Has Tropical Cyclone Disaster Risk Increased in Bangladesh: Retrospective Analysis of Storm Information, Disaster Statistics, and Mitigation Measures

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Abstract

Tropical cyclone (TC) disaster risk has likely increased in Bangladesh since the beginning of the 21st century. It is primarily due to the cumulative impact of rising coastal exposures such as population, insufficient funding to address disaster risks, and ineffective utilization of century-old early warning signals for TC. From 2000 to 2020, the average number of people affected by a Category 1–2 TC (according to Saffir Simpson Hurricane Wind Scale) was 3.18 million, representing a 28.91% increase from the average reported during 1979–1999. Moreover, the past two decades have witnessed a staggering 69.83% of all TC-induced disasters, and with the exception of Chattogram, all coastal districts have seen a rise in the number of TC disasters. Notably, the frequency of TCs and meteorological trends, which remain relatively constant over time, cannot account for either the size of the affected population or the number of TC-related disasters reported at the sub-national level. During 2000–2013, roughly 67% of the disaster management budget was provided by foreign and humanitarian aid, and a significant funding gap was observed during major TC disasters, such as TC Sidr in 2007. Our findings also suggest that the Bangladesh Meteorological Department (BMD) tends to issue higher levels of warnings irrespective of the intensity and potential hazard of a TC, which may have contributed to a reduction in the fatality rate in recent years. However, there is a growing concern that this approach may lead to an emerging type of TC disaster risk, where people may start to disregard the warnings due to their perceived lack of credibility.

Keywords

Tropical cyclone, disaster risk, coastal exposure, disaster mitigation, early warning system, Bangladesh

1 Introduction

Tropical cyclone (TC), responsible for causing hundreds of fatalities and inflicting billions of dollars in damages annually, is among the most devastating natural catastrophes worldwide (Geiger et al. 2018). TC induces a variety of hazards, including strong winds, storm surges, and heavy rain, and the effects of these multi-hazards can vary depending on the characteristics of a TC and where it makes landfall (Lal et al. 2012; Islam and Takagi 2020a). For example, while the Northern Indian Ocean (NIO) experiences 5% to 7% of global TCs each year (World Meteorological Organization 1993; Alam et al. 2003), Bangladesh alone experiences only 1% of these storms, but they are responsible for 53% of global deaths (Needham et al. 2015; Islam et al. 2021a). Overall, TCs that have impacted Bangladesh since 1900 have resulted in 0.75–1.23 million fatalities, affected 61.6 million people, and caused \$4.7–\$9.0 billion in damages (ADB 2016).

Historical evidence suggests that Bangladesh suffers a devastating TC every four and a half years (Shamsuddoha and Chowdhury 2007). The geography of the region, with its shallow bathymetry at the northern end of the Bay of Bengal and funnel-shaped coastline, along with low-lying flat terrain, increases the risk of storm surges that can be deadly, particularly in densely populated coastal areas (Islam and Peterson 2009). The worst TC on record in Bangladesh is Gorky (1991), a Category 4 Hurricane in the Saffir-Simpson Hurricane Wind Scale (SSHWS), triggered storm surges of ~6.7m, and claimed approximately 140,000 lives. In comparison, a similar intensity TC Sidr (2007) generated ~6.1m storm surges but claimed far fewer lives (~3,360) than Gorky (Bangladesh Meteorological Department 2021). However, the economic damage from Sidr was about 1.3 times higher than Gorky, amounting to \$1.78 billion, equivalent to 2.6% of the country's GDP in 2007 (RMMRU and SCMR 2013; Guha-Sapir et al. 2022). Some experts argue that technological advancement and improved risk communication, including early warning and people's awareness have significantly enhanced the country's preparedness for TC disasters (Alam and Collins 2010). Nevertheless, the increasing trend in TC induced economic damage and the number of affected people remain unchanged and in some cases, it surpasses the projected figure (ADB 2016). The World Bank Group (2010) reported that if a TC with a 10-year return period strikes the Bangladesh coasts, it would cause damages equivalent to 2.4% of GDP and affect as many as 10.04 million people. A recent example is TC Amphan (2020), equivalent to a Category 1 Hurricane made landfall nearby to the Bangladesh coast (West Bengal, India), affected some 10 million people, caused at least 25 deaths, and resulted in economic damage of $1.5 billion in Bangladesh (Hossain et al. 2021; Guha-Sapir et al. 2022).

Scientists have expressed concerns that human-induced climate change may be a significant contributing factor to the size of affected people and observed economic losses associated with TCs in recent decades. The impact of climate change may include an increase in the frequency of strong-intensity TCs (Mills 2005; Mendelsohn et al. 2012) and their compound effect with the rising mean sea level (Vitousek et al. 2017; Taherkhani et al. 2020). By contrast, several scientific studies have reported that the rise in losses can be attributed entirely to societal changes such as increasing wealth, infrastructures, and population (e.g., Pielke et al., 2008; Neumayer and Barthel, 2011; Weinkle et al., 2012). A critical question of interest to researchers and policymakers in disaster risk management is whether TC risk has increased in Bangladesh over time. It is particularly pivotal because Bangladesh has a long history of strong socio-economic connection with the sea. The Government of Bangladesh is currently focusing on the growth of ocean economy including marine fishing, transportation and coastal and marine tourism, as part of its growth strategy (Patil et al. 2018). With 60% of annual trade currently flowing through sea ports, Bangladesh's first deep sea port is expected to be operational by 2025 (Bhattacharjee 2021). This development resulted in an average annual coastal population growth rate of 1.36% and an expected population of 58 million by 2050 (The World Bank Group 2010). Nevertheless, TC disasters risk in coastal districts remains a major impediment to sustainable societies and economic development. Consequently, the United Nations Development Program has designated Bangladesh as the world's most vulnerable country to TCs (UNDP 2004).

To enhance our comprehension of mitigation efforts against TC disasters, an investigation of TC climatology and socio-economic factors can be beneficial (Pielke et al. 2008; Neumayer and Barthel 2011; Weinkle et al. 2012; Takagi 2019). While several studies have examined TCs in the Bay of Bengal, only a few have concentrated on the Bangladesh coast. For example, Alam et al. (2003) conducted a work on the frequency of TC that originated in the Bay of Bengal using data from 1974 to 1999. Islam and Peterson (2009) developed a landfalling TC database from 1877 to 2003 and analyzed TC climatology for the Bangladesh coast. Alam and Dominey-Howes (2015) performed a similar study of Islam and Peterson (2009) but for TCs in the northern Bay of Bengal. Most of the research on TCs in this region has involved either modelling work (e.g., Karim and Mimura, 2008; Dube et al., 2009; Steptoe et al., 2021) or evaluated the performance of early warning and TC disaster preparedness (e.g., Emdad Haque, 1997; Alam and Collins, 2010; Paul and Dutt, 2010; Paul et al., 2010; Islam et al., 2021; Ahamed, 2013). Takagi et al. (2023) have recently assessed the vulnerability of Bangladesh's coasts to TC disasters by analyzing fatality figures and TC landfall trends from 1960 to 2019. While previous studies have contributed to our understanding of TC disaster risk in Bangladesh, there is a significant opportunity to enhance our knowledge through an integrated analysis that considers various factors, including TC frequency and meteorological conditions, disaster statistics (e.g., reported no. of disasters, fatality rate, number of affected people, economic damage), and mitigation measures (e.g., early warning systems, disaster management budget) and how they interrelate.

This study is the first attempt to illustrate Bangladesh's TC disaster risk in a triadic approach combining historical TC frequency and meteorological conditions, related disaster statistics, and mitigation measures from 1979 to 2020. Its main innovation is utilizing the geocoded disasters (GDIS) dataset to report the number of historical TC induced disasters at the sub-national level in Bangladesh. Further, our study examines TC disaster risk for the first time by analyzing several historical TC best tracks, particularly in relation to the transition of the official warning signals.

2 Data and methods

2.1 Tropical cyclone selection

The Joint Typhoon Warning Center (JTWC) best track data archives (JTWC 2021) from 1979 to 2020 were utilized in this study to include all TCs that originated in the NIO and made landfall in the Bangladesh coasts. The pre-satellite era best track data before 1979 were not used due to significant uncertainties in data quality issues (Moon et al. 2019; Islam et al. 2022b). Although our study period was relatively short compared to the official historical TC record period (since 1945), it was the longest period covered by the JTWC with uniform data quality (Chu et al. 2002). We determined TC as a landfall TC when the center of a TC reaches the Bangladesh coasts without making landfall anywhere before. The approximate landfall point was detected in which a TC track intersects a coastline in Bangladesh. Further, the analyzed TCs were limited to TCs with a maximum sustained wind speed (V_{max}) greater than 33-kt (17 m s^{-1}) during the landfall time frame. This wind intensity threshold is necessary since TCs do not always have high intensity (e.g., tropical depressions) and may not result in significant disaster impacts. Therefore, it is more relevant to concentrate on tropical storms (TS; 34-kt ≤ V_{max} ≤ 63-kt) or stronger TCs (e.g., V_{max} ≥ 63-kt) when considering disaster risk management.

Finally, the analysis included 24 TCs that met the above criteria and can be considered the most economically destructive TCs in Bangladesh from 1979–2020.

2.2 TC meteorological data

We analyzed the JTWC best track dataset for selected TCs (n=24) that includes 6-hourly TC central position, wind intensity (V_{max}) and TC size (radius of 34-kt wind: R_{34}) information. TC forward speed at time T is calculated with the TC central positions at T and T – 6-h. Although TC meteorological information is available from birth to death, we focused on analyzing the meteorological conditions during the landfall time frame. It is because the impacts of a disaster (e.g., storm surge) tend to be amplified during landfall (Islam et al. 2022b). For cases in which V_{max}, R_{34}, and forward speed data were unavailable immediately before TC landfall time, those data were obtained via linear interpolation of the available data at two neighboring positions (nearest before and after landfall).

2.3 The Geocoded Disasters Dataset

In this study, we utilized a recently developed global dataset of geocoded disaster locations, the Geocoded Disasters (GDIS; Rosvold and Buhaug 2021)) to report the number of TC-induced disasters at the sub-national level (coastal district) in Bangladesh. Although other global disaster databases such as Emergency Events Database (EM-DAT; Guha-Sapir et al. 2022) has been extensively used for the international comparison of disaster risks and vulnerability (e.g., Jägermeyr and Frieler 2018; Takagi 2019), the textual format of the data and incomplete location information of some events limit their suitability for conducting comprehensive geospatial analyses (Kageyama and Sawada 2022). GDIS is an extension to the EM-DAT, and provides spatial geometry in the form of geographic information system polygons of disaster (e.g., TC) affected administrative units (Rosvold and Buhaug 2021). EM-DAT includes a natural disaster if it meets any of the following criteria: 10 or more fatalities, 100 or more people affected, and a state of emergency is declared and international assistance is requested (Guha-Sapir et al. 2022).

This study analyzed 24 selected TCs that made landfall in Bangladesh between 1979 and 2020. It should be noted that the current version of the GDIS dataset covers disaster (e.g., TC) information up to 2018. Therefore, we utilized information from the EM-DAT database to update the GDIS dataset beyond 2018. The EM-DAT categorizes TC events as 'Tropical cyclone' (Disaster Subtype) and distinguishes them by a combination of an eight-digit disaster code and a three-digit country code. On the other hand, the GDIS records a TC event as 'Storm' (disastertype) with the same eight-digit disaster code as in EM-DAT but without a country code. The 'Storm' category in GDIS also includes convective storms and extra-tropical storms and is not further divided into 'Disaster Subtype' as EM-DAT has. Hence, it is not straightforward to identify TC events in the GDIS dataset. To address this issue, we used an eight-digit unique event identifier (disasterno) to detect each TC selected in this study within the GDIS dataset.

GDIS assigns the same identifier to a disaster event that affects multiple administrative units (sub-national level) which allowed us to analyze the number of affected coastal districts in Bangladesh by a single TC event. Through this approach, we identified a total of 116 disaster events at the sub-national level induced by 24 landfalling TCs in Bangladesh. Other data including the total number of affected people, fatality, and economic damage were collected from EM-DAT.

2.4 TC activity and potential hazard metrics

There are multiple metrics in the literature that describe TC activity (e.g., accumulate cyclone energy (ACE) by Bell et al. 2000, power dissipation index by Emanuel 2005). Determining the energy of a cyclone is crucial in assessing its societal impacts, and as such, ACE is a widely recognized metric in this regard. ACE is an integrated measure of TC duration and intensity and defined as the sum of the squares of the estimated 6-hourly maximum sustained wind speed (V_{max} in kt) for a TC while it is at least tropical storm strength (V_{max} > 33-kt; Bell et al. 2000). The JTWC best track data was used to estimate ACE for each selected storm in this study.

Similarly, the literature provides a range of metrics that can be used to characterize hazards possess by a TC. For example, SSHWS for wind hazard (Saffir 1973), the extreme rain multiplier by Bosma et al. (2020), and storm surge hazard potential index (SSHPI) by Islam et al. (2021b). As Bangladesh has experienced significant loss and damage from storm surge events in the past (Needham et al. 2015; Takagi et al. 2023), we employed SSHPI as a primary hazard metric in this study to explore the statistical association between surge hazard and loss/damage. The SSHPI uses meteorological variables sensitive to storm surge, including TC intensity (e.g., V_{max}), size (e.g., R_{34}), and forward speed. In addition, the SSHPI considers TC landfall location sensitivity, coastal geometry (open coasts and bays) and regional scale bathymetry. These meteorological and geometrical variables are incorporated into a single measure of the expected surge hazard potential along the coast (Islam et al. 2021b, 2023). The JTWC best track data, particularly during landfall, was used to calculate the SSHPI for each selected TC. The bathymetry of the target region was obtained from the General Bathymetric Chart of the Oceans (2022).

2.5 TC disaster mitigation measures

TC disaster mitigation measures refer to actions and strategies aimed at reducing the impact of TC on people, infrastructure, and the environment. It primarily includes effective early warning systems, strong building codes, sustainable coastal land use planning, disaster preparedness, resilient coastal protection facilities, coastal afforestation, and well functional insurance system. Many of these largely depend on the country's disaster management budget. In this study, we considered the effectiveness of TC early warning signals and funding availability in recent decades as proxies to examine the current state of disaster mitigation measures for TC in Bangladesh. Information on official early warning signals for certain historical TCs including Sidr in 2007, Mora in 2017, and Bulbul in 2019, were gathered from publications (Islam 2009; Bangladesh Meteorological Department 2018) and social media account (Bangladesh Meteorological Department 2022) maintained by the Bangladesh Meteorological Department (BMD).

3. Results and discussion

3.1 Landfall TC frequency and their meteorological condition

Figure 1a shows the spatial distribution of TC landfall points (tracks are shown in Fig. S1 in SI appendix) along the Bangladesh coasts between P1 (1979–1999) and P2 (2000–2020). There were a total of 24 landfalls (see Section 2.1 for the definition of the TC selection criteria); among them, 63% (15) were recorded in P1 and an average of less than one TC per year. While no apparent increasing/decreasing TC frequency is observed at different longitudes, 58.33% TCs made landfall in 91°E–92°E longitude range which encompasses Chattogram and Cox's Bazar district. In this region, landfall TC frequency decreased by 50% in P2. Figure 1b compares the number of different categories of landfall TCs in Bangladesh and NIO over 42 years. It needs to be noted that here, we classified TCs based on their landfall wind intensities. The NIO and Bangladesh exhibit neither significant upward nor downward trend in any category of TC activity. Nevertheless, consistent with global TC activity studies (e.g., Klotzbach et al. 2022; Chand et al. 2022), we find a decadal decrease (not statistically significant) in total landfall TC activity in the Bangladesh coast. While tropical storm (TS; V_{max}: 35–63 kt) has contributed 54% (13) and 66% (80) of total landfall TCs in Bangladesh and NIO, respectively, 33% (5) of major TCs including Category 3–4 (V_{max}: 96–136 kt) in the NIO (15), made landfall in Bangladesh.

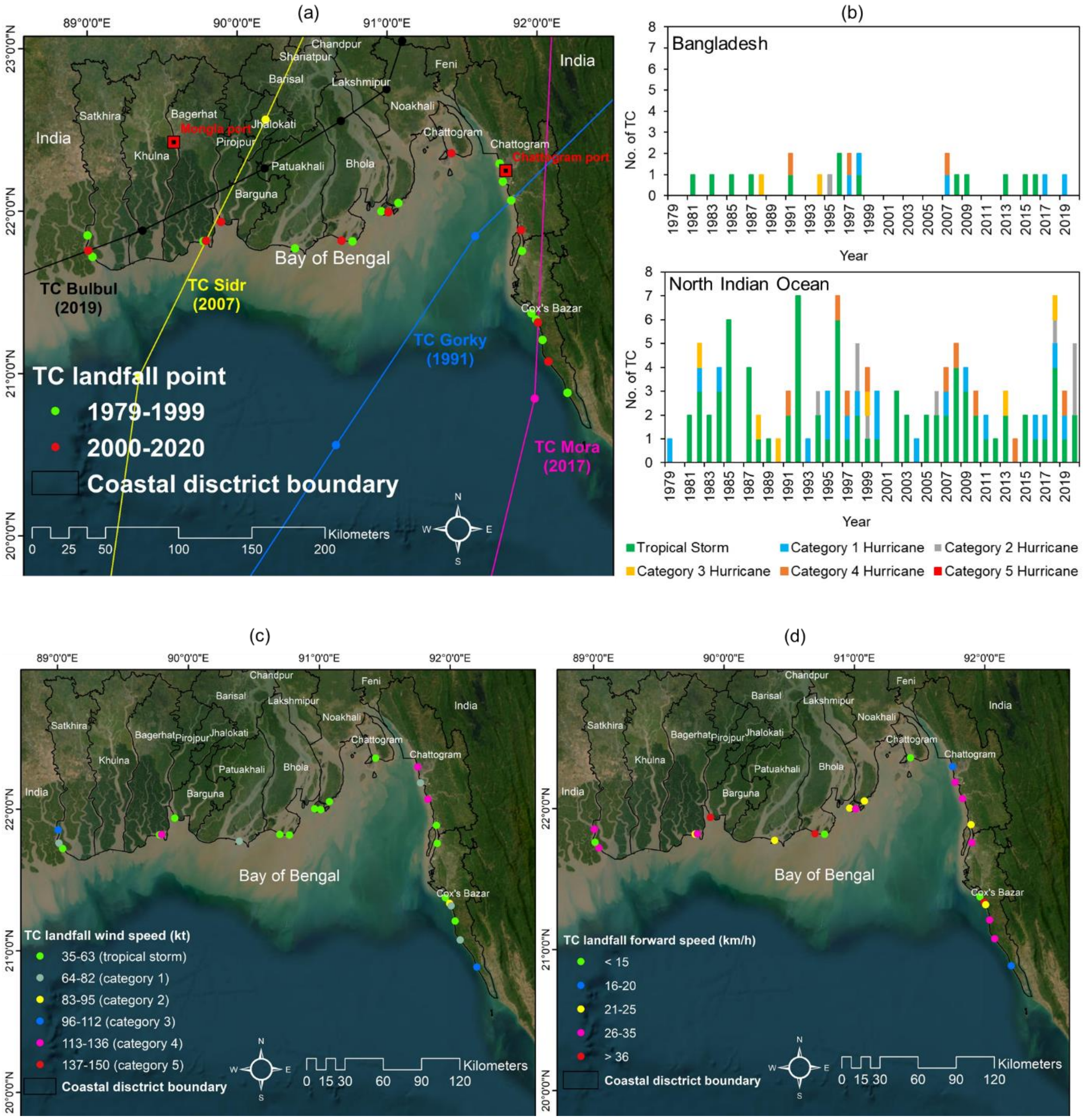

Fig. 1 TC made landfall in the Bangladesh coasts from 1979–2020: (a) spatial distribution of landfall points. Best tracks of several historic TCs: Gorky (1991; blue line), Sidr (2007; yellow line), Mora (2017; magenta line), and Bulbul (2019; black line) are included; (b) Different categories of landfall TC (classification method: SSHWS during landfall time) frequency in each year for Bangladesh (upper panel) in comparison with North Indian Ocean (lower panel; data source: JTWC 2021); (c) spatial distribution of landfall wind intensity (V_{max} in knot; classification method: SSHWS during landfall time); (d) spatial distribution of forward speed (km/h) during landfall time.

The wind speed distribution at landfall is displayed in Fig. 1c. It clearly demonstrates that 67% (7) stronger TCs such as $V_{max} > 63$-kt, have made landfall in the south-east coasts (Chattogram) and only one Category 4 TC, namely Sidr (2007) impacted south-west coasts of Bangladesh over the last 42-year period. TC Gorky (also known as Marian) in 1991 was the strongest (V_{max}: 135-kt) recorded storm in Bangladesh, 17% stronger than the second strongest event on record (115-kt in 1997 (unnamed TC) and in 2007 during TC Sidr).

Previous studies have neglected the importance of TC forward speed as a significant meteorological variable that can exacerbate storm surge disasters in varying coastal places (Rego and Li 2009; Islam and Takagi 2020b; Islam et al. 2021b). Furthermore, a direct relationship exists between the issuance of early warning signals and TC forward speed (Takagi et al. 2018). Figure 1d shows the spatial distribution of landfall TC forward speed along the Bangladesh coasts. The average forward speed is estimated to be 26 km/h. No apparent changes in frequency were observed during 1979–2020 (e.g., landfall TCs have neither become faster nor slower). Comparing Fig. 1c with Fig. 1d indicates that TC wind intensity and forward speed do not correlate (Pearson correlation coefficient $R = 0.06$).

Along with analyzing TC landfall location, intensity, and forward speed, we also investigate the variability of TC size (e.g., R_{34}). The JTWC best track data before 2004 does not contain TC size information and therefore, TCs in P2 (9) were analyzed only. The average R_{34} is found to be 85 NM. Although a few numbers of TC were analyzed, we have noticed a strong positive correlation ($R = 0.85$) between TC landfall wind intensity and size, meaning that stronger TCs tend to get larger and impact wider coastal region in Bangladesh (see Fig. S2 in SI appendix). For example, Category 4 TC Sidr (1991) was the largest (R_{34}: 135 NM) recorded storm in Bangladesh, 29% larger than the second largest TC Bulbul (R_{34}: 105 NM in 2019), equivalent to a Category 1 TC. This finding is consistent with Islam et al. (2022), which demonstrated the existence of a strong association between the intensity and size of TCs that made landfall in Japan during 1980–2019.

3.2 TC disaster statistics

Figure 2 illustrates the spatial distribution of recorded TC disasters among 16 coastal districts in Bangladesh during 1979–2020 based on GDIS. In total, 116 TC-related disasters were found. Although the number of TCs including their meteorological variables, have not remarkably changed in P2 (as shown in section 3.1), 69.83% (81) of TC-induced disasters were reported in recent 21 years and all coastal districts except Chattogram have experienced an increasing number of TC disasters. It is likely a result of the improvement in recording disasters in recent decades compared to the previous. Nonetheless, we cannot rule out the possible influence of an increasing number of exposed coastal elements and vulnerability, which are often the determinant factors in quantifying disaster risk (Cardona et al. 2012; Islam and Raja 2021). For example, Bangladesh's coastal areas experienced a net increase in agricultural land (5.44%) and built-up area (4.91%) during 1990–2017 (Abdullah et al. 2019) which significantly contributed to the country's GDP growth rate (6.6% in 2017; The World Bank Group 2023). Such development trends have driven a notable increase in population in most of the coastal districts including Cox's Bazar (29.11%), Noakhali (20.6%), Barguna (5.21%), Patukhali (5.14%), and Bhola (4.33%) (Bangladesh Bureau of Statistics 2001, 2011) where highest number of TC induced disasters were also reported in recent decades (Fig. 2).

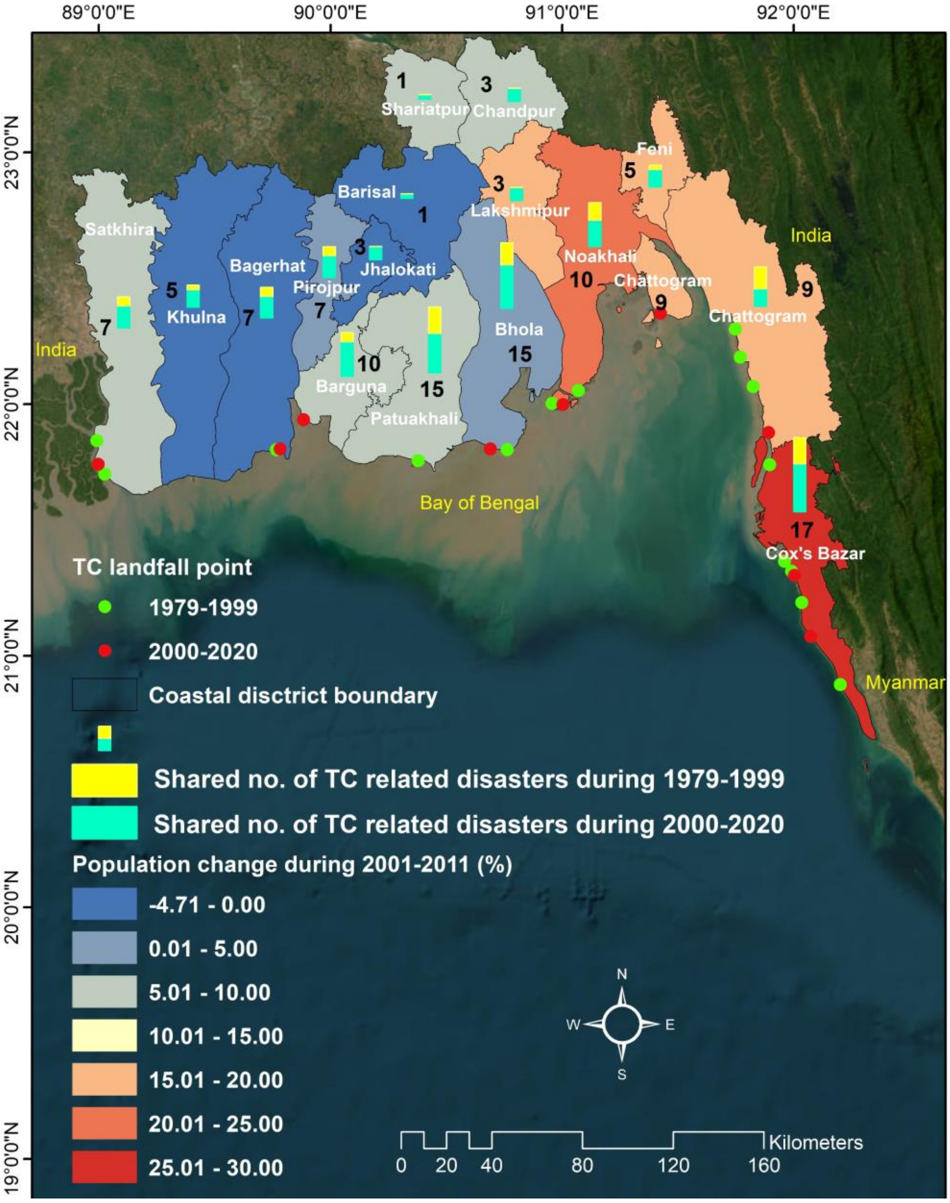

Fig. 2 Total number of reported TC disasters (black colored numeric value) in each coastal district of Bangladesh based on GDIS during 1979–2020. District-wise population change rate during 2001–2011 was estimated from the housing and population census by the Bangladesh Bureau of Statistics (Bangladesh Bureau of Statistics 2001, 2011).

The EM-DAT shows that the annual maximum fatality rate due to a single TC has been falling in recent decades in Bangladesh (Fig. 3). However, the annual maxima of affected people (during the TC disaster year) has increased remarkably. Between 2000 and 2020, a single Cat 3–4 TC, Cat 1–2 TC, and TS affected an average of 8.98 million, 3.18 million, and 1.06 million people, respectively. These figures are 20.87%, 28.91%, and 107.73% higher compared to the average numbers reported during 1979–1999. In terms of economic damage, it appears that TCs made landfall in P2 are more responsible for large-sized economic damage than the TCs in P1. A comparison of Fig. 1 with Fig. 3 illustrates that neither number of affected people nor economic damage can be explained by TC frequency and meteorological trends, which are basically constant over the 42-year period. On the other hand, Fig. 3 statistics corroborate with Fig. 2.

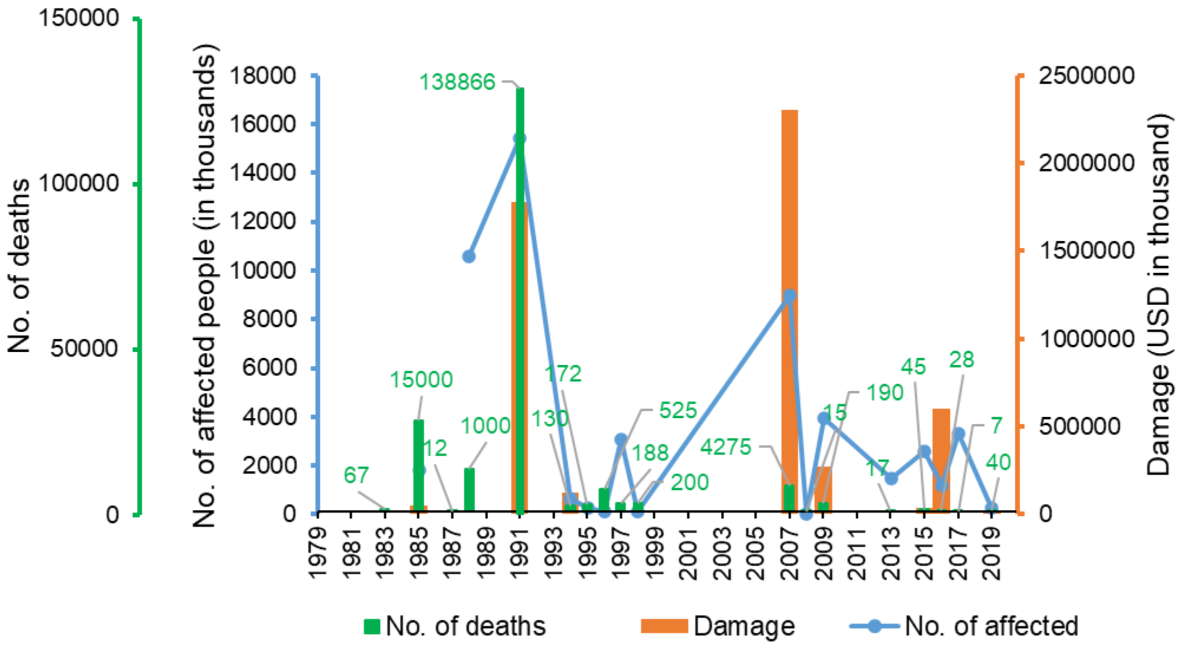

Fig. 3 Historical (1979–2020) records of annual maximum deaths, affected number of people, and economic damage in Bangladesh caused by a single TC in a year, based on EM-DAT. The green, blue, and orange colored Y-axis denotes no. of deaths, no. of affected people, and economic damage, respectively.

Furthermore, we have found that TC activity metrics such as ACE and hazard index such as SSHPI, to some extent, can be considered as proxies for explaining the variability in the number of affected people and economic damage from TCs. Figure 4 shows the correlations between the ACE and EM-DAT economic damage, reported no. of affected people and death tolls from landfall TCs in Bangladesh during 1979–2020. Both the number of affected people and damage figure significantly correlates with ACE ($R > 0.78$), while the R statistic drops when death toll is considered. Figure 4 further illustrates that ACE is strongly associated with the SSHPI ($R = 0.84$), suggesting that strong and long-lasting TC can exert a great potential for surge hazards. Thus, the coefficient remains almost the same when ACE is replaced with SSHPI. In particular, the coefficient increases for death figures ($R = 0.77$) because most of the recorded TC-induced deaths are directly attributed to storm surges in Bangladesh (Needham et al. 2015; Takagi et al. 2022).

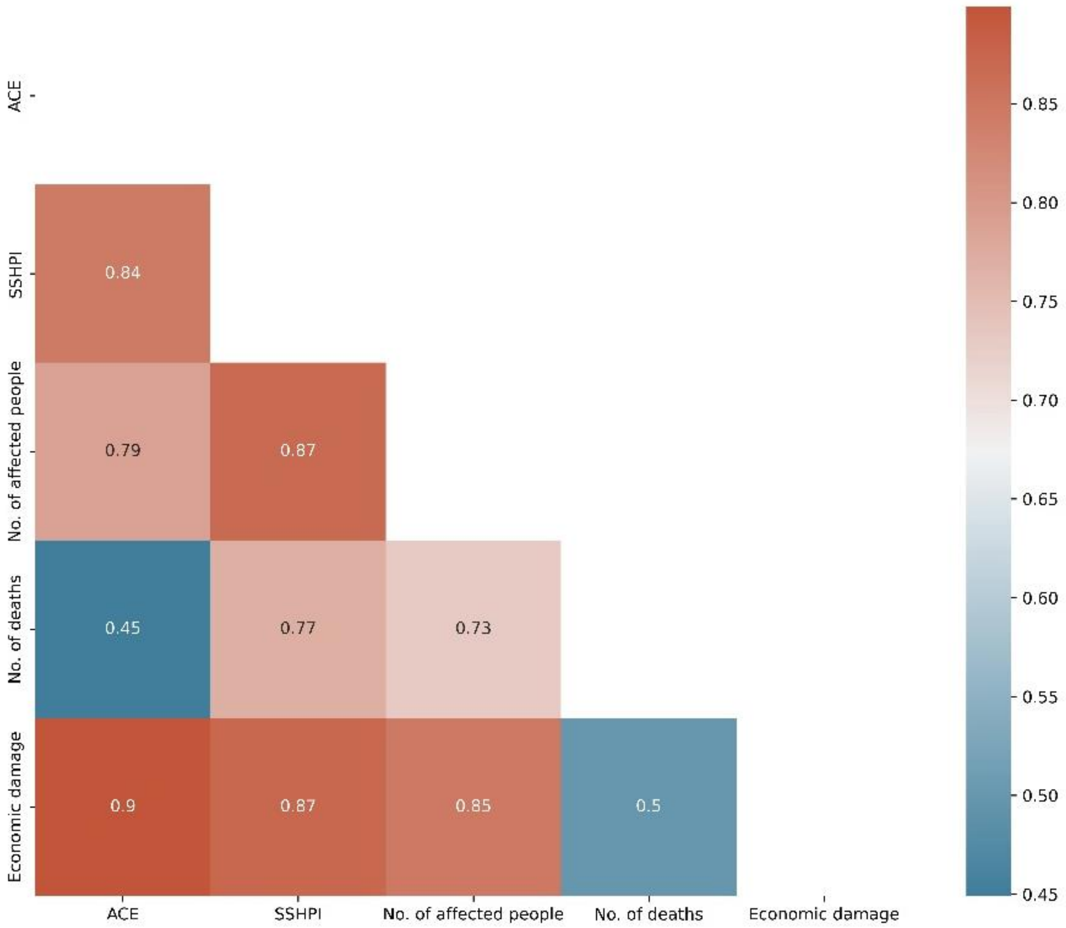

Fig. 4 Heatmap plot representing the correlation (Pearson) matrix. The column and row on the heatmap are split by five variables: ACE, SSHPI, no. of affected people, no. of deaths, and economic damage caused by historical landfall TCs (1979–2020) in Bangladesh.

3.3 TC disaster mitigation measures

3.3.1 Funding and disaster mitigation policy

Figure 5 summarizes economic losses incurred from disasters, as well as the available funding and the difference between the two during 2000–2013 in Bangladesh (ADB 2016). Although, this includes the combined annual costs for flood, severe storm, earthquake, and TC in terms of both loss and damage, it is a well representative of total budget allocations for mitigating TC disasters. Bangladesh runs small funding deficits or surpluses in the years without major disasters (e.g., 2006, 2008), however, funding gap is very substantial during the years of major TC disasters. For example, TC Sidr in 2007 impacted significantly 2.6% of the country's GDP (RMMRU and SCMR 2013), amounting to more than $2.7 billion economic damage in a single year, while the total available funding covered only 37%. A similar case can be seen in the economic aftermath of TC Aila in 2009, which resulted in a loss of $269 million (ReliefWeb 2009). Overall, only one quarter ($2.7 billion) of the total disaster-related impact ($10.8 billion) was funded for the said period, where 67% was contributed by foreign and humanitarian aid. Rehabilitation and reconstruction operations after a TC often encounter hurdles due to budgetary constraints as depicted in Fig. 5. For instance, after TC Aila in 2009, several embankments, also known as polders, were completely destroyed and did not receive any operations for several months, causing the areas inside to be inundated. As a result, people were compelled to rebuild their homes on or near the damaged polders, turning the communities into slums for two years (JICA 2013). In general, it implies that Bangladesh is at risk of experiencing significant disasters due to substantial funding shortfalls during major disaster years such as TC, and that the country's annual disaster-related budget is unstable because it relies heavily on aid.

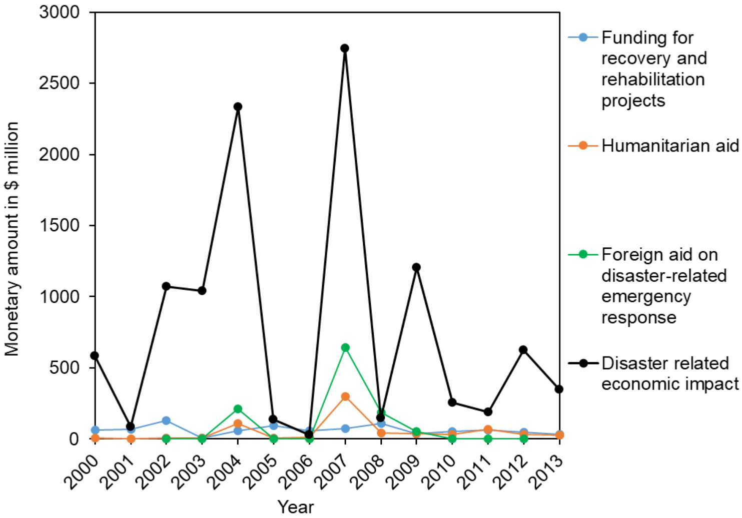

Fig. 5 Disaster-related economic impact and total available funding in Bangladesh during 2000–2013 (data source: ADB 2016). It needs to be noted that there may have been additional funding that was unidentified due to data gaps. Therefore, the total disaster-related fund could have been higher.

Bangladesh has substantially improved its legal and institutional framework for disaster management in recent decades. In 2004, the country shifted its disaster response approach from conventional relief practice to a more inclusive risk reduction culture and adopted the Hyogo Framework of Action in 2005. These efforts led to the implementation of various policies and acts such as the Standing Orders on Disasters (2010), Cyclone Shelter Construction, Maintenance and Management Policy (2011), Disaster Management Act (2012), and National Disaster Management Policy (2015) (Government of the People's Republic of Bangladesh 2016). The Bangladesh Meteorological Department (BMD) has been improving TC forecasting capacity by working closely with the National Oceanic and Atmospheric Administration (USA), Japan Aerospace Exploration Agency, and Japan Meteorological Agency (Bangladesh Meteorological Department 2021). Another noteworthy aspect of disaster management in Bangladesh is the Ministry of Disaster Management and Relief runs Cyclone Preparedness Program which has over 76,000 volunteers responsible for communicating risk effectively and improving community resilience (BBC 2022; Takagi et al. 2023). These continuous improvements in disaster management have resulted in noticeably fewer casualties in recent decades. While such soft measures have been implemented to some extent, hard measures have faced budget constraints and thus have not been able to progress significantly. The coastal areas have some moderate dikes, with heights ranging from 3.6 to 4.3 meters towards the sea and 4.5 meters inland. However, these dikes were mainly built using local materials (e.g., earthen) during the 1960s and 1970s (Khalil 1992; Paul and Dutt 2010) and do not receive sufficient funds for short to long-term maintenance (JICA 2013). This imbalance between structural and non-structural measures in Bangladesh has created hindrances in the pre and post-TC activities, such as evacuation, rehabilitation, and reconstruction processes, posing a significant risk to the coastal population.

3.3.2 TC early warning signal

BMD issues TC warning signals (1 to 10) for maritime ports (Chattogram and Mongla; Fig. 1a) that was introduced during the British colonial period, when the coastal region of Bangladesh was sparsely populated and warning messages were mainly used for ocean-going vessels (Roy et al. 2015; BMD 2023). The higher the TC signal number, the more precautionary measures are taken. For example, signal no. 5–7 and 8–10 is denoted as “danger” (port will experience V_{max} of 34–48 kt) and “great danger” (port will experience V_{max} > 48-kt) signal, respectively. The only difference between signal no. 5, 6, and 7 (and signal no. 8, 9, and 10) is the location of a TC center respective to a port. Although the scientific basis of this warning system is unclear and questioned by recent studies, this century-old system is creating a notion of a false alarm among the coastal population at risk (Roy et al. 2015; Ahsan et al. 2020). Here, we evaluated TC disaster risk by analyzing the recent three strongest TCs' (Sidr, Mora, Bulbul; Fig. 1a) best track from JTWC, particularly in relation to the transition of the official warning signals.

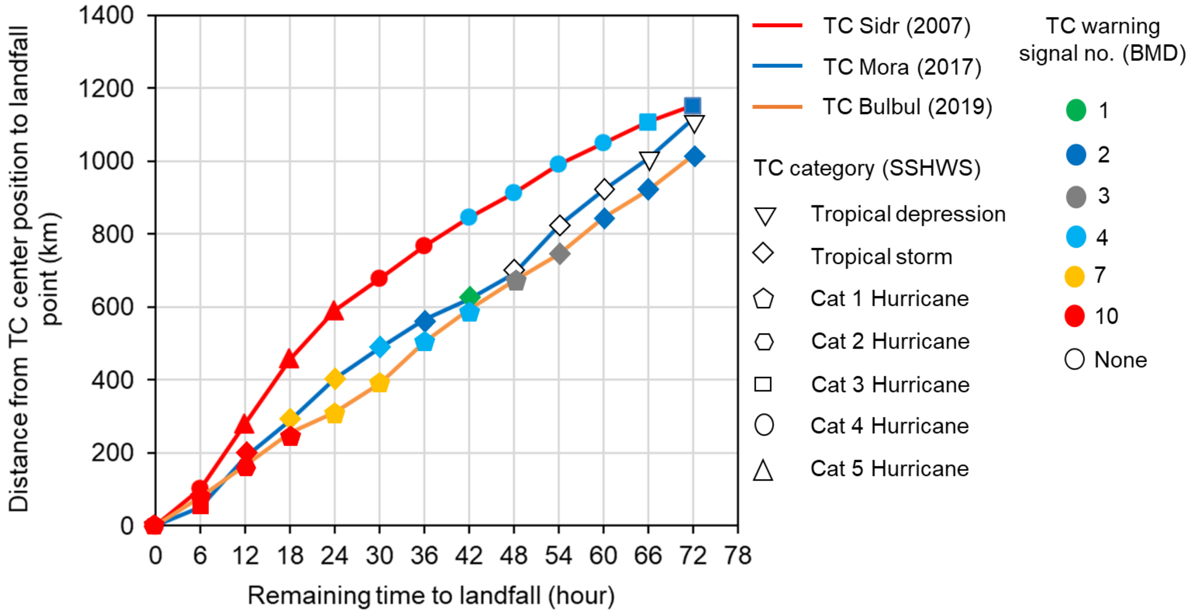

Fig. 6 Pattern of TC Sidr, Mora, and Bulbul’s intensity categories (SSHWS) in relation to their center position from landfall location and official warning signals issued by the BMD. Here, TC signals issued for the nearest port respective to each TC track are analyzed: Mongla port (Fig. 1a) during Sidr and Bulbul; Chattogram port (Fig. 1a) during Mora.

Figure 6 indicates TC Sidr reached Category 4 Hurricane strength 60-h prior (1050 km away from landfall location) to its landfall in 2007. Therefore, BMD issued local warning signal no. 4 for Mongla port and its command area (except Chandpur, Lakshmipur Noakhali, Feni, Chattogram, and Cox’s Bazar in Fig. 1a) 66-h before Sidr's landfall; while 30-h later (770 km away from landfall location), the danger level had suddenly changed from 4 to 10 (Fig. 6). Given the landfall intensity of Sidr (Category 4) and the devastating storm surges it brought

(~6.1 m; Bangladesh Meteorological Department 2021), the issuance of the highest warning signal was crucial in saving thousands of lives, as it prompted the evacuation of 3.2 million people (Paul et al. 2010) from the coastal regions. Nevertheless, the significant variation between two consecutive warnings created confusion among the public and put them at risk, which ultimately led to mistrust of the warning system and advisories (Ahsan et al. 2020).

Mora (2017) was the strongest TC that hit the Bangladesh coast after Sidr. In comparison, Mora made landfall along the southeastern coast of Bangladesh (Fig. 1a) with a Category-1 intensity, strong but not stronger than the Sidr. While Mora was approaching Bangladesh coast as a tropical storm, BMD declared danger level 7 and 10 for Chattogram port and its command area (Chandpur, Lakshmipur Noakhali, Feni, Chattogram, and Cox's Bazar in Fig. 1a) just 24-h (400 km away from landfall location) and 12-h (200 km away from landfall location) earlier of Mora's landfall, respectively (Fig. 6). Since the forecasted danger levels are same as that of Sidr, warning message receivers (e.g.., risk managers, residents) can judge that Mora would bring a similar catastrophe as Sidr did. Consequently, many people were forced to move to cyclone shelters ahead of time and the highest level of preparedness was ensured. The Bangladesh Government had initially planned to evacuate one million coastal residents (BBC News 2017), but ultimately only 0.3 million were able to be evacuated (ReliefWeb 2017), possibly due to the limited time available after the issuance of the "great danger" signal no. 10 (Fig. 6). Later, the catastrophe such as storm surge level (~1 m; Faisal et al. 2020) did not hit the danger level as anticipated, resulting in no major damage (Guha-Sapir et al. 2022). It seems that BMD took a safer and conservative decision during TC Mora by issuing the highest signal no. 10, nevertheless, this cannot be considered as effective decision-making. Such a false alarm can disrupt economic activities and eventually lower citizen trust over official warning (Takagi et al. 2018; Sawada et al. 2022). For instance, some recent reports suggest that despite BMD's warning signal, many fishermen and their boats went missing near the coast of Chattogram during cyclonic storms in July 2018 (The Daily Star 2018; The New Age 2018). This could be due to a lack of trust in official warnings, as those fishermen may recall the recent memory of TC Mora in 2017. According to the Standing Orders on Disasters (2010), BMD should issue warnings at least 10-h prior to the "great danger" signal. This was not a serious issue during TC Mora as it moved slowly (17 km/h; Fig. 6) and people had the least time to prepare before it arrived. However, BMD particularly needs to be careful when the situation changes suddenly due to a fast-moving TC (e.g., 35 km/h). It is because issuing an appropriate warning signal with a 10-h lead time is impossible and thus, can reduce preparation time including failing evacuation attempts. An effective early warning system that can reach community people including people living in distant places (i.e., islands) by 5–6-h should be introduced for such special cases.

After TC Mora, similar type of false alarms were reported during TC Bulbul (2019; Fig. 6) and TC Fani (2019; Ahsan et al. 2020). In both cases, around two million people were forced to evacuate (ReliefWeb 2019a, b). However, none of the TCs resulted in major damage as anticipated (Ahsan et al. 2020; Guha-Sapir et al. 2022). Such issues imply that BMD's existing early warning system is less efficient in providing credible warnings and reliable forecasts when compared to the Japan Meteorological Agency and National Hurricane Center in the USA. Here, BMD prefers to issue higher levels of warning without taking into account TC intensity and its hazard potential. Such an extreme level of preparedness in Bangladesh has some advantages, such as creating a high degree of fear among coastal inhabitants and reducing the fatality rate in recent decades (Fig. 3). As a result, the media and international communities have recognized Bangladesh as a role model for advancing preparedness against TC disasters (BBC 2022; The Daily Star 2022). Nonetheless, we argue that there may be an emerging type of TC disaster risk among coastal inhabitants that is not immediately apparent. This risk could potentially undermine the credibility of the current early warning systems in Bangladesh and hinder the implementation of preparedness measures during future extreme TC events.

4 Summary and conclusions

In this study, we have performed an integrated analysis of TC disaster statistics (i.e., reported number of disasters, number of affected people, fatality rate, economic damage), mitigation measures (i.e., early warning systems, disaster management budget), and meteorological variables (i.e., intensity, size, forward speed) of landfalling TCs in Bangladesh during 1979–2020. It suggests that TC disaster risk has likely risen in Bangladesh systematically including an increase in the annual maxima of affected people (during TC disaster year) and reported disaster events at the sub-national level. It is primarily due to the combined effect of increasing coastal exposures (e.g., population), substantial funding shortfalls for mitigating disaster risk, and inefficient use of century-old TC early warning signals. Interestingly, neither the size of the affected population nor the GDIS-reported TC-related disasters at the sub-national level can be explained by TC frequency and meteorological trends, which are basically constant on average over time. However, to some extent, TC activity metrics such as ACE and hazard indexes such as SSHPI can be considered as proxies for explaining the variability in the number of affected people and economic damage from TCs.

Bangladesh has improved significantly reducing TC-induced fatality rates in recent decades; this reduction was due to a clear improvement in soft measures. Nevertheless, new challenges have also arisen such as increased coastal exposures, decreased awareness due to less trustworthy early warning signals, and limited budget for disaster management. Therefore, it would not be surprising to experience continued TC disaster risk if the current situation remains unchanged. The increase in TC disaster risk can substantially affect the Bangladesh economy because much of the country's GDP is concentrated in the coastal area. Hence, with the growing number of coastal exposures, Bangladesh must need to address the new challenges to further reduce the number of victims and economic damage. In particular, conventional TC early warning signals should be updated to incorporate state of art in disaster science.

Due to limited recorded data and simplifications in the representations of the TC mitigation measures, the results provide a first-order snapshot of the state of TC disaster risk in Bangladesh during 1979–2020. Nonetheless, for the first time, this study illustrates country's TC disaster risk in a triadic approach combining historical TC meteorological conditions, related disaster statistics, and mitigation measures. The analyses presented in this study do not intend to assess the contribution of climate migration and sea level rise due to climate change in Bangladesh. The difference in reported TC-induced disasters and affected population size between P1 and P2 could be regarded as a trend associated with mean sea level rise and climate refuge in Bangladesh. However, Lincke et al. (2022) reported that coastal exposure and risk are almost entirely attributable to socio-economic development globally in the past decades. Thus, further research should include quantitative evaluations of the contributions of climate change and socio-economic factors.

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Statements & Declarations

Open Research

EM-DAT data can be downloaded from the EM-DAT website (https://www.emdat.be/). GDIS dataset can be obtained from the NASA's Socioeconomic Data and Applications Center website (https://sedac.ciesin.columbia.edu/data/set/pend-gdis-1960-2018). TC best track data can be derived from the JTWC (https://www.metoc.navy.mil/jtwc/jtwc.html?north-indian-ocean).

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