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REVIEW

Surface ocean-lower atmospheric processes in the Indian Ocean: Current understanding, knowledge gaps, and future directions

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Our understanding of surface ocean and lower atmosphere processes in the Indian Ocean (IO) region shows significant knowledge gaps mainly due to the paucity of observational studies. The IO basin is bordered by landmasses and an archipelago on 3 sides with more than one-quarter of the global population dwelling along these coastal regions. Therefore, interactions between dynamical and biogeochemical processes at the ocean–atmosphere interface and human activities are of particular importance here. Quantifying the impacts of changing oceanic and atmospheric processes on the marine biogeochemical cycle, atmospheric chemistry, ecosystems, and extreme events poses a great challenge. A comprehensive understanding of the links between major physical, chemical, and biogeochemical processes in this region is crucial for assessing and predicting local changes and large-scale impacts. The IO is one of the SOLAS (Surface Ocean-Lower Atmosphere Study) cross-cutting themes as summarized in its implementation strategy. This article attempts to compile new scientific results over the past decade focusing on SOLAS relevant processes within the IO. Key findings with respect to monsoon and air–sea interactions, oxygen minimum zones, ocean biogeochemistry, atmospheric composition, upper ocean ecosystem, and interactions between these components are discussed. Relevant knowledge gaps are highlighted, with a goal to assist the development of future IO research programs. Furthermore, we provided several recommendations to conduct interdisciplinary research to advance our understanding on the land–ocean–atmospheric interaction in the IO.

Keywords: SOLAS, Indian Ocean, Air–sea interaction, Oxygen minimum zone, Anthropogenic pollutants, Biogeochemistry

1. Introduction

The Indian Ocean (IO) is unique, when compared to the Atlantic and Pacific, due to being bordered by landmasses and an archipelago on 3 sides and the seasonally reversing winds and ocean currents (Hood et al., 2015). The IO is becoming increasingly important in terms of global and regional relevance as signals of climate change emerge rapidly in this basin with the adjacent coastlines harboring one-third of the global population (Cai et al., 2014; Doyle, 2018; Hermes et al., 2019; Jyoti et al., 2023). Observations reveal that the IO is consistently warming, with some areas showing accelerated warming, leading to extreme weather events (Dhame et al., 2020; Cai et al., 2021), such as cyclones (Deshpande et al., 2021; Singh and Roxy, 2022), storm surges (Dube et al., 2009; Shaji et al., 2014; Needham et al., 2015), and floods (Roxy et al., 2017; Ankur et al.,

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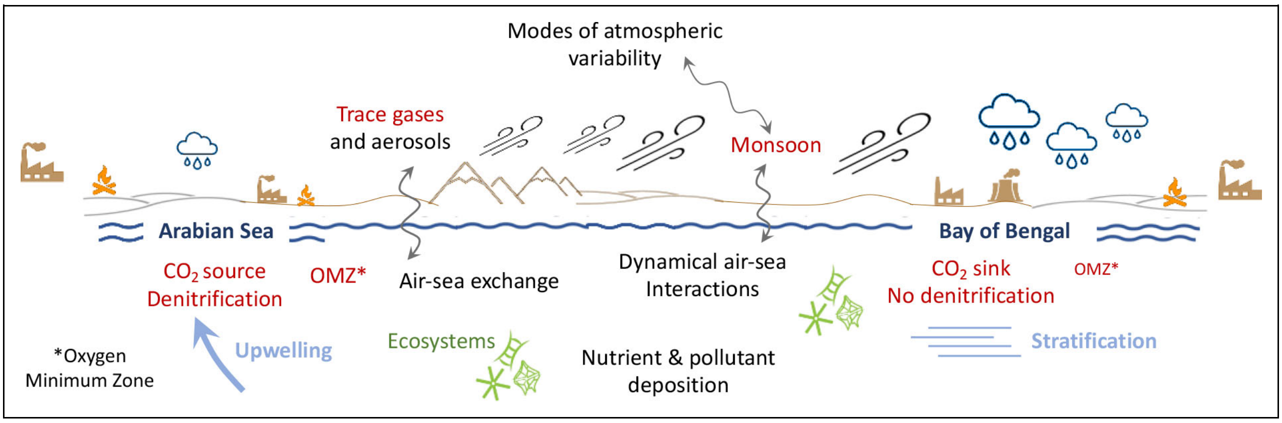

Figure 1. Schematic of dynamical and biogeochemical processes in and above the Indian Ocean relevant for Surface Ocean-Lower Atmosphere Study (SOLAS) science.

2020; Zhou et al., 2021). Apart from its influence on the global climate system, the IO has a major effect on millions of people who live around its shores and depend on its resources. In particular, the 2 semi-enclosed basins in the North Indian Ocean (NIO), namely, the Arabian Sea (AS) and the Bay of Bengal (BoB), are ecologically and socioeconomically vital as they provide marine living and nonliving resources to the IO rim countries and generating a significant revenue for them. With a confirmed steady warming of the NIO and increasing atmospheric temperatures, a steady decline in the marine primary production (due to increased oligotrophy) is a worrisome possibility (Roxy et al., 2015). This may have severe biogeochemical consequences for the rim countries by impacting the entire food chain and fishery resources. Moreover, continued deoxygenation and its intensification over large areas of the NIO could lead to massive fish killing events and shifts in fish migration habits affecting the income of fishery-dependent coastal communities (Techera, 2018; Gangal et al., 2023). With rapidly emerging concepts and implementation of blue economy (including elements like fisheries, aquaculture, industry, shipping, and tourism), the IO is likely to experience increases in marine pollution and habitat degradation leading to changes in the ecosystem and biogeochemical characteristics. In view of this development, it is crucial to assess and understand the complex and interactive processes of the physical and biogeochemical components at the air–sea interface of this oceanic basin.

Despite several international efforts made in the past, through programs such as, the International Indian Ocean Expedition (IIOE), Geochemical Section Study (GEOSECS), Joint Global Ocean Flux Study (JGOFS), World Ocean Circulation Experiments (WOCE), and Geotraces, the IO region is still remained as one of the most poorly sampled regions among the world's oceans, with various scientific gaps (Beal et al., 2020). Owing to this, the International Indian Ocean Expedition-2 (IIOE-2; Hood et al., 2016), a decadal review of the Indian Ocean Observing System (IndOOS-2; Beal et al., 2020), monsoon mission and repetition of WOCE transects are being carried out by international scientific community to improve our understanding of the IO and its role in the Earth climate. Such an improved understanding of physical, biogeochemical, and ecological processes also has strong relevance for the sustainable development of marine resources and environmental stewardship of the IO and surrounding coastal regions.

The Surface Ocean-Lower Atmosphere Study (SOLAS) program came into existence 2 decades ago to address some of the key surface water lower atmosphere coupled interactions and processes (Law et al., 2013). **Figure 1** displays a variety of processes, covered under the SOLAS domain that are relevant for the IO. The characteristic IO monsoon, which is a seasonal reversal of wind patterns (south-westerly during May–September and north-easterly during December–February), plays an important role in modulating, not only atmospheric dynamics and composition but also surface water currents and deep-water processes (Shankar et al., 2002; Phillips et al., 2021). One of the unique features of the IO atmosphere is the seasonally contrasting chemical regimes, which are controlled by anthropogenic emissions and natural mineral dust from the surrounding land masses (Lelieveld et al., 2001; Aswini et al., 2022; Tegtmeier et al., 2022) together with the large-scale monsoon circulations (McCreary et al., 2013). Air–sea exchange couples the atmospheric composition to biogeochemical processes in the surface IO and impacts elemental cycling (Kumar et al., 2020; Sarma et al., 2021). Another unique feature is the formation of vast oxygen minimum zones (OMZs) in the NIO (Naqvi et al., 2006; Sarma et al., 2020b; Gupta et al., 2021).

In the recent years, efforts have been made to review and synthesize various physical and biogeochemical processes that occur within the IO. Phillips et al. (2021) summarized new studies related to ocean–atmosphere coupling, highlighting the importance of small-scale processes on large-scale circulations, interactions between physical and biological processes as well as interaction between the surface and deep ocean. Vinayachandran et al. (2021) reviewed various features of upwelling along the coastal region of the IO, including underlying mechanisms and the impact on ecosystems. A review of the OMZ in the NIO and associated implications was carried out by Rixen et al. (2020) and, in particular, for the BoB by Sridevi and Sarma (2020) and Sarma and Udaya Bhaskar (2018). Tegtmeier et al. (2022) provided a comprehensive review of the atmospheric gas phase composition over the IO and its coupling to trace gas emissions from the land and ocean.

This article aims to synthesize new knowledge accumulated over the past decade focusing on SOLAS relevant processes within the IO. Important research questions and knowledge gaps that SOLAS science can help to address are highlighted in Section 2, to assist the development of future IO research programs. Furthermore, we discuss interdisciplinary efforts required to advance our understanding of this oceanic basin with possible future recommendations in Section 3. The last section summarizes this synthesis by highlighting important results in recent years over the IO.

2. Recent progress and knowledge gaps

2.1. Monsoon and air—sea interactions

Ocean–atmosphere interactions are crucial for understanding the dynamics of the seasonally reversing monsoon system, and recent studies have advanced our understanding of these interactions. Monsoon variability can be driven thermodynamically through the exchange of heat and moisture that regulate the formation of deep convective clouds and rainfall or dynamically through the exchange of momentum and changes in circulation due to winds and ocean currents (Seager et al., 2010). The IO is the breeding ground of the intraseasonal variability of the monsoon, particularly the northward propagating monsoon intraseasonal oscillations (MISO) in summer and the eastward propagating Madden–Julian oscillations (MJO) in winter. The MISO and MJO modulate rainfall and cyclogenesis in South Asia and throughout the global tropics and evolve in response to the ocean–atmosphere interactions in the tropical IO (Roxy et al., 2013; Sharmila et al., 2013; Beal et al., 2020). The 2 oscillations induce sea surface temperature (SST) variations that are larger in the IO than in the Pacific Ocean, and incorporating the ocean–atmosphere interactions associated with these SST variations can improve the tropical rainfall predictability (DeMott et al., 2015).

While the ocean–atmosphere interactions that drive the intraseasonal variability have been extensively investigated and documented, the role of ocean dynamics needs to be better understood. For example, the BoB receives substantial freshwater through monsoon rainfall and river runoff, leading to a strong salinity stratification that causes a thin mixed layer and thick barrier layer. This stratification suppresses vertical ocean mixing, thereby affecting the monsoon intraseasonal SST variability and associated convection (Sengupta et al., 2016). Furthermore, initiation and early development of MJO events are influenced by ocean–atmospheric processes in the Seychelles-Chagos Thermocline Ridge (SCTR), where ocean dynamics and processes play a significant role (West et al., 2020). However, these regions with complex ocean–atmosphere interactions, such as the BoB, the SCTR, and the Indonesian through-flow have only scarce high-resolution observations, limiting our understanding of the key processes associated with the monsoon intraseasonal variability and curtailing model predictability. In this context, noble observations can help to quantify the effects of physical processes on dissolved gases and to separate biological from physical impacts on constituents like oxygen, nitrogen, and carbon (Emerson et al., 2012).

Large gradients in nutrients were observed below and above stratified waters with higher concentration below than above. In such cases, nutrient diffusion through vertical eddy mixing is very important. While vertical eddy mixing has been used as a constant at the rate of 10^5 or 10^7 in the past, it can now be measured using noble gases (Hamme et al., 2017). Because noble gases have no biological function and respond only to physical processes, their measurements can be used to quantify these physical processes and estimate associated nutrient.

The SST variability is also an essential factor impacting monsoon variability on interannual and interdecadal-to-climate timescales. The Indian Ocean Dipole (IOD), a mode of variability characterized by the contrast in SSTs between the western and eastern IO, is a major driver of regional monsoon variability (Ashok et al., 2001) and influences the biogeochemical and ecosystem signatures (Parvathi et al., 2017). The IOD also plays a crucial role in the teleconnection between the El Niño Southern Oscillation (ENSO) and the monsoon (Cherchi et al., 2021). When positive IOD events (characterized by warmer SSTs in the western IO and cooler SSTs in the eastern IO) co-occur with El Niño events, the IO conditions act to counter El Niño's drought-inducing subsidence by enhancing moisture convergence over the Indian subcontinent, resulting in an average monsoon season (Ummenhofer et al., 2011; Chowdary et al., 2015). The IOD–monsoon relationship has strengthened in recent decades due to the nonuniform warming of the IO, while the ENSO–monsoon relationship has weakened (Cherchi et al., 2021). Meanwhile, the long-term monotonic warming of the IO with respect to the Indian subcontinent is altering the regional land–ocean thermal contrast, weakening the monsoon circulation and rainfall on interdecadal timescales (Roxy et al., 2015; Wang et al., 2021). These large-scale modes of climate variability (e.g., IOD, ENSO) influence the local atmospheric circulation which is coupled with the ocean, thereby modulating the ocean-lower atmospheric processes and biogeochemistry in the IO.

2.2. Oxygen minimum zones

The NIO, comprising the AS and the BoB, is characterized by low oxygen conditions below the subsurface layers (Wyrtki, 1971; Sen Gupta and Naqvi, 1984). The western boundary upwelling system (off Somalia and Oman) during summer, and convective mixing during winter, supply nutrients to the surface waters resulting in high productivity in the AS (Lachkar et al., 2023). Conversely, upwelling in the BoB is suppressed by the presence of low-saline waters (Sarma et al., 2015), and primary productivity is supported through riverine input (Krishna et al., 2016) and mesoscale eddies (Prasanna Kumar, 2004; Sarma et al., 2019). Based on the work carried out till now, we sum up existing results in a map depicting the OMZ in the NIO (**Figure 2**), which includes the open ocean perennial nitrite-bearing waters of the AS, the coastal seasonal hypoxic zone along the west and east coast of India and few locations in the BoB. Nitrogen loss in the OMZ can happen either via classical denitrification (Ward et al., 2008; Ward et al., 2009) or

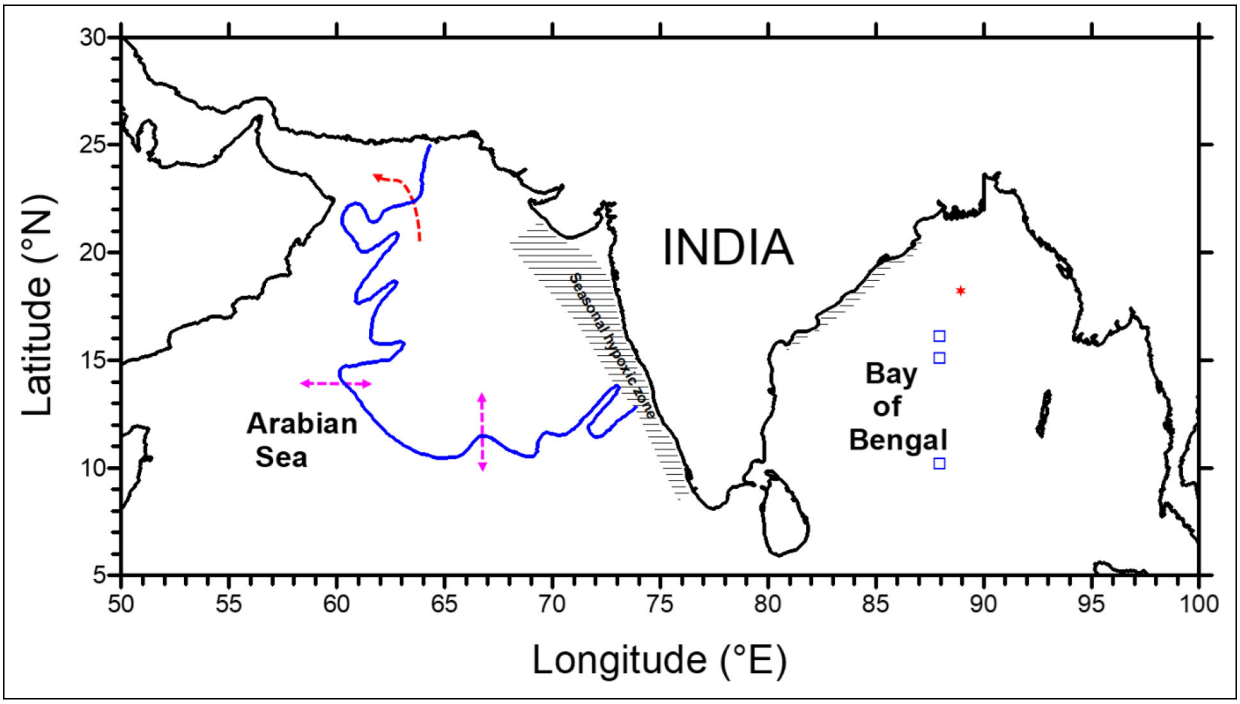

Figure 2. The Arabian Sea (AS) and the Bay of Bengal (BoB) both house low oxygen zones in the subsurface waters. The blue contour line demarcates 0.2 µM of secondary nitrite in the AS oxygen minimum zones (OMZs; Naqvi, 1991). The pink arrows show the seasonal changes in the AS OMZ as reported by Rixen et al. (2014) and Shenoy et al. (2020), whereas the red arrow indicates the northward expansion as reported by Lachkar et al. (2021). The shaded region shows the seasonal hypoxic zone in the Western Indian shelf (Naqvi et al., 2000) and Eastern Indian Shelf (Sarma et al., 2013a; Sarma et al., 2013b). The red star demarcates the station where secondary nitrite was detected by Bristow et al. (2017), and the blue squares are stations where Toyoda et al. (2023) observed high concentrations of N_2O in the BoB OMZ.

anammox (Jensen et al., 2011). The majority of the N-loss in the AS has been attributed to denitrification (Ward et al., 2009; Bulow et al., 2010) contributing to one-third of the global N-loss to the atmosphere (Naqvi et al., 2006; Ward et al., 2009; Jensen et al., 2011).

The intense OMZ and nitrite-bearing zone occurs in the northeastern AS associated with high primary production in the overhead and sinking fluxes to the depth (Naqvi, 1991; Morrison et al., 1999). While several theories have been put forth to explain this anomaly (McCreary et al., 2013 and references therein; Acharya and Panigrahi, 2016), through circulation, eddies, and transport of detritus from intense upwelling zone (off Oman) to east, using numerical models, there are no observational evidences are available. Recently, Sarma et al. (2020a) highlighted the role of cross-shelf transport of organic matter from the northwestern Indian shelf to the OMZ supporting its intensification using the backscatter data collected by Argo floats. However, the potential mechanism involved in transporting them and quantitative estimation of organic matter transported to the OMZ and its fate are unknown. Recent work has also shown the importance of AS high-saline water mass for supplying excess organic carbon and its possible role in sustaining the OMZ (Shetye et al., 2021). The interannual variability in OMZ is partly controlled by phytoplankton community composition and primary productivity due to ENSO events and biophysical coupling (Vidya and Kurian, 2018; Kurian et al., 2020; Chndrasekhararao et al., 2022).

While the first demarcation of the nitrite-bearing zone was carried out by Naqvi (1991), the first observation on the seasonality was reported by de Souza et al. (1996). Recent studies have also reported seasonal variations in the western (Rixen et al., 2014) and southern end (Shenoy et al., 2020) of the nitrite-bearing zone (**Figure 2**). Apart from the perennial OMZs in the NIO, the western continental shelf of India (WCSI) houses the world's largest seasonal hypoxic zone covering 180,000 km^2 during the southwest monsoon (SWM) (**Figure 2**). Earlier studies indicated that hypoxic conditions along the WCSI might have intensified due to eutrophication mainly induced by anthropogenic input (Naqvi et al., 2000). However, recent work suggested that the formation of the seasonal hypoxic-anoxic zone is a natural process initiated through upwelling of deoxygenated waters during the summer monsoon (Gupta et al., 2021). Using time-series data and modeling, Parvathi et al. (2017) demonstrated that a positive IOD prevents the formation of coastal anoxia, while a negative or neutral IOD are among the essential conditions for its formation.

Anoxic conditions in the water column cause accumulation of hydrogen sulfide (Naqvi et al., 2000) and production of high concentrations of radiatively important gases namely, nitrous oxide (N_2O; Naqvi et al., 2000), methane (CH_4; Shirodkar et al., 2018), and dimethylsulphide (DMS;

Bepari et al., 2020). Massive N-loss has been reported from the WCSI during the SWM (Naqvi et al., 2006; Bardhan and Naqvi, 2020; Sarkar et al., 2020) and accumulation of N_2O has been attributed to denitrification in the water column and sediments (Sudheesh et al., 2016), and also to chemolithoautotrophic denitrification (Pratihary et al., 2023). The emission of higher concentrations of radiatively important gases in this region has the potential to significantly contribute and modulate greenhouse gas budgets in the lower atmosphere. Thus, it is important to understand their long-term changes and feedback with processes at the air–sea interface.

Long-term variations of the strength of the OMZ and the denitrification in the AS have been debated in the literature and contrary statements can be found. Based on the available measured nonsystematic time-series dissolved oxygen (DO) data for more than 4 decades (1959–2004), Banse et al. (2014) reported a marked seasonality in the AS OMZ with higher oxygen concentrations during the northeast (NE) and spring intermonsoon than the SWM. The mean annual decrease in oxygen levels during NE and SWM seasons were -0.2 and -0.08 μM, respectively. Interestingly, the dataset also showed a statistically significant decrease of DO over 4 decades between 15°N and 20°N, but an opposing trend was noticed in the north of 21°N (Banse et al., 2014).

Based on the regional model, Lachkar et al. (2021) reported an expansion of the OMZ and attributed to the widespread warming of the sea surface resulting in a reduction in the ventilation of subsurface and intermediate layers (**Figure 2**). Recent observations in the Qatar exclusive economic zone revealed a decline in oxygen concentrations in the Persian (Arabian) Gulf over the past 4 decades accompanied by an expansion of seasonal near-bottom hypoxia (Al-Ansari et al., 2015; Lachkar et al., 2022). In contrast to regional models, the global models did not identify significant changes in the OMZ in the past several decades (Breitburg et al., 2018) and proposed the need for more observations to confirm the same. In recent years, modeling studies have revealed that the AS OMZ could shrink in the future due to an increased supply of DO from its southern boundary (Vallivattathillam et al., 2023).

The expansion of the OMZ can significantly influence nitrogen cycling, in particular the emission of nitrous oxide, which requires further evaluation. At the same time, decreasing oxygen concentrations in the northern AS have led to a regime shift in the pelagic ecosystem with dinoflagellates now dominating a usually diatom-dominated area (Rixen et al., 2020). As dinoflagellates are known to produce more DMS, it is paramount to assess the impact of such a regime shift on the production of DMS and their contribution to atmospheric aerosols from the region. The future of the OMZ intensity and expansion in the AS is largely unpredictable (Lachkar et al., 2023) in contrast to the other OMZs due to knowledge gaps with respect to ventilation, bacterial respiration, and supply of oxygen through water masses in the models. The biogeochemical feedback mechanisms such as iron inputs, N_2 fixation, and denitrification are neither well understood nor well represented in the models (Ulloa et al., 2012; Oschlies et al., 2019; Moffett and Landry, 2020; Wallmann et al., 2022). The biological production is one of the important processes that control the OMZ and its changes in the past and future were contrastingly represented. For instance, a decline in the primary production in the AS was reported due to warming and weakening of upwelling (Roxy et al., 2016; Kwiatkowski et al., 2020), whereas insignificant trends in net primary production were observed (Sridevi et al., 2023) except in the southwestern basin during summer, due to the compensation of nutrients through the atmospheric deposition. The variations in the circulation, including speed and direction of currents, are equally important on formation of the OMZ. Therefore, significant work needs to be carried out through time-series observations, moorings, and repetition of transect observation to understand behavior of OMZ and its possible changes in the future due to climate change.

The OMZ in the BoB is as intense as the AS OMZ, albeit it does not host a perennial nitrite-bearing zone (Sarma et al., 2016; Bristow et al., 2017). Recent DO data measured from the Argo-based sensors revealed significant spatial variability of OMZ's boundary and its thickness in the BoB (Udaya Bhaskar et al., 2021). The lower and upper boundaries of the OMZ were observed between 100–800 m and 60–200 m, respectively, with a thickness of 80–650 m in the BoB (Udaya Bhaskar et al., 2021). Associated with salinity stratification a thicker OMZ was found in the northern BoB when compared to the southern BoB. A thick and intense OMZ was found in the northwestern BoB region (with oxygen levels <1.5 μM) associated with strong salinity stratification and high primary production in contrast to the NE BoB region with higher oxygen concentrations (2.5 μM). Like in the AS, cross-shelf transport of organic matter was observed in the northern BoB that further supports the OMZ (Udaya Bhaskar et al., 2021).

Though earlier studies reported low primary production (Gauns et al., 2005) in the BoB, recent measurements of dissolved organic carbon (DOC) exudation rates indicate total primary production (particulate organic carbon production and DOC exudation) is almost same as in the AS (Rao et al., 2021). Such high primary production in the BoB is supported by organic nutrients (Sarma et al., 2021; Rao and Sarma, 2022). The weaker OMZ in the BoB was attributed to the ballast of organic matter in association with mineral particles (Ittekkot et al., 1992). Recent measurements using STOX (switchable trace oxygen) sensors suggested that oxygen levels in the BoB are at nano molar levels (Bristow et al., 2017) suggesting that ballast of organic matter may not be potential reason and OMZ is not weaker in the BoB. This is also supported by measurement by Kurian et al. (2023), which reported the sinking carbon fluxes at 430 m and found that only <5% of the primary production is sinking to the depth below. Though such low oxygen levels were observed (Bristow et al., 2017), maintaining such low oxygen levels for longer times may be unlikely due to the presence of anticyclonic eddies that ventilate oxygen from surface waters to the OMZ (Sarma et al., 2018; Sarma and Udaya Bhaskar, 2018). On the other hand, a recent study by Toyoda et al. (2023) reported an extensive accumulation of N_2O in the OMZ of the BoB and attribute to the archeal ammonia oxidation and denitrification in the micro-environment induced by riverine sinking particles during the monsoon and also raise the concern that the bay could be a source of N_2O to the atmosphere. The cross-shelf transport of organic matter (Udaya Bhaskar et al., 2021) may also bring sedimentary N_2O to the offshore region, however, there were no evidences to support. Considering the importance of air–sea interactions for the atmospheric gaseous budget, there is a need for sustained observations of climatically important gases in the low oxygen zones of the NIO.

2.3. Ocean biogeochemistry, air—sea exchange, and carbon cycling

The IO, particularly the NIO, is influenced by atmospheric forcing (monsoons), aerosol deposition, riverine outflow, as well as anthropogenic interferences. Associated interactions are complex and significantly impact surface water biogeochemical processes which include primary productivity, phytoplankton composition, and carbon dynamics. Recent observations and studies in the IO, that are highlighted in this section, significantly improved our understanding of the relevant biogeochemical processes.

The ocean–atmospheric exchange of CO_2, as well as changes in the surface ocean carbon system parameters are one of the least studied topics for the IO (Valsala et al., 2020; Chakraborty et al., 2021; Valsala et al., 2021), in particular for the southern IO (Valsala et al., 2012). The BoB is characterized by a high spatial and seasonal variability of CO_2 levels and the rate of ocean acidification (Sarma et al., 2012; Sarma et al., 2015; Sarma et al., 2021). Experimental studies assessing the impact of increasing CO_2 levels on phytoplankton communities in the BoB revealed that coastal communities show resilience to a short-term increase in CO_2 with enhanced carbon fixation rates and particulate organic carbon accumulation (Biswas et al., 2011; Biswas et al., 2012; Biswas et al., 2017). While the BoB acts as a sink for CO_2, the AS is a perennial source of CO_2 to the atmosphere due to upwelling and winter convective mixing (Valsala et al., 2013; Valsala and Maksyutov, 2013).

The prevalence of oligotrophy, in addition to change in pH, could potentially change the phytoplankton community and particularly low dissolved silicate availability, which could be one of the key players in a community shift. A series of experimental studies (Biswas et al., 2011; Biswas et al., 2012; Biswas et al., 2017; Shaik et al., 2017; Sharma et al., 2022a; Sharma et al., 2022b; Sharma et al., 2022c) have been published in the past years addressing the impacts of ocean acidification on natural phytoplankton communities. From all these studies, it is clear that the responses of natural phytoplankton communities to short-term and fast changes in pH/pCO_2 were highly diverse and species-specific. Moreover, the phytoplankton living close to the coastlines of both, the BoB and the AS, were more resilient and benefited from increased CO_2 supply. Some species of diatoms like Thalassiosira (Biswas et al., 2012; Biswas et al., 2017) and Chaetoceros (Shaik et al., 2017; Sharma et al., 2022a) exhibited higher resilience and growth rates indicating that they could be the species for future oceans. This higher resilience also explains their bloom development in the coastal waters as they adapt to a wide level of fluctuations in seawater pH even within a diel period.

The AS acts as a source of CO_2 and usually shows higher levels in many places, hence could act as a natural laboratory for ocean acidification experiments. In most of the experiments in the coastal (Sharma et al., 2022a) and shelf waters (Sharma et al., 2022c), as well as in the open ocean (Sharma et al., 2022b; Sharma et al., 2023), many diatoms showed enhanced growth in response to increasing CO_2 supply suggesting their pre-acclimatization to such conditions. Some genera/species did not change their growth rates at variable pH/pCO_2 levels indicating higher resilience (Sharma et al., 2022b). Multiple stressor studies, which include other abiotic factors like atmospheric dust, and trace metals (e.g., copper and zinc) showed that some species are resilient even under such combined stress conditions indicating their high potential to cope with increasing pollution levels. It should be noted that some pennate diatoms with the potential to produce toxins were prominent in many cases, and such community shifts could have some adverse biogeochemical consequences. In the open ocean region of the BoB, such studies have not been carried out and the responses of the plankton community are largely unknown. In this region, low salinity values along with increasing CO_2 may result in different outcomes compared to the AS, where high salinity persists. Nevertheless, the available results could be used for ecological modeling on a regional scale for predicting future responses.

Atmospheric extreme events, such as cyclones, depressions, and eddies as well as large-scale atmospheric variability such as the IOD and ENSO, significantly impact ocean biogeochemical processes in the NIO on shorter timescales of a few days to months. These events modify upper ocean mixing causing variations in nutrient input, temperature, primary production, and CO_2 fluxes (e.g., Sarma et al., 2015; Sarma et al., 2019). For instance, a cyclone can churn up the upper ocean and bring nutrients and CO_2-rich waters to the surface, which may enhance the CO_2 flux to the atmosphere. It can also lead to the absorption of CO_2 due to enhanced primary production, which would lead to a much smaller net impact of a tropical cyclone on CO_2 dynamics than believed previously (Lévy et al., 2012). Overall, previous investigations only covered snapshots of the full picture and therefore the average net impact of atmospheric extreme events is still unclear. The IO being a hub for such events, which are expected to increase in the future due to climate change (Swapna et al., 2022), underscores the need to study the impact of cyclones on biogeochemical processes in this basin.

In addition to decreasing pH, the increasing trend in SSTs (particularly in the mid-western AS; Roxy et al., 2015) has negatively impacted the overall primary productivity due to an enhanced stratification and restricted mixing that suppresses nutrient supply to the euphotic layers. In line with this, a comprehensive study covering a larger part of the IO from Dalpadado et al. (2021) confirmed an increasing warming trend in the last decade. Recently, Sridevi et al. (2023) noticed a decrease in net primary production in the southwestern AS and southeastern BoB. The absence of a significant trend in the northern AS and BoB may be due to an increased deposition of anthropogenic aerosols (Sarma et al., 2022) compensating for the deficit of nutrient input through vertical mixing caused by stratification (Sridevi et al., 2023).

Based on observations over the last decade, several researchers have highlighted frequent occurrences of heterotrophic dinoflagellate *Noctiluca* blooms during the NE monsoon concluding that it might occur during all seasons (do Rosário Gomes et al., 2014 and references therein). The occurrence of *Noctiluca* blooms is not new to the AS (Subrahmanyan, 1954), however, their seasonal occurrences were not well captured in previous studies. A comparison of the phytoplankton community observed during 1990 (Sawant and Madhupratap, 1996) in the boreal winter (December and January) with recent data collected during February, a community shift (diatoms to dinoflagellate) due to anthropogenic activities was reported (do Rosário Gomes et al., 2014). The isotopic studies using carbon and nitrogen did not reveal the contribution of anthropogenic inputs to the AS during winter (Sarma et al., 2019). Some studies have confirmed the succession of the bloom development from diatom to *Noctiluca* (Lotliker et al., 2018; Lakshmi et al., 2021; Sridevi and Sarma, 2022). Other studies, however, found contradictory results showing diatom-dominated phytoplankton bloom during summer monsoon comparable to earlier JGOFS data in the central (Chowdhury et al., 2021; Silori et al., 2021) and eastern AS (Albin et al., 2022; Chowdhury and Biswas, 2023). Two recent studies on the phytoplankton community structure in these regions highlighted the key role of the strength of monsoon winds in governing the phytoplankton community and cell size, which in turn control the intensity of the carbon export flux (Chowdhury et al., 2021; Chowdhury and Biswas, 2023). Importantly, the contribution of nanoplanktonic coccolithophores to the total phytoplankton community from the western Indian shelf waters has also been highlighted recently (Chowdhury et al., 2022; Shetye et al., 2022). As these calcifiers significantly modulate the calcium carbonate pump, their role in carbon transport to the sediment needs to be evaluated.

A special feature of the IO is relatively high atmospheric deposition of aerosols which controls the surface biological processes (Banerjee and Kumar, 2016; Bange et al., 2024 and references therein). Over the last 2 decades, the northern IO experienced the globally highest rate of aerosol increase (Lotliker et al., 2018; Lakshmi et al., 2021; Sridevi and Sarma, 2021; Yadav et al., 2021; Sridevi and Sarma, 2022). Several cruise-based campaigns have been undertaken in the NIO (Tindale and Pease, 1999; Kumar and Sarin, 2010; Srinivas and Sarin, 2013; Aswini et al., 2020; Bikkina et al., 2020; Panda et al., 2022 and references therein) to evaluate the chemical composition of aerosols and their possible sources. These studies highlighted the dominance of mineral dust (derived from surrounding arid/semi-arid and desert regions) and anthropogenic aerosols (derived from fossil fuel combustion and biomass burning) in both basins (Bange et al., 2024).

Large-scale mineral dust transport from the Arabian Peninsula and Northeast Africa has been reported during the SWM over the AS (Suresh et al., 2021; Aswini et al., 2022) while anthropogenic-rich aerosols are dominant in both basins during the NE monsoon when the continental outflow is maximum (Kumar et al., 2010; Bikkina et al., 2020; Nayak et al., 2022). Based on measured reactive nitrogen (inorganic nitrogen, IN) in aerosols and anthropogenic aerosol optical depth, atmospheric input of IN to the AS (1.7 TgN per year) and BoB (0.9 TgN per year) were estimated, contributing together approximately 30% of the total external sources of nitrogen to the NIO (Sarma et al., 2022). The contribution of atmospheric sources of total nitrogen may be much higher if organic nitrogen is also taken into account. Organic components (nitrogen, phosphorus) of aerosols over the IO are almost unknown in terms of their quantities as well as temporal variations. An important knowledge gap is the currently unconstrained macronutrient budget and its impact on the surface water biogeochemistry. The new production, supported by external sources of nitrogen (mainly IN), contributes about 23% and 53% of export production to the AS and BoB, respectively (Sarma et al., 2022).

Long-term studies in the northwestern coastal BoB revealed that rapid acidification of coastal waters has occurred due to the deposition of atmospheric aerosols (Sarma et al., 2015; Sarma et al., 2021). Very few studies have reported on the trace metal distribution over the IO, particularly from the NIO (Srinivas and Sarin, 2013; Panda et al., 2022 and references there in). Relatively high dry deposition fluxes of Fe, Mn, and Cu (757, 38.8, and 1.4 $\mu g\ m^{-2}\ day^{-1}$, respectively) to the AS surface waters with high fractional solubility were detected during SWM campaigns (Panda et al., 2022). These observations, although being only a snapshot, provide new insight to the solubility behavior of trace elements and thus underscore the need for more observations at varying spatial and temporal scale. In recent years, pyrogenic Fe, which is mainly derived from biomass burning emissions and other anthropogenic activities, has been found to contribute significantly to the soluble Fe budget (Hamilton et al., 2022). In case of the IO and particularly the BoB, emissions from the agricultural residue burning from the Indo-Gangetic Plains could be a potential supplier of soluble Fe (Kumar et al., 2010). Therefore, more observations need to be initiated over the Indo-Gangetic Plains, focusing on the quantification of mineral dust associated trace metals and their solubility as well as radiogenic isotope signature of dust. Recent dust flux estimates over the NIO (Panda et al., 2024) show a good agreement with previous model-based flux estimates by Grand et al. (2015) ($2.5 \pm 0.5\ g\ m^{-2}\ year^{-1}$), Jickells et al. (2005) ($2–5\ g\ m^{-2}\ year^{-1}$), and Mahowald et al. (2005) ($3 \pm 1\ g\ m^{-2}\ year^{-1}$). However, dust flux over the equatorial IO region is overestimated by a factor 5 ($2.5 \pm 1.8\ g\ m^{-2}\ year^{-1}$) to 2 ($1.1 \pm 0.1\ g\ m^{-2}\ year^{-1}$) compared to model estimates ($0.5 \pm 0.08\ g\ m^{-2}\ year^{-1}$; Grand et al., 2015). The latter are impacted by model uncertainties and the large variability of aerosol composition and solubility (Grand et al., 2015) highlighting the need for measurements to evaluate the model-performance for the IO. In the absence of real-time aerosol deposition data along with accurate river discharge data, biogeochemical models fail to reproduce actual CO_2 fluxes (Sarma et al., 2023).

2.4. Greenhouse gases and pollution over the IO

Trace gases and their air–sea exchange play an important role for the IO regarding atmospheric chemistry, oceanic processes, chemistry–climate interactions, and stratospheric composition. Therefore, their spatial and temporal distributions, in both the lower atmosphere and upper ocean, as well as the parameters that control their distributions and fluxes must be understood. Synergies of in situ measurements (shipborne, balloon borne, and aircraft based), remote sensing observations (satellite and ground-based), and modeling (regional and global) have improved our understanding of pollutants and greenhouse gases (GHGs) over the IO and associated atmospheric chemistry and dynamics (Tegtmeier et al., 2022; Bange et al., 2024 and reference therein). In this section, the main characteristics of various pollutants, GHGs, and short-lived gases are discussed together with current knowledge gaps. As an illustrative example, surface CO and CH_4 distributions during the winter and post-monsoon seasons are based on 2018 (Girach et al., 2020) and 2010 (Mallik et al., 2013) ship-based measurements, respectively; recent (2019) satellite observations (MOPITT—Measurements of Pollution in the Troposphere; GOSAT—Greenhouse Gases Observing Satellite); and CAMS (Copernicus Atmosphere Monitoring Service) model reanalysis are shown in **Figure 3**. Pollutants and GHGs exhibit relatively higher concentrations over the northern IO as compared to the southern or equatorial IO, as seen here for CO and CH_4, primarily due to transport from continental sources, that is, fossil fuel and biomass burning (Girach et al., 2014; Girach and Nair, 2014; Chandra et al., 2016; Sahu et al., 2019). For CO, higher levels exist not only at the surface (up to 450 ppbv) but also in the upper boundary layer (up to 300 ppbv at 0.75 or 1.5 km) over the southeast BoB during winter owing to the influence of biomass burning over Southeast Asia (Srivastava et al., 2012). Similar to CO, the variability of surface O_3 is relatively well known. The latter is driven by various factors such as outflow from South and Southeast Asia, en route and in situ photochemical production, losses due to HO_x and halogen chemistry, vertical transport, boundary layer processes, and cyclone-induced stratospheric intrusion (e.g., Mallik et al., 2013; Das et al., 2016a; Das et al., 2016b; Girach et al., 2017; Ajayakumar et al., 2019; Mahajan et al., 2019a; Mahajan et al., 2019b; Girach et al., 2020b, Inamdar et al., 2020; Mahajan et al., 2021; Soni et al., 2022).

For most trace gases, only a few in situ observations are available over the IO. One example is NO_2, for which higher mixing ratios have been found over coastal regions (approximately 1.2 ppbv) and shipping lanes (up to 4 ppbv) compared to background values of 0.05–0.2 ppbv (Takashima et al., 2012; Georgoulias et al., 2020). Satellite observed NO_2 over international shipping lanes has been demonstrated to be a tracer of global economic changes (de Ruyter de Wildt et al., 2012). Maritime shipping is known to emit also other pollutants including formaldehyde (HCHO) which has been found to be nearly twice as high along the major IO shipping lanes when compared to background levels (Gopikrishnan and Kuttippurath, 2021). Another example of limited in situ data is the pollutant SO_2, for which the few available observations suggest higher levels over the northern IO with prominent enhancements (0.05–0.15 DU) around the coastal regions and over volcanoes (Sarma et al., 2012; Chutia et al., 2022). Such elevated SO_2 abundances near active volcanoes could play a role in forming the recently discovered OH minimum in the eastern BoB during boreal spring (Kuttippurath et al., 2023).

Air–sea exchange impacts many trace gases over the IO such as CH_4, CO_2, N_2O, and volatile organic compounds (VOCs). Upwelling over the northern IO brings CH_4 (diffused from underlying sediments) up to the surface, which subsequently leads to sea-to-air CH_4 flux (Naqvi et al., 2010) in addition to strong continental sources. An important characteristic of atmospheric CH_4 is the seasonal variation of approximately 150 ppbv in the boundary layer (Kavitha et al., 2018), with model simulations suggesting that these are not present above 750 hPa (Guha et al., 2018). Overall CH_4 belongs to the group of rather understudied gases over the IO with surface satellite observations being uncertain (Girach et al., 2018) partially due to frequent cloudy conditions. For CO_2, another important GHG, variability in surface ocean partial pressure over the IO is mainly driven by SSTs with minor influence from the dynamics of dissolved inorganic carbon (Valsala and Murtugudde, 2015). The increasing level of CO_2 over the IO can change the intensity of IOD which has pronounced impact worldwide, including on the Indian summer monsoon (An et al., 2022).

Trace gas emissions from oceanic ecosystems are a major contributor to atmospheric VOCs over the IO, especially in the AS where high biological productivity prevails mainly due to upwelling and the influence of dust deposition (Singh and Ramesh, 2015; Guieu et al., 2019). The emissions through biogeochemical processes and sea-air exchange are influenced by incoming solar radiation, SST, wind speed, and microbial sources. Elevated levels of isoprene (i.e., the most abundant natural VOC) and alkenes are linked with higher chlorophyll-*a* (proxy for algae biomass) and phytoplankton species in seawater over the AS, which is an intense OMZ (Tripathi et al., 2020). According to the latest DMS climatology (Hulswar et al., 2022), the IO is one of the worldwide hotspots for DMS fluxes throughout all seasons. An interesting aspect of this updated climatology is that the DMS seawater concentrations and subsequent air–sea fluxes are less than those reported in the previous climatology (Lana et al., 2011), highlighting the uncertainty resulting from the IO being under sampled for DMS.

Relatively more O_3 and CO observations are available, however, surface observations of NO, NO_2, SO_2, NH_3, CH_4, CO_2, isoprene, monoterpenes, and other VOCs are very limited. Hence new in situ measurements and subsequent extensive studies combining observations with modeling exercises and satellite retrievals are highly desirable to

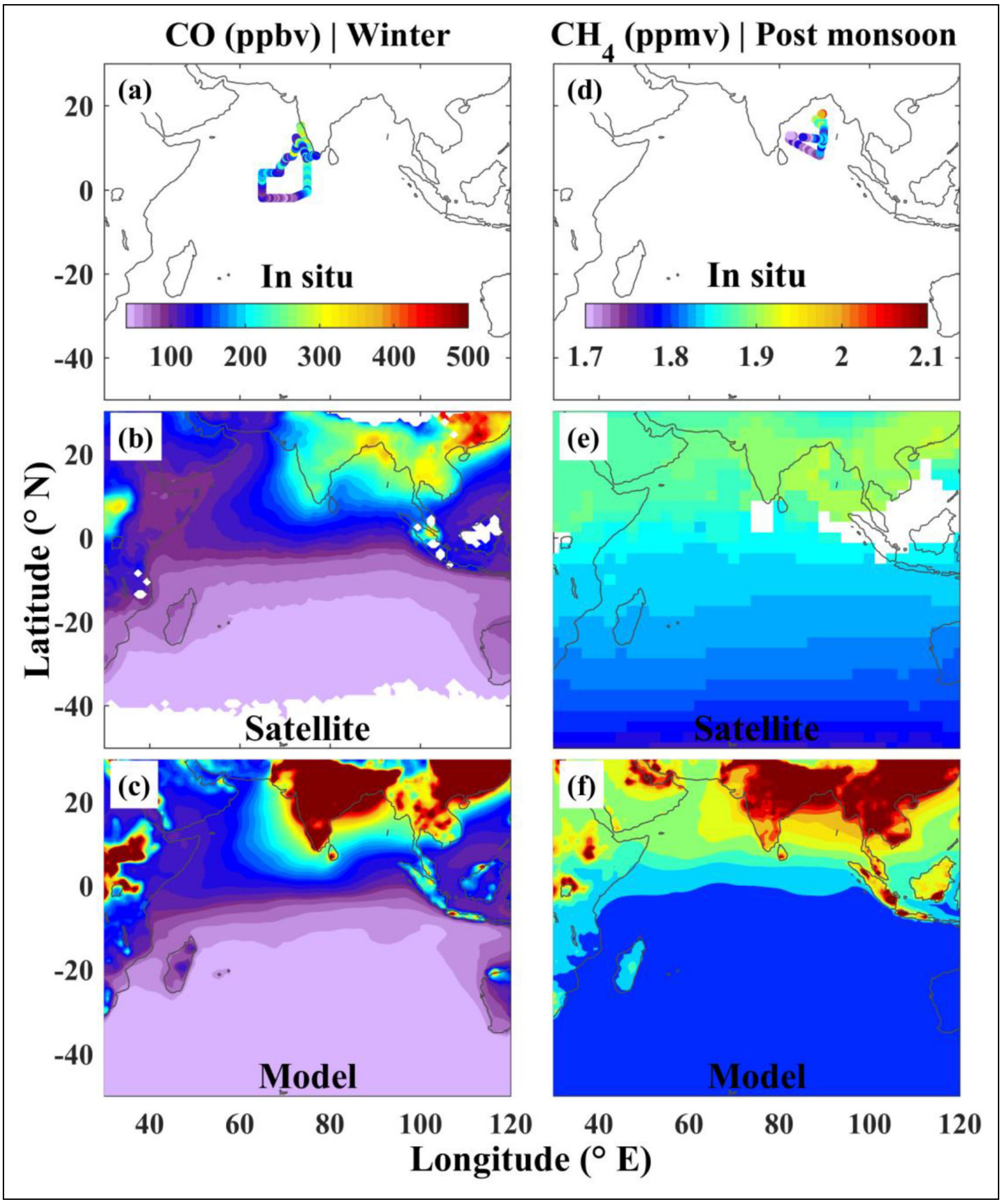

Figure 3. Spatial distribution of an air pollutant, CO, and a greenhouse gas, CH_4, during pre-winter and post-monsoon season over the Indian Ocean, respectively. The datasets are based on in situ observations (Girach et al., 2020 [a], Mallik et al., 2013 [d]), satellite observations (MOPITT [b], GOSAT [e]) and reanalysis output (CAMS [c], [f]). Shown are the surface or boundary layer mixing ratios, except figure [e] which is a tropospheric average.

address some of the following knowledge gaps: (a) Radical concentrations, O_3 formation, and biogeochemical fluxes of O_3-precursors; (b) Modifications of fluxes of CO_2 and hydrocarbons including VOCs by marine heatwaves (Mignot et al., 2022); (c) Chemical transformation of DMS to SO_2; (d) Gas-to-particle conversions (e.g., SO_2 to sulfate aerosols) and heterogeneous chemistry; (e) Deposition of pollutants to the sea surface and subsequent impact on the production/consumption of other trace gases in the sea surface and their air–sea exchange. Finally, long-term trends of many gases over the IO are not well known and often only poorly understood. For instance, despite increasing CO emissions as seen in the inventories, satellite, and in situ measurements suggest a declining trend in the surface CO (0.7% $year^{-1}$) over the northern IO (Worden et al., 2013; Girach et al., 2020a). Challenges of improved satellite retrievals of pollutants and GHGs over the ocean, especially under frequent cloudy conditions, need to be addressed for better characterizations of short- and long-term variability.

3. Interdisciplinary efforts and future recommendations to address the processes linked with SOLAS

The IO plays a key role in regional as well as global climate and is one of the most interesting areas to understand ocean–atmospheric interactions that have a pivotal role in biological productivity. The positive trend in SSTs of the IO with pronounced spatial variability (Roxy et al., 2014 and references therein) leads to several questions about the future responses of the biological systems and fisheries, as well as the climatic feedback. Since a significant area of the IO, particularly the NIO, fall within exclusive economic zones, a strong collaboration among the IO rim countries would be beneficial for answering these questions.

One of the major impediments in this research area is the limited IO observing system with poor instrument coverage over space and time. This shortcoming could be addressed by increasing the number of instruments that measure critical parameters including nutrients, pH, oxygen, and fluorescence, such as Bio-Argo floats with an enhanced number of sensors. Argo floats deployed in the southern IO have added to our understanding of seasonal/interannual variability of environmental variables such as subsurface ocean temperature, salinity, and chlorophyll (Masuda, 2020; Prakash et al., 2020), however, there is a dearth of observational data such as on nutrients, their transformation mechanisms, interactions between the abiotic and biotic components in the region, as well as in situ production and air–sea exchange of climate-relevant gases. Therefore, more continuous collaborative efforts are required from the observational scientist to generate such comprehensive datasets. These datasets could be used for basic research on biogeochemical aspects and for the evaluation or as boundary conditions for regional general circulation or biogeochemical models. Combining such new observations with recent advances in atmospheric dynamics and modeling can improve our understanding of the impact of extreme events on ocean biogeochemistry.

Quantifying ocean–atmosphere interactions at interannual to interdecadal timescales, understanding their influences on regional monsoon patterns, and attributing them to natural variability or anthropogenic forcing is an ongoing challenge, mainly due to the lack of high-resolution long-term observations of dynamical variables (Beal et al., 2020). Further, widely used SST datasets can use statistical methods to fill gaps between sporadic observations for constructing ocean temperature products, without explicitly involving subsurface oceanic processes that are crucial for representing the IO variability at interannual and climate timescales (Yang et al., 2020). Hence, comprehensive observations that better-resolve upper ocean processes and numerical models that incorporate these processes are critical for an improved understanding of ocean–atmospheric coupling and prediction of monsoon variability. Long-term monitoring and high-resolution modeling of the critical processes of the near-surface ocean, including diurnal mixed layer and barrier layer variability are highly recommended future exercises to meet the need for improved monsoon forecasting.

Considering the present trends of global change, it is pertinent to understand whether the AS-OMZ has expanded and intensified over the last few decades, and whether the BoB-OMZ will turn into a denitrifying zone in the future. The influence of the increasing peripheral human population on the cycling of carbon, nitrogen, and sulfur and the resultant impact on the ecosystem needs to be understood. Precise measurements of DO (using STOX sensors) are required to understand its seasonal variability and the redox transformations of nitrogen, sulfur, iron, and iodine as well as links to the sustenance of OMZ. As microbes play an important role in redox transformations, in-depth understanding of microbial ecology, including transcriptomics of the OMZ, needs to be a key element of future research. Studies in coastal regions focusing on the impact of anoxic and sulphidic conditions on primary and secondary producers are needed to understand the potential impact on fisheries. All these studies will require a dedicated platform for long-term observations and comparisons with other OMZs around the World.

Numerical models do not use real-time river discharge data to simulate biogeochemical processes in the BoB resulting in significant differences in the processes observed and simulated (Sarma et al., 2023). Trends in primary productivity are known to be impacted by the supply of nutrients from the atmosphere, submarine groundwater, and nitrogen fixation (Sridevi et al., 2023). Dissolved organic nutrients, DOC exudation, atmospheric deposition of nutrients, and the role of eddies for the supply of nutrients and oxygen ventilation are often not included in global models. Therefore, prediction of future changes of the OMZs or any other biogeochemical processes are questionable and significant improvements in the numerical models are warranted.

Biogeochemical and biological processes in the IO can also be altered by atmospheric deposition of particles, air-sea exchange of trace gases, as well as extraneous input of nutrients and toxic substances leading to potential climate feedbacks. Dedicated collaborations between atmospheric scientists studying aerosol-trace gas interactions and oceanic biogeochemists are needed to better understand the impacts of atmospheric pollution, dust and nutrients on the IO's biogeochemistry, and trace gas cycling. Considering relatively short lifetime of aerosols and other trace gases, large number of ship-based campaigns on varying seasons with large spatial converge should be undertaken for collection of aerosols as well as in situ and/or on-board measurements of atmospheric species. Model output of trace gases and aerosols over the IO should be compared with the observations in order to evaluate the representation of associated processes in regional and global models. Trace gas emissions, their conversions to aerosols and impact on clouds as well as feedbacks on ocean biogeochemistry are extremely important. This calls for extensive collaborations among researchers working on microphysics of aerosols as well as clouds, chemistry of trace gases, and biogeochemistry of the ocean.

The sources and distribution of macronutrients associated with organic phases and their role in biological processes are hardly known in the IO region except for a few reports (Shetye et al., 2019; Rao et al., 2021). Recent biogeochemical models have shown a substantial increase in nitrogen fixation when organic nutrients were considered (Hamilton et al., 2022). Thus, emphasis should be given toward the measurement of organic components (nitrogen, phosphorus) in aerosols in the IO region. Aerosol pH is another important factor which plays a major role for the availability of nutrients from aerosol deposition. Thus, the quantification of aerosol acidity along with nutrients are equally important to assess the relative roles of various processes (source, transport, and chemical transformation) affecting nutrient abundance over the IO. In general, aerosol pH is estimated using thermodynamic equilibrium models (e.g., ISORROPIA), which require the particulate and gas phase composition of ambient atmosphere as input parameters (Shukla et al., 2023). Simultaneous measurements of aerosol chemical species and trace gases are highly recommended as they will provide more robust information on the aerosol pH and other factors controlling nutrient availability over the IO region. Another important source of uncertainty in the atmospheric nutrient supply are the deposition rates and velocities associated with varying particle sizes. Measurements of the latter over the Ocean are difficult and prone to problems of temporal and spatial variability. A promising approach is the use of natural radionuclides (^{7}Be) delivered to the ocean from the atmosphere. Simultaneous measurement of ^{7}Be in seawater and aerosols will be helpful in constraining the deposition velocities and reducing uncertainties in nutrient flux estimations over the IO.

Microcosm experiments conducted to evaluate the impact of atmospheric aerosols on coastal and open ocean waters revealed a variety of changes in their biogeochemical features including surface water pH, primary productivity, and phytoplankton composition (Kumari et al., 2021; Kumari et al., 2022; Sharma et al., 2022b). Several published studies indicated the significant impact of aerosols on surface ocean biogeochemistry, while most of the data on aerosol composition come from field surveys that provide only snapshot information. The impact of aeolian dust supply on the surface ocean biogeochemical processes, including primary productivity, is important on daily to seasonal timescale. More insight can be gained via micro and mesocosm experiments, in particular at regional scales. However, only a very few experiments have been reported for the IO region. Efforts should be put into a higher number of laboratory and onboard simulation experiments to identify processes and ecology parameters that impact surface water biogeochemical processes.

Within the IO, the equatorial and southern part of the IO are the least explored regions in terms of observational and modeling studies related to SOLAS processes. A series of comprehensive measurements and research initiatives are crucial in order to unravel the complex interaction of physical, chemical, and biological processes in this remote area. Understanding the biogeochemistry of the Southern IO is not only essential for advancing our knowledge of global ocean dynamics but also for constraining the global biogeochemical cycles of carbon as well as macro- and micronutrients. It is imperative that we prioritize scientific exploration and measurement campaigns in this region to address the critical gaps in our understanding of its ecosystems and their interactions with the Earth's climate system.

4. Summary

This article provides a synthesis of observational and modeling results for the IO region related to SOLAS processes and obtained over the last 10 years. The significant increase in the number of observational as well as modeling studies found for this time frame has contributed to a better understanding of the atmosphere-oceanic coupled processes in this basin. Some of the key findings are summarized as follows:

1. Mesoscale events like IOD play a crucial role for the teleconnection between the ENSO and the Indian monsoon. When positive IOD events co-occur with El Niño events, the IO conditions act to counter El Niño's drought-inducing subsidence by enhancing moisture convergence over the Indian subcontinent, resulting in an average monsoon season.
2. One of the niche areas of the IO is the seasonal and perennial OMZs in the AS and possibly in the BoB. Modeling and observational results from the last decade suggest an expansion of the OMZ at the northern part of the AS, which is attributed to the widespread surface warming causing a reduction in the ventilation of subsurface and intermediate layers. The seasonal hypoxic-anoxic zone in the WCSI is primarily driven by the natural process of upwelling of deoxygenated waters during the summer monsoon. Oxygen data from the Argo-based sensors has shed new light on the seasonal variability of low oxygen zones in the BoB, which are mainly controlled by stratification, primary and export productions, organic matter decomposition, and eddy-driven mixing.
3. Ocean acidification experiments in the NIO revealed that the responses of natural phytoplankton to short-term and fast changes in pH/pCO_2 are highly diverse. Species-specific responses were found with phytoplankton living close to the coastline being more resilient and benefiting from enhanced acidification. In addition, the impact of decreasing pH with increasing SSTs on primary productivity is significant in the southwestern AS and southeastern BoB, but not in the northern parts of the 2 basins. The missing trend in the northern parts may be attributed to an increased deposition of anthropogenic aerosols compensating for the deficit of nutrients input through vertical mixing caused by stratification.
4. Significant advancements have been made in measurements of aeolian nutrient supply over the IO, particularly in the NIO, which may be considered as baseline information necessary for the regional and global scale models. The real-time flux measurements are far off from the model simulated output, particularly in the equatorial and southern part of the IO, suggesting the need for a large number of campaign-based observations in future.
5. Atmospheric pollutants and GHGs exhibit relatively higher concentrations over the northern IO as compared to the southern or equatorial IO primarily due

to transport from continental sources, that is, fossil fuel and biomass burning.

6. Trace gases like SO_2 show enhanced abundances near coastal and volcanic regions, while some pollutants (e.g., HCHO, NO_2) display clearly increased concentrations along the major IO shipping lanes. Recent observations highlighted that IO is one of the worldwide hotspots for DMS fluxes throughout all seasons.

Despite all efforts over the past decade, there are significant knowledge gaps and major research question that need to be addressed in the near future. Although there is a plethora of studies for the NIO, almost negligible work has been reported for the southern part of the IO. More observational studies in the southern region of the IO should be a major research focus for the future. In addition, long-term dedicated, observational time-series of physical, chemical, and biological parameters in the IO are necessary for addressing some of the most pressing research questions. These observations should be undertaken in a collaborative effort from all Rim countries surrounding the IO, which is important for their economic and sustainable development.

Data accessibility statement

All data used in this review article are published and the source of data have been indicated through article citation. All data are available in public domain.

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Competing interests

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Author contributions

All authors have approved the submitted version for publication: AK, ST, and SOF drafted the chapter outline and each one coordinated writing for different sections. MKR wrote Section 2.1. SOF coordinated writing of Section 2.2 with inputs from DMS, SK, and VVSSS. AK coordinated writing of Section 2.3 with inputs from HB and VVSSS. ST coordinated writing of Section 2.4 with inputs from IG and CAM. AK and ST wrote Abstract, Introduction, Conclusion, Section 3 with input from CAM, IG, and other coauthors. All the coauthors have commented during revision of the manuscript.

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