towards that particular region. The current investigation utilizes Empirical Orthogonal Function (EOF) analysis to examine the fluctuations in chlorophyll-a concentrations over the period of 1998 to 2022. An increase in the chlorophyll-a concentration was seen in the time series of PC1 throughout the whole monitored region, and this trend was observed across all four seasons. The year 2016 marked the beginning of this pattern of behavior. This is due to an increase in precipitation that occurred on the island of Papua during the years 2016 and 2022. In circumstances of higher precipitation, there exists a likelihood that a greater quantity of nutrients present in the soil will be transported by river outflow and subsequently accumulated in the ocean, thereby causing a rise in the concentration of chlorophyll-a.

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