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Assessing the Climatology and Synoptic Conditions of Tropical Cyclone Recurvature over the Bay of Bengal

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ABSTRACT

Recurvature in tropical cyclones is not very uncommon, but rare. There are instances of recurved tropical cyclones forming over the Bay of Bengal. Some of them have hit the coastal regions of Bangladesh. In this research, the climatology and synoptic conditions of such events have been assessed. It has been found that 25 recurved tropical cyclones have hit Bangladesh throughout the period from 1891 to 2019. Most of them have occurred during the post-monsoon season. Again, there have been more cases of recurvature in tropical cyclones that hit the southwest coastal region of Bangladesh than the southeast. Although there are some differences between the direction and speed for the two coasts, but there are not much differences between them for their vector or scalar speeds. In addition, further assessment of the wind speeds and the intensities of tropical cyclones have revealed some interesting findings. The analyses of synoptic conditions for the recurved tropical cyclones have also obtained some important results. All these results and findings will aid in better forecasting of recurved tropical cyclones in the future.

Introduction

The geographical setting of Bangladesh makes her susceptible to recurrent tropical cyclones (Islam and Peterson, 2008). These tropical cyclones have caused numerous deaths and also incurred massive damages (Hossain et al., 2008; Singh et al., 2001). So, tropical cyclones have a serious impact on the lives and livelihoods of the people in Bangladesh; especially those living near the coasts.

Tracking the movement of tropical cyclones along the Indian Ocean and the Bay of Bengal, in particular, has revealed some very interesting characteristics by researchers in past (Mohapatra et al., 2013; Yamada et al., 2010; Chan and Gray, 1982). Recurvature within the track of tropical cyclones is also commonly observed for the tropical cyclones that have previously formed over the Bay of Bengal (Bhattacharya et al., 2015; Murty and Neralla, 1992). Understanding the climatology and synoptic conditions associated with tropical cyclone recurvature is necessary for better predicting the events (Mohanty, 1994). There have been some attempts made to delineate climatology for the recurved tropical cyclones over the Bay of Bengal (Bhatla et al., 2018). Again, the possible reasons behind recurvature in tropical cyclones have been explored by researchers (Akter and Tsuboki, 2021; Sanap et al., 2020; Li et al., 2012). The possible relationships between the occurrences of recurvature in tropical cyclones with monsoon dynamics (Gadgil and Rajeevan, 2008), prevailing wind patterns (Mohapatra and Sharma, 2015), available thermodynamic characteristics (Sadhuram and Murty, 2006) and energy balances (Pal and Chatterjee, 2021) have also been well-reviewed. Generally, a recurved tropical cyclone possesses more threat to the already vulnerable exposed coastal regions similar to that of Bangladesh's; for they are accompanied by other natural disasters, such as – storm surges (Murty and Flather, 1994). Besides, the prediction of such events is always a challenge for operational meteorologists (KU et al., 2020).

This research aims to generate climatology for the recurved tropical cyclones that hit the coasts of Bangladesh and also generate an idea about the prevailing synoptic conditions for such tropical cyclones. Therefore, there are two particular objectives of this research; which include – deciphering climatology for the recurved tropical cyclones that hit Bangladesh; and, delineating ideas about the associated synoptic conditions for tropical cyclone recurvature over the Bay of Bengal. The ultimate goal of this

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research is to help in forecasting similar events in future.

Climatology for Tropical Cyclone Recurvature

The seasonal climatology for tropical cyclone (TC) recurvature has been prepared with data (available at https://rsmcnewdelhi.imd.gov.in/rsmc-tropical-cyclones.php) from RSMC (Regional Specialized Meteorological Centre). Also, this is to be noted that data from RSMC New Delhi have been utilized in this research. The data is valid from 1891 to 2019. During this period, 25 cyclonic disturbances (Figure 1) have shown recurvature characteristics within the study area at different seasons.

The study area for this research has been illustrated in Figure 2. For ease of analysis, the study area has further been segregated into eight (8) specified grids. Details about these grids have been given in Table 1.

Table 1: Extent of all the 8 grids within the study area for this research

	Latitude	Longitude
Grid 1	17.5°N to 20°N	87.5°E to 90°E
Grid 2	20°N to 22.5°N	87.5°E to 90°E
Grid 3	22.5°N to 25°N	87.5°E to 90°E
Grid 4	25°N to 27.5°N	87.5°E to 90°E
Grid 5	25°N to 27.5°N	90°E to 92.5°E
Grid 6	22.5°N to 25°N	90°E to 92.5°E
Grid 7	20°N to 22.5°N	90°E to 92.5°E
Grid 8	17.5°N to 20°N	90°E to 92.5°E

From the data, this is evident that most cyclonic disturbances with recurvature occur during the post-monsoon season. Both pre-monsoon and monsoon seasons have similarities in the total number of (7 in each season) cyclonic disturbances. Grids 1 and 2 have the highest occurrences (6 each) of cyclonic disturbances among all the grids. A total of 5 cyclonic disturbances were listed within Grid 8. Again, 4 cyclonic disturbances have been experienced within the extent of Grid 3 and Grid 7. But no cyclonic disturbances (with recurvature) have occurred within Grids 4, 5, and 6. Alongside that, no such activities have been found during the winter season.

Climatology for Wind Direction and Speed

The climatological patterns of wind direction and wind speed parameters have been given in Table 2. Wind direction and speed data for Cyclonic Storms (CS), Severe Cyclonic Storms (SCS), Very Severe Cyclonic Storms (VSCS), and Super Cyclonic Storms (SUCS) have been collected from RSMC. This is to be mentioned that RSMC stores data for this parameter for pre-monsoon and post-monsoon seasons only. The study area for this research has been divided into 4 quadrates from 0 degrees to 360 degrees; with each of the quadrates having an areal extent of 90 degrees. In this research, the data for Cyclonic Storms have not been analyzed. Besides, Figure 2 illustrates the distribution of the aforementioned parameters within the study area (which is divided into 08 grids).

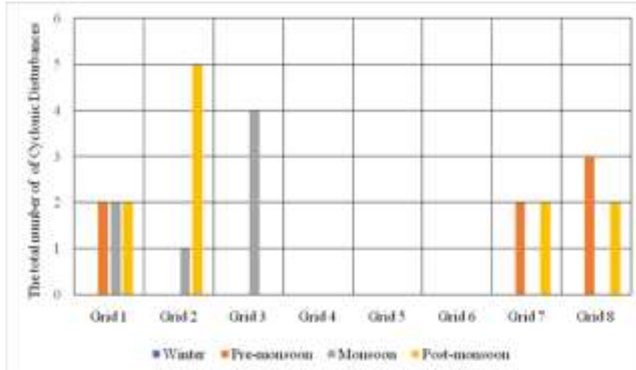

Figure 1: Seasonal climatology for TC recurvature within the study area; valid from 1891 to 2019

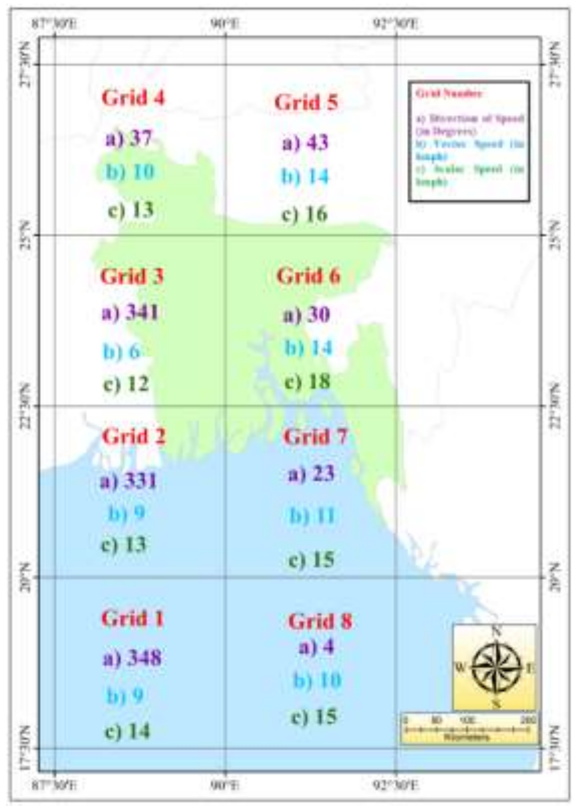

Figure 2: Distribution of wind direction and wind speed parameters within the study area; valid from 1891 to 2019

From Figure 2, it is clear that wind flows in a northeasterly direction in grids 1, 2, and 3. In all the other five grids, wind flows in the northwesterly direction. The wind speed is generally more over the landmass region rather than the oceanic region. However, this tendency is common within the grids (5 to 8) that are to the left potion within the study area. The wind direction has a more interesting spread than the wind speed. During pre-monsoon, Severe Cyclonic storms (SCS) that form in the 1st and 4th quadrants have a much larger radius when the wind is of 34 knots (KT). When the wind speed is 50 KT, the radius tends to be larger in the 4th quadrant only. The other quadrants have similarities in the radii values. But, 34 KT wind has larger radii in both 1st and 2nd quadrants for the SCS formed during the post-monsoon. Meanwhile, 50 KT wind has almost similar values in all four quadrants. The 34 KT winds for Very Severe Cyclonic Storms (VSCS) during the pre-monsoon have radii over 100 nautical miles (nm) for 1st, 3rd, and 4th quadrants. The radius of winds drops below 50nm for the first 3 quadrants when the speed increases up to 50KT. And when, the speed increases to 64KT for VSCS, the radii of all the four quadrants become smaller ranging between 24 to 27nm. The distributions for VSCS of post-monsoon are almost similar to that of pre-monsoon. The notable thing is that – values are slightly lower for winds of 34KT and 50KT, but slightly higher for winds of 64KT.

There are no records of winds for any pre-monsoon Super Cyclonic Storms (SUCS) around the Bay of Bengal from 1891 to 2019 from the records of RSMC. However, wind for the post-monsoon SUCS has a greater radius. The radius for 34KT wind within the 1st quadrant is almost 150nm. Both 2nd and 4th quadrants have radii of more than 130nm. The 50KT wind has radii of more than 75nm in all but the 3rd quadrant for the post-monsoon SUCS. Similarly, the 64KT wind also has radii of more than 50 in all but the 3rd quadrant.

So, this is clear from the description that – the areal coverage of cyclonic storms is greater with the change in their intensities. The wind has a steadily declining trend with the change in their translational speed.

Synoptic Conditions of Recurved Tropical Cyclones over Bay of Bengel

To understand the prevailing synoptic conditions of a recurved tropical cyclone, four such cases have been assessed. These four recurved tropical cyclone events have been selected after reviewing the data from RSMC and also relevant literature. The four recurved tropical cyclone events include– *Bulbul* (2019); *Sidr* (2007); *BOB-04* (2000), and *BOB-07* (1995). All of them had hit the coast of Bangladesh.

Tropical Cyclone Bulbul

The tropical cyclone Bulbul or more appropriately 'Very Severe Cyclonic Storm Bulbul' was a very powerful and devastating tropical cyclone that originated from the western Pacific Ocean onto the north Indian Ocean in October and November 2019, taking 41 lives and costing about US$3.537 billion in damage (Shamsuzzoha et al., 2021; Haque et al., 2019). Bulbul had originated from the remnants of 'Severe Tropical Storm Matmo' after emerging onto the Bay of Bengal and then redeveloping into a Depression on November 5 (Das et al., 2021). The cyclone made its landfall in the eastern Indian state of West Bengal on November 9, and around that time the storm turned towards the northeast, finally moving into Bangladesh (Rahman et al., 2021). Notably, this is only the second cyclone to make landfall over Bangladesh as a Category-1 hurricane-equivalent cyclone; according to Saffir–Simpson scale (Kantha, 2006).

Table 2: Quadrant wind radii (in nautical miles) in association with TCs of different intensities during both pre-monsoon and post-monsoon seasons

	0 – 90 degrees	90 – 180 degrees	180 – 270 degrees	270 – 360 degrees
(a) Severe Cyclonic Storms during pre-monsoon season				
Radius of 34 KT wind	71	52	61	72
Radius of 50 KT wind	31	32	29	43
(b) Severe Cyclonic Storms during post-monsoon season				
Radius of 34 KT wind	71	69	62	54
Radius of 50 KT wind	31	32	31	28
(c) Very Severe Cyclonic Storms during pre-monsoon season				
Radius of 34 KT wind	104	89	114	121
Radius of 50 KT wind	43	39	48	51
Radius of 64 KT wind	25	24	26	27
(d) Very Severe Cyclonic Storms during post-monsoon season				
Radius of 34 KT wind	110	112	93	94
Radius of 50 KT wind	45	42	40	42
Radius of 64 KT wind	26	26	27	28
(e) Super Cyclonic Storms during pre-monsoon season				
Radius of 34 KT wind	0	0	0	0
Radius of 50 KT wind	0	0	0	0
Radius of 64 KT wind	0	0	0	0
(f) Super Cyclonic Storms during post-monsoon season				
Radius of 34 KT wind	147	132	115	131
Radius of 50 KT wind	84	81	73	77
Radius of 64 KT wind	54	50	47	52

The prevailing synoptic conditions for Bulbul have been given in Table 3. The cyclone first appeared as a depression over the Bay of Bengal and swiftly turned into a cyclonic storm within 42 hours. The translations of cyclone Bulbul were very rapid, and it became a Very Severe Cyclonic Storm (VSCS) by 8th November.

Table 3: Synoptic conditions for tropical cyclone Bulbul; from the data of RSMC

Date	Time (UTC)	Latitude (decimal degrees)	Longitude (decimal degrees)	CI No (or T-number)	Estimated Central Pressure (hPa)	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade
05/11/2019	0000	13.1	91.5	1.5	1004	20	3	D
05/11/2019	0300	13.1	91.0	1.5	1003	25	3	D
05/11/2019	0600	13.1	90.7	1.5	1003	25	3	D
05/11/2019	1200	13.2	90.1	1.5	1003	25	3	D
05/11/2019	1800	13.3	89.8	1.5	1002	25	4	D
06/11/2019	0000	13.4	89.7	2.0	1001	30	5	DD
06/11/2019	0300	13.4	89.6	2.0	1001	30	5	DD
06/11/2019	0600	13.4	89.4	2.0	1001	30	5	DD
06/11/2019	1200	13.5	89.3	2.0	1000	30	6	DD
06/11/2019	1800	13.8	89.3	2.5	998	35	7	CS
07/11/2019	0000	14.2	89.3	2.5	998	35	7	CS
07/11/2019	0300	14.7	89.3	2.5	998	35	7	CS
07/11/2019	0600	15.3	88.7	2.5	996	40	8	CS
07/11/2019	0900	15.5	88.4	3.0	995	45	9	CS
07/11/2019	1200	15.9	88.0	3.0	994	45	10	CS
07/11/2019	1500	16.2	87.9	3.0	992	50	12	SCS
07/11/2019	1800	16.4	87.8	3.5	989	55	15	SCS
07/11/2019	2100	16.6	87.7	3.5	986	60	18	SCS
08/11/2019	0000	16.9	87.6	4.0	983	65	21	VSCS
08/11/2019	0300	17.2	87.6	4.0	982	65	22	VSCS
08/11/2019	0600	17.6	87.6	4.0	980	70	24	VSCS
08/11/2019	0900	18.1	87.6	4.0	980	70	24	VSCS
08/11/2019	1200	18.5	87.6	4.0	976	75	28	VSCS
08/11/2019	1500	19.2	87.7	4.0	976	75	28	VSCS
08/11/2019	1800	19.3	87.6	4.0	976	75	28	VSCS
08/11/2019	2100	19.6	87.7	4.0	976	75	28	VSCS
09/11/2019	0000	20.0	87.6	4.0	976	75	28	VSCS
09/11/2019	0300	20.4	87.6	4.0	980	70	24	VSCS
09/11/2019	0600	20.6	87.8	4.0	982	70	22	VSCS
09/11/2019	0900	20.9	87.9	4.0	982	70	22	VSCS
09/11/2019	1200	21.2	88.1	4.5	982	70	22	VSCS
09/11/2019	1500	21.4	88.3	4.5	986	60	18	SCS
09/11/2019			Crossed West Bengal Coast close to Sundarban Dhanchi forest near 21.55°N/88.5°E in between 1500 to 1800 UTC of 9th November 2019					
09/11/2019	1800	21.6	88.6	-	990	60	18	SCS
09/11/2019	2100	21.9	89.1	-	996	50	12	SCS
10/11/2019	0000	22.1	89.5	-	998	45	10	CS
10/11/2019	0300	22.2	89.7	-	1000	40	8	CS
10/11/2019	0600	22.3	90	-	1000	40	8	CS
10/11/2019	0900	22.4	90.1	-	1002	30	6	DD
10/11/2019	1200	22.5	90.4	-	1002	30	5	DD
10/11/2019	1800	22.7	91.2	-	1002	30	5	DD
11/11/2019	0000	23.1	91.9	-	1004	20	3	D
11/11/2019			Weakened into a well-marked low-pressure area over south Tripura & neighborhood at around 0300 UTC					

Notably, the direction of the cyclone had changed three times throughout its lifetime, the first – at around 0600 UTC of November 6, 2019. The cyclone had turned into a Deep Depression (DD) by that point and was about to turn into a Cyclonic Storm (CS). At that time – the Maximum Sustained Surface Wind (MSW) was 30 knots, and the Pressure Drop (PD) was 6 hPa. The second change was observed at around 0600 UTC on November 7. Although the cyclone remained to be CS at that point, the MSW was recorded to be 40 knots and PD was 8 hPa. Also, the Estimated Central Pressure (ECP) was 996 hPa. But the interesting curve was observed during the third time of recurvature. The path of Bulbul was seen to move towards a northeast direction; swaying away from the coast of India and heading towards Bangladesh's southwest (Figure 3). The curvature was initialized at around 0000 UTC of 9th November and continued until its eventual dissipation. The MSW at the time of initial curvature was 75 knots, which was the highest throughout its total lifespan. The PD was 28 hPa and the ECP was 976 hPa. Both these values are accordingly the highest and lowest of their respective distributions. The cyclone had already reached the VSCS stage by that time and remained so until 1500 UTC of November 9.

Tropical Cyclone Sidr

The tropical cyclone Sidr or 'Extremely Severe Cyclonic Storm Sidr' was one of the worst natural disasters in Bangladesh's history (Islam et al., 2011). Sidr formed around the central Bay of Bengal, and then quickly strengthened to reach a peak of 1-minute sustained wind to be 260 kmph (160 mph), which made it a Category-5 equivalent tropical cyclone according to Saffir–Simpson scale (Akter and Tsuboki, 2012). The storm eventually made landfall in Bangladesh on November 15, 2007 (Kumar et al., 2011). The total number of deaths was estimated to be more than 5,000 (Paul, 2010). The prevailing synoptic conditions have been listed in Table 4.

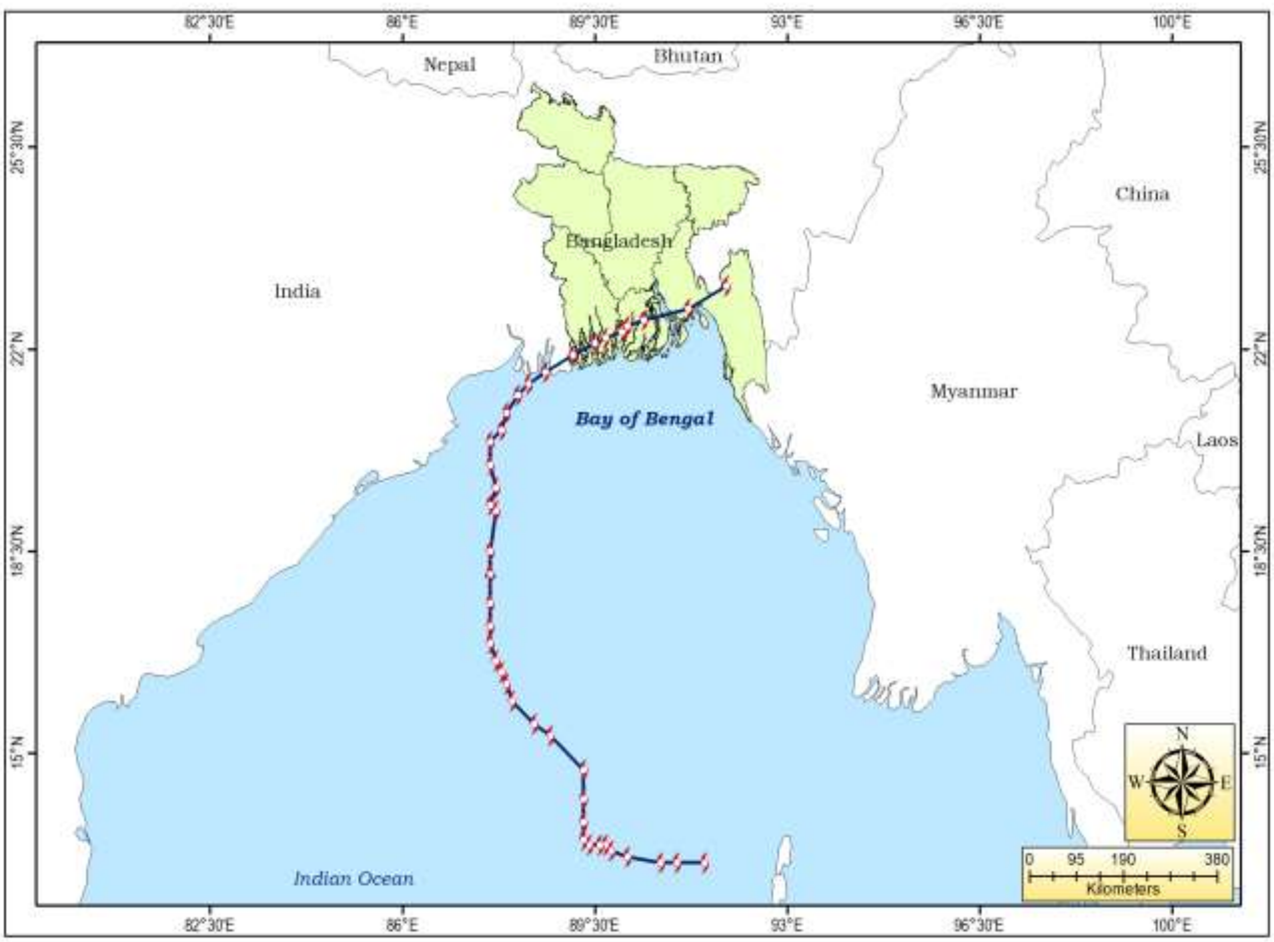

Figure 3: Track of tropical cyclone Bulbul; as per data from RSMC

Table 4: Synoptic conditions for tropical cyclone Sidr; from the data of RSMC

Date	Time (UTC)	Latitude (decimal degrees)	Longitude (decimal degrees)	CI No (or T-number)	Estimated Central Pressure (hPa)	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade
11/11/2007	0900	10.0	92.0	1.5	1004	25	4.0	D
11/11/2007	1200	10.0	92.0	1.5	1004	25	4.0	D
11/11/2007	1500	10.0	92.0	1.5	1004	25	4.0	D
11/11/2007	1800	10.5	91.5	2.0	1002	30	5.0	DD
11/11/2007	2100	10.5	91.5	2.0	1002	30	5.0	DD
12/11/2007	0000	10.5	91.5	2.0	1002	30	5	DD
12/11/2007	0300	10.5	91.0	2.5	1002	35	6	CS
12/11/2007	0600	11.0	90.5	3.0	998	40	10	CS
12/11/2007	0900	11.0	90.5	3.0	996	45	12	CS
12/11/2007	1200	11.5	90.0	3.5	992	55	16	SCS
12/11/2007	1500	11.5	90.0	3.5	992	55	16	SCS
12/11/2007	1800	11.5	90.0	4.0	986	65	20	VSCS
12/11/2007	2100	11.5	90.0	4.5	980	80	29	VSCS
13/11/2007	0000	12.0	89.5	5.0	968	90	40	ESCS
13/11/2007	0300	12.0	89.5	5.0	968	90	40	ESCS
13/11/2007	0600	12.0	89.5	5.0	968	90	40	ESCS
13/11/2007	0900	13.0	89.5	5.0	964	90	40	ESCS
13/11/2007	1200	13.0	89.5	5.0	964	90	40	ESCS
13/11/2007	1500	13.0	89.5	5.0	964	90	40	ESCS
13/11/2007	1800	13.5	89.5	5.0	964	90	40	ESCS
13/11/2007	2100	14.0	89.5	5.0	964	90	40	ESCS
14/11/2007	0000	14.5	89.5	5.0	964	90	40	ESCS
14/11/2007	0300	14.5	89.5	5.0	964	90	40	ESCS
14/11/2007	0600	15.0	89.5	5.0	964	90	40	ESCS
14/11/2007	0900	15.5	89.5	5.0	964	90	40	ESCS
14/11/2007	1200	16.0	89.0	5.0	964	90	40	ESCS
14/11/2007	1500	16.0	89.0	5.0	964	90	40	ESCS
14/11/2007	1800	16.5	89.0	5.5	956	105	55	ESCS
14/11/2007	2100	17.0	89.0	5.5	956	105	55	ESCS
15/11/2007	0000	17.5	89.0	5.5	956	105	55	ESCS
15/11/2007	0300	18.0	89.0	6.0	944	115	66	ESCS
15/11/2007	0600	19.5	89.0	6.0	944	115	66	ESCS
15/11/2007	0900	20.0	89.0	6.0	944	115	66	ESCS
15/11/2007	1200	21.0	89.0	6.0	944	115	66	ESCS
15/11/2007	1500	21.5	89.5	6.0	944	115	66	ESCS
VSCS crossed Bangladesh coast near longitude of 89.8 deg. East around 1600 UTC of 15th November 2007								
15/11/2007	1800	22.5	90.5	4.5	980	80	30	VSCS
15/11/2007	2100	23.5	91.0	3.0	996	45	12	CS
16/11/2007	0000	23.5	91.0	2.5	1000	35	7	CS
16/11/2007	0300	24.5	91.5	1.5	1002	25	4	D
The system weakened into a well-marked low-pressure area over northeastern states of India at 1200 UTC on 16th November								

Two curves had been observed from the track of cyclone Sidr (Figure 4). The first one was during 0300 UTC of November 12, 2007. At that time, the ECP was recorded to be 1002 hPa; the PD was 6 hPa, and the MSW was 35 knots. The cyclone was at the CS stage during that time. The 2nd curvature within the track of cyclone Sidr was observed on 15th November at around 1200 UTC. The recorded MSW was 115 knots, which is the highest value throughout the lifetime of the cyclone. Similarly, the PD value (66 hPa) was also at the highest for records of Sidr at that time. Finally, the ECP was 944 hPa; and this is the lowest value on record for cyclone Sidr. The cyclone was at ESCS (Extremely Severe Cyclonic Storm) stage during that time. The curved pattern for the movement of cyclone Sidr continued until its ultimate dissipation. A small change in the direction of track could also be observed (at 0900 UTC of 14th November), but that did not cause any overall changes to the track of cyclone Sidr. Therefore, that has not been considered for this discussion.

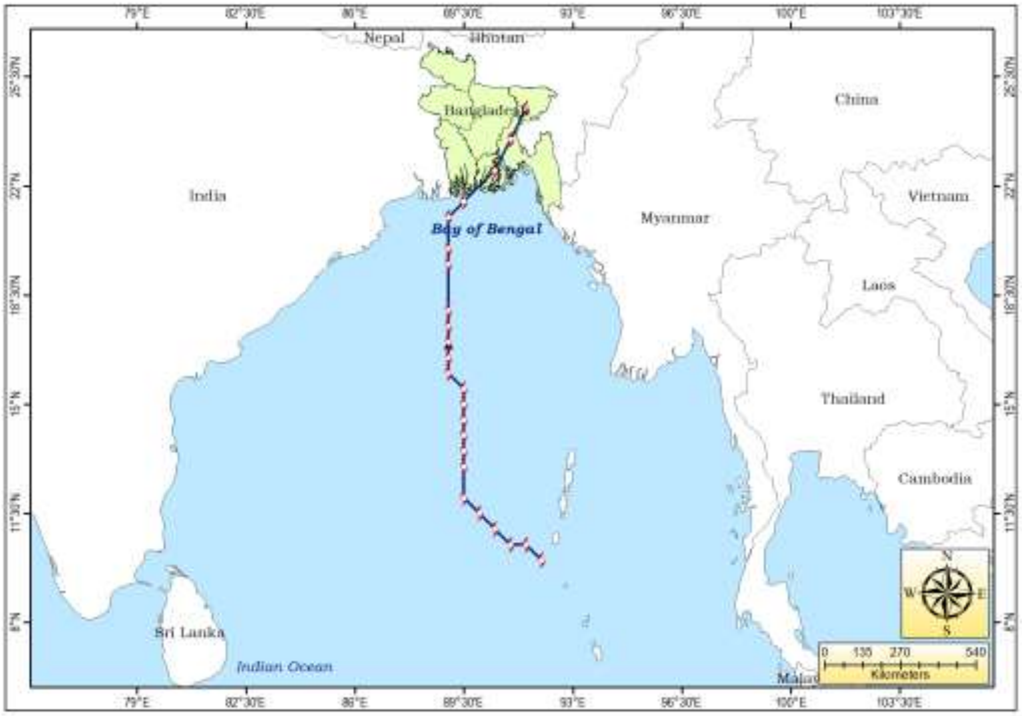

Figure 4: Track of tropical cyclone Sidr; as per data from RSMC

Tropical Cyclone BOB-04

This tropical cyclone was originated over the Bay of Bengal on October 24, 2000. The initiation process of this cyclone had relations with the monsoon trough (Takahashi et al., 2015; Molinari and Vollaro, 2013). It was soon recognized to be a Depression (D) by 25th October. This cyclone made landfall towards the southwest coast of Bangladesh around 28th October and then eventually dissipated on 29th. The synoptic conditions of the tropical cyclone have been given in Table 5.

Table 5: Synoptic conditions for tropical cyclone BOB-04; from the data of RSMC

Date	Time (UTC)	Latitude (decimal degrees)	Longitude (decimal degrees)	CI No (or T-number)	Estimated Central Pressure (hPa)	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade
25/10/2000	0900	13.5	93.0	1.5	1002	25	4	D
25/10/2000	1200	14.0	92.5	1.5	1002	25	4	D
25/10/2000	1800	14.5	92.0	1.5	1002	25	4	D
26/10/2000	0000	15.0	91.5	1.5	1002	25	4	D
26/10/2000	0300	15.5	90.5	1.5	1004	25	4	D
26/10/2000	0600	16.5	90.5	1.5	1002	25	4	D
26/10/2000	1200	16.5	89.5	1.5	1002	25	4	D
26/10/2000	1800	17.0	89.0	1.5	1004	25	4	D
27/10/2000	0000	17.5	88.5	1.5	1002	25	4	D
27/10/2000	0300	18.0	88.5	2.0	1002	30	6	DD
27/10/2000	0600	18.5	88.5	2.0	1002	30	6	DD
27/10/2000	1200	19.0	88.5	2.0	1000	30	6	DD
27/10/2000	1800	20.5	88.5	2.5	998	35	8	CS
27/10/2000	2100	21.0	88.5	2.5	998	35	8	CS
28/10/2000	0000	21.5	89.0	2.5	998	35	8	CS
crossed Bangladesh coast near Mongla between 01 UTC and 03 UTC								
28/10/2000	0300	22.5	89.0			30	6	DD
28/10/2000	0600	23.0	89.5			30	6	DD
28/10/2000	1200	23.5	90.5			25	4	D
28/10/2000	1800	24.0	93.0			25	4	D
29/10/2000	0000	24.0	94.0			25	4	D
weakened into a well-marked low-pressure area over Bangladesh and adjoining Assam and Meghalaya								

Two distinct curves have been observed within the track of cyclone BOB-04 (Figure 5). The first curve was seen on 0000 UTC of 27th October 2000. At that time – the MSW was 25 knots; the ECP was 1002 hPa and the PD was 4 hPa. Also, the cyclone was in a Depression (D) stage. The final curvature was seen on 0000 UTC of 28th October (which was 24 hours after the initial curve). During that time – the MSW was 35 knots (highest); the ECP was 998 hPa (lowest) and PD was 8 hPa (highest). Similar to the patterns of previously described cyclonic events, the distributions of MSW, ECP and PD were at the highest, lowest and highest values respectively.

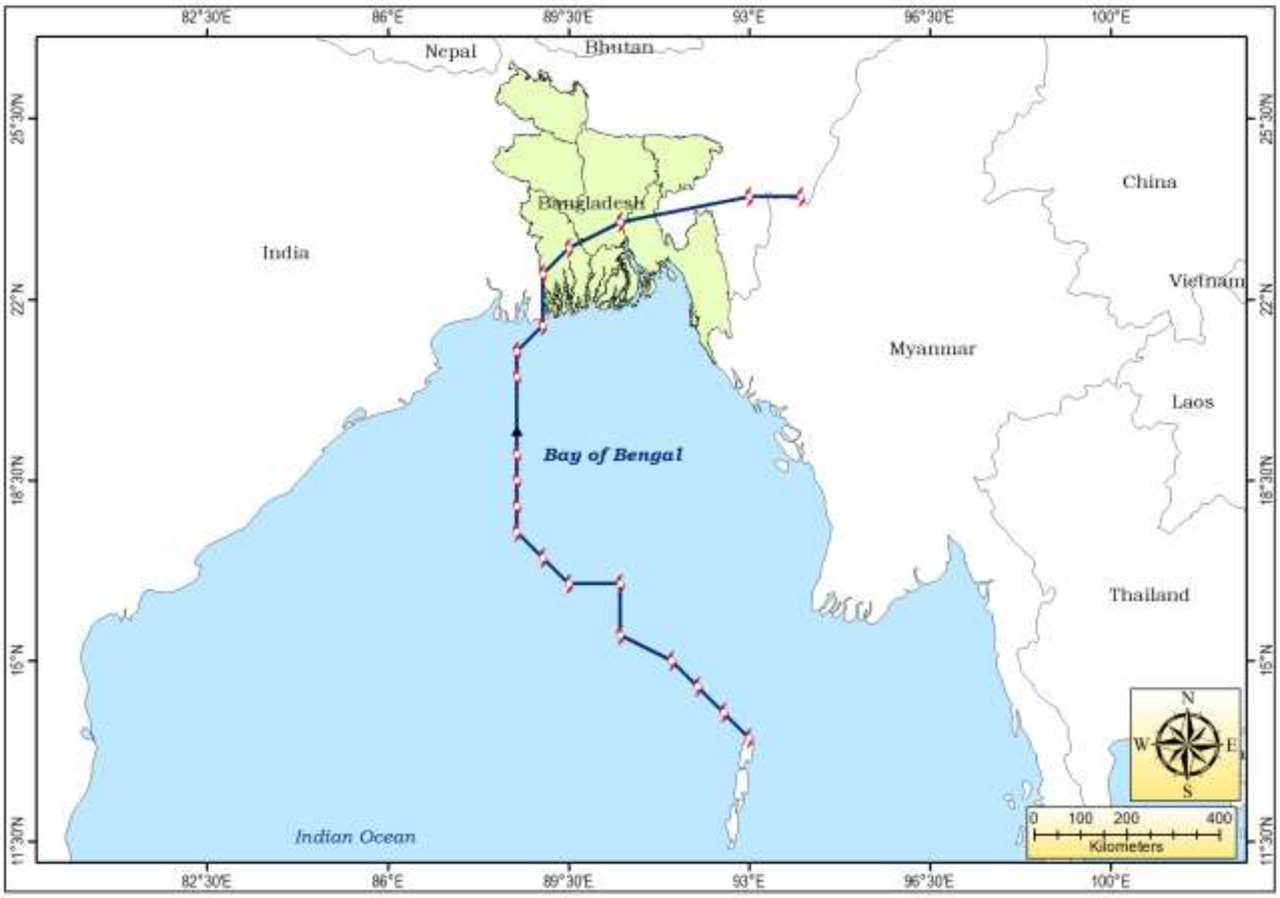

Figure 5: Track of tropical cyclone BOB-04; as per data from RSMC

Tropical Cyclone BOB-07

The origin of the tropical cyclone BOB-07 coincided with the dissipation of Cyclone Daryl (Callaghan, 1997). It was recognized to be Depression on November 21, 1995. Gradually, it translated into a Very Severe Cyclonic Strom (VSCS) for a brief period on 25th November. And then, it finally dissipated later that day (Table 6).

Table 6: Synoptic conditions for the tropical cyclone BOB-07; from the data of RSMC

Date	Time (UTC)	Latitude (decimal degrees)	Longitude (decimal degrees)	CI No (or T-number)	Estimated Central Pressure (hPa)	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade
21/11/1995	1200	6.5	91.0	1.5	1002	25	4	D
21/11/1995	1800	7.0	90.5	1.5	1002	25	4	D
22/11/1995	0000	7.5	90.0	1.5	1002	25	4	D
22/11/1995	0300	7.5	90.0	2.0	1000	30	6	DD
22/11/1995	0600	8.0	89.0	2.0	1000	30	6	DD
22/11/1995	0900	-	-	-	-	-	-	-
22/11/1995	1200	8.5	88.5	2.5	998	35	8	CS
22/11/1995	1800	9.5	87.5	3.0	994	45	12	CS
23/11/1995	0000	10.0	86.5	3.0	994	45	12	CS
23/11/1995	0300	10.0	86.0	3.5	990	55	16	SCS

Date	Time (UTC)	Latitude (decimal degrees)	Longitude (decimal degrees)	CI No (or T-number)	Estimated Central Pressure (hPa)	Maximum Sustained Surface Wind (kt)	Pressure Drop (hPa)	Grade
23/11/1995	0600	10.5	85.5	3.5	990	55	16	SCS
23/11/1995	1200	11.0	85.0	3.5	988	55	18	SCS
23/11/1995	1800	12.0	85.0	4.0	984	65	22	VSCS
24/11/1995	0000	13.5	85.0	4.5	976	77	30	VSCS
24/11/1995	0300	14.5	85.0	5.0	964	90	42	ESCS
24/11/1995	0600	15.0	85.0	5.0	960	90	46	ESCS
24/11/1995	1200	16.5	86.5	5.5	956	102	5.2	ESCS
24/11/1995	1800	18.0	88.8	5.0	962	90	46	ESCS
25/11/1995	0000	19.0	89.0	4.5	970	77	36	VSCS
25/11/1995	0300	20.0	90.5	4.5	972	77	34	VSCS
25/11/1995	0600	21.0	92.0	4.0	978	65	28	SCS
25/11/1995	0900	21.5	93.5	-	-	-	-	-
25/11/1995	1200	WML (well-marked low)						

Similar to the previous cases, this tropical cyclone event also had two curvatures within its track (Figure 6). The first curve was observed at 1200 UTC of 23rd November 1995. The MSW was 55 knots during that time. The ECP was at 988 hPa and the PD was at 18 hPa at that time. The tropical cyclone BOB-07 was at the Severe Cyclonic Storm (SCS) stage at that time. The second one was observed at 1200 UTC on November 24, 1995. By then, the MSW had become 102 knots; ECP became 956 hPa and PD became 52 hPa. The cyclone was at the ESCS stage then and similar to the previous three tropical cyclone events, the three synoptic parameters (MSW, ECP, and PD) were at their highest, lowest and highest values to their respective distributions.

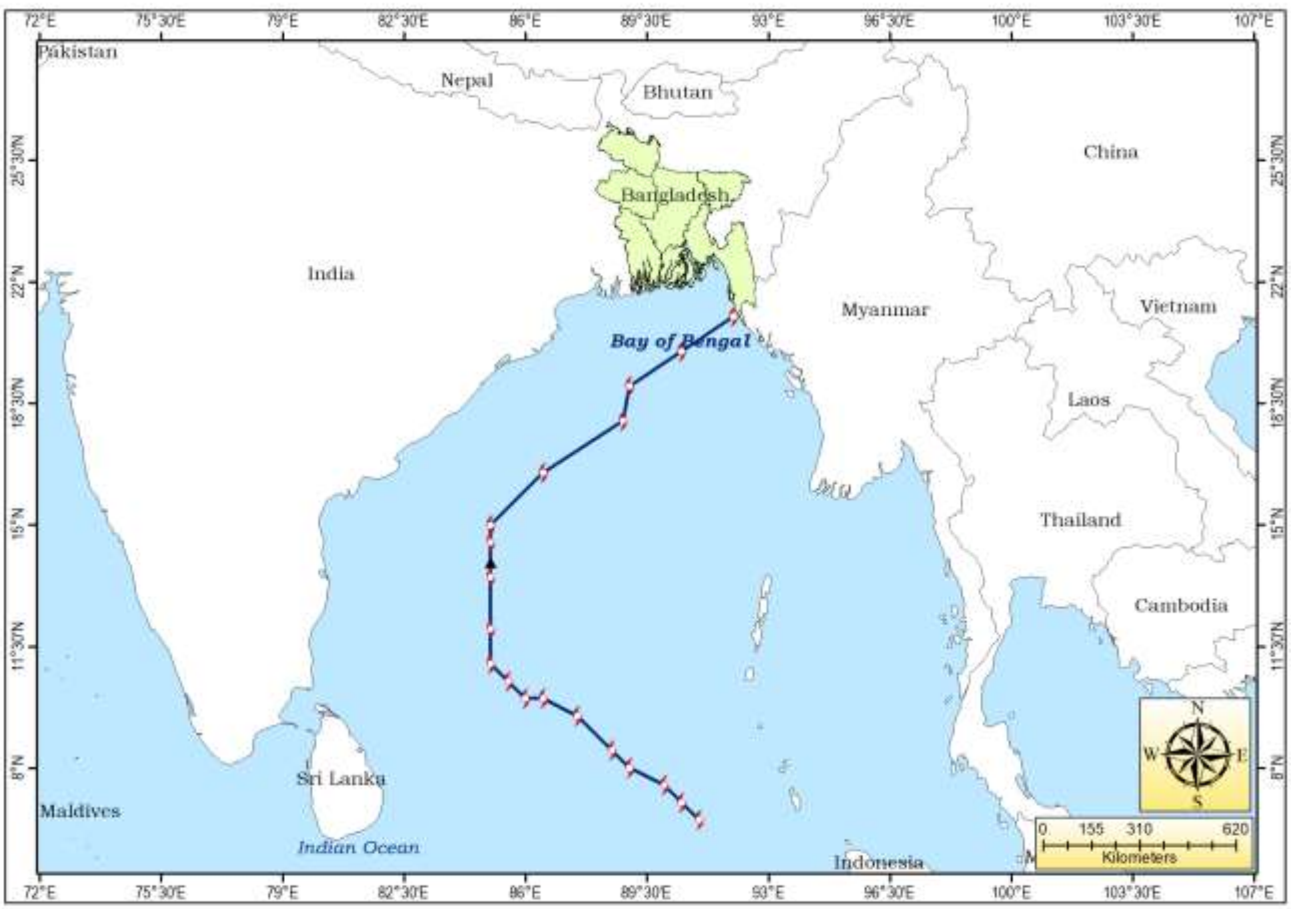

Figure 6: Track of the tropical cyclone BOB-07; as per data from RSMC

Discussions and Conclusion

The climatology and synoptic conditions for recurved tropical cyclones that formed over the Bay of Bengal have been assessed in this article. The specific objective of this research is to generate ideas on the recurved tropical cyclones that hit Bangladesh's coast. Therefore, four such tropical cyclones from that past have been further analyzed here. The synoptic conditions that prevailed during these events have been elaborately depicted. However, the analyses for climatology expanded beyond these four events and included all the recurved tropical cyclones. The total extent of the Bay of Bengal has not been considered in this research. Only the recurved tropical cyclones formed over the Bay of Bengal that hit the coast of Bangladesh, are being analyzed here.

The climatological analyses found that the highest number of recurved tropical cyclones occurred during the post-monsoon season. Also, recurvature activities are more prevalent towards the southwest coast of Bangladesh than the southeastern portion. There are no conspicuous differences between the two coasts for either scalar or vector speeds. But there are considerable differences within their direction and speed among the two coastal regions. Apart from that, there are also some relationships between the wind speed and the areal coverage of the tropical cyclones as well as their intensities.

The assessment of synoptic conditions found that the recurved tropical cyclones generally show a re-curvature tendency whenever they are at their peak intensity stage. At the peak intensity stage – the MSW has its highest value; the ECP drops to its lowest value, and the PD retains its highest value. It was also found that – after the ultimate curvature is achieved, then the tropical cyclones generally dissipate within a day or two.

Forecasting the recurvature of tropical cyclones with a significant lead-time is a challenge. Therefore, a good idea and clear knowledge about their climatological patterns and synoptic behaviors would benefit not only operational meteorologists but also scientific communities from various aspects. Above all, it could make forecasting such events a bit easier and thereby reduce the damages and catastrophes.

References

Akter, N. & Tsuboki, K. (2021). Re-curvature and movement processes of s over the Bay of Bengal. Q. J. R. Meteorological Soc., 147(740), 3681– 3702. https://doi.org/10.1002/qj.4148

Akter, N., & Tsuboki, K. (2012). Numerical simulation of Cyclone Sidr using a cloud-resolving model: Characteristics and formation process of an outer rainband. Monthly Weather Review, 140(3), 789-810. https://doi.org/10.1175/2011MWR3643.1

Bhatla, R., Raj, R., & Singh, M. (2018). Climatology of recurvature of tropical cyclone over the Bay of Bengal and the Arabian Sea. MAUSAM, 69(3), 437-442.

Bhattacharya, S. K., Kotal, S. D., & Kundu, P. K. (2015). An Analysis of Re-curvature and Decay of the Tropical Cyclone 'Madi' (2013) over the Bay of Bengal. Tropical Cyclone Research and Review, 4(1), 27-37. https://doi.org/10.6057/2015TCRR01.04

Callaghan, J. (1997). The South Pacific and southeast Indian Ocean tropical cyclone season 1995-96. Australian Meteorological Magazine, 46(4).

Chan, J. C. L., & Gray, W. M. (1982). Tropical Cyclone Movement and Surrounding Flow Relationships, Monthly Weather Review, 110(10), 1354-1374. https://doi.org/10.1175/1520-0493(1982)110<1354: TCMASF>2.0.CO;2

Das, K., Sarkar, S., Mukherjee, A., Das, P., & Pathak, A. (2021). Observing tidal and storm-generated wave height impact on groundwater levels in a tropical delta (the Sundarbans). Journal of Hydrology, 603, 126813.https://doi.org/10.1016/j.jhydrol.2021.126813

Gadgil, S., &Rajeevan, M. (2008). The Indian monsoon. Resonance, 13(12), 1117–1132. doi:10.1007/s12045-008-0111-0

Haque, M., Alam, M., Moniruzzaman, S., & Hoque, M. (2019). The Impact of Climate Change in the Coastal Areas of Bangladesh Affected by Cyclone Bulbul. Bangladesh J. Ext. Educ., 31 (1&2), 13-27.

Hossain, M. Z., Islam, M. T., Sakai, T., & Ishida, M. (2008). Impact of tropical cyclones on rural infrastructures in Bangladesh. Agricultural Engineering International: CIGR Journal.https://cigrjournal.org/index.php/Ejounral/article/view/1036/0

Islam, A. S., Bala, S. K., Hussain, M. A., Hossain, M. A., & Rahman, M. M. (2011). Performance of coastal structures during Cyclone Sidr. Natural Hazards Review, 12(3), 111-116.

Islam, T., & Peterson, R. E. (2008). Climatology of landfalling tropical cyclones in Bangladesh 1877–2003. Natural Hazards, 48(1), 115–135. doi:10.1007/s11069-008-9252-4

Kantha, L. (2006), Time to replace the Saffir-Simpson hurricane scale? Eos Trans. AGU, 87(1), 3–6. doi:10.1029/2006EO010003

KU, J., Kutty, G., & George, B. (2020). On the Predictability and Dynamics of Tropical Cyclone: Nargis (2008). Journal of Geophysical Research: Atmospheres, 125(9), e2019JD032040. https://doi.org/10.1029/2019JD032040

Kumar, A., Done, J., Dudhia, J., & Niyogi, D. (2011). Simulations of Cyclone Sidr in the Bay of Bengal with a high-resolution model: sensitivity to large-scale boundary forcing. Meteorology and Atmospheric Physics, 114(3), 123-137.https://doi.org/10.1007/s00703-011-0161-9

Li, W. W., Wang, C., Wang, D., Yang, L., & Deng, Y. (2012). Modulation of low-latitude west wind on abnormal track and intensity of tropical cyclone Nargis (2008) in the Bay of Bengal. Advances in Atmospheric Sciences, 29(2), 407-421. https://doi.org/10.1007/s00376-011-0229-y

Mohanty, U. C. (1994). Tropical cyclones in the Bay of Bengal and deterministic methods for prediction of their trajectories. Sadhana, 19(4), 567-582. https://doi.org/10.1007/BF02835640

Mohapatra, M. & Sharma, M. (2015). Characteristics of surface wind structure of tropical cyclones over the north Indian Ocean. J. Earth Syst. Sci., 124(7), 1573–1598.

Mohapatra, M., Nayak, D. P., Sharma, R. P., & Bandyopadhyay, B. K. (2013). Evaluation of official tropical cyclone track forecast over the north Indian Ocean issued by India Meteorological Department. Journal of Earth System Science, 122(3), 589-601. https://doi.org/10.1007/s12040-013-0291-1

Molinari, J., & Vollaro, D. (2013). What percentage of western North Pacific tropical cyclones form within the monsoon trough? Monthly Weather Review, 141(2), 499-505.https://doi.org/10.1175/MWR-D-12-00165.1

Murty, T. S., & Flather, R. A. (1994). Impact of Storm Surges in the Bay of Bengal. Journal of Coastal Research, 149-161.

Murty, T. S., & Neralla, V. R. (1992). On the recurvature of tropical cyclones and the storm surge problem in Bangladesh. Natural Hazards, 6(3), 275-279. https://doi.org/10.1007/BF00129512

Pal, A., & Chatterjee, S. (2021). The influence of upper level surrounding winds on tropical cyclone motion: a case study of the Bay of Bengal region. Proceedings of the Indian National Science Academy, 1-8. https://doi.org/10.1007/s43538-021-00036-3

Paul, B. K. (2010). Human injuries caused by Bangladesh's cyclone Sidr: an empirical study. Natural Hazards, 54(2), 483-495.https://doi.org/10.1007/s11069-009-9480-2

Rahman, M. A., HOKUGO, A., OHTSU, N., & Chakma, S. (2021). Evacuation Preparation Scenarios of Households during Early and Emergency Evacuation: A Case Study of Cyclone Bulbul in Southwestern Coastal Bangladesh. IDRiM Journal, doi: DOI10.5595/001c.29128

Sadhuram, Y., & Murthy, T. V. (2006). Estimation of tropical cyclone heat potential in the Bay of Bengal and its role in the genesis and intensification of storms. IJMS, 35(2), 132 – 138. http://hdl.handle.net/123456789/1512

Sanap, S. D., Mohapatra, M., Ali, M. M., Priya, P., & Varaprasad, D. (2020). On the dynamics of cyclogenesis, rapid intensification, and recurvature of the very severe cyclonic storm, Ockhi. Journal of Earth System Science, 129(1), 1-13. https://link.springer.com/article/10.1007/s12040-020-01457-2

Shamsuzzoha, M., Noguchi, R., & Ahamed, T. (2021). Damaged area assessment of cultivated agricultural lands affected by cyclone bulbul in the coastal region of Bangladesh using Landsat 8 OLI and TIRS datasets. Remote Sensing Applications: Society and Environment, 23, 100523.

Singh, O. P., Khan, T. M. A., & Rahman, M. S. (2001). Has the frequency of intense tropical cyclones increased in the north Indian Ocean? Current Science, 575-580.https://www.jstor.org/stable/24104250

Takahashi, H. G., Fujinami, H., Yasunari, T., Matsumoto, J., &Baimoung, S. (2015). Role of tropical cyclones along the monsoon trough in the 2011 Thai flood and interannual variability. Journal of Climate, 28(4), 1465-1476.https://doi.org/10.1175/JCLI-D-14-00147.1

Yamada, H., Moteki, Q., & Yoshizaki, M. (2010). The unusual track and rapid intensification of Cyclone Nargis in 2008 under a characteristic environmental flow over the Bay of Bengal. Journal of the Meteorological Society of Japan. Ser. II, 88(3), 437-453.