



Assessing the Impact of Various Controlling Factors on Chlorophyll Concentration in the Arabian Sea Using Remotely Sensed Observations

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Abstract

Present work examines a long-term trend (2003–2020) of the chlorophyll-a concentration and impact of various controlling factors on it in the Arabian Sea using robust non-parametric Man Kendall analysis, two-way ANOVA statistical test, and two-stage least square regression technique. Climatological means and interannual variations of chlorophyll-a (Chl_a) concentration and other controlling factors viz. Sea surface temperature (SST), Aerosol optical depth (AOD) and sea surface wind (SSW) have been analysed. From the seasonal variation of Chl_a and AOD it is observed that the highest Chl_a (1.4 mg/m³) is observed during July, August, September and October, and the highest AOD (0.8) is observed during June, July, August and September over the Arabian Sea. There was a two-month delay in the peak concentration of Chl_a/AOD, SSW; however, one month delay is observed in the peak concentration of Chl_a/SST in the Arabian Sea. A long-term trend of Chl_a concentration and SSW shows a decreasing trend, whereas SST and AOD show an increasing trend in the Arabian Sea. From ANOVA and two-stage least square regression it is observed that SST plays a significant role in influencing the decreasing trend of Chl_a in comparison to the other two controlling factors (AOD and SSW). A rise of 1% in SST results into a decrease of 0.138 percentage point in Chl_a concentration that is statistically significant at 1% significance level. The present work helps to understand the impact of various controlling factors on the ocean's primary productivity and the effect of climate change on the marine ecosystem.

Keywords ANOVA · Arabian Sea · Chlorophyll-a · Man Kendall · Primary productivity

Introduction

The Arabian Sea is one of the largest marginal seas in the world, with rich biodiversity (Wyrki 1973; Wang et al. 2021). The ecosystems of the Arabian Sea are susceptible to various factors that control the growth of algal blooms. The Arabian Sea is a basin of global importance with significant implications in ocean circulation, global signature in carbon budget and likely in biogeochemical cycling at ecosystem processes (Hussein et al. 2021; Tandule et al. 2022). Ocean primary productivity is limited by the availability of nutrients in the ocean surface layer. There are various sources of nutrients available to the surface layer, such as dust-induced aerosol particles settled over the ocean surface, which provides nutrients such as nitrogen (N), phosphorous (P), and

iron (Fe) and has positive feedback on the ocean's primary productivity. Another source of nutrient availability is deep water, which is rich in nutrients. Thermohaline upwelling affects the transfer of these nutrients from deeper waters to the surface (Sastry and d'Souza 1972). With the increase in global warming, there is an increase in ocean stratification that may weaken the supply of nutrients from deep water to the upper ocean (Bakun et al. 2015; Xiu et al. 2018). Therefore, the transfer of nutrient-rich dust-induced aerosol particles plays a significant role in ocean primary production.

Asian dust in the marginal sea helps in the growth of primary productivity, and hence, the long-term monitoring of biological productivity helps to understand ocean biogeochemistry (Tan and Shi 2009; Tan et al. 2013, 2016). Higher chlorophyll concentration in the marginal sea indicates high primary productivity for the fishing grounds. An accurate estimate of the biological productivity in the Arabian Sea with the help of valuable indicators like chlorophyll-a (Chl_a), sea surface wind (SSW), and sea surface temperature (SST) determines the availability of fish. This sort of information

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and understanding about the Chl_a data in the Arabian Sea is essential for the fisheries (Planque et al. 2011; Dan Teknik et al. 2015; Hao et al. 2019; Istnaeni and Zainuddin 2019).

Understanding the changes in the ocean's primary productivity helps to understand the growth of phytoplankton via photosynthesis and acts as a food web for the zooplanktons (Waga et al. 2022; Naselli-Flores and Padisák, 2022). Therefore, long-term trends in Chl_a concentration in marginal seas provide a better understanding of potential fishing zone planning. Several studies from the past investigated the observed changes in Chl_a concentration at a global scale and found that the changes are not geographically uniform (Gregg et al. 2003, 2005; Prakash et al. 2012; Boyce et al. 2014). According to Gregg et al. (2003), there is a 6% significant decrease in the global oceanic primary productivity. Bopp et al. (2013) forecast a mean decline in ocean primary productivity by 8% at the end of the century. Significant long-term changes in Chl_a concentration and essential drivers that limit primary productivity growth require a long-term dataset. Due to a sparse network of in-situ measurements in the ocean and significant spatial and temporal gaps, remotely sensed observation plays a crucial role (Klemas and Yan 2014).

Satellite ocean colour data and remotely sensed techniques are widely used for monitoring, estimating, and mapping phytoplankton blooms due to their comprehensive spatial and temporal coverage (Blondeau-Patissier et al. 2014). Several studies have shown the potential of remotely sensed observation in investigating the spatial and temporal distribution of phytoplankton blooms with some extent of accuracy (Gittings et al. 2017; Chen et al. 2022; Srichandan et al. 2022; Dai et al. 2023). Brewin et al. (2013) assessed the spatial and temporal distribution of phytoplankton blooms in the Red Sea using the MODIS/Aqua Chl_a dataset. Kopelevich et al. (2002) investigated the interannual variability of surface Chl_a concentration in the Black Sea using CZCS data collected from 1978 to 1986. Gurlin et al. (2011) used the MODIS and MERIS datasets to estimate the Chl_a concentration in Fremont Lakes in Nebraska, USA.

Wang et al. (2021) have used the satellite dataset to investigate frontogenesis, frontal variability and its influence on the Chl_a concentration in the Arabian Sea. Shen et al. (2020) investigated dust-induced aerosol particles' influence over Chl_a concentration in the South China Sea using the MODIS dataset. Tan et al. (2011) used the satellite datasets for Chl_a concentration and Aerosol optical depth in the coastal seas of China to investigate the correlation of Asian dust with primary production. Therefore, numerous studies from the past highlighted that dust-induced aerosol particles play a vital role in limiting the ocean's primary productivity across the globe.

Besides the aerosol particles, SST is another critical factor affecting the ocean's primary productivity. SST is an

essential factor influencing phytoplankton growth in oceans at an optimum temperature (Trombetta et al. 2019). SST negatively correlates with primary productivity; increased SST beyond the optimum level decreases ocean primary productivity. Nurdin et al. (2013) investigated that the excessive increase in SST decreases primary ocean productivity. Kumari et al. (2021) found a reduction in the primary productivity after 2012 along the Karnataka coast with a subsequent increase in SST. According to Behrenfeld et al. (2006) as climate warms, phytoplankton productivity decreases, resulting in less carbon sequestration in the ocean, producing more warming. The warming of upper layers of seawater can increase the stratification, which limits the nutrient supply to sunlit areas of the water, impacting phytoplankton growth (Polovina et al. 2008; Boyce et al. 2010; Hou et al. 2022). The warming of waters can also impact the metabolic rates of phytoplankton and their interactions with other ecosystem processes (O'Connor et al. 2009; Sommer and Lewandowska 2011). SSW has significant impact on the rate of primary productivity of the ocean. It is responsible for upwelling, bringing nutrient-rich waters from benthic regions of the sea to the surface (Lin et al. 2023). Winds can help in the vertical mixing of seawater, which helps in the production of phytoplankton, especially in seasons where sea stratification is prominent (Zhabin et al. 2019). In the Arabian Sea, precisely, the speed and direction of SSW determine the vertical velocity in the sea, which helps in mixing waters and regulates phytoplankton production (Halpern et al. 1998). However, a study by Kahru et al. (2010), mapping the correlation between winds and Chl_a concentration, found that areas with deep mixed layers negatively correlate Chl_a production and wind speed. However, the Arabian Sea has been an anomaly due to atmospheric dust deposition from the Saharan region; hence, there is a positive correlation between wind speed and Chl_a production in the region. Another critical factor that drives the ocean's primary productivity is the frontal variability determined by the intensity of alongshore wind stress. According to Chen et al. (2019), as wind stress increases, the possibility of frontal presence also increases.

Very few attempts have been made to investigate the essential drivers that limit the ocean's primary productivity in the Arabian Sea. Prakash et al. (2012) found the long-term trend of Chl_a in the Arabian Sea from 1997 to 2010 using long-term satellite observations. The results show that the decreasing Chl_a trend during summer monsoon results from the various controlling factors such as SST, Sea level anomaly, and analysis of winds. This study aims to examine the spatiotemporal variability of Chl_a and to identify the factors that govern the fluctuations in primary productivity across the Arabian Sea. To address the hypothesis, we have used the non-parametric Man-Kendall test to estimate the long-term trends of Chl_a concentration from 2003 to 2020.

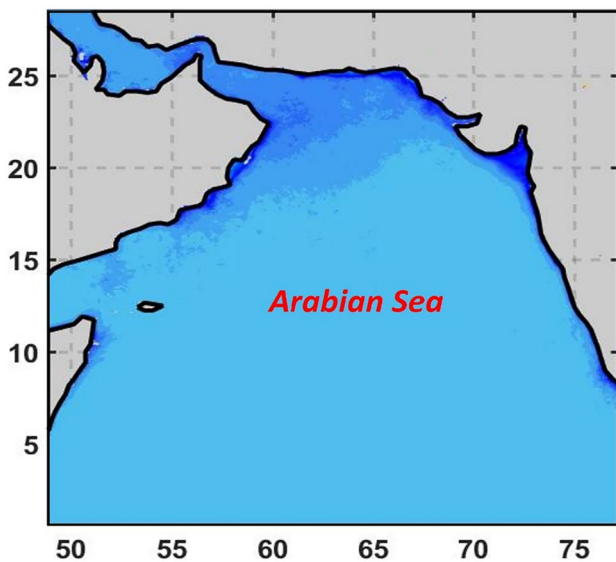


Fig. 1 Illustration of the study region that highlights the Arabian Sea

Two-way Analysis of Variance test (ANOVA) and two-stage least square regression technique are used to investigate the various controlling factors that limit the variation in the primary productivity across the Arabian Sea. The findings from the present work could have noteworthy implications for marine fisheries.

Materials and Methods

Study Area and Dataset Used

For the present work, we mainly emphasised the variability in the bio-physical properties over the Arabian Sea bounded by 0 – 28N and 47 – 78E. An illustration of the study region is highlighted in Fig. 1. For the present work, we have used the monthly Chl_a and SST products from Aqua MODIS Level 3 with a spatial resolution of 4.6 km for 18 years (2003 – 2020). We have also used the monthly AOD product from MODIS onboard Terra satellite at a spatial resolution of 1 degree that can be downloaded from the following link (<https://giovanni.gsfc.nasa.gov/>). Monthly Surface wind

speed (SSW) is obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2) reanalysis dataset at a spatial resolution of 0.5 X 0.6250 and can be downloaded from the following link (<https://giovanni.gsfc.nasa.gov/>).

For nitrate (NO₃) and phosphate (PO₄) concentrations, GLOBAL-REANALYSIS-BIO-001-029 with a grid interval of 0.25 X 0.25 were used in this study (Perruche 2018).

Details of the datasets used in the present work are listed in Table 1.

In the present work, we have considered Chl_a concentration as a proxy for primary productivity over the Arabian Sea, highlighted in Fig. 2a. The most widely used proxy for the phytoplankton biomass is total Chl_a concentration (Huot et al. 2007). Aerosol optical depth is mainly used to describe the optical information related to the atmospheric aerosols of the entire column. The Moderate Resolution Imaging Spectrometer (MODIS) mission provides oceanic optical observations from the Aqua instrument (<http://oceancolor.gsfc.nasa.gov/>), which can monitor aerosol distributions at high temporal and spatial resolutions. MODIS data has been widely used for Chl_a estimation in Marine waters because of the reliability and spatial resolution. Studies such as Shanmugam (2011); Harshada et al. (2021) and Ventura et al. (2022), have validated the operational Chl_a measurements with in-situ Chl_a measurements, indicating their accuracy. MODIS-derived AOD is reliable and readily available (Chu et al. 2002; Li et al. 2005; Yao et al. 2011). Here in the present work, we have monthly derived AOD from MODIS onboard Terra satellite for 18 years (2003 – 2020), highlighted in Fig. 2c. SST monthly product is considered from the MODIS onboard aqua satellite available at a spatial resolution of 4 km (highlighted in Fig. 2b).

Figure 3 highlights the time series of the primary limiting nutrients required for phytoplankton growth. Figure 3a shows the concentration of NO₃ nutrients over the Arabian Sea, highlighting the presence of the majority of NO₃ concentration near coastal areas compared to the open ocean that supports the growth of phytoplankton blooms. Similarly, Fig. 3b shows the concentration of PO₄ nutrients over the Arabian Sea, highlighting the presence of a higher concentration of PO₄ observed over the northern region of the Arabian Sea compared to other regions.

Table 1 Characteristics of datasets

| S.No. | Dataset used | Type of data | Level | Spatial Resolution | Temporal Resolution |
|-------|--|--------------------|-------|--------------------|---------------------|
| 1 | MODIS onboard Terra (AOD) | Satellite dataset | 3 | 1° | Monthly |
| 2 | MODIS onboard Aqua (Chlorophyll-a and SST) | Satellite dataset | 3 | 4 km | Monthly |
| 3 | MERRRA-2 (Surface wind speed) | Reanalysis dataset | - | 0.5 X 0.625° | Monthly |
| 4 | GLOBAL-REANALYSIS-BIO-001–029 (NO ₃ and PO ₄ data) | Reanalysis dataset | - | 0.25 X 0.25° | Monthly |

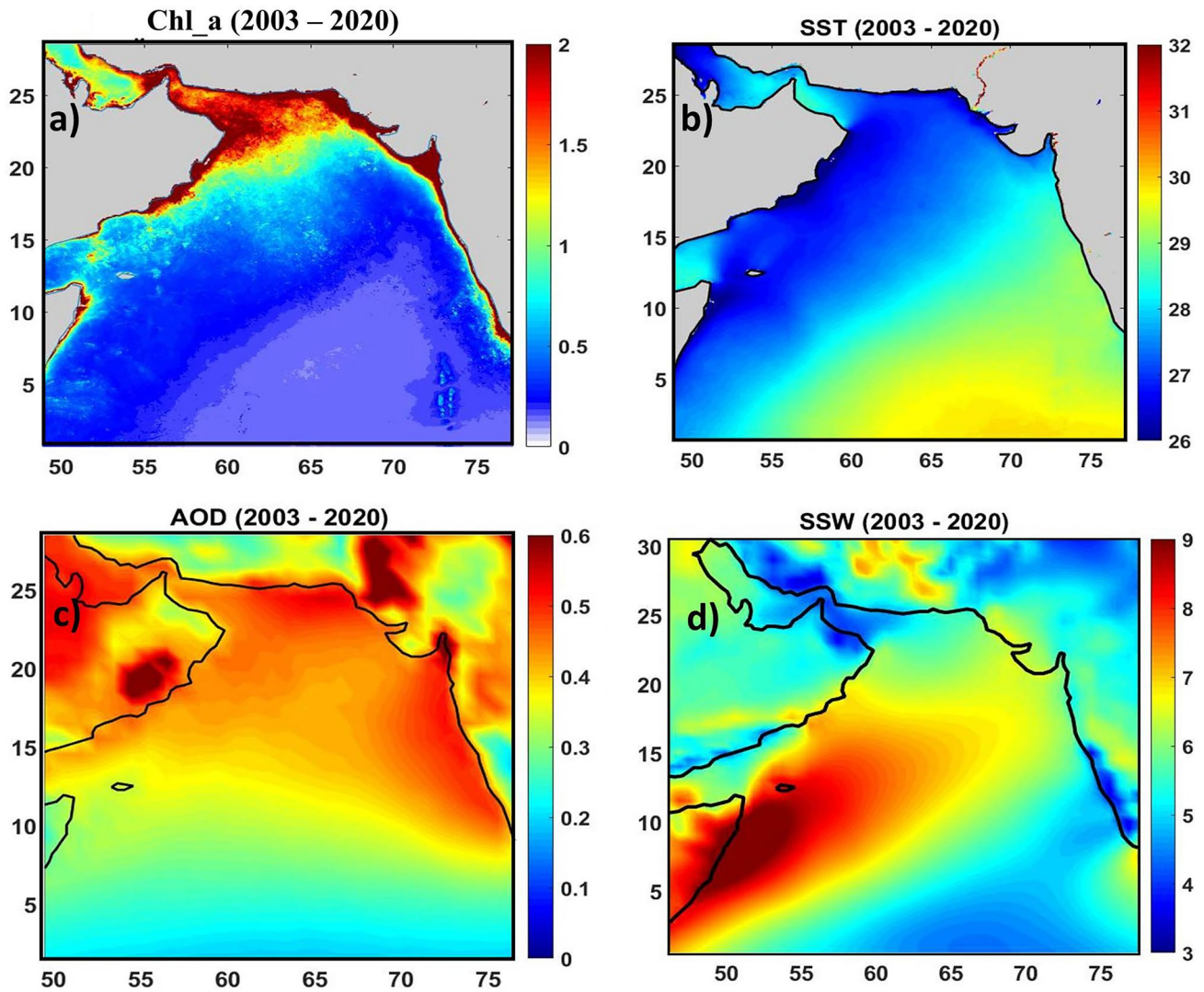


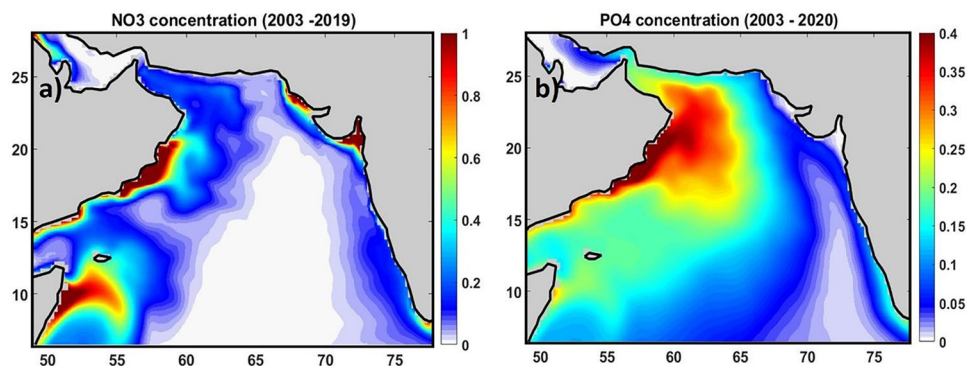
Fig. 2 a Time series of Chl_a concentration over the Arabian Sea during 2003 – 2020, b Time series of SST over the Arabian Sea during 2003 – 2020 and c Time series of AOD at 550 nm over the Arabian Sea during 2003 – 2020 and d Time series of sea surface wind speed over the Arabian Sea during 2003 – 2020

Methods

To investigate the statistically significant trends for Chl_a, AOD, SST and SSW, we have used the robust non-parametric

Mann–Kendall statistical test for 18 years (2003 – 2020). Mann Kendall is a well-established statistical test used to analyse trend patterns in climatological and hydrologic time series (Hu et al. 2020; Yue and Wang 2004; Alashan 2020; Dad et al. 2021;

Fig. 3 a Time series of NO3 concentration over the Arabian Sea during 2003 – 2019, b PO4 concentration over the Arabian Sea during 2003 – 2019



Budakoti and Singh 2021). Non-parametric Mann–Kendall test is superior to detecting linear and non-linear trends (Wu et al. 2008). The Mann–Kendall test is performed to test whether a trend exists under the null hypothesis.

To investigate the importance of various controlling variables and their influence on the Chl_a concentration, we have used the two-way Analysis of Variance (ANOVA) statistical test. The two-way ANOVA test helps to investigate whether the noted change in the response variable results from the controlling factors or their interactions. Based on the ANOVA test, we have considered various cases in which two controlling factors were considered simultaneously to determine whether the change in Chl_a is associated with the variation in either of the controlling variables. Analysis of the result is based on the computed F and P values of F-statistics for each case based on the prescribed significance level. For the two-way analysis of variance, we have considered SST as one of the first factors in each case due to its strong influence, which is evident from the correlation analysis. Interpretation of the results is based on the null hypothesis, which establishes the direct influence of the various controlling factors and their interactions separately on change in Chl_a, a response variable.

The null hypothesis is rejected for a given significance level when the associated p-value is less than 0.05 (95% confidence level), indicating the significance of that factor's influence on Chl_a. Further, we have used the two-stage least square regression method to investigate the unidirectional causal impact of explanatory variables on the Chl_a concentration in the Arabian Sea. For this purpose, the first lag of explanatory variables was used as the instrumental list in the regression model. In order to select the instrumental variable, two necessary conditions must be considered: 1) the Instrumental variable should be a core explanatory variable, and 2) the Instrumental variable should not be correlated with the error term in the regression model (Zeng et al. 2023).

Model which explained the impact of various controlling factors that limits the Chl_a concentration in the Arabian Sea given as:

$$\text{Chl}_a = \beta_0 + \beta_1 \text{SST} + \beta_2 \text{AOD} + \beta_3 \text{SSW} + \varepsilon \quad (1)$$

In the context of this study, Chl_a serves as the explained variable, while SST, AOD, and SSW function as explanatory variables that could potentially exert a crucial influence on the Chl_a concentration in the Arabian Sea.

Results and Discussion

Distribution of AOD, Chl_a, SST and SSW Over the Arabian Sea

Figure 4 shows the temporal variation of area-averaged Chl_a concentration along with AOD, SST and sea surface wind (SSW). From the time series plot, it is observed that the peak of Chl_a is in agreement with the peak of AOD, SSW and dip of SST over the Arabian Sea from 2003 – 2020, as evident from Fig. 2. The maximum peak of AOD matches the maximum peak of wind speed, and there is a two-month lag between the maximum peak of Chl_a and AOD over the Arabian Sea, as shown in Table 2. Therefore, the two-month lag between the peak of AOD and Chl_a indicates that the transported dust-induced aerosol particles slowly influence the primary productivity in the Arabian Sea. Hence, dust-induced aerosol particles from land influence Chl_a concentration in the Arabian Sea during summer monsoon months.

Table 2 and Fig. 4 show that the peak of Chl_a concentration occurs in September almost every year, whereas the peak of AOD occurs in July almost every year. A two-month lag exists between the peak of Chl_a concentration and AOD in the Arabian Sea. This indicates that the nutrient availability at the ocean surface that results from the Asian dust-induced

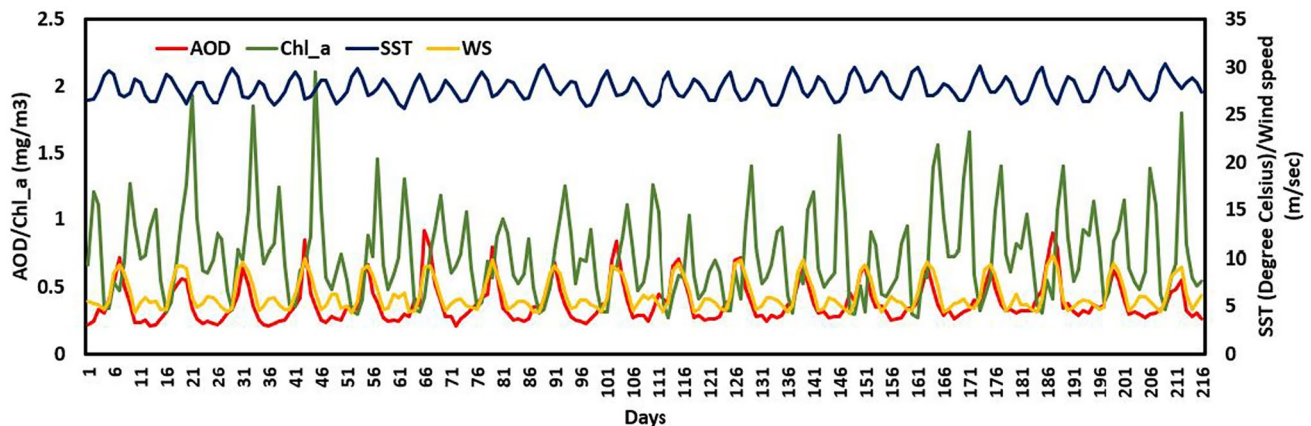


Fig. 4 Area averaged time series of Chl_a concentration with other controlling factors (AOD, SST and SSW) from Jan 2003 – December 2020

Table 2 High AOD and Chl_a concentration periods during 2003 – 2020 over the Arabian Sea

| Year | Peak of AOD | Peak of Chl_a (mg/m ³) |
|------|---------------|------------------------------------|
| 2003 | July (0.71) | September (1.27) |
| 2004 | August (0.55) | September (1.93) |
| 2005 | July (0.64) | September (1.85) |
| 2006 | July (0.84) | September (2.102) |
| 2007 | July (0.67) | September (1.45) |
| 2008 | June (0.91) | September (1.18) |
| 2009 | July (0.79) | September (1.001) |
| 2010 | July (0.68) | September (1.25) |
| 2011 | July (0.84) | September (1.11) |
| 2012 | July (0.71) | September (1.03) |
| 2013 | July (0.72) | September (1.4) |
| 2014 | July (0.63) | September (1.21) |
| 2015 | July (0.65) | August (0.91) |
| 2016 | July (0.66) | September (1.56) |
| 2017 | July (0.64) | September (1.4) |
| 2018 | July (0.9) | September (1.4) |
| 2019 | July (0.62) | September (1.14) |
| 2020 | August (0.54) | August (1.8) |

aerosol particles provides feedback to the ocean primary productivity in the Arabian Sea increases in ocean primary productivity. Along with the feedback from dust-induced aerosol particles, wind-driven upwelling during the southwest monsoonal months of August and September may also be a potential cause for the higher primary productivity in the Arabian Sea (Auer et al. 2023; Silori et al. 2023). Higher primary productivity during September is mainly attributable to higher Chl_a concentration over the North West Arabian Sea, as evidenced by Fig. 2a. Alauddin Talukder (2005) found that the higher Chl_a concentration over the northwest Arabian Sea resulted from the wind-driven upwelling during August and September that brings nutrient-rich water from the deep ocean to the ocean surface, enhancing primary productivity.

Seasonal variation of Chl_a, SST, AOD and SSW over the Arabian Sea

Figure 5 shows the monthly mean climatology plot for Chl_a, AOD, SST and SSW in the Arabian Sea. The monthly mean AOD climatology plot shows that the maximum aerosol loading occurs during July, with an annual peak greater than 0.8 in the Arabian Sea. Aerosol in the Arabian Sea started increasing during June, decreasing after July, and reaching a minimum during December, as highlighted in Fig. 5a. Prijith et al. (2013) and Tiwari et al. (2016) also found the maximum aerosol loading during July over the Arabian Sea. From the monthly climatology Chl_a concentration, it is observed

that the Chl_a concentration is higher during February, March with a maximum peak of 1.1 mg m⁻³ and then started decreasing till June and then started increasing with a maximum peak with a magnitude greater than 1.4 mg m⁻³ during September and then started decreasing till December evident from Fig. 5b.

Hussein et al. (2021) also found that February and March have higher Chl_a concentrations, especially in the Strait of Hormuz of the Arabian Sea. Presences of higher nutrient loading that result from the nutrient discharge from agriculture and aquaculture activities along the coastal shores. Higher Chl_a concentration during September resulted from the wind-driven upwelling southwest monsoon months of August and September that are responsible for the nutrient availability from the deep water to the ocean surface that may be a potential cause for the enhancement of primary productivity during these months in the Arabian Sea. The mean monthly climatology plot for wind speed shows the highest wind speed during July, with a magnitude greater than 9 m/sec in the Arabian Sea. Wind speed in the Arabian Sea started increasing during May, peaked in July, and decreased till December. There is a two-month lag between Chl_a concentration and AOD, wind speed in the Arabian Sea.

The monthly climatology average SST is shown in Fig. 5d. The figure shows that SST in the Arabian Sea is lower in August and September and peaks in May, with the highest peak having a magnitude greater than 29 degrees Celsius. Therefore, from Fig. 5, SST and Chl_a are in opposite phase relationships in the Arabian Sea. Hence, the low SST in the Arabian Sea during August and September may be a potential factor responsible for the higher primary productivity of the ocean during September. Therefore, to investigate the controlling factors that limit the primary productivity in the Arabian Sea, we have further examined the correlation and causality measure between Chl_a concentration and other controlling factors.

Trend Pattern of Chl_a and Other Controlling Factors

Figure 6 shows the pattern of Chl_a and other controlling factors (SST, AOD, and SSW) in the Arabian Sea from 2003 to 2020. From Fig. 6a it is observed that the Chl_a trend is not uniform in the Arabian Sea. The figure shows that the Chl_a trend over the northwest Arabian Sea has a negative trend. Chl_a over the Southwest Arabian Sea comprising the Oman coast and Somali coast shows a decreasing trend. South Eastern Arabian Sea comprising the west coast of India also shows negative trends of Chl_a. Over the Central Arabian Sea, Chl_a has mixed positive and negative responses. Hence, the trend is uniform over most regions. Therefore, Chl_a shows a decreasing trend over the Arabian Sea from 2003 to 2020.

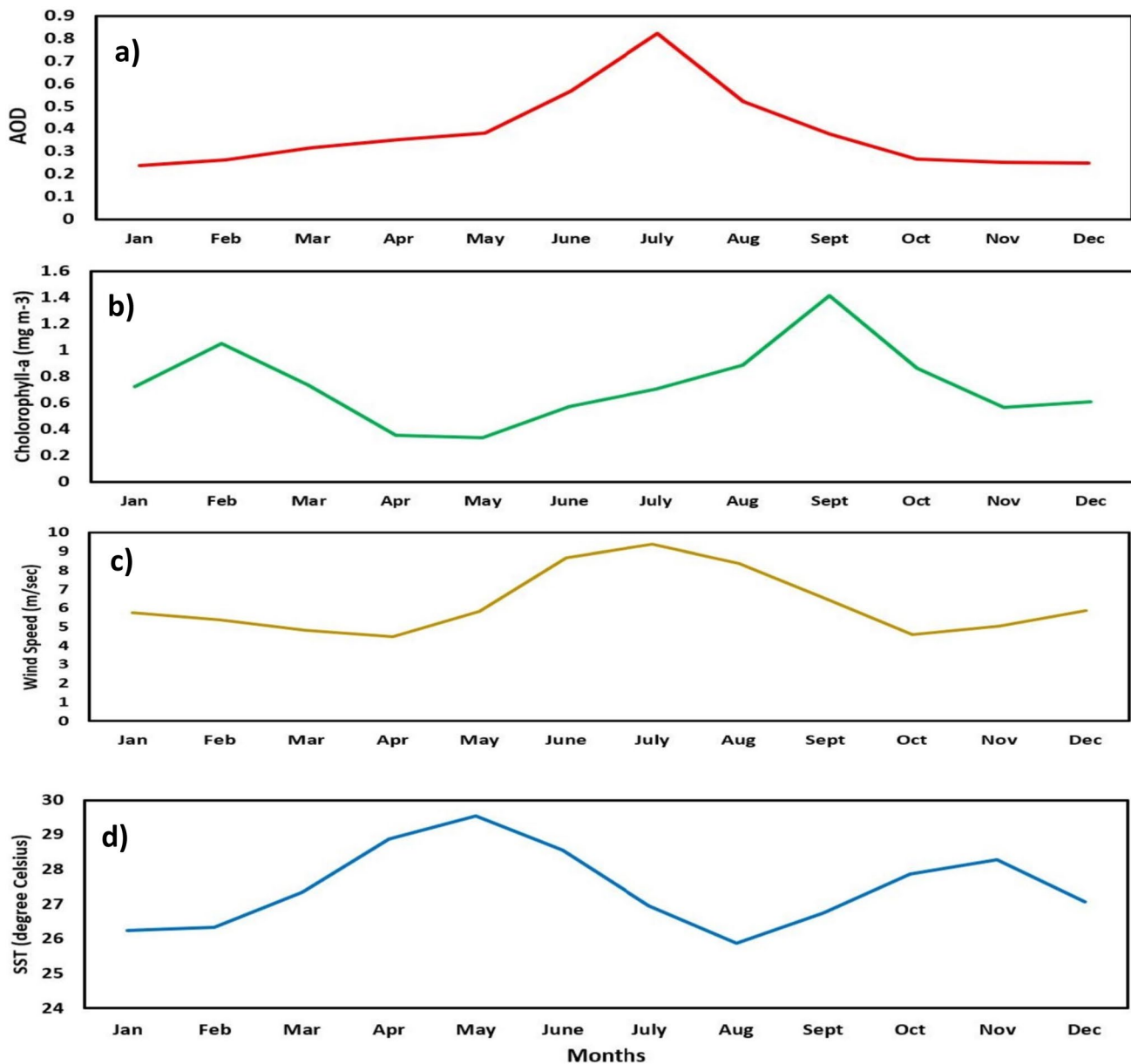


Fig. 5 a Climatological monthly mean of AOD at 550 nm over the Arabian Sea during 2003 – 2020, **b** Climatological monthly mean of Chl_a over the Arabian Sea during 2003 – 2020, **c** Climatological

monthly mean of SSW over the Arabian Sea during 2003 – 2020, and **d** Climatological monthly mean of SST over the Arabian sea during 2003 – 2020

The statistically significant decreasing trend for Chl_a is marked with yellow stipples over the spatial map that is significant at a 5% significance level.

Prakash et al. (2012) also found a decreasing trend for Chl_a after 2003 for the Somali coast in the Arabian Sea. Hussein et al. (2021) also found a decreasing trend of Chl_a in the Arabian Gulf and Gulf of Oman in the Arabian Sea. Figure 6b shows the spatial distribution of the SST trend in the Arabian Sea and shows that the SST trend is increasing in the Arabian Sea and is uniform over all the regions in the Arabian Sea. A statistically significant increasing trend for SST is observed over

the north and north-western parts of the Arabian Sea, marked with yellow stipples over the spatial map. Figure 6c shows the spatial distribution of long-term trends for AOD in the Arabian Sea. The figure shows that over the North West Arabian Sea and South West Arabian Sea AOD trend is increasing with a magnitude greater than -0.02 AOD per year, which is statically significant at a 5% significance level highlighted with yellow colour stipples over the spatial maps, An increasing trend of AOD is observed over the southeast Arabian Sea with a magnitude greater than 0.02 AOD per year. According to Prijith et al. (2018), an increasing trend of AOD was observed over the

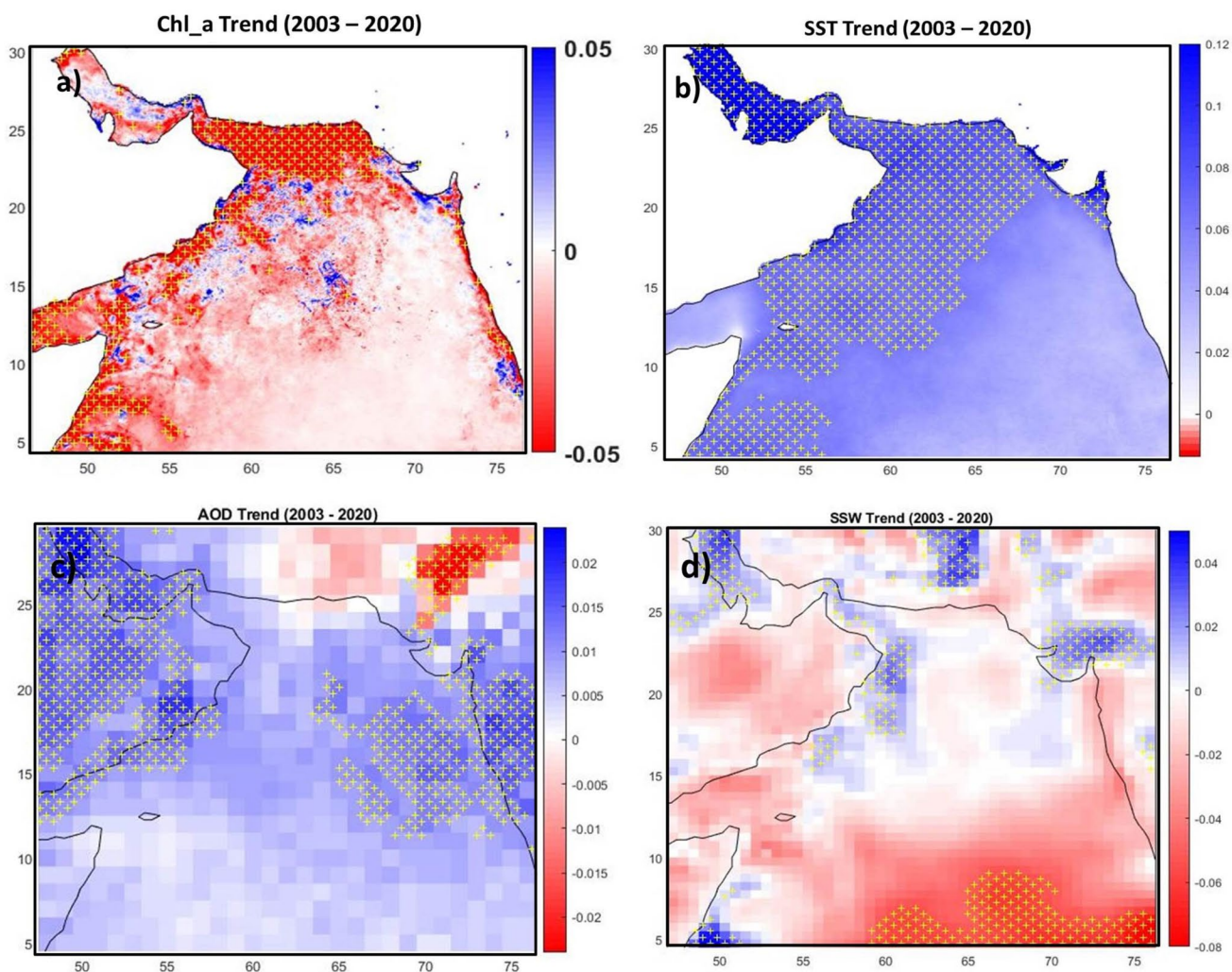


Fig. 6 **a** Trend of Chl_a over Arabian Sea during 2003 – 2020, **b** Trend of SST over Arabian Sea during 2003 – 2020 and **c** Trend of AOD at 550 nm over Arabian Sea during 2003 – 2020 and **d** Trend of SSW over Arabian sea during 2003 – 2020

Arabian Sea with a rate greater than 0.02 AOD per year. The increasing trend over the Arabian Sea results from the increasing aerosol load over southeast Asia that influences the surrounding oceanic regions. Song et al. (2021) also reported that the dust optical depth decreases over the Arabian Sea at -0.0013 per year. Figure 6d shows the trend pattern for sea surface wind speed in the Arabian Sea. The figure shows that the wind speed trend has decreased over the Southwest and southeast Arabian Sea. The northwest and southwest regions are the most productive regions in the Arabian Sea, resulting from the southwesterly monsoon winds leading to wind-driven upwelling in these regions. Hence, the decreasing trend of SSW indicates that wind-driven upwelling weakens over the northwest Arabian Sea, resulting in a less supply of elevated nutrients from the deep water to the ocean surface as a potential cause for less productivity over the Arabian Sea. Studies from the past have shown that wind-driven upwelling in the South East Arabian Sea is driven by both local and remote winds (Sharma 1978; Smitha et al. 2008; Rao et al. 2008; Huang et al. 2023). Prijith et al. (2018) also

found a strong negative trend for SSW over the Arabian Sea. Decreased surface wind over the Arabian Sea reveals decreased wind-driven aerosol production over the past decades. Figure 6 shows that the trend of Chl_a and SSW is decreasing, whereas the trend of SST and AOD is increasing over the Arabian Sea. The spatial trend pattern analysis shows that SST and SSW agree with Chl_a concentration in the Arabian Sea. Therefore, we have observed the seasonal trend of Chl_a and SST in the Arabian Sea from 2003 to 2020.

Figure 7 shows the seasonal trend of Chl_a and SST in the Arabian Sea during Post-monsoon (MAM), Monsoon (JJAS) and Post-monsoon (OND). The figure shows that during pre-monsoon (MAM) season Chl_a is showing an increasing trend over the western Arabian Sea, evident from Fig. 7a. In contrast, the spatial trend of SST shows decreasing trend highlighted in Fig. 7d. The spatial trend of Chl_a shows a decreasing trend. In contrast, SST shows an increasing trend during the monsoon season in the Arabian Sea, which is statistically significant at a 5% significance

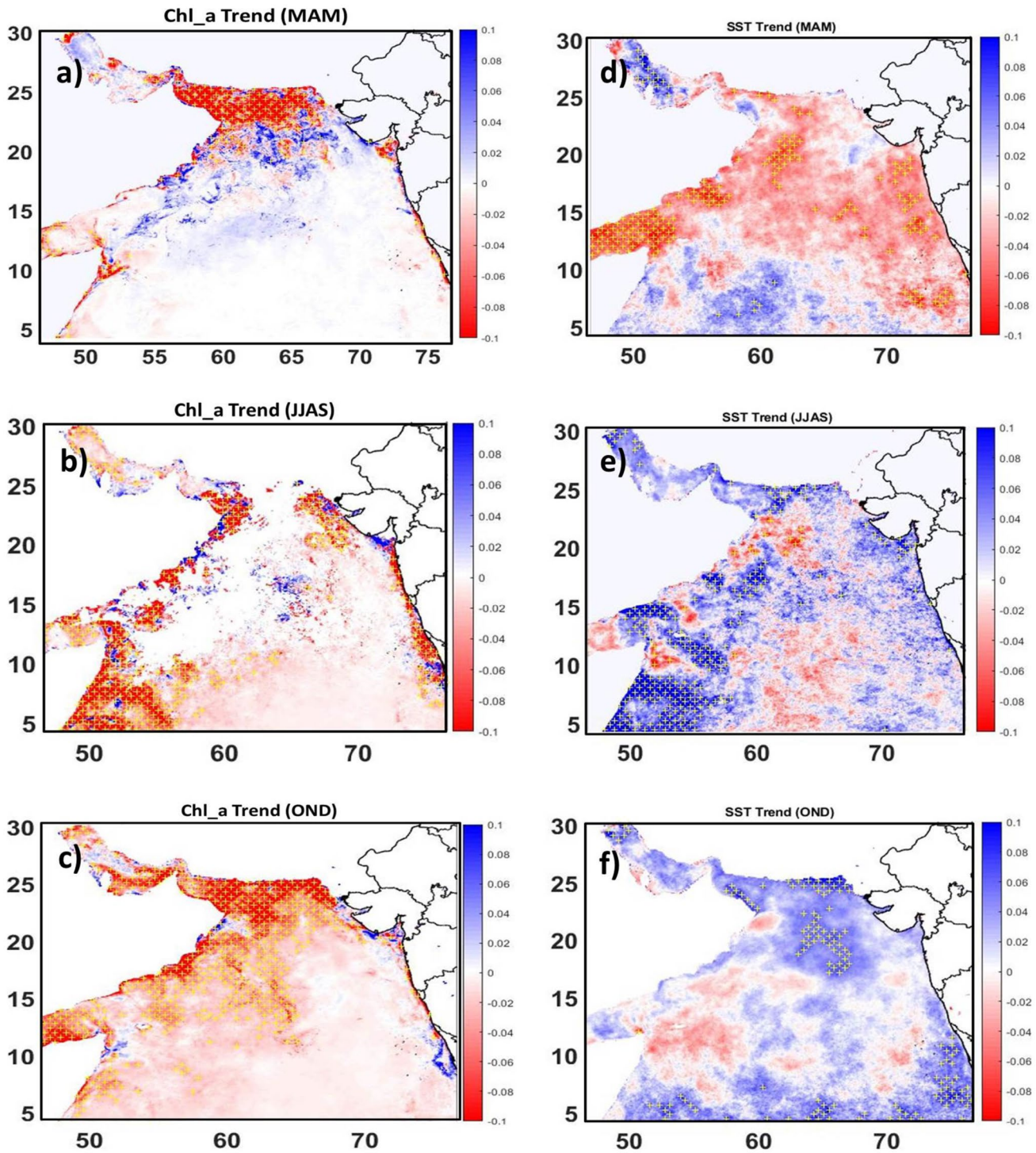


Fig. 7 Spatial trend of Chl_a in Arabian sea for the period 2003–2020 during **a** Pre-monsoon (MAM), **b** Monsoon (JJAS) and **c** Post monsoon (OND), Spatial trend of SST in Arabian Sea for the period 2003

to 2020 during **d** Pre-monsoon (MAM), **e** Monsoon (JJAS) and **f** Post monsoon (OND)

level highlighted with yellow stipples over spatial maps evident from Figs. 7b, e. From Fig. 7c, it has been observed that post-monsoon Chl_a shows a decreasing trend that is statistically significant at 5% significance level. SST

shows an increasing trend in the Arabian Sea during the post-monsoon season that is not statistically significant at the 5% significance level highlighted in Fig. 7f. From the seasonal trend plot for Chl_a and SST in the Arabian

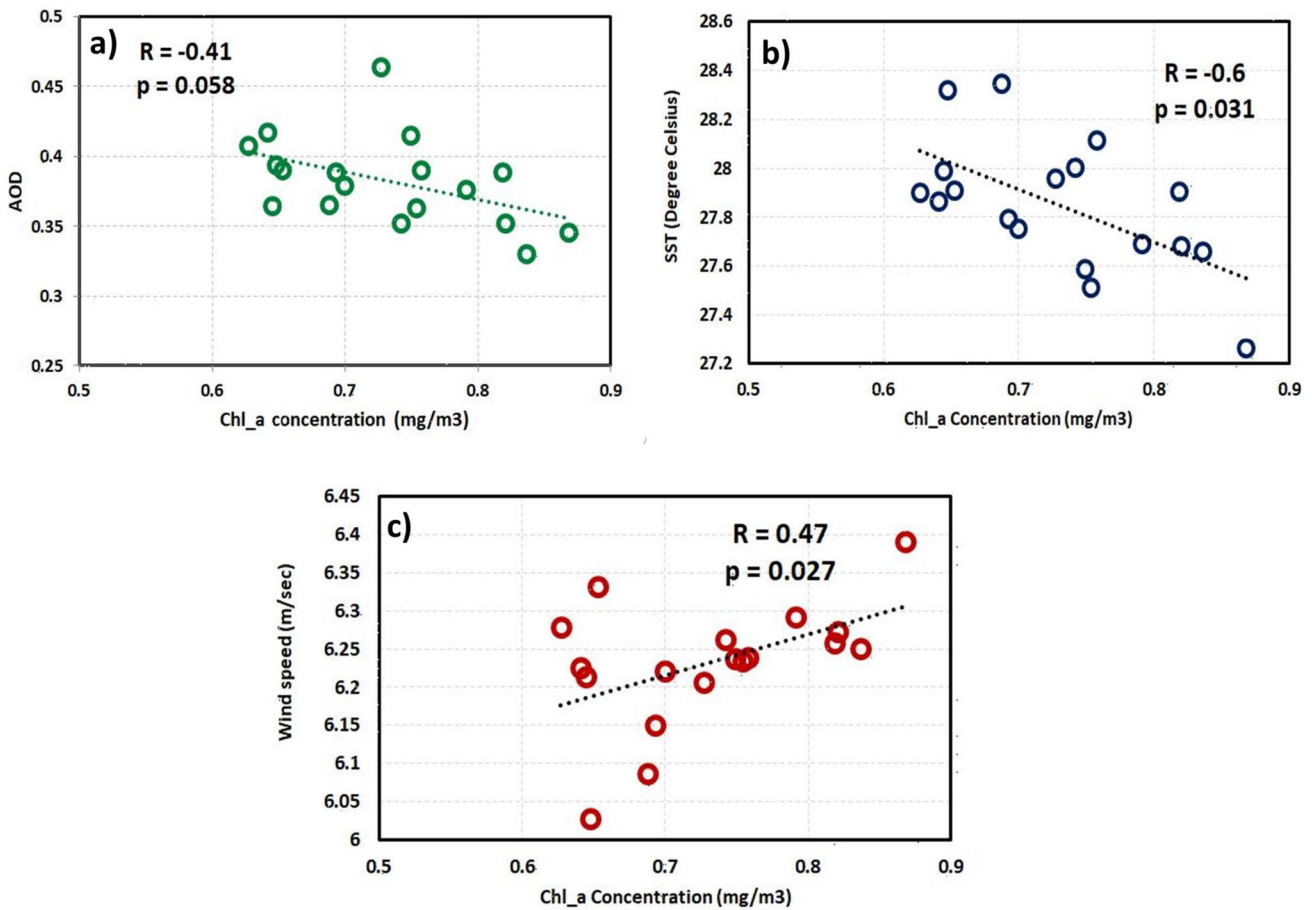


Fig. 8 a Scatter plot for AOD vs Chl_a concentration during the period 2003 – 2020 averaged over the Arabian Sea, b Scatter plot for SST vs Chl_a concentration during the period 2003 – 2020 averaged

over the Arabian Sea, and c Scatter plot for SSW vs Chl_a concentration during the period 2003 – 2020 averaged over the Arabian Sea

Sea, SST provides feedback on the primary productivity during pre-monsoon, monsoon and post-monsoon seasons. According to Roxy et al. (2014) western Indian Ocean shows a statistically significant warming trend (> 0.1 degree Celsius/decade). Ryther and Menzel (1965) show that the western Ocean areas are one of the biologically

productive regions that contribute maximum productivity to the global ocean biomass influenced by wind-driven coastal upwelling. Here from both annual and seasonal trends of SST and Chl_a, SST influences the primary productivity in the Arabian Sea. Therefore, we have used the two-way ANOVA test to confirm whether SST is the dominant factor

Table 3 Two-way ANOVA test results for the period (2003 – 2020) with controlling factors such as Sea surface temperature (SST), Aerosol optical depth (AOD) and sea surface wind (SSW)

| 2003 – 2020 Cases | ANOVA statistics | | |
|--|-------------------------------------|---------|--------|
| | F value | P value | |
| 1st case Chl_a as Response variable SST is the first factor AOD is the second factor | Influence of first factor (SST) | 64.08 | <0.001 |
| | Influence of second factor (AOD) | 1.844 | 0.168 |
| | Influence of interaction (SST: AOD) | 1.188 | 0.27 |
| 2nd Case Chl_a as Response variable SST is the first factor SSW is the second factor | Influence of first factor (SST) | 63.73 | <0.001 |
| | Influence of second factor (SSW) | 0.278 | 0.59 |
| | Influence of interaction (SST: SSW) | 1.46 | 0.197 |

Chl_a as the response variable and SST are considered the first factor in all the cases, and the second factor (AOD and SSW) varies from case to case. P values <0.001 are listed in the table for cases with calculated values smaller than 0.001

Table 4 Result of two-stage least square regression on Chl_a concentration

| S.NO | Parameters | Coefficient | SE | t Statistic | p-Value |
|------|------------|-------------|-------|-------------|-------------|
| 1 | Intercept | 4.559 | 0.846 | 5.386 | 1.9248e-07 |
| 2 | SST | -0.138 | 0.027 | -4.959 | 1.4535e-06* |
| 3 | AOD | -0.443 | 0.745 | -0.594 | 0.553 |
| 4 | SSW | 0.0283 | 0.059 | 0.473 | 0.636 |

*Indicates statistical significant at 1% significance level

significantly influencing the Chl_a concentration in the Arabian Sea.

Factors Controlling the Growth of Phytoplankton Blooms Over the Arabian Sea

From the long-term trend for Chl_a and controlling factors (AOD, SST and SSW), it is observed that both Chl_a and SSW trends are decreasing in the Arabian Sea. In contrast, SST and AOD trends have increased in the Arabian Sea in recent decades. Figure 8 shows the scatter plot between Chl_a with other controlling factors (AOD, SST and SSW). Figure 8a shows the scatter plot between Chl_a and AOD, indicating a negative correlation with a correlation coefficient of 0.41 between Chl_a and AOD. Figure 8b shows the scatter plot between Chl_a and SST in the Arabian Sea. The figure shows a strong negative association with a statistically significant correlation coefficient of 0.6 between Chl_a and SST in the Arabian Sea. A moderate negative association between Chl_a and AOD is evident from the decreasing trend of Chl_a and the increasing trend of AOD.

In contrast, a strong negative association between SST and Chl_a is evident from the opposite trends for Chl_a and SST in the Arabian Sea. Figure 8c shows a positive association between wind speed and Chl_a, which is statistically significant at a 5% significance level. Therefore, from the correlation measure, it is challenging to conclude which controlling factor is limiting the primary productivity in the Arabian Sea. The correlation measure shows that the

association between SST and Chl_a is statistically significant, with a strong negative association that is statistically significant at less than 5%. The association between SSW and Chl_a is strongly positive and statistically significant at a 5% significance level.

Therefore, we have used the two-way ANOVA test to understand the influence of SST as a controlling factor on Chl_a. Here, SST is considered the first factor in all the cases, whereas other controlling factors (AOD and SSW) vary from case to case. The results of the ANOVA statistics are presented in Table 3. Estimated p-values for SST at an annual scale are less than 1% significance level with p-values less than 0.001. The direct influence of other controlling factors (AOD and SSW) is not statistically significant at a 1% significance level. Interaction of SST with other controlling factors is also not significant at a 1% significance level. Therefore, from the ANOVA test, it has been observed that SST has a direct influence in limiting the variation in Chl_a in the Arabian Sea. From correlation analysis and ANOVA test, SST is the dominant factor driving primary productivity in the Arabian Sea compared to the other controlling factors (AOD and SSW).

Table 4 shows the results of two-stage least square regression for the Chl_a concentration and its relationship with the explanatory variables. The result shows that there exists a significant negative relationship between SST and Chl_a in the Arabian Sea. Results of the model depict that 1% increase in SST that results in the 0.138 percentage decrease in Chl_a concentration in the Arabian Sea that is statistically significant ($p < 0.001$) at 1% significance level. From Table 4 it is also observed that Chl_a does not have statistical significant relationship with other explanatory variables i.e. AOD and SSW in the Arabian Sea. Therefore from the two-stage least square method it is observed that SST is the key explanatory variable that limits the variation in Chl_a concentration in the Arabian Sea.

Hence, the results obtained from both the two-way ANOVA test and the two-stage least square regression methods indicate that SST significantly influences the concentration of Chl_a in the Arabian Sea.

Fig. 9 Climatological monthly means of NO₃ and PO₄ during 2003–2019 over the Arabian Sea

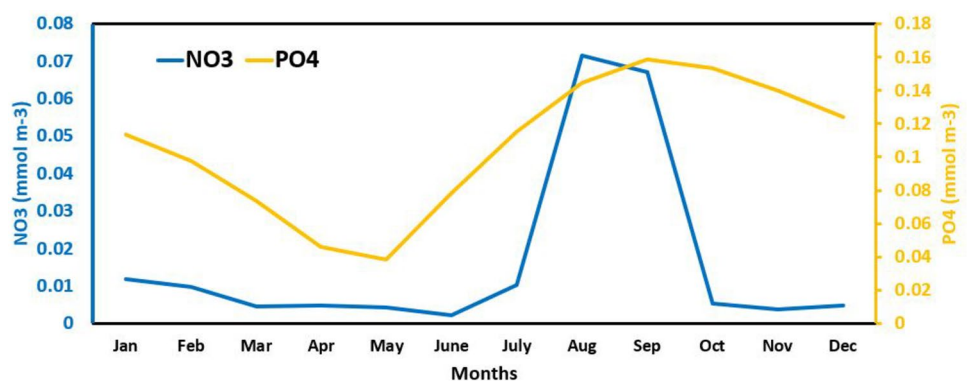
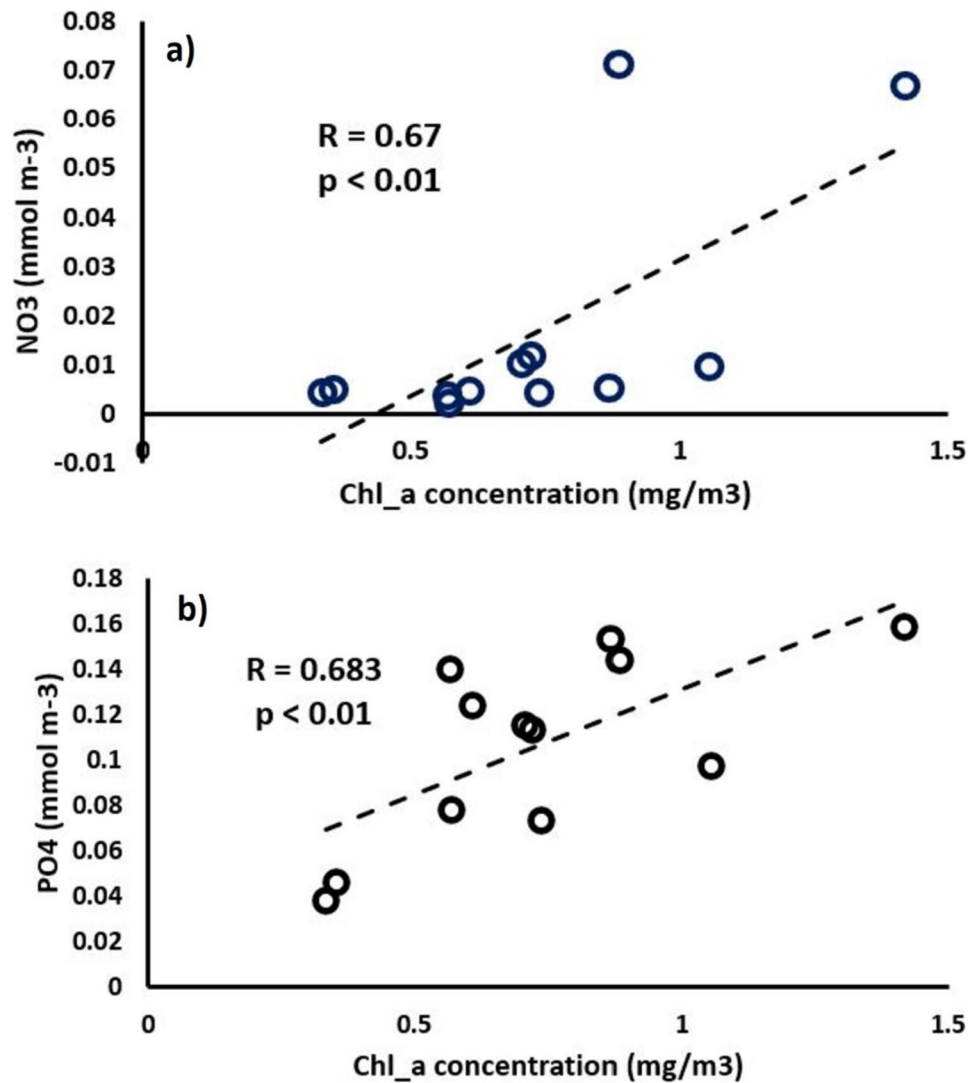


Fig. 10 **a** Scatter plot between Chl_a concentration and NO₃ and **b** Scatter plot between Chl_a concentration and PO₄



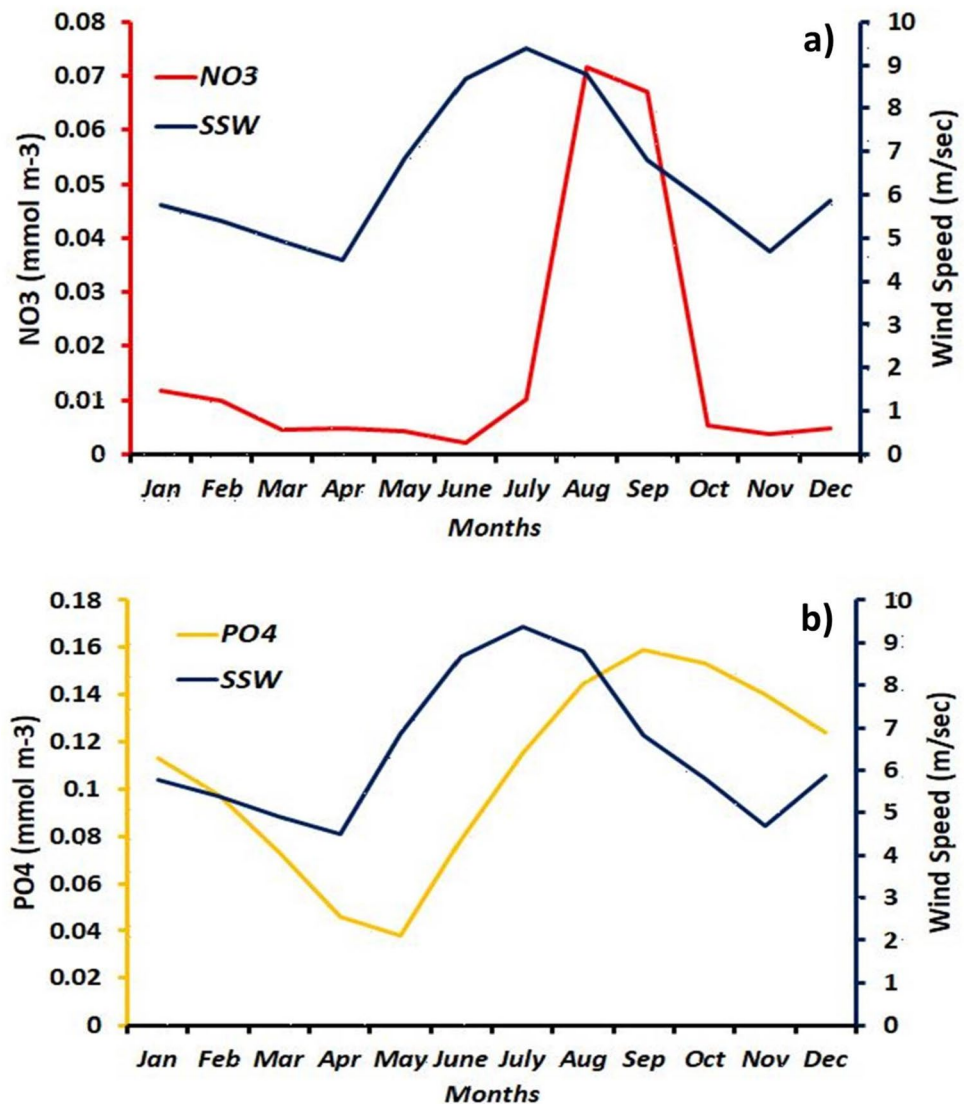
Influence of the Elevated Nutrient Concentration on Primary Productivity

Figure 9 shows the monthly climatological mean for elevated nutrients (NO₃, PO₄) in the Arabian Sea from 2003 to 2019. From the mean climatological plot for Chl_a, it is observed that the Chl_a is highest during September in the Arabian Sea; therefore, the mean climatological plot for elevated nutrients will provide evidence for higher Chl_a concentration. The figure shows that the PO₄ and NO₃ variations demonstrate good agreement with the Chl_a variation in the Arabian Sea. The figure shows that the highest peak for NO₃ concentration occurs between August and September. High NO₃ concentration during August supports phytoplankton growth along with the peak of PO₄ concentration. An increase in the elevated nutrients increases the Chl_a in the Arabian Sea, which is evident from the scatter plot between Chl_a and elevated nutrients (NO₃ and PO₄) shown in Fig. 10. Figure 10a shows the

scatter plot between NO₃ and Chl_a in the Arabian Sea from 2003 to 2019. It shows a strong statistically significant positive association between NO₃ and Chl_a with a correlation coefficient of 0.67 in the Arabian Sea. Similarly, a strong positive association exists between PO₄ and Chl_a with a correlation coefficient of 0.68, which is statistically significant at a 1% significance level.

The fluctuation of NO₃ and PO₄ is closely related to the fluctuation of wind speed in the Arabian Sea. Figure 11 shows the NO₃ and PO₄ concentration variation with wind speed variation. It also shows a one-month lag between NO₃ and wind speed in the Arabian Sea, whereas a two-month lag exists between PO₄ and wind speed. The wind blowing over the Arabian Sea generates wind-driven coastal upwelling that brings the nutrients from the deep water slowly moving to the ocean surface. Muskananfoli and Wirasatriya (2021) also found fluctuations in NO₃ and PO₄ in good agreement with the variation in Chl_a over the Savu Sea within the Indonesian region. Elevated nutrients from the deep water

Fig. 11 **a** Plot for comparison of mean monthly climatology of NO₃ with Wind Speed in the Arabian Sea from 2003 to 2019, **b** Plot for comparison of monthly mean climatology of PO₄ with wind speed in the Arabian Sea from 2003 to 2019



slowly influence the primary productivity in the Savu Sea, which is evident from a two-month lag between NO₃ and the wind speed's highest peak across the season.

Conclusions

The present work investigates the long-term characteristics of Chl_a in the Arabian Sea using the MODIS satellite dataset from 18 years, from 2003 to 2020. Variation in Chl_a in the Arabian Sea was analysed along with the other controlling factors (AOD, SST and SSW). From the spatial and temporal distribution of Chl_a along with the other controlling factors, it is noticed that there is a two-month time lag between the peak of AOD in July and the peak of Chl_a in September. Similarly, there is a two-month lag between the peak of wind speed in July and Chl_a in September. There exists a seasonal pattern between Chl_a and SST; when SST

is high, Chl_a is low, resembles that higher SST mainly resists the wind-driven upwelling as elevated nutrients from the deep ocean are unable to reach the ocean surface, which results in a decrease of ocean primary productivity. The long-term trend for Chl_a shows that the Chl_a trend is decreasing over the Southwest Arabian Sea and northwest and southeast Arabian Sea.

Similarly, the AOD trend is decreasing in the southwest Arabian Sea and agrees with the long-term trend of Chl_a. The long-term trend of SST and AOD is increasing in the Arabian Sea, whereas the wind speed trend is decreasing over the southwest and southeast Arabian Sea. Therefore, the long-term trend of Chl_a over the southwest Arabian Sea is decreasing despite the increasing trend of AOD but supported by the increasing trend of SST and a decreasing trend of SSW speed. We have used the correlation measure, two-way ANOVA test and two-stage least square regression to understand the dominant control of controlling factors on

Chl_a in the Arabian Sea. The correlation analysis shows a moderate negative association between AOD and Chl_a in the Arabian Sea with a correlation coefficient ($r = -0.41$) that is not statistically significant at a 5% significance level. A strong negative association exists between SST and Chl_a with a correlation coefficient ($r = 0.7$) that is statistically significant at a 5% significance level. The correlation between wind speed and Chl_a is also statistically significant in the Arabian Sea. From the correlation measure, SST has shown its potential in limiting the Chl_a in the Arabian Sea.

Moreover, the SST shows dominant control on Chl_a in the Arabian Sea with an estimated p-value for SST that is statistically significant at less than a 5% significance level. From two-stage least square regression, it is observed that a rise of 1% in SST leads to a decrease in Chl_a by 0.138 percentage points in the Arabian Sea, which is statistically significant at a 1% significance level. Therefore, the present study shows that SST is a primary factor contributing to the declining trend of Chl_a in the Arabian Sea. The increase in Chl_a concentration during August and September has been examined through the behaviour of elevated nutrients from the deep ocean to the ocean surface.

From monthly mean climatology plots, the fluctuation in Chl_a concentration agrees with the fluctuations in elevated nutrients (NO₃ and PO₄). Wind-driven coastal upwelling brings the nutrients from the deep ocean to the ocean surface and increases primary productivity during August and September, evident from the relative role of wind speed in the Arabian Sea. Therefore, from the present work, it has been observed that the Chl_a concentration is high in the Arabian Sea during September, which results from the feedback from dust-induced aerosol particles and wind-driven coastal upwelling. The long-term trend of Chl_a is decreasing over the southwest Arabian Sea, which resembles the long-term trend of AOD and SST in the Arabian Sea.

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Data Availability Datasets used in the present work can be downloaded from the following link <https://giovanni.gsfc.nasa.gov/giovanni/>.

Declarations

Ethical Approval Not applicable.

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