Regional contrasts in surface pCO_2 across Northern, Central and Southern Bay of Bengal

Louwin Anand D[1*], Ayyapan Saravankumar[1]

CAS in Marine Biology, Annamalai University, Faculty of Marine Sciences, Cuddalore, Tamil Nadu, India

Correspondence: louwinanand@gmail.com

Abstract

The Bay of Bengal (BoB) regulated by monsoonal seasons, driven by monsoonal winds, hydrography and riverine inputs responsible for the carbon equilibrium in ocean. In the present study, spatio-temporal variation of pCO_2 dynamics across Northern, Central and Southern BoB region assessed during the years 2022-2024. From the pCO_2 generated image, Northern BoB exhibited with higher pCO_2 values (upto ~450µatm) compared to Central and Southern regions. Post-monsoon and pre-monsoon resulted with pCO_2 enriched season attributed to the huge load of freshwater-discharge via Ganges-Brahmaputra system, enhanced solubility under reduced salinity and monsoonal upwelling which aids in transport pCO_2 enriched subsurface water to the surface. In contrast, summer season resulted with low pCO_2 levels (~221 to 285 µatm), mainly responsible due to elevated Sea Surface Temperature (SST), thus facilitates strong thermal stratification and inhibits the vertical mixing. The Central and Southern BoB regions exhibited more low and stable values mainly driven by East Indian Coastal Current (EICC) and South-west Monsoon current (SMC). The observed findings highlight the collaborative role of physical, chemical and biological process shaping the pCO_2 variability in regional carbon dynamics. The long-term monitoring is adequate to understand the global carbon cycle under climate change conditions.

Keywords: pCO_2 variability, CO_2 solubility, riverine flux, EICC, upwelling

1.Introduction

The ocean acts as ocean sink basin for about 25% of anthropogenic CO_2 annually (Sabine et al., 2004, Takahashi et al., 2009; Le Qu´ er´ e et al., 2018). This sequestering process results with the CO_2 levels present in the atmosphere (Sabine et al., 2004). Since the ocean sequester a atmospheric CO_2, the CO_2 exchange varies with space and time. The air-water CO_2 flux (fCO_2) is primarily governed by the CO_2 transfer velocity (k) and surface patrial pressure of CO_2 (pCO_2), together determines the efficiency of source and sink of capacity (Liu et al., 2022; Shen et al., 2023). The exchange among the CO_2 solubility pump, carbonate and biological pump can further modulate the conversion process of Dissolved Inorganic Carbon (DIC), thereby drive the sources and sink in aquatic ecosystem (Akhand et al., 2022).

The increased rate of acidification near coastal region reported to the various anthropogenic activities that modifies the carbonate chemistry in aquatic ecosystem (Doney, 2009; Cai et al., 2011,2020; Hall et al., 2020). Several factors which are responsible for the ocean acidification are atmospheric pollutants deposition via sulphate and nitrate aerosols attributed to the fossil fuel burning specifically in urbanized regions (Mackenzie et al., 1995; Schlesinger, 1997; Doney et al., 2007). Several recent studies reported that continental shelf considered as the sink basin (Laruelle et al., 2018). The south China sea, considered as the weak source (Dai et al., 2013, Zhai et al., 2013) and eventually turned out to be the atmospheric CO2 sink (Li et al., 2020). Although understanding the carbon dynamics and assessing surface pco2 trends relatively vital due to the lack of in-situ pCO2 measurements, which possess the challenge in pco2 estimation (Borges, 2005, Anderson, 2005, Anderson, 2010).

The present study explores the spatial variability of fCO_2 in the BoB region. The BoB region found unique due to its seasonal reversing and semi enclosed area with an opening in the south (Sheteye., 1996). The regions receive higher freshwater influx from major riverine inputs from Ganges-Brahmaputra (Unesco, 1969) and heavy precipitation. The BoB region experiences two distinct regions including Southwest Monsoon (June- September) and Northeast Monsoon (December - February) driven by north-westerly winds. Along with the monsoon and major river system, delivers the major freshwater input in BoB, thus influence the physical characteristics hence altering the carbon dynamics (Joshi et al., 2021). The study reported by Muraleedharan and Prasannakumar, (1996), suggests that the BoB coast acts as atmospheric CO_2 sink due the increased biological productivity facilitated by the nutrients derived from river-runoff, thus diminishes the surface pCO_2 values. Notably, the rate of pCO_2 increase along with southwestern BoB coast align with global average of approximately 1.5uatm.yr^{-1}, meanwhile, northern coast demonstrated 3-5 times higher at 6.7uatm.yr^{-1} (Sarma et al., 2015). The accelerated increase in northern BoB associated with increased deposition of sulphate and nitrogen aerosols during winter and spring months. The seasonal reversing coast currents such as East Indian Coastal Current (EICC) and West Boundary Current (WBC) responsible for the variations of hydrographic characteristics (Sarma et al., 2019).

Several studies examined the pCO_2 variability in BoB region across space and time. The present study aims to investigate the pCO_2 distribution with spatial and temporal variation in BoB regions subdivided into Northern, Central and Southern BoB regions with relation to SST and chl-a by integrating satellite images. This provides new insights into the carbonate dynamics of this climatically significant region and its role in regional and global carbon budgets.

2. Material and Methodology

The satellite derived pCO_2 maps were generated using the empirical algorithm proposed by Shanthi et al, (2016). Monthly SST and chl-a products were obtained from MODIS-Aqua satellite datasets. All graphical representation and visualizations were demonstrated using R studio. For regional assessment, the BoB region was sub divided into Northern, Central and Southern sectors to evaluate the pCO_2 variability in relation to distinct hydrographic and biogeochemical characteristics of subregions.

pCO_2 algorithm

$$pCO_2 = 1025.682 - 7.7794 * SST + 6.0874 * chl - 0.5777 * SST^2 + 19.9015 * chl^2$$

Where, pCO_2= Partial pressure of Carbon-di-oxide, SST = Sea Surface temperature, chl = Chlorophyll concentration

The BoB region is sub categorized in to Northern, Central and Southern BoB based on the study carried out by Feng et al, (2022) and Cui et al, (2024), shown in Fig.1.

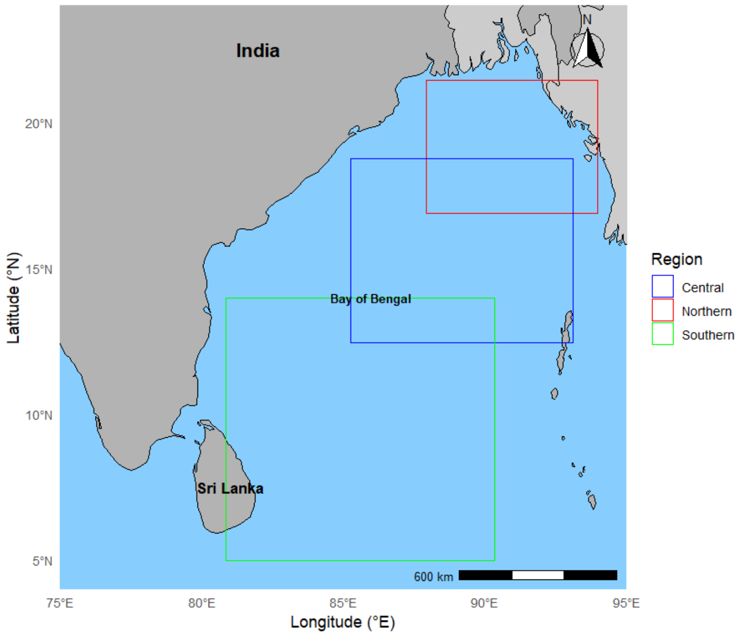

Fig.1 Map showing study area

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3.Results

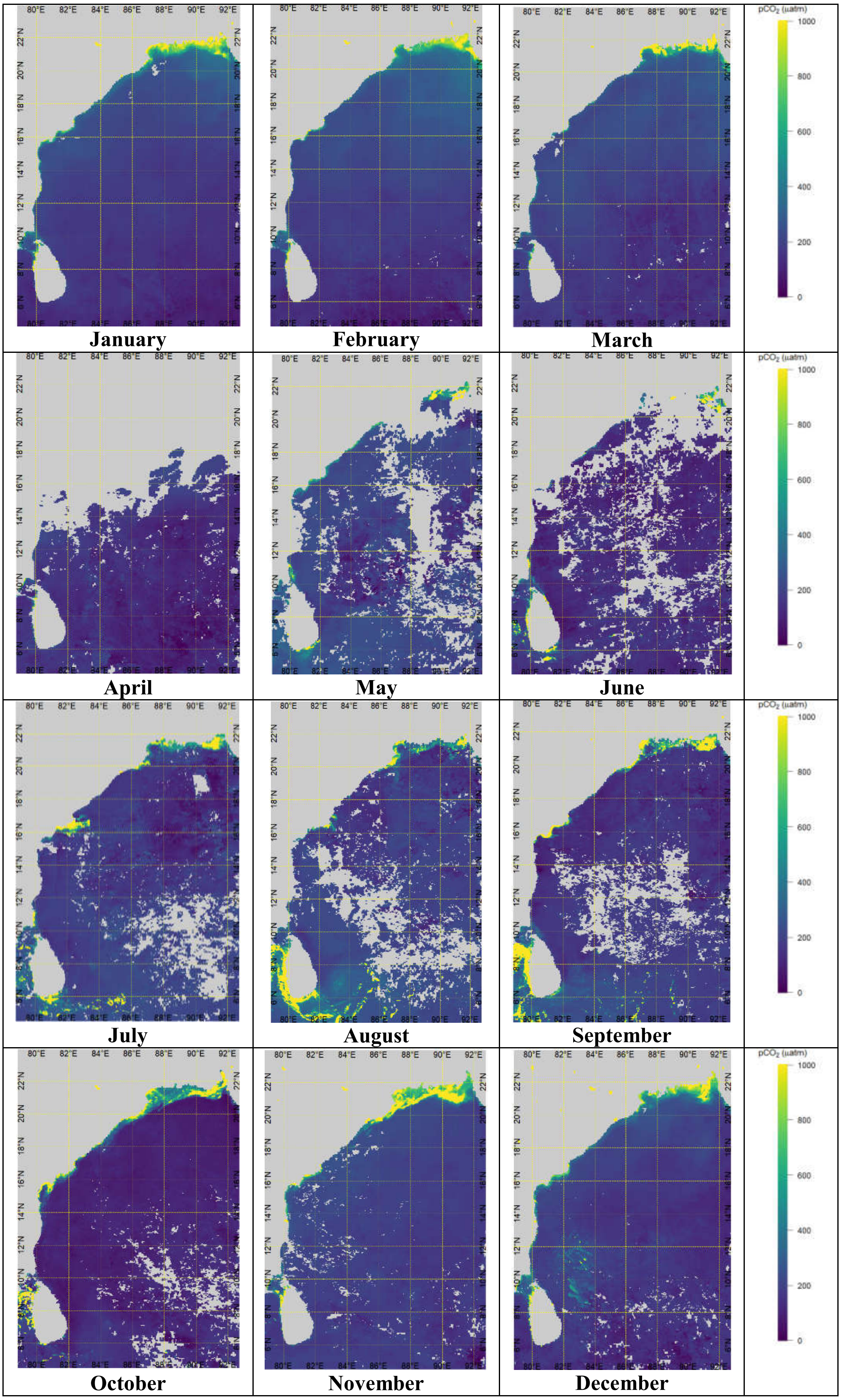

Fig.2 Monthly pCO_2 variation during the year 2021

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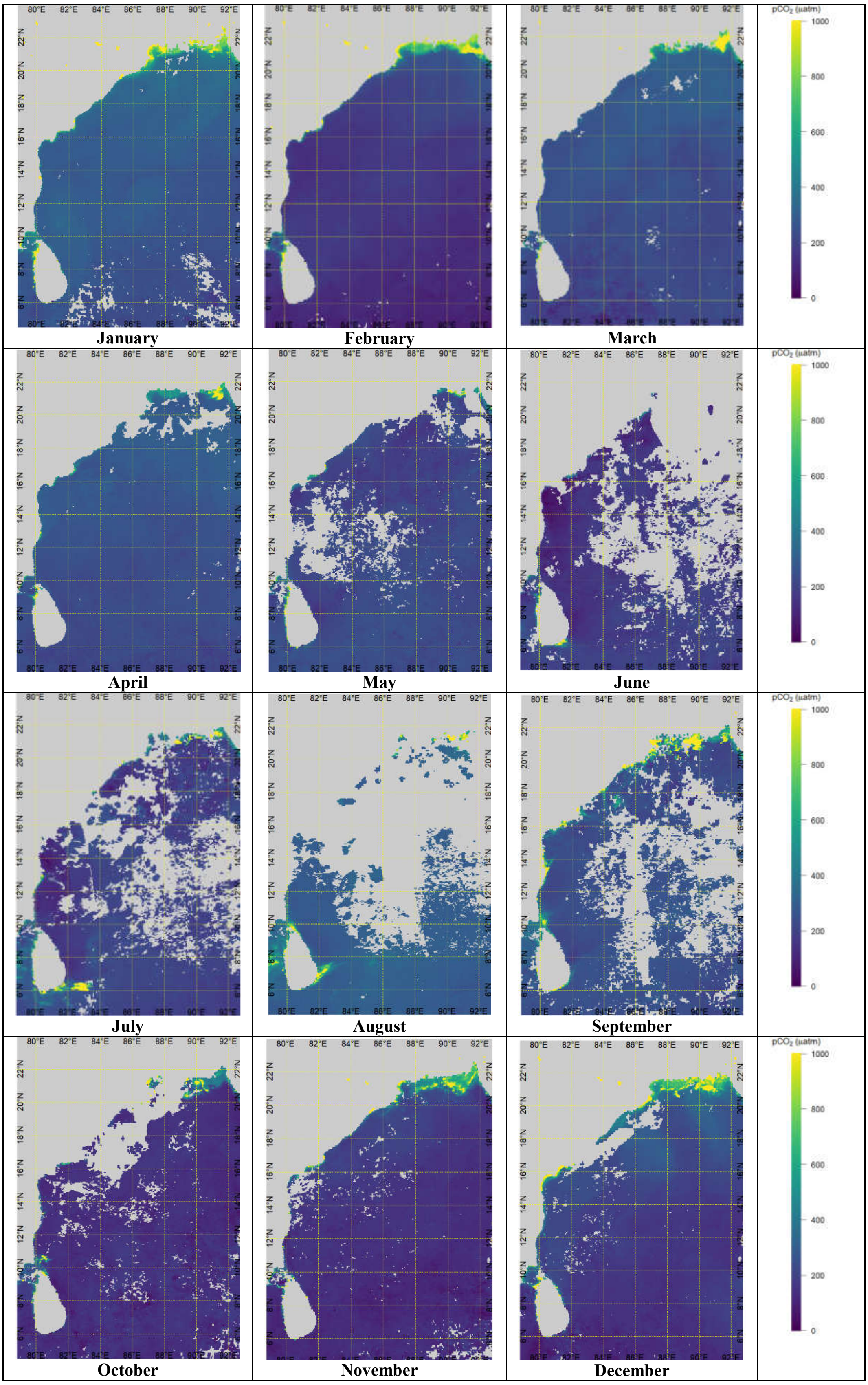

Fig.3 Monthly pCO_2 variation during the year 2022

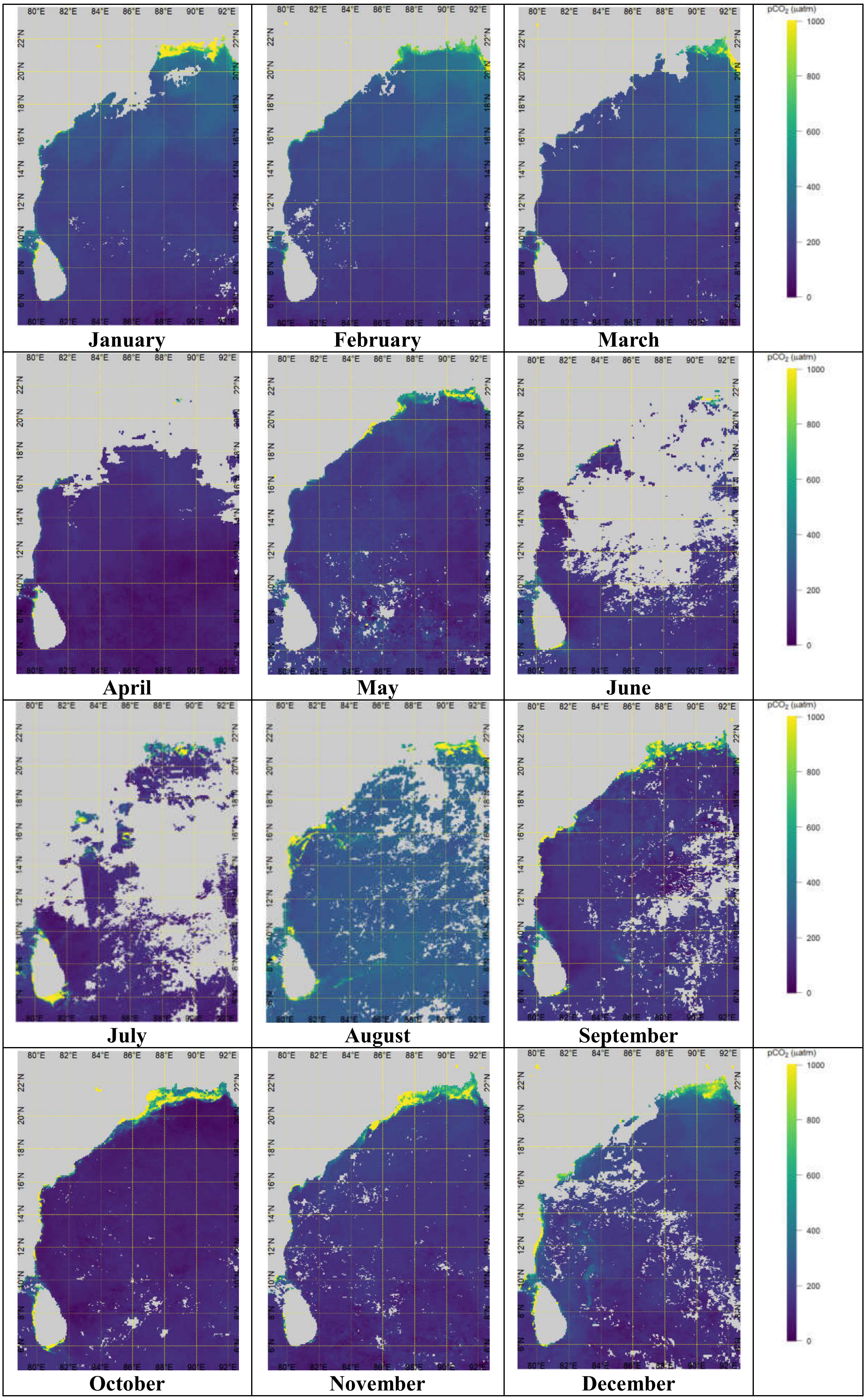

Fig.3 Monthly pCO_2 variation during the year 2023

3.1. Seasonal Variability of pCO_2 in the Bay of Bengal (2022–2024)

The seasonal distribution of pCO_2 across the Northern, Central, and Southern Bay of Bengal revealed distinct spatiotemporal patterns over the three-year period from 2022 to 2024. Across all three years, peak pCO_2 concentrations were consistently observed during the Pre-Monsoon and Post-Monsoon (Po-Monsoon) seasons, while relatively minimum values were recorded during the Summer and Monsoon periods.

3.1.1. Northern BoB

In 2022, Pre monsoon and Post monsoon registered higher pCO_2 levels 457.47µatm (January) and 410.99 µatm (September), meanwhile minimum concentration observed in Monsoon (283.54 µatm, October) and Summer (294.34 µatm, May). In 2023, The minimum pCO_2 concentration noted were 274.68 µatm (June, Summer), 275.62 µatm (May, Summer) and in summer (274.68 µatm, June). In 2024, post-monsoon (488.78 µatm) and pre-monsoon (411.23 µatm) exhibited higher pCO_2 levels, meanwhile minimum pCO_2 levels noted are 248.75 µatm (May, Summer) and 307.31 µatm (October, Monsoon).

3.1.2. Central BoB

During 2022, low pCO_2 conditions observed during summer and monsoon are 244.62 µatm (April, summer) and 260.21 µatm (October, Monsoon). The peak pCO_2 levels observed in 392.26 µatm (February, Post-monsoon) and 351.89 µatm (September, Pre-monsoon). In 2023, 258.16 µatm and 293.12 µatm are the minimum pCO_2 levels observed, meanwhile, maximum pCO_2 levels registered during 394.4 µatm (January, post-monsoon) and 364.94 µatm (September, Pre-monsoon). During 2024, 388.63 µatm (January, Post-monsoon) and 346.08 µatm (December, Monsoon) noted as maximum pCO_2 levels and the other hand 215.88 µatm (May, Summer) and 272.93 µatm (October, Monsoon).

3.1.3. Southern BoB

In 2022, the low pCO_2 conditions observed are 290.33 µatm (March, Po-monsoon) and 307.68 µatm (July, pre-monsoon) and maximum pCO_2 levels are 342.55 µatm (January, po-monsoon) and 359.93 µatm (September, pre-monsoon). In 2023, 240.06 µatm (April, summer), 285.65 µatm (August, pre-monsoon) and 296.87 µatm (November, monsoon) are the maximum pCO_2 levels noted meanwhile, maximum pCO_2 levels registered are 372.89 µatm (January, po-monsoon) and 322.88 µatm (September, pre-monsoon). The minimum pCO_2 levels noted during 2024, 217.51 µatm (May, summer) 275.62 µatm (November, Monsoon) and the maximum pCO_2 levels are, 339.51 µatm (January, Po-monsoon) and 317.78 µatm (August, pre-monsoon).

Across all regions Po-Monsoon and Pre-Monsoon periods were marked by elevated pCO_2 levels, likely driven by enhanced remineralization, decreased biological uptake or physical mixing. Summer and Monsoon seasons noted a decline trend in pCO_2, possibly due to higher primary productivity and dilution from freshwater input via precipitation during monsoonal seasons. The Northern BoB exhibited the highest seasonal amplitudes, while the Southern BoB remained relatively stable.

These seasonal variations underscore the dynamic nature of carbon dynamics in the BoB, suggests that biological activity and monsoonal forcing play dominant roles in shaping surface pCO_2 distributions.

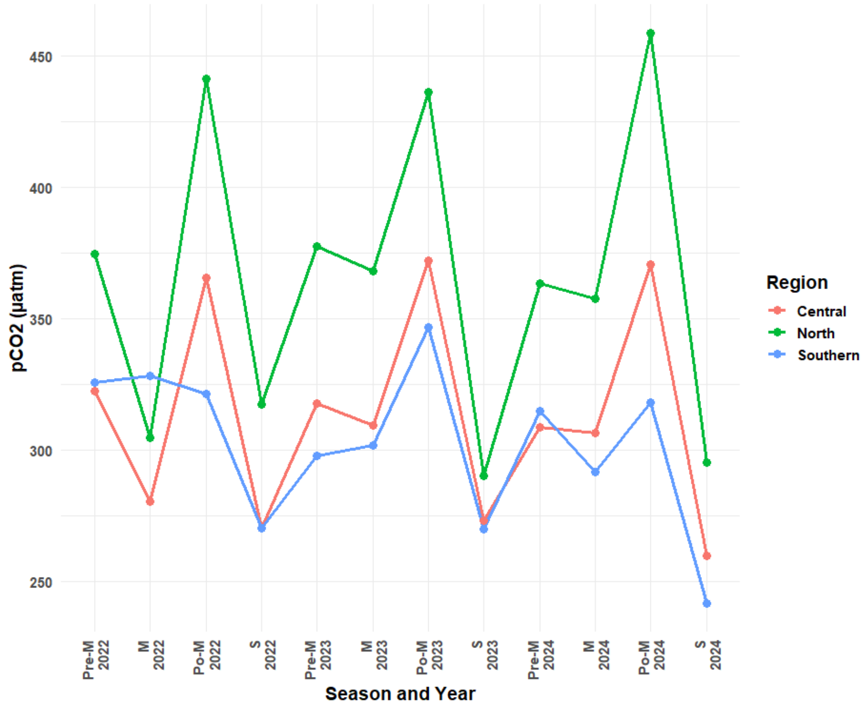

Fig.5 seasonal pCO_2 variation during the year 2021-2023

3.2. Seasonal and Spatial Variation of pCO_2 based on the heatmap correlation (2022–2024)

The spatial and seasonal patterns of pCO_2 across BoB regions exhibited distinct seasonal and inter-annual variations during the years 2022-2024.

In 2022, northern BoB regions exhibited highest seasonal pCO_2 values, peaking during the post-monsoon season (441.2 µatm), while lower pCO_2 values were observed during summer (317.6 µatm). The central BoB exhibits peak pCO_2 values in post-monsoon season (365.4 µatm) with diminished pCO_2 levels noted during summer (270.5 µatm). In contrast, southern BoB exhibits relatively stable values across seasons, although higher pCO_2 conditions during pre-monsoon (325.9 µatm) and lowest during summer (270.3 µatm), represented in Fig.6(a).

In 2023, a similar trend was observed, with Northern BOB exhibited a maximum pCO_2 levels during post-monsoon (436.2 µatm) and reduced levels during summer (290.3 µatm). The central BoB exhibited a similar pattern where peak pCO_2 levels noted during post-monsoon (372.1 µatm). while, lowest during summer (273.5 µatm). Southern BoB too exhibited a constant pattern registering minimum pCO_2 levels during summer (269.9 µatm) and maximum during post-monsoon season (346.8 µatm), demonstrated in Fig.6(b).

In 2024, post-monsoon season found consistent with peak pCO_2 levels in Northern (458.5 µatm), central (370.6 µatm) and Southern BoB (318.1 µatm). Meanwhile, summer values with constantly low with Northern (295.6 µatm), Central (259.9 µatm) and Southern BoB (241.7 µatm), shown in Fig.6(c).

Throughout the study, post-monsoon season found to be dominant across the BoB and summer with poor pCO_2 levels. Among the regions, Northern BoB regions found consistently high followed by Central and Southern BoB regions. The dominant pCO_2 levels in Northern BoB region attributed to the influence of major riverine inputs and stratification. On the other hand, reduced pCO_2 levels in southern region indicates reduced mixing leads to the diminished carbon input.

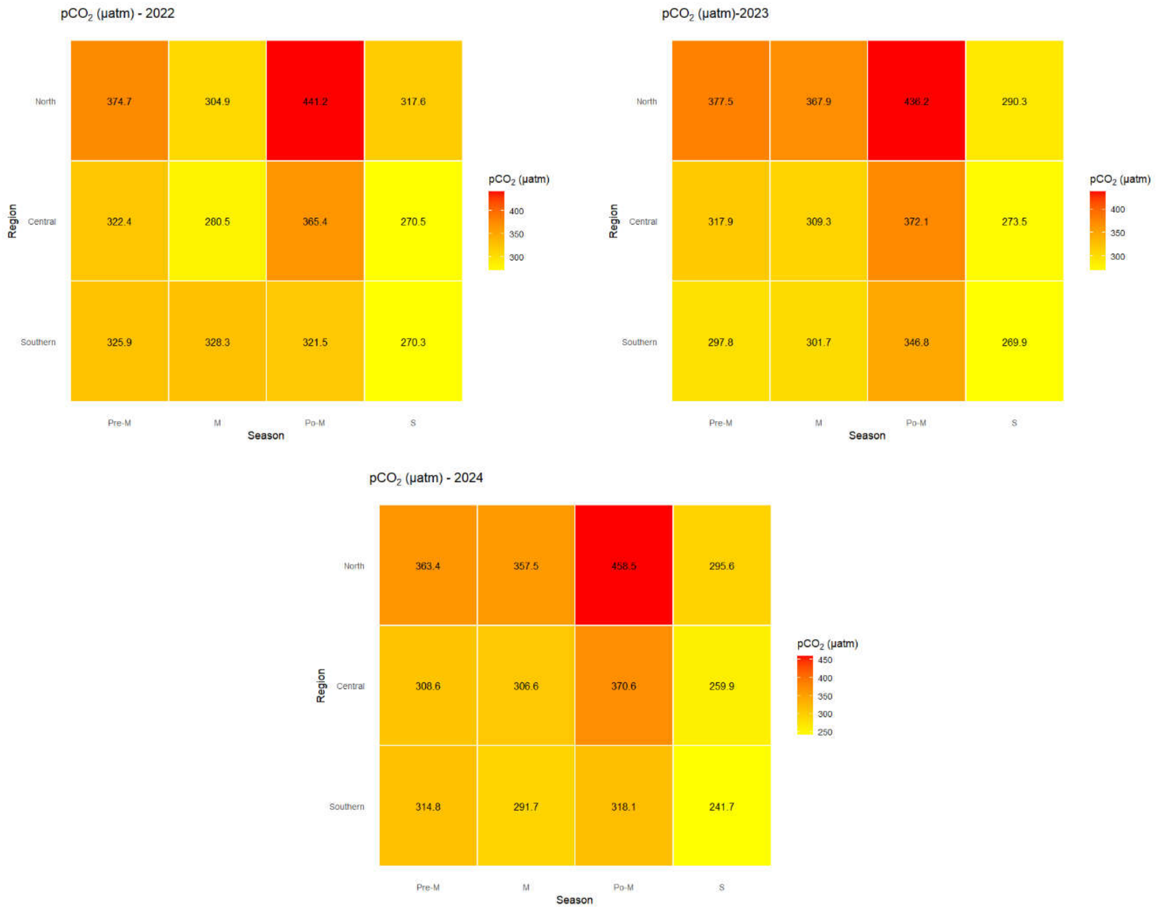

Fig.6 heatmap of pCO_2 variability (a) 2021, (b) 2022 and (c)2024

4. Discussion

The uptake of atmospheric CO_2 by the surface ocean is primarily regulated by the air–sea CO_2 flux. This flux is controlled by the partial pressure gradient of CO_2 between the ocean and atmosphere, together with environmental factors such as sea surface temperature (SST), sea surface salinity (SSS), and gas transfer velocity, the latter being strongly influenced by wind speed (Wanninkhof, 1992, 2014; Nightingale et al., 2000; Ho et al., 2006; Wanninkhof et al., 2009; Blomquist et al., 2017). In the present study, pCO_2 exhibited substantial variability among the northern, central, and southern Bay of Bengal, which can be attributed to regional differences in water column mixing and biological productivity (Joshi & Warrior, 2022).

In the Northern BoB, the highest pCO_2 levels (488.78 µatm) were recorded during the post-monsoon season (Fig. 5). This observation is consistent with earlier reports by Sarma et al. (2012) and Shaik et al. (2023), which suggest that intense precipitation during the preceding monsoon reduces both salinity and temperature, thereby enhancing CO_2 solubility and resulting in elevated surface pCO_2. Since CO_2 solubility is a key factor regulating the regional carbon sink, this process plays a critical role in shaping the seasonal variability of surface pCO_2. Elevated values during February can also be linked to northeast monsoon winds, which promote upwelling and transport CO_2-enriched subsurface waters to the surface, increasing pCO_2 concentrations (Joshi & Warrior, 2022). Conversely, the lowest pCO_2 levels (248.75 µatm) were observed in May (summer), largely due to elevated sea surface temperatures that reduce CO_2 solubility (Sarma et al., 2012; Sridevi & Sarma, 2021). In addition to hydrographic drivers, surface pCO_2 in this region is influenced by biological productivity, which is regulated by nutrient inputs from riverine fluxes (Kumar et al., 1996). The Ganges–Brahmaputra river system serves as a major nutrient source, stimulating primary production. Furthermore, the East India Coastal Current (EICC) flows southward from February to May, introducing high-salinity waters into the coastal region and promoting stratification, which is associated with reduced surface pCO_2 (Sarma et al., 2018).

In the central Bay of Bengal (BoB), pCO_2 concentrations ranged from 215.88 µatm in May, 2022 to 394.4 µatm in January, 2022, indicating generally lower values compared to the northern and southern BoB (Fig. 5). This reduction is strongly influenced by the seasonal reversal of the East India Coastal Current (EICC), which alternates between equatorward and poleward flow, transporting low- and high-salinity waters. The resulting surface stratification suppresses vertical mixing, thereby contributing to the overall lower pCO_2 trend across the region (Rao et al., 1994; Naqvi et al., 1994; Kumar et al., 1996; Shetye et al., 1993; Sanilkumar et al., 1997; Babu et al., 2003; Gangopadhyay et al., 2013; Sarma et al., 2013). Elevated pCO_2 values, however, were observed during the monsoon seasons, when northeast and southwest monsoon winds promote upwelling and bring CO_2-rich subsurface waters to the surface (Shetye et al., 1996). The lowest pCO_2 levels, recorded in April, are associated with the southward transport of low-salinity waters by the EICC, coupled with Ekman pumping (Hongyu et al., 2022). The presence of fresher water enhances CO_2 solubility, which, as suggested by Shaik (2023), contributes to reduced surface pCO_2. Moreover, during April (summer), elevated sea surface temperatures further influence salinity. As highlighted by Vajravelu et al. (2018), higher temperatures increase evaporation and salinity, disrupting CO_2 solubility and reinforcing the low pCO_2 conditions observed during this period.

In the southern BoB, pCO_2 values ranged from 217.51 µatm (April–May, 2022) to 372.89 µatm (January, post-monsoon 2023), following a seasonal pattern similar to that observed in the central BoB (Fig. 5). Seasonal hydrographic conditions, coupled with variable riverine inputs influenced by the incursion of the Southwest Monsoon Current (SMC), play a vital role in regulating productivity in this region. Enhanced nutrient supply promotes primary production, which subsequently increases biogenic carbon flux to the southern BoB (Ittekot, 1991). Consistent with observations by Naveen et al. (2023), pCO_2 minima generally occurred during summer, while maxima were recorded during the monsoon season. Elevated pCO_2 during the monsoon can be attributed to the influx of organic and inorganic matter from terrestrial sources delivered through riverine discharge. These inputs stimulate heterotrophic bacterial respiration, releasing CO_2 into subsurface waters (Kempe et al., 1991; Cai & Wang, 1998). The CO_2-enriched subsurface waters are then transported to the surface via physical and biological processes, including nutrient upwelling driven by strong monsoonal winds (Sarma et al., 1996). Conversely, minimum pCO_2 levels during summer are associated with elevated sea surface temperatures that enhance stratification, thereby restricting the upward transport of CO_2-rich subsurface waters (Kumar et al., 2007; Sarma et al., 2000; Takahashi, 2002).

5. Conclusion

The present study highlights the spatial and temporal variability of surface pCO_2 across Northern, Central and Southern BoB during 2022 – 2024. Distinct seasonal patterns observed, with consistently higher pCO_2 observed with post-monsoon and pre-monsoon season and diminished levels during summer across entire BoB. The higher pCO_2 levels in Northern BoB attributed to the riverine influx from Ganges-Brahmaputra region, reduction in salinity diminishes the CO_2 solubility and monsoon-driven upwelling. In contrast, Central BoB exhibited a comparatively low pCO_2 levels primarily regulated by EICC current, which takes control of salinity and stratification. The southern BoB too exhibits a similar trend with Central BoB but the main responsible factors are river inputs and upwelling process. In regard with the outcome of the present study suggests that BoB function as dynamic and heterogenous system, where regional hydrography and seasonal monsoon variations governs that carbon dynamics. Long term monitoring of carbon dynamics, satellite observation found vital to understand the BoB's role in global carbon cycle under increasing climate change.

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