A BLEAK FUTURE, DICHOTOMY BETWEEN CLIMATE CHANGE AND GEOMORPHIC INEQUILIBRIUM: INSIGHTS INTO INDIAN SUNDARBAN

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ABSTRACT

The ongoing unprecedented increase in global temperature casting its effects on the global climatic system is termed climate change. In a broader perspective, it includes the long term changes in Earth's climate which had been experienced previously. Since the mid-1800s this current warming trend has been common largely due to anthropogenic activities. This current change in warming is proceeding at an alarming rate, roughly ten times faster than the average rate of warming after an ice age. The Indian part of Sundarban, a portion of the retrograding Western Ganga-Brahmaputra delta is facing increased vulnerabilities in this scenario of climate extremities. Tropical cyclones Aila (2009), Bulbul (2019), Amphan (2020), Yaas (2021) and Remal (2024) have left the riparian communities in jeopardy. Satellite altimetry with the use of multi satellite data observed general positive trends of sea level change in Bay of Bengal (3.11 ± 0.44 mm/yr) during 1993-2010. There was a gradual increase of surface water temperature in the deltaic complex of Indian Sundarbans from 1980 to 2007 at a rate of 0.5ºC per decade and this rate is much higher than the globally observed warming rate of 0.06ºC per decade (Mitra *et al.*, 2009). Number of cyclones having landfalls in Sundarbans is on an increase within the time frame of 1951 to 2010. This increasing frequency of cyclones is brought about by an increase in sea surface temperature (Mahadevia and Vikas, 2012). However, the frequent problem of inundation cannot be attributed to climate change alone. The inherent geomorphic character of the Ganga Brahmaputra delta is another factor in play, the effects of which are accentuated by anthropogenic interference and ensuing climate extremities. This paper inquires into the multiple factors behind the vulnerabilities of Indian Sundarban using quantitative approaches of sea level estimates using satellite altimetry and tide gauges, erosion accretion behaviour using Survey of India toposheets and satellite images and qualitative approaches in field visits.

Keywords: *Climate change, Sea level rise, Sundarban delta, Coastal erosion, Tropical cyclones, Geomorphic imbalance, Mangrove vulnerability*

INTRODUCTION

An increasing trend of global temperature (0.74ºC ± 0.18ºC from 1906-2005) was predicted by the IPCC, also stating that the global ocean surface temperature has increased by 0.6ºC during the 20th century. Time span between 1901-1980, saw an increase in mean annual temperature by about 0.4ºC/100 year in India (Hingane *et al.*, 1985). WWF INDIA had predicted an increasing trend in surface temperature (0.019ºC/yr), predicted that more than 1.3 million people shall be exposed to risks of sea level rise, storm surges, coastal erosion and inundation. It is also predicted that the temperature will increase up to 1ºC by 2050 (Danda, 2010). An increase in average temperature from 31ºC to 32.6ºC between 1980 and 2007, in pre monsoon periods was observed (Mitra *et al.*, 2009).

A long-term rising trend of 1 mm/yr for mean sea level was observed (Unnikrishnan *et al.*, 2006). Eustatic sea level coupled with land subsidence has led to a relative sea level of 10-20 mm/yr in the seaward portion of the delta (Allison, 1998; Coleman, 1969). Hugli estuary records a sea level rise of 0.76 mm/yr and 5.22 mm/yr (Nandy and Bandyopadhyay, 2011). Increasing sea level at the rate of 4.101 mm/yr was observed for the time span of 1992-2016 from satellite altimetry. Eastern end of Sundarban at 21ºN, 89ºE records a sea level rise at the rate of 4.200 mm/yr. Sea level is seen to increase progressively towards the northern end of the Hugli estuary (1.1851 mm/yr at Gangra, 2.7867 mm/yr at Haldia and 4.0059 mm/yr at Diamond Harbour) mainly due to the funnel shape of the estuary. Global average sea surface temperature records an increase of 0.06ºC per decade. In comparison, sea surface temperature in Sundarbans has increased at the rate of 0.5ºC per decade between 1980 and 2007. Both the global average land and sea surface temperature increased by 0.6 ± 0.2ºC over the 20th century (Raha *et al.*, 2015). Within the time span 1951-2010, no of cyclones having landfall in Sundarban has increased.

MATERIALS AND METHODS

For analysis of sea level rise, satellite altimetry using data from NASA Jet Propulsion Laboratory was carried out. Average sea surface height was plotted using tide gauge data of stations Diamond Harbour (1948-2012), Haldia (1971-2012) and Gangra (1974-2006) procured from Permanent Service for Mean Sea Level. Inventory of cyclones spanning from 1891 to 2022 was prepared from IMD Cyclone E Atlas.

Table 1: *Inventory of maps and satellite images used.*

Map/Image used	Scale/Spatial Resolution	Survey Year	Source
79C/1, 79C/2	1 : 50,000	1968	Survey of India
79C/1, 79C/2	1 : 50,000	2005	Survey of India
Landsat 8	30 m	13.01.2020	USGS Earth Explorer

EROSION ACCRETION BEHAVIOUR

Strong tidal activities, longshore currents, waves by erosion and deposition have modified Sundarban (Chakrabarti, 1995; Bandyopadhyay *et al.,* 2004; Raju *et al.,* 2010; Jana *et al.,* 2012; Chakraborty, 2013; Das *et al.,* 2013; Addo, 2015). Within 1904-24 and 2015-16, area lost by erosion (9.7% of total area) was nearly 1.8 times of the area gained by accretional processes (5.4% of total area). Accretion was greater than erosion in the northern islands. It can be foreseen that the general rate of erosion of western Sundarban would be 2.54 times greater than its eastern counterpart (northern sector records accretion of 104 $m^2/km^2/yr$; central sector records erosion of 306 $m^2/km^2/yr$ and southern sector records erosion of about 1577 $m^2/km^2/yr$). It was observed that 26 of the 46 islands losing more than 10% area fell in the southern group as compared to central (16 of 64) and northern (4 of 94) group of islands. These type of islands of the central group are lined by major estuaries (Bandyopadhyay *et al.,* 2023).

The Hugli estuary exhibits an ephemeral character when it comes to erosion and accretion pattern. Time span of 1922-23 and 1967-69, saw the erosion of the eastern bank of the estuary and eastern Sagar

Island. Between 1967 and 2001, parts of Kabasgadi Island got fused to the left bank of the estuary. As Baratala river was observed to widen through past 200 years, it can be inferred that Gangasagar Island was attached to the area to its east previously (Bandyopadhyay, 2000). The estuary underwent slow, rapid and slow erosion in the three time periods. Inner islands responded through rapid accretion, while the outer islands responded through slow accretion and slow erosion (Das, 2022).

Table 2: Areal change of bars on Hugli estuary (*Calculated by authors)*

1968	**2005**	**2020**	**2025**				
Bar	**Area (km^2)**	**Bar**	**Area (km^2)**	**Bar**	**Area (km^2)**	**Bar**	**Area km^2)**
Kabasgadi Island	3.311	Kabasgadi Island	3.414	Kabasgadi Island	2.245	Balari	5.22
Kabasgadi Island (Reserve Forest)	0.546	Kabasgadi Island (Reserve Forest)	1.779	Shikarpur, Dhanir Char and Kankramari Char cumulatively Kankramari char has joined the mainland of Mousuni Island	7.556	Kabasgadi Island	1.829
Shikarpur Island	2.255	Shikarpur Island	0.915			Sikarpur Island	5.75
Kankramari Char	1.247	Dhanir Char	1.075				
Lohachara	2.045	Kankramari Char	1.997				
Suparibhanga	4.169						

Changes in the islands of the Hugli are strongly linked to the changes in its tidal channels and sand ridges.

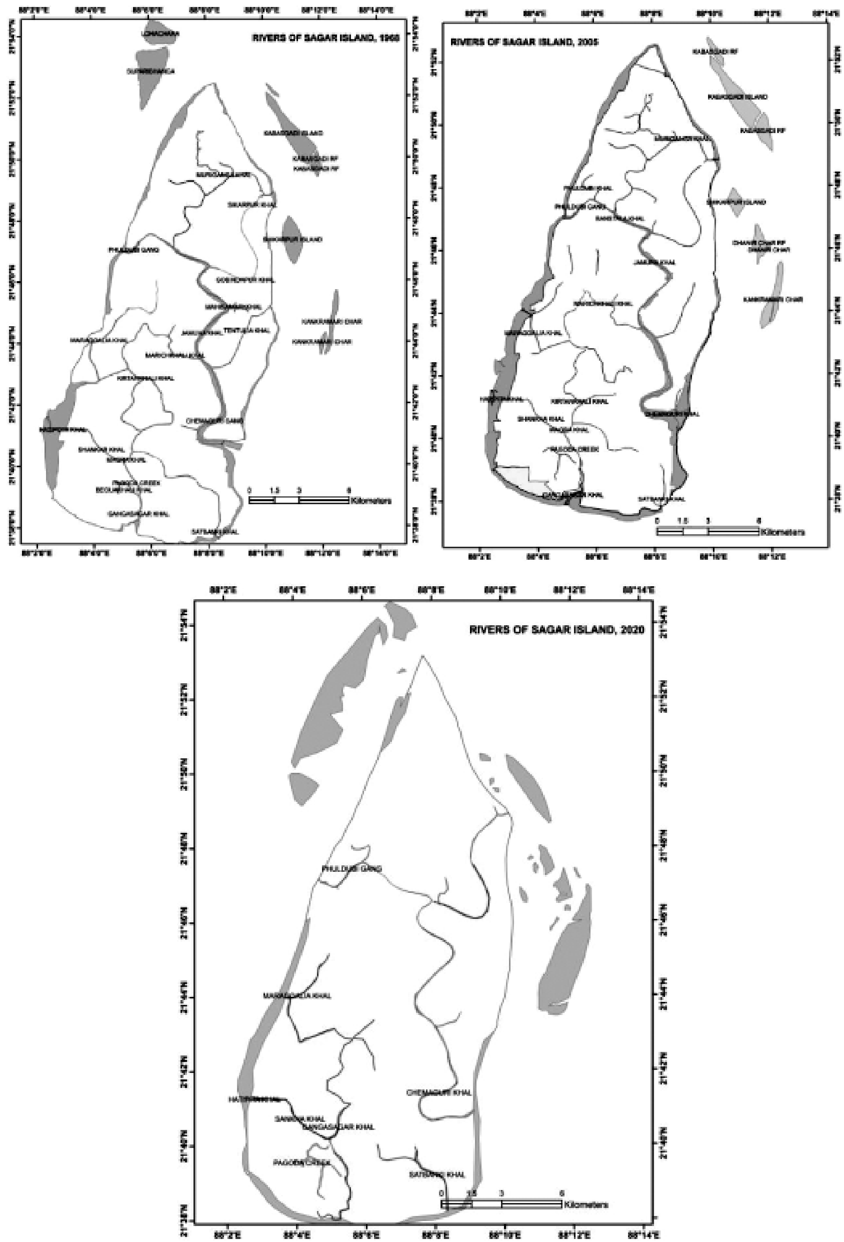

Figure 1: *Changes in shoals of Hugli estuary (Das et al., 2024)*

Table 3: *Areal change of Ghoramara and its surrounding islands. (Calculated by authors)*

Islands	Area km²								
	1967-68	**1978**	**1991**	**2003**	**2009**	**2013**	**2019**	**2021**	**2025**
Lohachara	1.990	0.554	0.027	Lohachara has submerged					
Suparibhanga	4.106	2.631	0.145	Suparibhanga has submerged					
Ghoramara	8.3845	7.514	6.235	4.430	4.860	4.348	3.999	3.703	3.305
Nayachar	17.327	32.280	48.279	50.738	48.847	46.204	51.988	55.117	50.155
Shiber Char	_	0.477	1.375	1.511	3.552	6.666	6.121	8.34	
Shoal near Shiber Char		_	0.406	_					

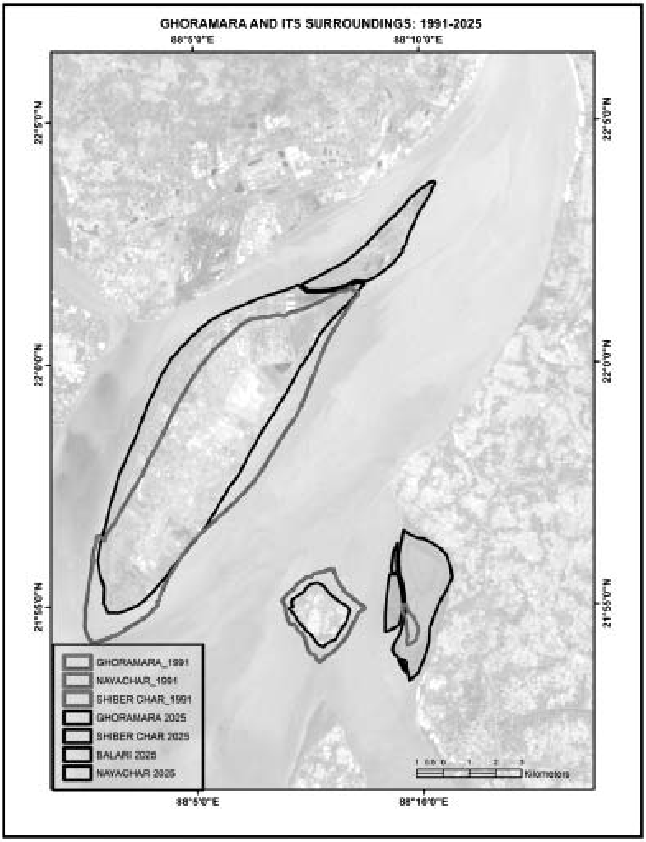

Figure 2: *Change of Ghoramara and its surrounding islands: 1991-2025.*

RETROGRADING WESTERN GANGA BRAHMAPUTRA DELTA

Fluvial environment in the upper portions of a large delta bring about cyclical processes of erosion and accretion along with avulsion and course shift of the distributaries. The prograding and retrograding nature of the coastline is influenced by the occupation or abandonment of the delta by the distributary channels. Temporary pause in replenishment of sediments in a portion causes erosive tidal or wave processes to take over causing erosion (Woodroffe, 2003; Bird, 2010). Also, the stability of a delta depends on the relative dominance of wave, tide and fluvial forces. While rivers aid in delta progradation, wave and tide influence result in delta modification by sediment reworking.

Ganga-Brahmaputra delta has progressively prograded towards east, with relative younging to the east (Allison *et al.*, 2003; Sarkar *et al.*, 2009). Major rivers except Hugli-Baratala to the west and Baleswar Haringhata to the east have lost their connections with river Ganga and are tidally fed with tides entering about 6.7 m in the interior. Erosion rate was maximum at the west central section between estuaries of Thakuran and Gosaba at the sea front reaching up to 40 m/yr gradually reducing west and eastward and almost becoming nil at the western limit of Haringhata estuary (Bandyopadhyay *et al.*, 2023)

The erosion of the sea facing islands of Indian Sundarban can be attributed to offshore sediment trapping by Swatch of No Ground submarine canyon (Sherwill, 1858; Vernon-Harcourt, 1897), abandonment of the delta and reduction in sediment input from the western distributaries (Oldham, T., 1870; Oldham, R., 1893) and regional to local scale subsidence of the delta (Fergusson, 1863; Morgan & McIntire, 1959) to local scale subsidence (Fawcus, 1927). Later workers suggested that low sediment input from the western distributaries of river Ganga (Chakraborty, 1970, Basu and Chakraborty, 1972; Basu, 1992) and/or in channel sedimentation of tidal distributaries (Sen *et al*., 1996), high tidal range and tidal currents (Ray, 1966; Coleman, 1969; Petts and Foster, 1985; Jana *et al*., 2017), increase in relative sea level and global warming (Hazra *et al*., 2002, 2016; Jayappa *et al*., 2007; Rahman *et al*., 2011, Raha *et al*., 2012, 2014; Sarwar and Woodroffe, 2013; Thomas *et al*. 2014; Pahlowan and Hossain, 2015; Quader *et al*., 2017), incidence of tropical cyclones and storm surges (Islam *et al*., 2011; Sarwar and Woodroffe, 2013; Jana *et al*., 2017), sediment trapping by dams and reservoirs in the catchment area of river Ganga (Bandyopadhyay and Bandyopadhyay, 1996) and coastal reclamation and allied actions (Raha *et al.*, 2012; Bera and Maity, 2019; Besset *et al.*, 2019) might be the causes behind erosion of sea face of Indian Sundarban.

CLIMATE CHANGE IMPACT ON INDIAN SUNDARBAN

Species diversity of mangroves has changed as a response to effects of climate change, cyclones and saltwater incursion. Dominance is high among *Avicenniaalba* and *Avicennia marina* closely followed by *Excoecariaagallocha*, *Sonneratiaapetala* and *Bruguieragymnorrhiza*. *Excoecariaagallocha* has high tolerance to salt and thus has probably increased followed by *Phoenix* sp. Reduction of mangroves might also be attributed to sea level rise (Giri *et al.*, 2014). Preference of some mangroves to hypo saline environment can be attributed to the absence of *Heritierafomes* which prefers low saline condition around 2-4 psu (Mitra *et al.*, 2015).

The western sector of Indian Sundarban abounds in growth of dominant mangrove flora as compared to the central sector. As freshwater flow is reduced in the central sector due to high salinity, *Sonneratiaapetala* has reduced but increased salinity could not influence *A. alba* and *E. agallocha* as their physiological adaptations like excretion of salts through roots and salt glands, can outdo the effects of salinity. *S. apetala*, a salt accumulating species experiences low tolerance to hyper saline environment. Gradual disappearance of sweet water loving mangrove floral species like *Heritierafomes* (Sundari) and *Nypafruticans* (Golpata) justifies Cyclone Aila had severely affected major parts of mangrove forests in Sundarban, mainly in the north western and central western region degrading mangrove forests into open type (Ray *et al.*, 2011).

There has been a reduction in the total number of disturbances from 1891-2010, but the frequency of severe storms has increased. The frequency of both depressions and cyclones has decreased in the period from 1981 to 2010 in case of Sundarban. According to World Bank report, over the last 120 years, there has been 26% increase in the frequency of severe cyclonic storms. An increasing sea surface temperature has a role to play behind the genesis of tropical cyclones. Also, an increase in number of cyclonic landfalls in Sundarban was observed between 1951 and 2010 (Mahadevia and Vikas, 2012).

Periods	Recurrence Interval		
	Depression Storm	Cyclonic Storm	Severe Cyclonic Storm
1891-1920 (30 Years)	0.33	0.33	0.20
1921-1950 (30 Years)	0.87	0.20	0.23
1951-1980 (30 Years)	0.87	0.17	0.33
1981-2010 (30 Years)	0.43	0.10	0.20
2011-2022 (12 Years)	0.55	0.09	0.27

About 8 storms with sustained wind speeds more than 63 km/hour form in the Bay of Bengal each year. Of these, on an average, two become tropical cyclones (Sen, 2021). The giant funnel shaped estuary of the Bay of Bengal has a wide and shallow offshore which acts as a catalyst for amplification of storm surges. It can also be understood that the shallower mixed layer over the north-western Bay of Bengal promotes the warm sea surface front in that region (Samanta *et al.*, 2018). Potential of damage of cyclones has been on the increase in the last decades.

ROLE OF MANGROVES IN COMBATING CLIMATE CHANGE

Mangroves act as efficient carbon sink and sequester huge amounts of carbon in their biomasspool (stems, leaves, branches, wood, roots) and sediments. Mangrove species globally can sequester about 4 Gigatons carbon which are basically accumulated as biomass in both above ground and below ground structures (Twilley *et al.*, 1992). Carbon sequestration in mangroves is a function of biomass production capacity depending on the interaction between climate, soil and topography of an area. Species like *Sonneratiaapetala*, *Avicennia alba*, *A. marina*, *A. officinalis* and *Excoecariaagallocha* have considerable scrubbing capacity of carbon, though it is salinity specific (Mitra *et al.*, 2018). Above ground biomass of *A. marina* of Henry Island (a plantation of mono species of 190 ha) was 236 tonnes with a carbon stock of 4.9 tonnes respectively (Manna *et al.*, 2014). Overall carbon stored in above ground biomass and live below ground biomass in the forests of Sundarban is estimated to be 21.13 Tg C (teragrams of carbon: 1012 grams of carbon) (Ray *et al.*, 2011). Carbon sequestration potential of Prentice island of Indian Sundarban was 7.58 t C/ha/yr (Agarwal *et al.*, 2017).

Blue carbon sequestration in soil increases with multiple species of mangroves compared to degraded mudflats under the dominance of stress tolerant mangrove associates. Plantation of multispecies mangroves bearing several offsprings improves the ecological functions and services of the degraded mudflats under anthropogenic stress (Chowdhury *et al*., 2023).

CONCLUSION

The increasing instances of tropical cyclones attributed to increasing sea surface temperature can be attributed to climate change. However, the geomorphic character of the Hugli estuary, further jeopardized by the premature reclamation has led to the inherent polderization of the islands and inundation and erosion though the ensuing effects of climate change and sea level rise can accentuate the problems in sediment starved retrograding deltaic environment. A trend of increasing recurrence interval is observed both for depressions and severe cyclonic storms. In order to cope up with such extremity an enhancement in capacity building is necessary. In case of vulnerable areas, a decrease or reduction of exposure and enhancement in capacity must be aimed at. Well equipped storm shelters located at a central, elevated position with access of people to their resources are indeed necessary. In this case, the models of various types of storm shelters need to be followed. Maintenance of access roads and embankments (concrete, brick pitching and porcupine mesh) is necessary.The dearth of intertidal space increases the risk of breaching. Efforts must be taken to ensure silt deposition by maintaining silt arrestors. The crest of the embankments must be raised and the side slopes must be flattened. In addition to this, the embankments must be strengthened using bamboo reinforcements. Circuit embankments towards the settlements will ensure safety and the land in between can be used for creating a vegetative buffer. The coasts should be classified first to assess the various site specific management strategies. It is necessary to construct two parallel dykes with cross embankments at regular intervals to prevent flooding. Realignment of embankments coupled with provision of green defence structures is required. Also, the buffer zone between old and new embankment should be treated as no construction zone and should be used as a vegetative buffer. An integrated farming system needs to be practiced in Sundarban encompassing livestock rearing, plantation of fruits, orchards, growing various seasonal vegetables according to the topography, rearing fish and duck following a land shaping system. This can protect coastal ecology with provision of livelihood options. In the new agricultural system, a combined farm pond model can be used where fish rearing is done using the ponds both in rainy season and post rainy dry season. Various initiatives of mangrove regeneration like the one under MISHTI scheme under the purview of Ministry of Environment and Forest, collaborating with Government of West Bengal need to be undertaken. Added attention should be extended towards ensuring sound carbon finance in the sites where accretion is dominant.

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