Chapter 9
Past Trends and Future Projections of Marine Primary Productivity in the Tropical Indian Ocean

Aditi Modi and Mathew Koll Roxy

Abstract Changes in marine phytoplankton are crucial to understand the complex but significant climate change impacts on the marine ecosystem and fisheries. Detecting the climatic response in phytoplankton has been a challenge due to the unavailability of long-term observed data and biases and inadequacies in representing the ocean biogeochemistry in ocean models. Research has been indicating that long-term SST warming stratifies the low-latitude waters, impacting nutrient mixing and phytoplankton production. Now, with extended satellite datasets and improved Earth system models, we find that the marine primary productivity in the tropical Indian Ocean, particularly the Arabian Sea and the coastal regions of the Bay of Bengal, shows a significant declining trend during 1998–2022. Future simulations from the Coupled Model Intercomparison Project phase 6 (CMIP6) further project that the decreasing trend will continue in the Arabian Sea, Bay of Bengal, and Sri Lankan coast. Meanwhile, an increasing trend is projected along the coast of Sumatra and Java and coastal regions of the northeast Arabian Sea and northwest Bay of Bengal. Gaps in in situ and satellite data still prevent us from gaining clarity on regional trends at fine temporal scales, particularly in terms of shifts in the timings of phytoplankton blooms. Future response of phytoplankton changes is poorly constrained in the Earth system models since they typically include only 2–3 phytoplankton types and are inadequate to assess the changes in phytoplankton community structure. Regardless, the observed trends and future projections give a clear signal of a steady and rapid decline in phytoplankton

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A. Modi (✉)
Centre for Climate Change Research, Indian Institute of Tropical Meteorology,
Ministry of Earth Sciences, Pune, India

IDP in Climate Studies, Indian Institute of Technology, Bombay, India
e-mail: aditi.modi@tropmet.res.in

M.K.Roxy
Centre for Climate Change Research, Indian Institute of Tropical Meteorology,
Ministry of Earth Sciences, Pune, India

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production in the Indian Ocean. These changes need to be closely monitored for phytoplankton community reorganization and abrupt shifts and collapses in the marine ecosystem.

Keywords Chlorophyll · Net primary productivity · Tropical Indian Ocean · Earth system model · Phytoplankton trends · Future projections · CMIP6

1 Introduction

Phytoplankton are single-celled aquatic photoautotrophs that serve as the primary food source for marine species. They regulate the availability of food for higher trophic levels of the marine ecosystem and drive the ocean carbon cycle by converting inorganic carbon into organic carbon through photosynthesis (Cabré et al., 2015; Falkowski et al., 2004; Laufkötter et al., 2015; Smetacek, 1999). Net primary productivity (NPP) is the net organic carbon produced by phytoplankton after subtracting the costs of its metabolic processes from the total organic carbon produced (Falkowski et al., 2003). This NPP is the most critical element in assessing organic carbon export from the ocean surface to the deep ocean (Sarmiento et al., 2007). As a result, variations in the marine NPP can be used to deduce global carbon budget trends (Wernand et al., 2013).

Primary production exhibits variability on timescales ranging from months to years. The tropical Indian Ocean is typically characterized by two annual blooms of phytoplankton – primary bloom during summer (June–September) and a secondary bloom during winter (December–February) (Banse, 1987; Kumar et al., 2013). Changes in physical forcing, especially related to the southwest (summer) and northeast (winter) monsoons, are linked to these seasonal bloom episodes (Kumar et al., 2001; Schott & McCreary, 2001; Wiggert et al., 2005). Due to the various physical mechanisms driving primary production in the Indian Ocean, these seasonal blooms also exhibit spatial diversity (Beal et al., 2019; Kumar et al., 2013). Apart from seasonal fluctuations, the principal climatic modes – El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) – influence interannual variations in primary productivity in the Indian Ocean (Currie et al., 2013; Murtugudde & Busalacchi, 1999). These climatic modes also have the potential for ocean rearrangement such as demonstrated by the strongest El Niño of the twentieth century, the 1998/1999 El Niño. It led to a dramatic collapse of mackerels, resulting in the recruitment of oil sardines along India’s Malabar coast (Krishnakumar & Bhat, 2007).

In the past, in situ data on indices of ocean primary production in the Indian Ocean were scarce, as opposed to the Pacific and Atlantic Oceans. This is one of the main reasons why the Indian Ocean is the least studied of all the tropical basins. Only since the satellite era has it become able to discern the impact of anthropogenic climate change on the ocean (Henson et al., 2010; Werdell et al., 2009). Satellites collect a uniform spatiotemporal sample of the surface ocean, resulting in an ocean color dataset that spans more than two decades, allowing us to better understand ocean biophysical interactions (Sathyendranath et al., 2019). Remote-sensed ocean color provides measurements of chlorophyll – the phytoplankton pigment that undergoes photosynthesis and is a proxy for marine phytoplankton. Chlorophyll concentrations are generally employed to discern trends in aggregate plankton types because data on different taxonomic categories of phytoplankton is relatively few as compared to satellite-derived primary production records. At the same time, there are in situ records and model data relating to individual phytoplankton kinds that have been utilized to examine trends and are discussed in this chapter.

Observations over the past century have reported a consistent rise in sea surface temperatures (SST) in the tropical Indian Ocean, particularly in recent decades (Beal et al., 2019; Rao et al., 2012; Roxy et al., 2020; Webster et al., 2006). This rate of warming (0.15 °C/decade) in the tropical Indian Ocean is the fastest among tropical oceans and accounts for about one-quarter of the increase in global oceanic heat content over the last two decades despite being the smallest of the tropical oceans (representing only 13% of the global ocean surface) (Beal et al., 2019; Gnanaseelan et al., 2017). Moreover, the Indian Ocean warm pool has substantially expanded during recent decades (Roxy et al., 2019; Dalpadado et al., 2021). In the low-latitude regions, which are primarily nutrient limited as sunlight is abundant, an increase in ocean surface temperature is projected to enhance upper water column stratification, resulting in less mixing and lesser flow of nutrients from the subsurface into the surface (Behrenfeld et al., 2006; Boyce et al., 2011; Roxy et al., 2016). This increased stratification might affect the phytoplankton growth and species distribution and spread across the region's food web, eventually leading to the restructuring of marine biomes (Cheung et al., 2011; Pörtner et al., 2014). It is, therefore, critical to have a clear understanding of productivity trends in this highly productive ocean basin, particularly since it has been witnessing one of the most significant warming trends, which is the objective of this chapter. Hence, this chapter reviews the historical changes in marine primary productivity in the Indian Ocean as a whole and in the subregions of the Indian Ocean that serve as biodiversity hotspots. This chapter also discusses on the future long-term projections of marine primary productivity based on simulations from Coupled Model Intercomparison Project (CMIP) phase 5 (CMIP5) and available phase 6 (CMIP6).

2 Past Trends in Marine Primary Productivity

The Arabian Sea is one of the largest hotspots for biodiversity and one of the most economically significant, thus forming a unique ecosystem within the Indian Ocean basin (Alexander, 1993; Piontkovski & Queste, 2016). Due to the upwelling of cold nutrient-rich water and enhanced vertical mixing provided by the periodically reversing monsoon winds, this region experiences enormous phytoplankton blooms in the summer and a smaller bloom in the winter, owing to convective vertical mixing (Kumar et al., 2001; Ryther & Menzel, 1965; Wiggert et al., 2005). Behrenfeld et al. (2006) reported a decrease in net primary production (NPP) due to surface thermal stratification in most of the tropics but an increase in NPP in response to rising SSTs across the western Indian Ocean from 1998 to 2004. Other research (Goes et al., 2005; Gregg et al., 2005) found similar results during the same time period, showing that the western Indian Ocean saw the second biggest rise in chlorophyll concentrations (a phytoplankton biomass indicator) among open-ocean regions. Goes et al. (2005) found a 350% increase in marine phytoplankton in this region, which they attributed to the strengthening of summer monsoon winds in the western Indian Ocean. The increasing trend during the short data period appears to be corresponding to the initial year (1998) with a strong El Niño and a positive Indian Ocean Dipole, which results in warmer SST anomalies in the western Indian Ocean and a corresponding reduction in chlorophyll concentrations (Currie et al., 2013; Murtugudde et al., 1999; Roxy et al., 2016).

Extending the dataset over a 16-year (1998–2013) period, Roxy et al. (2016) report a 30% decline in chlorophyll in the western Indian Ocean. Their study also assessed CMIP5 models, which simulated a 20% decrease in long-term chlorophyll in the western Indian Ocean from 1950 to 2015, thus agreeing with the observations. The increased stratification of the oceanic water column in response to the strong warming of the ocean surface is linked to these declining phytoplankton trends. Another study by Prakash et al. (2012) used SeaWiFS sensor chlorophyll data and found that chlorophyll increased during 1998–2002 and declined since 2003 in the western Arabian Sea. The study suggests that the observed chlorophyll response is not governed by global warming but rather is a result of the decadal oscillations in sea-level anomaly and the thermocline. Diatoms, which are the predominant phytoplankton group in the Arabian Sea, have been reported to be declining in the region (Garrison et al., 2000; do Rosário Gomes et al., 2014). As a result, changes in the trophic interactions of the aquatic food web are to be expected.

We analyze the changes in summer marine primary production during 1998–2022 in the western Indian Ocean remote-sensed chlorophyll concentrations provided by European Space Agency's Ocean Color-Climate Change Initiative (OC-CCI) v6.0 (Henson et al., 2010; Hollmann et al., 2013; Sathyendranath et al., 2019). The chlorophyll-a time series (chl-a) obtained from OC-CCI is a multi-mission product derived by merging data from the SeaWiFS, MODIS, MERIS, and VIIRS sensors. The level-3 data from different sensors were band-shifted to SeaWiFS wavebands and bias-corrected for the signal-to-noise ratio, thus resulting in a climate-quality dataset. The analysis suggests that chlorophyll has declined in the western Indian Ocean during the past 25 years (inset box in Fig. 9.1a). The time series of chlorophyll anomalies indicate a high year-to-year variability with a linear downward trend (red dashed line in Fig. 9.1b). A major decrease in chlorophyll concentrations is seen in the north Indian Ocean, particularly in the north-western Arabian Sea and along the coasts of Bay of Bengal (Fig. 9.1a). However, patches of increased chlorophyll in some of the coastal areas, such as the eastern Indian Ocean off the coasts of Sumatra and Java and the Sri Lankan upwelling dome, are observed. The local biophysical processes need further examination to understand the spatial variability in the observed chlorophyll trends.

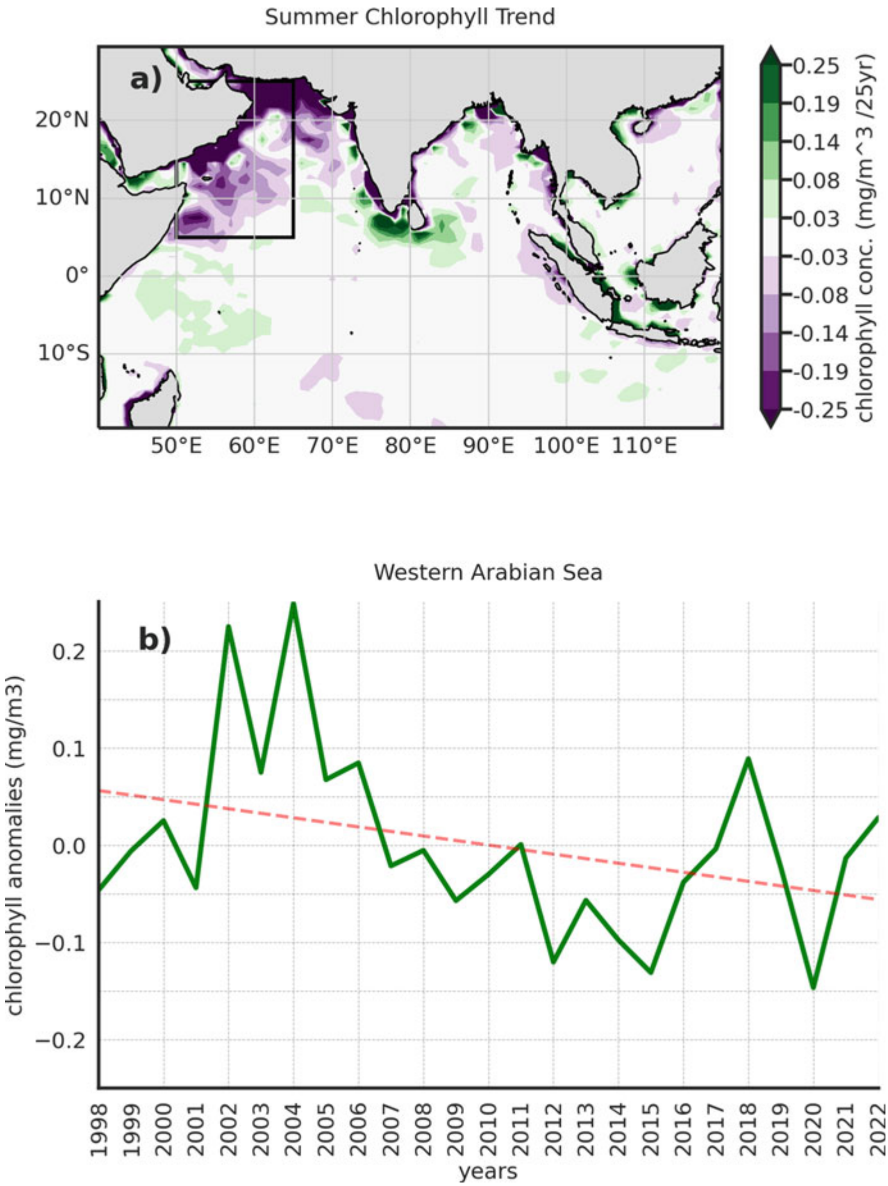

Fig. 9.1 (**a**) Summer (June–September) chlorophyll trend (mg/m^3/25 year) in the tropical Indian Ocean in OC-CCI remote-sensed observations during 1998–2022. The inset box (50–65°E, 5–25°N) indicates the region with the largest trends in chlorophyll concentrations. (**b**) Mean summer anomalies of chlorophyll (mg/m^3) in the western Indian Ocean (50–65°E, 5–25°N; inset box in (**a**)). Dashed line (red) in the chlorophyll time series indicates the trend line. (Data used is from European Space Agency Ocean Color-Climate Change Initiative (OC-CCI) version 6.0 (https://climate.esa.int/en/projects/ocean-colour/))

In comparison to the Arabian Sea, the Bay of Bengal is characterized as a region of low primary productivity. This low primary production in the Bay of Bengal is a result of upper water column stratification caused by high ocean surface temperatures, combined with lower surface water salinity caused by excess precipitation from the southwest monsoon and river discharge (Kumar et al., 2004; Mahadevan et al., 2016). However, despite the low productivity, on longer timescales, the high new production (production by nitrate) in the Bay of Bengal makes it more efficient in removing the atmospheric CO_2 (Kumar et al., 2004). A decrease in primary productivity in the Bay of Bengal has been seen consistently across the observed records, including proxy data, Earth system models, and satellite imagery (Behrenfeld et al., 2006; Gregg & Rousseaux, 2019; Roxy et al., 2016; Shetye et al., 2014). However, the factors underlying this apparent decline differ among datasets. According to evidence from the oldest geological records dating back over 5000 years, the availability of iron on the ocean surface is linked to a decline in primary production over millennial timescales. The current satellite and climate simulations ascribe the recent decline to upper ocean stratification linked to significant temperature rise over the past half-century. Historically available records show that diatoms, eukaryotic plankton, and cyanobacteria are the dominant primary producers in the Bay of Bengal (Bhaskar et al., 2007; Gauns et al., 2005; Lin et al., 2012; Madhupratap et al., 2003; Pujari et al., 2019). The rate of decline of diatoms and chlorophytes has been 16% per decade and can be linked to the declining rate of primary production in the Bay of Bengal. Concurrently, cyanobacteria have grown at a rate of 17% per decade (Gregg & Rousseaux, 2019). Each of these phytoplankton species has a potential community shift, but the evidence is inconclusive because of the high spatial and temporal variability. Löscher (2021) provides a detailed review of the changes in various phytoplankton types.

The subtropical gyre dominates the southern hemisphere of the tropical Indian Ocean. Despite being classified as oligotrophic regions with low nutrient concentrations and consequently having lower biomass and net primary production year-round, the subtropical gyres' enormous size (about 40% of the Earth's surface) makes their overall contribution to biological productivity significant (Jones et al., 1996; refer to Fig. 9.1. in McClain et al., 2004). Despite a significant variation in growth rates, the phytoplankton biomass of the subtropical gyres is relatively stable (Laws et al., 1987; Maranon et al., 2003). Hence, an expansion in the gyre is associated with more oligotrophic waters and reduced biomass. According to satellite data, the southern Indian Ocean gyre grew marginally between 1997 and 2003 (McClain et al., 2004). A growth in the south Indian Ocean gyre and significant falling trends in the chlorophyll and net primary production are also seen in the most recent satellite data records ($>$10 years) (Polovina et al., 2008). Using multi-sensor satellite observations for the period 1998–2010, an estimation of a decline of 12% in the Indian Ocean subtropical gyre and an SST increase of 0.42 °C has been made (Signorini & McClain, 2012). This decrease in primary productivity is ascribed to the stratification of the upper ocean, less mixing, and warming of the gyres (increase in SST), as well as a shallower mixed layer (MLD). This shift in the gyre-specific ecosystem indicators is a strong sign of how biological processes have responded to the different forms of climate variability (Karl et al., 2001; Oschlies, 2001). However, further research is required to fully understand how climate modes affect ecosystem variability within the southern Indian Ocean gyre.

The north and equatorial Indian Oceans have been demonstrated to have seen a rapid drop in phytoplankton of 0.16 and 0.69 PgC year^1 decade^{-1} since 1998 to 2015, respectively, which accounts for the majority of the contributions to the global NPP decline (-0.8 PgC year^{1}decade^{-1}). The fall in diatoms and chlorophytes, as indicated by an ocean biogeochemical model, is indicative of a significant reduction in productivity (Gregg & Rousseaux, 2019). In the Indian Ocean basin, the concentrations of nitrate and silicate have decreased by 32% and 23%, respectively, during 1998–2015. These lower nutrient contents are a sign that the thermocline's supply of nutrients into the mixed layer may be decreasing (Steinacher et al., 2010). The reported loss in the main phytoplankton group, diatoms, reflects the fall in these important nutrients. This suggests that a shift in phytoplankton composition has begun in these tropical and subtropical Indian basins. If SSTs in tropical basins continue to rise, there is a greater chance of a gradual shift of fish stocks to higher latitudes (Solanki et al., 1998).

Chlorophyll levels in the Indian Ocean continued to fall from 0.37 to 0.18 mg/m^3 between 1898 and 1993, according to in situ ocean color observations that have been recorded since 1890 in various expeditions. The observations are filtered into two datasets, one for the open-ocean region 100 km away from coasts and the other located 500 km away from coasts. Figure 9.2a, b depicts the results for the Indian Ocean, which show a blueing ocean for both datasets, with an average decay of -0.0021 mg/m^3 per year. In contrast, we observe a growing tendency in the Atlantic and Pacific Oceans between 1898 and 1993 (Wernand et al., 2013). The "lost" Forel-

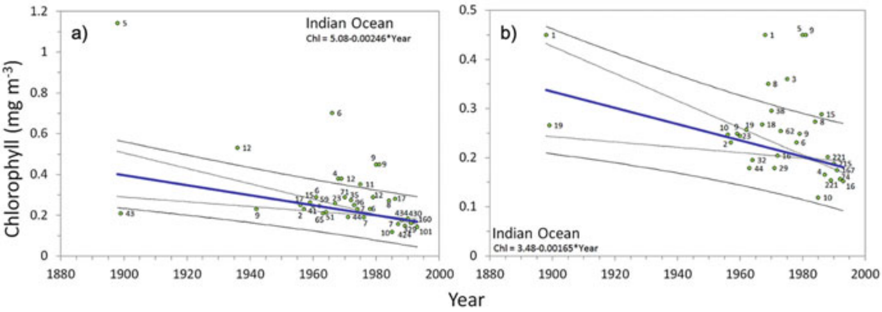

Fig. 9.2 Chlorophyll trend (blue line) in (**a**) open-ocean observations at a distance of more than 100 km off coast. It is chosen to avoid anthropogenic pressure's effects on water coloration in coastal zones, such as locally increased nutrient loading (eutrophication), which tends to increase phytoplankton biomass, or high sediment loading brought on by changes in land use or erosion. (**b**) Open-ocean observations at a distance of more than 500 km from the shore. This region is chosen in order to incorporate the oceans, while also avoiding the effects of mixing with the variously colored water of surrounding seas. All trend lines shown are statistically significant ($P < 0.05$). Regression coefficients are indicated in each graph. (Figure adopted from Wernand et al. (2013))

Ule scale, which was the "then" simplest method of getting the geophysical properties of the natural waters, was used in these observations, making this one of the earliest oceanographic archives. This is the oldest long-term ocean color dataset yet created, thanks to the recent mapping of these observations. More information on the Forel-Ule scale can be found in Wernand and Woerd (2010).

3 Future Projections of Marine Primary Production

Indian Ocean rim nations are dependent on the pelagic ecosystem for their food and livelihood; hence managing it is becoming increasingly challenging than ever. The stressors impacting the marine environment and the corresponding challenges are expected to intensify further as ocean surface warming is projected to continue rapidly in response to an unabated increase in greenhouse gas emissions into the future (Goddard & Groeneveld, 2008; Guillotreau et al., 2012; Houghton et al., 1996; Lee et al., 2005; Levitus et al., 2000; Piontkovski et al., 2015). A majority of Earth system models project a mean global decline in phytoplankton growth during the twenty-first century, which will lower the global NPP thus signaling a net reduction in carbon export into the deeper ocean (Behrenfeld et al., 2006; Bopp et al., 2001; Boyce et al., 2010; Fung et al., 2005).

According to Bopp et al. (2013), all the CMIP5 models, under different emission scenarios, forecast a decrease in NPP in the tropical Indian Ocean. This drop might be as high as 30% under the highest carbon emission scenario (RCP8.5), thus proving detrimental to the basin's marine biodiversity. These NPP and phosphate levels in the ocean's surface and subsurface are expected to keep declining by the year 2300 (Moore et al., 2018). The majority of the CMIP5 models (7 out of 9) project a decrease in NPP, though the mechanism for this reduction varies among the models (Laufkötter et al., 2015). According to simulations from four coupled carbon cycle models of increasing complexity, the primary production in the Indian Ocean is expected to fall relative to preindustrial levels under the earlier set of IPCC emission scenarios (IPCC SRES A2) (Steinacher et al., 2010). A minor rise in net primary productivity is anticipated in some regions of the Indian Ocean close to Australia, nevertheless. This rise is potentially due to the increased upwelling that has improved the flow of nutrients into the mixed layer. In response to the ocean surface freshening and global warming, Cabré et al. (2015) assessed all 16 CMIP5 models that were available and reported a consistent estimate of a decline in marine primary productivity during the twenty-first century across all models.

Diatoms, which make up the majority of marine phytoplankton and represent more than 40% of the biological pump for CO_2 (Tréguer & Pondaven, 2000), are also predicted to experience a rapid decline in the Indian Ocean relative to other phytoplankton types due to a stronger nitrate stress (Bopp et al., 2005; Cermeño et al., 2008). Contrary to other studies, Sarmiento et al. (2004) predict a net rise in global primary production in 2050 and 2090 relative to the preindustrial climate; nevertheless, the low-latitude oceans are expected to experience a loss. According to the CMIP5 Earth system models' high emission scenarios (RCP 8.5), marine primary production in the Indian Ocean is expected to fall, with the western and equatorial Indian Oceans expected to experience the greatest declines (Seelanki & Pant, 2021). However, it is projected that the northern Arabian Sea would experience an increase in chlorophyll levels (Seelanki & Pant, 2021).

The majority of the studies argues that the model predictions of a fall in marine production in the twenty-first century (both near and far future) in the low and mid-latitudes are due to the decrease in upwelling resulting in a reduced nutrient supply from bottom layers of the ocean. Reduced stratification and a more stable (less-mixed) ocean will result from the ocean's continued monotonous warming; these changes will prevent cold, nutrient-rich deep waters from mixing with the surface. Consequently, there would be a net adverse effect on marine output in the tropical Indian Ocean (Marinov et al., 2010). In striking contrast, the anticipated ocean warming could help the phytoplankton development in high-latitude locations, where growth is limited by the availability of light and other environmental factors (Bopp et al., 2001; Doney, 2006; Moore et al., 2018; Steinacher et al., 2010).

The CMIP6 ensemble mean analysed under medium-to-high emission scenarios projects a further reduction in the phytoplankton stocks in both the near future (2041–2070) and far future (2071–2100), with respect to the recent period (1976–2005) in most parts of the tropical Indian Ocean, (Fig. 9.3) (Roxy et al., 2022). By the end of the twenty-first century, the western Arabian Sea region

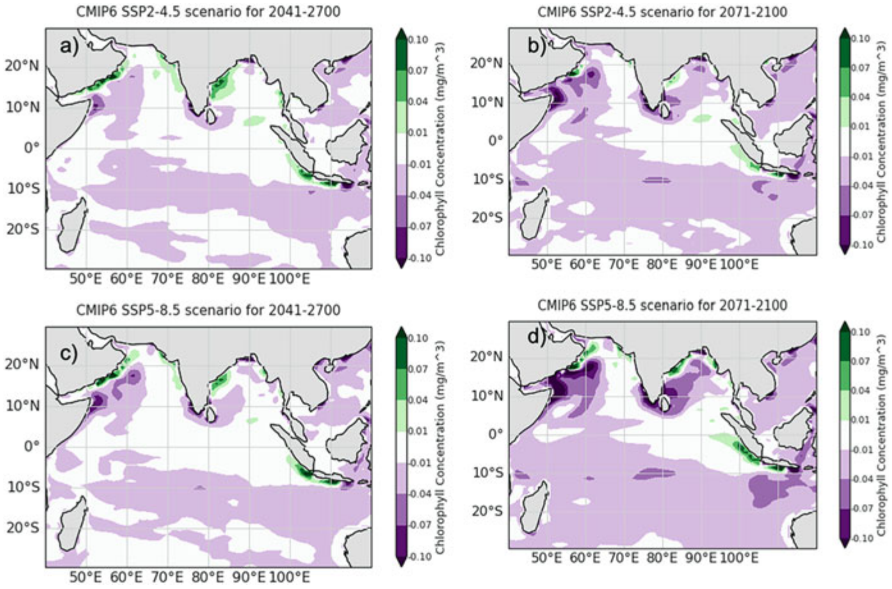

Fig. 9.3 Projected changes in ocean surface chlorophyll (in mg m^{-3}) during the summer monsoon (June–September) in (**a**) SSP2-4.5 for 2041–2070, (**b**) SSP2-4.5 for 2071–2100, (**c**) SSP5-8.5 for 2041–2070, and (**d**) SSP5-8.5 for 2071–2100, with respect to the reference period 1976–2005, in CMIP6 (ensemble mean) simulations. (Figure adopted from Roxy et al. (2022))

(50–65°E, 5–25°N) is projected to have an 8–10% decline in surface chlorophyll under medium-to-high emission scenarios (Fig. 9.3). However, the models project a slight increase in chlorophyll in the southeast Indian Ocean near the shores of Sumatra and Java, as well as along the majority of the northern Indian Ocean's coastal regions (Oman, western and eastern India, Myanmar).

Notably, the inter-model differences and uncertainties in NPP projections are inducted into projected risk assessments under varied climate change scenarios. According to a recent study (Tagliabue et al., 2021), the Indian Ocean is one of the basins with the greatest inter-model spread in the projected changes in NPP. These large inter-model uncertainties are due to the model representation of physical and biogeochemical processes (Whitt & Jansen, 2020). Even though the representation of ocean biogeochemistry in the current generation of Earth system models has improved, further representation of biophysical and biogeochemical feedback is required (Séférian et al., 2020). This necessitates a larger variety of observational datasets so that we can better comprehend the process underlying these ocean emissions.

4 Summary and Future Research Direction

Remote-sensed ocean color observations have made it feasible to examine the trends on regional and global scales. Over the past two decades, satellite records of ocean color have shown a decline in the marine primary production in the western Indian Ocean. This decrease in phytoplankton biomass is attributed to the increased stratification associated with the surface warming of the ocean. However, in other areas, such as along the Java and Sumatra coasts, primary production has increased slightly. To explain these changes, a greater comprehension of the local biophysical processes is required. The Earth system models ensemble also projects a net decline in marine primary production in both the near and far future. The continued warming of the ocean is projected to be the cause of the decline.

Historically, the Indian Ocean has been under-sampled in terms of biogeochemistry and ocean productivity when compared to the Pacific and Atlantic. The vertically generalized productivity model (VGPM; Behrenfeld & Falkowski, 1997), for example, was created with the help of a global database of 1698 primary productivity stations. None of these data are sourced from the Indian Ocean. The absence of any validation data for this satellite productivity algorithm in the Indian Ocean casts doubt on its accuracy despite the fact that it has become the global industry standard for estimating ocean primary productivity and its change over time (Beal et al., 2019; Beal et al., 2020). Recent research has shown that trend detection using satellite ocean color records is extremely sensitive to data processing and drift corrections (Gregg & Rousseaux, 2014; Gregg & Rousseaux, 2019). Assimilation of in situ data with models is needed to reduce this disparity in chlorophyll measurements obtained from different satellites.

Another major limitation of the satellite data is the presence of missing values due to the presence of cloud cover over the north Indian Ocean during the summer monsoon. This renders the data unsuitable for examining the trends in phytoplankton phenology in the Indian Ocean. If chlorophyll in situ records are consistently available, it can be used to fill in the gaps in satellite data. The gaps in the satellite data, however, cannot be filled by the current distribution of in situ observations (Modi et al., 2022). The population of the Indian Ocean rim, which is heavily dependent on fisheries for its sustenance, needs ecological forecasting; therefore, this calls for rapid attention. With the recent launch of the sustained Indian Ocean Observing System (IndOOS) program and similar ongoing observational programs (IOGOOS and SIBER, IIOE2), which aim to improve observations in the tropical Indian Ocean's surface and subsurface by implementing more observing networks like Argo floats, RAMA moorings, satellites, and drifters, we are optimistic that improved observations will be available for the Indian Ocean. While this is a significant collaborative step forward, more global participation is required to sustain the observational networks.

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