Lead Author : Laurent Testut(1)
Contributors : Mélanie Becker(1), Jamal Khan(1), Celine Grall(1,2), Nathalie Long(1), Yann Krien(3), Fabien Durand(3), Valérie Ballu(1), Mikhail Karpytchev (1), Stéphane Calmant (3), CK Shum(4)
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Affiliations:

1. LIENSs UMR 7266, CNRS- La Rochelle University, 17000 La Rochelle, France
2. LDEO of Columbia University, Palisades, NY, USA
3. LEGOS UMR 5566, CNRS/CNES/IRD/UPS, 31400 Toulouse, France
4. Division of Geodetic Science, School of Earth Sciences, The Ohio State University, Columbus, OH 43210, USA

Title: Sea level variations in the Sundarbans

Abstract:

In this chapter we will review the main factors that affect the sea level at different time scales in the Sundarbans region. We will show that on average over the past millenia, the tidal part of the Ganges-Brahmaputra-Meghna delta has been aggrading during the mid Holocene and have progradated during the late Holocene and is roughly subsiding at 4 ± 1.4 mm/a. This value is twice higher than the subsidence in the upper part of the delta 2 ± 0.7 mm/a. From the last few decades, the use of the tide gauge records and satellite altimetry demonstrates that the sea level is rising at rates comparable with the global mean sea level which makes this region particularly sensitive to sea level rise due to the land subsidence pattern and the flat topography. We the help of high-resolution numerical ocean simulation we are also able to better characterize the tidal pattern in the Sundardans and draw future scenarios of the tidal evolution and extreme water level events.

1: Introduction

Sundarbans, a UNESCO World Heritage Site since 1987, is the world’s largest mangrove forest (Figure 1). This unique ecosystem situated in the Ganges-Brahmaputra-Meghna (GBM) delta spreads across the border of Bangladesh and India. It is known for its diverse wildlife including the Bengal tiger, and is emerging as a vulnerable ecosystem impacted by climate change (Hussain and Islam, 2020). Sundarbans is also home to several million people, many of whom depend on the resources provided by the forest. Many households have depended on this ecosystem for decades for their livelihoods and income-generating activities, such as wood collection, shrimp and crab fry fishing, and plant and fruit collection (Mallick et al., 2021).

The Sundarbans Forest has been through several periods of management, ranging from the conversion of the ecosystem to agriculture in the late 18th to late 19th centuries, to extraction of wood until the mid-1950s, before entering periods of successive inventories and then integrated management and co-management with local communities in the late 20th century

(Mahmood et al., 2021). Since 1966, the forest department has established a mangrove planting program to reconstitute “a coastal green belt”. Indeed, mangroves play an essential role in mitigating the impacts of extreme events (Rahman and Rahman, 2015). However, these programs are not effective: the species planted are not adapted to withstand cyclones, they are non-native species and their establishment is not optimal (space between trees too small, establishment near banks or on forest edges), which makes them more vulnerable to cyclones (Rahman and Rahman, 2015; Halder et al., 2021). Despite the determination to preserve this ecosystem, many problems persist, such as overexploitation of resources, the presence of invasive species, poaching and trafficking of species, pollution, and uncontrolled tourism (Rahman and Rahman, 2015; Mahmood et al., 2021). Studies of forest dynamics, in terms of changes in forest density and area covered, species composition, diversity and distribution, show a tendency to be increasingly vulnerable during cyclones. As salinity increases, the Sundarbans tend to be increasingly dominated by more salt-tolerant species and less commercially interesting tree species (Sarker et al., 2019; Mahmood et al., 2021). Using remote sensing approaches, Hussain and Islam (2020) showed that Cyclone Sidr in 2007 damaged 31% of the total forest area resulting in an increase in low-density forest. Remote sensing was also used by Samanta et al. (2021) to show a persistent trend of deterioration over the period 2000-2020 which is driven by the combined effect of an increase in salinity, a temperature rise, and rainfall reduction in the pre-monsoon and the post-monsoon periods. The degradation is more pronounced in the sea-facing parts of the mangrove forests.

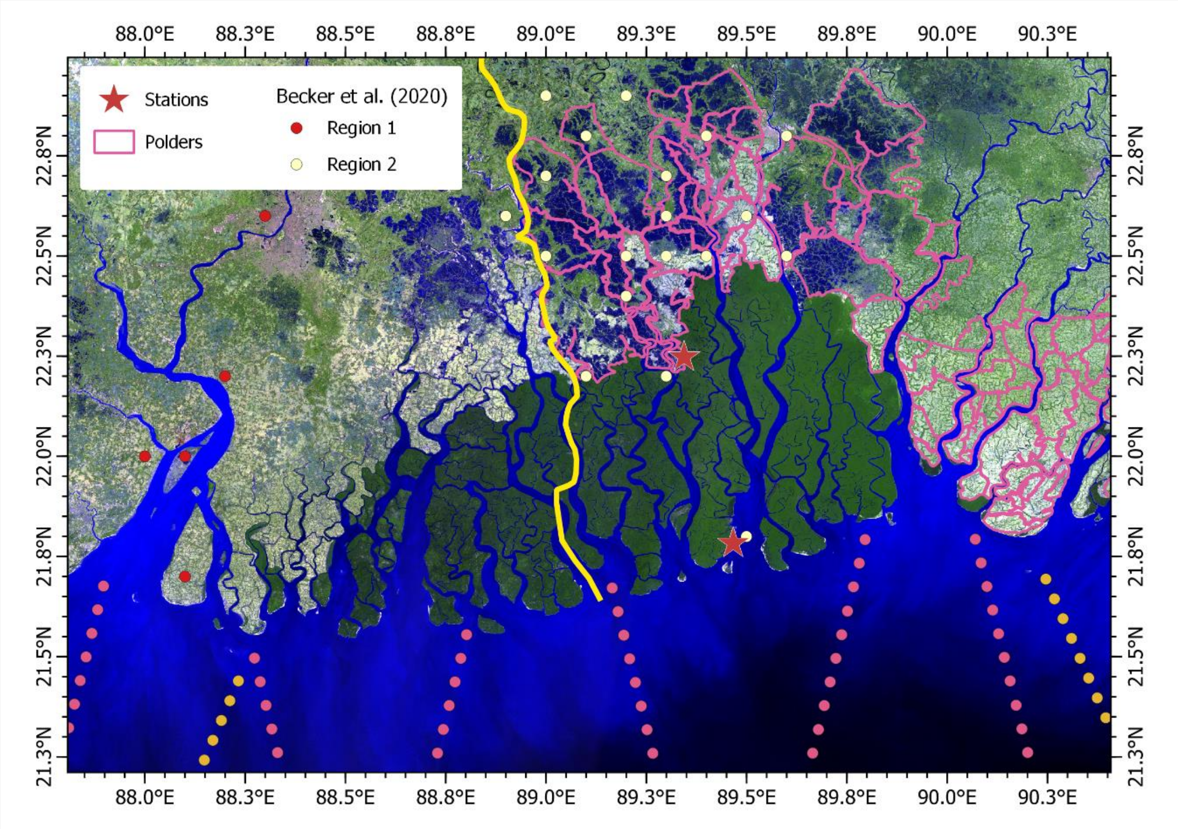

Figure 1 : Satellite map of the Sundarbans showing the limit of the polders, the tide gauges stations discussed in the text and on the seaside the points corresponding to the tracks of the principal satellite altimeters mission

Thanks to the increase of freely available high resolution remote sensing dataset in the last two decades the Sundarbans region has been increasingly studied and present in the scientific literature and its change in response to climate related factors (rain, sea level, temperature, salinity, …) has been clearly demonstrated. Among all these factors, the variation of the sea level at the coast is of primary importance. Indeed, from the high frequency tide which rhythm the daily dynamic of the Sundarbans ecosystem and controls the distribution of mangroves, aquatic lives and much more to the long-term increase in sea level which come with increasing sea temperature and landward displacement of the salinity front (Sherin et al., 2020), the sea variation has a strong impact on the Sundarbans at all time scales.

The main objective of this chapter is to present the state of the art of the knowledge about the sea level variations at different time scales in the Sundarbans region. Most of the knowledge presented below has been consolidated since 2012 through the Belmont Forum BANDAID project, a research initiative aimed at improving our understanding of the interactions between the ocean and atmosphere in the Bay of Bengal. The project specifically focuses on the Bay of Bengal, one of the world's most dynamic and complex coastal systems, and aims to improve our understanding of the processes that control the interactions between the ocean and atmosphere in the region (https://www.belmontforum.org/projects).

In the first section an overview of the relative sea level variation over the last millennia, the period during which the present-day main features of the delta were shaped, will be given as well as a coarse idea of the subsidence pattern over the whole delta. In the second section, based on the few instrumental records available (tide gauges and satellite altimetry) we will review the present-day estimation of the sea level rise. Then high frequency variation of the sea level will be reviewed for the tides (section 3) and extremes events (section 4).

2: Relative mean sea level rise and land subsidence pattern in the last millenia

The tidal part of the delta is a low-lying land with an average regional slope of ~10-4 (Wilson et al., 2015), one order of magnitude lower than the fluvial domain of the GBM (Grall et al., 2018). Relative Sea Level (RSL) history over the Holocene has been reconstructed according to tube-wells stratigraphic data over the whole delta and in particular in the tidal domain of the delta. Holocene stratigraphic history over the tidal part of the delta is characterized by a pattern of sediment accumulation that mimics the evolution of the mean Absolute Sea Level (Grall et al., 2018). During the rapid sea level rise in the mid Holocene with rate > 1 cm/yr (Goodbred and Kuehl, 2000), sediment accumulated at a fast rate while during the late Holocene, when sea level rose at a slower rate (< 1 mm/yr), sediment accumulated at a lower rate (Grall et al., 2018, Pickering et al., 2014). This is in agreement with the stratigraphic model proposed by Goodbred et al., 2003 in which the tidal domain of the delta has been aggrading during the mid Holocene and have progradated during the late Holocene.

The RSL reconstructions during the Holocene allows on estimating averaged subsidence rates and patterns over the tidal part of the delta (Grall et al., 2018). Subsidence gently increases in the seaward direction and average value over the tidal domain is 4 ± 1.4 mm/a. This value is twice higher than the subsidence in the upper part of the delta 2 ± 0.7 mm/a. The potential driven forces of the subsidence have been evaluated and a particular attention has been done to the role of sediment isostasy. Sediment isostasy may contribute to one third of the total subsidence (Karpytchev et al., 2018 and Steckler et al., 2022). The complex tectonic setting of the region can increase the value of subsidence driven by sediment isostasy, as tectonic may localize the subsidence in a narrower domain (Krien et al., 2019).

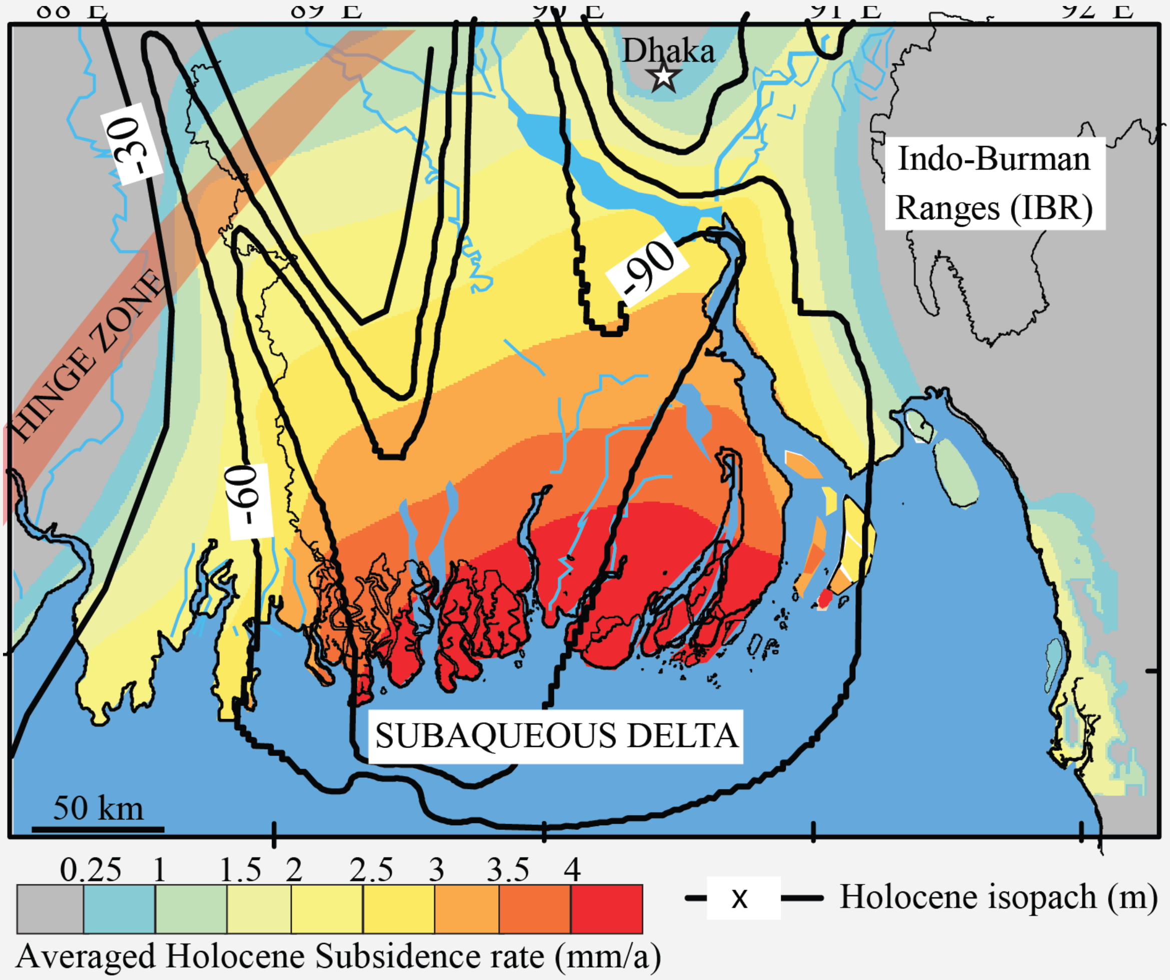

Figure 2: Averaged Holocene Subsidence rates and Holocene isopach (in meter relatively to present topography) over the GMB Delta (adapted from Grall et al., 2018). The Holocene subsidence and sedimentation have been determined from a large exploration of the tube well records and multichannel seismic data over the delta (refer to Grall et al., 2018, Pickering et al., 2018, Steckler et al., 2022 for more details).

2: Present day sea level rise

2.1 from tide gauge observation

Along the Hooghly River, in the Indian part of Sundarbans, the local RSL trends were estimated, from upstream to downstream, from 0.9 to 5.2 mm/yr, based on tide gauges with records longer than 25 years, i.e. Diamond Harbour (70 km from the sea), Haldia and Gangra (31 km from the sea coast) stations (Unnikrishnan & Shankar, 2007; Nandy & Bandyopadhyay, 2011; Becker et al., 2019). Pethick and Orford, (2013) showed a rapid RSL rise in the Sundarbans area. They used the only three available tide gauges, provided by Institute of Water Modelling of Bangladesh: Hiron Point (34 years), Mongla (20 years) and Khulna (72 years). Pethick and Orford, (2013) found strong local RSL trends of about: 8mm/yr at Hiron Point (at the mouth of Pussur Estuary), ~6mm/yr at Mongla and ~3mm/yr at Khulna (located 120 km inland), but some of these high rate of RSL rise are questionable and may have been influenced by the dubious quality of some part of the dataset. Becker et al., (2020), from regional water level reconstructions over 1968-2012 (45 yr), by using a set of 25 river and tide gauges, showed a rise in relative water level (RWL) in the Bangladeshi part of the Sundarbans of 2.7±1.3 mm/year and of 2.1±0.8 mm/year in Indian part (along the Hooghly river), increasing at approximately the same pace that the global mean sea level over the same time period (See Figure 1 for the locations of the tide gauge used). Becker et al. (2020) have also identified two distinct regional RWL trend periods in this region: A moderate increase over the 1968 to 2004 period (~2.5 ± 1 mm/y) and a stronger increase from 2005 to 2012 (6.5 ± 3 mm/y) mainly due to wind-driven redistribution of heat within the Indian Ocean observed during this period (Srinivasu et al., 2017). Moreover, Becker et al (2020) showed that the regional RWL variations in the Sundarbans, over 1993-2012 are very close to the absolute sea-level changes inferred from satellite altimetry data, explaining 82% and 50% of the regional RWL variance in Indian and Bangladeshi parts, respectively. Computing the difference between absolute sea level from altimetry and RWL over 1993-2012, Becker et al. (2020) estimated a maximum expected subsidence rate of 1.5 mm/y and 2.4 mm/y in Indian and Bangladeshi parts, respectively. These estimates are coherent with the average subsidence rate of 2.8 mm/yr, the lowest rate observed in Ganges-Brahmaputra delta given by Brown and Nicholls, (2015) in their review of all available data, literature and documentary sources. Assuming that the regional maximum expected subsidence rates are representative of centennial and longer periods, Becker et al. (2020) added them to sea-level projections to further refine estimates of relative sea-level rise in the GBM delta. The predicted sea-level increase (relative to the 1986-2005 from AR5 CMIP5) ranges between 14 to 30 cm by 2050 and reaches from 34 to 74 cm by 2100, under a greenhouse gas emission mitigation scenario (i.e. scenario RCP 4.5). Thus, by 2050, on the basis of the RCP4.5 scenario upper limit, the regional subsidence rates will enhance the relative sea-level rise by ~23% (~37 cm) and 36% (~41 cm) in Indian and Bangladeshi parts, respectively. By 2100, the Sundarbans area can undergo a relative sea-level rise of ~85 cm and reach as much as ~120 cm under a high greenhouse gas emission scenario (i.e., RCP8.5: 50 to 103 cm). Payo et al., (2016) have assessed, through a numerical model (including sediment supply, erosion and inundation) with different a sea level rise scenarios of 148 cm by 2100 and a subsidence of 25 cm, that the potential area loss could represent 10% of the Bangladeshi Sundarbans.

2.2 from satellite altimetry

Thanks to the advent of precise satellite altimetry at the beginning of the 1990's we now have access routinely to the quasi-global absolute sea level elevation. Many different services provide easy access to different products derived from the satellite altimetry missions. The Copernicus Climate Change Service distributes updated versions of the regional sea level trends derived from a linear fit of the altimeter sea level maps. The dataset used in this chapter is the sea level ocean monitoring indicator DUACS delayed-time (DT-2021 version) based on a stable number of altimeters (two) in the satellite constellation (Copernicus, 2022). The evolution of the sea level on the northern Bay of Bengal from this product is shown in Figure 3. If we consider the full altimetry period (1993-2022), the ASL of northern Bay of Bengal is rising at a rate ranging between 3 and 6 mm/yr. These numbers give the broad picture of the sea level rise in the region, but cannot be directly extrapolated to the Sundarbans coast for different reasons as well as it cannot be extrapolated in time. First, as shown in Figure 1 there are not many altimetry tracks reaching the Sundarbans coast, and the quality of the altimetry is known to rapidly collapse in the last 10 km from the coast (Birol et al. 2017). Secondly, even with almost thirty years of observation from altimetry, the rate of rise is highly influenced by the ocean decadal variability in this region (see Figure 3 right which shows a comparison of the annual mean sea level averaged over the globe and the northern bay of Bengal). It means that a simple linear regression over a certain period of time is only a crude estimation of the real behavior of the sea level rise at the coast. The variability of the trade winds in the Indian Ocean is able to cool or warm the ocean surface, and to decrease or increase the sea level rise for certain periods. This is what happened between 2004 and 2014 when heat built up in the northern Indian Ocean and enhanced the rate of sea level rise to value twice as large as for this period (> 10 mm/yr) compared to the precedent period (Thomson et al., 2016). We can see in this Figure the high variability of the evolution of sea level for this region, which is driven by the complex and coupled ocean-atmosphere and climate dynamic at many different spatial scales.

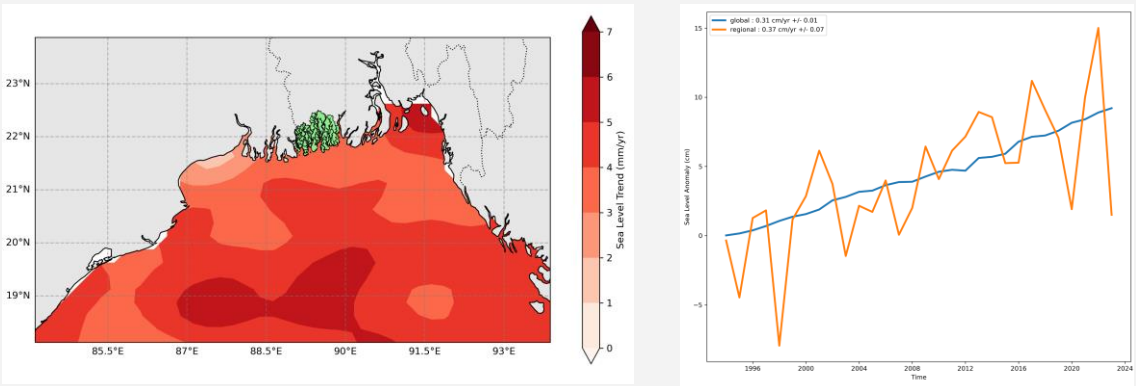

Figure 3: Left map shows the linear trend of Sea Level Anomaly (SLA) in mm/yr computed from satellite altimetry observation over the northern Bay of Bengal for the period (1993-2022). On the right side is the comparison of the time evolution of the annual mean SLA in Northern Bay of Bengal compared to the global one.

3. Tidal variability

The variability of tides inside the Sundarbans is controlled mainly by two factors - 1) the tidal condition in the southern sea-face, 2) the geometric features of the water bodies inside Sundarbans. The freshwater input from the GBM system has minor influence on the tide (Pitchaikani and Bhaskaran 2019), but will not be further discussed in this chapter.

Our knowledge of the hydrodynamical features of Northern Bay of Bengal has been improved significantly thanks to in situ and satellite observations (Antony and Unnikrishnan 2013, Antony et al. 2014), and numerical modeling efforts (Sindhu and Unnikrishnan 2013, Krien et al. 2016, Tazkia et al. 2017). The tide in this zone is semi-diurnal in nature and the tidal range varies along the coastline with two maxima (Khan et al. 2020). The Eastern Maxima is located in the mouth of the Meghna Estuary, along Chittagong coastline with a tidal range of more than 5m. The Western maxima is located in the mouth of Hooghly estuary with a tidal range about 4m. Along the open coastline of Sundarbans, tidal range varies from 2m (East) to 3.5m (West). All along the coastline, four main harmonics - M2, S2, N2, K1, O1 - are found to be the major constituents (Sindhu and Unnikrishnan 2013, Krien et al. 2016). In addition to that, the sea level also changes seasonally with an amplitude in the range of 30-40cm, which manifests itself as an annual (Sa) harmonic in tidal analysis (Tazkia et al. 2017). Expectedly, the tidal dynamics becomes increasingly complex in the estuarine systems due to the complex geometry as well as the interaction with the riverine flows (Mukhopadhyay et al. 2006, Chatterjee et al. 2013).

The Sundarban estuarine system is composed of rivers formed from the off-shoots of the Ganges-Brahmaputra-Meghna river system. The estuarine system is extremely complex, with some 100 estuaries. (On the Indian side, the major estuaries of Sundarbans are - Saptamukhi, Thakuran, Matla, Gosaba, Harinbhanga, Rajmangal. On the Bangladesh side of the Sundarbans, Kholpetua-Arpangasia, Passur-Sibsa, Balaswar are the major estuaries.) These predominantly south-north estuaries are interconnected through a network of east-west oriented rivers, channels, and creeks. A large part of the Sundarbans is intertidal - with periodic wetting and drying during high-tide and low-tide respectively. The topology of the riverine network of Sundarbans is relatively well surveyed, thanks to recent advancements in high-resolution remote sensing technologies (Figure 1, Khan et al. 2019). However, the bathymetry and topography of these rivers are not well known, with large errors in the global datasets (Krien et al. 2016). Additionally, the region surrounding the Sundarbans is often protected by embankments, whose dimension is often not well known (Richards and Flint 1990). Additionally, the region is also going through strong morphological changes due to natural processes or induced by anthropogenic activities (Wilson et al. 2017, Auerbach et al. 2015, Van Maren et al. 2023).

This knowledge gap of bathymetry and topography imposes a general limit on the realistic modeling of the tide and storm surge in this region (Khan et al. 2021). This gap in the knowledge of river bathymetry is exacerbated by general lack of water level and discharge observation in and around the Sundarbans (Chatterjee et al. 2013, Becker et al. 2020). On the Bangladesh side of Sundarbans, there are a few water level monitoring stations skirting the northern border of Sundarbans (Becker et al. 2020, Van Maren et al. 2023). For the tide gauge at Hiron Point, located in the mangroves at the mouth of the Passur-Sibsa estuary (Figure 1), hourly data is available in the global data repositories. In addition, recently another sea level observation time series at Jorshing (Kholpetua-Arpangshia estuary) is available through PSMSL (https://psmsl.org/data/gnssir/site.php?id=10361) derived using GNSS Interferometric Reflectometry (GNSS-IR). On the Indian side of the Sundarbans, no continuous monitoring stations are currently publicly available to our knowledge. Aside from these observation stations, it is noteworthy to mention the field campaign by Chatterjee et al. (2013). They have observed the water level from a network of 30 tide gauges (mostly temporary) and mapped the tidal range along and surrounding the Indian part of the Sundarbans (except the reserved forest where the access was not permitted).

The tide in the open ocean facing the Sundarbans, is semi-diurnal as shown in the time series plot of Hiron Point tide gauge in Figure 4(a) and the harmonic analysis in Figure 4(b). The amplitude of M2 and S2 at Hiron Point is 83 cm and 38 cm respectively. According to the available measurements inside and surrounding of Sundarban, the tide remains semi-diurnal in nature throughout the whole Sundarban estuarine system (Chatterjee et al. 2013, Van Maren et al. 2023). At Jorshing (northern edge of Sundarban, 50 km inland), the tide is still found to be strongly semidiurnal with an M2 amplitude of 1.45m, and S2 amplitude of 0.60m.

A tidal amplification is observed in Figure 4(b) where we compare the amplitude of harmonic constituents at the southern (Hiron Point) and northern (Jorshing) boundary of the Sundarbans. It is to be noted that Hiron Point and Jorshing are not located in the same estuary. The estuary mouth of Jorshing is about 10 km apart from Pussur-Shibsha estuary. However, based on published modeling studies (e.g., Khan et al. 2020), the tidal amplitude characteristics at the mouth of Pussur-Shibsha estuary (Hiron Point) is a reasonably good substitute for the Kholpetua-Arpangshia estuary mouth. Similar amplification is consistently found everywhere of the Sundarbans and reported in the previous studies (Chatterjee et al. 2013, Pethick and Orford 2013, Pitchaikani and Bhaskaran 2022, Van Maren et al. 2023). The very few existing modeling studies which cover the estuaries of Sundarbans also reproduce the along-channel amplification feature (Khan et al. 2020)

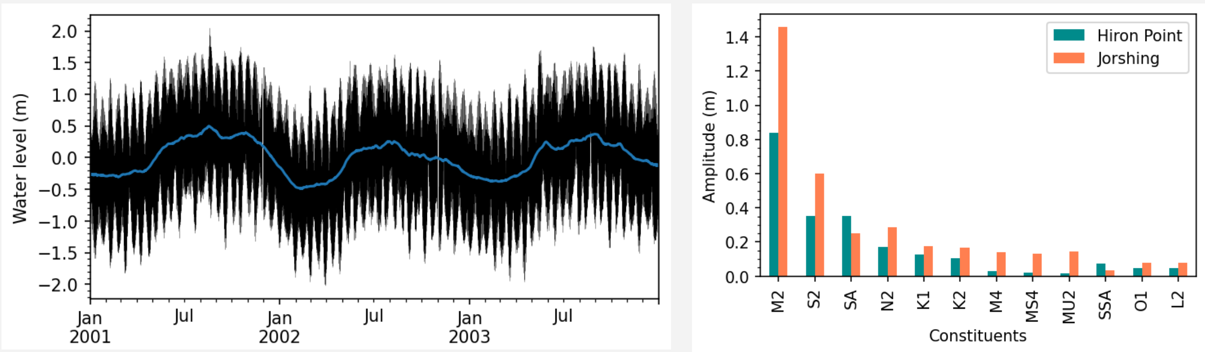

Figure 4. (a) Sea Level time series at Hiron Point and seasonal evolution (in blue) (b) Major tidal constituents at Hiron Point and Jorshing.

We can also see the seasonal variations of sea-level in Figure 4(a) in blue line, computed using a rolling monthly mean. The amplitude of this seasonal variation is captured by the Sa component in Figure 4(b). The seasonal sea-level variation is about 35 cm at Hiron Point, and is still observed at the northern edge of Sundarban (Jorshing) with a reduced amplitude of 25 cm.

In the long term, tides inside and around Sundarbans region can be expected to change in response to sea level rise (Khan et al. 2020), and feedback loop between bathymetry and topography change (Van Maren et al. 2023). Current knowledge indicates that Sundarbans might continue to gain sediments and keep up with the sea level rise (Aeurbach et al. 2015). In such cases, the tide may continue to amplify with sea level rise. On the other hand, if the sediment gain is stopped and the land elevation cannot keep up with sea level rise, as large scale submersion may create a regional tidal damping (Khan et al. 2020), which may consequently cause the loss of the mangroves. The actual evolution of tide will likely be between these two scenarios and warrants further research.

4. Extremes water level

Analysis of the Hiron point tide gauge dataset suggests that, extreme water level around Sundarbans is predominantly due to extreme tide and seasonal mean sea level variation (Antony et al. 2016). Over the 1977-2003 period, Antony et al. (2016) observed a linear trend of about 5.5 mm/year in yearly extreme water level identified as 95-99.9th percentiles, which is comparable to the rate of mean sea level rise, about 4 mm/year (Lee 2013, Khan 2020).

Storm tides, combination of storm surges and tide (Gregory et al. 2019), caused by tropical depressions and cyclonic storms is another reason for extreme water levels (Antony et al. 2013, Krien et al. 2017). These storms occur predominantly during pre-monsoon (March-May) and post-monsoon (September-November) seasons (Brammer 2014, Khan et al. 2022). In recent years several strong cyclones made landfall in this region - namely Sidr (November 15, 2007), Bijli (April 18, 2009), Cyclone Aila (2009), Cyclone Amphan (2020). All of these cyclones caused massive damages through strong wind and massive flooding to the Sundarbans ecosystem and the surrounding. Hence, water level extremes due to storm tide are often of particular focus.

As extreme water levels encompass both cyclonic and non-cyclonic origin, often the cyclonic water level extremes are analyzed in terms of storm surges, e.g, non-tidal residual. Lee (2013) separated tide and storm surges using ensemble empirical mode decomposition (EEMD), and applied extreme value analysis (EVA) to estimate the risk of extreme surge. They estimated a 1.75m surge at 100 year return period. Since, tide and surge interact non-linearly (Krien et al. 2017, Khan et al. 2021), the EVA estimates of surge are not linearly additive. Hence, obtaining an estimation of storm tide risk is challenging. This technical problem is further exacerbated by the practical problem of reliable observation during storms, as tide gauges in this region are known to malfunction due to damage during cyclonic storms (Antony and Unnikrishnan 2013). Khan et al. (2022) used numerical modeling of thousands of statistical storms to better quantify the storm tide risk. They simulated the same set of storms with and without tides to quantify the return periods of tide surge (with tide) and surge (without tide). In both cases, their model was coupled to a spectral wave model to account for the wave setup. Figure 5 shows an extraction from their results at Hiron Point tide gauge location. Their estimate for a 100-year surge is about 40 cm higher than the estimate of Lee (2013).

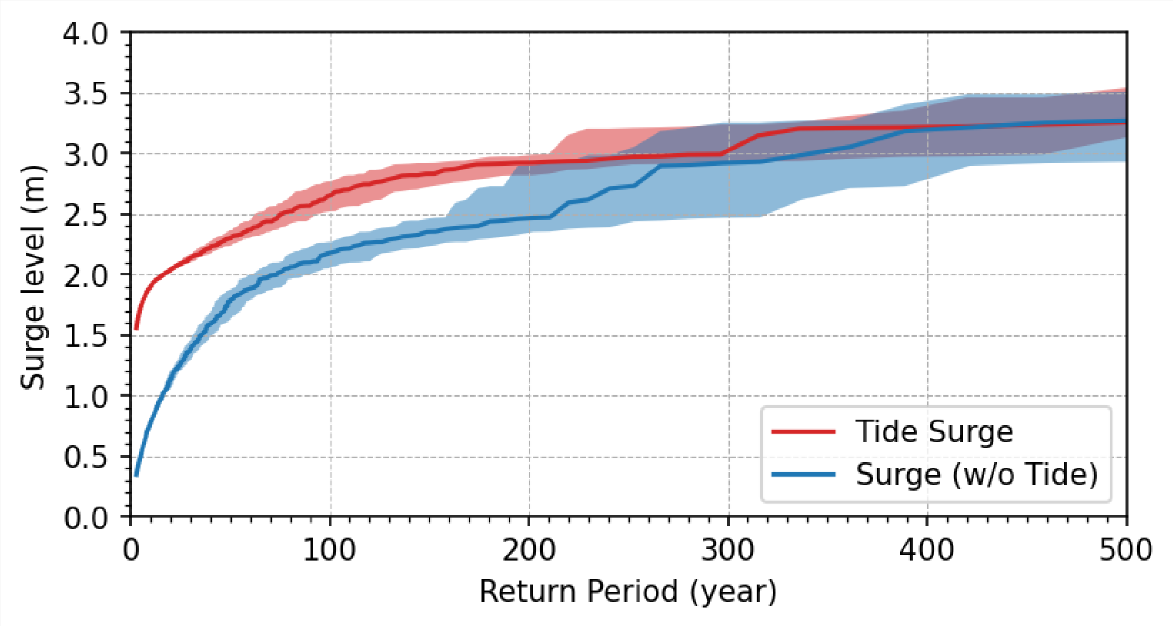

Figure 5. The return period levels of tide surge (red) and surge (blue) at Hiron Point estimated by Khan et al. (2022).

The more interesting result in Figure 5 is however the evolution of tide surge (e.g., total water level). The total water level is significantly higher at lower water levels, until around 100 year return level, due to positive contribution from tide. However, the higher water levels are attenuated, reaching a plateau around 3-3.25m. On the other hand, the surge (blue curve) continues increasing with higher return periods. This suggests that tide surge interaction combined with large floodable mangrove areas has a regulating effect on the higher storm surges in this region. This attenuating effect has already been reported in other parts of the world (Bertin et al. 2015).

Indeed, the mangroves are already known to significantly dampen the wind gusts, and attenuate storm surges providing a natural protection to such extreme hydro-meteorological events (Krauss and Osland, 2020). The contribution of the Sundarbans mangroves on the attenuation of coastal flooding is however not well quantified. Better understanding and quantification of these ecosystem services may provide valuable insight into the development of natural protection from future storm surge flooding which is expected to increase under a warming climate.

5. Conclusion

The Sundarbans are highly vulnerable to sea level change and particularly susceptible to impacts such as increased flood tides, extreme water levels, and land subsidence. As sea levels rise, the Sundarbans will be further threatened, making it essential that effective adaptation measures are implemented in order to protect the region from further damage. We presented in the chapter a review of the knowledge about the different component of the sea level variation accumulated in the past decades from observations and modelling. One of the critical points to advance further in a precise knowledge of the processes driving the sea level variation at all time scales is the lake of good quality in situ observation. It is then important and urgent to develop real monitoring system to follow the evolution of this highly complex region.

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