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The Variability in the Distribution of Nitrate Concentration at the Surface of the Southeast Indian Ocean

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ABSTRACT

The waters that surround the Indonesian archipelago are home to some of the most fruitful primary resources that can be found anywhere in the southeastern Indian Ocean. In this work, an investigation of seasonal fluctuations in nutrient content within the region, utilizing 30-years reanalysis data generated by Copernicus Marine Service, was presented. The month of September, October, November (SON) exhibits the maximum concentration of nitrate content, primarily observed in the southern region of Java and the Lombok Strait. The concentrations of nitrates experience significant changes that are notably impacted by Indian Ocean Dipole (IOD) occurrences. Specifically, a positive IOD event is associated with elevated nitrate levels, particularly during the period spanning from June to December. Furthermore, in the southern Java region, an inverse correlation was identified between nitrate concentrations and surface zonal currents, commonly referred to as the South Java Current (SJC). Concurrently, the reinforcement of the Indonesian Throughflow (ITF) in the Lombok Strait is consistently accompanied by an elevation in nitrate concentration within the southern region.

Keywords: nitrate, IOD, southern waters of Indonesia, ITF, SJC.

INTRODUCTION

The limitation of phytoplankton production in marine environments is commonly acknowledged to be primarily caused by the presence of mixed inorganic nitrogen, which serves as the major nutrient. There is a substantial amount of nitrogen being transported within river systems. The nitrogen in question is sourced through fertilizers, manure, waste materials, and various human activities. The flow of nitrogen into maritime areas is influenced by various factors, including rainfall intensity and the discharge of river water. As a consequence, there has been an increase in the concentration of nutrients in aquatic ecosystems (Lihan et al., 2008; Chazottes et al., 2008). Nutrients are of paramount importance in the environment, since they serve to enhance life and furnish vital constituents, such as a nourishment supply for another organism. Nitrate, a compound consisting of essential nutrients, serves as an indication for the assessment of water quality.

Nitrate is the major nitrogen component that is consumed by primary producers in marine environments. These producers include algae, bacteria, and fungi. In addition, it plays an important role in the process of photosynthesis as the primary nutrient that is necessary for it. The optimal growth and development of phytoplankton are dependent on the presence of nitrate within a concentration range of 5 to 19 mmol/m^3 (Suryadi et al. 2017; Wijaya and Elfiansyah 2022). The persistent release of organic waste into the water that flows through rivers causes an accumulation of nutrients along coastal areas. This, in turn, leads to eutrophication and upsets the delicate ecological balance that exists there (Xu et al. 2010; Rahman et al. 2021). Eutrophic water is characterized as an aquatic milieu in which the content of nitrate is between the designated range of 27.8 to 416.7 mmol/m^3 (Wetzel 2001). Coastal and open-ocean nitrate concentration increases are frequently correlated with upwelling phenomena (Bode et al. 1997; Hauschildt et al. 2021).

The archipelagic region of Indonesia, located in the southeastern Indian Ocean, frequently experiences upwelling. This phenomenon affects the southern islands of Indonesia, a territory spanning from Java to East Nusa Tenggara (Amri et al. 2013; Wirasatriya et al. 2020). The oceanographic state of the waters in southern Indonesia is subject to the influence of a number of established factors (Figure 1). The South Java Current (Wijaya et al. 2023; Ningsih et al. 2021), Indonesian Throughflow (Feng et al. 2018; Makarim et al. 2019), South Equatorial Current (Wu et al. 2019), Rossby and Kelvin wave, and others are examples of such factors. The El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are strong ocean-atmosphere phenomena that play a substantial role in the modulation of upwelling patterns within the southern Indonesian waters.

Using reanalysis data gathered over a thirty-year period, the purpose of this investigation was to determine the degree to which nitrate concentrations vary across the southern Indonesian archipelago. This was accomplished by examining the data. In addition, it is quite important to determine the characteristics that have a role in influencing its distribution. In addition, the patterns of oceanic currents, wind patterns, and the temperature of the sea surface were investigated in relation to the spatial distribution of nitrate as part of this study.

MATERIAL AND METHOD

The geographical scope of the study area extends from 100°E to 130°E and 4°S to 15°S in the southeast of the Indian Ocean. The dataset used for the analysis of nitrate distribution spanning from January 1993 to December 2022 was obtained from a global biogeochemical multi-year hindcast given by Copernicus Marine Environment Monitoring Service (CMEMS). PISCES, a model available on the NEMO platform, was utilized in order to carry out the process of acquiring the reanalysis data (Aumont et al. 2015). The examination of nitrate reanalysis data and World Ocean Atlas (WOA) data demonstrates a significant level of global agreement. The nitrate data that was included in this study possesses a spatial resolution of 0.25 degrees and represents surface-level measurements.

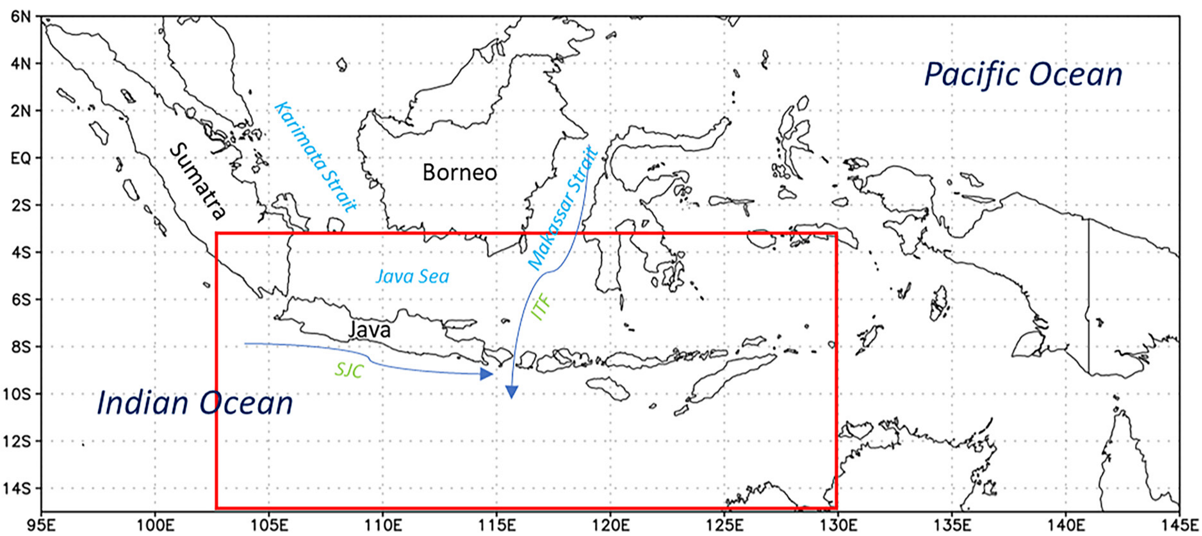

Figure 1. The observation region is marked by a red box. The ITF, denoted by a blue arrowhead, reaches the Indian Ocean via the Lombok Strait after traversing the Makassar Strait. In addition, a zonal flow known as the SJC occurs just south of Java

The conducted research used the CMEMS global ocean reanalysis data, which has a spatial resolution of 0.083 degrees in both longitude and latitude. The reanalysis data presented herein was acquired from a model in which the NEMO platform serves as a component, with surface-level propulsion facilitated by the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis. The study of this data showcases positive results through the utilization of assimilated data, including satellite altimetry, satellite sea surface temperature (SST), and in situ measurements of temperature and salinity. This data was collected expressly for the purpose of conducting an analysis of ocean current and SST data (Jean-Michel et al. 2018; Lellouche et al. 2018).

In addition to this, the zonal and meridional wind components at a height of 10 meters are used on a monthly basis in the analysis. The aforementioned components were obtained from the fifth version of the ECMWF reanalysis data; Hersbach and Dee (2016) reported the specifics of the acquisition. As a direct result of the earlier ECMWF efforts to compile reanalysis data packages, the ERA5 product has been subjected to additional enhancements. The ERA5 atmospheric reanalysis employed data sourced from the assimilation system of the integrated prediction system (IFS) version 41r2. A grid spacing of 0.25 degrees by 0.25 degrees has been applied to these wind components. The utilization of ERA5 reanalysis data has facilitated a more comprehensive examination of atmospheric interaction events occurring in the Indian Ocean (Luo et al. 2022; Naseef and Kumar 2019).

RESULTS

Variations in nitrate concentration with the seasons

Figure 2 presents a visual representation of the seasonal variations that occur in the spatial distribution of nitrates in the southern region of Java. The data clearly indicates that the concentration of nitrate exhibits a noticeable upward trend during the months of June, July, and August (JJA) and September, October, and November (SON), culminating in its peak during the SON period. The result aligns with the occurrence of upwelling in the region, which can be attributed to the passage of the southeast monsoon from Australia to Asia (Wen et al. 2023; Wirasatriya et al. 2020; Iskandar et al. 2017). The presence of changes in nitrate concentrations is seen not only in the southern region of Java, but also in the Lombok Strait, which serves as the exit route for the ITF (Sprintfall and Révelard 2014).

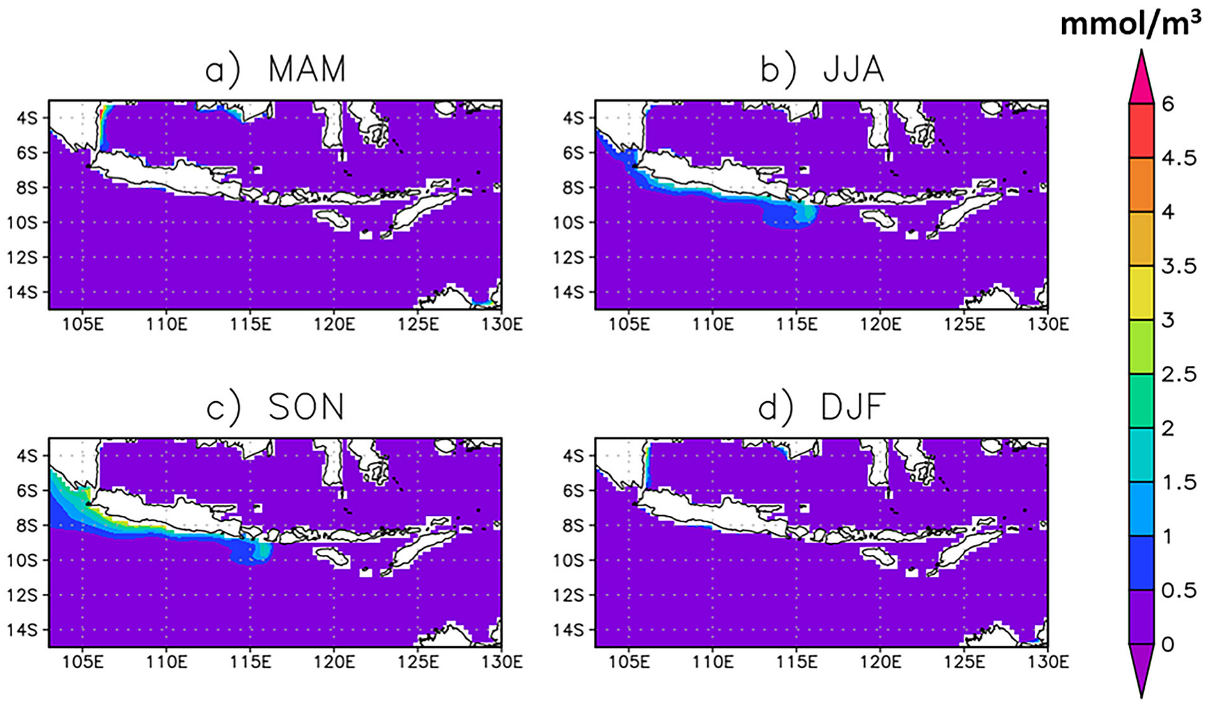

Figure 2. The seasonal distribution of nitrates in the southern region of the Indonesian archipelago Picture a) for Months MAM; b) for JJA; c) for SON; and d) for DJF

The primary mode for each season was found by Empirical Orthogonal Function (EOF) analysis in order to enhance the understanding of the variations in nitrate concentrations over the course of the past three decades (Figure 3). The findings from the EOF analysis suggest that the significant gradient of nitrate observed in the southern waters of the Indonesian archipelago is the primary driver for most of the observed variables. The dominant EOF (EOF1) mode explains more than 70% of the overall variability in nitrate concentrations throughout all seasons, with the exception of MAM. The four seasonal periods of MAM, JJA, SON, and DJF contributed to the total variance in the subsequent proportions: 45%, 80%, 89%, and 74%, respectively.

The spatial distribution of the EOF1 for the months of MAM reveals that the positive anomaly of nitrate in southern Java exhibits a near-uniform pattern. The attributes of this pattern exhibit a resemblance to the typical distribution of nitrates as depicted in Figure 2. The observed phenomenon can perhaps be attributed to infrequent upwelling occurrences in the southern region of Java, resulting from the coastward movement of Ekman transport (Wirasatriya et al. 2020). The time series data (PC1) reveals a decline in nitrate concentrations in the proximity of the observation site throughout the previous two-year period (2021-2022), characterized by a prominent negative trend.

During the months of JJA, Southern Java and the exit route of ITF (Lombok Strait) displayed notable favorable anomalies in the EOF1. The transportation of nitrate to the ocean surface can occur due to upwelling phenomena induced by the prevailing east monsoon winds, which exhibit their maximum intensity during this period. The analyzed time series data reveals that the highest positive phase was observed in both 1994 and 2019. A positive Indian Ocean Dipole (IOD) event will lead to the generation of an upwelling Kelvin wave in the central region of the Indian Ocean. The aforementioned wave will proceed to travel towards the southern regions of Java, resulting in the amplification of the pre-existing upwelling phenomenon in that area (Susanto et al. 2001; Horii et al. 2018). Furthermore, the occurrence of the negative phase has been observed during the course of the past three years (spanning from 2020 to 2022).

The spatial distribution pattern depicted by the EOF1 for the months of SON closely resembles that of JJA. This remains associated with the monsoon system that influences the Indonesian archipelago, leading to the generation of seaward Ekman transport upwelling (Wirasatriya et al. 2020; Shi and Wang 2021). Positive phases that were most prevalent were identified in PC1 in the years 1994, 1997, 2006, and 2019. A powerful positively charged IOD can be considered to be the cause of this.

The DJF EOF1 analysis reveals a notable positive anomaly located to the west of the Sunda Strait. Distinction exists between the observed patterns and the average spatial distribution illustrated in Figure 2. Indeed, during the month of DJF, occurrences of upwelling in southern Java are exceedingly uncommon, owing to the northwest monsoon that prevails (Kurniawati et al. 2021). This indicates that other significant factors led to the predominance of the nitrate distribution pattern over the past three decades. On the basis of the linked time series PC1, it can be observed that positive phases were exclusively observed in the years 1998, 2007, and 2020. The years subsequent to the customary peak of positive IOD events in the months of SON. In the years with a preponderantly positive phase, such as 1997/1998, 2007/2008, and 2019/2020, it is extremely intriguing to observe the distribution of nitrate further.

Figures 4, 5, and 6 depict the nitrate distribution from September to February (+1) in the years 1997, 2006, and 2019, respectively. The regions of Southern Java and the Lombok Strait consistently exhibit elevated levels of nitrate concentrations during the months of September to November, as observed across every year of observation. The December distribution is represented differently. West of the Sunda Strait, elevated nitrate concentrations were observed in both 1997 and 2019. The distribution pattern exhibits similarities to the EOF1 pattern observed during the DJF. Conversely, elevated levels of nitrate were still detectable in the southern region of Java Island in 2006. During all years of observation, nitrate concentrations did not increase during the months of January and February, with the exception of 1998, when trace amounts were detected west of the Sunda Strait. In the year 2006, it was observed that there was a wider distribution of high nitrate levels in the western region of southern Lombok (September and November). The year 1997 saw a somewhat lesser degree of westward expansion in terms of nitrate concentrations, as compared to the two remaining years. The exploration of the

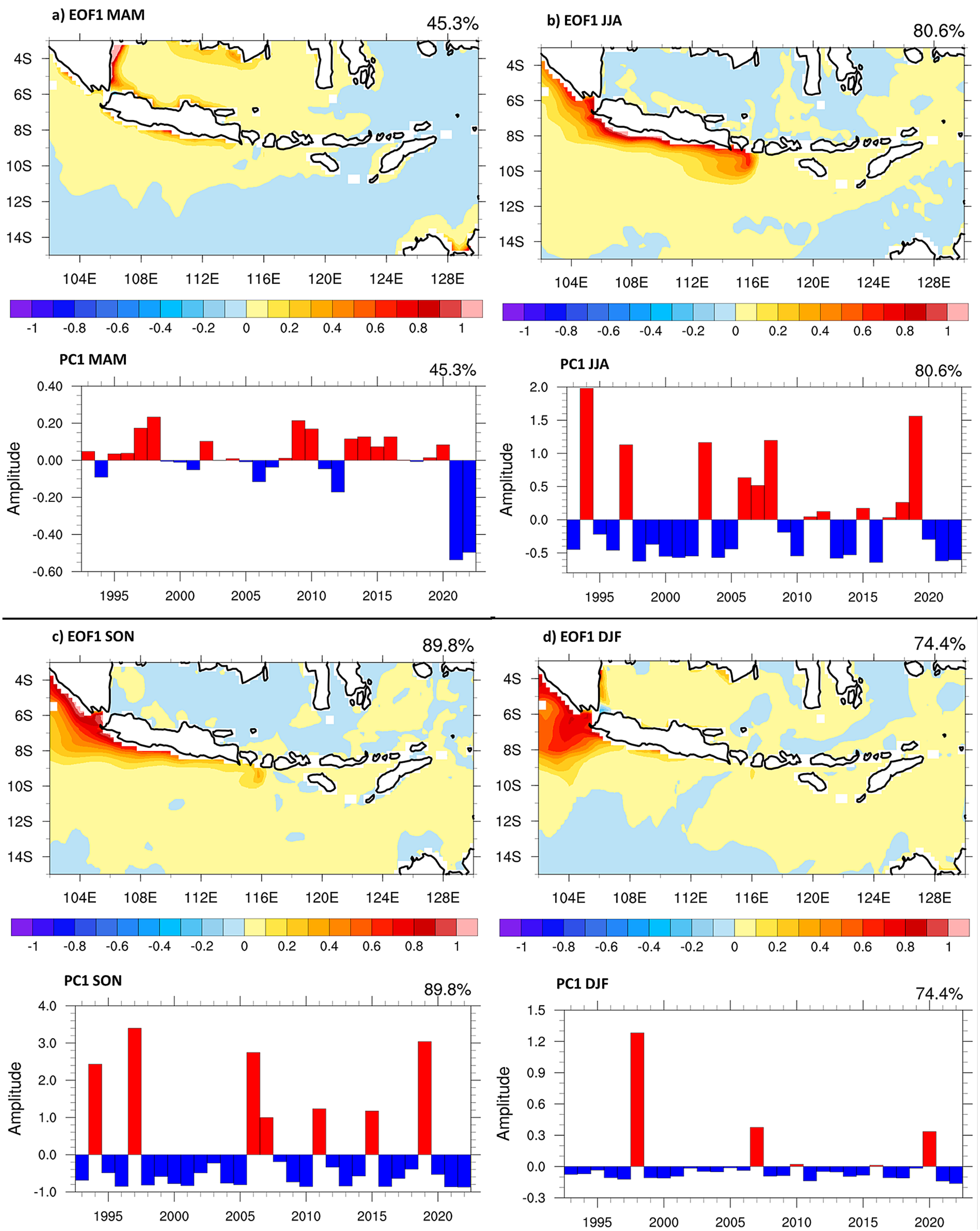

Figure. 3. Nitrate's primary mode of EOF and PC. A) represents the month MAM; b) represents JJA; c) represents SON; and d) represents DJF

variations in nitrate levels in southern Java and the Lombok Strait presents a highly captivating area for additional investigation.

The interplay between the atmosphere and the ocean, known as the IOD, has a notable impact on the distribution of nitrate in the southeastern region of the Indian Ocean. The information shown above provides evidence of an association between positive IOD events and elevated nitrate concentrations throughout time. The several manifestations of the IOD exert a significant influence on various climatological and oceanographic

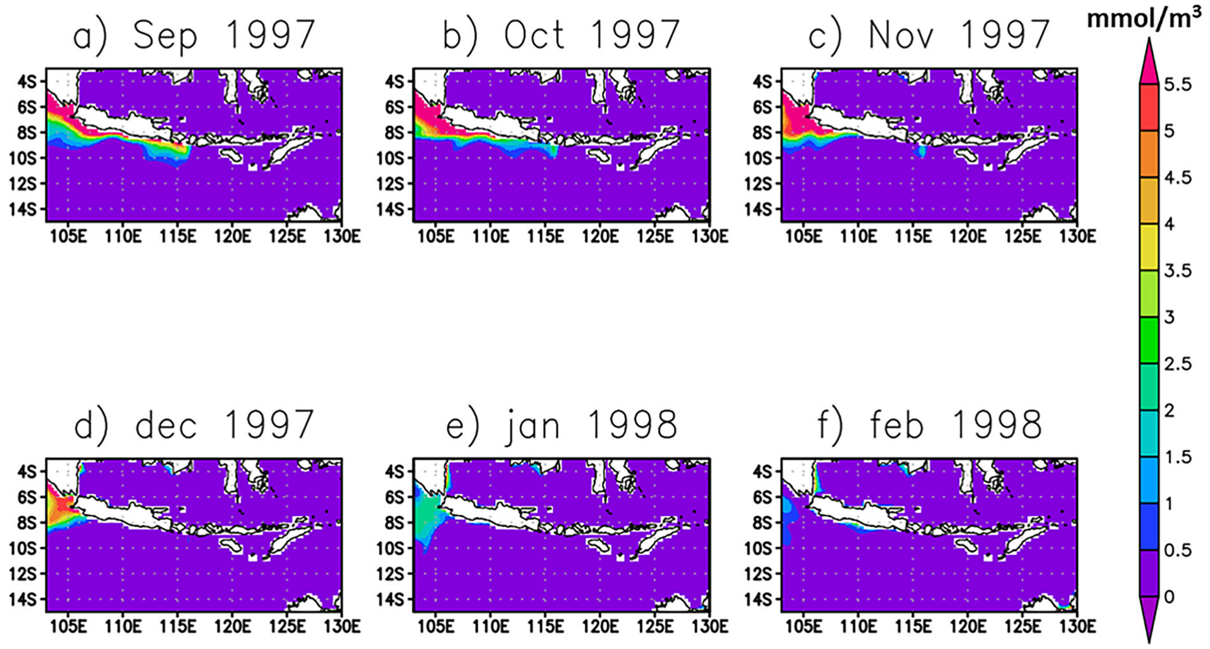

Figure 4. The monthly means of the distribution of nitrate. The corresponding months are as follows: a) September 1997, b) October 1997, c) November 1997, d) December 1997, e) January 1998, and f) February 1998

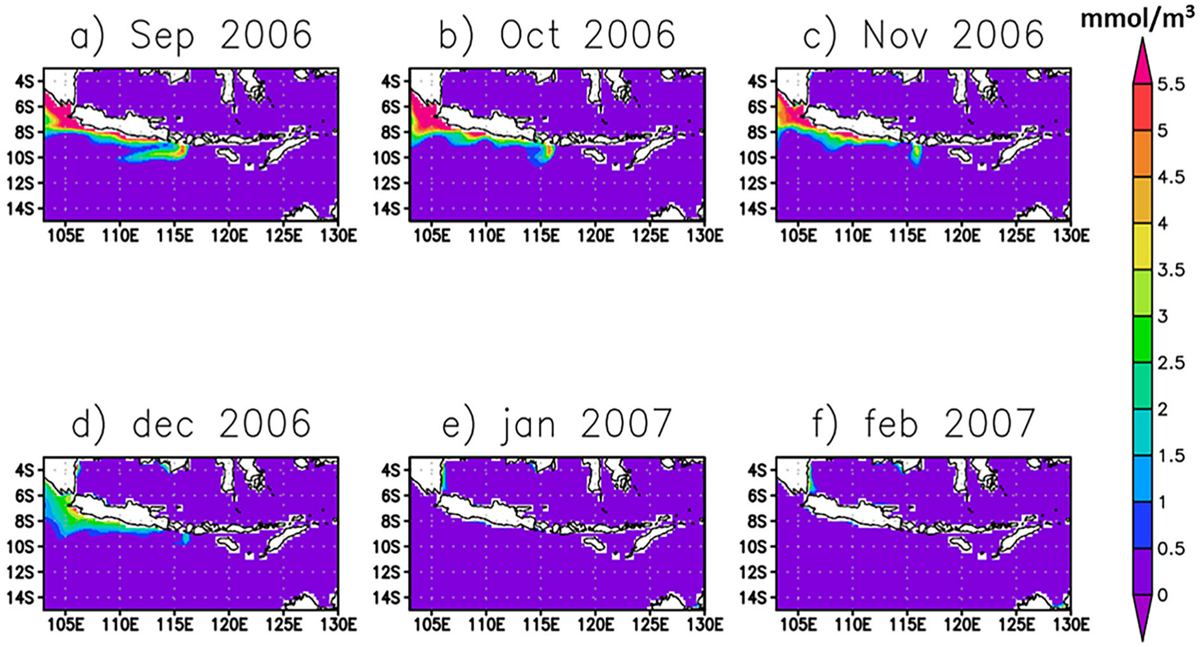

Figure 5. The monthly means of the distribution of nitrate. The corresponding months are as follows: a) September 2006, b) October 2006, c) November 2006, d) December 2006, e) January 2007, and f) February 2007

parameters within the Indian Ocean region, including wind patterns, ocean currents, and SST. The forthcoming subsection will determine which among these factors exerts the greatest influence of the dispersion of nitrate.

The correlation between the fluctuations of several variables and the spatial arrangement of nitrate concentrations in certain places was calculated and graphically depicted in Figures 7 and 8.

The South Java Current (SJC) is a dynamic zonal current that exhibits seasonal variability. Its behavior is controlled by various factors, including wind patterns and the propagation of oceanic waves within the region. The average zonal current speed and nitrate content in the southern Java region (103°E to 111°E and 6.8°S to -9°S) were computed and subsequently compared to the graphical representation shown in

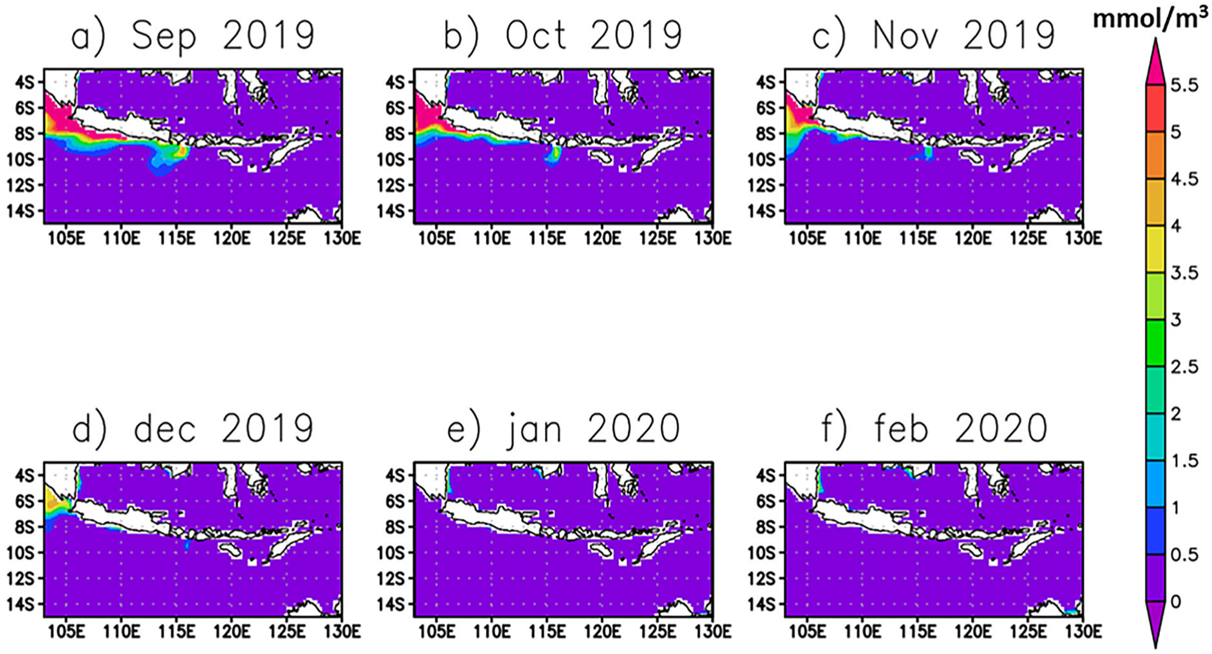

Figure 6. The monthly means of the distribution of nitrate. The corresponding months are as follows: a) September 2019, b) October 2019, c) November 2019, d) December 2019, e) January 2020, and f) February 2020

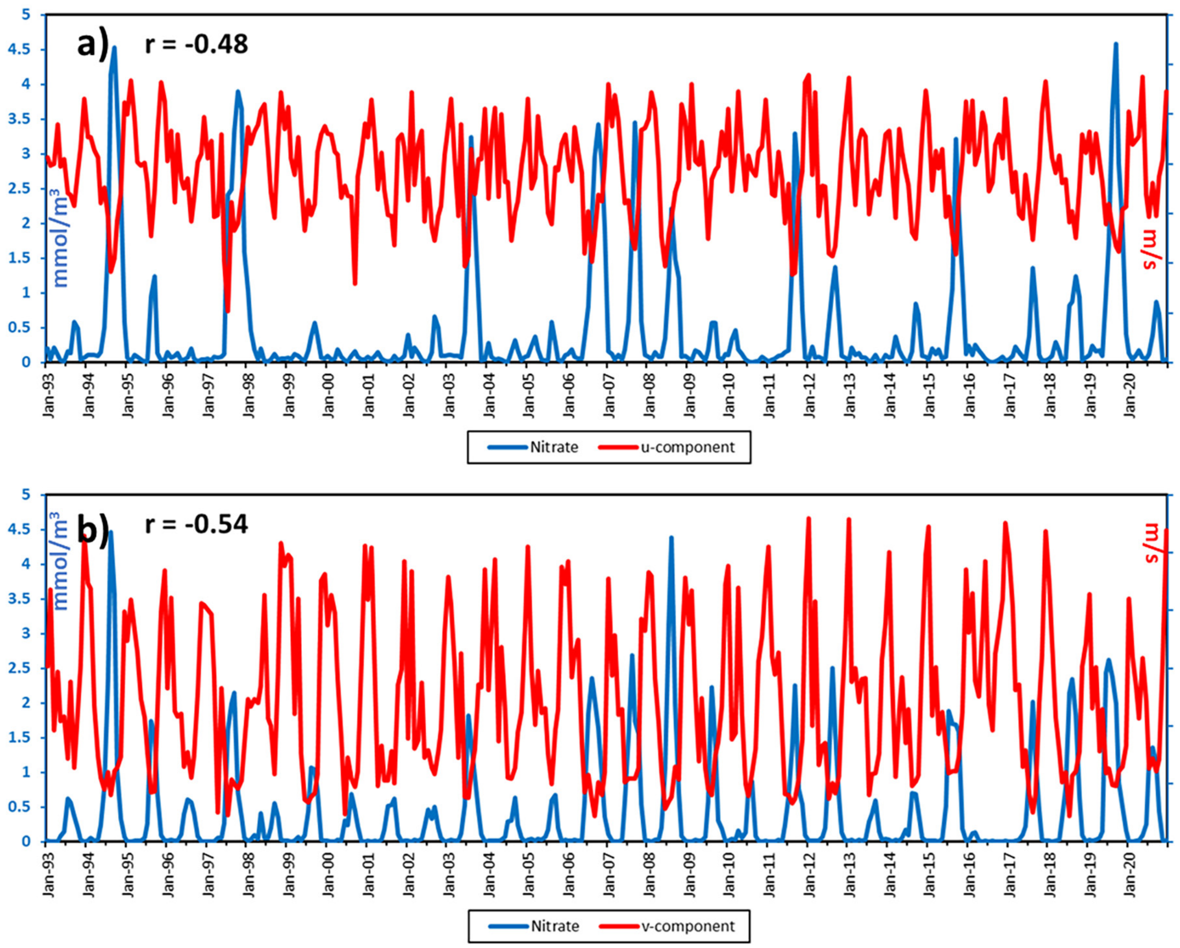

Figure 7. a) An analysis of the relationship between nitrate distribution (blue line) and zonal current (red line) in the southern region of Java; b) A comparison of nitrate distribution (blue line) and meridional current (red line) in the southern portion of the Lombok Strait

Figure 7a. ITF responsible for the transport of water masses from the Pacific Ocean, follows multiple pathways to reach the Indian Ocean. One of these pathways involves traversing the Makassar Strait before proceeding through the Lombok Strait and ultimately reaching the Indian Ocean. Therefore, the meridional velocity of surface currents in the Lombok Strait (115.5°E to 115.9°E and 8.2°S to 9°S) is quantified, subsequently facilitating a comparative analysis with the mean nitrate concentration in the southern region (115.2°E to 116.5°E and 9°S to 10.2°S) (Figure 7b).

On the basis of the data depicted in Figure 7, a discernible link can be established between the current at the two observation locations and nitrate concentrations, indicating a moderate relationship (-0.4 < r < -0.6). SJC is a zonal oceanic current that exhibits a prevailing eastward tendency. This observation indicates that a rise in nitrate concentration occurs when SJC has negative or weakened characteristics, or when the flow direction of SJC is westward (Figure 7a). According to the study conducted by Wijaya et al. in 2023, it was shown that SJC exhibits a negative association with the Indian Ocean Dipole (IOD). Consequently, during periods of positive IOD phases, there is an observed weakening of the eastward flow of SJC. This is the reason why, in the context of IOD, a positive phase of IOD is associated with elevated nitrate concentrations in the southern region of Java. Moreover, there exists an inverse correlation between the meridional surface current in the Lombok Strait and the distribution of nitrate in the southern region of Lombok Strait (Figure 7b). The result suggests that the intensification (weakening) of the southward surface flow in the Lombok Strait is concomitant with an augmentation (diminishment) of the nitrate concentration in the southern region of the Lombok Strait, which is consistent with the findings of the research conducted by Ayers et al. (2014).

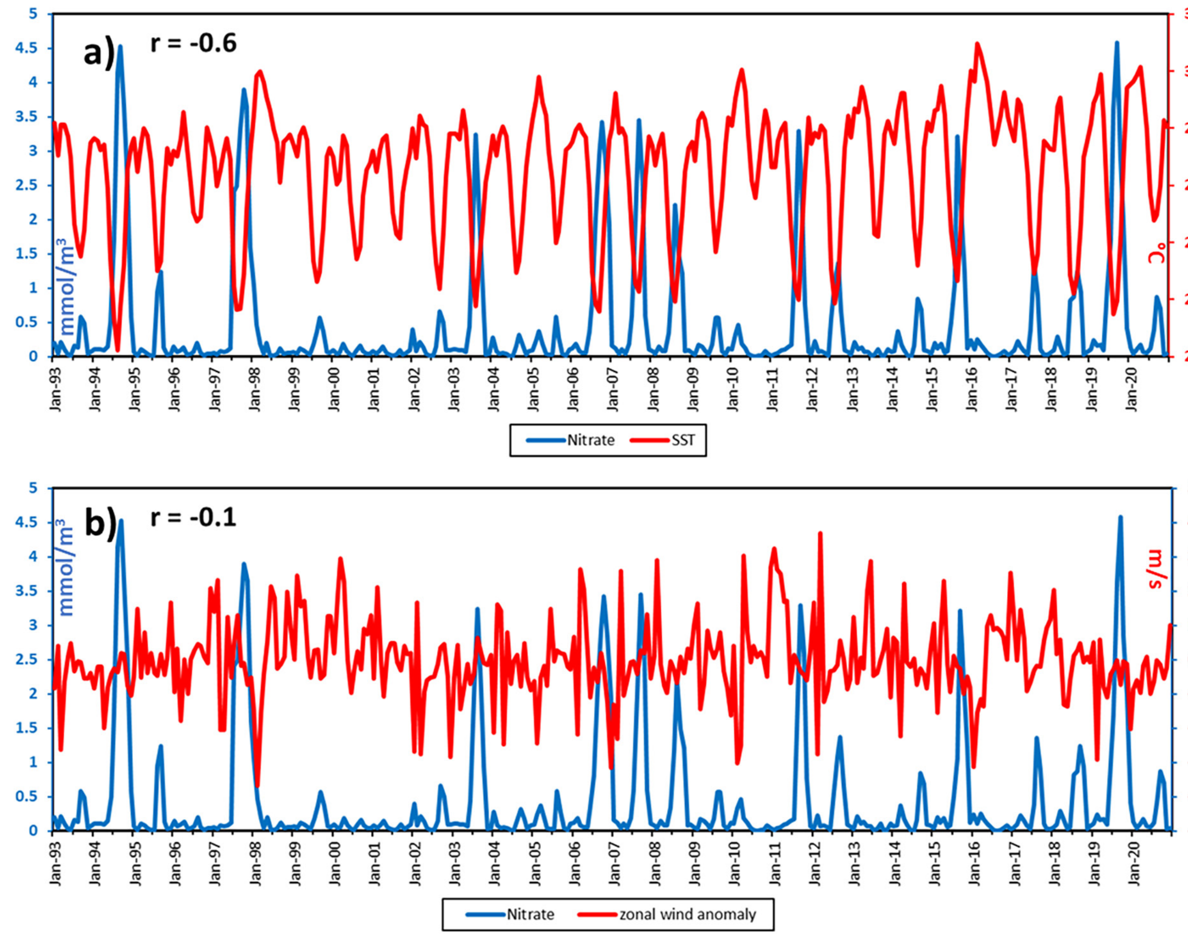

Figure 8. a) An analysis of the relationship between nitrate distribution (blue line) and SST (red line) in the southern region of Java; b) A comparison of nitrate distribution (blue line) and zonal wind anomaly (red line) in the southern region of Java

Subsequently, an analysis was conducted to determine the correlation between the distribution of nitrate and SST as well as zonal wind patterns in the southern region of Java (Figure 8). It was observed that the concentrations of nitrate exhibit an upward (downward) trend in response to the cooling (warming) of the water (Figure 8a). The reduction in sea surface temperature (SST) in the southern region of Java serves as an indicator of an upwelling phenomenon, wherein nutrients located at the lower depths of the water column are transported to the surface. IOD has a positive phase, leading to the cooling of water masses in the southeastern area of the Indian Ocean (Higuchi and Tozuka, 2022; Nur'utami and Hidayat, 2016). This cooling phenomenon is mostly attributed to the propagation of the upwelling Kelvin wave. In contrast, there is no discernible direct association between the distribution of nitrate and wind patterns in the southern region of Java (Figure 8b).

CONCLUSIONS

The nitrate distribution in the southern waterways of the Indonesian archipelago exhibits a distinct seasonal pattern, characterized by the maximum peak in nitrate concentrations occurring during the month of SON. The distribution of nitrates exhibits a significant correlation with the phenomena of IOD. Specifically, during the years characterized by a positive IOD, there is an observed elevation in nitrate concentrations that surpasses the typical levels. SJC is associated with the spatial distribution of nitrate in the southern region of Java. When the strength of SJC is diminished, there will be an observed increase in nitrate concentration. Conversely, when SJC is reinforced, a decrease in nitrate concentration will be observed. The inverse relationship can be observed between ITF traversing the Lombok Strait and the distribution of nitrate in the southern region of the Strait. The increase (decrease) in nitrate concentration occurs simultaneously with the increase (decrease) in ITF surface currents.

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