

Impact of lockdown on the environmental quality along the Indian coast and a tropical estuary

***Karnan, C., Sandhya, S.V., Gauns, M., Pratihary, A**

CSIR-National Institute of Oceanography, Dona Paula, Goa, India

*Corresponding author; Telephone: +91 832 2450 254; Fax: +91 832 2450 606

*E-mail address: karnanc@nio.org

Abstract

The COVID-19 lockdown significantly improved the global environmental quality by restricted anthropogenic activities. We aimed to understand the response of Indian coastal environmental quality and an estuarine (Zuari estuary, central west coast of India) water quality to the lockdown using satellite-derived data sets and in-situ measurements, respectively. The in-situ study was carried out for two weeks (during August and September) to measure chlorophyll-*a* and macro-nutrients. Recent 5-years (2015-2019; March - August) data sets of aerosol optical depth (AOD), rainfall, air temperature, sea surface temperature (SST), chlorophyll-*a*, particulate inorganic carbon (PIC) and particulate organic carbon (POC) were compared with lockdown period (2020). The AOD was decreased during the lockdown period ($23 \pm 11\%$) as compared with recent 5-years shows the significant impact of lockdown on industrial, transport and urbanization activities. The other water quality parameters and chlorophyll-*a* biomass have remained similar to the past data sets, indicating the insignificant effect of lockdown on these parameters. The results of the case study were compared with the previous reports, which showed a decrease in the concentration of nitrate, phosphate and silicate and comparable concentration of chlorophyll-*a*. Recent studies show significant impacts of lockdown on the atmospheric parameters and water quality parameters, however the present study did not observe any significant variations in the in-*situ* and satellite derived data sets of water quality and chlorophyll-*a*. We have discussed the possible reasons underlying in the less/undetectable response of the chlorophyll-*a* and water quality of the Indian coastal waters and estuaries during the lockdown.

Keywords: aerosol optical depth, chlorophyll-*a*, environmental quality, tropical estuary; coastal waters.

1. Introduction

The corona viral disease-2019 (COVID-19) outbreak has been reported for the first time in humans from the Wuhan city of China during December, 2019 and swift spread of this disease in a short period resulted in the global pandemic. The effective way to constrain this disease is to maintain personal hygiene and social distancing (WHO, 2020). Therefore, all countries have implemented strict lockdown to arrest the spread of virus and eradicate the disease, with few exceptions to access the daily essentials. India is one of the most populated developing countries, where the nationwide lockdown was implemented at different time phases. In the year 2020, the first phase of lockdown was started from 25th March to 31st May (complete lockdown) and the second phase during June onwards partial lockdown/unlock phases (night and weekend curfews) until October. As a result, there was a significant drop in the production and distribution of pollutants from all industrial activities, social events, and vehicle transports. Pollution control boards, news articles and publications from scholarly journals reported the satisfactory results in air quality index (Arora et al., 2020; Gautham, 2020; Mahato et al., 2020; Ranjan et al., 2020; Sharma et al., 2020; Shehzad et al., 2020; Singh and Chouhan, 2020; Naqvi et al., 2021) and improved water quality (surface and subsurface waters of rivers, ponds and coastal regions) (Aman et al., 2020; Arora et al., 2020; Garg et al., 2020; Lokhandwala and Gautham, 2020; Mandal and Pal, 2020; Patel et al., 2020; Selvam et al., 2020; Yunus et al., 2020) from the Indian sub-continent. Overall, a noticeable improvement in the quality of global environment has been reported due to the lockdown (Braga et al., 2020; He et al., 2020; Mendez-Espinosa et al., 2020; Mesas-Carrascosa et al., 2020; Niroumand-Jadidi et al., 2020; Saraswat and Saraswat, 2020; Albayati et al., 2021; Cecchi, 2021; Latif et al., 2021; Liu et al., 2021; Ryan et al., 2021). The recent studies reported a significant drop in turbidity/nutrients/pollutants/nitrogenous inputs to the aquatic systems during lockdown period by which decline/enhancement in phytoplankton biomass in aquatic systems were reported (Arora et al., 2020; Avtar et al., 2020; Braga et al., 2020; Mishra et al., 2020; Pal et al., 2020; Lotliker et al., 2021). The changes in environmental parameters during the lockdown period reported in different regions are summarized in Table 1.

Indian sub-continent has a vast coastline of ~5400 km that covers eight major river systems associated with a large number of tributaries (Latha and Prasad, 2010; Chawla et al., 2015; Rani et al., 2015). Usually, the coastal waters are more productive due to available nutrients from terrestrial sources, re-suspension of sediments caused by bottom currents, tidal currents, and wind mixing, and coastal upwelling. Indian estuaries are known as tropical monsoonal estuaries which receive enormous rainfall and river discharge during the southwest monsoon (SWM; Jun-Sep) and the northeast monsoon (NEM; Nov-Feb) (Qasim and Gupta, 1981; Qasim, 2003). The Mandovi and Zuari estuaries are located

along the central west coast of India. Mandovi (north) and Zuari (south) are the two major rivers (~50 kms each) forming the estuarine system and they flow from the Western Ghats into the eastern Arabia Sea (~15.45°N). The catchment areas get significant rainfall and terrestrial run-off during the SWM and negligible quantity of terrestrial run-off during remaining periods (Shetye, 2007; Vijith et al., 2009). The estuarine system receives significant amount of effluents from tourism and industrial activities such as mining, harbor, pharma, iron and steel industries (Kessarkar et al., 2012; Shynu et al., 2017). The macro-nutrients (nitrate, phosphate and silicate) are moderately concentrated in the estuaries during the SWM and post-SWM (De Sousa et al, 1981; Qasim and Gupta, 1981). Past studies showed abundant microbes (pollution indicators and human pathogens) during the SWM and post-SWM in both estuarine systems (Ramaiah et al., 2007; Rodrigues et al., 2011; Gauns et al., 2015). The phytoplankton abundance and chlorophyll-*a* concentration were usually lower during the SWM as compared to pre- and post-SWM seasons in the estuary (Bhargava and Dwivedi, 1974; Devassy and Bhargava, 1978; Redekar and Wagh, 2000; Parab et al., 2013; Gauns et al., 2015). Numerous studies were conducted on the hydrography and biological characteristics of the estuarine system (Qasim and Gupta, 1981; Shetye, 2007; Vijith et al., 2009; Parab et al., 2013). In this study, we set a hypothesis that the national level lockdown decreases the chlorophyll-*a* biomass by decreased addition of nutrients due to lockdown. We aimed to understand the responses of the chlorophyll-*a* and hydrography in the coastal waters of India and a case study on the Zuari estuary during the COVID-19 lockdown period and tested the above hypothesis.

2. Study area and methods

National level lockdown completely stopped field based research activities and restricted the laboratory based researches in almost all research institutions in the country. So, we have utilized the satellite data sets and an in-situ case study was conducted at the Zuari estuary, central west coast of India. Our goal was to show the variation in environmental parameters during the lockdown period, for which we have analyzed the satellite data sets from March to August during 2020 and compared with recent 5-years. Under the lockdown restrictions, we have collected water samples during the late southwest monsoon (August and September) to understand any significant change happened in the phytoplankton biomass and the concentrations of essential macro-nutrients in the Zuari estuary. Though our sampling periods and selected parameters are different in both modes of studies, we have compared the lockdown impacts within their individual timelines and respective parameters.

2.1. Indian coastal region

The study area covers entire coastal waters of India which was demarcated by 0.5° distance (~55 kms) into the sea from the coastline to effectively distinguish terrestrial influences (Fig. 1). This was achieved by the daily satellite derived water quality parameters (chlorophyll-a, PIC, POC and SST) from Giovanni online database (giovanni.gsfc.nasa.gov; MODIS-Aqua) for no-lockdown period (2015-2019) and lockdown period (2020). The other environmental parameters were retrieved from the coastal land area marked by 1° distance (~111 kms) landside from the coastline which has direct influence on the coastal water quality. The hourly/daily data sets such as AOD (MODIS-Terra; 0.55 μ), rainfall (GPM) and air temperature (AIRS) were retrieved (giovanni.gsfc.nasa.gov) for both the coastal water and land area which were divided into multiple sub-regions (Fig. 1; a1-a6) to understand regional influences of lockdown. The relevant data sets were re-gridded to select the sub-regions of the coastal waters (0.5°) and the coastal land area (1°) by using QGIS and PyFerret software tools. The satellite data were analyzed by using PyFerret (v7.4), mapping and sub-region selections were done using QGIS (v3.8.3) and graphs and statistical analysis (t-test) were done using R-Studio software (v1.3) and Golden Grapher (v7.2).

2.2. Case study area - Zuari estuary

Due to restrictions on boat operations during the lockdown period to carryout field sampling, we collected samples from the Dona Paula bay region of the Zuari estuary (Fig. 1 inset). We set the sampling location which can clearly reflect the dynamics of the estuarine system. We carried out daily water sample collection (~0.5 m depth from surface) using a Niskin sampler from the site for two weeks in August and September, 2020. The salinity of the water was measured using a handheld refractometer. The macro-nutrients (nitrate, phosphate and silicate) were colorimetrically analyzed by a Skalar auto-analyzer (Grasshoff et al., 1999). The detection range was 0.06-50 μ M for nitrate, 0.01-4 μ M for phosphate and 0.5-150 μ M for silicate. The chlorophyll-*a* concentration was analyzed by following the fluorometric methods (Turner Designs, AU-10, CA, USA), by collecting a subsample of 0.5 L and filtered through a GF/F (47 mm; 0.7 μ m) glass microfiber filter and which was immersed (24 h) in 10 ml of 90% acetone for pigment extraction (UNESCO, 1994).

3. Results and Discussion

3.1. Coastal regions

The Indian sub-continent is located in the tropical region and surrounded by the Arabian sea in the west and Bay of Bengal in the east. The Asian monsoon system drives the biogeochemical processes in these twin seas. It is well known that the Bay of Bengal receives a huge quantity of fresh water (1.6

$\times 10^{12} \text{ m}^3 \text{ yr}^{-1}$) through the major rivers which is 5-folds higher than the freshwater received by the Arabian Sea (Subramanian, 1993). The river-born nutrients play significant role in supporting various phytoplankton communities in the coastal waters throughout the year (Gomes et al., 2000). Also it was reported that the rivers bring large amount of suspended sediments into the Bay of Bengal (1.4×10^9 tonnes) than the Arabian Sea (200×10^6 tonnes) (Madhupratap et al., 2003). Qasim (1977) marked three regions along the Indian coast as high primary productivity zones based on the data collected from International Indian Ocean Expedition-1. They are (a) the southwest coast of India, (b) the central east coast of India and (c) the northeast coast of India. Nair and Pillai (1983) showed that the waters of southwest and southeast coast of India as highly productive. The primary productivity/chlorophyll-a significantly varies with respect to time in different regions/spots (Nair and Pillai, 1983) due to irregular addition of nutrients through various sources such as terrestrial runoff, aeolian input, coastal upwelling, eddies, etc. Recent studies presented that the selected coastal waters of India showed significant decline in chlorophyll-a during the lockdown due to abrupt cessation in the nutrient input from the terrestrial sources (Mishra et al., 2020). Lotliker et al. (2021) compared the water quality of lockdown period (2020) with 17-years climatology (2003-2019) for selected sampling domains (2° square area) along the Indian coast. Above study reported a significant decrease in the concentration of water quality parameters. In present study, we have omitted long term data to compare with lockdown time environmental quality because, when we compare the concentration of pollutants over a decade, underestimation (during lockdown) can be expected due to less developmental activities (industries and transports) in the past as compared to recent years (Ranjan et al., 2020; Lotliker et al., 2021). Hence, we compared the chlorophyll-a of 2020 lockdown period with recent 5-years mean (2015 - 2019; March - August) along the Indian coast. The results showed that the chlorophyll-a anomaly was minimum along the major coastal areas during the lockdown period (**Fig. 2**).

The AOD is the measure of extinction of light by the particles/aerosols (size $< 2.5 \mu\text{m}$; mineral dusts and smoke) present in the atmosphere which is considered as a proxy to estimate air pollution (Kaufman and Fraser, 1983). Numerous studies have reported that a significant decrease in AOD during the lockdown (Kant et al., 2020; Ranjan et al., 2020). In our study, the AOD in the coastal regions of India showed a clear decline ($23 \pm 11\%$) as compared to the mean of recent 5-years ($p < 0.001$; Fig. 3; Table 2) and concentration in all the sub-regions showed lower than recent 5-years mean (Fig. 3). The AOD was highest along the north west Indian coasts (a1-a2) which decreased by $> 35\%$ and a decrease of $30 \pm 12\%$ along the west coast of India (a1-a3) during the lockdown period. The highest range of AOD found along the north west coast can be attributed to the developmental and high industrial activities in this region. The east coast of India has always lower AOD than the west

coast and around $15 \pm 3\%$ of decrease was observed along the east coast (a4-a6) during lockdown. The lowest AOD was found along the southeast coast of India (i6) and it was increased towards north. This could be due to increasing sources towards north as the land area increases where relatively more anthropogenic activities occurred. The significant decline in AOD over the coastal regions of India indicates decreased activities of industries, ports, harbours and transports over the regions due to lockdown.

The mean rainfall over Indian coastal areas was higher ($\sim 17\%$) than the mean of recent 5-years (Fig. 4; Table 2). Especially, the west coast of India received $31.2 \pm 27.9\%$ additional rainfall during 2020 as compared to east coast (2.5%). The excess rainfall occurred during the SWM could have washed and diluted the nutrients/pollutants stored in the terrestrial regions as an output of agricultural and industrial activities. Usually the northwest sub-region (a1) gets less rainfall, but during 2020 it got surplus rainfall (+ 62.7%; t-test p value = 0.02) which could have washed large area and brought high concentration of nutrients to the coastal waters and enhanced the chlorophyll-a by 7.8% ($p > 0.05$). Usually, the sub-region a2 gets high rainfall during the SWM. In addition to the lockdown, which decreased the anthropogenic input, the excess rainfall (+ 21.1%) occurred during 2020 could have diluted the nutrients/pollutants (Fig. 4; Table 2).

It was found that the near-surface air temperature decreased slightly (0.8%; $p > 0.05$) along the north Indian coasts during the lockdown period (SM. 1), which could be due to cessation of anthropogenic input of greenhouse gases. The mean air temperature was decreased along the Indian coastal area during 2020 as compared to the 5-years mean (SM. 1; Table 2) and this was more pronounced especially in the northern sub-regions (a1-a2 and a4-a5). It was reported that the air temperature decreased with respect to decline in the atmospheric pollution during lockdown period (Pal et al., 2020). Present study showed a positive relationship between AOD and air temperature ($r = 0.44$). The aerosols in the atmosphere can directly absorb and scatter the solar radiation by which it can increase the air temperature (Torres et al., 2002; Jung et al., 2019). Further, the aerosols can act as condensation nuclei and alters rainfall pattern (Torres et al., 2002; Cheng et al., 2005). The decreased air temperature along the Indian coastal regions can be attributed to the decreased aerosols in the atmosphere. The variability of air temperature also depends on other factors such as wind velocity, cloud cover, water bodies, etc. (Willmot, 1987). A focused long-term study is required to have a better understanding on the role of aerosols on Indian climate system.

The mean POC decreased along the southern coasts of India (a2, a3 and a6), and increased in the northern sub-regions ($p > 0.05$; a1 [16.27%], a4 [121.14%] and a5 [36.24%]; SM. 2). The chlorophyll-a also increased in the northern most sub-regions (a1 [7.8%] and a4 [25.9%]; Fig. 5; Table 2).

Similarly, the PIC was increased in a1, a2 and a4 sub-regions and decreased in the rest (Fig. 6). The POC, chlorophyll-a and PIC were positively correlated with each other ($r > 0.7$). The POC in the coastal waters includes organisms and detritus material consist of both autochthonous and allochthonous origin (Kharbush et al., 2020). The availability of nutrients and optimum light are essential to enhance in-situ biological production (chlorophyll-a) by which POC can be produced and transported through ocean currents. On the other hand, the land derived POC can be added to the sea through river discharges. Though fluctuations were there in the rainfall pattern along the Indian coast during 2020, the rainfall was slightly higher than the mean of recent five years ($p > 0.05$), and significant in a1 sub-region ($p < 0.05$). The unusual high rainfall might have brought higher quantity of nutrients, PIC and POC to the coastal waters in the northern sub-regions.

The SST increased along the Indian coastal belt during 2020 than the recent 5-years (SM. 3) can be attributed to the impacts of changing climate (Roxy et al., 2014) and decreased AOD. The heat loss to the atmosphere decreased due to decreased aerosols which can absorb, scatter and reflect solar energy. The less concentrated aerosols allowed heat energy directly to the surface by which the SST could have increased during lockdown period (Harris and Highwood, 2011). The middle sub-regions (a2 and a5) showed highest surface warming ($\sim 2\%$) and as a response the chlorophyll-a decreased in respective sub-regions (14.9 and 9%).

3.2. Estuarine hydrography

The Zuari estuary has relatively high area ($73 \times 10^6 \text{ m}^2$) and volume ($310 \times 10^6 \text{ m}^3$) as compared to the Mandovi estuary ($31.4 \times 10^6 \text{ m}^2$ and $145 \times 10^6 \text{ m}^3$, respectively) (Vijith, 2014). The region gets highest rainfall and land runoff during the SWM season (Shetye et al., 1995; Suprit and Shankar, 2008). Though Mandovi river has 2-times more catchment area than Zuari river, the runoff rate is almost comparable in both rivers (258 and $204 \text{ m}^3 \text{ s}^{-1}$, respectively; Vijith et al., 2009; Vijith, 2014). The Zuari estuary characterized by mixed and semi-diurnal tides with a maximum range of ~ 2.3 m and during the present sampling, tide height varied between 0.54 m and 2.04 m. As a response to the seasonality in rainfall and river runoff, the freshwater dominates the estuary during wet season (SWM) and salt water dominates the remaining periods (Shetye et al., 1995). During the present study, the salinity ranged between 7 to 25 PSU due to river runoff and tidal action. The concentration of major nutrients such as nitrate ($1.88 \pm 0.67 \mu\text{M}$), phosphate ($0.73 \pm 0.14 \mu\text{M}$) and silicate ($50.1 \pm 5.92 \mu\text{M}$) decreased during 2020 as compared the results of previous studies (Fig. 7 and references therein). Similarly, the chlorophyll-a concentration was $2.42 \pm 1 \mu\text{g/L}$ during the sampling period and almost similar to earlier reported concentrations (Fig. 7). These results indicate a decrease in anthropogenic input of nutrients to the estuary during the SWM season, probably due to lockdown.

3.3. Role of lockdown on anthropogenic input to estuary

The lockdown in India significantly stopped the commercial activities which led to the decrease in the release of industrial effluents and sewages. The lockdown enhanced the air and water quality in most parts of India (Arora et al., 2020; Selvam et al., 2020; Patel et al., 2020; Ranjan et al., 2020; Yunus et al., 2020; Murari, 2020). The state of Goa is famous for its active tourism and recreation, which significantly contribute to the state's economy; on the other hand, they are the sources of sewage and solid wastes from hotels, restaurants, shacks and water sports to the estuaries and coastal waters (Qasim and Gupta, 1981). Besides tourism, there are many other developmental activities, such as industrial activities (mining of iron and manganese ores, iron and steel industries, ship building, pharmaceuticals, fertilizers, cement, and cashew processing, etc), construction of buildings, roads, and bridges, harbor and shipping activities, fishing and farming, healthcare sectors which are adding major pollutants to the Mandovi - Zuari estuarine systems (Pathak et al., 1988; De Souza, 1981; and 1999; Kessarkar et al., 2012; Shynu et al., 2012 and 2017; Veerasingam et al., 2015). During the lockdown periods, all the above human activities were stopped in the state, which have enhanced the water quality during the Pre-SWM (March-May; Shweta, 2020). Otherwise also (no lockdown), the pollutants which associated to particulate matter usually aggregate and settle around the source point due to the intrusion of sea water into the estuary (Shynu et al., 2012). Along with the discontinuity in the addition of pollutants from industrial and other developmental activities during Pre-SWM lockdown periods, the tidal flow/currents in the estuary also diluted the effluents regularly. The domestic release of sewage and direct dumping of wastes into the estuary and associated water bodies are very common (Qasim and Gupta, 1981; Shetye, 1995). We could expect a reduction in the domestic sewage discharge due to lockdown, but it couldn't be great because of the huge population living around the estuary and limited changes in their daily discharges from kitchen, bathroom, and laundry usages. Especially due to COVID-19 spread, people were highly concerned about their cleanliness which could lead to more sewage discharges from domestic sector (Patel et al., 2020; Sivakumar, 2020).

3.4. Role of rainfall pattern on the estuarine hydrography

It is well known that the western part of India gets negligence amount of rainfall during Pre-SWM and significantly high quantity of rainfall and land runoff during the SWM (Fig. 4; Shetye, 1995; Suprit and Shankar, 2008). As per Vijith (2014), the river runoff at the head of the Zuari estuary was 204 m³/S during June-October period and 4.7 m³/S during the remaining period. During the lockdown in the Pre-SWM periods, there was no noticeable rainfall occurred over the state (281 mm [Mar-May, 2020]). The great importance of the rainfall is that it could washout all the pollutants from its sources into the estuary and adjacent coastal waters. During Pre-SWM months, the state followed a strict

lockdown so that we couldn't collect and analyze the water samples. During the peak SWM, we have collected samples for two weeks, 7 samples in each month of August and September, 2020, when partial lockdown was followed. Apparently, absence of rainfall and cessation of industrial activities, the sources of nutrients to the estuary reduced during Pre-SWM. But the heavy rainfall during the SWM (4176 mm [Jun-Sep, 2020]) could have washed entire catchment areas of the estuary which contains huge amount of domestic and municipal sewage, industrial effluents, weathered nutrients and especially the fertilizers from the farm lands (SM. 4; Qasim and Gupta, 1981; De Souza, 1981). During this situation, it is very difficult to understand the effects of lockdown in the pollutants distribution aspects in the estuary, because of both dilution and flush out effects. A schematic picture is presented to understand the effluents releases from domestic, agricultural and industrial sectors during the combination of no-lockdown, lockdown, no-rainfall, and rainfall situations in to the estuary (SM. 4). The large quantity of rainfall in 2020 as compared to the past, could have significantly diluted the available nutrients in the water column. Tourism also more active during October - February (dry season) and the accumulated pollutants were presumably washed out during the SWM. Though high concentration of macro-nutrients remains available in the estuary throughout the year (De Souza, 1999; Pednekar et al., 2011; Parab et al., 2013), the chlorophyll-a was relatively less during the SWM and that too dominated by smaller sized phytoplankton such as nano- and pico- plankton (Qasim, 2003; Jyothibabu et al., 2006; Madhu et al., 2007; Maya et al., 2011; Mitbavkar and Anil, 2011; Mitbavkar et al., 2012; Mohan et al., 2016; Rajaneesh et al., 2018). Shynu et al. (2012) observed a decreasing trend of concentration of certain trace metals from the upstream (source point) to downstream (sea side) of the Mandovi river and estuarine system during non-monsoon periods, which indicates the dilution effect of sea water through the tidal incursion. When the industries stopped adding the effluents, it can be noticed immediately closer to the source points. But the farming/agricultural and domestic wastes could be significantly higher, when the rain water flush out (Qasim and Gupta, 1981). From our understandings, we could suggest that the strong imprints of the lockdown can be seen in the water bodies and its biological communities where one way dilution dominates, such as (a) the water bodies receiving perennial riverine flow which always dominated over the tidal fluxes, (b) the water body which is located far away or at a high elevation from the sea and (c) enclosed/semi-enclosed water bodies such as ponds, lakes, lagoons where effluents/pollutants diluted by either rainwater or sea water. So, we can hypothesize that the tropical monsoonal estuaries like the Zuari estuary, wherein high rainfall and riverine flow dominate during the monsoon season and the tidal flux dominates rest of the year could not show noticeable imprints in the phytoplankton biomass due to a short time/half-yearly lockdown, though there could be a decrease in the macro-nutrients.

3.5. Impact of lockdown on phytoplankton

As discussed above, the anthropogenic input of essential nutrients to the estuary and coastal waters decreased in many parts of the country due to lockdown and which lowered the chlorophyll-a in the coastal waters (Mishra et al., 2020; Lotliker et al., 2021). Studies by Avtar et al (2020) and Pal et al. (2020) also indicated that the halt in pollutant discharge and decrease in suspended particulate materials/turbidity in the water bodies led to a stress free or relatively pristine ambience which facilitated the phytoplankton growth. A recent study based on satellite imageries (Avtar et al., 2020) discussed the possible reasons behind the consistency in chlorophyll-a in the Vembanad Lake, southwest coast of India despite lockdown. Earlier studies have reported a two-fold higher growth rate of phytoplankton ($0.8 - 1.1 \text{ day}^{-1}$) in nutrient-rich conditions as compared to nutrient deficient conditions ($0.4 - 0.5 \text{ day}^{-1}$) in the Arabian Sea (Landry et al., 1998; Caron and Dennett, 1999). It shows that the phytoplankton responds to the enrichment of nutrients in a shorter period of time. The re-suspension of sediments in the estuary due to tidal currents also supplies nutrients to the water column (Kessarkar et al., 2012). Though high concentration of nutrients available in the estuaries throughout the year (Pednekar et al., 2012) and maximum nutrients were added during the SWM, phytoplankton bloom events were reported at the end of SWM and the onset of NEM (Devassy, 1983; Mitbavkar and Anil, 2000; Parab et al., 2013). However, we did not find any bloom events during our sampling period. It could be due to highly dynamic (low residence time) nature of water in the estuary, highest fluctuation in the salinity/density and high turbidity which could resist light (Qasim and Gupta, 1981; Madhu et al., 2010; Maya et al., 2011; Rajaneesh et al., 2018). Though nutrient input to the estuary significantly dropped during the lockdown period, the available nutrients were apparently higher than the assimilation capacity of the estuarine phytoplankton (SM. 4; Karnan et al., 2021). In this study, we could not analyze the phytoplankton community structure to show the variation in diversity due to imposed lockdown. The phytoplankton productivity along the west coast of India is significantly higher during the SWM due to coastal upwelling induced nutrient enrichment rather than the river brought nutrients (Karnan et al., 2020).

4. Conclusion

Present study compared the Indian coastal water and environmental quality parameters during COVID-19 lockdown period (2020) with recent 5-years mean (2015-2019) by using satellite measurements. Also a case study was conducted in the Zuari estuary, central west coast of India during the late-lockdown period. The study revealed that the AOD significantly decreased along the coastal area by 13-42% during the lockdown period compared to recent 5-years. There were no discernible changes in the chlorophyll-a in the estuary and coastal waters due to lockdown on the industrial, transport,

domestic, and all other urbanization activities. The excess rainfall recorded in the northern coastal regions during 2020 supported high chlorophyll-a production either by diluting pollutants or supplied additional nutrients from land drain. The decreased chlorophyll-a in the middle and southern west coast indicates a nutrients dilution by rainfall. Usually, the estuary contains loads of nutrients in the sediments as well as water column due to prolonged contribution of rivers in the past which washed out the industrial effluents, fertilizers from farm lands and huge amount of domestic wastes from the catchment area during the monsoon season. Though lockdown followed over six months, the rainwater washed the previously used/stored sources to the estuary which possibly added nutrients as well as diluted the concentration of pollutants. Also, the concentration of macronutrients was generally higher than the assimilation capacity of the estuarine phytoplankton. This study suggests that the chlorophyll-a biomass in the tropical monsoonal estuaries are not significantly altered by the short period of lockdown, although it decreased the nutrients concentrations considerably. But in the coastal waters wherein the phytoplankton production is sustained by land-derived nutrients, which in turn depends on rainfall and river flow. The dilution and mixing of pollutants are slower in the water column as compared to atmosphere resulting in overall insignificant changes in the coastal waters than the atmosphere.

Acknowledgments

The authors thank the Director of CSIR - National Institute of Oceanography, India for facilities and encouragement. We are thankful to the anonymous reviewers for their constructive comments to improve this manuscript. This is CSIR-NIO contribution.

References

- Ahmed, A., Naik, H., Adel, S.S., Bardhan, P., Gauns, M., Naik, B., Naqvi, S.W.A., 2019. Nitrogen fixation and carbon uptake in a tropical estuarine system of Goa, western India. *Journal of Sea Research* 144, 16-21.
- Albayati, N., Waisi, B., Al-Furaiji, M., Kadhom, M., Alalwan, H., 2021. Effect of COVID-19 on air quality and pollution in different countries. *Journal of Transport & Health* 21, 101061.
- Aman, M.A., Salman, M.S., Yunus, A.P., 2020. COVID-19 and its impact on environment: Improved pollution levels during the lockdown period-a case from Ahmedabad, India. *Remote Sensing Applications: Society and Environment* 20, 100382.
- Anand, S.S., Anju, K.J., Mathew, D., Kumar, M.D., 2014b. Sub-hourly changes in biogeochemical properties in surface waters of Zuari estuary, Goa. *Environmental monitoring and assessment* 186, 719-724.
- Anand, S.S., Sardesai, S., Muthukumar, C., Mangalaa, K.R., Sundar, D., Parab, S.G., Kumar, M.D., 2014a. Intra-and inter-seasonal variability of nutrients in a tropical monsoonal estuary (Zuari, India). *Continental Shelf Research* 82, 9-30.
- Andreadis, K.M., Schumann, G.J.P., Pavelsky, T., 2013. A simple global river bankfull width and depth database. *Water Resources Research* 49, 7164-7168.
- Arora, S., Bhaukhandi, K.D., Mishra, P.K., 2020. Coronavirus lockdown helped the environment to bounce back. *Science of the Total Environment*, 140573.
- Avtar, R., Kumar, P., Supe, H., Jie, D., Sahu, N., Mishra, B.K., Yunus, A.P., 2020. Did the COVID-19 Lockdown-Induced Hydrological Residence Time Intensify the Primary Productivity in Lakes? Observational Results Based on Satellite Remote Sensing. *Water* 12, 2573.
- Bardhan, P., Karapurkar, S.G., Shenoy, D.M., Kurian, S., Sarkar, A., Maya, M.V., Naik, H., Varik, S., Naqvi, S.W.A., 2015. Carbon and nitrogen isotopic composition of suspended particulate organic matter in Zuari Estuary, west coast of India. *Journal of Marine Systems* 141, 90-97.
- Bhargava, R.M.S., Dwivedi, S.N., 1974. Diurnal variation in phytoplankton pigments in Zuari estuary, Goa. *Indian Journal of Geo-Marine Sciences* 3, 142-145.
- Braga, F., Scarpa, G.M., Brando, V.E., Manfe, G., Zaggia, L., 2020. COVID-19 lockdown measures reveal human impact on water transparency in the Venice Lagoon. *Science of The Total Environment*, 139612.
- Caron, D.A., Dennett, M.R., 1999. Phytoplankton growth and mortality during the 1995 Northeast Monsoon and Spring Intermonsoon in the Arabian Sea. *Deep Sea Research Part II: Topical Studies in Oceanography* 46, 1665-1690.
- Cecchi, T., 2021. Analysis of volatiles organic compounds in Venice lagoon water reveals COVID 19 lockdown impact on microplastics and mass tourism related pollutants. *Science of The Total Environment* 783, 146951.

- Chawla, P., Kumar, P., Singh, M., Hasteer, N., Ghanshyam, C., 2015. Prediction of pollution potential of Indian rivers using empirical equation consisting of water quality parameters, 2015 IEEE Technological Innovation in ICT for Agriculture and Rural Development (TIAR). IEEE, pp. 214-219.
- De Sousa, S.N., 1999. Effect of mining rejects on the nutrient chemistry of Mandovi estuary, Goa. *Indian Journal of Geo-Marine Sciences* 28, 355-359.
- De Sousa, S.N., Gupta, R.S., Sanzgiri, S., Rajagopal, M.D., 1981. Studies on Nutrients of Mandovi & Zuari River Systems. *Indian Journal of Geo-Marine Sciences* 10, 314-321.
- Devassy, V.P., 1983. Plankton production associated with cold water incursion into the estuarine environment. *Mahasagar - Bulletin of the National Institute of Oceanography* 16, 221-233.
- Devassy, V.P., Bhargava, R.M.S., 1978. Diel changes in phytoplankton population in the Mandovi and Zuari estuaries of Goa. *Mahasagar* 11, 195-199.
- Garg, V., Aggarwal, S.P., Chauhan, P., 2020. Changes in turbidity along Ganga River using Sentinel-2 satellite data during lockdown associated with COVID-19. *Geomatics, Natural Hazards and Risk* 11, 1175-1195.
- Gauns, M., Mochamadkar, S., Patil, S., Pratihary, A., Naqvi, S.W.A., Madhupratap, M., 2015. Seasonal variations in abundance, biomass and grazing rates of microzooplankton in a tropical monsoonal estuary. *Journal of Oceanography* 71, 345-359.
- Gautam, S., 2020. The influence of COVID-19 on air quality in India: a boon or inutility. *Bulletin of environmental contamination and toxicology* 104, 724-726.
- Gomes, H.R., Goes, J.I., Saino, T., 2000. Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research* 20, 313-330.
- Grasshoff, K., Kremling, K., Ehrhardt, M., 1999. Methods of seawater analysis-chapter 10-nutrients. *Methods of seawater analysis*, 159-228.
- Harris, B.M., Highwood, E.J., 2011. A simple relationship between volcanic sulfate aerosol optical depth and surface temperature change simulated in an atmosphere-ocean general circulation model. *Journal of Geophysical Research: Atmospheres* 116.
- He, G., Pan, Y., Tanaka, T., 2020. The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nature Sustainability*, 1-7.
- Jung, J., Souri, A.H., Wong, D.C., Lee, S., Jeon, W., Kim, J., Choi, Y., 2019. The impact of the direct effect of aerosols on meteorology and air quality using aerosol optical depth assimilation during the KORUS-AQ campaign. *Journal of Geophysical Research: Atmospheres* 124, 8303-8319.
- Jyothibabu, R., Madhu, N.V., Jayalakshmi, K.V., Balachandran, K.K., Shiyas, C.A., Martin, G.D., Nair, K.K.C., 2006. Impact of freshwater influx on microzooplankton mediated food web in a tropical estuary (Cochin backwaters-India). *Estuarine, Coastal and Shelf Science* 69, 505-518.
- Kant, Y., Mitra, D., Chauhan, P., 2020. Space-based observations on the impact of COVID-19-induced lockdown on aerosols over India. *Current Science (00113891)* 119.

- Karnan, C., Jyothibabu, R., Arunpandi, N., Albin, K.J., Parthasarathi, S., 2021. Implications of microplankton and micro-detritus on the food web in the largest monsoonal estuary along the west coast of India. *Estuarine, Coastal and Shelf Science* 250, 107149.
- Karnan, C., Jyothibabu, R., Arunpandi, N., Albin, K.J., Parthasarathi, S., Krishnan, S.S., 2020. Response of microplankton size structure to summer stratification, freshwater influx and coastal upwelling in the Southeastern Arabian Sea. *Continental Shelf Research* 193, 104038.
- Kessarkar, P.M., Shynu, R., Rao, V.P., Chong, F., Narvekar, T., Zhang, J., 2012. Geochemistry of the suspended sediment in the estuaries of the Mandovi and Zuari rivers, central west coast of India. *Environmental Monitoring and Assessment* 185, 4461-4480.
- Kharbush, J., Close, H., van Mooy, B., Arnosti, C., Smittenberg, R., Le Moigne, F., Mollenhauer, G., Scholz-Bottcher, B., Obreht, I., Koch, B., 2020. Particulate organic carbon deconstructed: Molecular and chemical composition of particulate organic carbon in the ocean. *Frontiers in Marine Science* 7.
- Krishnakumari, L., Bhattathiri, P.M.A., Matondkar, S.G.P., John, J., 2002. Primary productivity in Mandovi-Zuari estuaries in Goa. *Journal of the Marine Biological Association of India* 44, 1-13.
- Landry, M.R., Brown, S.L., Campbell, L., Constantinou, J., Liu, H., 1998. Spatial patterns in phytoplankton growth and microzooplankton grazing in the Arabian Sea during monsoon forcing. *Deep Sea Research Part II: Topical Studies in Oceanography* 45, 2353-2368.
- Latha, S.S., Prasad, M.B.K., 2010. Current status of coastal zone management practices in India, in: Ramanathan, A., Bhattacharya, P., Dittmar, T., Prasad, B., Neupane, B. (Eds.), *Management and Sustainable Development of Coastal Zone Environments*. Springer, pp. 42-57.
- Latif, M.T., Dominick, D., Hawari, N.S.S.L., Mohtar, A.A.A., Othman, M., 2021. The concentration of major air pollutants during the movement control order due to the COVID-19 pandemic in the Klang Valley, Malaysia. *Sustainable cities and society* 66, 102660.
- Liu, F., Wang, M., Zheng, M., 2021. Effects of COVID-19 lockdown on global air quality and health. *Science of the Total Environment* 755, 142533.
- Lokhandwala, S., Gautam, P., 2020. Indirect impact of COVID-19 on environment: A brief study in Indian context. *Environmental research* 188, 109807.
- Lotliker, A.A., Baliarsingh, S.K., Shesu, R.V., Samanta, A., Naik, R.C., Nair, T.M.B., 2021. Did the Coronavirus Disease 2019 Lockdown Phase Influence Coastal Water Quality Parameters off Major Indian Cities and River Basins? *Frontiers in Marine Science* 8, 648166.
- Madhu, N.V., Jyothibabu, R., Balachandran, K.K., 2010. Monsoon-induced changes in the size-fractionated phytoplankton biomass and production rate in the estuarine and coastal waters of southwest coast of India. *Environmental monitoring and assessment* 166, 521-528.
- Madhu, N.V., Jyothibabu, R., Balachandran, K.K., Honey, U.K., Martin, G.D., Vijay, J.G., Shiyas, C.A., Gupta, G.V.M., Achuthankutty, C.T., 2007. Monsoonal impact on planktonic standing stock and abundance in a tropical estuary (Cochin backwaters-India). *Estuarine, Coastal and Shelf Science* 73, 54-64.
- Madhupratap, M., Gauns, M., Ramaiah, N., Kumar, S.P., Muraleedharan, P.M., De Sousa, S.N., Sardessai, S., Muraleedharan, U., 2003. Biogeochemistry of the Bay of Bengal: physical, chemical and

- primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001. *Deep Sea Research Part II: Topical Studies in Oceanography* 50, 881-896.
- Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science of the Total Environment* 730, 139086.
- Mandal, I., Pal, S., 2020. COVID-19 pandemic persuaded lockdown effects on environment over stone quarrying and crushing areas. *Science of the Total Environment* 732, 139281.
- Maya, M.V., Soares, M.A., Agnihotri, R., Pratihary, A.K., Karapurkar, S., Naik, H., Naqvi, S.W.A., 2011. Variations in some environmental characteristics including C and N stable isotopic composition of suspended organic matter in the Mandovi estuary. *Environmental Monitoring and Assessment* 175, 501-517.
- Mendez-Espinosa, J.F., Rojas, N.Y., Vargas, J., Pachon, J.E., Belalcazar, L.C., Ramirez, O., 2020. Air quality variations in Northern South America during the COVID-19 lockdown. *Science of the Total Environment* 749, 141621.
- Mesas-Carrascosa, F.-J., Perez Porras, F., Trivino-Tarradas, P., Garcia-Ferrer, A., Merono-Larriva, J.E., 2020. Effect of Lockdown Measures on Atmospheric Nitrogen Dioxide during SARS-CoV-2 in Spain. *Remote Sensing* 12, 2210.
- Mishra, D.R., Kumar, A., Muduli, P.R., Equeenuddin, S., Rastogi, G., Acharyya, T., Swain, D., 2020. Decline in Phytoplankton Biomass along Indian Coastal Waters due to COVID-19 Lockdown. *Remote Sensing* 12, 2584.
- Mitbavkar, S., Anil, A.C., 2000. Diatom colonization on stainless steel panels in estuarine waters of Goa, west coast of India. *Indian Journal of Geo-Marine Sciences* 29, 273-276.
- Mitbavkar, S., Anil, A.C., 2011. Tiniest primary producers in the marine environment: an appraisal from the context of waters around India. *Current Science* 100, 986-988.
- Mitbavkar, S., Rajaneesh, K.M., Anil, A.C., Sundar, D., 2012. Picophytoplankton community in a tropical estuary: detection of Prochlorococcus-like populations. *Estuarine, Coastal and Shelf Science* 107, 159-164.
- Mohan, A.P., Jyothibabu, R., Jagadeesan, L., Lallu, K.R., Karnan, C., 2016. Summer monsoon onset-induced changes of autotrophic pico- and nanoplankton in the largest monsoonal estuary along the west coast of India. *Environmental Monitoring and Assessment* 188, 93.
- Murari, S., 2020. Lockdown shows positive impact on Goa's air quality, *Times of India, City News* ed, Panaji, p. 75544613.
- Nair, P.V., Pillai, V.K., 1983. Productivity of the Indian seas. *Journal of the Marine Biological Association of India* 25, 41-50.
- Naqvi, H.R., Datta, M., Mutreja, G., Siddiqui, M.A., Naqvi, D.F., Naqvi, A.R., 2021. Improved air quality and associated mortalities in India under COVID-19 lockdown. *Environmental Pollution* 268, 115691.

- Niroumand-Jadidi, M., Bovolo, F., Bruzzone, L., Gege, P., 2020. Physics-based bathymetry and water quality retrieval using planetscope imagery: Impacts of 2020 Covid-19 lockdown and 2019 extreme flood in the Venice Lagoon. *Remote Sensing* 12, 2381.
- Pal, N., Barman, P., Das, S., Zaman, S., Mitra, A., 2020. Status of brackish water phytoplankton during COVID-19 lockdown phase. *NUJS Journal of Regulatory Studies Special Issue*, 83-86.
- Parab, S.G., Matondkar, S.G.P., Gomes, H.d.R., Goes, J.I., 2013. Effect of freshwater influx on phytoplankton in the Mandovi estuary (Goa, India) during monsoon season: Chemotaxonomy. *Journal of Water Resource and Protection* 5, 349-361.
- Patel, P.P., Mondal, S., Ghosh, K.G., 2020. Some respite for India's dirtiest river? Examining the Yamuna's water quality at Delhi during the COVID-19 lockdown period. *Science of the Total Environment* 744, 140851.
- Pathak, M.C., Kotnala, K.L., Prabakaran, N., 1988. Effects of bridge piers on a tropical estuary in Goa, India. *Journal of coastal Research*, 475-481.
- Pednekar, S.M., Bates, S.S., Kerkar, V., Matondkar, S.G.P., 2018. Environmental factors affecting the distribution of *Pseudo-nitzschia* in two monsoonal estuaries of Western India and effects of salinity on growth and domoic acid production by *P. pungens*. *Estuaries and Coasts* 41, 1448-1462.
- Pednekar, S.M., Kerkar, V., Matondkar, S.G.P., 2014. Spatiotemporal distribution in phytoplankton community with distinct salinity regimes along the Mandovi estuary, Goa, India. *Turkish Journal of Botany* 38, 800-818.
- Pednekar, S.M., Matondkar, S.G.P., Gomes, H.D.R., Goes, J.I., Parab, S., Kerkar, V., 2011. Fine-scale responses of phytoplankton to freshwater influx in a tropical monsoonal estuary following the onset of southwest monsoon. *Journal of Earth System Science* 120, 545.
- Pednekar, S.M., Prabhu Matondkar, S.G., Kerkar, V., 2012. Spatiotemporal distribution of harmful algal flora in the tropical estuarine complex of Goa, India. *The Scientific World Journal* 2012, 596276, 1-11.
- Qasim, S.Z., 1977. Biological productivity of the Indian Ocean. *Indian Journal of Geo-Marine Sciences* 6, 122-137.
- Qasim, S.Z., 2003. *Indian estuaries*. Allied publishers, Heredia Marg, Ballard Estate, Mumbai. pp-259.
- Qasim, S.Z., Gupta, R.S., 1981. Environmental characteristics of the Mandovi-Zuari estuarine system in Goa. *Estuarine, Coastal and Shelf Science* 13, 557-578.
- Rajaneesh, K.M., Mitbavkar, S., Anil, A.C., 2018. Dynamics of size-fractionated phytoplankton biomass in a monsoonal estuary: Patterns and drivers for seasonal and spatial variability. *Estuarine, Coastal and Shelf Science* 207, 325-337.
- Ramaiah, N., Rodrigues, V., Alwares, E., Rodrigues, C., Baksh, R., Jayan, S., Mohandass, C., 2007. Sewage-pollution indicator bacteria. *National Institute of Oceanography, India*, pp. 115-145.
- Rani, N.N.V.S., Satyanarayana, A.N.V., Bhaskaran, P.K., 2015. Coastal vulnerability assessment studies over India: a review. *Natural Hazards* 77, 405-428.

- Ranjan, A.K., Patra, A.K., Gorai, A.K., 2020. Effect of lockdown due to SARS COVID-19 on aerosol optical depth (AOD) over urban and mining regions in India. *Science of the Total Environment* 745, 141024.
- Redekar, P.D., Wagh, A.B., 2000. Planktonic diatoms of the Zuari estuary, Goa (West coast of India). *Seaweed Research and Utilization* 22, 107-112.
- Rodrigues, V., Ramaiah, N., Kakti, S., Samant, D., 2011. Long-term variations in abundance and distribution of sewage pollution indicator and human pathogenic bacteria along the central west coast of India. *Ecological Indicators* 11, 318-327.
- Roxy, M.K., Ritika, K., Terray, P., Masson, S., 2014. The curious case of Indian Ocean warming. *Journal of Climate* 27, 8501-8509.
- Ryan, J.P., Joseph, J.E., Margolina, T., Hatch, L.T., Azzara, A., Reyes, A., Southall, B.L., DeVogelaere, A., Peavey Reeves, L.E., Zhang, Y., 2021. Reduction of Low-Frequency Vessel Noise in Monterey Bay National Marine Sanctuary During the COVID-19 Pandemic. *Frontiers in Marine Science* 8, 587.
- Saraswat, R., Saraswat, A.D., 2020. Research opportunities in pandemic lockdown. *Science* 368, 594-595.
- Selvam, S., Jesuraja, K., Venkatramanan, S., Chung, S.Y., Roy, P.D., Muthukumar, P., Kumar, M., 2020. Imprints of pandemic lockdown on subsurface water quality in the coastal industrial city of Tuticorin, south India: A revival perspective. *Science of The Total Environment*, 139848.
- Sharma, S., Zhang, M., Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. *Science of the Total Environment* 728, 138878.
- Shehzad, K., Sarfraz, M., Shah, S.G.M., 2020. The impact of COVID-19 as a necessary evil on air pollution in India during the lockdown. *Environmental Pollution* 266, 115080.
- Shetye, S.R., DileepKumar, M., Shankar, D., 2007. The Mandovi and Zuari Estuaries. *National Institute of Oceanography, Goa, India*, pp. 1-145.
- Shetye, S.R., Gouveia, A.D., Singbal, S.Y., Naik, C.G., Sundar, D., Michael, G.S., Nampoothiri, G., 1995. Propagation of tides in the Mandovi-Zuari estuarine network. *Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences* 104, 667-682.
- Shirodkar, P.V., Deepthi, M., Vethamony, P., Mesquita, A.M., Pradhan, U.K., Babu, M.T., Verlecar, X.N., Haldankar, S.R., 2012. Tide dependent seasonal changes in water quality and assimilative capacity of anthropogenically influenced Mormugao harbour water. *Indian Journal of Geo-Marine Sciences* 41, 314-330.
- Shweta, K., 2020. Goa recharges in lockdown: How nature and our lifestyles are sporting a healthier look, *Herald, Panaji*, p. 161435.
- Shynu, R., Rao, V.P., Kessarkar, P.M., 2017. Major and trace metals in suspended and bottom sediments of the Mandovi and Zuari estuaries, western India: distribution, source, and pollution. *Environmental Science and Pollution Research* 24, 27409-27429.

- Shynu, R., Rao, V.P., Kessarkar, P.M., Rao, T.G., 2012. Temporal and spatial variability of trace metals in suspended matter of the Mandovi estuary, central west coast of India. *Environmental Earth Sciences* 65, 725-739.
- Singh, R.P., Chauhan, A., 2020. Impact of lockdown on air quality in India during COVID-19 pandemic. *Air Quality, Atmosphere & Health* 13, 921-928.
- Sivakumar, B., 2020. COVID-19 and water. *Stochastic Environmental Research and Risk Assessment* 35, 531–534.
- Subramanian, V., 1993. Sediment load of Indian rivers. *Current Science*, 928-930.
- Suprit, K., Shankar, D., 2008. Resolving orographic rainfall on the Indian west coast. *International Journal of Climatology: A Journal of the Royal Meteorological Society* 28, 643-657.
- Tokatli, C., Varol, M., 2021. Impact of the COVID-19 lockdown period on surface water quality in the Meric-Ergene River Basin, Northwest Turkey. *Environmental Research* 197, 111051.
- UNESCO, 1994. Protocols for the Joint Global Ocean Flux Study. Manual and Guides, 29. UNESCO, Paris, p. 170.
- Veerasingam, S., Vethamony, P., ManiMurali, R., Babu, M.T., 2015. Sources, vertical fluxes and accumulation of petroleum hydrocarbons in sediments from the Mandovi estuary, west coast of India. *International Journal of Environmental Research* 9, 179-186.
- Vijith, V., 2014. Physical oceanography of the Mandovi and Zuari, two monsoonal estuaries in Goa, central west coast of India, *Marine Sciences*. Goa University, Goa, p. 119.
- Vijith, V., Sundar, D., Shetye, S.R., 2009. Time-dependence of salinity in monsoonal estuaries. *Estuarine, Coastal and Shelf Science* 85, 601-608.
- WHO, 2020. Coronavirus disease (COVID-19) advice for the public, Diseases, Emergency. World Health Organization, Geneva, Switzerland.
- Willmott, C.J., 1987. Models, climatic. *Encyclopedia of Climatology*, in: Oliver, J.E., Fairbridge, R.W. (Eds.). Van Nostrand Reinhold, New York, pp. 584-590.
- Yunus, A.P., Masago, Y., Hijioka, Y., 2020. COVID-19 and surface water quality: Improved lake water quality during the lockdown. *Science of The Total Environment* 731, 139012.

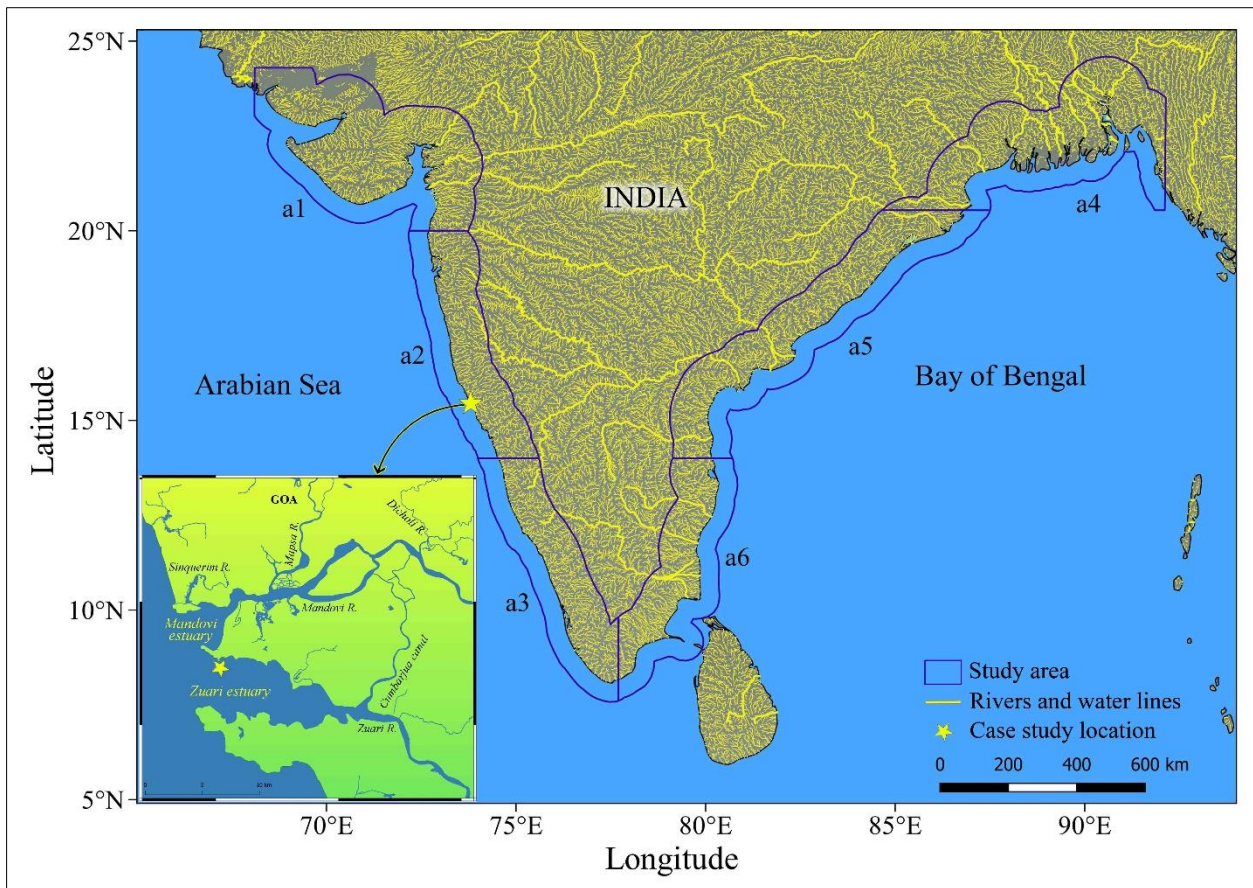


Fig. 1 - The map shows the sampling sub-regions west (a1-a3) and east coast of India (a4-a6). The major rivers and water lines were represented by yellow lines (Andreadis et al., 2013). The case study location in the Zuari estuary (central west coast) is represented by a star mark in the sub-region a2 and in the inset map.

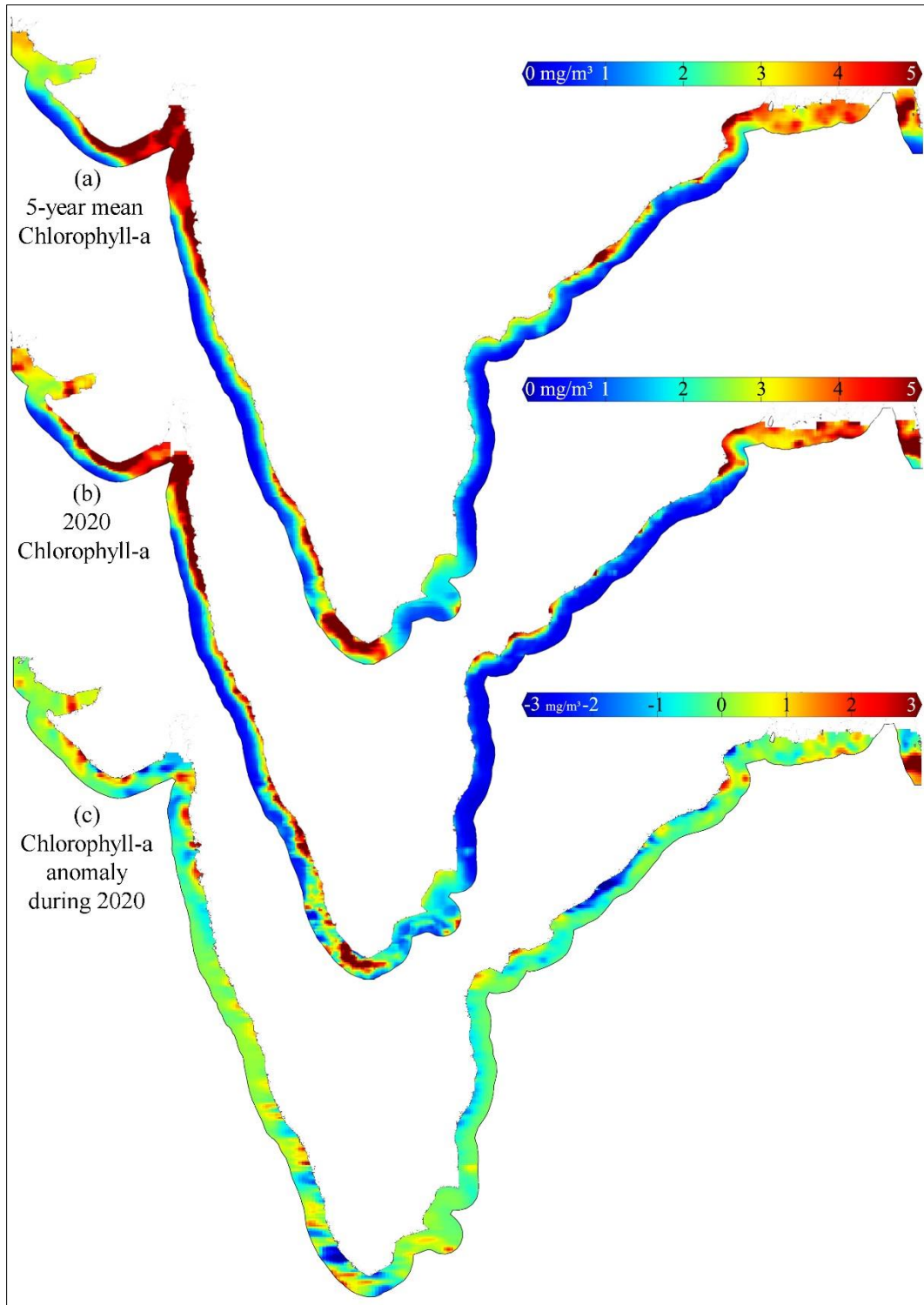


Fig. 2 - The mean chlorophyll-a concentrations (March-August) during (a) recent 5-years and (b) 2020 along the Indian coast. The chlorophyll-a rich and poor regions shaded with red and blue colors respectively in panels a and b, and the concentration >5 truncated. The panel (c) represents chlorophyll-a anomaly during 2020. The negative and positive anomalies shaded with blue and red colors respectively. Refer web version for legend interpretations.

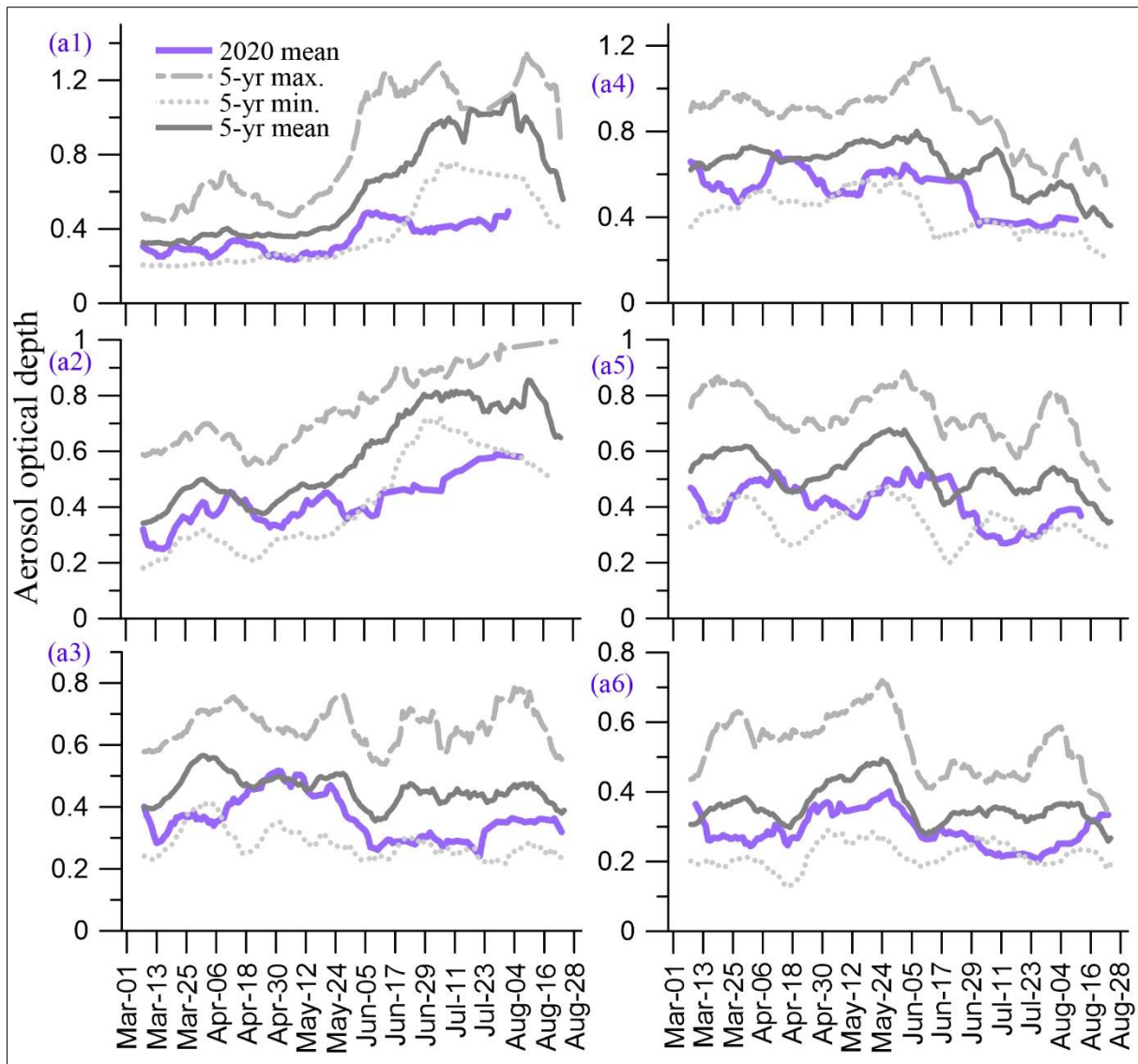


Fig. 3 - The running mean of AOD distribution during 2020 (violet) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.

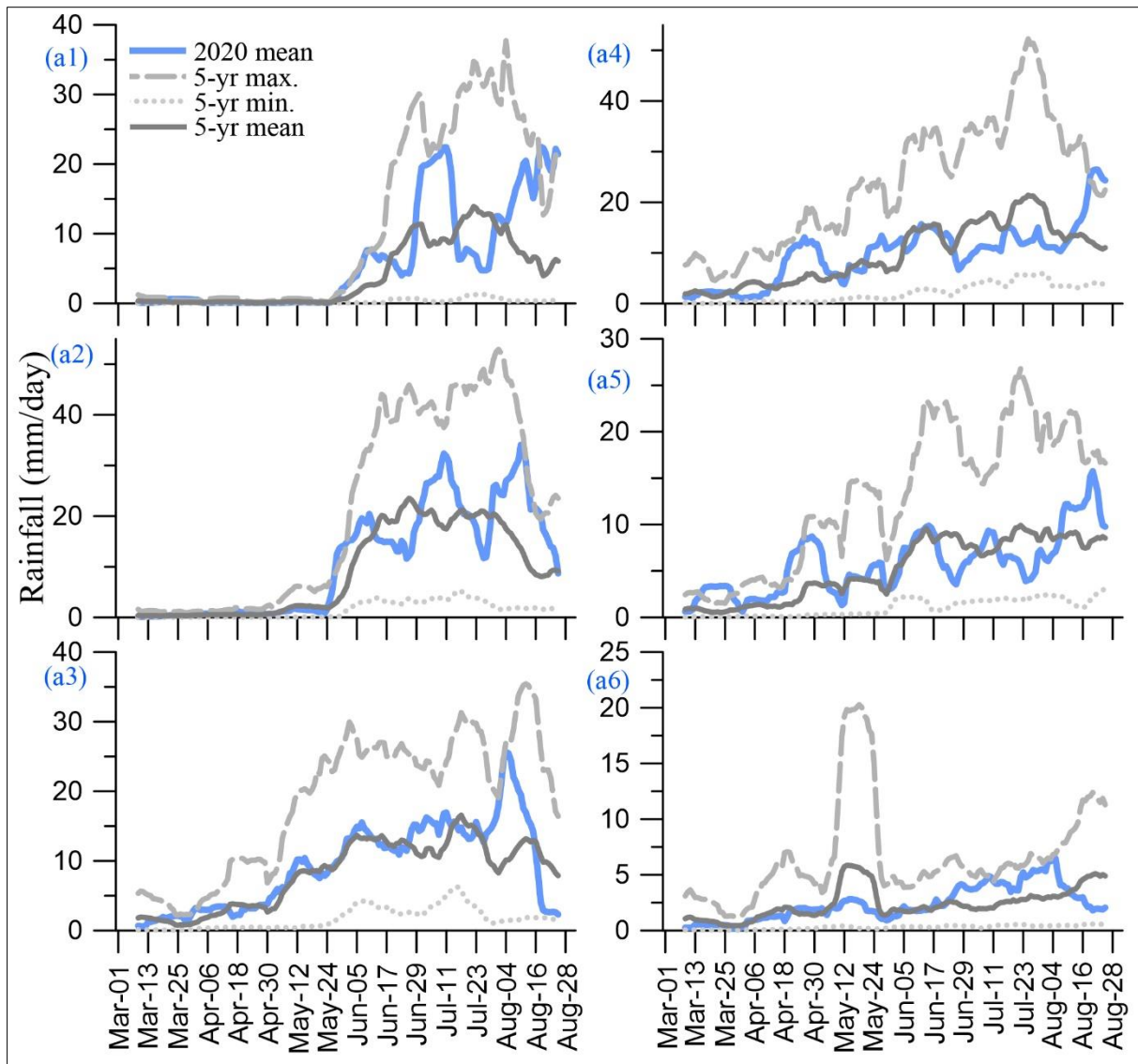


Fig. 4 - The running average of rainfall distribution during 2020 (blue) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.

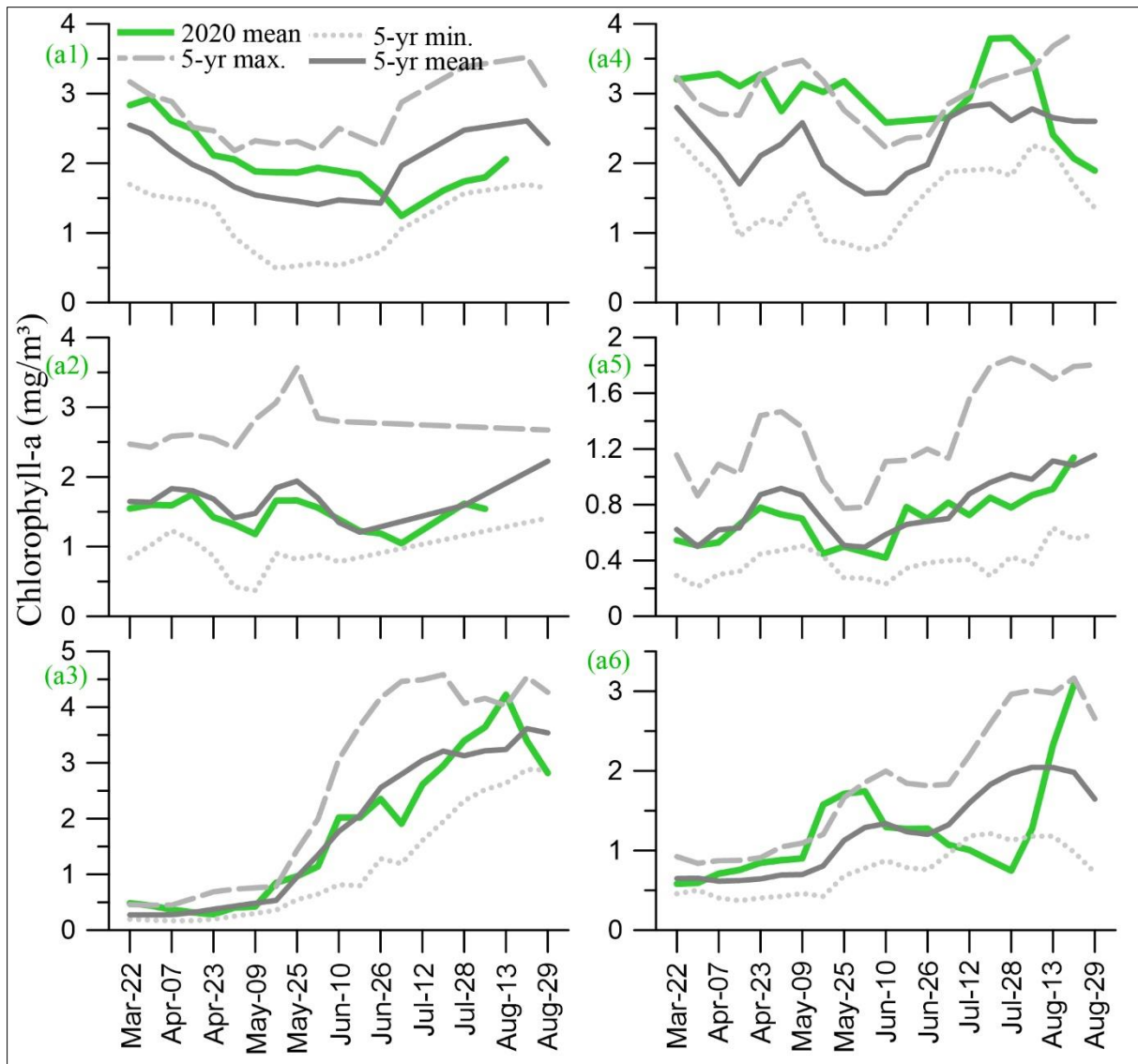


Fig. 5 - The running average of chlorophyll-a distribution during 2020 (green) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.

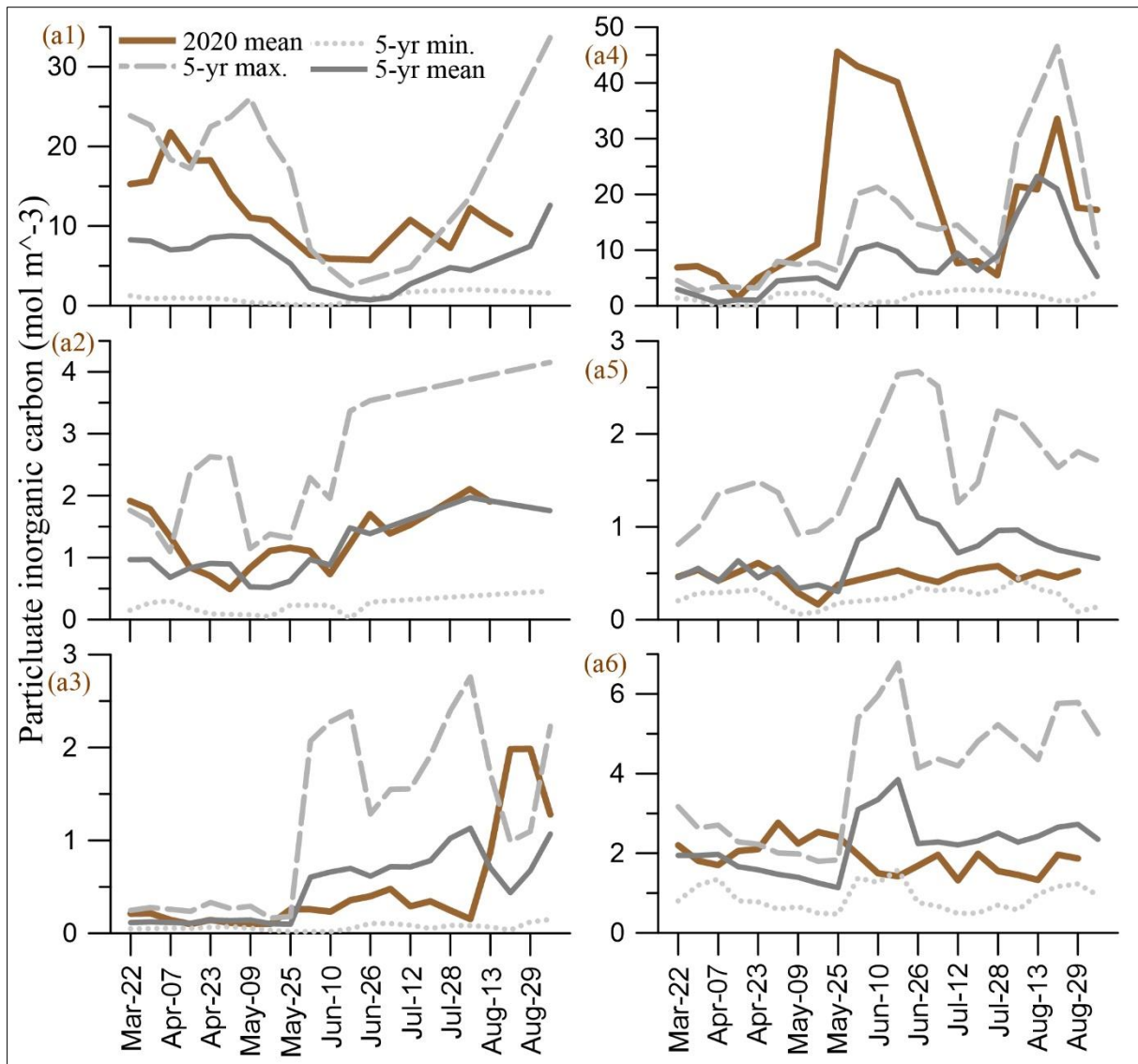


Fig. 6 - The running mean of particulate inorganic carbon distribution during 2020 (brown) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.

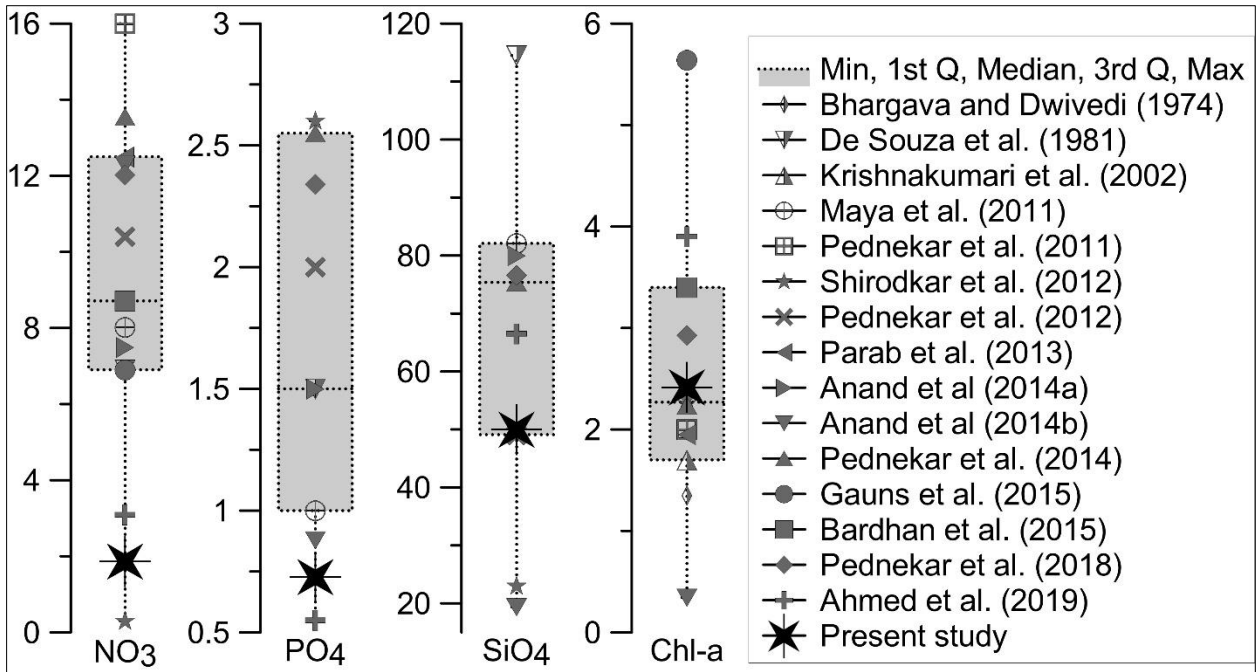


Figure 7 - Major nutrients (in $\mu\text{M/l}$) and chlorophyll-a (chl-a; $\mu\text{g/l}$) in the Zuari estuary during southwest monsoon.

Table 1 - Changes in environmental parameters during lockdown period reported in different regions. The pre-lockdown and lockdown periods are varied in each study (months to multi-years) in different regions. The ‘-/+’ symbols used (where no values mentioned for pre-lockdown period) to represent ‘decrease/increase’ during the lockdown period. Abbreviations: PM: particulate matter, CO: carbon monoxide, NO₂: nitrogen dioxide, O₃: ozone, TDS: total dissolve solid, DO: dissolved oxygen, SO₂: Sulphur dioxide, NH₃: ammonia, SPM: suspended particulate matter; AQI: air quality index, WQI: water quality index, EC: electrical conductivity, TDS: total dissolved solids, NO₃: nitrate, As: arsenic, Fe: iron, Se: selenium, Cd: cadmium, Pb: lead, TCB: total coliform bacteria, FCB: fecal coliform bacteria, MPN: most probable number, BOD: biological oxygen demand, COD: chemical oxygen demand.

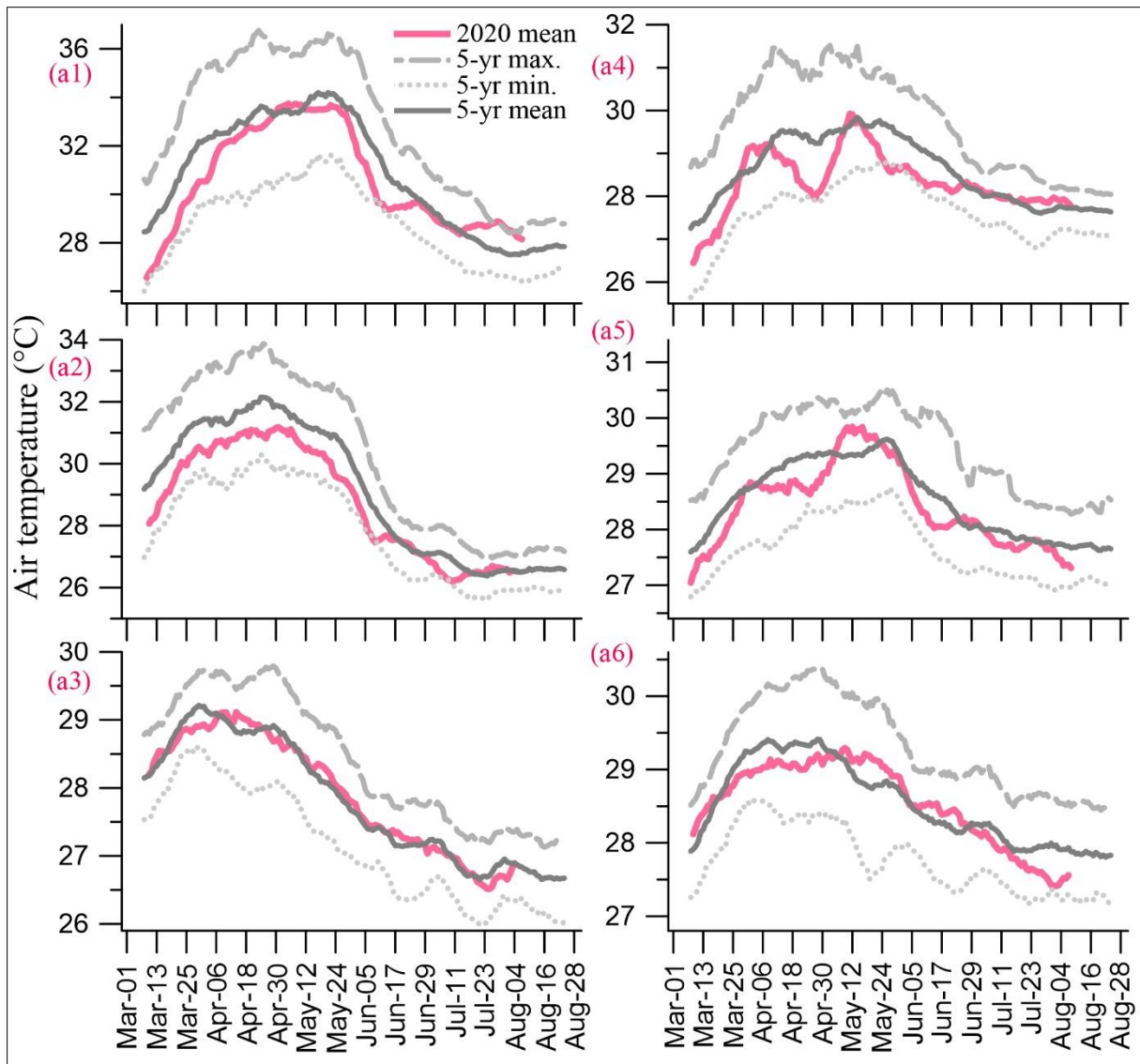
No.	References	Study region	Parameters	Pre-lockdown	During lockdown
India					
1	Mahato et al., 2020	Delhi (air quality)	PM ₁₀ (µg/m ³)	176.07	84.79
			PM _{2.5} (µg/m ³)	80.51	37.75
			SO ₂ (µg/m ³)	16.08	13.19
			NO ₂ (µg/m ³)	42.59	20.16
			CO (mg/m ³)	1.03	0.72
			O ₃ (µg/m ³)	34.05	34.32
			NH ₃ (µg/m ³)	33.93	29.75
			National AQI	185.99	72.64
2	Mandal and Pal, 2020	Quarry regions of Jharkhand and West Bengal (air quality)	PM ₁₀ (µg/m ³)	189-278	50-60
			Land temperature (°C)	31.25-35.11	25.14-30.24
			Noise level (dBA)	>85	<65
			TDS (mg/l)	2383 ± 72	1106 ± 135
3	Pal et al., 2020	Delhi (air quality)	Air temperature (°C)		-3
		Kolkata (air quality)			-2.5
		Mumbai (air quality)			-2
		Chennai (air quality)			-2
4	Sharma et al., 2020	22 cities from India (air quality)	PM _{2.5} (%)		-43
			PM ₁₀ (%)		-31
			CO (%)		-10
			NO ₂ (%)		-18
			O ₃ (%)		+17
5	Aman et al., 2020	Sabarmati River (water quality)	Turbidity (mg/l)	12.72	8.08
6	Arora et al., 2020	Ganga river (water quality)	DO (ml/l)	3.8	6.8

7	Avtar et al., 2020	Vembanad Lake (water quality)	Chlorophyll-a ($\mu\text{g/l}$)	~2.2-3.2	~2.3-3.6
8	Mishra et al., 2020	North eastern coastal Arabian Sea (water quality)	Chlorophyll-a (%)		-50
		North western coastal Bay of Bengal (water quality)			-30
9	Patel et al., 2020	Yamuna river (water quality)	WQI (%)		+37
			BOD (%)		-42.83
			COD (%)		-39.25
			FCB (%)		-40
10	Selvam et al., 2020	Tuticorin industrial city (water quality)	pH	8.1	7.7
			EC ($\mu\text{s/cm}$)	1866	2943
			TDS (mg/l)	1815	2879
			NO_3 (mg/l)	84	28
			As (mg/l)	0.071	0.03
			Fe (mg/l)	0.381	0.174
			Se (mg/l)	0.114	0.054
			Cd (mg/l)	0.002	0.001
			Pb (mg/l)	0.017	0.006
			TCB (MPN/ml)	138	47
			FCB (MPN/ml)	119	39
11	Yunus et al., 2020	Vembanad Lake (water quality)	SPM	14.4	12.1
World					
12	He et al., 2020	China (air quality)	AQI		-19.84
			$\text{PM}_{2.5}$ ($\mu\text{g/m}^3$)		-14.07
13	Latif et al., 2021	Klang Valley, Malaysia (air quality)	PM_{10} ($\mu\text{g/m}^3$)	38	24.6
			$\text{PM}_{2.5}$ ($\mu\text{g/m}^3$)	27.6	18.7
			NO_2 (ppb)	18.9	6.35
			SO_2 (ppb)	1.38	0.83
			O_3 (ppb)	23.2	23.9
			CO (ppb)	0.98	0.65
14	Mendez-Espinosa et al., 2020	Northern regions of South America (air quality)	PM_{10} ($\mu\text{g/m}^3$)	57.8	31.2
			$\text{PM}_{2.5}$ ($\mu\text{g/m}^3$)	38.6	22.2
			NO_2 ($\mu\text{g/m}^3$)	45.5	16.9
15	Mesas-Carrascosa et al., 2020	Spain (air quality)	NO_2 ($\times 10^{-5}$ mol/m ²)	5.78	3.5

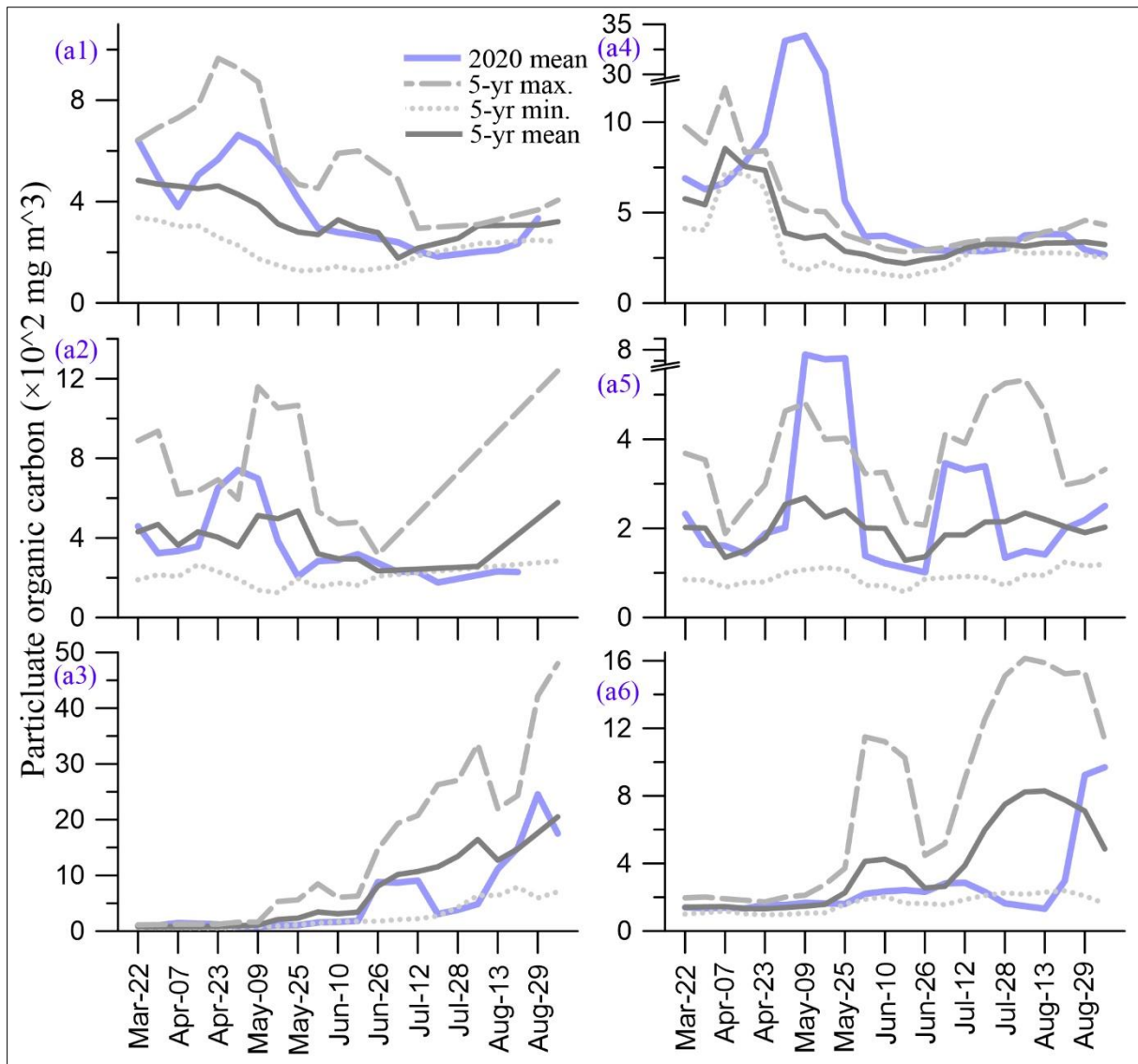
16	Avtar et al., 2020	Wuhan water bodies, China (water quality)	Chlorophyll-a ($\mu\text{g/l}$)	2.86	6.22
17	Braga et al., 2020	Venice lagoon, Italy (water quality)	Mean wave height (due to water traffic) (cm)	Dec-13	05-Jun
18	Ryan et al., 2021	Monterey Bay, USA (water quality)	Vessel noise (dB re 1 $\mu\text{Pa}^2 \text{Hz}^{-1}$)	>3	1
19	Tokatli and Varol, 2021	Meric-Ergene River Basin, Northwest Turkey (water quality)	DO (mg/L)	8.9	6.65
			pH	8.96	8.32
			EC ($\mu\text{S/cm}$)	1242	1270
			Tur (NTU)	22.46	38.89
			TSS (mg/L)	34.08	49.16
			COD (mg/L)	32.82	34.33
			BOD (mg/L)	8.23	9.22
			Cr ($\mu\text{g/L}$)	13.76	0.83
			Mn ($\mu\text{g/L}$)	26.3	28.01
			Ni ($\mu\text{g/L}$)	9.06	0.97
			Cu ($\mu\text{g/L}$)	4.3	0.71
			Zn ($\mu\text{g/L}$)	8.18	1.29
			As ($\mu\text{g/L}$)	3.51	1.4
Cd ($\mu\text{g/L}$)	0.046	0.021			
Pb ($\mu\text{g/L}$)	0.51	0.15			
20	Liu et al., 2021	Global (air quality)	PM ₁₀ (%)		-14 to -20
			PM _{2.5} (%)		-7 to -16
			NO ₂ (%)		-23 to -37
			SO ₂ (%)		-2 to -20
			O ₃ (%)		+10 to +27
			CO (%)		-7 to -11

Table 2 - P-values (statistical t-test) represent difference between the means of 5-year (2015-19) and 2020. The percentage of difference noted in parenthesis with positive and negative symbols. Abbreviations: AIRT- air temperature; AOD: aerosol optical depth; SST- sea surface temperature; PPT-rainfall; PIC- particulate inorganic carbon; POC- particulate organic carbon; Chl-a- chlorophyll-a.

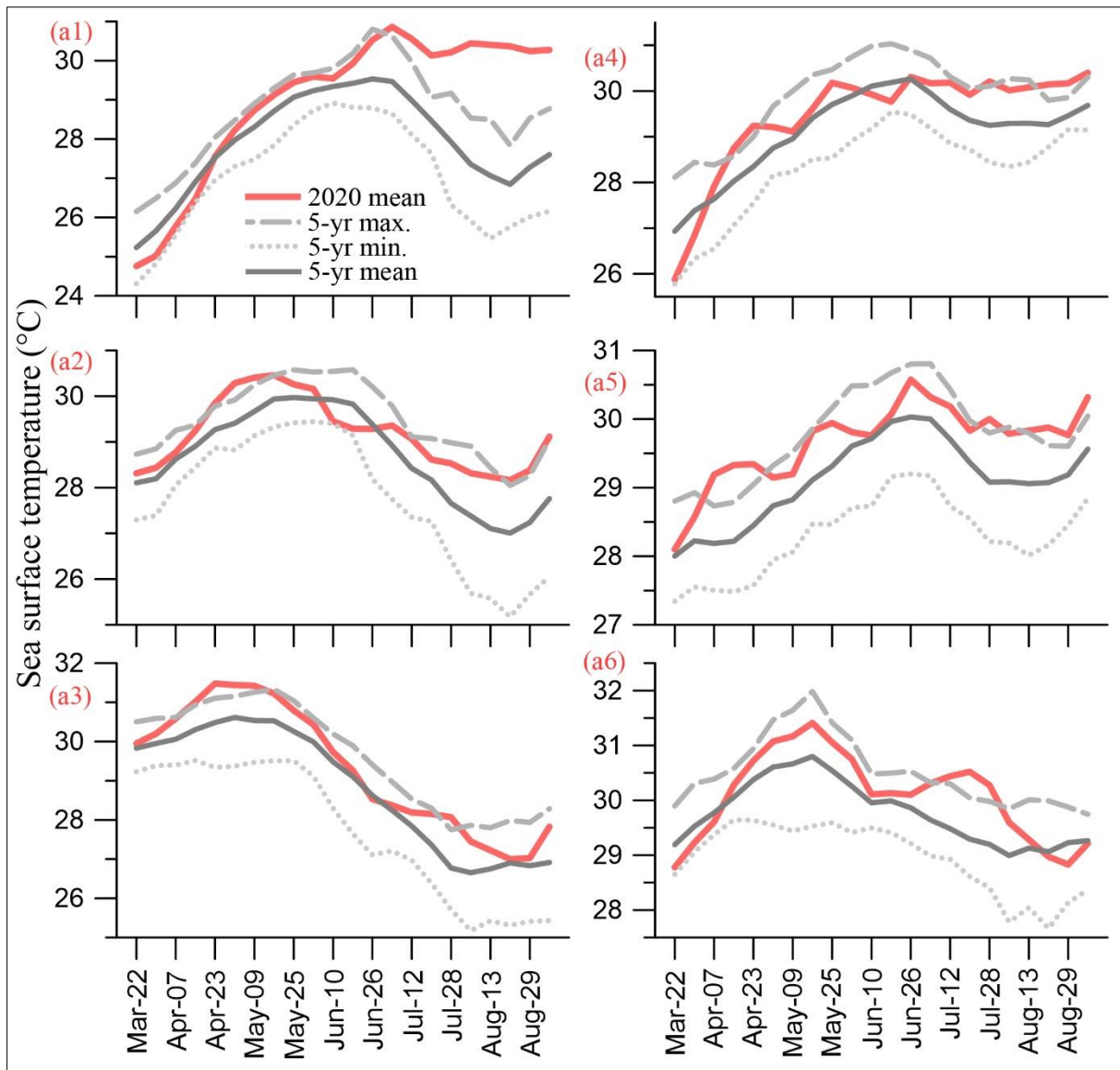
	a1	a2	a3	a4	a5	a6
AIRT	0.35 (-0.9)	0.24 (-1)	0.23 (0.5)	0.02 (-1)	0.15 (-0.5)	0.97 (0)
AOD	<0.001 (-41.6)	<0.001 (-30.1)	<0.001 (-18)	<0.001 (-12.8)	<0.001 (-18.3)	<0.001 (-14.8)
SST	0.06 (3.7)	0.05 (2)	0.18 (2.1)	0.54 (0.8)	0.03 (1.9)	0.18 (1.1)
PPT	0.02 (62.7)	0.19 (21.1)	0.37 (9.9)	0.8 (2.9)	0.45 (9.3)	0.69 (-4.7)
PIC	0.09 (71.2)	0.46 (23.1)	0.72 (-13.8)	0.14 (112.6)	0.03 (-34.5)	0.37 (-13.3)
POC	0.29 (16.3)	0.5 (-14.5)	0.48 (-23.4)	0.16 (121.1)	0.35 (36.2)	0.33 (-25.8)
Chl-a	0.49 (7.8)	0.17 (-14.9)	0.86 (-4)	0.01 (25.9)	0.4 (-9)	0.8 (4.6)



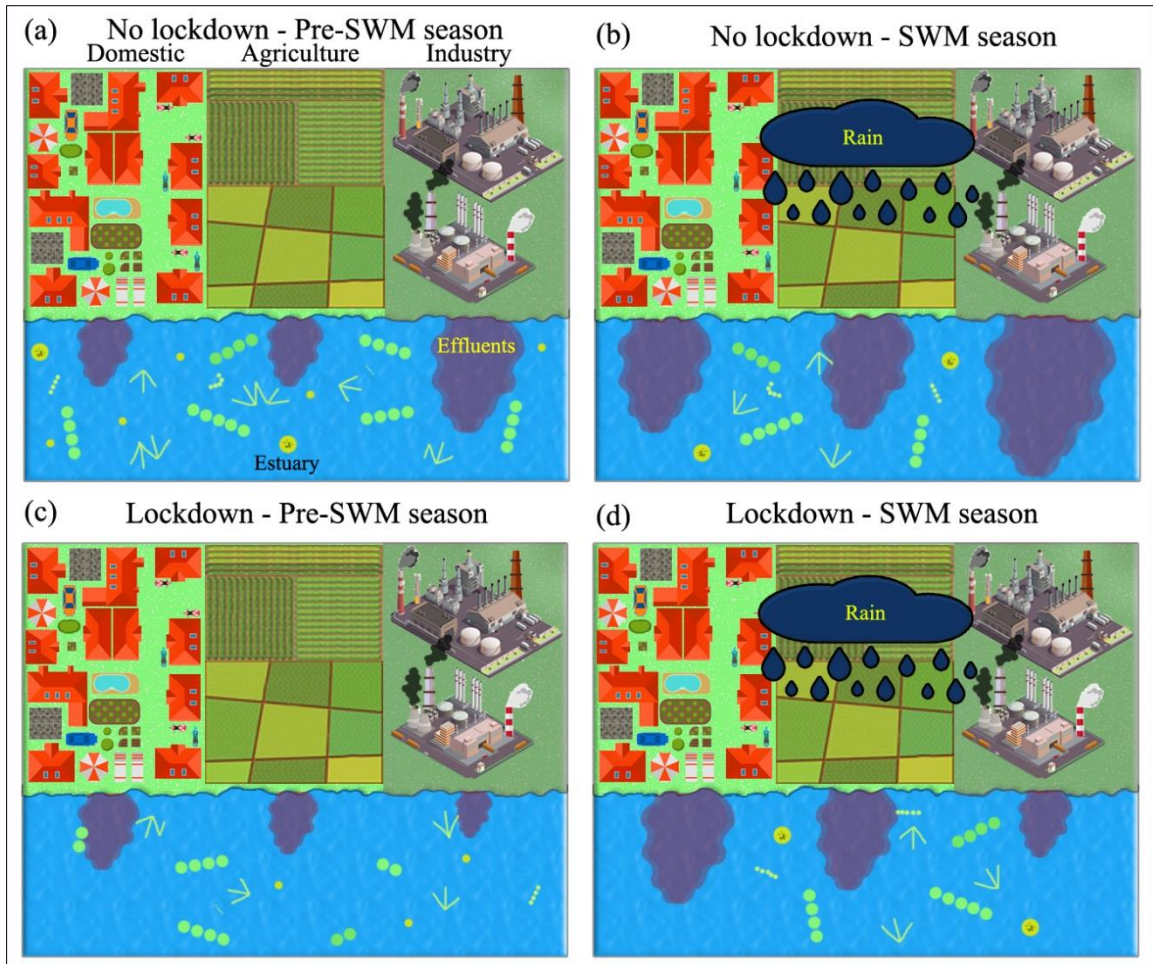
Supplementary material 1 - The running mean of air temperature distribution during 2020 (red) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.



Supplementary material 2 - Running average distribution of particulate organic carbon during 2020 (blue) and recent 5-years in the Indian coastal sub-regions (a1-a6). Refer web version for legend interpretations.



Supplementary material 3 - The running mean of sea surface temperature distribution during 2020 (red) and recent 5-years (mean, minimum and maximum) in the Indian coastal regions (a1-a6). Refer web version for legend interpretations.



Supplementary material 4 - Schematic picture represents the effluents releases from domestic, agricultural and industrial sectors during (a) no-lockdown and no-rainfall (Pre-SWM), (b) no-lockdown and rainy (SWM), (c) lockdown and no-rainfall (Pre-SWM), and (d) lockdown and rainy (SWM) situations in to the estuary.

Research highlights

- Compared satellite derived environmental quality parameters during lockdown (2020) with recent 5-years (2015-2019).
- Measured and compared nutrients and chlorophyll-*a* concentration in a tropical estuary during lockdown with past studies.
- Aerosol optical depth was significantly decreased during lockdown period.
- Rainwater washed the previously used/stored sources to the estuary which is neutralizing the lockdown effects on nutrients/pollutants input to the estuary.
- There is no significant change in the *in-situ* and satellite derived chlorophyll-*a* biomass due to short period of lockdown.