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Warming of the Indian Ocean and its impact on temporal and spatial dynamics of primary production

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ABSTRACT

The Indian Ocean, the third largest among the world's oceans, is experiencing unprecedented changes in sea surface temperature (SST). We present temporal and spatial dynamics of phytoplankton and their response to warming in the Indian Ocean (~25°N to 30°S) during 1998–2019 using remote sensing data. Our study revealed that the area of the Indian Ocean Warm Pool (IOWP), defined as waters with SST values >28 °C, is significantly expanding in most regions, particularly in the most recent decade. The increase in IOWP area was greatest (~74%) in the south-central basin. Furthermore, SST increased significantly in most areas of the Indian Ocean (10 out of 11 regions explored) over the 22-year study period with the highest increase of 0.7 °C observed in the south-central regions. Most other regions showed an average increase in temperature of 0.4–0.5 °C. At the same time, net primary production (NPP) showed large interannual variability in northern and central regions of the Indian Ocean, with slightly decreasing trends in a few northern regions. Overall, years of the first decade (1998–2008) showed more often cooler temperatures and higher productivity, except for a few years, whereas years of the last decade (2009–2019) showed more often warmer temperature and lower productivity, except in very recent years (2017–2019) when productivity was high. Mean Chl *a* concentrations increased in the last decade during the northeast monsoon period in the northwestern regions, suggesting increased NPP in December to March period as a future scenario in this highly productive area of the Indian Ocean. We also observed increasing SST in several major upwelling areas during the study period, whereas Chl *a* showed high interannual variability with no marked significant trends in most areas. Results from this study corroborate the importance of the southwest monsoon as a key driver of seasonal patterns in Chl *a* in major upwelling areas of the Indian Ocean.

1. Introduction

The Indian Ocean is the world's third largest ocean, covering an area of ~70 million km^2. It is home to 30% of the world's coral reefs and ~14% of global wild-catch fisheries (Roxy et al., 2020; FAO, 2020). Unique features of this ocean due to its position are the annual reversal of monsoon winds and the landlocking in the north by the Asian continent (Momin et al., 2011; Hood et al., 2017). The monsoon wind systems in the Indian Ocean act as the major physical drivers for the coastal and open-ocean upwelling processes (Sreeush et al., 2018). Primary production and its variability over these coastal upwelling systems are a major concern for the fishing communities (Roxy et al., 2016; Hood et al., 2017; Sreeush et al., 2018). The Indian Ocean holds a key strategic position in the region because it i) provides staple protein food sources and livelihood to about a third of the world's population, ii) impacts weather and climate processes in vast areas, and iii) acts as one of the most vital sea routes. Recently, much attention has been paid to the Indian Ocean due to rapid warming and subsequent potential consequences on the ecosystem.

Observations have shown that the Indian Ocean is consistently warming, and the Indian Ocean warm pool (IOWP), defined as areas with sea surface temperature (SST) values > 28 °C, is expanding, particularly in recent decades (Rao et al., 2012; Roxy et al., 2020). Signatures of strong Indian Ocean Dipole (IOD), which refers to the

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