Oceanologia, Vol. 66, No. 3, 2024

https://doi.org/10.5697/DMDO7507

Long-term responses of phytoplankton biomass to the ocean surface variables in the central parts of the Arabian Sea and the Bay of Bengal

Chinnadurai Karnan*, Sreedharan Gautham, Soolamkandath Variem Sandhya, Shajahan Shahin

Abstract

The northern Indian Ocean has been warming steadily for over a half-century, especially the north-western Indian Ocean. It is widely reported that the increasing sea surface temperature in the global oceans decreases phytoplankton biomass and productivity. The impacts of long-term variations in the sea surface properties on the phytoplankton biomass (chlorophyll *a*) are least studied in the northern Indian Ocean. In this study, we have retrieved satellite, model, and ARGO float data sets to investigate the long-term variations in the distributions and trends of major oceanic variables for a better understanding of the respective changes that occurred in chlorophyll *a* concentration in the central regions of the Arabian Sea (AS) and the Bay of Bengal (BB). We have selected variables such as sea surface temperature (SST), sea surface salinity (SSS), photosynthetically available radiation (PAR), euphotic depth (ZEU), mixed layer depth (MLD), wind speed, mean sea level anomaly (MSLA), surface currents, etc., to relate with chlorophyll *a*. We found significant increasing trends in SST and positive-MSLA in both basins, and the chlorophyll *a* was decreased in the AS but contrastingly increased in the BB. Further data analysis revealed the possible reasons, such as seasonal changes in mean sea level anomaly and meridional currents, for the increasing trend of chlorophyll *a* in the central Bay of Bengal. The northward flow of the meridional currents during the southwest monsoon (SWM), transports the nutrient-rich water from the coastal upwelling zone of the southwest coast of India to the southern and central BB, and enhances chlorophyll *a*. Contrastingly, the southward flow of low-saline and nutrient-depleted Bay of Bengal water reduces the chlorophyll *a*. In addition, the large area of cold-core eddies found during the NEM enhanced the chlorophyll *a* in the central BB. Though contrasting trends between both basins in chlorophyll *a* distribution were found, the mean concentration of chlorophyll *a* in the northern Indian Ocean decreases. The present study signifies the importance of monsoon currents and eddies in regulating the chlorophyll *a* biomass and primary productivity in the AS and BB.

Keywords

Chlorophyll *a*; Sea surface temperature; Sea level anomaly; Meridional currents; Arabian Sea; Bay of Bengal

CSIR – National Institute of Oceanography, Dona Paula, Goa, India
***Correspondence**: karnanc@nio.org (C. Karnan)

Received: 8 February 2023; **revised:** 12 May 2024; **accepted**: 22 May 2024

1. Introduction

The global ocean is warming by 0.2°C decade^{-1} (Doney, 2006; McCulloch et al., 2024) and the north-western Indian Ocean (Arabian Sea) experiences the most significant warming among the tropical seas (Mohan et al., 2021; Roxy et al., 2014). The seasonally reversing winds over the northern Indian Ocean drive major variability in physical, chemical, and biological variables of the water column (Chowdhury et al., 2021; Jyothibabu et al., 2015; Prasanna Kumar et al., 2004). The reversing ocean surface currents are the outcomes of monsoon, which exchange water mass between the Arabian Sea (AS) and the Bay of Bengal (BB) (Figure 1). In general, the AS is one of the most productive oceanic regions because of strong coastal upwelling along the western and parts of eastern boundaries during the southwest monsoon (June–September; SWM), advection of the same to the open ocean and the winter convection in the northern AS during the northeast monsoon (November–February; NEM) (Banse, 1968; Madhupratap et al., 1996). The BB (north-eastern Indian Ocean) is known to be a zone with low productivity compared to the AS due to the large volume of freshwater influx and warm sea surface, causing stratification in the surface water column (Prasanna Kumar et al., 2002; Sarma et al., 2016). The global ocean primary productivity and phytoplankton

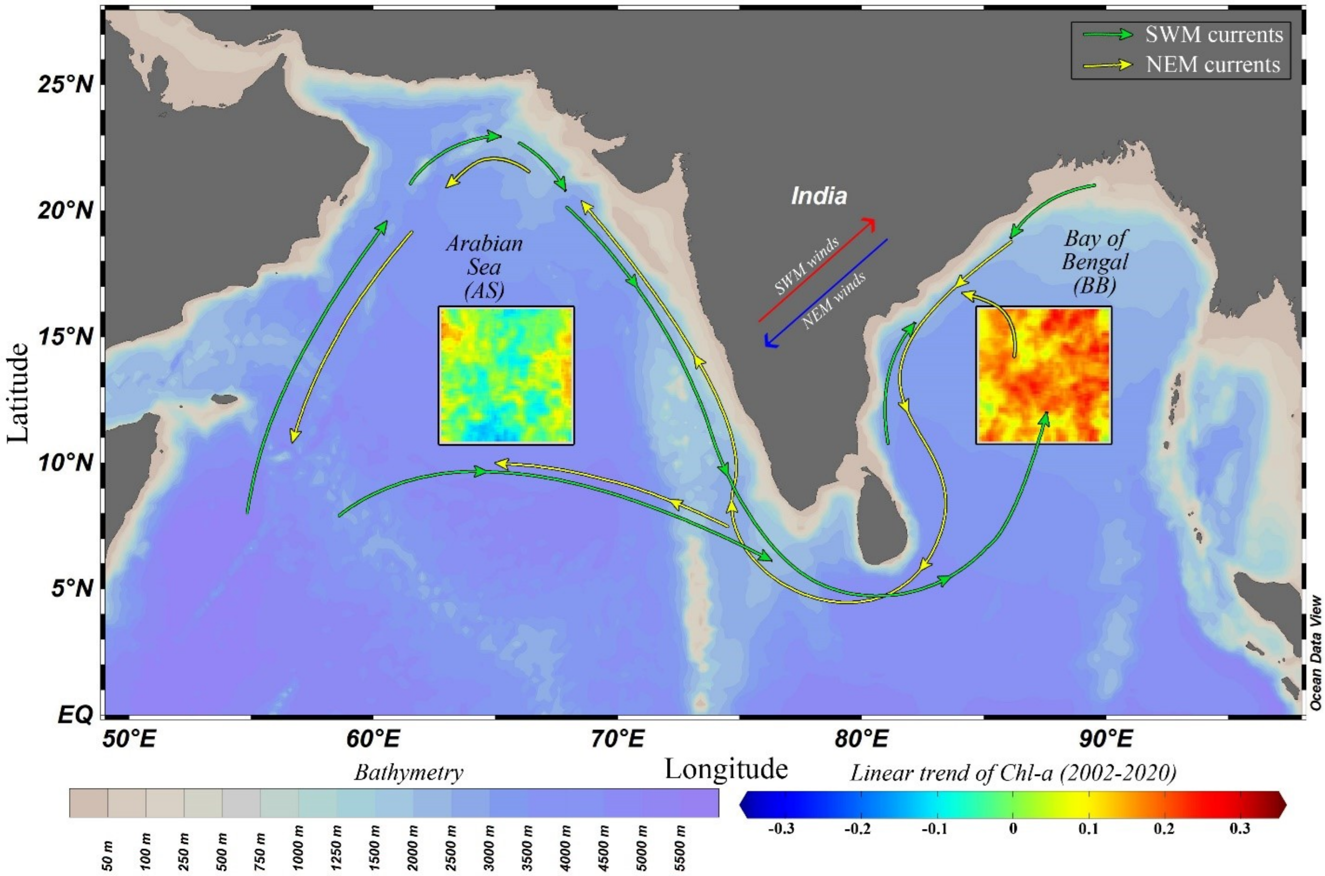

Figure 1. Study area in the central Arabian Sea and the central Bay of Bengal showed in the map as black square boxes. The color gradients within the square boxes overlaid on the bathymetry map represent the linear trend of chlorophyll *a* concentration over the selected time period (2002–2020). The blue and red color gradients indicate decreasing and increasing trend in chlorophyll *a*, respectively. The pattern of major near-surface currents during the southwest monsoon (green arrows) and northeast monsoon (yellow arrows) overlaid. The near-surface circulation patterns adopted from Shenoi et al. (1999). The cumulative wind directions during each season also showed. Photo-editing tool was used to overlay the features.

biomass in the water column have been continuously decreasing during the recent decades due to the increasing SST and associated changes in the water column (Behrenfeld et al., 2006; Sarmiento et al., 2004).

Studies on long-term processes or climatic effects require effort in standardisation and uniformity in measurements over a considerable period, as they are occurring slowly (Yang et al., 2013). The uniformity of the on-site measurements during a longer timespan is hard to achieve due to varying coverage areas, irregular sampling intervals, advancement of methods, and varying resolution of instruments over time (Venrick et al., 1987). Similarly, the oceans are under increasing anthropogenic activity pressures and local-scale natural changes, which lead to high irregularities in data measurements. Laboratory or field-based micro-, meso- and macrocosm experiments can predict the future ecosystem changes (Anil et al., 2021; Calbet et al., 2014; Yadav et al., 2016). Global and regional mathematical models are developed to predict future climate changes (Araujo and Rahbek, 2006; Giorgi, 2005; Luo et al., 2012; Mohan et al., 2021). The experiments-based research and the ocean biophysical and biogeochemical models are providing valuable results on ocean food webs and elemental cycling (Gregg and Rousseaux, 2019; Murphy et al., 2019; Wiggert et al., 2005; Wollrab et al., 2021). As the continuous monitoring and data collection from the field is more expensive, long-term satellite observations, data re-analysis, and numerical modeling are considered to be suitable and standard methods to understand the changes in the ocean parameters over a longer period of time (Dalpadado et al., 2021; Gregg and Rousseaux, 2019; Jiang and Wang, 2018; Sarmiento et al., 2004; Singh and Oh, 2007).

The coastal ecosystem is highly dynamic, where various local scale influences are introduced by river influx, tidal activity, wave activity, coastal currents, and anthropogenic inputs (ports and harbor, industries, recreation, farming, domestic, etc.). It is very complex to understand the trends of ecosystem change on a long-term scale for such coastal and bay regions. To avoid high instabilities that occur in the shelf waters (optically complex), the open ocean regions are more suitable for such studies (Behrenfeld et al., 2005). The remote sensing and ARGO floats cover large open ocean areas with reliable and standard/uniform measurements over a longer period (Guinehut et al., 2004; Ma et al., 2021). The long-term trends in physical and biological properties in the AS and the BB showed inconsistency (Goes et al., 2005; Khan et al., 2004; Kumar et al., 2016; Lotliker et al., 2020; Prakash et al., 2012; Prakash and Ramesh, 2007; Pramanik et al., 2020; Prasanna Kumar et al., 2010). For example, the studies by Goes et al. (2005) and Prakash and Ramesh (2007) reported huge and insignificant changes in chlorophyll *a* concentration in the AS, respectively. In the current study, we have used remote sensing data to deepen the existing knowledge of the long-term variations in oceanic variables and the ecosystem responses. We focused on phytoplankton biomass (chlorophyll *a*) because of their importance in carbon fixation and the food web (primary food in the ocean made through photosynthetic activity to the utmost marine organisms) (Falkowski et al., 2008; Raymont, 2014).

Phytoplankton are more sensitive to environmental variabilities and therefore they can be considered an important ecological indicators of the oceans. The increasing SST and associated changes in the surface hydrography significantly alter the phytoplankton diversity, biomass, and productivity, ultimately affecting the entire aquatic food web and carbon fixation/cycling (Doney, 2006; Lewandowska et al., 2014). The significance of the present study will be to understand different responses (decreasing/increasing trend) of chlorophyll *a* to the long-term changes in the ocean surface variables in the central parts of the AS and the BB. As these two ocean basins support a significant number of livelihoods, this study may have better implications on the policymaking for fisheries and climatologists. The specific objectives of this study are (a) to find the relationship between the trend of surface chlorophyll *a* and the trend of surface temperature, (b) to recognize similar/different responses of chlorophyll *a* to the other hydrographical settings of the central Arabian Sea, and the Bay of Bengal and (c) to distinguish specific parameters controlling the chlorophyll *a* variability in each basin.

2. Methods

2.1 Study area

The AS and the BB are semi-enclosed seas located almost in the same latitude, but the AS is in the west and the latter in the east. The reversing monsoon winds and currents have a significant impact on the biological productivity of these regions (Jyothibabu et al., 2015; Shankar et al., 2002). In the present study, we have selected only the central regions of the basins to avoid possible coastal fluctuations in the long-term trends. We fixed a representative area of $\sim$555 km^2 in the same latitudes (11–16°N) of each basin (AS: 63–68°E; BB: 85–90°E) (Figure 1). The selected regions are far away from the coast, located in the open ocean (depth $>$3000 m).

2.2 Data retrieval

The long-term monthly time series data sets from satellite-remote sensing and ARGO floats were retrieved and used in this study. The merged mean SST (AVHRR, ship, buoy, GSFC-ice, and daily-OI-V2) from 2002 to 2020 was retrieved from CSIR-NIO's live access server (las.nio.org). The sea surface salinity (SSS) and mixed layer depth (MLD) were retrieved from BOA-ARGO (2004–2020; argo.ucsd.edu; change in density by 0.03 kg m^{-3} from that at 10 m depth; Hosoda et al., 2010; Li et al., 2017) by downloading directly from the respective FTP server. The ARGO-derived data, depth of 26°C isotherms (D26), was retrieved from INCOIS's live access server (2004–2019; las.incois.gov.in). The wind speed was retrieved from Quickscat (2002–2007; las.nio.org) and ASCAT (2007–2020; oceanwatch.pifsc.noaa.gov), and both datasets were combined to derive long-time data series (2002–2020). The mean sea level anomaly (MSLA), zonal currents (u), and meridional currents (v) were retrieved from AVISO live access server (2002–2020; las.aviso.altimetry.fr). The MODIS-Aqua derived PAR, ZEU, and chlorophyll *a* were retrieved from NOAA's Ocean Watch data access server (2002–2020; oceanwatch.pfeg.noaa.gov). NASA Ocean Biogeochemical Model derived nitrate (NO^3) concentration was also retrieved (spatial resolution: 0.67° $\times$ 1.25°; 2002–2015; giovanni.gsfc.nasa.gov; Gregg and Casey, 2007; Rousseaux and Gregg, 2012).

2.3 Data processes and analyses

2.3.1 Spatial and temporal trend analysis

The spatial means of the above parameters for the AS and the BB were individually computed using the software PyFerret (v7.63) and converted to monthly time series. The spatial variation (linear trend) in chlorophyll *a* over a long time (18 years; 2002–2020) for the selected regions overlaid on the map (Figure 1) was generated by converting each time step as a number (n = 216) and the spatial correlation analysis was done between time and the chlorophyll *a* variable in PyFerret. The time-series data was split to estimate the trend (T_t; long-term orientation), seasonality (S_t; repeating/cyclical patterns), and random (R_t; irregularities) components by applying mathematical equations which are available in RStudio via the decompose function (Coghlan, 2018). As the magnitudes of seasonal variations of the time series data sets did not increase or decrease noticeably (graphical method), we selected the additive model ($D_t = T_t + S_t + R_t$) to decompose the data sets. In this model, the D_t is time series data, T_t is trend, S_t is seasonal, and R_t is residual components. The time-series trend was calculated as $T_t = D_t - (S_t + R_t)$. In this study, we have focused on the trend component, which is changing over the decade due to changing climate. The slope and intercept for the trend data were analyzed to understand the linearity. The longitude-time plots were made for selected parameters for the recent decade (2010–2020 for better visualization) to understand the associations among those parameters in both basins (PyFerret v7.63). The spatial maps of MSLA and chlorophyll *a* for selected months were prepared for both basins to explain the impacts of MSLA on the chlorophyll *a* concentration.

2.3.2 Change-point and wavelet analysis

The change-point analysis is one of the standard methods to identify significant changes in a time series data set. The analysis was carried out to assess whether significant changes occurred in chlorophyll *a* over the selected period (2002–2020). Analysis was done using the changepoint package (v2.2.3), and the pruning method (PELT) was selected in RStudio (Killick et al., 2012). In addition to the trend analysis, the wavelet power spectrum and their mean were analyzed for selected parameters (showed signatures to explain variations in chlorophyll *a*) to understand the hidden periodical changes and dominant signal frequencies concerning the time (2002–2020) (Liu et al., 2014).

2.3.3 Correlation and generalized additive model statistics

The monthly means of each parameter (D_t; calculated in PyFerret) and the computed trend values by subtracting seasonality and residuals (T_t; calculated in RStudio) for each basin were used to analyze the non-parametric Spearman multivariable correlation. The correlation results were presented as a matrix of shades and pie charts (in the lower-left diagonals) and correlation coefficients (in the upper-right diagonals) to get accurate links among the parameters (in RStudio; corrgram and corrplot packages; Friendly, 2002). Also, the generalized additive model analysis was done to understand the partial impacts of selected variables on the change in chlorophyll *a* (in RStudio; package: mgcv). We have followed the attribution guidelines to map the study area (Figure 1) using Ocean Data View and other spatial data presentations using PyFerret tool (v7.63). The graphs were plotted using Grapher v7.2. (Golden Software, USA) and RStudio (v 1.3.1093).

3. Results

3.1 Trend distributions and change-points

The chlorophyll *a* concentration in the AS showed a decreasing trend ($n = 219$; $r = 0.22$; slope $= -0.0004$ and intercept $= 0.44$) over the selected period (Figure 2a). There were three significant peaks (>0.5 mg m^{-3}; 2004, 2006, and 2008) found in the trend before 2010 in chlorophyll *a*, and later, there was only one peak found in 2018. The SST showed a positive trend with respect to time ($n = 209$; $r = 0.22$; slope $= 0.0008$ and intercept $= 27.9$). Especially after 2010, the SST trend increased noticeably and exhibited a clear opposite trend to chlorophyll *a* (Figure 2a). The trend of MSLA also displayed a significant increasing pattern (Figure 2b; $n = 209$; $r = 0.83$; slope $= 0.0004$ and intercept $= 0.02$). No noticeable trend change was found in MLD, ZEU, and PAR in the AS (Figure 2c–e).

In the BB, trends of the variables were much similar to the Arabian Sea, except ZEU ($n = 216$; $r = -0.56$; slope $= -0.04$ and intercept $= 104.8$), which was decreasing (Figure 2f–j). An important feature we noticed in the BB was the trend of chlorophyll *a*, which was increasing with respect to the time ($n = 216$; $r = 0.64$; slope $= 0.0001$ and intercept $= 0.15$), along with increasing SST (Figure 2f). It particularly increased after 2010 with few significant peaks.

There were three significant change-points in chlorophyll *a* found in the AS (Figure 3a) till December 2003 (0.25 ± 0.013 mg m^{-3}), 2008 (0.54 ± 0.26 mg m^{-3}), 2010 (0.25 ± 0.01 mg m^{-3}) and 2020 (0.37 ± 0.09 mg m^{-3}). In the BB, there was a drop point (0.13 mg m^{-3}) found between March and May 2011, and it was slightly increased later (0.17 ± 0.002 mg m^{-3}) than before (0.16 ± 0.001 mg m^{-3}) (Figure 3b). Among the basins, the AS showed an apparent decline (December 2010), but the BB showed an upsurge (March 2011).

3.2 Meridional (inter-annual) variations

The changes in selected physical parameters and chlorophyll *a* over a period of time (after 2010) were presented to show the significant features, inter-annual variations, seasonal patterns, and possible linkages among them in the AS (Figure 4) and the BB (Figure 5). The Hovmoller plots give a clear indication of warmer (positive MSLA) and cooler (negative MSLA) waters with low and high chlorophyll *a*, respectively, in both basins.The spatial comparisons of MSLA and chlorophyll *a* during selected periods clearly indicate the positive and negative impacts of MSLA on chlorophyll *a* in the Bay of Bengal.

3.2.1 Variations in the Arabian Sea

Although clear seasonality was noticed in the selected time series data, inter-annual variations were also found with stronger and weaker features. Out of 124 months selected, cold water (avg. $\leq 27^{\circ}$C) was found during 23 months, and warm surface water (avg. $\geq 29^{\circ}$C) was found during 28 months in the central AS (Figure 4a). The MSLA was positive (avg. 0.14 ± 0.03 m) during the warm phases and mostly negative (avg. 0.03 ± 0.05 m) during the cold phases (Figure 4b). The MLD was deeper during the cooler period (avg. 66 ± 14 m) and shallow during the warm months (avg. 26 ± 12 m; Figure 4c). The ZEU was deeper (avg. 125 ± 14 m) during the warm period and shallower (avg. 60 ± 10 m) during the cooler months (Figure 4d). The surface PAR was relatively higher (avg. 52.5 ± 5.6 E m^{-2} d^{-1}) during the warm-SST period and lower (avg. 46.7 ± 3.8 E m^{-2} d^{-1}) during the cold-SST period (Figure 4e). The cooler surface water, negative/lower MSLA, and

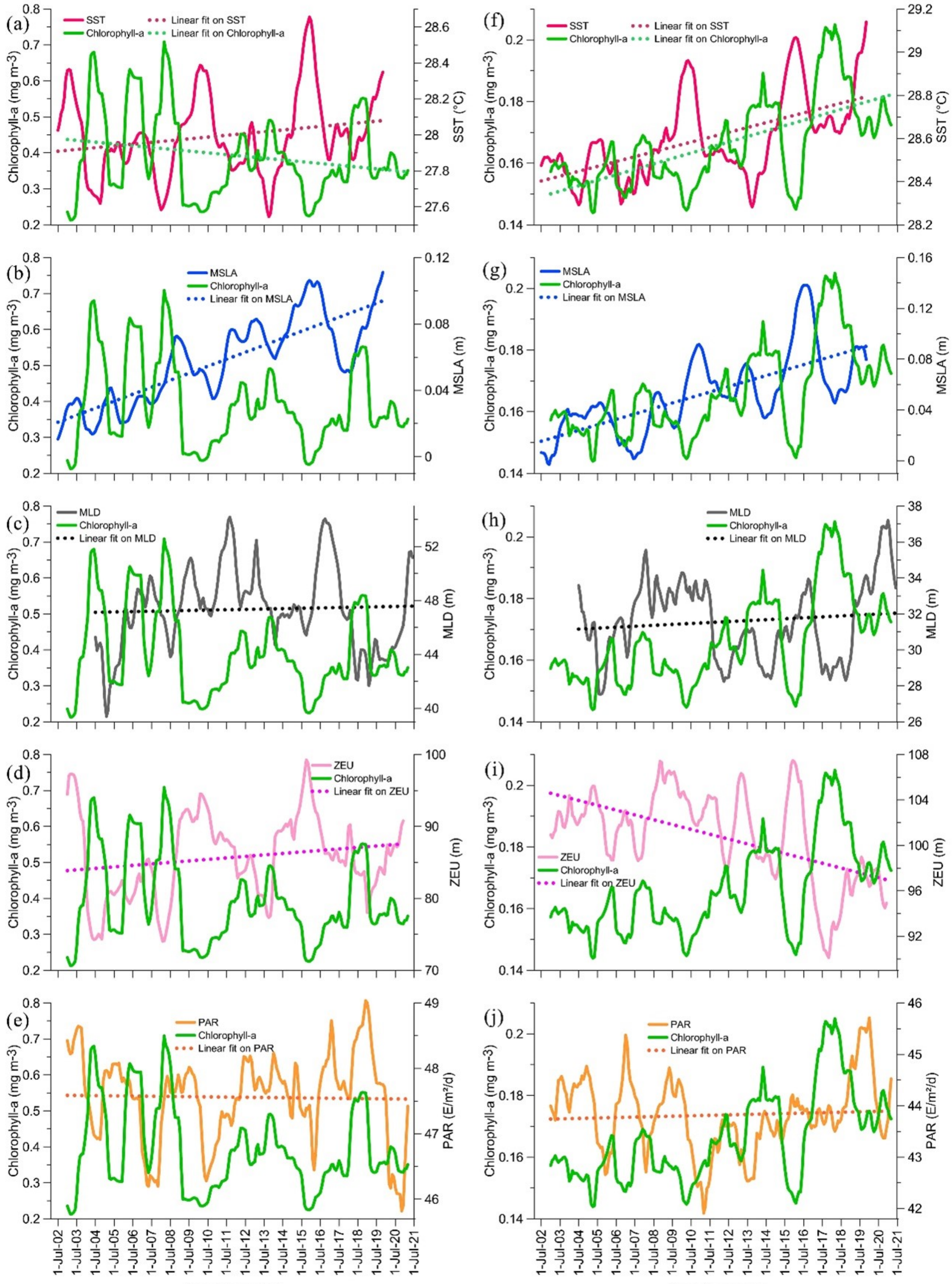

Figure 2. The long-term trends of chlorophyll a plotted against the trends of SST(a), MSLA (b), MLD (c), ZEU (d) and PAR (e) in the central Arabian Sea (left side panels) and (f–j) same in the central Bay of Bengal (right side panels). Scales in y-axes vary in both side panels.

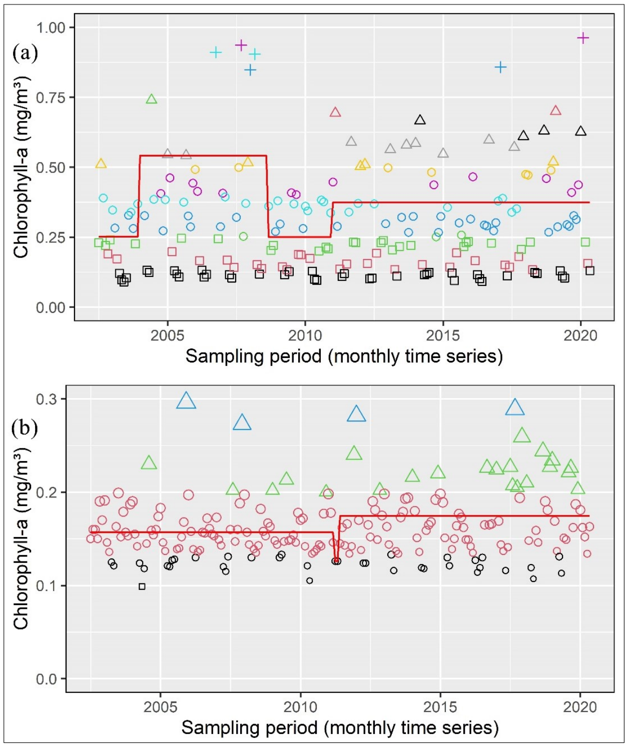

Figure 3. The chlorophyll *a* distribution along with significant change-points are presented for the central Arabian Sea (a) and the central Bay of Bengal (b). Each type of a symbol indicates range of mean chlorophyll *a*.

shallow ZEU showed the highest chlorophyll *a* concentration (avg. 0.76 ± 0.4 mg m^{-3}), and the opposite conditions showed the lowest chlorophyll *a* (avg. 0.13 ± 0.04 mg m^{-3}; Figure 4f). A northward increase of chlorophyll *a* was evidenced during each productive season.

3.2.2 Variations in the Bay of Bengal

As the BB is also located in the same latitude belt of the AS, it exhibited almost similar seasonality in selected variables (Figure 5). However, as compared with the AS, the BB was fairly warmer, and it was relatively cooler (avg. ≤ 27°C) only for 4 months in the selected period (124 months) and warmer for almost 46 months (avg. ≥ 29°C; Figure 5a). The surface cooling was stronger in the north, and warming was efficient in the south of the selected region, similar to the AS. During the warm months, the MSLA was more positive (avg. 0.1 ± 0.06 m) and negative or weaker positive during cooler months (avg. 0.07 ± 0.05 m). Also, it was evidenced that there was a delay in the response of SST to the decrease in MSLA (Figure 5b). The MLD was shallower in the BB than the AS during cooler months and similar during the warmer months. In the BB, it was relatively deeper (avg. 40 ± 4 m) during the cooler periods and shallower (avg. 26 ± 10 m) during the warm periods (Figure 5c). The difference in the ZEU between colder and warmer periods was narrow (17 ± 8 m), but comparatively, the ZEU was deeper in the BB than the AS during cooler months. Relatively deeper ZEU (avg. 109 ± 15 m) was found during the warm periods and shallower (avg. 91 ± 7 m) during the cooler periods (Figure 5d). The surface PAR levels were seasonally varied between 29 E m^{-2} d^{-1} and 57 E m^{-2} d^{-1}, but during the warm and cold months, the PAR was comparable (cooler: avg. 48 ± 4 E m^{-2} d^{-1} and warmer: avg. 46 ± 7 E m^{-2} d^{-1}; Figure 5e). The AS had more chlorophyll *a* concentration than the BB during the cooler period and comparable during the warmer period. The cooler months were found with a proportionately high concentration of chlorophyll *a* (avg. 0.19 ± 0.02 mg m^{-3}) than during the warmer months (avg. 0.14 ± 0.03 mg m^{-3}; Figure 5f).

3.3 Importance of MSLA in structuring chlorophyll *a*

As per the understanding from the above results, it is clear that the MSLA was one of the prime variables which control the SST and chlorophyll *a* in both the AS and the BB basins. So, further, we have processed and compared the MSLA and chlorophyll *a* parameters during selected months (Figures 6 and 7), which are marked by vertical bars in Figures 4 and 5 for AS and the BB, respectively. The positive or higher MSLA in the central AS was represented by selected time periods that showed the lowest chlorophyll *a*, and the negative or lower MSLA periods had the highest concentration of chlorophyll *a* (Figure 6). Similarly, in the BB, we found strong spatial control of chlorophyll *a* by MSLA also evidenced by positive and negative MSLA conditions during the same periods adjacently (Figure 7).

3.4 Periodicity of variables

The wavelet power spectrum and its means of selected variables in the central AS showed statistically significant ($p < 0.05$) variances with semi-annual (6-months) and annual (12-months) periodicity/intervals, and most parameters showed dominant periodicity of 6-months (Figure 8). Though the euphotic depth variance was significant and followed the above intervals, the annual periodicity was stronger than the prior one (Figure 8a–b). The annual signals have become dominant during the recent decade (Figure 8a). The SST showed a stronger variance with a 6-month periodicity, and the annual signals of variance were significant but weaker (Figure 8c–d). The PAR showed comparable variance during both periodicities (Figure 8e–f). The variability in chlorophyll *a* was predominant with semi-annual periodicity and weaker in the annual case (Figure 8g–h). The periodicity of chlorophyll *a* variability was shorter during the 2005–2010 period.

Unlike the AS, the periodicity of variabilities of most parameters in the central BB was showed predominantly annual (Figure 8). The selected parameters, such as ZEU (Figure 8a–b) and MSLA (Figure 8c–d), showed significant variance with an annual periodicity. The variability trend was similar between meridional currents and chlorophyll *a*; both showed more robust annual periodicity and weaker semi-annual signals (Figure 8e–h). The variability in most

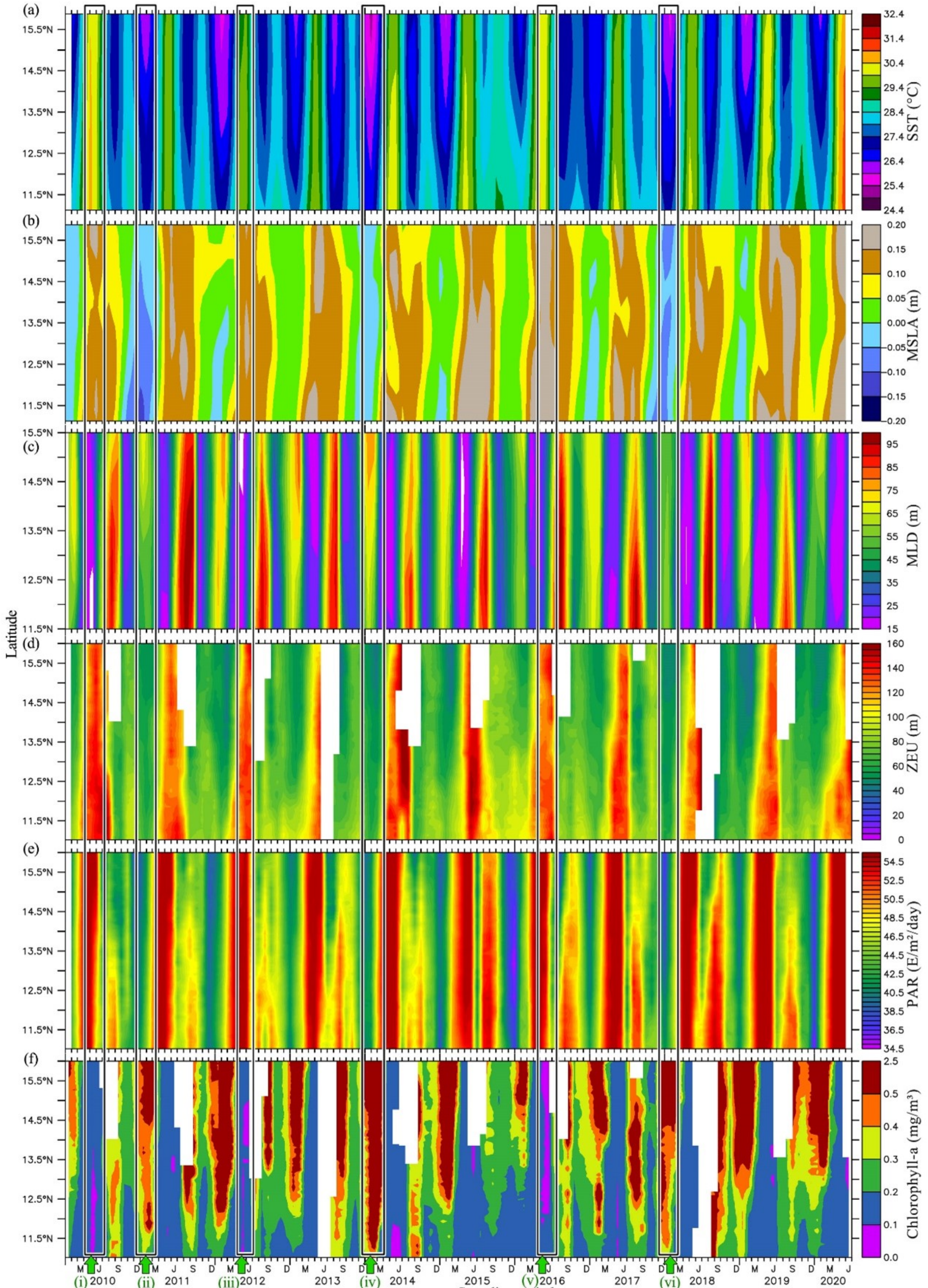

Figure 4. The monthly (January 2010 – June 2020) meridional mean distribution of SST (a), MSLA (b), MLD (c), ZEU (d), PAR (e) and chlorophyll *a* (f) in the central Arabian Sea. The boxes across each panel indicate the selected incidences of low and high chlorophyll *a*.

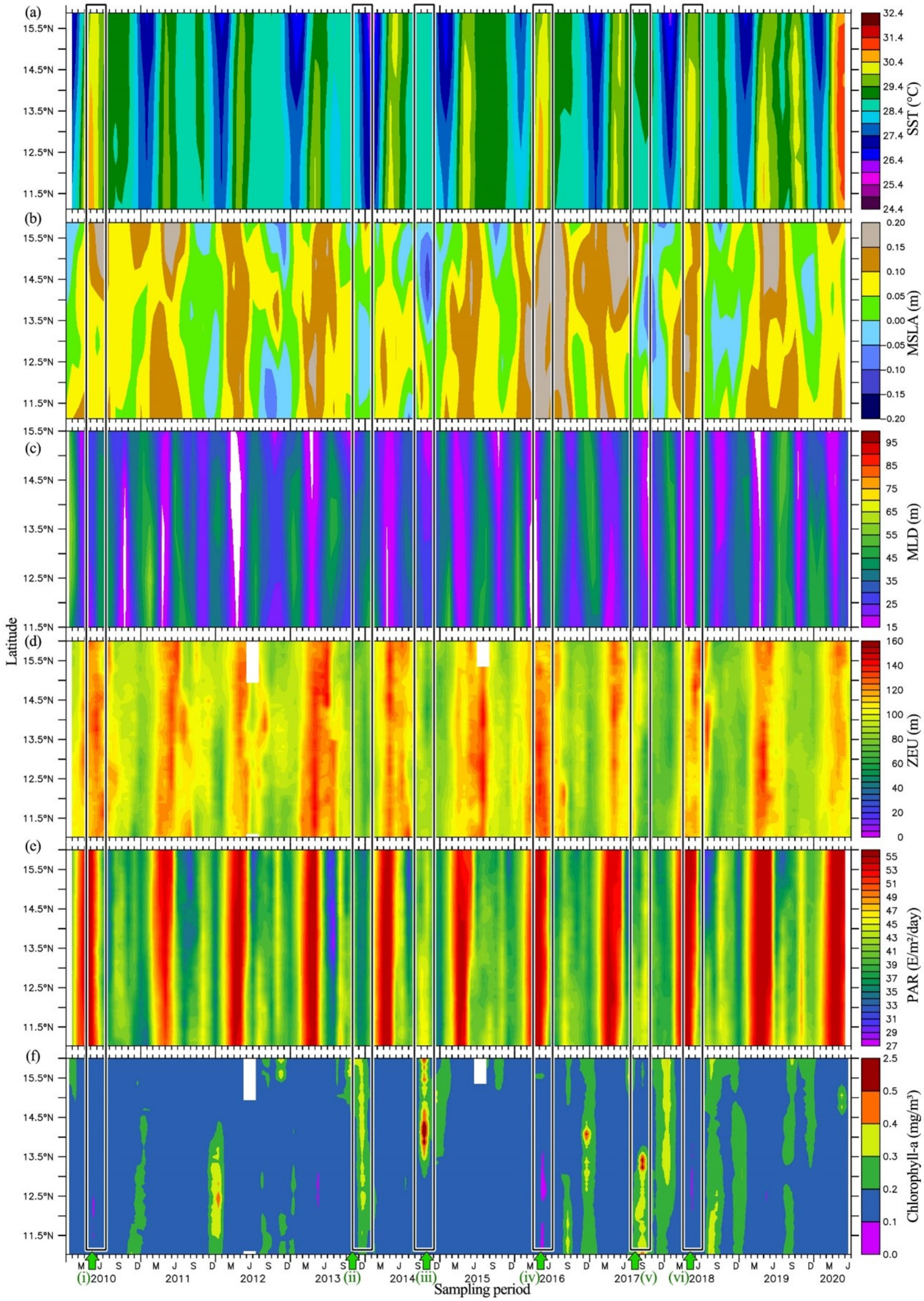

Figure 5. The monthly (January 2010 – June 2020) meridional mean distribution of SST (a), MSLA (b), MLD (c), ZEU (d), PAR (e) and chlorophyll *a* (f) in the central Bay of Bengal. The boxes across each panel indicate the selected incidences of low and high chlorophyll *a*.

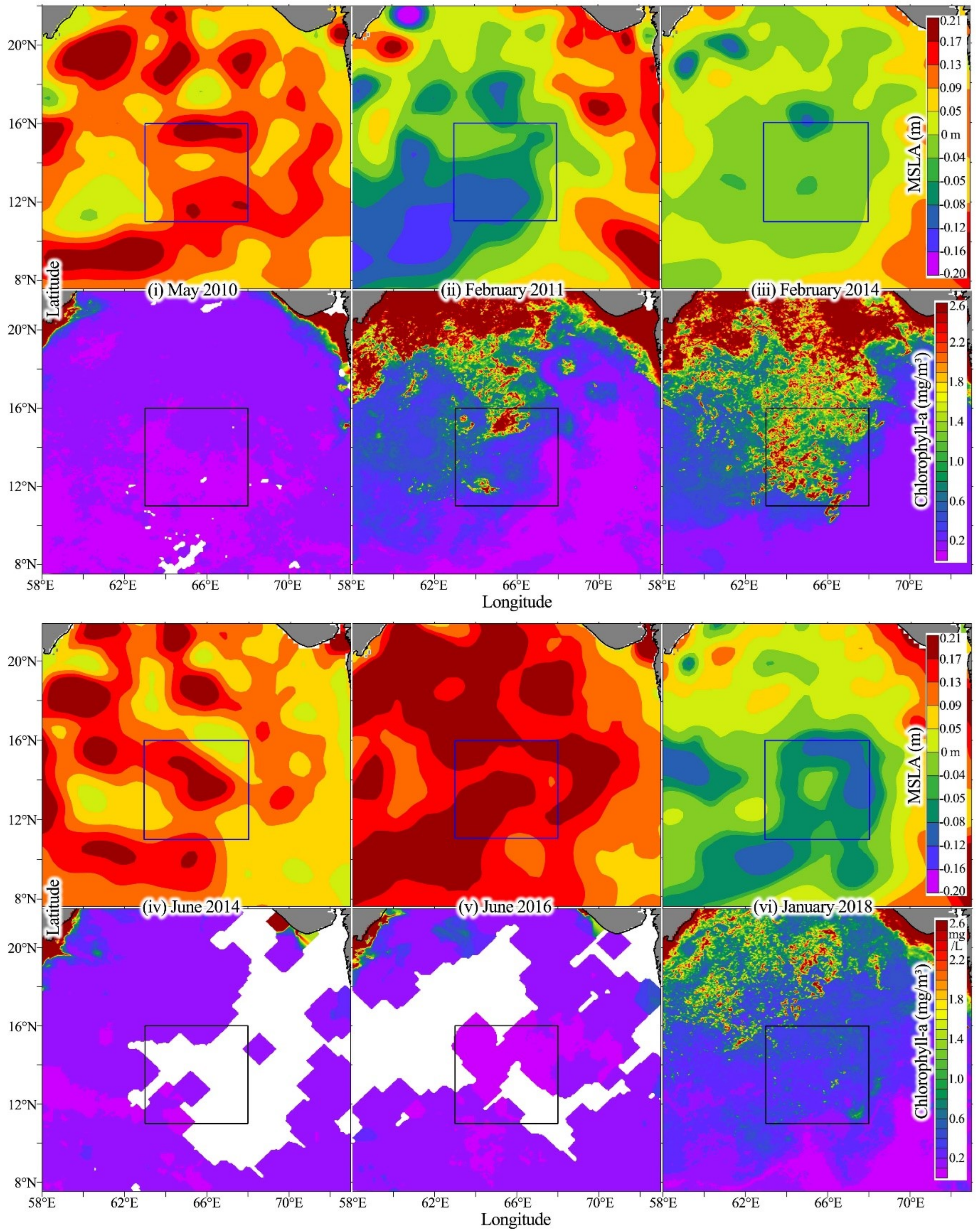

Figure 6. The spatial comparisons of MSLA and chlorophyll *a* during selected periods indicate the positive and negative impacts of MSLA on chlorophyll *a* in the central Arabian Sea. The panels i, iv and v are representing positive MSLA with low chlorophyll *a*, and the panels ii, iii and vi are representing negative MSLA with high chlorophyll *a* incidences.

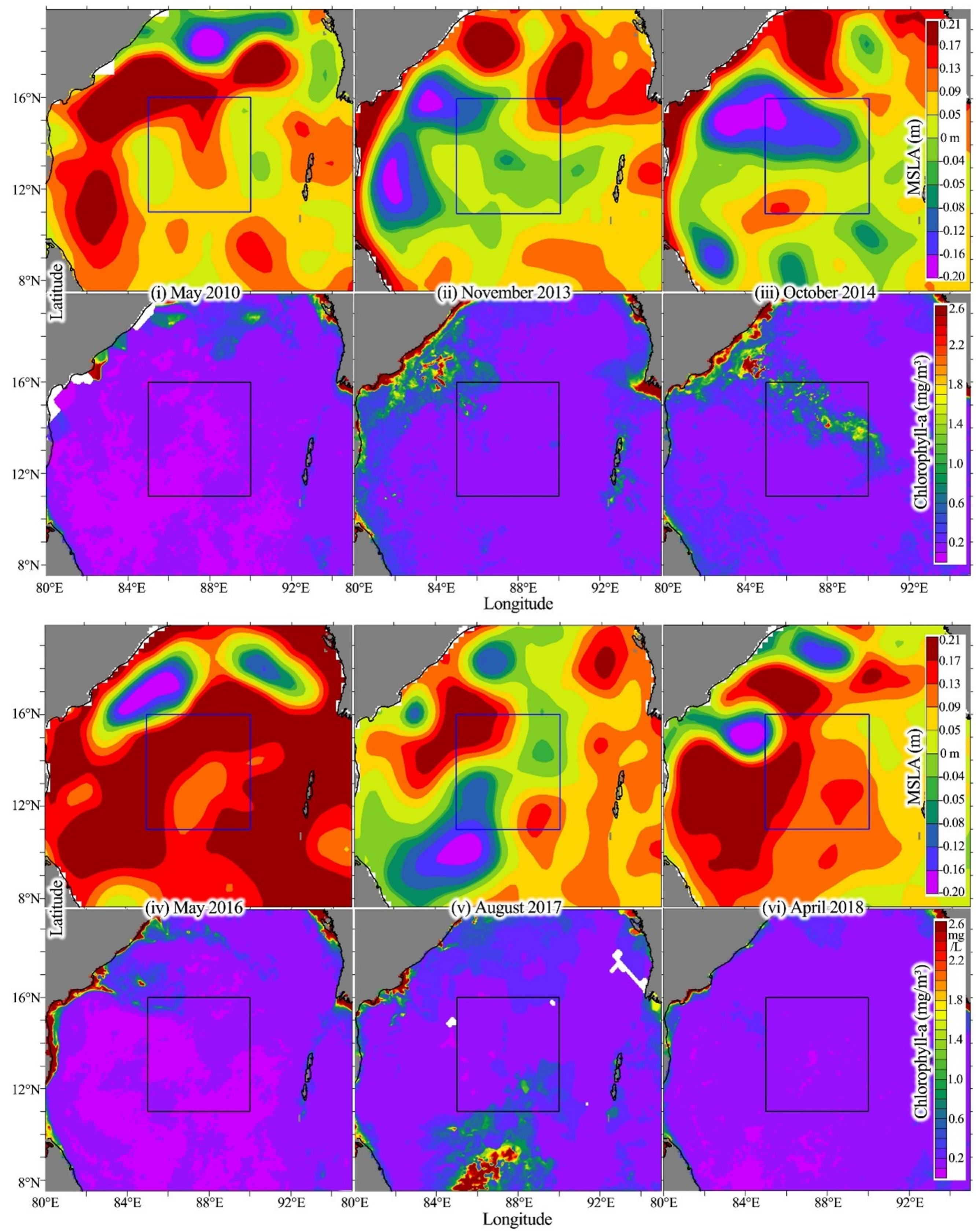

Figure 7. The spatial comparisons of MSLA and chlorophyll *a* during selected periods clearly indicate the positive and negative impacts of MSLA on chlorophyll *a* in the Bay of Bengal.

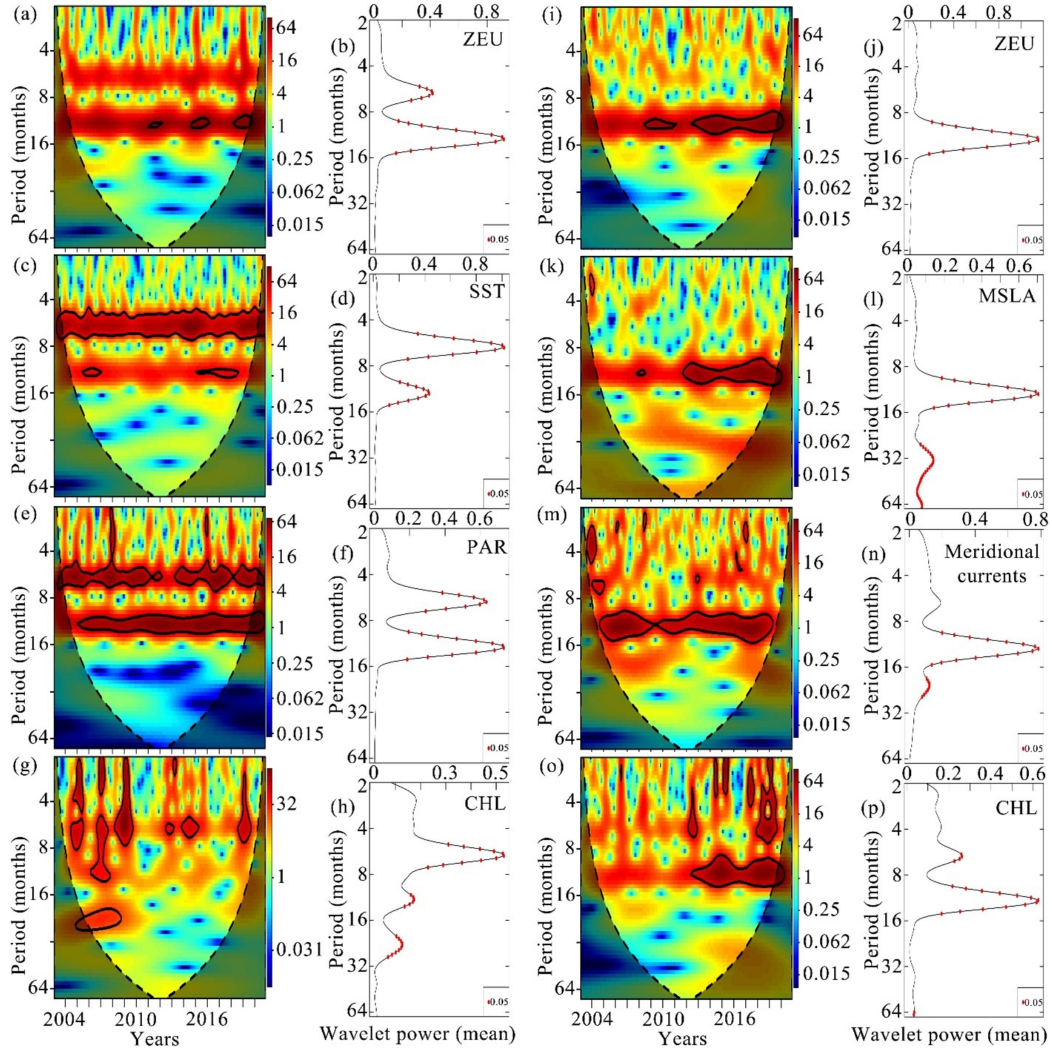

Figure 8. The wavelet power spectrums and mean plots of wavelet power are presented for the central Arabian Sea (a–h) and the Bay of Bengal (i–p). The left side panels present (a–b) ZEU, (c–d) SST, (e–f) PAR (g–h) chlorophyll *a* for the Arabian Sea and right side panels (i–j) ZEU, (k–l) MSLA, (m–n) meridional currents and (o–p) chlorophyll *a* for the Bay of Bengal.

of the parameters was stronger from 2013 to 2020. The periodicity of chlorophyll *a* variability was shorter during the above period (Figure 8e).

3.5 Correlation among the variables

Multiple variables and their trends were correlated with each other and with chlorophyll *a* concentration in both the AS and the BB, and it delineated the positively- and negatively-impacting variables (Figure 9). Though the pattern of impacts of variables on chlorophyll *a* was similar in both basins, the strength was varied. In the AS, the sea surface temperature, euphotic depth, and sea level anomaly were negatively related to chlorophyll *a* (Figure 9a), but in the BB, in addition to the above parameters, PAR and depth of 26°C isotherms (D26) also affected negatively (Figure 9b). The parameters such as surface salinity, wind speed, mixed layer depth, and nitrate concentration showed a positive relationship with chlorophyll *a* in the AS (Figure 9a), and additionally, zonal and meridional currents were positively correlated with chlorophyll *a* in the BB (Figure 9b). The trend data (after removing the seasonality and residue/noise values) showed significant positive relationships ($n > 150$; $p < 0.05$) of wind speed, zonal currents, meridional currents, and nitrate with chlorophyll *a* in the AS (Figure 9c). The trends of surface temperature, salinity, euphotic depth, sea level anomaly, mixed layer depth, and D26 were negatively correlated with chlorophyll *a* in the AS (Figure 9c). In the BB, the trend of SLA, nitrate, and meridional currents are the parameters positively correlated with chlorophyll *a*, and the surface salinity, PAR, euphotic depth, zonal currents, mixed layer depth, and D26 were negatively related (Figure 9d). The GAM

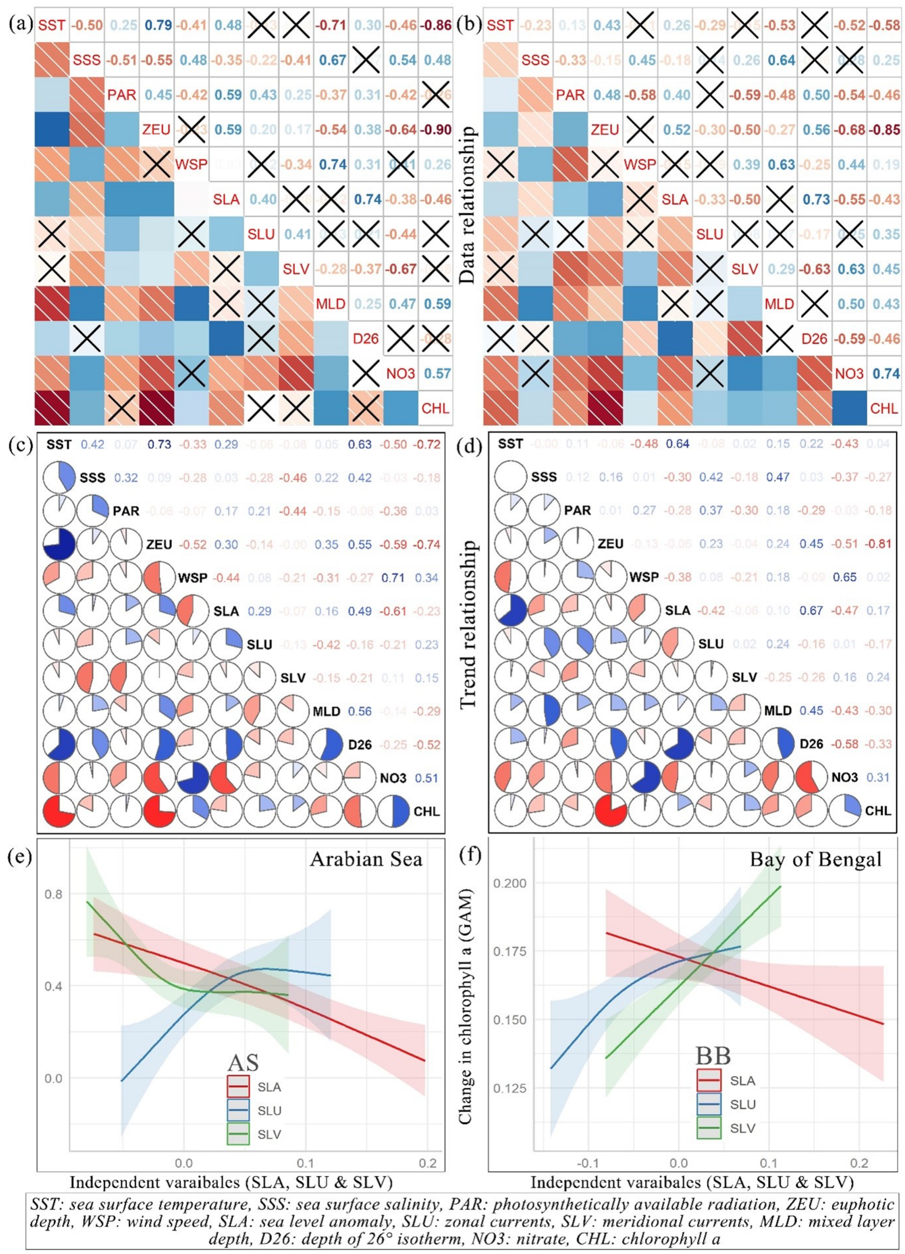

Figure 9. The multivariable correlation (Spearman) among the parameters presented for the raw data (upper panels) for (a) the central AS and (b) the central BB and (c and d) the trends the same regions. The brown/red colour shade and correlation coefficient values with negative symbols indicate negative correlation and blue colour of the same indicate positive relationship. The cross marks in the top panels represent insignificant relationships ($p > 0.05$). The results generalized additive model between the response variable (chlorophyll *a* in y-axis) and selected predictor/independent variables (SLA, SLU and SLV in x-axis) for (e) the AS and (f) the BB.

results showed the SLA in both basins negatively affecting chlorophyll *a* (Figure 9e–f). In the AS, the negative (eastward) or weaker zonal currents and the southward flow of meridional currents showed enhancing effects on chlorophyll *a* (Figure 9e). In the BB, the eastward (+zonal) and northward (+meridional) flow of water currents showed positive effects on chlorophyll *a* (Figure 9f).

3.6 Link between chlorophyll *a* and meridional currents in the BB

The correlation analysis revealed that chlorophyll *a* was significantly supported by zonal and meridional currents in the BB, unlike in the AS. It was found that the meridional currents in the BB showed a peculiar connection with chlorophyll *a* (Figure 10). An increase/relatively high

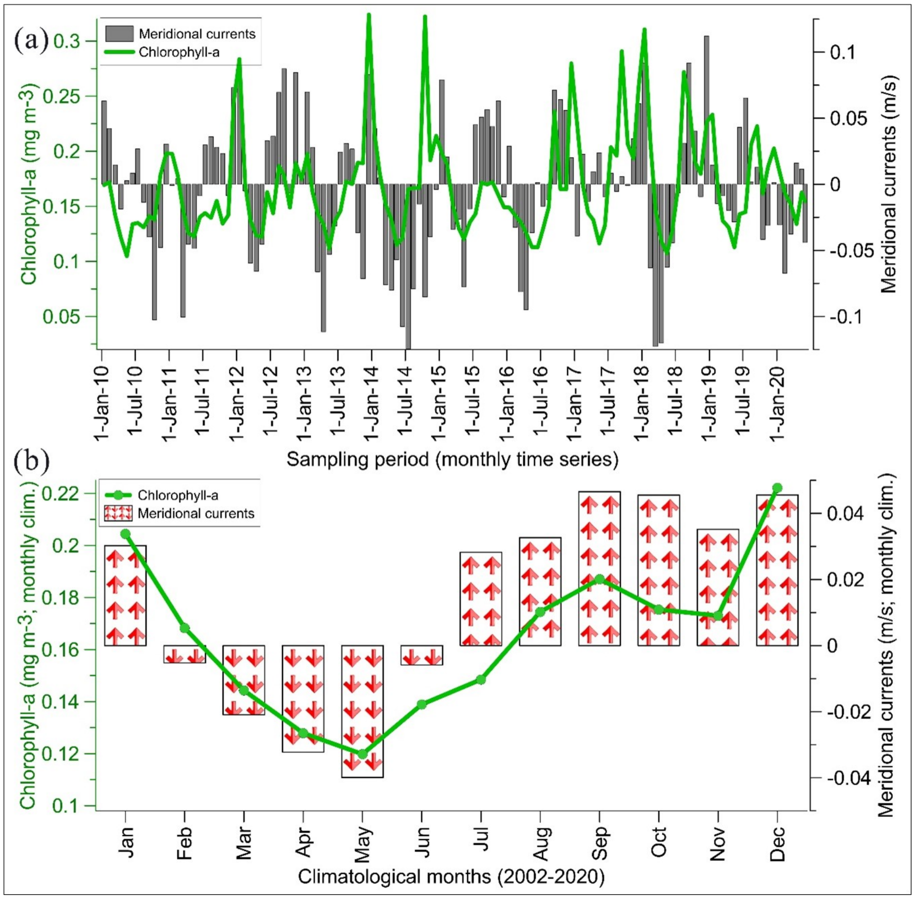

Figure 10. The monthly mean concentration of chlorophyll *a* (green lines) plotted over the velocity of meridional currents (bars) to visualize their direct relationships from the time series (a) and climatological monthly data (b) in the central Bay of Bengal. The positive and negative values in the meridional currents represent northward and southward flow of water current, respectively.

concentration of chlorophyll *a* was found when the meridional flow was northward (positive), and it was decreased during the dominance of the southward flow of surface currents (negative) (Figure 10a). The 18-year monthly climatology also clearly represented the above findings (more consistent), with the northward flow from July to January (increase in chlorophyll *a*) and southward flow from February to June (decrease in chlorophyll *a*) (Figure 10b).

4. Discussion

The long-term data analyses from the northern Indian Ocean were conducted by many researchers and gave valuable information on the inter-annual variability of temperature, mean sea level anomaly, primary productivity, and chlorophyll *a*. Many previous studies reported inconsistent results on the longer time changes both in the Arabian Sea and the Bay of Bengal (Goes et al., 2005; Khan et al., 2004; Kumar et al., 2016; Lotliker et al., 2020; Prakash et al., 2012; Prakash and Ramesh, 2007; Pramanik et al., 2020; Prasanna Kumar et al., 2010). Goes et al. (2005) reported a consistent increase in chlorophyll *a* by more than 300% in the western Arabian Sea due to increased wind speed. A 9-year time series suggested a lack of significant change in chlorophyll *a* over the north and south-eastern Arabian Sea (Prakash and Ramesh, 2007). However, Prasanna Kumar et al. (2010) revealed a basin-scale weaker increase in concentration due to the dust-born nutrients supply in the entire Arabian Sea. Other time-series studies conducted in the western AS (Prakash et al., 2012), and the BB (Chen et al., 2014) showed an increasing trend till 2003 that later declined. A study evidenced a significant rise of chlorophyll *a* during the NEM in the entire AS (Dalpadado et al., 2021). Also, it was recorded that the primary productivity in the entire northern Indian Ocean is declining due to surface ocean warming (Gregg and Rousseaux, 2019; Roxy et al., 2016). The above-mentioned studies showed different trends and magnitudes in the chlorophyll *a* distribution in different regions of the northern Indian Ocean, especially the AS. Fewer studies focused on the long-term variability of chlorophyll *a* or primary productivity in the

Bay of Bengal (Chen et al., 2014; Lotliker et al., 2020; Miranda et al., 2020; Pramanik et al., 2020; Xu et al., 2021). The present study focuses on understanding long-term trends and changes in the hydrography of the central Arabian Sea and the central Bay of Bengal and their impacts on chlorophyll *a* (phytoplankton biomass). We have analyzed large, standard data sets retrieved from various sources, such as satellite remote sensing data, arithmetic model-derived data, and data acquired from ARGO floats, and found significant changes in trends over the selected period (18 years). We selected central parts of the basins to avoid highly dynamic coastal influences on the hydrography. When comparing both basins (Figure 2), the trend of SST shows that the BB is warmer than the AS, due to the enormous volume of river water supply into the BB (Gopalakrishna et al., 2002; Jyothibabu et al., 2021; Prasad, 2004; Prasanna Kumar et al., 2002; Sarma et al., 2016). That forms surface stratification and weaker/restricted vertical mixing in the BB, eventually causing shallow MLD, positive MSLA, and low chlorophyll *a*. As biological production is lower, the water becomes clear and light penetration is deeper compared to the AS.

4.1 Possible reasons for the chlorophyll *a* trend and change-points

The long-time trends of chlorophyll *a* in both the central Arabian Sea and the central Bay of Bengal were opposite. Multiple secular peaks in trends found before 2010 and absent later led to the declining trend of chlorophyll *a* in the AS. Similar secular peaks in chlorophyll *a* trend were found after 2010 in the BB, and both were confirmed by the change-point statistics. Most of these peaks and lows were well aligned with the trends of sea surface temperature and mean sea level anomaly, which limited the phytoplankton production by restricting vertical mixing and nutrient supply to the euphotic water column of the ocean (Prakash et al., 2012; Roxy et al., 2016). The trends of MLD and ZEU were positively related, but they correlated negatively with chlorophyll *a*, which could be a response of phytoplankton to avoid high-light (PAR) in the surface waters. Though deep mixing brings nutrients to the surface water column, the availability of light significantly alters the depth of phytoplankton production. In the BB, Jyothibabu et al. (2018) observed that on days with high PAR, phytoplankton production and accumulation occurred in deeper waters, while on low PAR days, phytoplankton rose to the surface to access light. This high-light avoidance mechanism likely explains these observations, as ZEU and MLD were both deeper, and a significant negative relationship was found between PAR and chlorophyll *a* in the BB. The decreasing and increasing trends of chlorophyll *a* in the central regions of the AS and the BB explain the deepening and shallowing trends in ZEU, respectively (Aksnes and Ohman, 2009). The increase in phytoplankton production in the surface water column releases a high quantity of detritus, and the presence of abundant phytoplankton cells jointly reduces the water clarity and leads to shallow euphotic depth (Lee et al., 2007). Warmer water causes thermal stratification, which depletes nutrients, and high PAR damages the photosynthetic systems of phytoplankton. Together, these factors cause phytoplankton to either shift their position vertically (though limited by their drifting nature) or experience cell damage in stressed near-surface waters, while achieving better growth in more favorable deeper waters. In situ time series measurements are necessary to gain better insights into whether the cells die or shift vertically.

4.2 Longitude-time variations

The northward increase in chlorophyll *a* within the selected 5° area box in the central AS indicates the advection of nutrients and phytoplankton biomass from the north. This specific feature in chlorophyll *a* distribution was observed only in the AS, not in the BB, though both basins showed the cooling of surface water towards the north. It was reported that through the mesoscale filaments, the upwelled nutrients from the north-western AS were introduced to the central AS during the SWM, which enhanced the biological productivity (Keen et al., 1997; Prasanna Kumar et al., 2001, 2000; Resplandy et al., 2011). However, the present study showed noticeably very high chlorophyll *a* levels during the NEM season compared to the SWM season. This increase could be attributed to the nutrients supplied by the advection of winter convection (Albin et al., 2022; Jyothibabu et al., 2010; Madhupratap et al., 1996). The time-series results show that winter convection-associated biological productivity is over-dominating the upwelling-induced productivity in the selected region of the central Arabian Sea. The cloud cover during the SWM is one of the possible reasons for the lack of data to represent the true impact of upwelling-dependent productivity. The percentage of invalid pixels (represents cloudy region) in the AS was 28% and in the BB was 32.5%, which is the possible reason for lower PAR in BB than in the AS.

As the above physical forces are alternatively dominating during each season (SWM-upwelling and NEM-convection; Albin et al., 2022; Jyothibabu et al., 2010; Madhupratap et al., 1996), during the selected period, the Arabian Sea is nearly balanced in warm (22.6%) and cool phases (18.5%). Nevertheless, the Bay of Bengal showed the dominance of warm phases (37%) over the cool phases (3.2%) due to a lack of strong physical forces which can break the surface stratification and mix the water column (Shetye et al., 1991). Instead, the surface stratification in the BB is supported by higher temperature during spring inter-monsoon (thermal stratification) and heavy freshwater influx during the SWM/NEM (density stratification) (Mahadevan et al., 2016; Prasanna Kumar et al., 2002; Sarma et al., 2016; Vinayachandran and Kurian, 2007).

In addition, the predominance of warm-phases was sustained with positive mean sea level, shallow vertical mixing, deeper euphotic depth, and high PAR at the surface, which jointly decreased the biological productivity in the surface water column of the central Bay of Bengal.

The increasing water temperature in the ocean affects the phytoplankton by size decrease, lower primary production, change in growth rate (increases initially and stops at a point) and community shift (Jorgensen, 1968; Montagnes and Franklin, 2001; Thomas et al., 2012). The water temperature is significantly altering the physiological processes/metabolism of phytoplankton. The warmer water enhances the metabolic activities of phytoplankton, which can enhance the excretion of organic solutes (Zlotnik and Dubinsky, 1989). In natural systems, warmer water (less dense) sits over the cooler water mass (denser), creating stratification, which restricts vertical mixing. The landlocked topography and the weakened differential heating between land and sea lead the northern Indian Ocean to warm more steadily than other oceans (Mishra et al., 2019; Singh and Oh, 2007). The stratification further increases surface temperature and cuts nutrient supply to the surface euphotic water column from the subsurface (Prasanna Kumar et al., 2002). A recent experimental study by Murphy et al. (2019) showed that the increase in temperature significantly impacted the higher trophic predators of the plankton food web than the primary producers due to their increased metabolic activities in warmer temperatures led to higher feeding rates. However, meta-analysis showed that ocean warming negatively impacted all the plankton food web groups and was highly significant in phytoplankton (Murphy et al., 2019). The higher metabolic activity and unavailability of nutrients in the warm surface waters might be the possible reasons for decreased phytoplankton growth and productivity.

Tropical phytoplankton is susceptible to increasing temperatures, but they can adapt to the slow changes over time because of their fast reproduction (Schaum et al., 2017; Thomas et al., 2012). Though the chlorophyll *a* concentrations measured through satellite remote sensing showed a declining trend, it is uncertain owing to the depth limitation of the measurements (Huot et al., 2005). The optimum light and nutrients are essential for phytoplankton production, and both are available in the subsurface waters of the AS and the BB (Ravichandran et al., 2012; Thushara et al., 2019). The deep chlorophyll maxima layer contributes major primary production in the stratified water columns, and such chlorophyll concentration and phytoplankton production could not be reflected in the satellite measurements (van Leeuwen et al., 2013). It is required to consider the long-term deep-water in situ measurements and autonomous underwater profilers to hint at changes in subsurface productivity with respect to increased surface temperature. Also, as the lifespan of phytoplankton is short, the impact of climate change might be lesser on their biomass, but it may reflect on the community structure (Boyce et al., 2010; Chowdhury et al., 2021; Roxy et al., 2016). The local hydrography and the grazing impact of zooplankton could be the predominant factors that impact the phytoplankton biomass instantly rather than long-time changes (Chowdhury et al., 2021).

4.3 Role of MSLA and meridional currents

The MSLA and associated surface currents significantly control the biological productivity and the long-time trends in the northern Indian Ocean through the formation of mesoscale eddies (Jyothibabu et al., 2015; Prakash et al., 2012; Sarma et al., 2020). The present study (Figure 6 and 7) also signifies the importance of MSLA on the phytoplankton production in the central AS and the BB over a longer period. We have evidenced different MSLA situations in the study area, such as highly positive (≥ 0.15 m) and negative (≤ -0.15 m) in the AS and combined situations (positive and negative together) in the BB. In the AS, any one of the features was dominating over a large area at a time. But in the BB, two mesoscale eddies (cyclonic and anti-cyclonic) co-occur adjacently. These features were reflected in the chlorophyll *a* pictures with isolated high and poor concentrations with respect to the negative (cold pool) and positive (warm pool) MSLA situations. The mesoscale (cyclonic) eddies can inject nutrient-rich deeper water into the photic zone and increase isolated patches of phytoplankton blooms (Prasanna Kumar et al., 2004). Similarly, the prolonged presence of anti-cyclonic eddies (warm core) is reported to cause extreme oligotrophy in the BB (Chinnadurai et al., 2021), especially they were found dominant in the southern region of the western BB (Dandapat and Chakraborty, 2016).

We found a significant increase in MSLA both in the AS and the BB during the selected period, which could be due to the increase of ocean surface temperature, which melts the polar ice as well as expands the water mass, as a result of climatic global warming (Kerr, 2012; Rhein et al., 2013; Roxy et al., 2016). The rate of increase of MSLA in both basins (3.6 ± 0.2 mm yr^{-1}) is comparable with the reported global mean change (3.1 ± 0.7 mm yr^{-1}; Thompson et al., 2008). Though the positive MSLA occurs due to the convergence of surface water, in specific cases, it supports biological productivity by converging nutrient-rich upwelled or shelf water (Batten and Crawford, 2005; Feng et al., 2007; Jyothibabu et al., 2015). The strength of the eddy has a significant role in transporting water mass along with all the physical, chemical, and biological properties (Batten and Crawford, 2005; Chinnadurai et al., 2021; Sarma et al., 2020). As a large area of the BB is occupied by the warm core eddies (Jyothibabu et al., 2021), and it showed a significant increase in MSLA over selected time, a noticeable decline is expected in chlorophyll *a*. Sarma et al. (2020) stated that warm core eddies transport the shelf waters towards the open seas and enhances biological production. The present study showed an increasing trend in the central BB, which is mainly supported by the meridional currents (Figure 10) as well as zonal currents which may carry the shelf waters (Sarma et al., 2020). Especially the northward flow of the meridional currents evidenced the enhancement of chlorophyll *a*, and southward flow was found with declined chlorophyll *a*. Usually, the high chlorophyll *a* was found and reported during the NEM due to the significant increase in the cold core eddy area (Jyothibabu et al., 2021). During the SWM, the coastal upwelling occurs along the southwest coast of India, which brings nutrient-rich high saline water to the shelf, and it is transported to the southern and central BB through the summer monsoon currents (Jyothibabu et al., 2015; Vinayachandran, 2009). The northward flow of nutrient-rich summer monsoon current directly supports higher phytoplankton biomass than the southward flow of low saline Bay of Bengal water. The GAM analysis also evidenced the positive flow (northward) of meridional currents enhancing chlorophyll *a* in the BB ($p < 0.0001$). It also showed that none of the other variables enhance chlorophyll *a* significantly, but the deepening of the ZEU significantly decreases the chlorophyll *a* in the BB ($p < 0.001$). Additionally, the multivariable Spearman correlation is strongly supported above findings with a positive relationship of chlorophyll *a* with salinity, wind speed, surface currents, and MLD in the BB.

4.4 Periodicity of variables

The periodicity was noticeably different in both basins of the northern Indian Ocean, indicating a significant difference in seasonality. The central Arabian Sea followed a semi-annual periodicity of most variables, such as euphotic depth, surface temperature, and PAR, and they showed strong implications on the phytoplankton biomass (chlorophyll *a*). The impacts of physical forces during the SWM and the NEM are evidenced in the semi-annual increase of chlorophyll *a* in the central AS (Madhupratap et al., 1996; Prasanna Kumar et al., 2001). However, the Bay of Bengal showed the dominance of annual periodicity in most of the variables (mainly ZEU, MSLA, and meridional currents), and their impacts on chlorophyll *a* are also evidenced in this study. As the winter convection weakly impacts the central BB during the NEM due to huge freshwater influx (density stratification), the nutrient supply to the central BB is through the river influx (limited to the continental shelf) and the cold core eddies (isolated supply) (Jyothibabu et al., 2021; Madhupratap et al., 1996; Sarma et al., 2016; Subramanian, 1993). Recently, Sarma et al. (2019) reported that dissolved organic nutrients transported from shelf regions increase the primary production in the central BB. Similarly, the coastal upwelling is insignificant and restricted to a narrow coastal region during the SWM (Shetye et al., 1991), showing a lack of phytoplankton biomass in the BB. The increasing trend in chlorophyll *a* in the central BB is reflected in the wavelets by high frequency in the annual as well as semi-annual variance during recent years (2013–2020). Though the present study suggested the possible reasons for the different periodicity of chlorophyll *a* between the central regions of the AS and the BB, further studies are needed to reveal the actual mechanism operating behind the periodicity of the hydrography. The modelling studies need to be conducted at different smaller regions of the AS and BB to enlighten the impact of different variables on the enhancement or declining of chlorophyll *a*.

5. Conclusion

The present study used a long time series data sets (18 years; 2002–2020) from satellite, model, and ARGO floats to understand the long-term variations in the chlorophyll *a* with respect to other environmental and hydrographic parameters in the central regions of the Arabian Sea and the Bay of Bengal. We observed significant increasing trends in SST and positive-MSLA in both basins, and the chlorophyll *a* was decreased in the AS in contrast to the BB. Further, the data and statistical analysis revealed that the meridional currents mainly controlled the time series trend in the chlorophyll *a* distribution in the central BB. The seasonal changes in the meridional currents and mean sea level anomaly could be the possible reasons for the increasing trend of chlorophyll *a* in the central Bay of Bengal. From 2016 and later, the high chlorophyll *a* patches that appeared during the late SWM led to the distribution trend to be elevated. The northward flow of the meridional currents evidenced the enhancement of chlorophyll *a*, and southward flow was found with declined chlorophyll *a*. During the SWM, the summer monsoon currents transport the nutrient-rich water from the coastal upwelling zone of the southwest coast of India to the southern and central BB. This water mass directly supports high phytoplankton biomass compared to the southward flow of low-saline Bay of Bengal water. In addition, the large area of cold-core eddies found during the NEM enhanced the chlorophyll *a*.

Acknowledgement

The authors express their gratitude to the Director of the CSIR – National Institute of Oceanography, India, for providing facilities and encouragement. We also thank the anonymous reviewers for their constructive comments. The CSIR-NIO contribution number is 7242.

References

Aksnes, D.L., Ohman, M.D., 2009. *Multi-decadal shoaling of the euphotic zone in the southern sector of the California Current System*, Limnol. Oceanogr. 54, 1272–1281.

Albin, K.J., Jyothibabu, R., Alok, K.T., Santhikrishnan, S., Sarath, S., Sudheesh, V., Sherin, C.K., Balachandran, K.K., Devi, C.R.A., Gupta, G.V.M., 2022. *Distinctive phytoplankton size responses to the nutrient enrichment of* *coastal upwelling and winter convection in the eastern Arabian Sea*. Prog. Oceanogr. 203, 102779.

Anil, A.C., Desai, D.V., Khandeparker, L., Krishnamurthy, V., Mapari, K., Mitbavkar, S., Patil, J.S., Sarma, V., Sawant, S.S., 2021. *Short term response of plankton community to nutrient enrichment in central eastern Arabian Sea: Elucidation through mesocosm experiments*, J. Environ. Manage. 288, 112390.

Araujo, M.B., Rahbek, C., 2006. *How does climate change affect biodiversity?*, Science 313, 1396–1397.

Banse, K., 1968. *Hydrography of the Arabian Sea Shelf of India and Pakistan and effects on demersal fishes*, Deep-Sea Res. 15, 45–79. https://doi.org/10.1016/0011-7471(68)90028-4

Batten, S.D., Crawford, W.R., 2005. *The influence of coastal origin eddies on oceanic plankton distributions in the eastern Gulf of Alaska*, Deep-Sea Res. Pt II 52, 991–1009.

Behrenfeld, M.J., Boss, E., Siegel, D.A., Shea, D.M., 2005. *Carbon-based ocean productivity and phytoplankton physiology from space*, Glob. Biogeochem. Cy. 19.

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., Boss, E.S., 2006. *Climate-driven trends in contemporary ocean productivity*, Nature 444, 752–755.

Boyce, D.G., Lewis, M.R., Worm, B., 2010. *Global phytoplankton decline over the past century*, Nature 466, 591–596.

Calbet, A., Sazhin, A.F., Nejstgaard, J.C., Berger, S.A., Tait, Z.S., Olmos, L., Sousoni, D., Isari, S., Martinez, R.A., Bouquet, J.-M., 2014. *Future climate scenarios for a coastal productive planktonic food web resulting in microplankton phenology changes and decreased trophic transfer efficiency*, PloS One 9, e94388.

Chen, X., Pan, D., Bai, Y., He, X., Wang, T., 2014. *Are the trends in the surface chlorophyll opposite between the South China Sea and the Bay of Bengal?*, [in:] *Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions Conference Proceedings 2014*, SPIE, 270–277.

Chinnadurai, K., Retnamma, J., Nagarathinam, A., Subramanian, P.R., Singaram, P., Shoba, S., 2021. *Microplankton size structure induced by a warm-core eddy in the western Bay of Bengal: Role of Trichodesmium abundance*, Oceanologia 63(3), 283–300. https://doi.org/10.1016/j.oceano.2021.02.003

Chowdhury, M., Biswas, H., Mitra, A., Silori, S., Sharma, D., Bandyopadhyay, D., Shaik, A.U.R., Fernandes, V., Narvekar, J., 2021. *Southwest monsoon-driven changes in the phytoplankton community structure in the central Arabian Sea (2017–2018): After two decades of JGOFS*, Prog. Oceanogr. 197, 102654.

Coghlan, A., 2018. *A little book of R for time series*, Available online at: https://buildmedia.readthedocs.org/media/pdf/a-little-book-of-r-for-time-series/latest/a-little-book-of-r-for-time-series.pdf

Dalpadado, P., Arrigo, K.R., van Dijken, G.L., Gunasekara, S.S., Ostrowski, M., Bianchi, G., Sperfeld, E., 2021. *Warming of the Indian Ocean and its impact on temporal and spatial dynamics of primary production*, Prog. Oceanogr. 198, 102688.

Dandapat, S., Chakraborty, A., 2016. *Mesoscale eddies in the Western Bay of Bengal as observed from satellite altimetry in 1993–2014: statistical characteristics, variability and three-dimensional properties*, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 9, 5044–5054.

Doney, S.C., 2006. *Plankton in a warmer world*, Nature 444, 695–696.

Falkowski, P.G., Fenchel, T., Delong, E.F., 2008. *The microbial engines that drive Earth's biogeochemical cycles*, Science 320, 1034–1039.

Feng, M., Majewski, L.J., Fandry, C.B., Waite, A.M., 2007. *Characteristics of two counter-rotating eddies in the Leeuwin Current system off the Western Australian coast*, Deep-Sea Res. Pt. II 54, 961–980. https://doi.org/10.1016/j.dsr2.2006.11.022

Friendly, M., 2002. *Corrgrams: Exploratory displays for correlation matrices*, Am. Stat. 56, 316–324.

Giorgi, F., 2005. *Climate change prediction*, Clim. Change 73, 239–265.

Goes, J.I., Thoppil, P.G., Gomes, H. do R., Fasullo, J.T., 2005. *Warming of the Eurasian landmass is making the Arabian Sea more productive*, Science 308, 545–547.

Gopalakrishna, V.V., Murty, V.S.N., Sengupta, D., Shenoy, S., Araligidad, N., 2002. *Upper ocean stratification and circulation in the northern Bay of Bengal during southwest monsoon of 1991*, Cont. Shelf Res. 22, 791–802. https://doi.org/10.1016/S0278-4343(01)00084-X

Gregg, W.W., Casey, N.W., 2007. *Modeling coccolithophores in the global oceans*, Deep-Sea Res. Pt. II 54, 447–477. https://doi.org/10.1016/j.dsr2.2006.12.007

Gregg, W.W., Rousseaux, C.S., 2019. *Global ocean primary production trends in the modern ocean color satellite record (1998–2015)*, Environ. Res. Lett. 14, 124011.

Guinehut, S., Le Traon, P.Y., Larnicol, G., Philipps, S., 2004. *Combining Argo and remote-sensing data to estimate the ocean three-dimensional temperature fields-a first approach based on simulated observations*, J. Marine Syst. 46, 85–98.

Hosoda, S., Ohira, T., Sato, K., Suga, T., 2010. *Improved description of global mixed-layer depth using Argo profiling floats*, J. Oceanogr. 66, 773–787. https://doi.org/10.1007/s10872-010-0063-3

Huot, Y., Brown, C.A., Cullen, J.J., 2005. *New algorithms for MODIS sun-induced chlorophyll fluorescence and a comparison with present data products*, Limnol. Oceanogr. Methods 3, 108–130.

Jiang, R., Wang, Y.-S., 2018. *Modeling the ecosystem response to summer coastal upwelling in the northern South China Sea*, Oceanologia 60 (1), 32–51.

Jorgensen, E.G., 1968. *The adaptation of plankton algae: II. Aspects of the temperature adaptation of Skeletonema costatum*, Physiol. Plant. 21, 423–427.

Jyothibabu, R., Arunpandi, N., Jagadeesan, L., Karnan, C., Lallu, K.R., Vinayachandran, P.N., 2018. *Response of phytoplankton to heavy cloud cover and turbidity in the northern Bay of Bengal*, Nature Sci. Rep. 8, 1–15. https://doi.org/10.1038/s41598-018-29586-1

Jyothibabu, R., Karnan, C., Arunpandi, N., Santhi Krishnan, S., Balachandran, K.K., Sahu, K.C., 2021. *Significantly dominant warm-core eddies: An ecological indicator of the basin-scale low biological production in the Bay of Bengal*, Ecol. Indic. 121, 107016. https://doi.org/10.1016/j.ecolind.2020.107016

Jyothibabu, R., Madhu, N.V., Habeebrehman, H., Jayalakshmy, K.V., Nair, K.K.C., Achuthankutty, C.T., 2010. *Re-evaluation of "paradox of mesozooplankton" in the eastern Arabian Sea based on ship and satellite observations*, J. Marine Syst. 81, 235–251.

Jyothibabu, R., Vinayachandran, P.N., Madhu, N.V., Robin, R.S., Karnan, C., Jagadeesan, L., Anjusha, A., 2015. *Phytoplankton size structure in the southern Bay of Bengal modified by the Summer Monsoon Current and associated eddies: Implications on the vertical biogenic flux*, J. Marine Syst. 143, 98–119. https://doi.org/10.1016/j.jmarsys.2014.10.018

Keen, T.R., Kindle, J.C., Young, D.K., 1997. *The interaction of southwest monsoon upwelling, advection and primary production in the northwest Arabian Sea*, J. Marine Syst. 13, 61–82.

Kerr, R.A., 2012. *Experts agree global warming is melting the world rapidly*, Science 338, 1138.

Khan, T.M.A., Quadir, D.A., Murty, T.S., Sarker, M.A., 2004. *Seasonal and interannual sea surface temperature variability in the coastal cities of Arabian Sea and Bay of Bengal*, Nat. Hazards 31, 549–560.

Killick, R., Fearnhead, P., Eckley, I.A., 2012. *Optimal detection of changepoints with a linear computational cost*, J. Am. Stat. Assoc. 107, 1590–1598.

Kumar, G.S., Prakash, S., Ravichandran, M., Narayana, A.C., 2016. *Trends and relationship between chlorophyll-a and sea surface temperature in the central equatorial Indian Ocean*, Remote Sens. Lett. 7, 1093–1101. https://doi.org/10.1080/2150704X.2016.1210835

Lee, Z., Weidemann, A., Kindle, J., Arnone, R., Carder, K.L., Davis, C., 2007. *Euphotic zone depth: Its derivation and implication to ocean-color remote sensing*, J. Geophys. Res.-Oceans 112. https://doi.org/10.1029/2006JC003802

Lewandowska, A.M., Hillebrand, H., Lengfellner, K., Sommer, U., 2014. *Temperature effects on phytoplankton diversity – the zooplankton link*, J. Sea Res. 85, 359–364.

Li, H., Xu, F., Zhou, W., Wang, D., Wright, J.S., Liu, Z., Lin, Y., 2017. *Development of a global gridded Argo data set with Barnes successive corrections*, J. Geophys. Res.-Oceans 122, 866–889. https://doi.org/10.1002/2016JC012285

Liu, M., Liu, X., Ma, A., Li, T., Du, Z., 2014. *Spatio-temporal stability and abnormality of chlorophyll-a in the Northern South China Sea during 2002–2012 from MODIS images using wavelet analysis*, Cont. Shelf Res. 75, 15–27.

Lotliker, A.A., Baliarsingh, S.K., Sahu, K.C., Kumar, T.S., 2020. *Long-term chlorophyll-a dynamics in tropical coastal waters of the western Bay of Bengal*, Environ. Sci. Pollut. Res. 27, 6411–6419.

Luo, J.-J., Sasaki, W., Masumoto, Y., 2012. *Indian Ocean warming modulates Pacific climate change*, Proc. Natl. Acad. Sci. 109, 18701–18706.

Ma, C., Zhao, J., Ai, B., Sun, S., Zhang, G., Huang, W., Wang, G., 2021. *Assessing responses of phytoplankton to consecutive typhoons by combining Argo, remote sensing and numerical simulation data*, Sci. Total Environ. 790, 148086.

Madhupratap, M., Gopalakrishnan, T.C., Haridas, P., Nair, K.K.C., Aravindakshan, P.N., Padmavati, G., Paul, S., 1996. *Lack of seasonal and geographic variation in mesozooplankton biomass in the Arabian Sea and its structure in the mixed layer*, Curr. Sci. 17(11), 863–868.

Mahadevan, A., Jaeger, G.S., Freilich, M., Omand, M.M., Shroyer, E.L., Sengupta, D., 2016. *Freshwater in the Bay of Bengal: Its fate and role in air-sea heat exchange*, Oceanography 29, 72–81.

McCulloch, M.T., Winter, A., Sherman, C.E., Trotter, J.A., 2024. *300 years of sclerosponge thermometry shows global warming has exceeded 1.5°C*, Nat. Clim. Change 14, 171–177. https://doi.org/10.1038/s41558-023-01919-7

Miranda, J., Baliarsingh, S.K., Lotliker, A.A., Sahoo, S., Sahu, K.C., Kumar, T.S., 2020. *Long-term trend and environmental determinants of phytoplankton biomass in coastal waters of northwestern Bay of Bengal*, Environ. Monit. Assess. 192, 1–13.

Mishra, A.K., Dwivedi, S., Das, S., 2019. *Role of Arabian Sea warming on the Indian summer monsoon rainfall in a regional climate model*, Int. J. Climatol. 40, 2226–2238.

Mohan, S., Mishra, S.K., Sahany, S., Behera, S., 2021. *Long-term variability of Sea Surface Temperature in the Tropical Indian Ocean in relation to climate change and variability*, Glob. Planet. Change 199, 103436.

Montagnes, D.J.S., Franklin, M., 2001. *Effect of temperature on diatom volume, growth rate, and carbon and nitrogen content: reconsidering some paradigms*, Limnol. Oceanogr. 46, 2008–2018.

Murphy, G.E.P., Romanuk, T.N., Worm, B., 2019. *Cascading effects of climate change on plankton community structure*, Ecol. Evol. 10, 2170–2181.

Prakash, P., Prakash, S., Rahaman, H., Ravichandran, M., Nayak, S., 2012. *Is the trend in chlorophyll-a in the Arabian Sea decreasing?* Geophys. Res. Lett. 39.

Prakash, S., Ramesh, R., 2007. *Is the Arabian Sea getting more productive?* Curr. Sci. 667–671.

Pramanik, S., Sil, S., Gangopadhyay, A., Singh, M.K., Behera, N., 2020. *Interannual variability of the Chlorophyll-a concentration over Sri Lankan Dome in the Bay of Bengal*, Int. J. Remote Sens. 41, 5974–5991.

Prasad, T.G., 2004. *A comparison of mixed-layer dynamics between the Arabian Sea and Bay of Bengal: One-dimensional model results*, J. Geophys. Res.-Oceans 109. https://doi.org/10.1029/2003JC002000

Prasanna Kumar, S., Madhupratap, M., Kumar, M.D., Gauns, M., Muraleedharan, P.M., Sarma, V., De Souza, S.N., 2000. *Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea*, J. Earth Syst. Sci. 109, 433–441.

Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., De Souza, S.N., Sardesai, S., Madhupratap, M., 2002. *Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea?*, Geophys. Res. Lett. 29, 88-1–88-4.

Prasanna Kumar, S., Narvekar, J., Nuncio, M., Kumar, A., Ramaiah, N., Sardessai, S., Gauns, M., Fernandes, V., Paul, J., 2010. *Is the biological productivity in the Bay of Bengal light limited?*, Curr. Sci. 98, 1331–1339.

Prasanna Kumar, S., Nuncio, M., Narvekar, J., Kumar, A., Sardesai, S., De Souza, S.N., Gauns, M., Ramaiah, N., Madhupratap, M., 2004. *Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal?*, Geophys. Res. Lett. 31.

Prasanna Kumar, S., Ramaiah, N., Gauns, M., Sarma, V., Muraleedharan, P.M., Raghukumar, S., Kumar, M.D., Madhupratap, M., 2001. *Physical forcing of biological productivity in the Northern Arabian Sea during the Northeast Monsoon*, Deep-Sea Res. Pt. II 48, 1115–1126.

Ravichandran, M., Girishkumar, M.S., Riser, S., 2012. *Observed variability of chlorophyll-a using Argo profiling floats in the southeastern Arabian Sea*, Deep-Sea Res. Pt. I 65, 15–25.

Raymont, J.E.G., 2014. *Plankton & productivity in the oceans. Volume 1: Phytoplankton*, Elsevier, 660 pp.

Resplandy, L., Levy, M., Madec, G., Pous, S., Aumont, O., Kumar, D., 2011. *Contribution of mesoscale processes to nutrient budgets in the Arabian Sea*, J. Geophys. Res.-Oceans 116.

Rhein, M., Rintoul, S.R., Aoki, S., Campos, E., Chambers, D., Feely, R.A., Gulev, S., Johnson, G.C., Josey, S.A., Kostianoy, A., 2013. *Observations: Ocean*, Cambridge University Press, Cambridge, UK, New York, USA.

Rousseaux, C.S., Gregg, W.W., 2012. *Climate variability and phytoplankton composition in the Pacific Ocean*, J. Geophys. Res.-Oceans 117. https://doi.org/10.1029/2012JC008083

Roxy, M.K., Modi, A., Murtugudde, R., Valsala, V., Panickal, S., Prasanna Kumar, S., Ravichandran, M., Vichi, M., Levy, M., 2016. *A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean*, Geophys. Res. Lett. 43, 826–833.

Roxy, M.K., Ritika, K., Terray, P., Masson, S., 2014. *The curious case of Indian Ocean warming*, J. Clim. 27, 8501–8509.

Sarma, V., Rao, G.D., Viswanadham, R., Sherin, C.K., Salisbury, J., Omand, M.M., Mahadevan, A., Murty, V.S.N., Shroyer, E.L., Baumgartner, M., 2016. *Effects of freshwater stratification on nutrients, dissolved oxygen, and phytoplankton in the Bay of Bengal*, Oceanography 29, 222–231.

Sarma, V.V.S.S., Rajula, G.R., Durgadevi, D.S.L., Kumar, G.S., Loganathan, J., 2020. *Influence of eddies on phytoplankton composition in the Bay of Bengal*, Cont. Shelf Res. 208, 104241. https://doi.org/10.1016/j.csr.2020.104241

Sarma, V.V.S.S., Rao, D.N., Rajula, G.R., Dalabehera, H.B., Yadav, K., 2019. *Organic Nutrients Support High Primary Production in the Bay of Bengal*, Geophys. Res. Lett. 46, 6706–6715. https://doi.org/10.1029/2019GL082262

Sarmiento, J.L., Slater, R., Barber, R., Bopp, L., Doney, S.C., Hirst, A.C., Kleypas, J., Matear, R., Mikolajewicz, U., Monfray, P., 2004. *Response of ocean ecosystems to climate warming*, Glob. Biogeochem. Cy. 18.

Schaum, C.E., Barton, S., Bestion, E., Buckling, A., Garcia-Carreras, B., Lopez, P., Lowe, C., Pawar, S., Smirnoff, N., Trimmer, M., 2017. *Adaptation of phytoplankton to a decade of experimental warming linked to increased photosynthesis*, Nat. Ecol. Evol. 1, 1–7.

Shankar, D., Vinayachandran, P.N., Unnikrishnan, A.S., 2002. *The monsoon currents in the north Indian Ocean*, Prog. Oceanogr. 52, 63–120.

Shetye, S.R., Shenoi, S.S.C., Gouveia, A.D., Michael, G.S., Sundar, D., Nampoothiri, G., 1991. *Wind-driven coastal upwelling along the western boundary of the Bay of Bengal during the southwest monsoon*, Cont. Shelf Res. 11, 1397–1408.

Singh, G.P., Oh, J., 2007. *Impact of Indian Ocean sea-surface temperature anomaly on Indian summer monsoon precipitation using a regional climate model*, Int. J. Climatol. RMetS 27, 1455–1465.

Subramanian, V., 1993. *Sediment load of Indian rivers*, Curr. Sci. 64, 928–930.

Thomas, M.K., Kremer, C.T., Klausmeier, C.A., Litchman, E., 2012. *A global pattern of thermal adaptation in marine phytoplankton*, Science 338, 1085–1088.

Thompson, B., Gnanaseelan, C., Parekh, A., Salvekar, P.S., 2008. *North Indian Ocean warming and sea level rise in an OGCM*, J. Earth Syst. Sci. 117, 169–178.

Thushara, V., Vinayachandran, P.N.M., Matthews, A.J., Webber, B.G.M., Queste, B.Y., 2019. *Vertical distribution of chlorophyll in dynamically distinct regions of the southern Bay of Bengal*, Biogeosciences 16, 1447–1468.

van Leeuwen, S.M., van der Molen, J., Ruardij, P., Fernand, L., Jickells, T., 2013. *Modelling the contribution of deep chlorophyll maxima to annual primary production in the North Sea*, Biogeochemistry 113, 137–152.

Venrick, E.L., McGowan, J.A., Cayan, D.R., Hayward, T.L., 1987. *Climate and chlorophyll a: long-term trends in the central North Pacific Ocean*, Science 238, 70–72.

Vinayachandran, P.N., 2009. *Impact of physical processes on chlorophyll distribution in the Bay of Bengal*, Indian Ocean Biogeochem. Process. Ecol. Var. - Geophys. Monogr. 71–86.

Vinayachandran, P.N., Kurian, J., 2007. *Hydrographic observations and model simulation of the Bay of Bengal freshwater plume*, Deep-Sea Res. Part Oceanogr. Res. Pap. 54, 471–486.

Wiggert, J.D., Hood, R.R., Banse, K., Kindle, J.C., 2005. *Monsoon-driven biogeochemical processes in the Arabian Sea*, Prog. Oceanogr. 65, 176–213. https://doi.org/10.1016/j.pocean.2005.03.008

Wollrab, S., Izmestyeva, L., Hampton, S.E., Silow, E.A., Litchman, E., Klausmeier, C.A., 2021. *Climate Change-Driven Regime Shifts in a Planktonic Food Web*, Am. Nat. 197, 281–295.

Xu, Y., Wu, Y., Wang, H., Zhang, Z., Li, J., Zhang, J., 2021. *Seasonal and interannual variabilities of chlorophyll across the eastern equatorial Indian Ocean and Bay of Bengal*, Prog. Oceanogr. 198, 102661.

Yadav, K., Sarma, V., Rao, D.B., Kumar, M.D., 2016. *Influence of atmospheric dry deposition of inorganic nutrients on phytoplankton biomass in the coastal Bay of Bengal*, Mar. Chem. 187, 25–34.

Yang, J., Gong, P., Fu, R., Zhang, M., Chen, J., Liang, S., Xu, B., Shi, J., Dickinson, R., 2013. *The role of satellite remote sensing in climate change studies*, Nat. Clim. Change 3, 875–883.

Zlotnik, I., Dubinsky, Z., 1989. *The effect of light and temperature on DOC excretion by phytoplankton*, Limnol. Oceanogr. 34, 831–839.