Total Suspended Matter Distribution in the Hooghly River Estuary and the Sundarbans: A Remote Sensing Approach

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***Abstract*—Monitoring of total suspended matter (TSM) concentration in the coastal waters is vital for water quality monitoring and coastal management. In this study, TSM over the highly dynamic Hooghly estuary region is derived using moderate resolution imaging spectroradiometer (MODIS) surface reflectances at 645 nm and *in situ* TSM observations. MODIS TSM products show a correlation of 0.95, root-mean-square error of 24.72 g/m^3, and mean absolute and percentage errors of 18.25 g/m^3 and 23.2%, respectively, when compared with *in situ* measurements. Subsequently, TSM variability in the Hooghly estuary from the derived TSM maps was analyzed during the period 2003–2018 on monthly and seasonal time scales. The annual cycle of TSM showed peak concentration (>250 g/m^3) during the southwest monsoon season that could be attributed to large-scale river discharge as compared with the northeast and intermonsoon seasons (∼100–150 g/m^3). Interannual variability showed higher TSM during the years 2004, 2012, and 2013 and low during 2005 and 2015. It could be concluded that the fine tuning of the existing TSM retrieval algorithm is essential based on the long-term earth observation data for monitoring the sediment distribution in the coastal and estuarine regions utilizing available satellite observations, particularly in the highly turbid estuaries, such as the Hooghly estuary.**

***Index Terms*—Hooghly estuary, moderate resolution imaging spectroradiometer (MODIS), sundarbans, total suspended matter (TSM).**

I. Introduction

MONITORING and assessment of suspended sediments are pursued across different estuaries and coastal regions of the world using *in situ* observations. However, *in situ* data-based approaches are insufficient to estimate the complex dynamics of the suspended sediments owing to their limited spatial and temporal coverage. This limitation could be overcome by the usage of multitemporal remote sensing data that are available at high spatial and temporal resolutions with good coverage. Although satellite remote sensing observations cannot entirely replace *in situ* measurements, they provide an alternate and effective means for monitoring the distribution of total suspended matter (TSM) at multispatial and temporal scales. Particularly, this is not feasible with the traditional observational sediment sampling techniques and *in situ* measurements [1], [2]. The application of remote sensing technique for mapping TSM has gained importance in water quality-related studies pertaining to coastal areas as well [3]. The major limitations of satellite-based studies are in terms of the information being restricted to the surface waters alone in addition to the need for proper corrections in the parameter retrieval from satellite imagery. However, an integration of satellite-derived products with *in situ* observations has enabled researchers to generate a wealth of data in the coastal and estuarine waters in recent years, thereby resulting in more effective analysis of the suspended sediment dynamics in regional waters.

The availability of observations from a moderate resolution imaging spectroradiometer (MODIS) remote sensing platform has provided a unique opportunity to monitor the sediment dynamics for more than a decade and a half continuously [4]. Several researchers used these data products for the estimation of TSM concentration in different estuaries across the global oceans [5]–[8]. All of these studies primarily focussed to analyze the distribution of TSM concentration or turbidity in the coastal and estuarine regions dominated by river discharges utilizing MODIS surface reflectances and *in situ* observations through the development of regional suspended sediment retrieval algorithms. Region-specific algorithms are specifically necessary to capture the variations induced by hydrographical and optical properties that are unique to the corresponding regions [7]. Furthermore, in the absence of a globally valid operational algorithm to retrieve turbidity products, analysis of sediment dynamics in the different coastal regions also required the generation of regional products. Given the strong dependence of MODIS TSM retrieval algorithms, the present study was carried out to fine tune an existing TSM retrieval algorithm based on MODIS reflectance for the highly dynamic Hooghly estuarine region and calibrate it with *in situ* observations. Furthermore,

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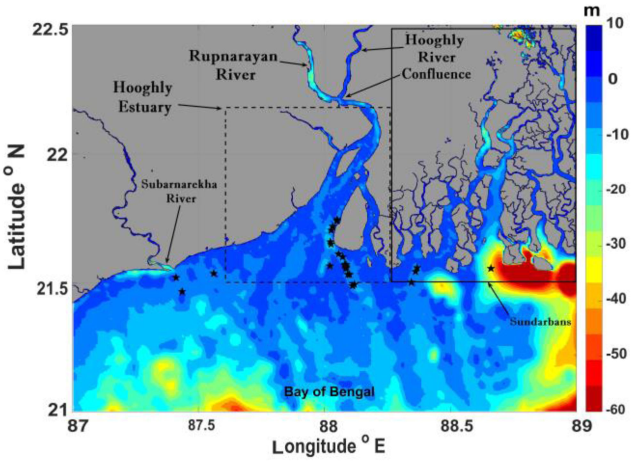

Fig. 1. Study area (87 °E–89 °E and 21 °N–22.5 °N) showing the Hooghly estuary region [box: 87.7 °E–88.2 °E and 21.5 °N–22.2 °N] and the Sundarban region (88.2 °E–89 °E and 21.5 °N–22.5 °N). Bathymetry is overlaid. Black stars indicate the *in situ* sampling locations.

the variability of TSM in this region located in the head Bay of Bengal (BoB) was analyzed from the long-term data retrieved from MODIS using our modified algorithm. This work aims to analyze the variability of suspended sediments at monthly and seasonal scales from MODIS reflectance utilizing a region-specific improved TSM algorithm and reliable *in situ* time-series observations encompassing more than 15 years of consistent observations in the Hooghly estuary and its adjacent regions.

II. Study Area

The Hooghly estuary and adjoining Indian part of Sundarbans lying within 21.00 °N and 22.50 °N latitudes and 87.00 °E and 89.00 °E longitudes is the region of the present analysis. Hooghly estuary is a funnel-shaped estuary and it is the first deltaic offshoot of the river Ganges (see Fig. 1). The Ganges, being a perennial river, discharges water into this estuary throughout the year, including the lean period (February–May) and is regulated at Farakka barrage [9]. This is a well-mixed estuary with a depth of ∼6 m [10] and drains a catchment of around 6×10^4 km^2 with a semidiurnal tidal system ranging from 5.2 m at spring to 1.8 m at neap [11]. The study region experiences three major seasons classified as premonsoon (March–May), monsoon (June–September), and postmonsoon (October–January) as suggested by Mukhopadhyay *et al*. [11], Rakshit *et al*. [12], and references therein. The southwest monsoon (SW: June–September) is dominant by heavy rainfall. The premonsoon season (March–May) is a dry period and the postmonsoon season (October–January) is prevailed by lower temperature and precipitation [13]. During the monsoon season, average rainfall in this region is ∼1700 mm, which is approximately 70%–80% of the annual rainfall [12], resulting in relatively higher discharges of 3000 $\pm$ 1000 m^3/s. On the contrary, during the lean period of the premonsoon season, the discharge is minimal at 1000 $\pm$ 80 m^3/s [11], [13], [14]. The currents in the Hooghly estuary are greater than 100 cm/s irrespective of the season during both ebb and flood tide conditions [10].

The river discharge in the Hooghly estuary is accompanied by higher sediment loads of approximately 65.19×10^6 tons deposited uniformly in the region of which 88% could be accounted for by the discharge during the SW monsoon [11]. Furthermore, during the SW monsoon period, tidal force diminishes considerably due to the massive riverine discharges into the BoB. Studies on TSM concentration and water quality of the Hooghly estuary were carried out by several researchers mainly using *in situ* measurements [13]–[15]. Pitchaikani *et al*. [16] assessed the suspended sediment concentration in this region based on Oceansat-2 ocean color monitor and field observations for the year 2014. Poddar *et al.* [17] have analyzed the short-term chlorophyll-*a* concentration variability from Landsat-8, Sentinel-2 and COMAPS observations in the region. However, most studies are limited to the time of observations and did not discuss the long-term variability of TSM. Chacko and Jayaram [18] assessed the seasonal and interannual variability of TSM in the northern coastal BoB using global TSM products available from GlobColor [19] (GlobCOLOR: An EO-based service supporting global ocean carbon cycle research) data for the period 2003–2011. However, this product is not validated for the study region. It is quite evident from the literature that studies on the use of long-term satellite data for TSM variability in the Hooghly estuarine and Sunderban region, in particular, are missing/limited. Hence, in this study, long-term MODIS time-series observations were exploited to study the seasonal and interannual variability of TSM in the Hooghly estuary and the adjoining Sundarban region along with their validation. The present study also envisages calibration of a single-band regional scale algorithm for TSM retrieval using MODIS-Aqua reflectances ($\lambda =$ 645 nm) by the existing *in situ* measurements in this region.

III. Data

Medium-resolution optical remote sensing imagery is suitable for studying the temporal fluctuations in coastal waters [20]. In this study, surface reflectance values at 250 m spatial resolution (MYD09GQ) from MODIS-aqua data obtained from the Land Processes Distributed Active Archive Centre (LP-DAAC) of the U.S. Geological Survey (USGS) and NASA are used for assessing the TSM in the Hooghly estuarine region during the period 2003–2018. The MYD09GQ daily surface reflectance product comprises reflectance data for two bands centered at 645 and 858.5 nm. The MYD09GQ is a georeferenced surface reflectance product and corrected for aerosols effects, Rayleigh scattering, absorption, atmospheric coupling effects, and contamination by thin cirrus clouds following the work of Vermote *et al*. [21]. This product has also been identified to be appropriate for application in turbid coastal waters [22].

TSM retrieval was carried out using 645 nm (Red) data after applying georeferencing and atmospheric corrections, as suggested by Yang *et al*. [8], [21], [22]. These data are highly useful for studying turbid coastal waters as the measurements in these bands do not saturate in turbid waters [23], [24]. The MYD09GQ data were reprojected from the sinusoidal grid to WGS-84 and further processed using SeaDAS 7.4 package [25] that includes the necessary tools to generate MODIS-level 2B datasets [5].

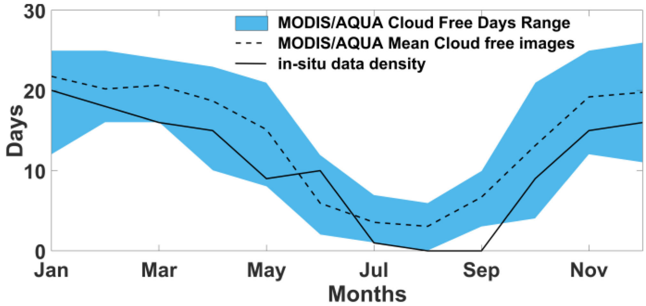

Fig. 2. Average number of valid observations in the long-term monthly mean TSM. Dotted line denotes the average number of observations from MODIS AQUA, and the thick black line represents the average *in situ* observations during the study period.

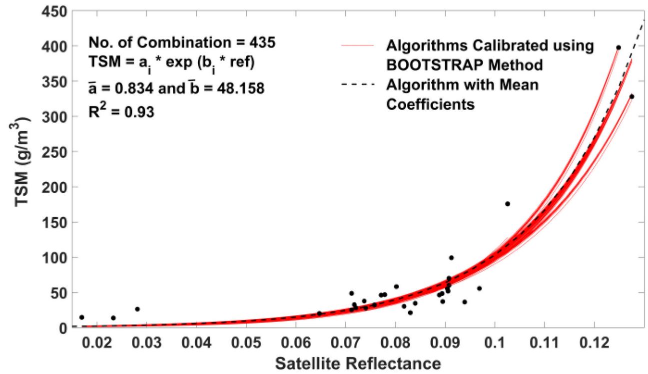

Fig. 3. Exponential model between MODIS reflectance data and *in situ* observations, calibrated using the bootstrap method. a_i and b_i are the coefficients for each iteration, while $\bar{a}$ and b are their respective averages.

The *in situ* data comprising biogeochemical parameters, such as Chlorophyll and suspended sediment concentration, were collected under the COMAPS program of the Ministry of Earth Sciences, Government of India [26]–[29]. Seasonal observations in the Hooghly estuarine region were carried out at different locations, as shown in Fig. 1. The data collection protocols are discussed in detail by Kaisary *et al.* [29]. A total of 249 *in situ* data samples were collected during the period 2002–2010 in the study region. Furthermore, 2683 noncloudy MODIS images were also obtained during the study period. The utilization of both the datasets resulted in a total of 30 matchups between *in situ* and MODIS satellite observations for the entire study period considering cloud-free conditions and collocation criteria of ± 2 h from the *in situ* sampling time to satellite overpass, as suggested by Chen *et al.* [5]. Thus, in the absence of simultaneous *in situ* reflectance and TSM data, a model was developed to fit the collocated satellite-detected water leaving reflectance with *in situ* TSM data following the work of Manzo *et al.* [2] and Chen *et al.* [5]. Bootstrap combinations of the collocated datasets were considered for the calibration of the TSM algorithm following the articles presented in [5] and [30], which are detailed in Section IV.

IV. Results and Discussion

A. Calibration of TSM Retrieval Algorithm

Various TSM retrieval algorithms were developed using the relation between MODIS reflectance measurements and *in situ* observations for different regions of the world [3], [8], [30]–[33]. In the study region, TSM retrieval algorithm was developed based on the MODIS single-band reflectance in the red region (λ = 645 nm) and the available *in situ* observations through regression-based best-curve fit method and is given as follows:

$$\mathrm{TSM} = a * e^{b*\mathrm{ref}} \tag{1}$$

where TSM is the total suspended matter concentration in g/m^3, ref is the surface reflectance (reflectance units), and a and b are the calibration coefficients. Nearly, 2683 noncloudy MODIS images were obtained during the study duration after eliminating the data for cloudy days.

The monthly distribution of *in situ* and satellite data for the period of collocation (2003–2010) is shown in Fig. 2. It is evident from the figure that the data availability is low during the SW monsoon season and relatively high in the pre- and postmonsoon seasons. The lesser number of observations for both satellite and *in situ* could be attributed to the extensive cloud cover over this region during monsoon season in addition to the fact that the *in situ* data collection during this period also becomes cumbersome, thus resulting in 30 matchups between both the datasets for the study.

Calibration coefficients of the TSM algorithm were obtained using the bootstrap iteration method [5], [30]. The observational dataset is resampled 435 $\times$ after selecting the optimum number of observation points for the calibration and validation datasets, following which the calibration coefficients were not found to improve appreciably [30]. The mean of all the iterations from the bootstrap method (see Fig. 3) was then computed to arrive at the final calibration coefficients ($a = 0.834$ and $b = 48.158$). The final recalibrated algorithm showed root-mean-square error (RMSE) of 24.72 g/m^3 and correlation coefficient (R) of 0.95 with mean absolute error (MAE) of 18.25 g/m^3 and mean percentage error (MPE) of 23.2% when compared with the *in situ* data. RMSE, MAE, and MPE were computed using the expressions as follows:

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{N} \frac{(X_i - Y_i)^2}{N}} \tag{2}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{N} |X_i - Y_i|}{N} \tag{3}$$

$$\mathrm{MPE} = \frac{100\%}{N} \sum_{i=1}^{N} \frac{X_i - Y_i}{X_i} \tag{4}$$

where X_i is the actual value, Y_i is the predicted value, and N is the number of samples.

Comparison between the TSM obtained by the fine-tuned algorithm and *in situ* TSM observations showed good correlation and good regression estimate, thereby validating the adaptability of the proposed TSM algorithm (see Fig. 4). Daily TSM values from MODIS reflectance for the study region were then retrieved

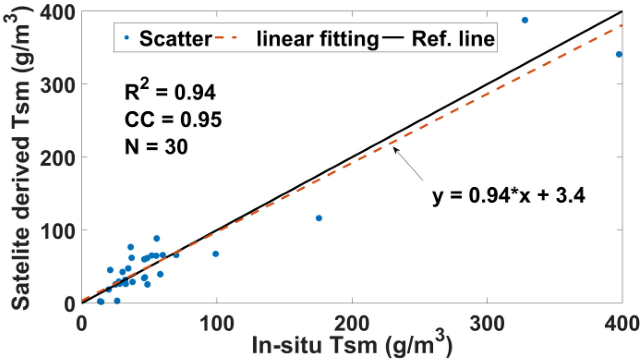

Fig. 4. Scatters between *in situ* and model-derived TSM concentration.

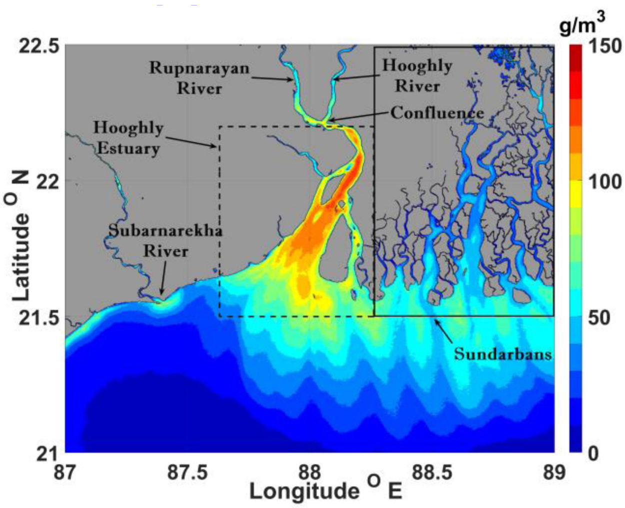

Fig. 5. Mean TSM in the Hooghly estuary and its adjacent regions for the period 2003–2018.

for the entire study period 2003–2018 using the proposed regionally fine tuned, calibrated, and validated single-band TSM retrieval algorithm. Subsequently, retrieved daily TSM values were used to study the long-term variability of TSM in the Hooghly estuary and the adjoining Sundarban region during the study period of 15 years. These daily data were also used to compute monthly and seasonal mean TSM concentration that was subsequently utilized to generate the monthly and seasonal climatology of TSM concentration for analyzing the temporal variability over the study region.

B. Monthly and Seasonal Distribution of TSM

The mean TSM concentration computed for the entire study period (see Fig. 5) showed large variations in the Hooghly estuarine region with the maximum values greater than 150 g/m^3 in the lower parts of the estuary, decreasing further toward the upstream with values ranging from 40 to 100 g/m^3. The Hooghly estuary is fed by two major river systems, namely the Hooghly/Ganges and the Roopnarayan, as also seen in Fig. 5. The abundance of TSM was observed to begin at the confluence of Roopnarayan and Hooghly rivers that increased further downstream. The influence of river discharge on TSM is also evident from the higher concentrations off the mouth of the Subarnerekha river. The creeks inside the Sundarban mangrove region showed relatively less TSM concentration compared with the Hooghly river. Variations in the TSM distribution over Hooghly estuary could possibly be attributed to the discharge originating in the river, while it is absent in the case of the creeks in the Sundarbans [18].

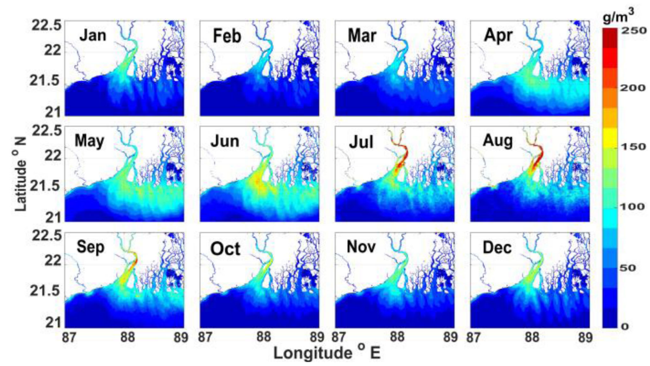

Fig. 6. Distribution of TSM monthly climatology in the Hooghly estuary and its adjacent riverine stretch computed from the long-term monthly data during 2003–2018.

The distribution of monthly TSM climatology in the study region (generated by averaging TSM values from 2003 to 2018) is shown in Fig. 6. TSM concentration is found to be less than 50 g/m^3 during February and March within the estuary and the offshore region. An increase in the concentration is observed during the premonsoon season of April–May (100–130 g/m^3), which further enhanced up to $\sim$250 g/m^3 during the SW monsoon season (June–September).

This phenomenon could be attributed to the heavy river discharge during this period. In the figure, the mean annual discharge of river Hooghly, as measured by Rudra [34], is shown as bars that clearly reveal a strong river discharge during the southwest monsoon months. Furthermore, the analysis of Fig. 6 shows the veracity of spatial distribution in TSM wherein a distinct surge (>200 g/m^3) in TSM is observed in the riverine sections (Roopnarayan and Hooghly) during the months of July and August, that is gradually reduced by September. A similar pattern is discernable off the mouth of river Subarnarekha also.

The high TSM values of $\sim$250 g/m^3 are observed all along the stretch of the Hooghly estuary during the peak SW monsoon season, i.e., July and August months. However, the moderate concentrations of TSM were observed during the months representing the start (June) and end (September) of the monsoon season. Thus, the variability of the TSM pattern indicates that it builds up with the arrival of the summer monsoon season in June, reaching a peak during July–August when the Hooghly estuarine region is fed with full spate river discharge corresponding to peak monsoon rainfall in the catchment area. The gradual decrease in the TSM concentration in the estuarine region toward the end of the monsoon season (the month of September) signifies the role of rainfall and discharge (see Fig. 7) in the intraseasonal variability. Mean monthly TSM values in the annual cycle map are observed to be high during the SW monsoon months of June–September with a peak concentration value during July (see Fig. 7) coinciding with the annual cycle of river discharge

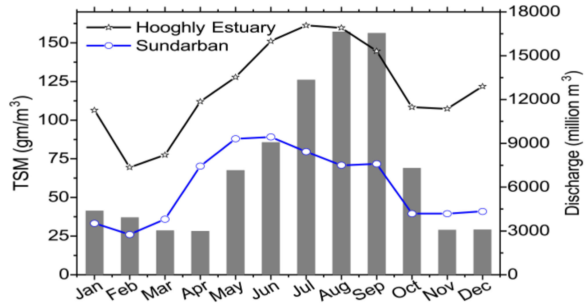

Fig. 7. Annual cycle of monthly averaged TSM (in gm/m^3) for the Hooghly Estuary and Sundarbans region. Bars represent the mean monthly discharge (in million m^3) from the Hooghly estuary into the BoB (Source: [34]).

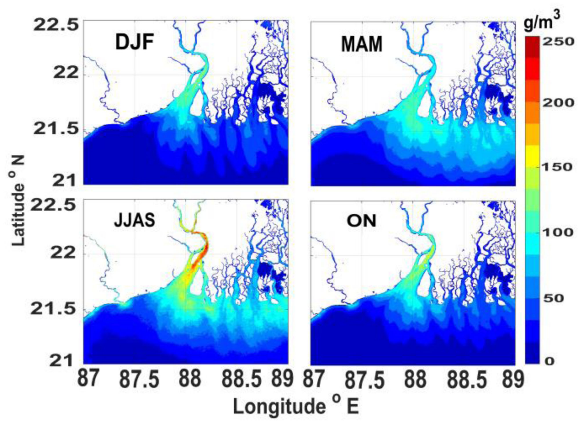

Fig. 8. Seasonal mean TSM computed from the long-term MODIS-Aqua data for the study period for Winter (DJF: December, January, and February); Summer (MAM: March, April, and May); Summer Monsoon (JJAS: June, July, August, and September), and Postsummer Monsoon (ON: October and November).

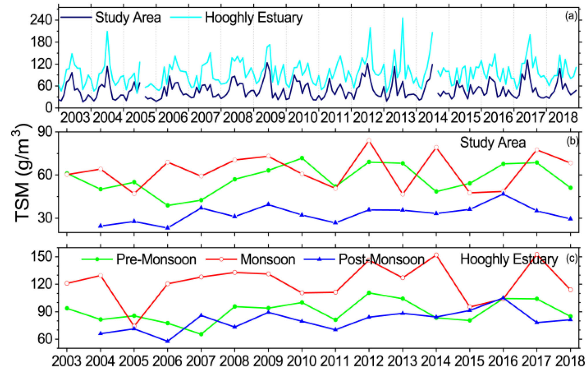

Fig. 9. Time series of MODIS-Aqua TSM. (a) Monthly and seasonal average for (b) Hooghly estuary, and (c) Sundarban region.

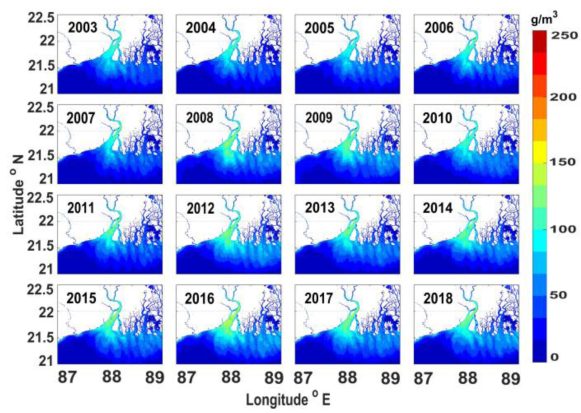

Fig. 10. Annual mean of TSM in the study region for all years (2003–2018).

[34]. Earlier, Madeswaran *et al*. [28] had reported that TSM in the Hooghly estuary could range between 8.19 and 1055 g/m^3.

The seasonal climatology computed from the long-term seasonal average for all the seasons during the period 2003–2018 is depicted in Fig. 8. The seasonal mean TSM variability in the region during October–November and December–February is similar to that of the Hooghly river estuary ($<$100 g/m^3) and Sundarban region ($<$50 g/m^3) (see Fig. 8). The lower TSM concentration in the region during these seasons could be attributed to the lower river discharge owing to lesser precipitation [11], [14]. TSM increased moderately during the premonsoon season of March–May where the concentration is observed to be $\sim$150 g/m^3 with the highest TSM concentration during June–September ($>$250 g/m^3) due to the heavy river discharge as a result of high rainfall [11], [14]. The riverine influence on TSM distribution is more prominent in the Hooghly river estuary.

C. Interannual Variability of TSM

The monthly time series of TSM concentration computed from the spatial mean for the Hooghly estuary and the Sundarban region is presented in Fig. 9(a)–(c). It is observed from Fig. 9(a) that the TSM concentration is higher in the Hooghly estuarine region compared with the Sundarban region during all the years. Higher values ($\sim$200 g/m^3) are observed during the years 2004, 2012, and 2013, while lower values are observed during 2005 and 2015 among the study years. The seasonal mean TSM computed for different seasons in the Hooghly estuarine [see Fig. 9(b)] and the Sundarban regions [see Fig. 9(c)] showed higher concentrations during SW monsoon followed by moderate values during the premonsoon and lower values during the postmonsoon seasons. TSM in premonsoon is higher than that in postmonsoon during 2005, 2010, and 2016 in the Hooghly estuarine region [see Fig. 9(b)]. While for the Sundarban region, the premonsoon TSM is higher than that in the postmonsoon season for almost all the years of study.

Furthermore, the annual mean TSM for the study period 2003–2018 is computed to decipher the spatial inconsistencies in different years and is shown in Fig. 10. From the figure, the interannual variability is profound, especially in the Hooghly estuarine region with the lowest TSM concentration during 2005 ($<$110 g/m^3) and the highest during 2016 ($>$150 g/m^3). The offshore spread of sediments is almost uniform below $\sim$21.2 °N. Another noticeable feature is the rise in TSM concentration in the Sundarban region since 2008. The differences in the spatial pattern between the Hooghly estuarine region and the Sundarban region can be attributed to the dominance of creeks and streams that are mainly fed by the tidal influx and precipitation rather than freshwater flux. TSM is low in the Sundarban region during the periods 2003–2007 and 2010, while higher sediment concentrations were observed in the years 2008, 2012, and 2016.

This analysis depicted the temporal pattern of TSM in the region with apparent interannual variability.

V. Conclusion

In the present study, TSM distribution in the Hooghly estuary and adjoining Sundarbans region was assessed using MODIS 250 m spatial resolution (MYD09GQ) reflectances at $\lambda = 645$ nm (red) imagery and the available *in situ* TSM observations in the study area through a regionally fine tuned, calibrated, and validated single-band algorithm for TSM retrieval from MODIS reflectance during the period 2003–2018. The single-band exponential algorithm was calibrated using the bootstrap iteration method between *in situ* TSM and satellite reflectance. TSM derived from this algorithm shows a correlation of 0.95 with an RMSE of 24.72 g/m^3, mean absolute error of 18.25 g/m^3, and mean error percentage of 23.2% with reference to *in situ* observations. Daily TSM products for the period 2003–2018 were then retrieved from MODIS-Aqua reflectances, which were further analyzed for spatiotemporal distribution in the region.

TSM monthly climatology revealed the varied spatial distribution of sediments in the estuary and Sundarban region. Sediment surge was observed from the start of the confluence of Roopnarayan and Hooghly rivers to downstream, coinciding with the SW monsoon season. The high concentration of TSM ($>$250 g/m^3) was observed in the Hooghly estuary during the months of July and August and low during February and March ($<$50 g/m^3). The annual cycle of TSM variability showed gradual enhancement from premonsoon ($\sim$150 g/m^3) to monsoon ($\sim$250 g/m^3), which decreased thereafter. The monthly time series of TSM showed higher sediment concentration in the Hooghly estuary as compared with the entire study area with peak concentrations during the years 2004, 2012, and 2013 and lower values during 2005 and 2015, respectively. The annual averages computed for the study area showed a distinct interannual variability in the spatial distribution of TSM with higher values during 2016 ($>$150 g/m^3) and lower during 2005 ($<$110 g/m^3) that could be due to the variations in river runoff.

This work demonstrates the mapping and monitoring of TSM using long-term ocean color satellite measurements and *in situ* data in the highly dynamic and least studied Hooghly estuary and Sundarban regions. The study emphasizes the fact that the analysis of long-term satellite retrieved TSM would not only help in building the knowledge base on the sediment dynamics in the coastal regions but also enhance the awareness of the changes in the environment.

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