Variation of Surface Chlorophyll-a and its Teleconnection to the Climatological Factors in the Bay of Bengal

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Abstract

The Bay of Bengal (BoB), a subtropical basin in the northeastern part of the Indian Ocean, is one of the Largest Marine Ecosystems (LME). It occupies 8% and 12% of mangroves and coral reefs respectively, as well as it provides 6 million tons of fisheries production annually that valuing 4 billion USD. Parameters like Sea Surface Temperature (SST), Mixed Layer Depth (MLD), Sea Level Anomaly (SLA), and Chlorophyll-a (Chl-a) are predominant and showed present trends of all the parameters interpreting the correlation with El-Nino Southern Oscillation (ENSO). It is found that the southeastern part of the bay is comparatively more ecologically healthy and productive compared to others due to the influences of East Indian Coastal Current (EICC) other parameters as well. MLD and Chl-a concentration have also been affected by the change in climate over recent years. Furthermore, the impact of El-Nino and La-Nina was significant all over the BoB, though there could be more factors responsible for affecting BoB. In all of the analyses according to monthly and yearly observation, a significant changing pattern has been shown in SST, SLA, MLD, and Chl-a from 1997 to 2020. As it is the home of thousands of species and the source of livelihood for 4.5 million people, its importance can't be denied. Therefore, for a sustainable ecosystem and to conserve the LME, we should have a cumulative effort on restoring a healthy climate by reducing pollution and carbon emissions.

Keywords: Bay of Bengal, ENSO, SST, Chlorophyll-a, Large Marine Ecosystem.

1. Introduction

The Bay of Bengal, a land lock and the largest bay in the world, situated in the north-eastern part of the Indian Ocean, is an active subtropical basin. It has a distinct geography and climate. This basin is not necessarily related to polar water. Seasonal

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winds from the Asian landmass and south-westerlies blow through this basin. Most of the moisture has been found in the south-westerlies, which are normally wet. The north-easterlies, on the other hand, have less moisture and are often dry and cold (S. P. Kumar and Narvekar 2005). During the summer monsoon (June to September), south-westerly winds prevailed, while north-easterly winds prevailed during the winter monsoon (November to February). It has one of the largest SSTs in the world as well as the lowest salinity. This is due to the intense seasons in this region. It has received a significant amount of freshwater from rivers as well as precipitation.

The upper-ocean does seem to have a massive spatio-temporal in comparison to the rest of the ocean, and is, therefore, a vital zone to comprehend short-to long-term change as well as climate change. The extreme combination of heat, energy, and freshwater at the top of the ocean leads to the development of a uniform layer known as the mixed layer, which has almost consistent characteristics. It's also the layer that, by certain materials and momentum transfer, links the underlying ocean to the atmosphere. As with heat flow and cyclones, the heat stored in the mixed layer affects the interaction process between the air and the sea. Aside from that, the majority of ocean biological development is heavily reliant on this substrate, particularly as physical and chemical changes occur (Narvekar and Prasanna Kumar 2014). Spatially, the depth of the mixed layer grows from several tens of meters to several hundred meters at the poles of the equator (D'Ortenzio et al. 2005), it can range from diurnal to inter-annual timescales though perceptually (Kara, Rochford, and Hurlburt, 2003). However, the mixed layer's composition and variability are mainly determined by regional oceanographic and atmospheric features in a specific geographic area (Masud-Ul-Alam, Khan, Barrett, Rivero-Calle, et al. 2022), such as the tropics.

All along with the physical components of the sea which vary from place to place. It creates a demonstrative impact on the marine environment and changes obsolete values. As the SST has been rising during the last few decades, it is an indicator of the global temperature rise. All the oceans have been warming for the last few decades, and still, it is on the rise. This could be detected far from the pelagic zones (Barnett *et al.*, 2005; Levitus, Antonov, and Boyer, 2005). The ocean circulation pattern has been disrupted because of these trends (Hakkinen and Rhines 2009; Toggweiler and Russell 2008). Humans and other components of the Earth have been compromised because of the increased temperature of the oceans, which is leading to global change. The Indian Summer Monsoon (ISM) is the only leading opportunity for the south Asian region for monsoon rain. Following the transition of the season, the wind circulation pattern varies. The summer monsoon, as well as the other three major monsoons in the BoB area, including the winter monsoon and two inter-monsoons, play various roles during the year. These monsoons are extremely dependent on the variables of the BoB seawater. Some disturbances can change the whole weather system and change the climate of that region.

The key mechanism of variability in the BoB is the seasonal period of hydrography and circulation, which is well understood and documented (Potemra, Luther, and O'Brien 1991; Rao and Sivakumar 2003). Slower cycles, such as multi-annual and, in particular, global mean temperature variability, are less debated, resulting in a rudimentary understanding of the Indian Ocean's long-term variability in the face of climate change. On the other hand, some research has been done on the slowing of the warming of SST in the Pacific and Atlantic Oceans (Kosaka and Xie 2013; Trenberth and Fasullo 2013; Chen and Tung 2014; Trenberth et al. 2014). Based on a study of SST data from 1904 to 1994, was the first to demonstrate that the Indian Ocean was warming at a rate of 0.5° C every 100 years (K. R. Kumar et al. 2002). Based on SST data collection from 1960 to 2005, Kumar et al., (2009) discovered that the Arabian Sea experienced secular warming and regional climate change after mid-1990. However, there are no such dataset or reports exists that deals with long-term fluctuations within the BoB (Masud-Ul-Alam, Khan, Sunny, et al. 2020). It's due to climatic changes brought about by monsoons. We have always heard about the dangerous cyclones that can occur in the BoB. As a result, there are a lot of activities in this bay during the pre-monsoon season. Freshwater accumulation in the BoB causes all the conditions in the bay to change. Because rivers primarily transport massive amounts of sediments, suspended matter and freshwater (Masud-Ul-Alam, Khan, Islam, et al. 2020) from the Himalayas, there is a distinct difference in salinity and temperature, exclusively in the sea surface areas. In the summer monsoon, salinity rapidly decreases in the northern BoB, and in the winter monsoon, the salinity holds on to 30 ppm-34 ppm about all over the bay.

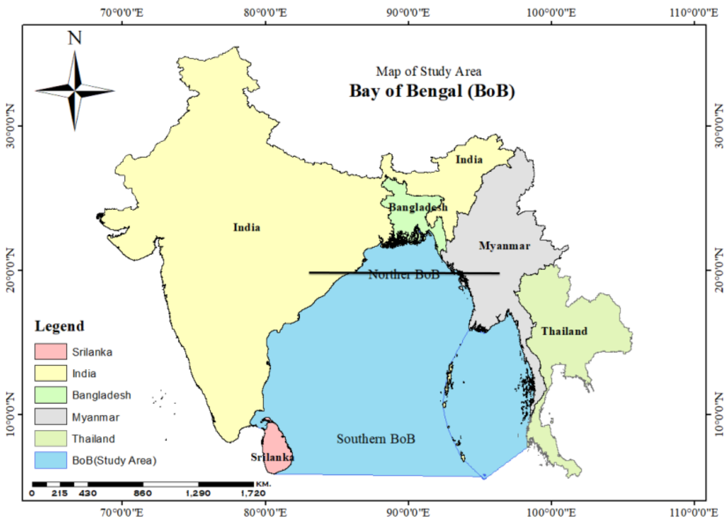

Figure 1. The study area of the BoB (Northern and Southern) with the surroundings.

It is in this context of the present study, using the last 25 years of data on SST, chlorophyll-a concentration, sea level anomalies, and Mixed Layer Depth, we will examine; the long-term trends of SST, SLA, MLD changes; the rate of change of surface seawater temperature, sea level height, and chlorophyll-a concentration; and finally identify the factors responsible for the observed changes in the BoB.

2. Methods and Methodology

2.1 Study area of the Bay of Bengal

The BoB is the largest bay in the world, which is partially surrounded in the west, north, and east by Sri Lanka, India, Bangladesh, Myanmar, and Indonesia. It also has access to the Indian Ocean to the south. Around 4% of global cyclone genesis occurs over the BoB, which is the world's largest single cyclone genesis basin. In addition, the bay is home to the world's largest active GBM Delta system. It is quite special for a variety of reasons, and it has the largest population among the coastal countries.

2.2 Data

In our entire study, different data have been used from multiple sources. The climatological data SST, SLA, MLD, SSH, and Chl-a concentration; all these data had obtained from E.U. Copernicus Marine Service Information Level-4, 0.25 x 0.25^{o} resolution, data in NetCDF-4 format and then conducted the analyses using Ferret on Ubuntu version 20.04 LTS.

The material is collected from a mixture of satellite and in-situ data, which offers monthly reprocessed (REP) data over several years. In the OC-CCI v5's case, a fusion of SeaWiFS, VIIRS, MERIS, MODIS-Aqua, and OLCI-S3A with the most pertinent atmosphere correction and chlorophyll algorithms with a temporarily weighted bias correction to help minimize variations among the sensors. The Ocean Color Climate Change Initiative has been included in an ESA program to generate 'climate-grade' essential climatic variables based on the data of satellites. There is an annual algorithm update, and a bi-annual time series update that Plymouth Marine Laboratory (PML) incorporates into the CMEMS distribution as GLO REP products. Only the daily Global Chlorophyll Climatology at 4km is currently available. The historical multivariate ENSO Index data was used from the physical science laboratory of the National Oceanographic and Atmospheric Administrations (Zhang et al. 2019; Kobayashi et al. 2015; Wolter and Timlin 1993; 1998; 2011)**.** The Model Data Index of Indian Ocean Data has been used by American Satellite Meteorology Education & Training (ASMET) (Ihara, Kushnir, and Cane 2008; “ASMET: Drought in East Africa: SST Anomaly Indices for 2008 to 2009,” n.d.).

The bathymetry and maritime region of the BoB, Andaman Sea have been used by IMIS (“IMIS | Flanders Marine Institute,” n.d. 14th March 2021) . The study area map has been developed using ArcGIS 10.5.

2.3 Method

The climatological data for Spatiotemporal analysis of SST, Chl-a, and SSS has been carried out using Ferret on Ubuntu version 20.04 LTS. For proper visualization of chlorophyll-a spatiotemporal analyses, we use a log transformation scale of Chl-a concentration following the standard method and algorithm (Gaxiola-Castro 2010). The study area map builds using a freely available shapefile on QGIS. On the other hand, other climatological variables’ time series analyses made visualization using statistical software R. Among the tree method to calculate the MLD from Level 3 satellite data, we use the threshold method considering the density parameter as a threshold value (Masud-Ul-Alam, Khan, Sunny, et al. 2020; Thomson and Fine 2003). The time series of the leading combined Empirical Orthogonal Function (EOF) of five distinct variables across the tropical Pacific basin is the bi-monthly Multivariate El Niño/Southern Oscillation (ENSO) index (Wolter and Timlin 2011; Zhang et al. 2019). To account for ENSO's seasonality and decrease the impacts of intra-seasonal variability, EOFs for 12 overlapping "seasons" are produced using data from the JRA-55 reanalyses of SST, SSS, Sea Level Pressure (SLP), surface zonal, and meridional wind.

3. Results

All the results collected from the data sources show a tremendous change in physical factors.

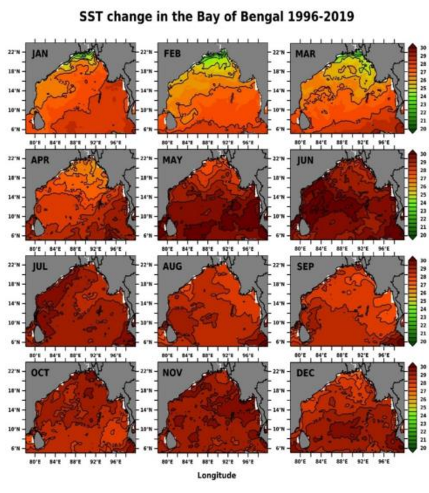

Figure 3. Climatological SST in the BoB for the period of 1993-2019. The color bar indicates the SST in degree Celsius.

Most of them have been showing linear trends. Most of the changes are seen in the northern BoB rather than the southern BoB.

3.1 Seasonal variability of the physical parameters

The northern part of the BoB is very complex, with a lot of seasonal variability within a year. From December to February, the dry season or pre-monsoon season has an impact, while the monsoon season lasts from July to August. During the summer and winter monsoon, all the data are showing significant values.

SST (Fig. 2) starts to rise in the BoB from May and continues until the first of August. In July, there is a small drop in temperature along the southern coasts of the south BoB. If we look up the monsoonal pattern, the summer monsoon is highly significant. The temperature variation in the southern BoB is not as significant as in the northern part.

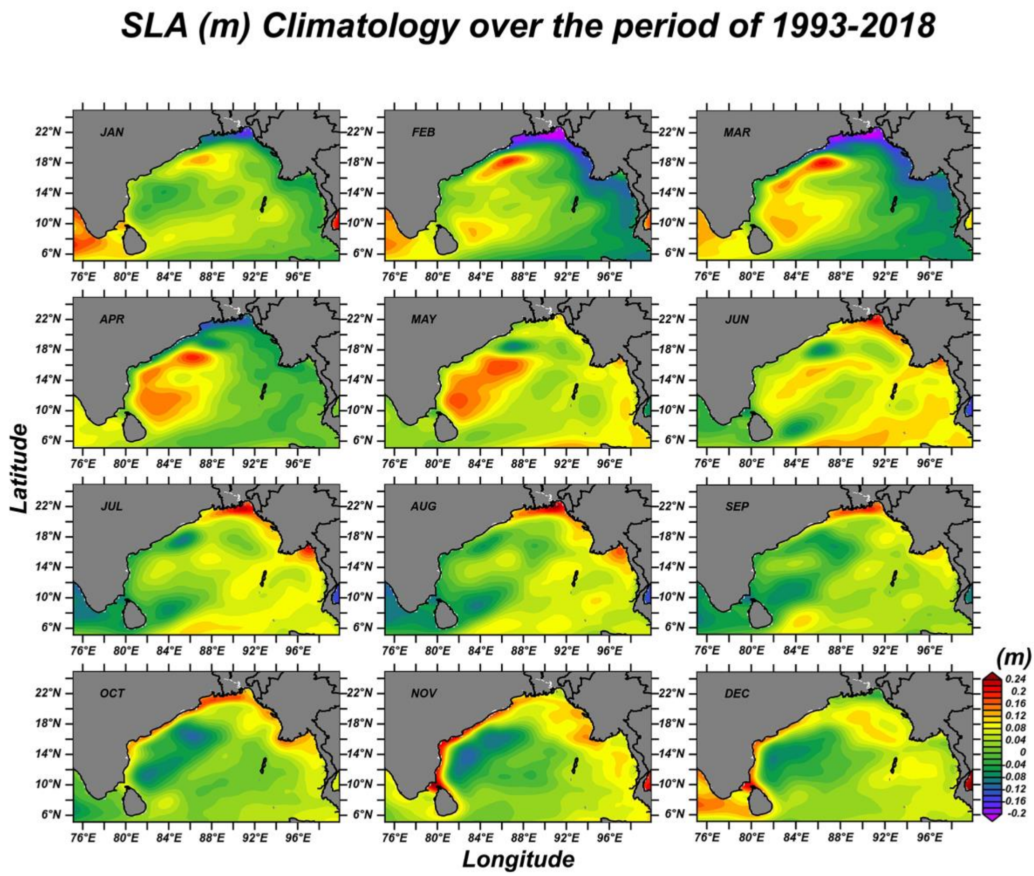

Figure 4. Climatology of sea level anomaly for in the BoB over the period of 1993-2018. Write a line describing the color bar

Throughout the year, the data of the SLA, (Fig. 3) reveals two distinct features: the mean flow and the mean high. During the winter to pre-monsoon season, the lowest mean low begins moving from the coast of Bangladesh to the middle of the northern BoB. The highest mean highs, on the other hand, prevail along the western coast of the BoB in the north during the winter and begin to migrate towards the Bangladesh coast during the monsoon. The results can be related to SST and MLD (Fig. 2, 4), which is significant. Leaving the coasts, especially the western and northern coasts, which continue to change abruptly.

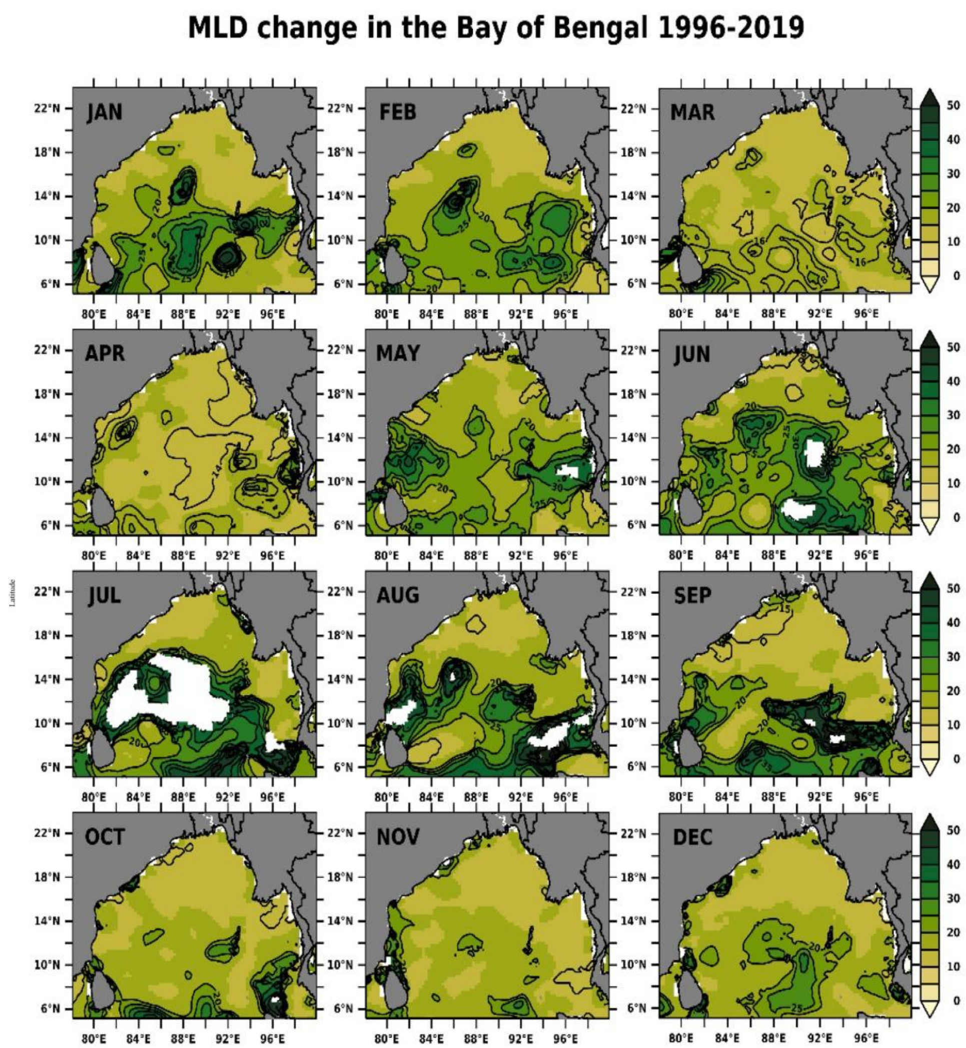

Figure 4. Monthly analysis of the MLD in the BoB and its variance through the average period of 1997-2020. Follow the same of previous figs.

We have seen some (Fig. 4) variations in the BoB's MLD. The height of the MLD is higher at certain points along the western boundary during the starting of the summer monsoon. In the southern BoB, from May to September, the whole area is covered with about 30 m -50 m of MLD. It drops to about 10 m in the pre-monsoon period. The Chl-a concentration is a continuous variable with seasonality and corresponds to primary productivity and phytoplankton abundance in typical coastal waters. The concentration of Chl-a was found to be highest during the monsoon and post-monsoon seasons, and lowest during the winter season. During the monsoon (May-August), the concentration of Chl-a started to rise along the whole coastal belt of Bangladesh. This high concentration in the coastal areas of both the country lasted till the post-monsoon (September-October) and continued to decrease from the winter season. Chl-a concentration was stated to rise in the Northern BoB (June for Irrawaddy and July for Krishna and Godavari River) while it has decreased at the start of winter in both the rivers. Moreover, this pattern applied to other rivers as well.

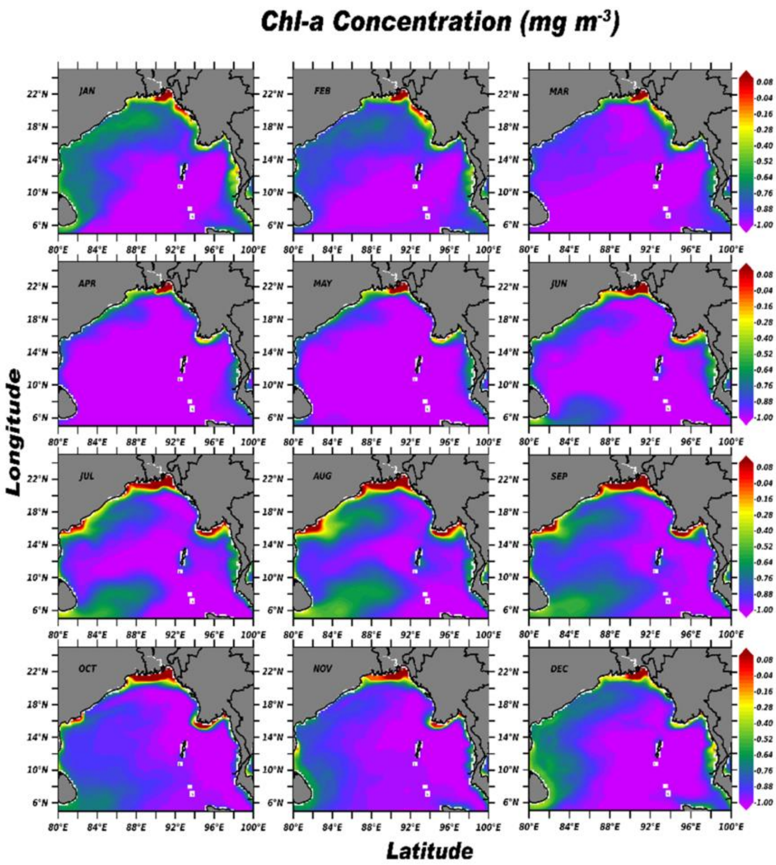

Figure 5. Sea Surface chlorophyll-a concentration (log scale) in the BoB for the period of 1993-2019 (Average).

3. 2 Climatological Time series analyses:

3.2.1 Time series analyses of SST

Fig. 6(a) depicts the chronology of the temperature profile in the BoB. From 1997 through 2020, it depicts a linear trend of rising temperatures, which is continuing. The BoB has warmed up to 0.4 ºC -0.5 ºC over the last 23 years. At the south BoB, the tendency is increasing, whereas at the north BoB, it is somewhat decreasing. The ratios in the north BoB are extremely near to each other. However, we have seen higher peaks in 1999, 2006, and 2019. The higher peaks in the south BoB are in 1998, 2010, and 2016. Both P_N and P_s do not have a meaningful value in this case. Nonetheless, the chart shows an upward trendline.

3.2.2 Time series analyses of SLA

Fig. 6(b) demonstrates that the sea level has been rising over time, according to an analysis of 23 years of evidence. In the trend, a straight line can be noticed. Every year, the rise in sea level has been significant. On both sides of the Bay, the P_N and P_s values are substantial. On both sides of the BoB, there is a slight divergence between the trendlines. The south BoB has seen a higher rise in sea level in recent years than the north BoB. However, in the northern BoB, the change over time was higher.

3.2.3 Time series analyses of MLD

MLD in the north BoB does not show any significant values, as shown in Fig. 6(c), because the potential line is parallel to the time, as shown in Fig. 6(b). However, in recent years (2012-2019), there has been a minor increase, which will be followed by a fall in 2020. The graph exhibits a linear pattern, indicating that MLD is increasing in the southern bay. As there are no significant values in P_N. P_s, on the other hand, have substantially higher significance than P_N.

3.2.4 Time series analyses of Chl-a

The BoB (both in its northern and southern parts) has shown decreasing trends over the years. Among them, a higher decreasing trend in the northern BoB. Since 1998, there have been three significant highs in Chl-a concentrations in 1998, 2012, and 2019, all of which have a positive relationship with ENSO. The p values for the northern and southern BoB, on the other hand, are 0.0001 and 0.0427, respectively, indicating that the Chl-a at the northern bay is more variable than the southern bay.

3.2.5 ENSO time series analyses (Warm (red) and cold (blue) periods based on a threshold of +/- 0.46)

The El Niño/Southern Oscillation (ENSO) is an anomalous state of tropical Pacific coupled ocean-atmosphere conditions that occurs naturally. ENSO is the most reliable indicator of global climate change. The time series of the leading combined EOF of five different variables is the bi-monthly MMEI.v2. The canonical features of the atmosphere and ocean anomalies are shown schematically below during the typical peak of ENSO in late fall or early winter. From 1998 to 2020, the table below is based on a composite of 11 historical El Niño and La Nina events (NOAA, n.d.).

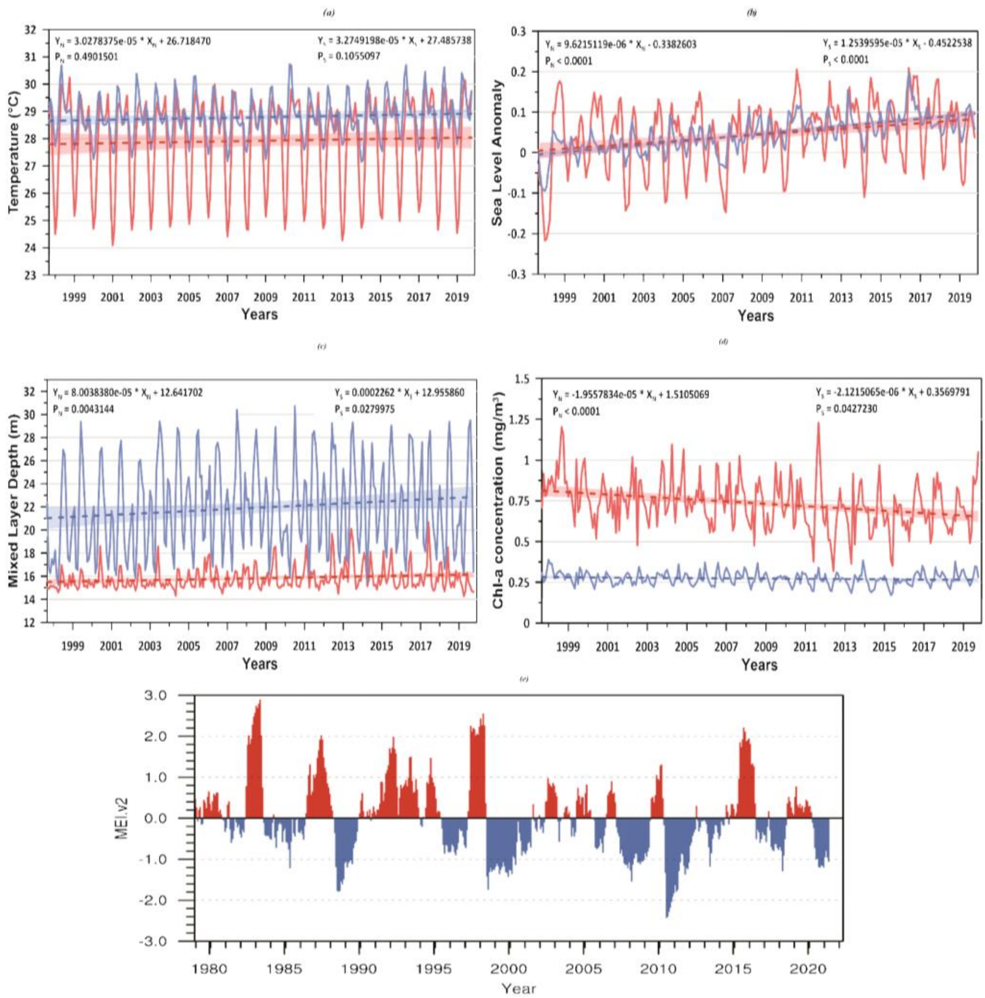

Figure 6. Time series of (a) SST (°C); (b) SLA (m); (c) MLD (m); and (d) Chlorophyll-a (mg/m^3) for the period of 1997-2020; (Red and blue lines represents respectively the northern and southern BoB) (e) Multivariate ENSO Index version-2 for the period of 1980-2020

Discussion

The dynamic BoB faces seasonal variation both in terms of SST, SLA, MLD, and Chl-a concentration depending on spatial scale. Several driving factors are involved in influencing spatial variation. The evolution of 25 years of remote sensing observation of SST, MLD, SLA, and Chl-a concentration found variable in the seasonal circulation over the Bay of Bengal.

The SST of the northern part of the BoB Oceanic Banks is influenced by several large rivers that fall into it. The floating freshwater decreases the temperature up to 24 ºC-28 ºC (Masud-Ul-Alam, Khan, Barrett, and Rivero-Calle 2022). Data, especially temperature, is still lacking in parts of the BoB (Srivastava et al. 2020). The monsoonal change also affects the temperature rise and fall in the north BoB (Fig. 2, 6a). As previously mentioned, the temperature of the BoB has been increasing at a rate of 0.014 ºC per year for the past few decades (D'Mello and Prasanna Kumar 2016).

In the southern part of Bangladesh's BoB in spring and summer, the warmest waters are found near the coast of Bangladesh and Myanmar. Although there are no large eddies or gyres in the BoB, there are a few small eddies near the western boundary formed by the effects of the western boundary current (Shankar, Vinayachandran, and Unnikrishnan 2002) and also has the impact of the Rossby waves (S. P. Kumar and Narvekar 2005). The Southeast Monsoon Current entered the BoB beside Sri Lanka during the summer monsoon and several eddies predominantly surrounded it. In the summer, hot surface water moves from the eastern coast to the western coast with seasonal wind flow, whereas it reverses in the monsoon. Sri Lanka has anti-cyclonic eddies to the southeast and cyclonic eddies to the east of Sri Lanka (Patnaik 2020). The monsoon blows from May to October, accompanied by heavy rain that causes over 75% - 90% of the rainfall in the BoB during summer. During the winter, monsoons and reversal conditions developed (GOSWAMI and WU 2006).

The southern region of Indonesia is always warmer than the northern part since it interacts with the equatorial currents and the Indonesian Throughflow (Vranes, Gordon, and Ffield 2002). P_N value is not significant in this area, as well as P_s. So, the temperature shown in the trend is not variable but still increasing. And there was a short gap of 3 years to 7 years, which indicates some irregular movement of the climate. The temperature of the seawater was higher than it should be. So much for ENSO and La Nina theories (Islam and Parvez 2020). That means the temperature did not merely rise on its own but had to be forced to do so. Other variables are causing the temperature to rise in both parts of the bay. Moreover, the sea was also warming up due to global warming (S. P. Kumar et al. 2009).

We observed that during the summer monsoon, the water column moves towards the western boundary, especially in the middle and southern BoB. It could be the Eddies on the western boundary (Kara et al. 2003), or Rossby waves (Narvekar and Prasanna Kumar 2014) which are diverging from the water column and heading towards the coastal areas. But there are some ultimate factors like the rising temperature, Indonesian Throughflow (Vranes, Gordon, and Ffield 2002), and EICC at the western boundary (Shankar, Vinayachandran, and Unnikrishnan 2002) of the BoB, etc. As a result, the temperature and sea level anomalies' maximum peak change over time. Peak SLA is found mostly near the western coast of BoB and north of Sri Lanka. Higher SLA required small-scale gyres and small eddies, especially in the Southwestern part of Bengal (Pirro et al. 2020). While looking at the 25-year datasets (Fig. 6b), it varied from year to year. From a climatological view (Fig. 3), it varies from monsoon to monsoon. Between the years, there is a higher ratio of around 0.1-0.2. Higher SLA represents an upwelling zone and small-scale eddies formed seasonally. The formation of seasonal eddies is highly related to the East India Coastal Current (EICC), the western boundary current (Dandapat, Chakraborty, and Kuttippurath 2018). However, the trend is accelerating (Fig. 6b).

In both the northern and southern BoB, the temperature played a role in rising sea levels. The sea level has risen to its highest point in 2011 and 2016 and fallen to its lowest point in 1998. There could be several issues concerning this. The major influencing factor could be positive La Lina as well as the teleconnections of ENSO and IOD. MLD is too variable from region to region, especially where the Eddies and gyres are located (Yesubabu et al. 2020). In comparison, the MLD of the Arabian Sea is deeper than the BoB because of the eddies. When we compared the north and south BoB, we found that the difference was significant. The northern part of the BoB shows small trends of MLD which differ from 14-25 m. The southwest corner (Fig. 4) near the Indian Eastern coast was exceptional, but most of the region was below 20 m MLD. In fig. 6(d), we have observed a huge difference between both parts of the bay (Vinayachandran, Murty, and Babu 2002), and less upwelling (fewer eddies) in the northern BoB’s center could contribute to Chl-a concentration. Furthermore, the south end of this bay offers a completely different picture (Fig. 4). On the northeast side of the bay, where the Irrawaddy and Rangoon rivers discharge their freshwater into the bay, there is a small impact of river water. That is the reason the MLD is low in this region rather than in the South Bay. High temperatures and high saline water are the major factors for the increasing MLD in the south of BoB. We've seen larger trends in Fig. 6(c), and they've been increasing for years. The ratio was 15 m -31 m in the south BoB. But the more the seawater is mixed, the more it gets dense with nutrients. By this, there is a chance of an increase in the Chl-a in the BoB. But that is hardly observed of the lack of research work in that particular region (north BoB).

Surface chlorophyll-a concentration in the BoB is also highly dependent on the direction of the Rossby wave, which can be determined by the movement of the MLD layer contour to the left (Fig. 4). Fig 6(d) shows Chl-a levels in the northern and southern BoB over time (Narvekar and Prasanna Kumar 2014). According to Swansea University researchers, the formation of Chl-a may increase the molecule's abundance on both the seafloor and in the atmosphere. It may also split the depth of the barrier layer as well as the eddies, potentially increasing the depth of the mixed layer.

El Niño is the most significant climate driver in the BoB, Fig. 6(e) refers to the year-to-year shift in western and eastern Indian tropical sea temperatures. Changes in the wind south of Indonesia cause cool water to rise from the ocean depths, resulting in less cloud formation in the Eastern Indian Ocean. On the other hand, the westerly winds are weakening, and easterly winds are forming, allowing warm water to flow toward Africa. This affects the weather system, causing it to receive more rain than normal.

Conclusion

The trend of temperature, sea level height, and MLD has changed a lot between 1997 and 2020, according to all the analyses based on monthly and yearly observations. The results of this study show that global, regional, and local change in the parameters, as measured by increasing temperature and sea level, has had an effect on the mixed layer depth across the BoB. The decline in Chl-a abundance would affect the food abundance of BoB's marine organisms, and this could bring disaster to the marine ecosystem in the future. The northern BoB might be affected faster, which would be unable to provide food after a few decades. El Niño and La-Nina impacts in the BoB due to rising temperatures are triggered by a warming in the southern BoB. The sea-level rise in the BoB has caused some disruption in the climatology of the region, as a result of El Niño and La-Nina, which is altering the climate of the area. For the past few years, the height of the sea water level has increased more than expected, which might hamper the depth of MLD. Less MLD, lower the production rate of fisheries and creates an ecological imbalance. Because of the large freshwater flux and high precipitation along the coast, distinct spatial variations have been observed. Except on a weekly or seasonal basis, the BoB retains its character and exhibits a significant response to climate change which gives exposure to the seasonal change and the long-term change in the temperature and Chl-a concentration.

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Appendices

List of acronyms

ArcGIS- Aeronautical Recownnaissance Coverage Geographic Information System
ASMET- American Satellite Meteorology Education & Training
BoB- Bay of Bengal
Chl-a- Chlorophyll-a
CMEMS- Copernicus Marine Environment Monitoring Service
EICC- East Indian Coastal Current
ENSO- El Nino Southern Oscillation
ESA- European Space agency
GBM Delta- Ganges Brahmaputra Meghna Delta
IMIS- Integrated Management Information System
IOD- Indian Ocean Dipole
ISM- Indian Summer Monsoon
LME- Largest Marine Ecosystem
LTS- Long Term Support
MEI- Multivariate ENSO Index
MERIS- MEdium Resolution Imaging Spectrometer
MLD- Mixed layer Depth
MODIS- Moderate Resolution Imaging Spectroradiometer
NetCDF- Network Common Data Form
NOAA- National Oceanographic and Atmospheric Administration
OLCI- Ocean and Land Colour Instrument
PML- Plymouth Marine Laboratory
SeaWIFS- Sea-viewing Wide Field-of-view Sensor
SLA- Sea Level Anomaly
SSH- Sea Surface Height
SSS- Sea Surface Salinity
SST- Sea Surface Temperature
VIIRS- Visible Infrared Imaging Radiometer Suite