

## Article

# Assessment of Sea Level and Morphological Changes along the Eastern Coast of Bangladesh

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**Abstract:** Bangladesh is one of the climate risk-prone countries in South Asia facing tremendous challenges to combat sea-level rise and its associated coastal morphological changes. This study aimed to determine the interaction of the sea-level rise and morphological changes, particularly at Cox's Bazar and Kutubdia Island along the eastern coast of Bangladesh. Available hourly tide gauge data, daily temperature, daily rainfall data, and 15 LANDSAT satellite images for the period of 1983–2016 were analyzed to examine the sea level shore morphological change and associated climate change phenomenon. First, we identified the historical nonlinear sea-level trend using Hilbert-Huang Transformation (HHT) based on the complete ensemble empirical mode decomposition (CEEMD) technique. We divided the study period into three distinct sea-level change periods of 1983–1993, 1993–2003, and 2003–2014 based on nonlinear sea-level trend analysis. The study revealed that the sea level on the east coast of Bangladesh had a moderate rising trend during 1983–1993, slight decrease during 1993–2003, and steep rising trend during 2003–2014. We also observed that a sea-level change within a particular period impacted the shore morphological change after approximately two years, such that the average sea-level change during the period of 1993–2003 might have affected the shore morphology for 1996–2005. Alarming shore erosion was found for the period of 2005–2016 compared to the previous periods of 1989–1996 and 1996–2005 for both Cox's Bazar and Kutubdia Island. The shore morphology of some segments was also substantially affected due to the geometric shape of the land, significant waves, and shore protection works. This study encourages policymakers to minimize the threats of sea-level rise and ensure sustainable coastal management strategies are introduced to sustain the vital eastern coast of Bangladesh.

**Keywords:** sea-level rise; shore morphology; east coast of Bangladesh; Cox's Bazar; Kutubdia Island**Citation:** Anwar, M.S.; Rahman, K.; Bhuiyan, M.A.E.; Saha, R.Assessment of Sea Level and Morphological Changes along the Eastern Coast of Bangladesh. *J. Mar. Sci. Eng.* **2022**, *10*, 527. <https://doi.org/10.3390/jmse10040527>

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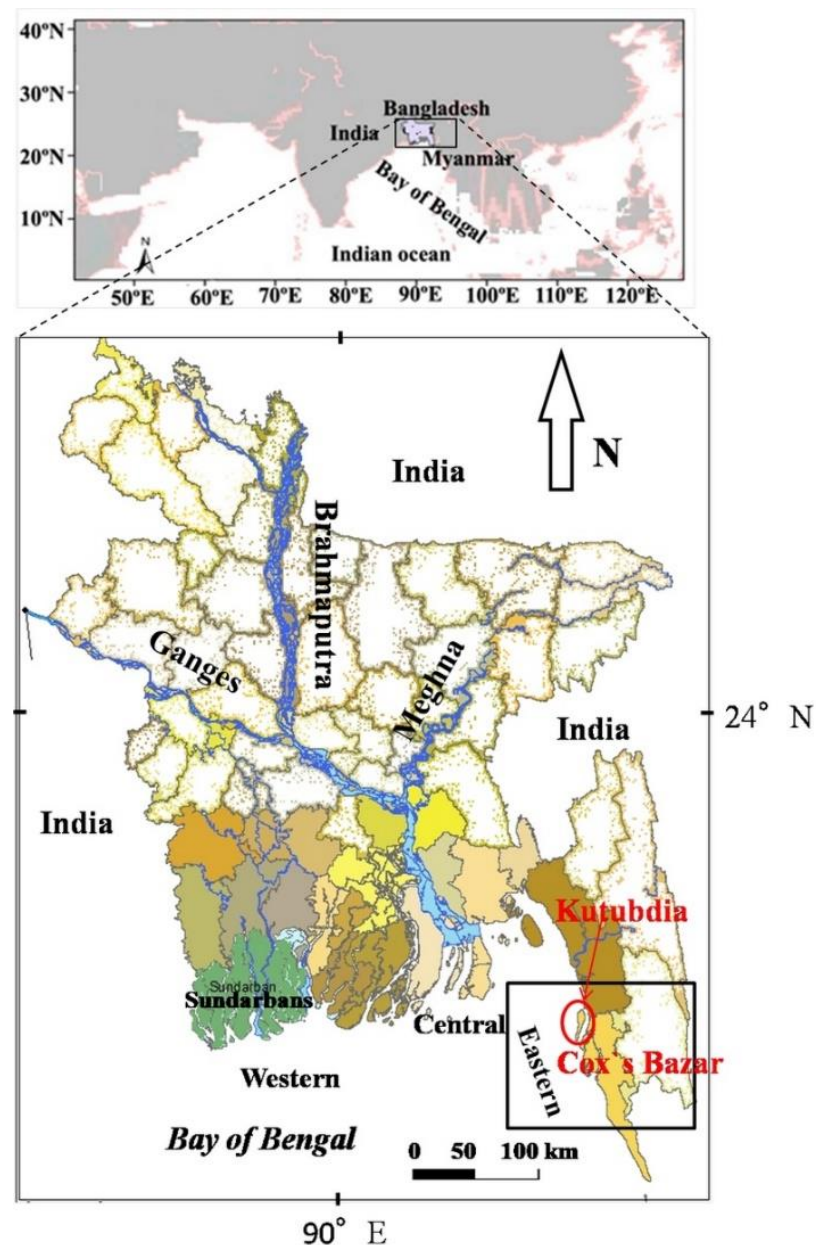


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## 1. Introduction

With a projected increase in the global population living in coastal areas of more than one billion by the end of this century, sea-level rise is regarded as one of the most serious concerns throughout the world [1]. The severity and extent of sea-level changes throughout the short, medium, and long term are largely uncertain, making public policy-making difficult [2]. Coastal hazards are exacerbated by rising sea levels, the increasing frequency of extreme hydro-meteorological events, rising groundwater levels, and saltwater intrusion, thus exposing people and assets [3]. The global mean sea level increased to 0.21 m between 1902 and 2015 according to the Intergovernmental Panel on Climate Change [4] (p. 334). Considering different representative concentration pathway (RCP) scenarios, the sea level is expected to rise 0.43–0.84 m by 2100, compared to 1986–2005 [4,5]. As a low-lying South Asian country, Bangladesh has a high risk of inundation and submersion with the sea-level

rise [6–8]. According to the Intergovernmental Panel on Climate Change (IPCC)’s fifth assessment report, the impacts of climate change mean the widespread coastal populations living in low-lying countries such as Bangladesh are becoming vulnerable to the imposing threat of sea-level rise [6–8]. A one-meter sea-level rise will significantly affect the coastal areas and deltaic regions, and about 90% of the land of Bangladesh is less than ten meters above the mean sea level. Figure 1 shows a map of Bangladesh displaying three coastal zones: eastern, central, and western [9].



**Figure 1.** Map of Bangladesh showing the different coastal zones and major river system.

Earlier studies showed significant spatial and temporal variation in sea-level trends across different parts (i.e., western, central, and eastern) of the Bangladeshi coast. For example, the rising sea-level trends at Hiron Point (western coast), Char Changa (central coast), and Cox’s Bazar (eastern coast) were found to be 4.0, 6.0, and 7.8 mm/year, respectively, when derived from the tide gauge record of 22 years for the period of 1977–1998 [10]. The rate of sea-level rise is almost double on the eastern coast that on the western coast. The Center for Environmental and Geographic Information Services

(CEGIS) also reported a similar pattern of a rising sea-level trend with considerable variation from observed data. The mean annual rise of sea level was found to be 5.5 mm/year for the western coast at Hiron Point station, and 7.5 mm/year for the central region at Sandwip station. Meanwhile, the sea-level rise in the eastern region at the Moheshkhali station was 7.5 mm/year, followed by 5.05 mm/year in the Cox's Bazar station [11]. In contrast, according to Sarwar [12], the rising sea-level trend along the eastern coast of Bangladesh is very low (1.63 mm/year for Cox's Bazar station), as derived from PSMSL and BIWTA data for the 1979–2000 period for different stations on the eastern coast. Moreover, other stations of the eastern coastal zone, i.e., Sadarghat (−11.75 mm/year), Maheshkhali (−5.59 mm/year), and Teknaf (−8.33 mm/year), show a falling sea-level trend [12]. Sarwar's [12] sea-level trend analysis was further supported by Brammer [13] from his nationwide sea-level analysis, which found the opposite of the study by CEGIS. Brammer found the highest sea-level trend for the central coast at Khepupara station (19 mm/year), moderate for the western coast at Hiron point station (3.6 mm/year), and lowest for the eastern coast Cox's Bazar station (1.4 mm/year), for 1979–2000. Despite great concern about sea-level rises on western and central parts of the coast, the eastern coastal zone can be considered less vulnerable to sea-level rise [13].

Moreover, sea-level variation on the Bangladeshi coast is mostly seasonal, highest during the monsoon (May–August) and post-monsoon periods (September–December) because of the peak rainfall-runoff processes [7,8]. In comparison, the sea level is much lower during the pre-monsoon period (January–April). Seasonally, variation of the mean sea level ranges from 0.3 to 0.5 m [14]. Khan et al. [15] observed a trend of 4.3 mm/year in May and 10.9 mm/year in November along the Cox's Bazar coast. Inter-annual variation of the sea level is much higher on the western and central coasts because of the seasonal contribution of GBM river discharge to the Bay of Bengal. For instance, a large-scale airflow system blows over this region due to the southwest (SW) monsoon wind. Consequently, it raises the level of water along the coast of the Bay of Bengal and brings plenty of rainfall (70 to 85 percent of the annual total). Most of the floodplains of the country are inundated during this period.

Morphological changes (erosion-accretion) to the shore and islands along the Bangladeshi coast are the outcomes of several issues, i.e., sea-level rise, wave action, monsoon winds and rainfall, cyclones, river discharge, the shape of the Bay of Bengal, and some anthropogenic activities [7,8]. Hoque et al. [16] proposed a Coastal Vulnerability Index (CVI) for the eastern coast of Bangladesh, incorporating coastal erosion, floods, cyclones, and salinity. According to the findings, roughly 121 km (32%) of the eastern coastline is in high-to-very-high vulnerability zones due to high sea-level changes, mild slopes, low elevations, storm surges, sandy coasts, and high shoreline erosion rates. Similarly, Ahmed et al. [17] used numerous physical and socioeconomic characteristics to assess the coastal erosion susceptibility of Bangladesh's eastern coast, concluding that Cox's Bazar and Kutubdia Island are prone to significant levels of erosion. Ahmed et al. [18] utilized Fuzzy Cognitive Maps (FCMs) to gather expert opinions on recent and anticipated coastline erosion in Bangladesh, where several relevant criteria for current and future erosional vulnerability were identified, including sea-level rise, tidal energy, tidal range fluctuations, and bathymetry. Rahman et al. [19] found an average erosion rate on the western coast of Bangladesh of 7.2 km<sup>2</sup>/year from 1973 to 2010 using LANDSAT satellite images. Sarwar and Woodroffe [20] reported that Hatiya Island, located on the central coast of Bangladesh, accreted its shoreline by 50 km<sup>2</sup> in the period of 1989–2009, but lost 65 km<sup>2</sup> through erosion elsewhere. The shore of the eastern coast along Chittagong to Cox's Bazar is comparatively stable in terms of shore erosion than that of western and central regions [12]. Moreover, the average change in shoreline reached 120 m in erosion and 100 m in deposition along the Cox's Bazar shore for the data period of 1980–2017 [21]. Navera and Ahmed [21] further studied the erosion-accretion behavior of different locations along the shore to identify vulnerable areas. Another study performed by Islam et al. [22] estimated the rates of shoreline erosion along Kutubdia Island as −4.0,

−33.7, −2.6, and −5.6 m/year along the north, south, east, and west shores, respectively, for the period of 1972–2014.

The exposed eastern coast of Bangladesh embraces the sea directly, which may mean it is highly affected by the anticipated sea-level rise. Cox's Bazar (part of the eastern coast) is the world's longest stretch of sandy sea beach, and it plays a vital role in the national economy through tourism, fishing, and salt production. In addition, Kutubdia, a densely populated island located on the eastern coast, is famous for its essential lighthouse facilities. The adverse effects of sea-level rise and shore erosion will affect the country's most incredible tourist locations and only lighthouse.

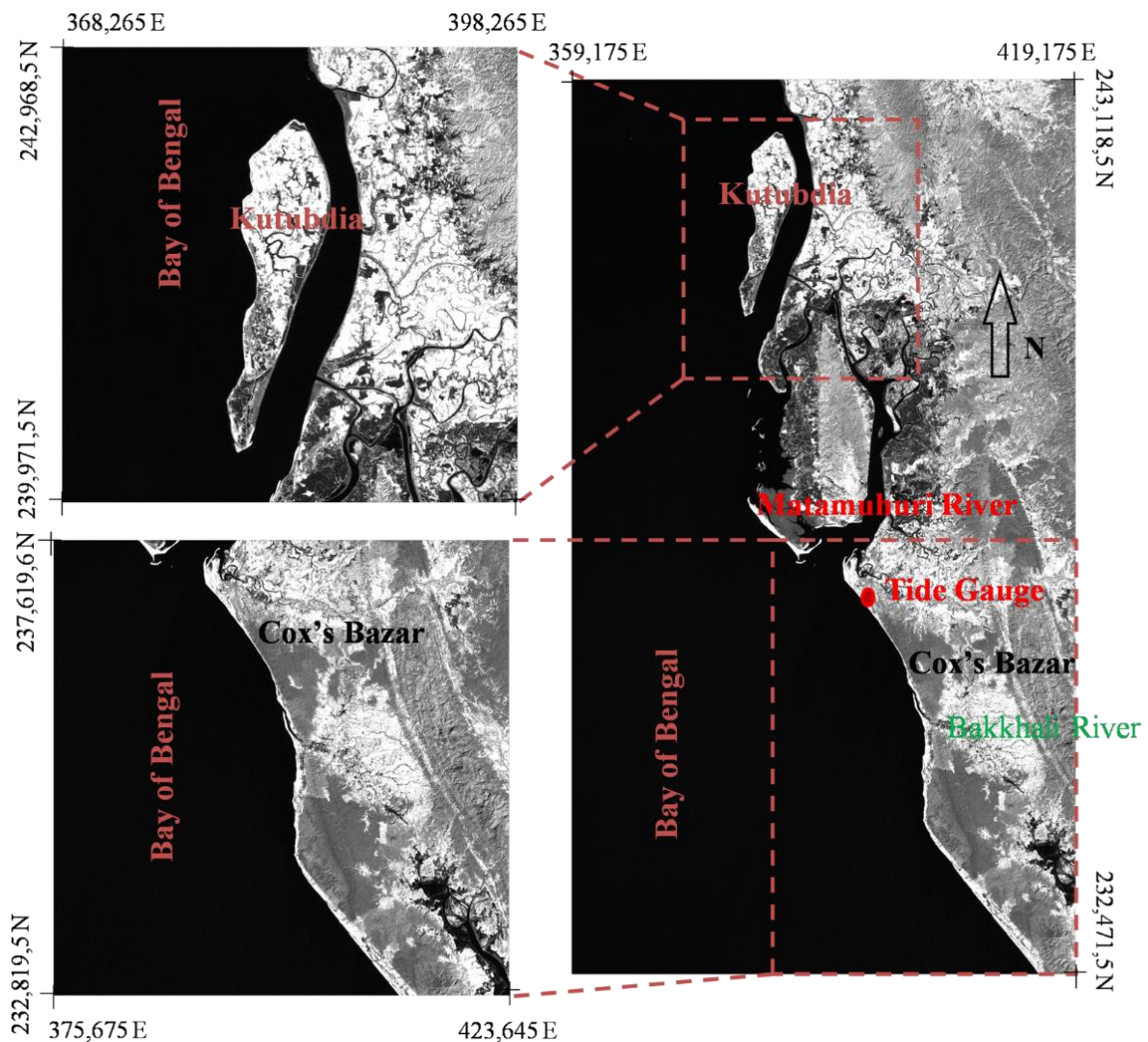
Previous studies have not investigated the interaction of the sea level with morphological change along the eastern coast of Bangladesh. We set our objectives to observe historical sea-level changes along Cox's Bazar (eastern coast of Bangladesh) and find out the possible correlation between sea-level changes and local influencing factors, i.e., the meteorological temperature and rainfall. Furthermore, this study aimed to identify the morphological changes (rates of erosion and accretion) along the eastern coast with the sea level variation, using LANDSAT satellite images emphasizing Cox's Bazar and Kutubdia Island. Studies such as this one on sea-level trends and morphological changes in coastal areas have significant value for determining sustainable coastal development strategies. In particular, the interaction of the sea level and shore morphology is of paramount importance from the viewpoint of land erosion, loss of national and human properties, afforestation, and human resettlement of Bangladesh.

## 2. Study Area

Bangladesh is a densely populated South Asian country; its three landlocked sides are surrounded by India, with Myanmar bordering the southeastern corner of the country. The southernmost part of Bangladesh is bordered by about a 710 km-long coastline of the Bay of Bengal, part of the Indian Ocean. The coastal area of Bangladesh covers 19 districts out of 64 [23]. Among the three coastal zones of Bangladesh, this study focused on the eastern coast encompassing Cox's Bazar and Kutubdia Island. Submerged sands and mudflats dominating the eastern coastal zone have formed the world's largest stretch (145 km long) of flat sandy beach from Cox's Bazar toward Teknaf [9].

The eastern coastal zone is very narrow, and a series of small hills run parallel to this zone. The Karnaphuli, Sangu, Naf, and Matamuhuri Rivers fall into the Bay of Bengal in this area. Cox's Bazar, world's longest stretch sandy sea beach and most attractive tourist destination is located in this region. Figure 2 shows the locations of Cox's Bazar and Kutubdia Island. Kutubdia island is about 30 km long, located just off the Cox's Bazar coast, and holds the only lighthouse facility in Bangladesh. This study focused on Cox's Bazar and Kutubdia Island to represent the sea-level and morphological changes along the eastern coast of Bangladesh.

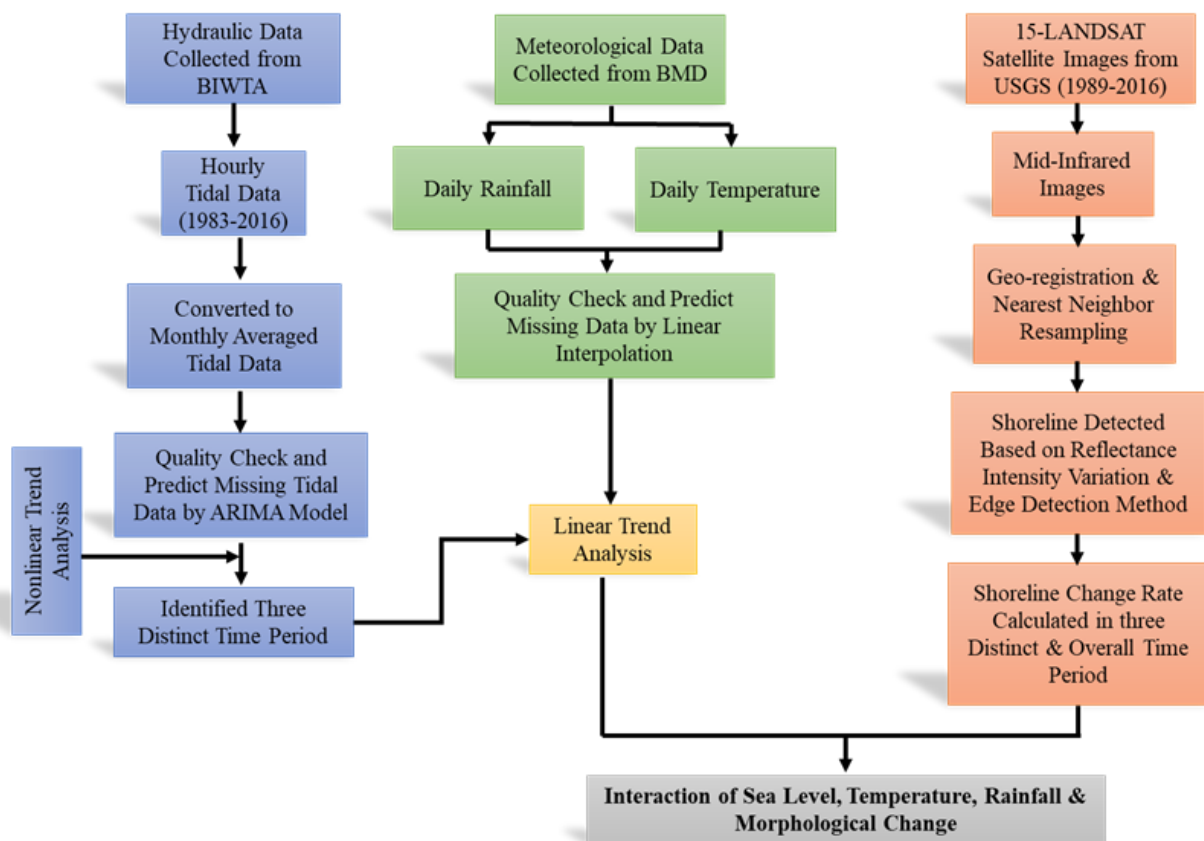




**Figure 2.** Close view of study area of Cox's Bazar (black rectangular box in Figure 1) and nearby Island Kutubdia. The dark portion is the water body, and the bright portion is the land surface (Base Image: LANDSAT 4, Band 5).

### 3. Methodology

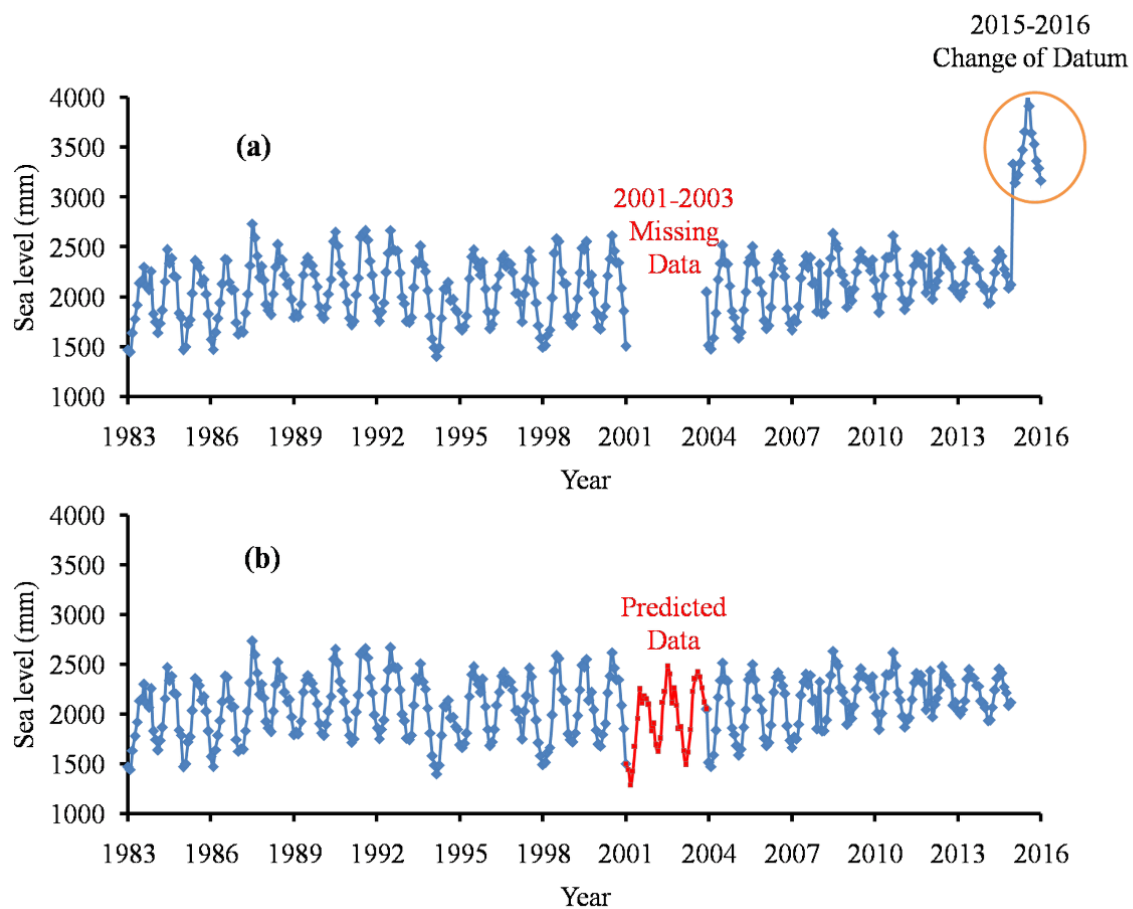
This study collected tide-level data at Cox's Bazar station (St. ID-1476, location—21.45' N, 91.83' E) from Bangladesh Inland Water Transport Authority (BIWTA) for the period of 1983 to 2016, to observe the historical changes in the sea level on the eastern coast of Bangladesh. In addition, we collected climate data such as the daily temperature and rainfall data for Cox's Bazar and Kutubdia Island for the period of 1983–2017 from the Bangladesh Metrological Department (BMD) to identify correlations among the sea level, temperature, and rainfall. Furthermore, LANDSAT satellite images from 1989–2016 were collected from the USGS website to estimate the rate of shore erosion-accretion along the Cox's Bazar shore and around Kutubdia Island. Figure 3 shows a flowchart containing the methodological approach to evaluating sea level and morphological changes in this study.



**Figure 3.** Flowchart used for evaluating sea level and morphological changes in this study.

### 3.1. Sea Level, Rainfall, and Temperature Data-Processing and Analysis

Primarily, the hourly tide-level data were converted to average monthly tide data, which represented average monthly sea-level variations. Some of the extreme values were avoided by converting hourly to monthly tide levels. Such extreme values affect the short-term change of sea level but have a minimal effect on long-term trend analysis. Furthermore, missing tide data from 2001 to 2003 were predicted by using the Autoregressive Integrated Moving Average (ARIMA) model. The ARIMA model was used successfully in a different study to predict missing data [24]. The predicted values obtained from the ARIMA model were further validated with the available hourly tide data by comparing the percentage of error between predicted and observed data. Considering the 1983–2000 dataset, we predicted the 1995–1996 data and validated those with observed data. The predicted data satisfied a 95% confidence level after validating the model. So, we predicted the missing data for the years 2001, 2002, and 2003 and used those for additional trend analysis. Figure 4a shows the mean monthly sea-level trend with missing data along with a change in datum level (2015–2016). Likewise, Figure 4b illustrates the predicted data for 2001–2003 and the data series for further sea-level trend analysis. Sea level data for 2015 and 2016 were eliminated from our further trend analyses. The missing rainfall and temperature data were predicted by simple linear interpolation as the number of missing data was minimal.



**Figure 4.** Sea-level trend: (a) time series of mean monthly sea level data at Cox's Bazar station, (b) time series of mean monthly sea level data with predicted missing data (red series).

### 3.2. Trend Analysis

This study performed both linear and nonlinear trend analyses of sea-level data for 1983–2014. Nonlinear trend analysis was performed by Complete Ensemble Empirical Mode Decomposition (CEEMD) and Hilbert-Huang transformation (HHT), which are widely used data analysis techniques to investigate geophysical data. HHT systematically decomposes the sea level dataset based on empirical mode decomposition (EMD) and Hilbert spectral analysis [25,26]. EMD assumes that long-term geophysical data comprise several intrinsic modes of oscillations. Hence, original data can be expressed using the inherent oscillation modes within the dataset by deriving intrinsic mode functions (IMFs). Complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) is an improved technique versus empirical mode decomposition (EMD). CEEMDAN was developed by Torres et al. [27] and attains comprehensiveness by enhancing the strength algorithm for noisy signals such as sea-level fluctuations [28]. The CEEMDAN method was used in this study to analyze the monthly sea-level variations at the Cox's Bazar tide gauge station using the package “Rlibeemd” in statistical software R. The ensembles and standard deviation were set to 250 and 0.2, respectively. The residual derived from the CEEMD test demonstrated the nonlinear sea-level trend for the Cox's Bazar station for the period of 1983–2014 (see Figure 7 in Section 4.1).

Finally, linear trend analyses were performed for the climate data (sea level, rainfall, and temperature) using the statistical Linear Regression Rate (LRR) method for a period spanning 34 years (1983–2016) [29]. Moreover, based on the nonlinear sea-level trend analysis, the linear trend analysis of the sea level was estimated for four distinct time periods, i.e., 1983 to 1993, 1993 to 2003, 2003 to 2014, and 1983 to 2014 (see Figure 7 in Section 4.1). It is worth noting that the process of selecting sub-periods from the long-term

nonlinear sea-level trend analysis was completely automated. Therefore, sensitivity analysis (e.g., adjustment of sub-periods by a couple of years and reevaluating the trends) was not performed. Monthly, yearly, and seasonal trend analyses were performed to eliminate error from the linear rates of change and obtain the rate of change for the sub-periods and overall time period, i.e., 1983 to 2014.

### 3.3. LANDSAT Images

Fifteen Images (path 136 and row 45) from the LANDSAT USGS archive were acquired during the years of 1989–2016 to evaluate the rates of shoreline position change (erosion-accretion) along Cox’s Bazar and Kutubdia Island, to understand the change of morphological behavior on the eastern coast of Bangladesh. We mainly relied on LANDSAT dry-season cloud-free images that are available for the months of November to February. Dry-period satellite images were chosen because the sea level is relatively consistent during the dry season, which is essential for assessing the inter-annual change of erosion and accretion [30]. A brief description of the images is provided in Table 1. Among the 15 images, there was a malfunction of LANDSAT images for those obtained from 2002 to 2010. The LANDSAT image malfunction may be reduced by taking a line between two points through a visible assessment [31]. The water level variation between the images is approximately one meter.

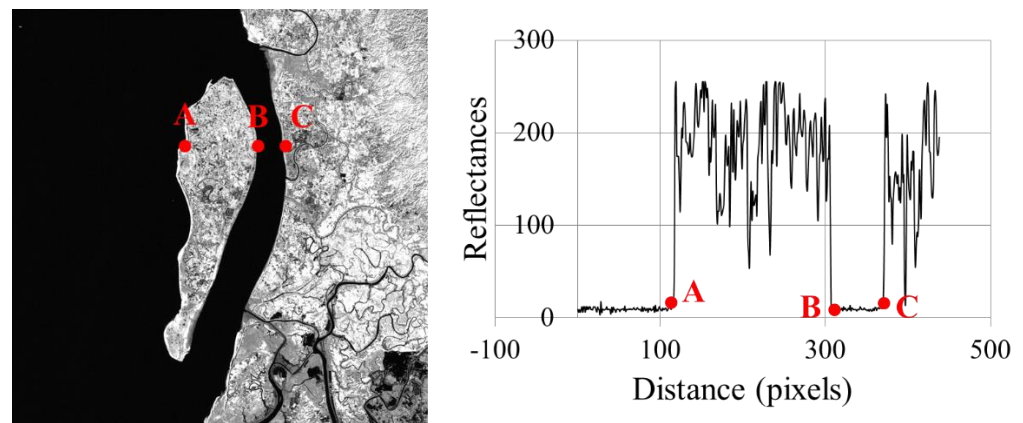
**Table 1.** Acquisition dates of LANDSAT images, resolution of each image, and sea level at Cox’s Bazar station at the image acquisition time.

Image Acquisition Date	Sensor Type	Tide Level (mm)			Image Resolution(m)
		9.00 am	10.00 am	11.00 am	
01/21/1989	LANDSAT-4 TM	854	700	620	30
11/08/1993	LANDSAT-7 ETM	1880	2239	2531	30
02/02/1996	LANDSAT-7 ETM	698	525	630	30
12/19/1999	LANDSAT-7 ETM	650	1068	1687	30
02/07/2001	LANDSAT-7 ETM	NA	NA	NA	30
01/28/2003	LANDSAT-7 ETM	NA	NA	NA	30
01/15/2004	LANDSAT-7 ETM	2342	2450	2224	30
01/17/2005	LANDSAT-7 ETM	2417	2530	2287	30
12/22/2006	LANDSAT-7 ETM	1036	670	400	30
12/25/2007	LANDSAT-7 ETM	NA	2560	2960	30
02/27/2008	LANDSAT-7 ETM	310	710	NA	30
12/17/2010	LANDSAT-7 ETM	258	250	213	30
12/22/2012	LANDSAT-8 OLI	340	320	305	30
12/20/2014	LANDSAT-8 OLI	444	440	412	30
12/25/2016	LANDSAT-8 OLI	380	360	320	30

### LANDSAT Image Processing

Due to the high degree of infrared energy absorption by water and strong reflectance by vegetation, the mid- and near-infrared bands of the LANDSAT satellite show a great contrast between land and water features, allowing separation of land from water and thus delineation of the coastline’s location [32]. Figure 5 depicts the reflectance intensities of a LANDSAT Band-5 image for Kutubdia Island for the year 1999. The water body appears black (reduced reflectivity), with grey areas representing vegetation cover or land surface (higher reflectance). The land-water interface is indicated in Figure 5 by points A, B, and C (shoreline).





**Figure 5.** The reflectance intensity variation of LANDSAT Band 5 image. Points A, B, and C represent the land-water interfacial points.

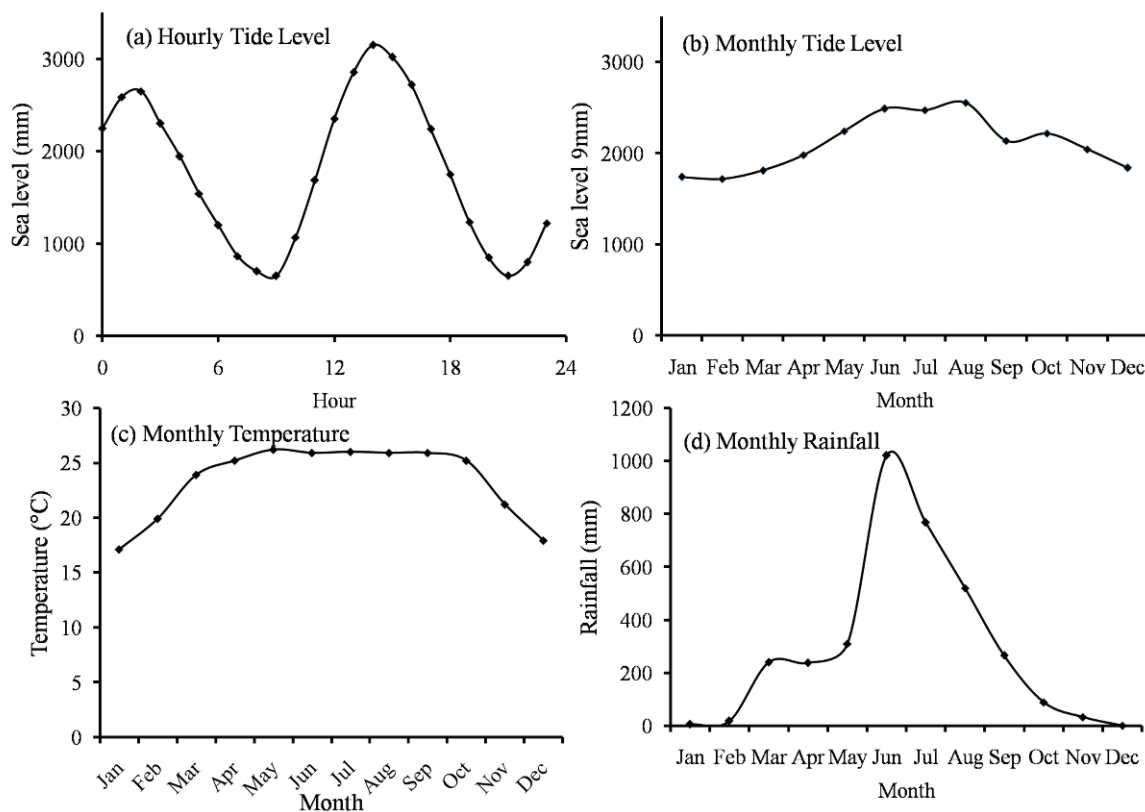
During the first stage of image processing, we performed geo-registration based on the World Geodetic System (WGS-84) to adjust the geographic positions of all images. To maintain the image integrity, we used the nearest-neighbor re-sampling approach with the 1989 image as the basis image [31]. In the second step, an edge-detection algorithm was used to demarcate coastline positions along the various vertical transects with 30-m spacing [31]. East- and west-facing shoreline positions were outlined by fixing several transect lines for Kutubdia Island, and west-facing shoreline positions were delineated along different transactions for Cox’s Bazar. Finally, manual inspection was used to rectify any incorrect data. For each transaction, the rates of change in shoreline position were calculated using the standard linear regression rate (LRR) approach.

When utilizing an intensity-based detection approach for single-band-category images, mixing pixels between land-water borders may influence shoreline placements. To reduce the effects of mixed pixels, a variety of strategies can be utilized (for example, water index, color composite, producing images using the band ratio, and so on). Eliminating mixed pixels using the single-edge detection method is problematic for a specific application [33]. If the changes in shoreline positions are significant, and the goal is to extract reasonable shoreline positions to estimate the long-term rates of shoreline change, the edge-detection method using a single band is quite acceptable [31]. Using the above-mentioned shoreline detection approach, Anwar and Rahman [31] compared satellite-based shoreline change rates with in-situ measured rates near the Daulatkhan station on the east coast of Bhola Island in the Meghna Estuary of Bangladesh, which is located in the central coastal zone. Results from satellite images around the Daulatkhan station, revealed that the shoreline erosion rate differed by 3% from the rate of erosion measured from in-situ data, validating the accuracy of the extracted shoreline change rates from satellite imagery. Moreover, tidal variation, waves, currents, anthropogenic activities, and other factors may influence the shoreline position. Due to the high rate of shoreline change at Kutubdia Island, which may not be affected by mixed pixel errors and tidal variations, we had to rely on shoreline change rate analysis [31]. Yet, the shoreline position along Cox’s Bazar may be affected by tidal variation due to the flat nature of the beach. We required sequential radar images with a low spatial resolution that were consistent with the tide level data at the same place and time interval, to determine the effect of tidal variation on shoreline change rates with “mm”-level precision. Still, the lack of reliable tidal and wave data, as well as LANDSAT images with a resolution of 30 m, was a major impediment to explaining the tidal effect on shoreline change rates.

## 4. Results

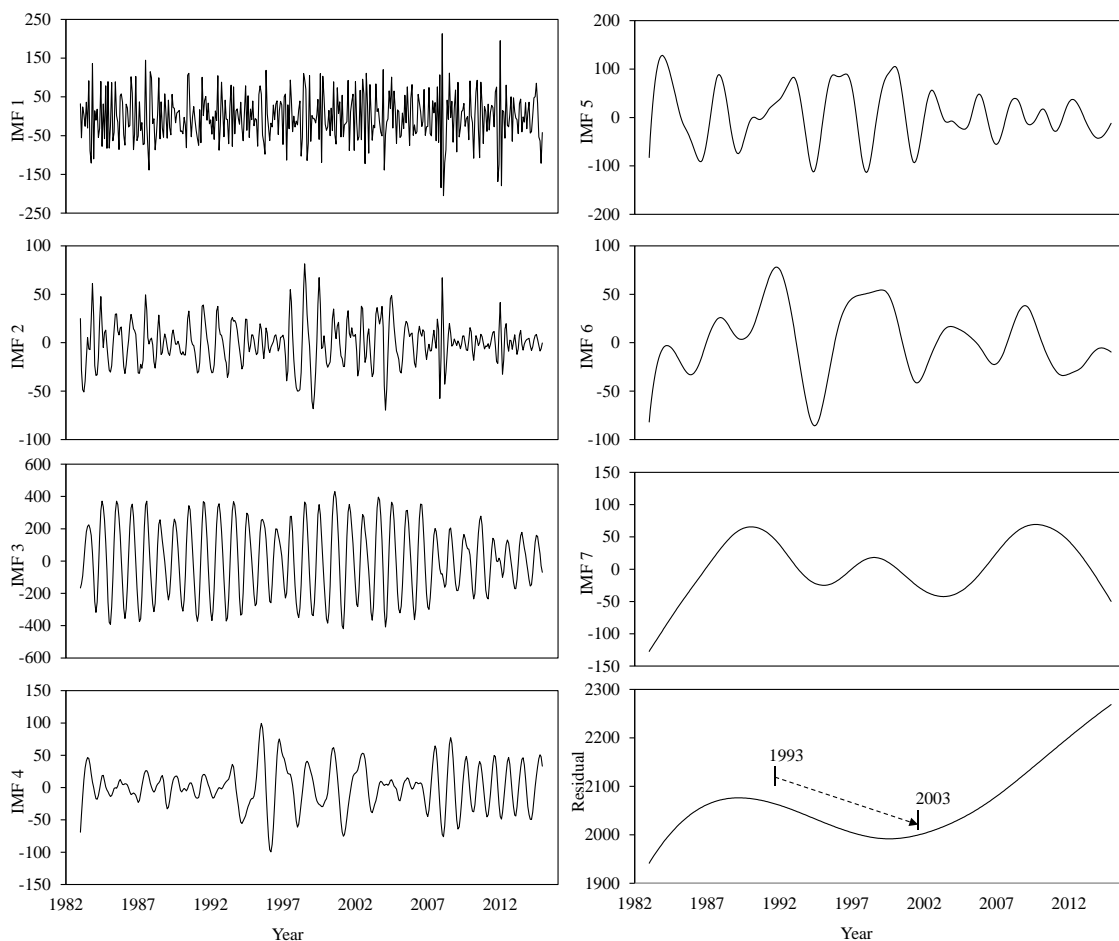
### 4.1. Sea Level Variations at Cox's Bazar

This study utilized hourly tide level data at Cox's Bazar station from 1983–2016 to analyze the long-term sea-level variation. Figure 6a shows the hourly sea level for 19 December 1999, while Figure 6b represents the mean monthly sea level for the year 1999 at Cox's Bazar Station. The figure demonstrates that the difference between the maximum and minimum daily sea-level variation was approximately 2 m, whereas the mean monthly seasonal variation was approximately 1 m. Therefore, sea-level variation and seasonal trend analysis are crucial to understanding the rising sea-level status of Cox's Bazar. From Figure 6, it can be observed that the sea level started to increase from the month of March, continuing to May (the hottest month) primarily due to expansion of water associated with high temperatures, and reached its maximum level from June to August due to the accumulation of monsoon rainfall (please see Figure A1 of Islam and Sato [34]). Again, the sea level started to decrease from October during the winter season with the lowest sea level in February because of low temperatures and rainfall (Figure 6c,d). Observing the similar pattern of seasonal variation of the sea level, precipitation, and temperature, we assumed that these local factors considerably influence the sea-level variation, in addition to global sea-level rise associated with global warming and climate change in the long run.



**Figure 6.** (a) Hourly sea level on December 19, 1999, (b) mean monthly sea level for the year 1999, (c) monthly temperature (degree Celsius) for 1991, and (d) monthly variation of rainfall (mm/day) for the year 1994 at the Cox's Bazar station.

Figure 7 depicts the CEEMD-based nonlinear sea-level trend (monthly tide-level data from 1983 to 2014) at the Cox's Bazar station. The nonlinear trend (residual in Figure 7) shows that the sea level rose from 1983 to 1993, dropped somewhat from 1993 to 2003, then increased sharply from 2003 to 2014. As a result of this pattern, we divided the study period into three independent parts (i.e., 1983–1993, 1993–2003, and 2003–2014) for linear trend analysis.



**Figure 7.** Complete ensemble empirical mode decomposition (CEEMD) consists of intrinsic mode functions (IMFs) and residuals for the sea-level time-series data from Cox's Bazar tide gauge station for the period of 1983–2014.

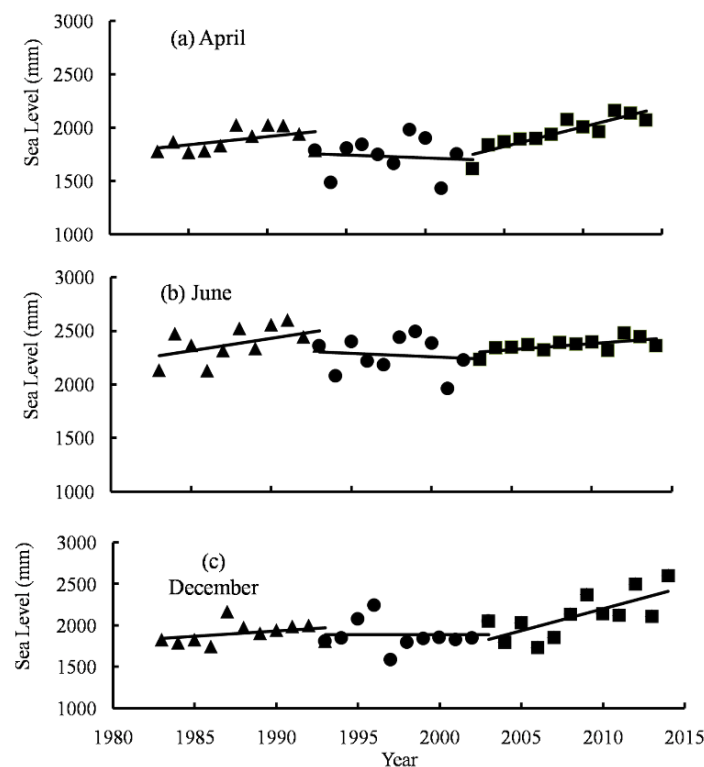
The results of monthly sea-level linear trend analysis for three distinct periods—1983–1993, 1993–2003, and 2003–2014—are presented in Table 2. Though we considered 1983–2016 tide data, the trend analysis ignored 2015–2016 data as these two years' data had a sudden jump from the previous dataset (Figure 4), which may have been due to a change in datum level. The results showed an overall trend for the entire study period of 1983–2014. Trend values in bold represent statistically significant data at the 99% and 95% confidence levels, and negative values represent decreasing trends. The different periods had different values of sea-level trends for the different months (Table 2). It can be noted that some of the trend analysis cases were not statistically significant. However, the overall mean yearly sea-level trend rose +5.34 mm/year for the period of 1983–2014. In the middle period of 1993–2003, the sea level declined by approximately  $-0.85$  mm/year, which was negligible compared to the other two periods (1983–1993 and 2003–2014). In the periods of 1983–1993 and 2003–2014, the sea-level rising trends (+23.5 mm/year and +26.1 mm/year, respectively) were much higher than the average rising trend for the entire study period of 1983–2014. Moreover, the monthly trend analysis of the sea level showed a similar pattern of sea-level changes as the mean yearly sea-level trend. The first period (1983–1993) and the latest period (2003–2014) had a rising trend in sea level, with much higher values than the middle period of 1993–2003. The slight decline tendency or relatively stable nature of the sea level in the middle period of 1993–2003 may have minimized the rising sea-level trend of the Bay of Bengal along the eastern coast of Cox's Bazar station. Figure 8 shows a graphical representation of the trend analysis for the months of April (pre-monsoon), June (monsoon), and December (post-monsoon) for the periods of 1983–1993, 1993–2003,

and 2003–2014. The solid straight line indicates the trend between the chosen time periods. The flat trend line in the middle period demonstrates the stable or insignificant increasing or decreasing sea-level trend. The mean annual sea level rising trend of 5.34 mm/year endorses the findings from other studies, including  $3.4 \pm 1.7$  mm/year as per Becker et al. [35] and 11–21 mm/year by the Climate Change Cell of Bangladesh [36]. However, other studies contradict our observation of a trend of sea-level rise, such as a rising trend of 1.36 mm/year observed at the Cox's Bazar station, when utilizing the PSMSL dataset, by Sarwar [12]. Furthermore, Sarwar [12] marked sea-level falling trends of 11.75 mm/year, 5.59 mm/year, and 8.33 mm/year at the Sadarghat, Moheshkhali, and Teknaf stations, respectively, which are adjacent stations to Cox's Bazar.

**Table 2.** Trend analysis of sea-level changes (mm/year) for Cox's Bazar station.

Month	1983–1993	1993–2003	2003–2014	1983–2014
January	39.5 **	−2.1	50.1 **	14.1 *
February	31.2 **	−7.2	43.6 **	9.7 *
March	15.9 *	−14.73	47.57 **	5.71
April	15.35 *	−5.35	36.8 **	5.86 *
May	21.42 *	−8.6	24.0 **	5.07
June	23.4 *	−6.5	11.32 **	0.78
July	30.1 *	14.11	−1.27	0.81
August	23.35 *	1.37	−2.89	−0.64
September	32.8 **	5.39	−1.4	5.02 *
October	26.35 **	11.98	12.0 *	3.97
November	9.9	1.76	13.18	−0.09
December	14.95	−0.421	28.7 *	7.44 *
Yearly	23.5 **	−0.85	26.1 **	5.34 *

\*\* Statistically significant in 99% confidence level and \* 95% confidence level.

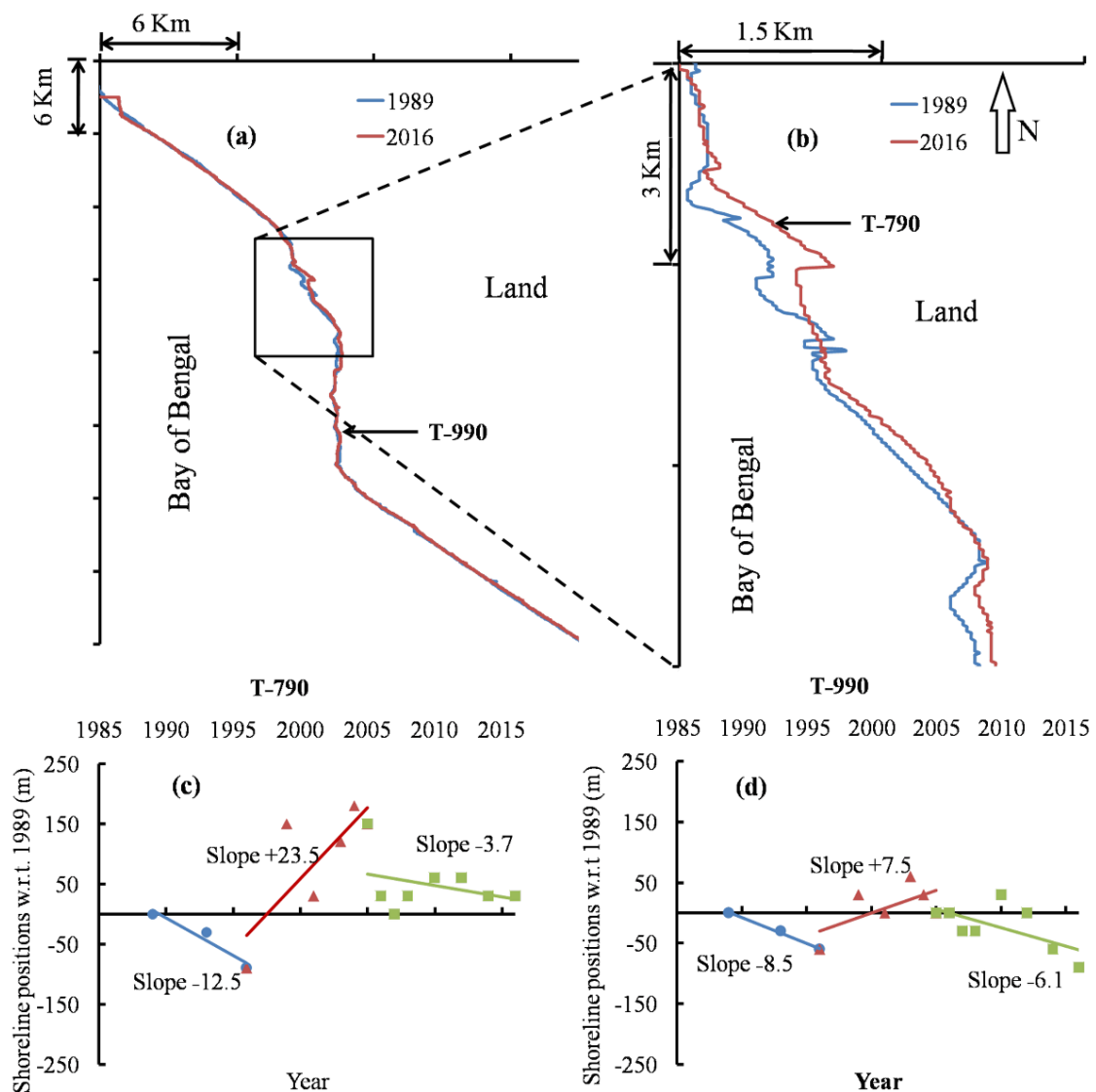


**Figure 8.** Sea level variation for the months of (a) April, (b) June, and (c) December from 1983 to 2014. Solid straight line represents the trend. Triangles, circles and squares are the mean yearly sea levels of the designated months for the period of 1983–1993, 1993–2003 and 2003–2014, respectively.

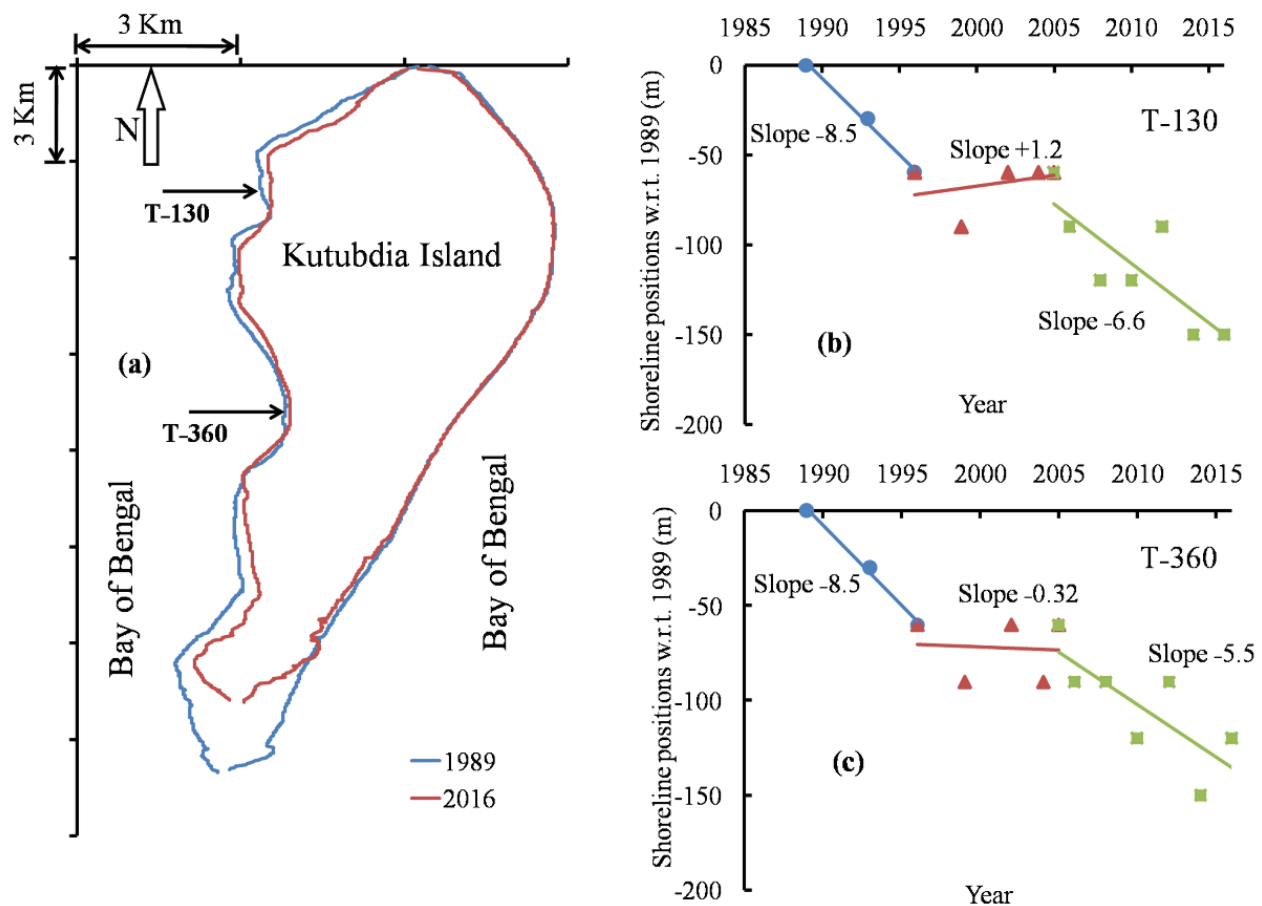


#### 4.2. Shoreline Changes

We examined the variation of sea-level trends for different time periods (Table 2 and Figure 8) and detected shoreline positions for different transects along Cox's Bazar and Kutubdia Island from available LANDSAT images. Figures 9 and 10 show the relative shoreline positions of Cox's Bazar and Kutubdia Island, respectively. To analyze the rate of shoreline position change, we divided the study period into sub-periods (i.e., 1989–1996, 1996–2005, and 2005–2016) based on the relative coastline positions over the years for various transects along the Cox's Bazar and Kutubdia shores. For most of the transects along Cox's Bazar and Kutubdia Island, we found similar patterns of erosion during 1989–1996 and 2005–2016, while there was accretion or a relatively stable shoreline during 1996–2005 (Figures 9c,d and 10b,c).



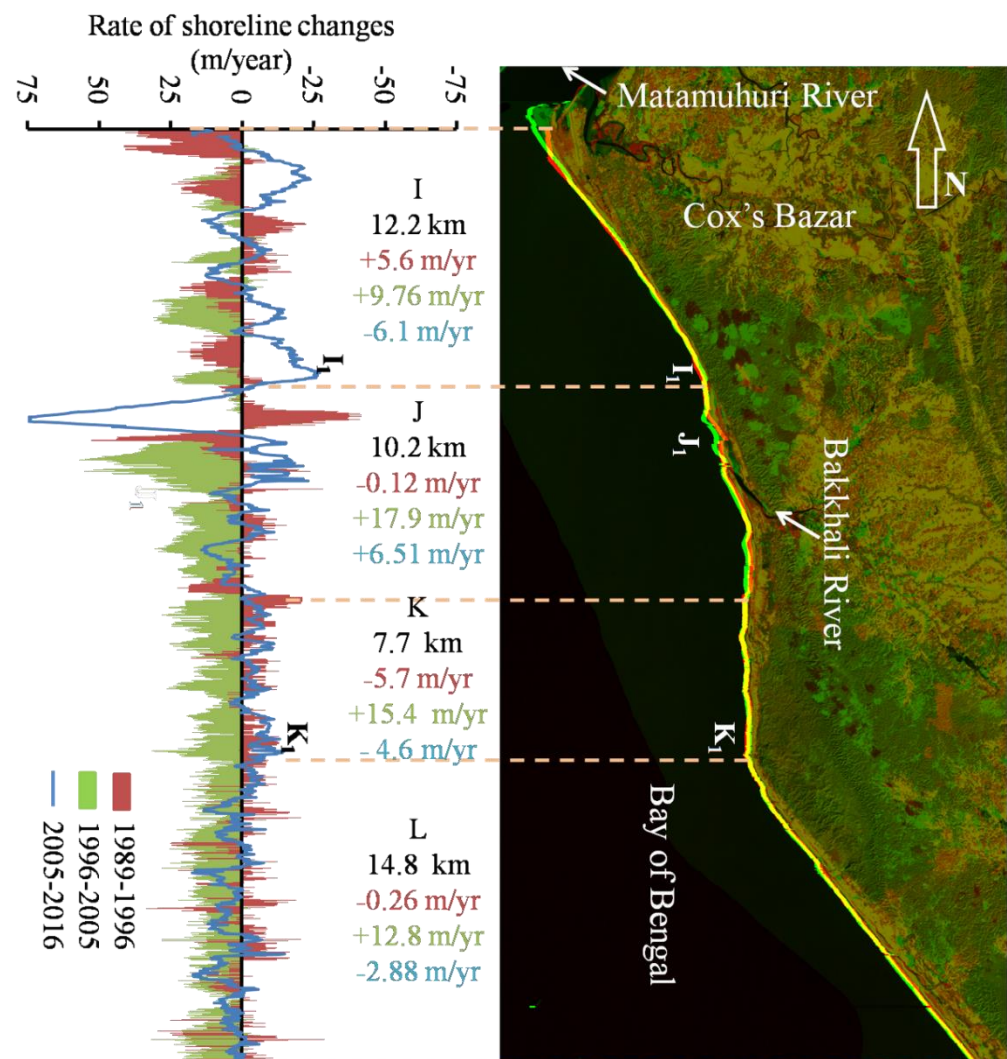
**Figure 9.** (a) Shoreline positions along Cox's Bazar in 2016 (red) and 1989 (blue), (b) zoomed view of the shoreline positions (black square in (a)), (c) shorelines relative to 1989 for transect no. T-790, (d) shorelines relative to 1989 for transect no. T-990.



**Figure 10.** Shoreline positions (a) around Kutubdia Island in 2016 (red) and 1989 (blue), (b) relative to 1989 for transect T-130, (c) relative to 1989 for transect T-360.

#### 4.2.1. Rate of Shoreline Change along Cox's Bazar

Figure 11 shows the rates of shoreline change of Cox's Bazar for the periods of 1989–1996 (red), 1996–2005 (green), and 2005–2016 (blue) along different vertical transects from west to east. The rates of changes in shoreline position were examined for the different designated segments I, J, K, and L located from north to south of Cox's Bazar. It was observed that for the shoreline in the first period 1989–1996 and the recent period 2005–2016, erosion was dominating along the coastline of segment I to L. Exceptionally, along segment J, especially at the mouth of the Bakkhali River ( $J_1$ ), the shoreline was gaining land in the two recent periods, i.e., 1996–2005 and 2005–2016. On the contrary, accretion was dominating along the Cox's Bazar shoreline in the middle period from 1996 to 2005. The rate of change was not significant over the whole period. Overall, shore accretion and erosion were regular along the Cox's Bazar coastline, but not significant. Yet, some significant shoreline changes were observed at the mouth of the Matamuhuri River (upper portion of segment I) and the Bakkhali River (Segment J). Table 3 explains the rates of shoreline change for different periods for each segment. It was deemed that accretion was dominating along the Cox's Bazar shoreline. The rate of change was +3.91 mm/year for the entire study period of 1989–2016, though some segments (I, K, and L) were experiencing erosion in the recent period. Segment J was the most stable part when considering erosion, whereas segments I and K were comparatively vulnerable versus other segments.



**Figure 11.** Shoreline change rates along Cox's Bazar for the periods of 1989–1996 (red), 1996–2005 (green), and 2005–2016 (blue). Negative values indicate erosion (landward movement of shoreline).

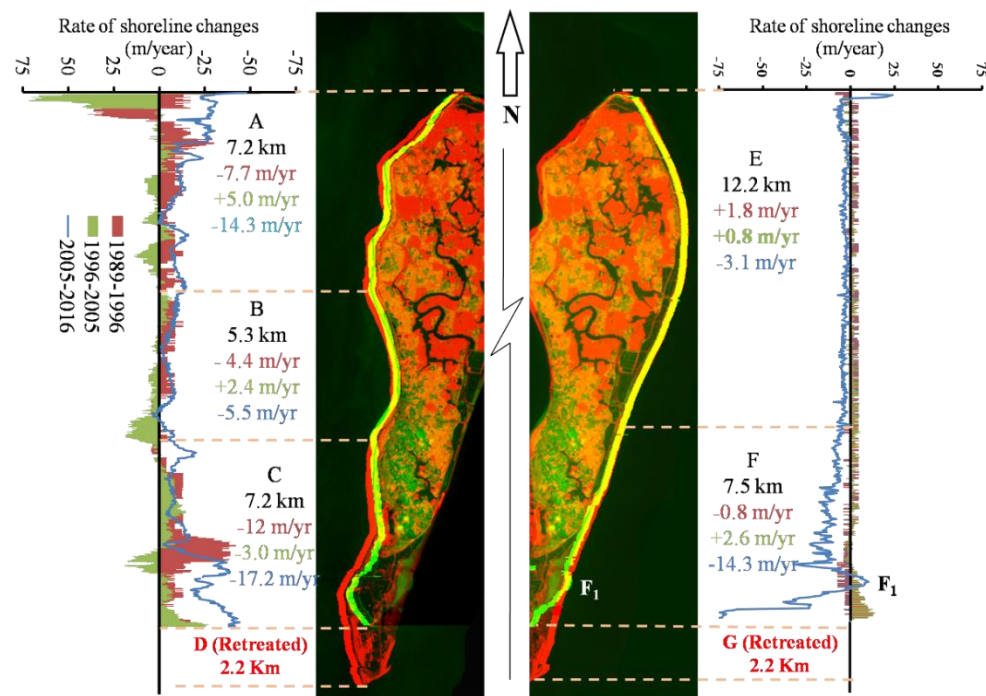
**Table 3.** Rates of shoreline changes for the different segments of Cox's Bazar in the study period of 1989–2016.

Years	Rate of Shoreline Change (mm/Year)			
	I (12.2 Km)	J (10.2 Km)	K (7.7 Km)	L (14.8 Km)
1989–1996	+5.6	−0.12	−5.7	−0.26
1996–2005	+9.76	+17.9	+15.4	+12.8
2005–2016	−6.1	+6.61	−4.6	−2.88
1989–2016	+2.22	+8.62	+1.78	+3.02
		+3.91 (average of all segments)		

#### 4.2.2. Rate of Shoreline Changes around Kutubdia Island

The rates of shoreline change around Kutubdia Island for the periods of 1989–1996 (red), 1996–2005 (green), and 2005–2016 (blue) are presented in Figure 12. The west side of the island was facing erosion from 1989–1996 and in the recent period of 2005–2016. Meanwhile, during the middle period of 1996–2005, the rate of shoreline changes was low compared to the other two periods. Moreover, segments A and B gained land during that period of 1996–2005. Segments C and D faced continuous erosion in all periods, and segment D retreated about 2.2 km from 1989 to 2016. The east side of Kutubdia Island was

more stable than the west side. However, in the recent period, some erosion along segments E and F became a matter of concern for their continuous land loss along the shore. On the east face of the island at segment G, approximately 2.2 km of shoreline also disappeared over the study period of 1989 to 2016. Table 4 demonstrates the rates of shoreline change around Kutubdia Island. The shoreline change rates were  $-5.23$  mm/year along the west side and  $-2.85$  mm/year along the east side from 1989 to 2016. The average rate of change around Kutubdia Island was  $-4.28$  mm/year for 1989–2016. Yet, in the middle period, accretion was observed along most of the segments of Kutubdia Island, except for along segment C, which was continuously eroded over the study period.



**Figure 12.** Shoreline change rates around Kutubdia Island for the periods 1989–1996 (red), 1996–2005 (green), and 2005–2016 (blue). Negative values indicate erosion.

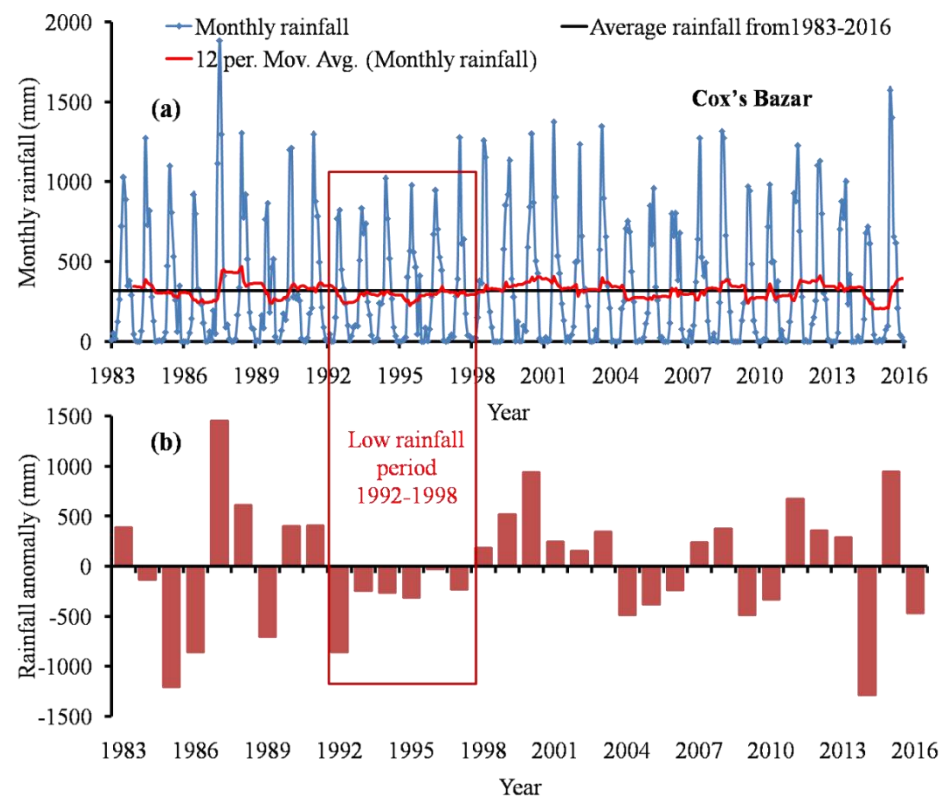
**Table 4.** Rates of shoreline change along the different segments of Kutubdia Island for the study period of 1989–2016.

Years	Segment-Wise Shoreline Rate of Change in mm/Year				
	A (7.2 Km)	B (5.3 Km)	C (7.2 Km)	E (12.2 Km)	F (7.5 Km)
1989–1996	−7.70	−4.40	−12.00	1.80	−0.80
1996–2005	+5.00	+2.40	−3.00	+0.80	+2.60
2005–2016	−14.30	−5.50	−7.00	−3.10	−14.30
1989–2016	−6.16	−2.58	−6.96	−0.53	−5.17
Average		−5.23 (west)		−2.85 (east)	
		−4.28 (average of all segments)			

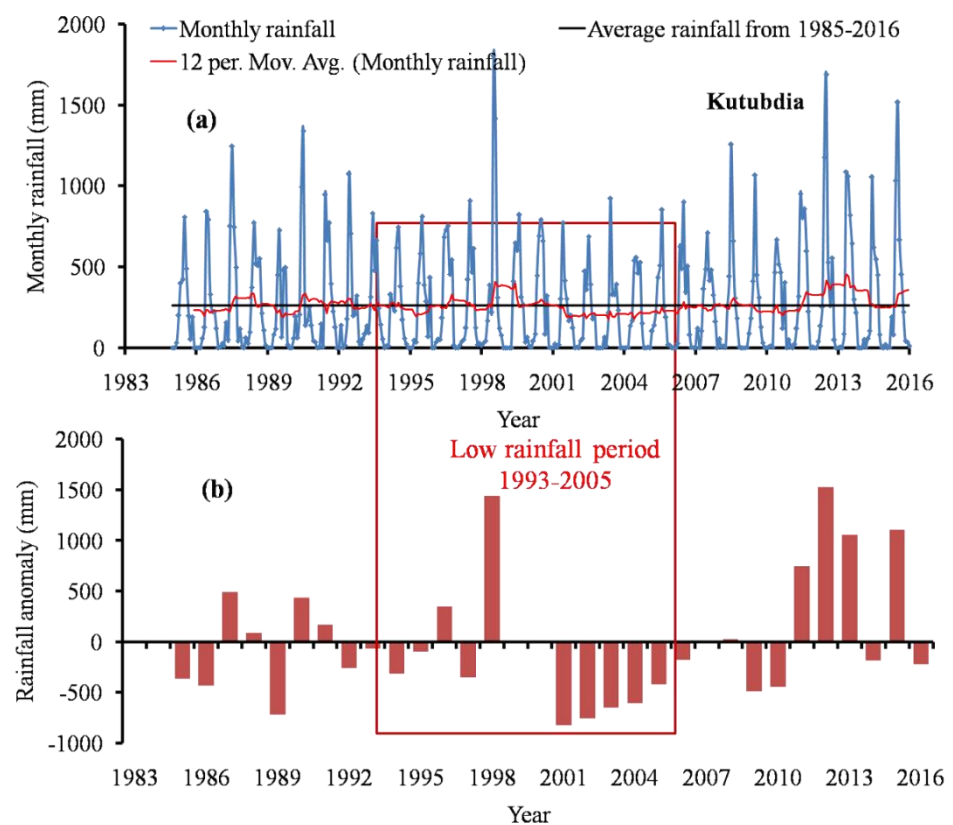
#### 4.3. Variation of Rainfall at Cox's Bazar and Kutubdia Island

Figures 13 and 14 represent the time series of monthly rainfall data for Cox's Bazar and Kutubdia Island, respectively, with their yearly fluctuation of anomaly from the zero mean annual rainfall. Specifically, low rainfall was observed at the Cox's Bazar station from 1992 to 1998. A similar low rainfall pattern was noted at Kutubdia station for the period of 1993 to 2005. There was less rainfall intensity in and around the eastern coastal zone of Bangladesh during the period of 1995–2005.





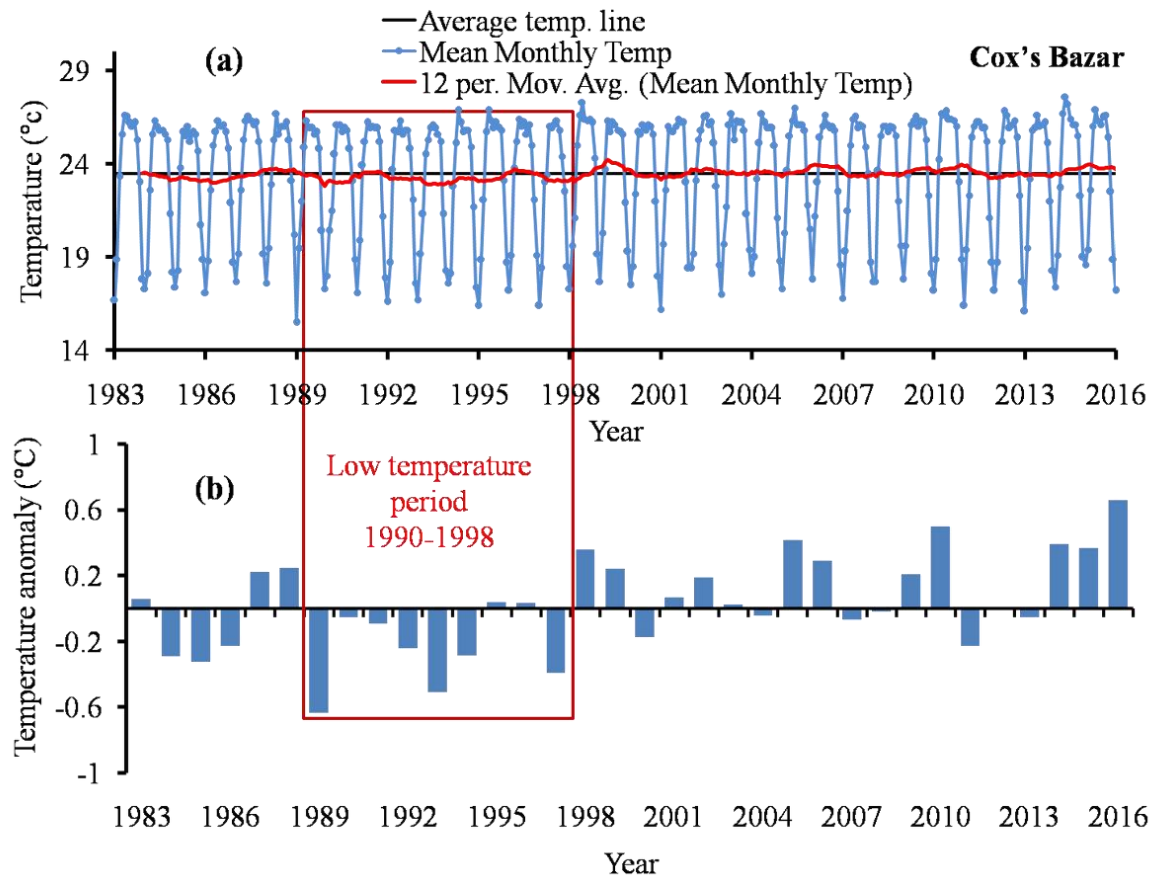
**Figure 13.** (a) Time-series rainfall data of the Cox's Bazar station. (b) Rainfall anomaly from 1983–2016. Anomaly represents the fluctuation of the yearly rainfall from the zero mean.



**Figure 14.** (a) Time-series rainfall data from Kutubdia station. (b) Rainfall anomaly from 1983–2016. Anomaly represents the fluctuation of the yearly rainfall from the zero mean.

#### 4.4. Variation of Temperature at Cox's Bazar Station

Figure 15 represents the time series of monthly temperature data with their yearly fluctuation for Cox's Bazar. The solid line in Figure 15a represents the average temperature from 1983 to 2016, and the red line shows the 12-month moving average. To explain the variation of temperature over the period, the temperature anomaly (Figure 15b) was prepared. The temperature had no significant change over the periods. However, from 1990 to 1998, the average temperature was comparatively lower than in recent years. Recently, a slight rising trend in temperature can be observed from the collected data.



**Figure 15.** (a) Time series of temperature data for Cox's Bazar station. (b) Temperature anomaly from 1983–2016. Anomaly represents the fluctuation of the yearly temperature from the zero mean.

#### 5. Discussion

In this study, we investigated the trend of sea-level changes along the eastern coast of Bangladesh using tide-level data from Cox's Bazar station to understand the sea-level fluctuations. Moreover, we used LANDSAT satellite imagery to visualize the morphological changes along the coastline. We reported that the sea level in the eastern coastal zone was rising for the period of 1983–1993 and slightly decreasing or fairly stable for the period of 1993–2003. This stable nature of sea level might be attributed to a relatively lower amount of yearly rainfall during 1995–2005 for both Cox's Bazar and Kutubdia Island (Figures 13 and 14). Meanwhile, the mean annual temperature was also at a lower level for the period of 1990–1998 for both the stations (Figure 15). Temperature rise enhances the water-holding capacity in the atmosphere. According to a recent study by Berg et al. [37], the water-holding power of the atmosphere increases (decreases) approximately at a rate of 7% for every 1 °C increase (decrease) in temperature, which is known as the Clausius–Clapeyron rate. Therefore, a decrease in mean annual temperature subsequently triggered a drop in the mean annual rainfall amount during the period of 1993–2003 for both Cox's Bazar and Kutubdia Island. Simultaneously, decreased rainfall for the same period might

have influenced the sea level to remain stable, with a strong connection between sea level and precipitation found in this region [34]. Our study also revealed that sea-level fluctuations might impact the shore morphology accordingly. For example, the relatively steady sea level during the period of 1993–2003 was associated with a stable shore morphology for the period of 1996–2005 (Figures 11 and 12). In fact, stable sea-level conditions promoted a land-gaining process along different segments of both Cox's Bazar and Kutubdia Island (green values shown in Figures 11 and 12). It is important to note that shore morphology may not change immediately after sudden sea-level fluctuations. Therefore, we emphasize that an average sea-level change during the period of 1993–2003 *might* have affected the intermediate shore morphology for 1996–2005.

Unlike previous periods, we observed a sharp increasing trend in the sea level for the recent period of 2003–2014 using both nonlinear and linear trend analysis (Figures 7 and 8). This rising trend may have been caused by the wind-induced redistribution of energy in the Bay of Bengal and Indian Ocean region [35,38,39]. Such a rising sea-level trend corresponds with several other recent studies around the Bay of Bengal [35,40,41]. For example, a swift climb in sea level was reported by Lee et al. [40] in the North Indian Ocean during the recent period of 2004–2013. Similarly, the absolute sea-level change on the Chittagong coastal plain that encompasses the Cox's Bazar region was calculated as  $3.4 \pm 1.7$  mm/year for the period of 1993–2012 in the study conducted by Becker et al. [35]. Yet, the recent trend is higher than the global mean sea-level rate reported as  $2.1 \pm 0.2$  for the period of 1968 to 2012 [42]. Therefore, it is evident that the sea level has recently increased along the eastern coastal zone of Bangladesh. However, the trend value differs from one study to another due to the nature of analysis and data availability [9,11–13].

It is important to note that the accuracy of researchers' results on sea-level trends depends on many factors, including the measurement principle, land subsidence, availability of data, location of the station, seasonal variation of the sea level, major flood events, sedimentation process, geology, tectonic activities, etc. Unlike data obtained from the permanent service for the mean sea level (PSMSL) and US/European ocean altimeter satellites, data derived from tide gauge stations are the only data source in Bangladesh to verify the sea level changes along the coast. However, reliable tide gauge data are not adequate along the coastline to perform a time-series analysis of the sea-level changes [36]. In addition, the Cox's Bazar tide gauge station is located at the mouth of the Moheshkhali River. Such location of the tide gauge station may be problematic because during high (low) river discharge/flood events, the tide gauge may overestimate (underestimate) the sea level elevation. Considering seasonal variations and abrupt changes to the sea level in a particular year due to extreme flood events (e.g., 1988, 1998, and 2007 as the years of major flood events in Bangladesh), the sea level may not be increasing at a constant rate, especially considering local effects. Therefore, performing linear trend analysis with a single numerical trend value indicating the sea-level rise/fall trend may be perplexing. Accordingly, we are not ultimately concerned with the numerical value of the sea level's rate of change.

Beyond this, the Ganges-Brahmaputra-Meghna (GBM) delta and Chittagong coastline are subsiding at alarming rates according to the findings of recent studies by Becker et al. [35], Ericson et al. [43], and Ostanciaux et al. [44]. Land subsidence may enhance the relative sea-level rise in the near future. Consequently, the sea level has been rising in the recent period, and it might have affected the shore morphology along the eastern coast of Bangladesh, more so than the previous two periods of 1989–1996 and 1996–2005. Moreover, under the representative concentration pathways (RCP) 4.5 scenario, it is expected that the relative sea level may increase from 14 to 30 cm by the end of 2050 and 34 to 74 cm by the end of 2100 [35]. Hence, a clear understanding of how the shore morphology will be impacted due to the rising sea-level trend is essential for coastal management strategies in Bangladesh.

Dominating erosional patterns were observed along the different segments of the Cox's Bazar shoreline (i.e., segments I to L) in the first period of 1989–1996 and the recent period of 2005–2016 due to the implications of a sea-level rise (Figure 11). We observed a rapid shore

erosional problem for the current period of 2005–2016 compared to the previous periods of 1989–1996 and 1996–2005. A similar morphological change pattern was observed for Kutubdia Island. Both the east and west faces of the island encountered erosional problems for the periods 1989–1996 and 2005–2016 (Figure 12). However, land-gaining processes were observed along segment J of the Cox's Bazar shoreline, especially at the mouth of the Bakkhali River ( $J_1$ ) for the recent two periods of 1996–2005 and 2005–2016 due to the construction of a marine roadway system between 1993–2008 and a 400 m-long revetement structure to further protect the roadway in 2008–2009 [45]. However, the Bakkhali River mouth had undergone significant morphological changes during 1996–2000 (Figure 11). In the year 2000, significant sand deposition was observed at the mouth of the Bakkhali River. Soon after completing the marine roadway system in 2008, the embankment went through rapid erosion around the mouth of the Bakkhali River. Attempts were made to solve the erosional problem with a newly implemented revetment structure during 2009–2010. The revetement work protected the area via sand accumulation in front of the structure [45]. However, the structure was not able to protect the roadway system due to sandspit formation and growth; consequently, a new adjacent area was eroded to the north ( $I_1$ , Figure 11) and south ( $K_1$ , Figure 11) of the river. The formation and growth of the reported sand spit were evident from a computational study using MIKE21FM SM software considering sediment transport and wave-dominated currents along the shoreline [45]. In terms of coastline erosion, the eastern coast from Chittagong to Cox's Bazar is rather stable compared to the western and central zones [12]. Furthermore, during the data period of 1980–2017, the average change in coastline reached 120 m erosion and 100 m deposition along the Cox's Bazar beach [21]. To identify vulnerable sites, Navera and Ahmed [21] studied the erosion-accretion behavior of various locations along the beach. For the period of 1972–2014, Islam et al. [22] estimated the rates of coastline erosion around Kutubdia Island to be  $-4.0$  m/year,  $-33.7$  m/year,  $-2.6$  m/year, and  $-5.6$  m/year, respectively, along the north, south, east, and west shores.

Shore morphological changes depend on many other factors, including the geometric shape of the land, significant waves, rainfall-runoff processes, cyclones and winds, river/shore protection works, and anthropogenic activities. For instance, the bottom of Kutubdia Island eroded because its width was much smaller than those of its other portions and thus could not withstand the significant waves coming from the Bay of Bengal (Figure 12). The west face of the island eroded more than the east face due to southwest wind-induced waves hitting the island at an angle of  $201^\circ$  [32]. Meanwhile, the east portion of Kutubdia Island is protected by the mainland and thus less affected by the dominating waves (Figure 12). Beyond this, as no abrupt morphological changes were observed, we could say that there was no effect of cyclones on the Cox's Bazar and Kutubdia Island shorelines. In this study, we were not able to clarify the effect of the water level on the shoreline rates of change. Furthermore, information on extreme hourly tide levels may be obscured by averaging hourly tides to give monthly data, which may fail to indicate short-term changes to the coastline location.

Ahmed et al. [17] conducted a socioeconomic vulnerability assessment of Bangladesh's eastern coastal zone and discovered that Kutubdia Island might be the most affected in terms of human settlement, socioeconomics, and physical vulnerability along the island's eastern part. The shoreline of Cox's Bazar, on the other hand, is primarily a flat sandy beach that is popular with tourists. As a result of coastline erosion, the road network and some tourist spots may be impacted, but human settlements will be unaffected because the residential areas are located far from the shoreline.

## 6. Conclusions

This study investigated the sea-level and morphological changes along the eastern coast of Bangladesh, specifically at Cox's Bazar and Kutubdia Island, utilizing hourly tide-level data, and 15 LANDSAT satellite images from the period of 1983 to 2016. We first employed the nonlinear sea-level trend analysis to determine whether the tide-level data



were nonlinear. Based on the analysis, we divided the total period into three, recognizing sea-level fluctuations and morphological change interactions. Our findings revealed that the rising sea-level trend was higher in the recent period of 2003–2014 than in the previous periods of 1983–1993 and 1993–2003. In fact, the sea level around the mid-1990s to mid-2000s was relatively stable. Such sea-level change behavior may have affected the shore morphology around Cox’s Bazar and Kutubdia Island. We observed a similar pattern of shoreline change rates for both Cox’s Bazar and Kutubdia Island, with a higher rate of shore erosion in the recent period than previous periods. We also attempted to identify whether rainfall and temperature may impact the sea-level rise. Our analysis showed that temperature and precipitation impacted the sea level variation. A higher temperature may have induced higher rainfall in this hilly topographic region, and the rainfall-runoff process may have affected the sea-level rise.

Bangladesh is regarded as the largest deltaic region globally, and most susceptible to climate change-induced sea-level rise and coastal hazards. The eastern coast of Bangladesh could represent a source of new opportunities associated with exploring and expanding our use of natural resources, including natural gas, tourism, coastal fisheries, and salt production. Therefore, understanding the sea level and morphological phenomena of the eastern coast should be given utmost priority, especially if we are to sustainably secure the world’s longest stretch, at Cox’s Bazar, of sandy sea beach and the country’s only lighthouse, on Kutubdia Island. Future studies should aim to reduce the uncertainties related to the sea-level measurements around the coastal zones of Bangladesh by applying state-of-the-art instrumentation and local radar to monitor microscopic morphological changes.

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