Assessment of the Relationship between Passages of Tropical Cyclones and their Origins of Genesis for Managing Risk of the Coast of Bangladesh

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Abstract: To understand risk from upcoming tropical cyclones (TCs) of Bangladesh, Impact of Indian Ocean Dipole (IOD) on origins of TCs genesis historically over Bay of Bengal (BoB) should be considered. So, the correlation between Dipole Mode Indexes (DMI) and frequencies of TCs generated in BoB has been investigated for (1877-2018) era. Changes in decade-wise mean DMI have been found linearly correlated with changes in decade-wise TC frequency. Then, a quadrant reference frame has been used to follow the behavior of TCs origins of genesis of different decades with respect to the changes in decade-wise mean DMI. In the decades having negative (positive) decade-wise mean DMI values, most of TCs generated from the western part (middle and eastern parts) of BoB and had an approach towards the middle (southeastern part) of BoB with the increase of decade-wise mean DMI. In addition, almost all the category 4 TCs (Saffir-Simpson scale) of BoB has been generated from the southeastern part of BoB. Therefore, this study conclude that most of the TCs of upcoming decades might generate from the southeastern part of BoB that may induce more category 4 TCs and have high possibilities to pass through the coasts of Barishal and Chittagong (Chattogram).

Keywords: TC frequencies; decade-wise mean DMI; Saffir-Simpson scale; Indian Ocean Dipole (IOD); Dipole Mode Indexes (DMI); TCs origins of genesis.

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1. Introduction

North Indian Ocean (NIO) is one of the active cyclone basins of the world. Most of the tropical cyclones (TCs) of NIO have been generated in Bay of Bengal (BoB). Bangladesh is one of the coastal countries of BoB. Historically, Bangladesh has counted unrecoverable deaths and economic lose due to deadly cyclones generated in BoB. Comparatively low elevation and highly dense population are loudly asking for proper management to reduce risk from cyclones.

Now-a-days, Bangladesh Meteorological Department (BMD) is regularly managing forecasting with the collaboration of Indian Meteorological Department (IMD). There are few non-governmental agencies that are also helping with preparatory movements against cyclones, but they don't have long term plans to work with. Different scenarios of future TCs generated in the BoB and TCs landfall on the coast of Bangladesh might be very helpful in this case.

Indian Ocean Dipole (IOD) is one of the most important climate drivers of Indian Ocean. IOD is the sea surface temperature (SST) difference between two dipoles of Indian Ocean, the West dipole is situated on Arabian Sea and the East dipole is situated in eastern part of the ocean around Indonesia as shown in Figure 1. IOD can be divided into 3 categories: positive IOD, neutral IOD and Negative IOD. Neutral IOD refers having only warm area on the East dipole. As shown in Figure 1(a), Negative IOD refers warm east dipole with cold west dipole that induces wind to flow from west to east and reverse process can be seen with positive IOD (see Figure 1(b)).

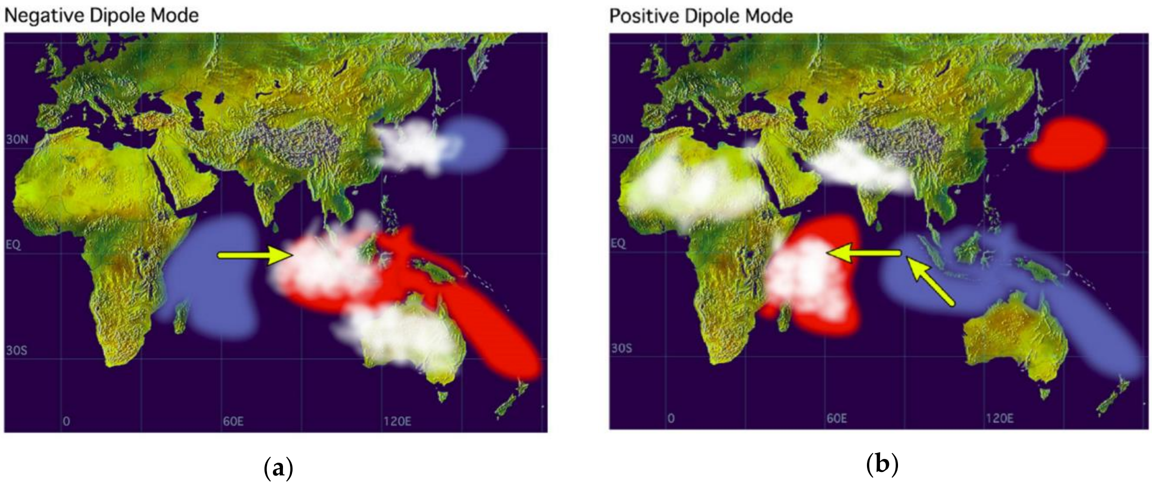


Figure 1. Red and Blue shaded areas have warm and cold average SST comparing with surrounding SST and yellow arrow indicates wind direction. (a) East dipole is warm and West dipole is cold (Negative IOD), (b) West dipole is warm and East dipole is cold (Positive IOD). (Source: [5])

According to the study of [5], During positive IOD years between 1981 and 2010, strong winds can be found from east to west dipole and wind over BoB are not so strong, but direction is toward southeast corner of BoB (as shown in Figure 2(a)). They also found strong wind from west to east dipole during negative dipole years between 1981 and 2010 while strong winds can be found toward western part of BoB (as shown in Figure 2(b)).

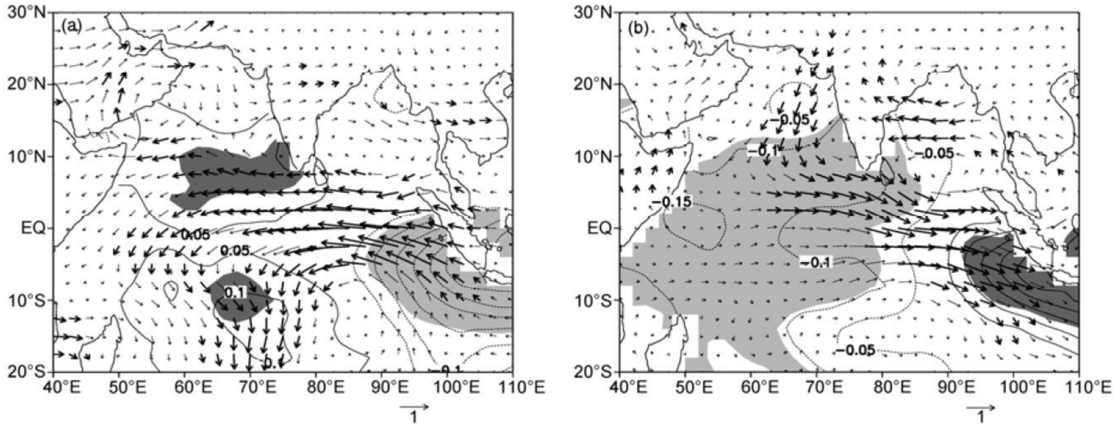


Figure 2. SST and Wind anomalies from 850hPa (a) Positive IOD years, (b) Negative IOD years, for 1981-2010 era. (Source: [18])

Using historical data of tropical cyclones (TC) tracks of the Bay of Bengal, averaged synthetic tracks have been calculated by using Inverse Distance Weighted (IDW) method for four different states of the east coast of India on the study of [13]. In this technique, they mentioned about an average origin of cyclogenesis and a point of landfall for each state considering pre-monsoon and post-monsoon TCs separately. But it is too ambitious to specify the area of Bay of Bengal from which TCs may generate and hit a specific area of the coast of Bay of Bengal. There is no pole-ward movement of cyclogenesis origins making some clusters of last few decades TCs (maximum wind speed > 62 km/h) genesis origins where a longitudinal straight line at 90°E longitude was assumed in [13]. They pointed out an east-west oscillatory pattern of decadal cyclogenesis origins which may oscillate with decadal changes of SST. According to [1], very severe tropical cyclones (maximum wind speed > 119 km/h) are generating around high average temperature (more than 29°c) of (1997-2014) on southeastern part of Bay of Bengal and have 2.3° eastern longitudinal shift of recent decade's cyclogenesis origins. In addition, [5] describes that positive (negative) Indian Ocean Dipole (IOD) induces anti-cyclonic (cyclonic) circulation anomaly over Bay of Bengal, as a result, weakening (strengthening) the cyclone vorticity at low level that decreases (increases) the number of TC generations and also strengthening (weakening) westerly steering flow that decreases (increases) the number of TC generations from western part of the Bay of Bengal. The effect of IOD on TC generation should be counted and investigate decade-wise changes of cyclogenesis origins with respect to IOD so that nearest future scenario of TC origins of genesis can be assumed and TCs landfall on the coast of Bangladesh.

In the study of [17], they proposed an integrated statistical approach to count TC passage frequency of the Western North Pacific Ocean based on their origins of genesis. But it is good for integrating climate drivers with cyclogenesis origins instead of understanding the effects of one climate driver on cyclogenesis origins. To investigate impacts of IOD on TC origins of genesis, [9] divided 117 years (1891-2007) into 3 categories considering positive IOD, no IOD and negative IOD years and found that cyclogenesis origins are higher (lower) in northern part of the Bay of Bengal during negative (positive) IOD years and higher (lower) in the southern part of the Bay of Bengal with positive (negative) and no IOD years. It will be interesting how will be the impact of IOD in decade-wise averaged IOD values on TC origins of genesis of the Bay of Bengal. A quadrant has been considered as a reference frame in [4] and the number of cyclogenesis origins has been calculated to compare and to draw conclusions. This approach is simple and effective to analysis the changes of TC origins of genesis. In this study, the TC origins of genesis landfall on the coast of Bangladesh and origins of genesis of Category 4-5 (according to Saffir-Simpson scale, maximum wind speed > 209 km/h) TCs have been identified to follow their trends in response to decade-wise averaged IOD. Also, few trials dividing the coast of Bangladesh into 2 (Sundarban and the rest) and 3 subregions (Sundarban, Barishal and Chittagong (Chattogram)) have been executed to follow trends of TC origin of genesis landfall on those subregions.

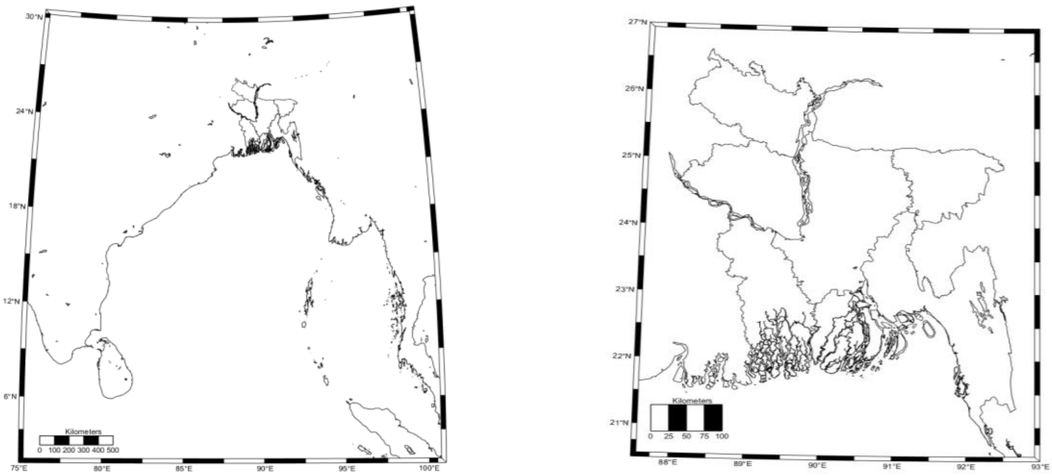
Since SST and wind play major roles in TC generation, the effects of IOD should be counted on TC genesis and TC frequency. Thus, objectives of this study can be described in few steps. Firstly, to trace TCs that generated in BoB and TCs that landfall on the coasts of Bangladesh (the coast of Sundarban, the coasts of Barishal and Chittagong (Chattogram)) in order to specify regions of their origins of genesis. Then, to investigate the correlation between IOD and TC frequencies in BoB by calculating correlation coefficients between them and comparing decade-wise statistical properties (maximum, minimum, mean, median, 1st quartile, 3rd quartile, outliers) of DMI with TC frequencies. After that, to find approaches of origins of TCs genesis with respect to decade-wise mean DMI of different decades based on the above findings. As a result, some expected scenarios of TCs can be calculated that may landfall on Bangladesh in the coming closest decades using the same approach of this study. Finally, some potential implications of this study have been discussed in managing risk from TCs of the coasts of Bangladesh.

2. Study of Region and Data Sets

Domain of this study is the Bay of Bengal (BoB) which is a sub-basin of NIO and the coast of Bangladesh. The BoB sub-basin which lies between 2°N-23°N latitude and 78°E-101°E longitude (shown in Figure 3(a)) has been followed to study TCs origin of genesis. The coast of Bangladesh is situated between 20.34°N-22.83°N latitude and 88.01°E-92.41°E longitude (shown in Figure 3(b)) The coast of Bangladesh can be named approximately with corresponding regions and those are the coast of Sundarban (between 89.11°E-89.93°E longitude and 21.64°N-21.81°N latitude), the coast of Barishal (between 89.94°E-90.795°E longitude and 21.82°N-22.02°N latitude), the coast of Chittagong (Chattogram) (between 90.796°E-92.37°E longitude and 20.703°N-22.33°N latitude).

The GSHHG latest data [16] has been used to draw the BoB domain (Figure 3(a)), ETOPO bathymetry data [11] and administrative domain of Bangladesh [4] with a mapping package [12] of MATLAB.

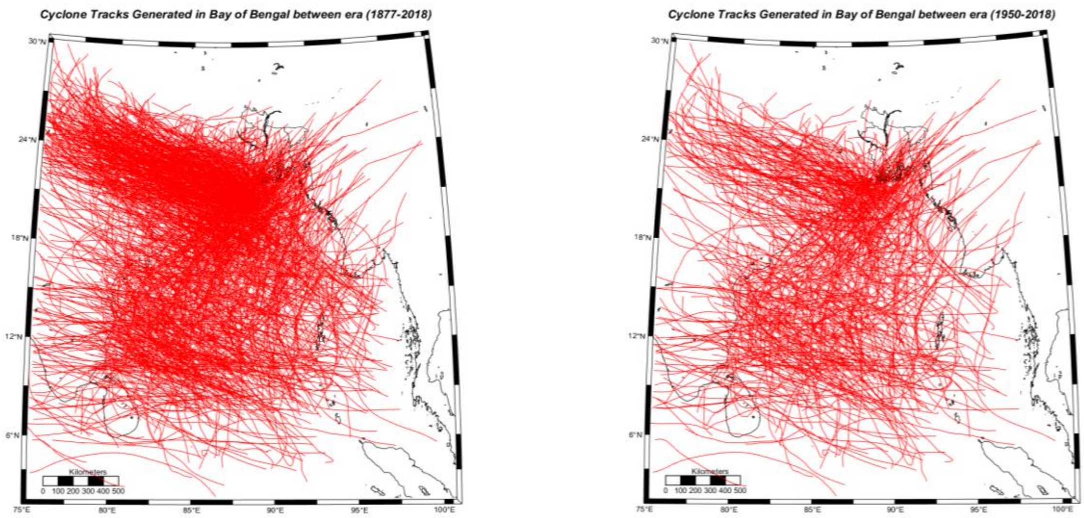
International Best Track Archive for Climate Stewardship (IBTrACS) [version 4] has been used for (1877-2018) era [7] to specify TC frequency, TC origins of genesis, TC landfall on the coast of Bangladesh and category 4 TCs (according to Saffir-Sampson Scale). The study of [8] discloses that IBTrACS data set has been created after assessing quality (quality of track positions and maximum wind) and combining available sources. Therefore, IBTrACS is giving more longer periods of data with acceptable quality.



(a) (b)

Figure 3. (a) Bay of Bengal Sub-basin, (b) Bangladesh and it's coast.

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is providing SST DMI data sets (monthly) from 1870 to 2018 which have been derived from HadISST dataset [6]. This DMI dataset has been used to find the relation between DMI and TC frequency and later divided into decades to find decade-wise mean DMI to follow the trends of TC origins of genesis.



(a) (b)

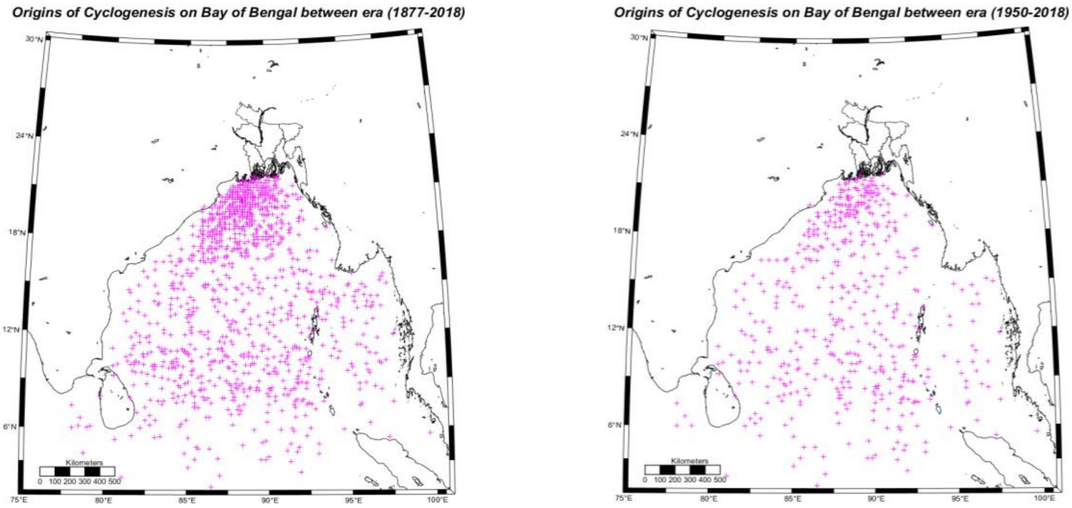
Figure 4. (a) TCs tracks (red lines) generated in BoB for (1877-2018) era; (b) TCs tracks (red lines) generated in BoB for (1950-2018) era.

3. Methods

The following investigations have been gone through for finding origins of TCs genesis land falling on the coast of Bangladesh, assessing correlation between TC frequency and DMI and following behavior of TCs origins of genesis in the BoB.

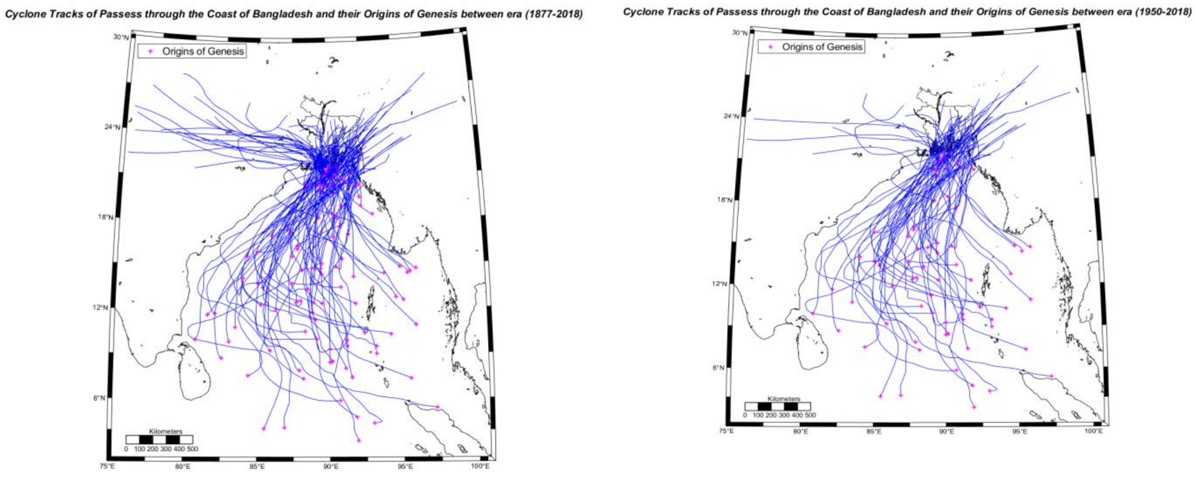
3.1. Behavior of TCs Origins of Genesis in the Bay of Bengal

In the beginning, all those TCs tracks have been separated from IBTrACS data for (1877-2018) era that have been generated on the BoB basin (shown in Figure 4(a)). Also the same filtration has been implemented for (1950-2018) to follow recent approaches of TCs tracks (shown in Figure 4(b)). The first points of those tracks are their origins of genesis. Thus all those TCs origins of genesis have been obtained that are generated on the BoB (shown in Figure 5(a) and Figure 5(b)). Then, all those TCs tracks that passed through the coast of Bangladesh have been separated (shown in Figure 6(a) and Figure 6(b)).



(a) (b)

Figure 5. (a) TCs origins of genesis (magenta crosses) generated in BoB for (1877-2018) era; (b) TCs origins of genesis (magenta crosses) generated in BoB for (1950-2018) era.



(a) (b)

Figure 6. (a) TCs tracks (blue lines) and their origins of genesis (magenta crosses) that landfall on the coast of Bangladesh for (1877-2018) era; (b) TCs tracks (blue lines) and their origins of genesis (magenta crosses) that landfall on the coast of Bangladesh for (1950-2018) era.

The coast of Bangladesh has been divided into 3 sub regions: the coast of Sundarban, the coast of Barishal and the coast of Chittagong (Chattogram) (shown in Figure 7), based on the corresponding states of Bangladesh to follow the trend of TCs origins of genesis. Then, TCs tracks and their origins of genesis have been separated for each of 3 sub regions (shown in Figure 8(a), Figure 8(b) and Figure 8(c)). At the end of this stage, all TCs origins of genesis have been checked for finding clusters of similar TCs (shown in Figure 8(d)).

Since it was hard to separate origins of genesis that landfall on the coast of Barishal (green crosses) from origins of genesis that landfall on the coast of Chittagong (Chattogram) (magenta crosses) (see Figure 8(d)), the coasts of Barishal and Chittagong (Chattogram) have been merged and so, TCs tracks and TCs origins of genesis have been separated (shown in Figure 9(a) and Figure 9(b)).

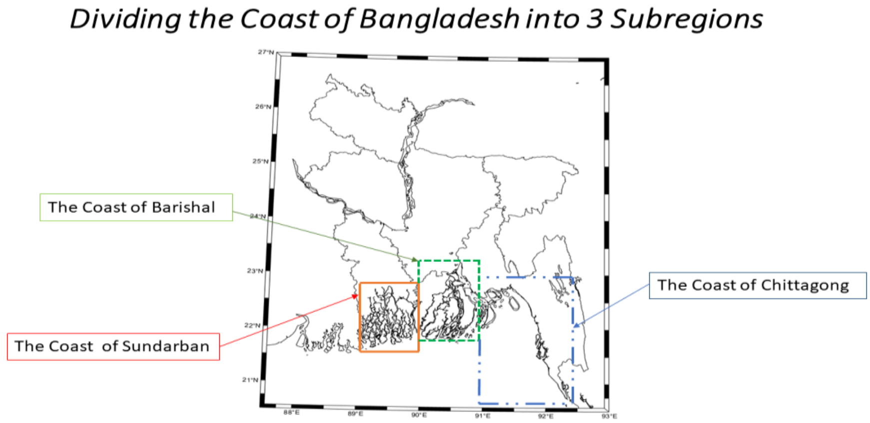
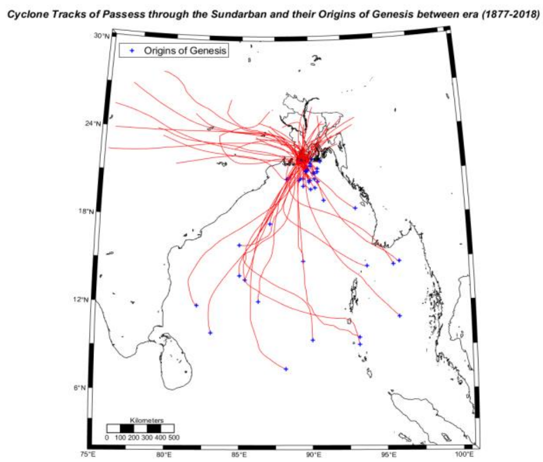
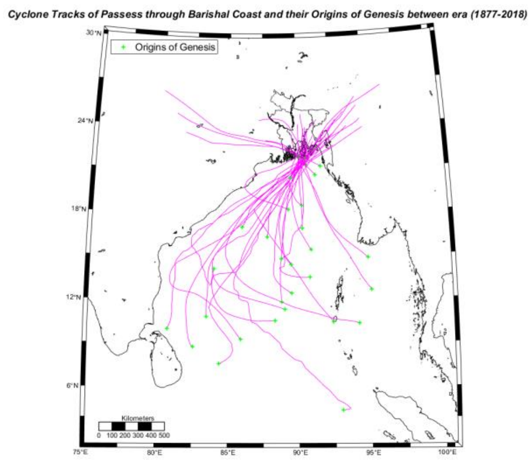


Figure 7. Subregions of the coast of Bangladesh.



(a)



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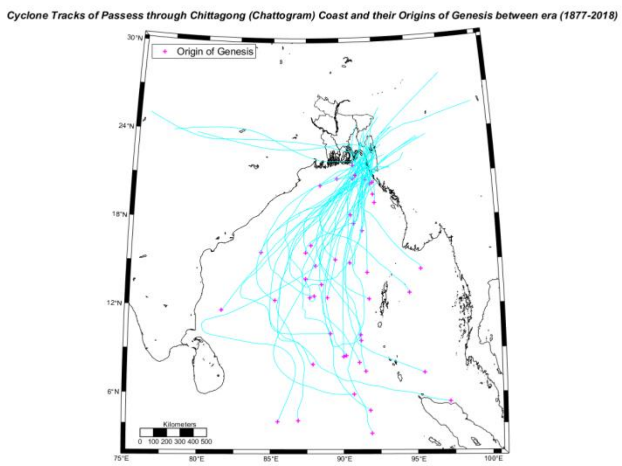

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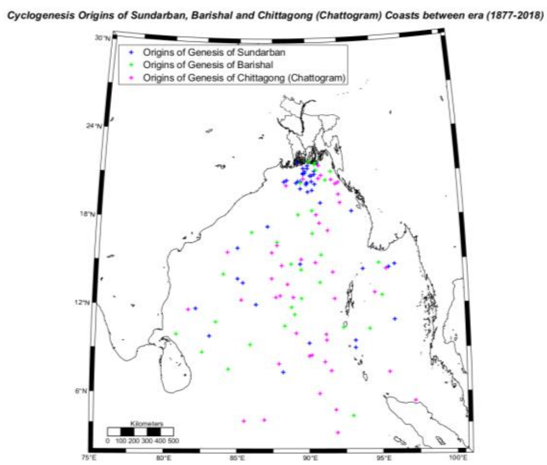


(d)

Figure 8. (a) TCs tracks (red lines) and their origins of genesis (blue crosses) that landfall on the coast of Sundarban for (1877-2018) era; (b) TCs tracks (magenta lines) and their origins of genesis (green crosses) that landfall on the coast of Barishal for (1877-2018) era; (c) TCs tracks (cyan lines) and their origins of genesis (magenta crosses) that landfall on the coast of Chittagong (Chattogram) for

(1877-2018) era; (d) TCs origins of genesis generated in BoB that landfall on the coast of Sundarban (blue crosses), the coast of Barishal (green crosses) and the coast of Chittagong (Chattogram) (magenta crosses) for (1877-2018) era.

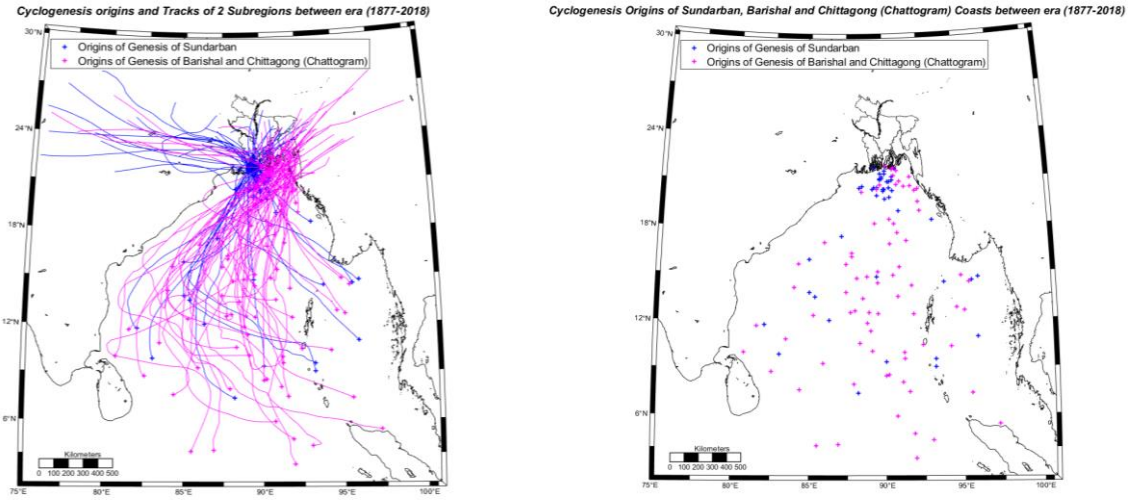


Figure 9. (a) TCs tracks and their origins of genesis generated in BoB that landfall the coast of Sundarban and the coast of Barishal (blue lines with blue crosses) and Chittagong (Chattogram) (magenta lines with magenta crosses) for (1877-2018) era; (b) TCs origins of genesis generated in BoB that landfall on the coast of Sundarban (blue crosses), the coast of Barishal and Chittagong (Chattogram) (magenta crosses) for (1877-2018) era.

3.2. Correlation between TC Frequency and Dipole Mode Index (DMI)

At first, TCs frequencies have been plotted for all TCs, for TCs that landfall on the coast of Bangladesh and for TCs of category 4-5 according to Saffir-Sampson Scale (as shown in Figure 10) against time and DMI time series between (1877-2018) era (shown in Figure 11) to investigate similarities between them. But it was hard to compare (see Figure 12).

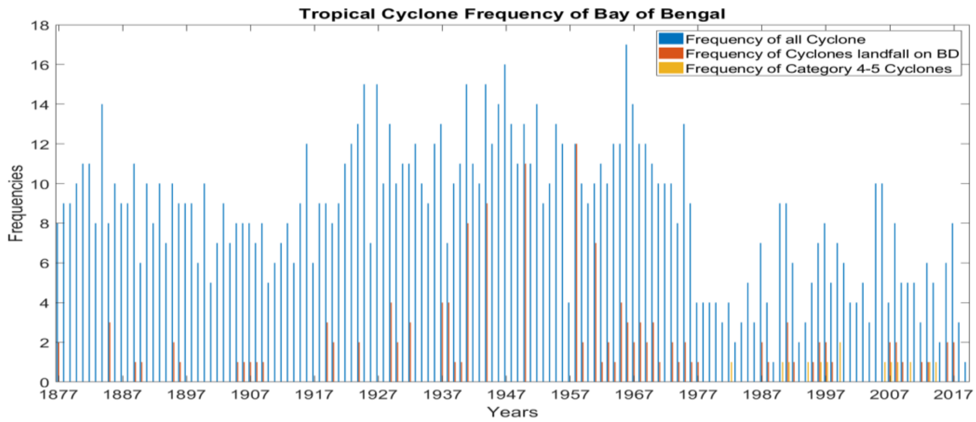


Figure 10. TC frequencies for all TCs (blue), for TCs that landfall on the coast of Bangladesh (red) and for TCs of category 4-5 (orange) for (1877-2018) era.

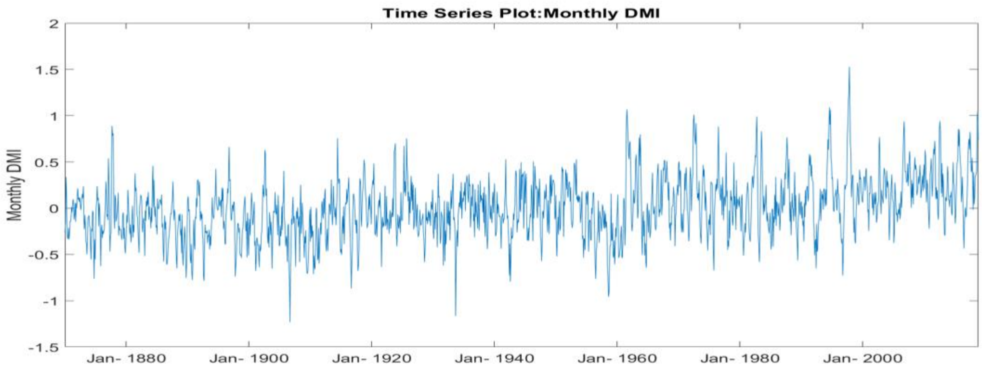


Figure 11. Monthly DMI timeseries for (1877-2018) era.

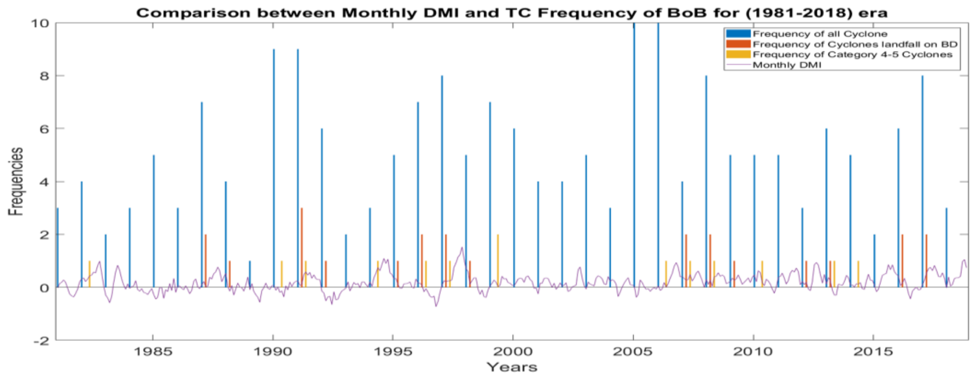


Figure 12. Yearly TC frequencies of BoB and monthly DMI for (1981-2018) era.

Monthly TC frequencies have been calculated to compare with monthly DMI values (shown in Figure 13) and then correlation coefficients between each monthly TC frequencies and monthly DMI has been taken. Later, pre-monsoon (March-May) and post-monsoon (October-December) seasonal TC frequencies and DMI have been computed to observe correlation coefficients of themselves.

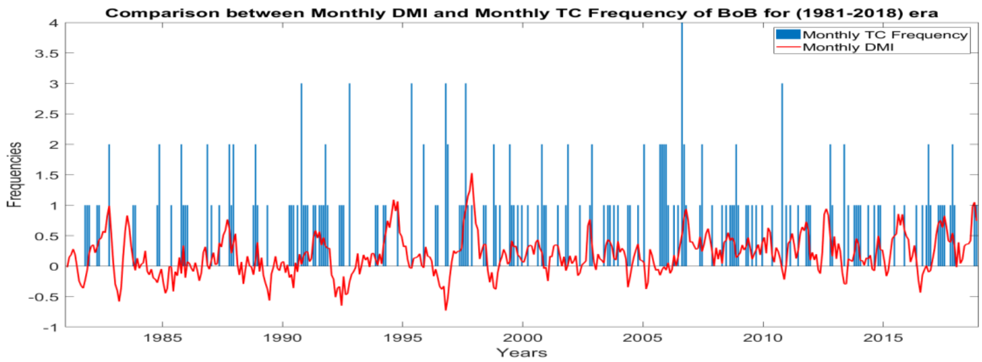


Figure 13. Monthly TC frequency for all cyclone of BoB and Monthly DMI for (1981-2018) era.

In the second part of this investigation, Decade-wise TC frequencies and DMI have been calculated which lead us some fruitful results that has been discussed in section 4.

3.3. Behavior of TCs Origins of Genesis in the Bay of Bengal

In this section, the approach of using quadrant as a reference frame [9] has been used to follow the changes of TCs origins of genesis of BoB. A vertical line at 87.3°E longitude and a horizontal line at 16.3°N latitude have been taken to build the quadrant frame as shown in Figure 14. As usual (+,+) quadrant is the 1st, (-,+) quadrant is the 2nd , (-,-) quadrant is the 3rd and (+,-) quadrant is the 4th.

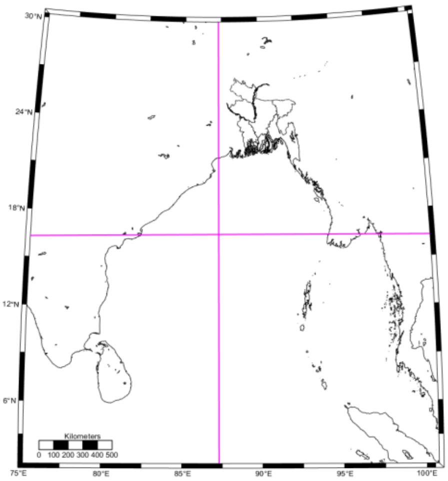


Figure 14. Quadrant (magenta colored lines) as reference frame on the study domain.

4. Results

4.1. Correlation between TC Frequencies in Bay of Bengal and DMI

4.1.1. Correlation Coefficients between TC Frequencies in Bay of Bengal and DMI

From Table 1–2, Overall Correlation Coefficient of TC Frequency of all TCs of Bay of Bengal and DMI for (1877-2018) is low (-0.0691), but it has 95% significance level. From Figure 15, it is clear that TCs have frequently occurred from May to December and TCs landfalls on Bangladesh are more frequent in May-June, August and October-November. Category 4 TCs are coming more frequently in April and October than other months. Though their month-wise correlation coefficients of February and May are showing 95% significance, but season-wise correlation coefficients of

Table 1. Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different Time Periods (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs) [RED underlined: 95% or more significance and Green: 90% significance]

	1877-2018			1877-1976			1977-2018		
	All	BD	Cat. 4	All	BD	Cat. 4	All	BD	Cat. 4
Overall	-0.0691	0.0243		**-0.0315**					
Jan	0.0391	0.0303		0.0579			-0.0585	-0.0175	
Feb	0.1853			0.1952			0.2168		
Mar	0.0909		0.2286	0.0411			0.2151		
Apr	0.1163	0.2525	0.0216	0.0866			0.3412	0.3655	0.2766
May	-0.1985	0.0416		-0.1851	-0.1154		-0.2250	0.2087	-0.0498
Jun	-0.0513	0.0180		0.0146	-0.0011		0.0531	0.3035	
Jul	-0.1326	-0.1141		0.0655	-0.0926		0.2358		
Aug	-0.0938	-0.0030		0.0158	0.0753		0.2564		
Sep	-0.1979	0.1942	0.0741	0.0440	0.2264		0.1456	0.3538	
Oct	-0.2875	0.0202	-0.0532	-0.1909	0.1246		-0.3743	-0.1445	-0.0391
Nov	-0.0151	-0.0776		0.0911	-0.0330		-0.1635	-0.1817	-0.1987
Dec	0.0461	0.0325	0.1155	0.1745	0.0650		-0.1414	0.0420	
Pre-Monsoon	-0.0405	0.0673	0.0315	-0.0538	-0.0648		0.0216	0.2104	0.1149
Post-Monsoon	-0.1132	-0.0084	0.0437	-0.0277	0.0531		-0.2056	-0.1130	-0.0563

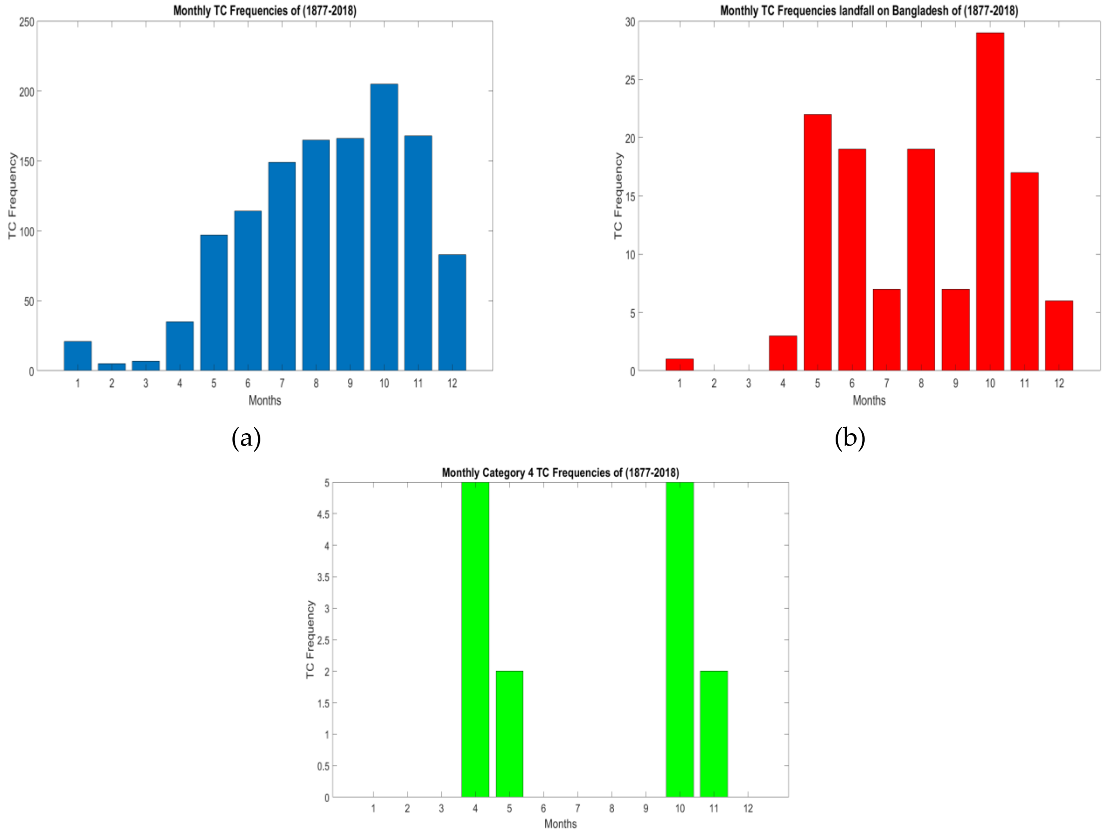
pre-monsoon is not significant for them for (1877-2018) era. On the other hand, their month-wise correlation coefficients of September-October and so season-wise correlation coefficients of post-monsoon are significant for (1877-2018) era.

Their season-wise correlation coefficient of post-monsoon is significant for (1977-2018) period rather than before. In (1961-1976) period, TCs landfalls on Bangladesh were very frequent. In this period, correlation coefficients between TCs landfall on Bangladesh and DMI of May, September-October are significant but post-monsoon's is not. Only significant correlation coefficient of Category 4 TCs with DMI is in April for (1982-2018) period in which category 4 TCs have been started to occur. It seems that TC frequency in BoB and DMI are more correlated in two seasons (pre-monsoon and post-monsoon).

Then, correlation coefficients between TC frequencies of BoB and DMI for decade-wise periods have been followed to prepare Tables 3–7. After observing these values, still relation between TC frequencies of BoB and DMI is unclear though decades after 1961 correlation coefficients significance have increased comparing with previous decades.

Table 2. Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different Time Periods (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs) [RED underlined: 95% or more significance and Green: 90% significance]

	1961-1976			1982-2018		
	All	BD	Cat. 4	All	BD	Cat. 4
Overall	-0.1475					
Jan	-0.2197			-0.0891	-0.0279	
Feb	-0.0439			0.2166		
Mar				0.2240		
Apr	0.0327			0.3441	0.3686	0.2775
May	-0.5038	-0.5097		-0.1877	0.2327	-0.0741
Jun	-0.1305	-0.1669		0.0353	0.3038	
Jul	-0.3521			0.2006		
Aug	-0.5345	-0.2348		0.2248		
Sep	0.2927	0.5318		0.1368	0.3660	
Oct	0.1466	0.4718		-0.3834	-0.1923	-0.0668
Nov	-0.3588	-0.3352		-0.1762	-0.1824	-0.2265
Dec	0.0207	-0.2405		-0.0708	0.0333	
Pre-Monsoon	-0.3381	-0.3468		0.0592	0.2382	0.1087
Post-Monsoon	-0.0715	0.0991		-0.1969	-0.1287	-0.0761



(a) (b)

(c)

Figure 15. (a) Month-wise TC frequency of all TCs of BoB for (1877-2018); (b) Month-wise TC frequency of all TCs of BoB that landfall on Bangladesh for (1877-2018); (c) Month-wise TC frequency of category 4-5 TCs of BoB for (1877-2018).

Table 3: Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different decades (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs) [RED underlined: 95% or more significance and Green: 90% significance]

	1877-1890			1891-1900			1901-1910		
	All	BD	Cat. 4	All	BD	Cat. 4	All	BD	Cat. 4
Overall									
Jan							-0.2664		
Feb									
Mar							0.6002		
Apr				-0.0290			0.0601		
May	-0.1944	0.1937		-0.7027			-0.3385		
Jun	0.4332	0.1925		0.3547	0.2062		0.3238	0.4636	
Jul	0.5014			0.4318			0.0158	-0.3857	
Aug	0.6077	0.5383		-0.0904	-0.3880		0.5824		
Sep	-0.0829			0.1855	0.2261		0.1346		
Oct	-0.5083	-0.5242		-0.6701	-0.2487		-0.0648	0.1852	
Nov	-0.0234	-0.0070		0.3603			-0.3775	-0.1050	
Dec	-0.1429			-0.2924	0.0275		-0.0352	0.3623	
Pre-Monsoon	-0.0462	0.1198		-0.1054			0.0306		
Post-Monsoon	-0.2618	-0.3036		-0.2228	-0.1161		-0.2067	0.1088	

Table 4: Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different decades (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs)
[RED underlined: 95% or more significance and Green: 90% significance]

	1911-1920			1921-1930			1931-1940		
	All	BD	Cat. 4	All	BD	Cat. 4	All	BD	Cat. 4
Overall									
Jan	0.3389			0.1326			-0.5324		
Feb									
Mar				-0.2583			0.2899		
Apr	-0.1944			0.3469			-0.1391		
May	-0.1113	-0.2684		-0.1991			-0.4394	0.4178	
Jun	-0.1347	-0.2216		-0.4092	-0.4812		0.2825	-0.4813	
Jul	0.3035			-0.4101	-0.0571		0.4596		
Aug	-0.3014	-0.0828		0.0263	0.2637		-0.3693	0.3215	
Sep	-0.1834	0.2634		0.1787			-0.0659	0.2036	
Oct	-0.4825			-0.1307	0.1200		-0.1886	0.3021	
Nov	0.3039			-0.0108			-0.0470	-0.5169	
Dec	0.1353			-0.0801			-0.4461		
Pre-Monsoon	-0.1151	-0.1359		-0.0395			-0.0943	0.2310	
Post-Monsoon	-0.0829			0.0569	0.1032		-0.2136	-0.1000	

Table 5: Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different decades (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs)
[RED underlined: 95% or more significance and Green: 90% significance]

	1941-1950			1951-1960			1961-1970		
	All	BD	Cat. 4	All	BD	Cat. 4	All	BD	Cat. 4
Overall				**-0.2677**					
Jan	-0.2213			**0.5723**			0.0180		
Feb	0.4850			0.1290			-0.0633		
Mar									
Apr	0.4097			0.1749			-0.3857		
May	0.0973	-0.1445		-0.2534	-0.0919		-0.0081	-0.4496	
Jun	-0.1147	-0.0334		-0.0629			0.3449	0.0269	
Jul	0.1066	-0.1734		0.0550	-0.0532		-0.2033		
Aug	-0.2511	0.0500		0.3709			**-0.6790**	-0.3636	
Sep	-0.0752			-0.4156			0.0552	**0.6141**	
Oct	-0.2323	0.0055		-0.4237	-0.3237		0.3617	0.4602	
Nov	0.5355	0.0639		-0.1410	0.2908		**-0.7779**	-0.2399	
Dec	0.3950			0.5213			-0.4846	-0.4928	
Pre-Monsoon	0.1930	-0.0400		-0.2715	-0.1367		**-0.3723**	**-0.3476**	
Post-Monsoon	0.1192	0.0094		-0.2255	-0.1276		-0.0767	0.1942	

Table 6: Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different decades (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs) [RED underlined: 95% or more significance and Green: 90% significance]

	1971-1980			1981-1990			1991-2000		
	All	BD	Cat. 4	All	BD	Cat. 4	All	BD	Cat. 4
Overall									
Jan	-0.4068			0.0974	0.0815		-0.0327		
Feb									
Mar							0.4962		
Apr	0.4681			0.1296		0.4633	0.6595	0.6595	0.6595
May	-0.6566	-0.2985		0.1054	0.3032	-0.2209	-0.3620	0.2094	0.0389
Jun	-0.1214	0.0475		-0.3075			-0.3906		
Jul	-0.1496						0.2675		
Aug	0.1651			-0.1791			0.5706		
Sep	0.2846						0.5715	0.6183	
Oct	-0.7607	0.1402		0.2560	-0.2307		-0.6288	-0.4708	-0.0057
Nov	0.1979	-0.1761		-0.4238	-0.4060		-0.2533	-0.1092	-0.4156
Dec	0.2331	0.1554		0.5818	0.2082		-0.2921		
Pre-Monsoon	-0.1821	-0.1958		0.1686	0.2216	0.1136	0.1026	0.3752	0.3217
Post-Monsoon	-0.0826	0.0142		0.1457	-0.1806		-0.3924	-0.2721	-0.1167

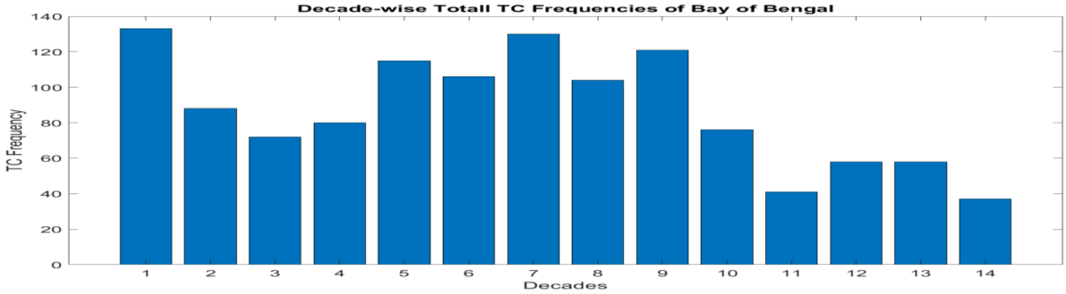
Table 7: Correlation Coefficients between DMI and TC Frequency in Bay of Bengal for different decades (All: for all TCs; BD: for TCs that landfall on Bangladesh; Cat.4: for category 4 TCs) [RED underlined: 95% or more significance and Green: 90% significance]

	2001-2010			2011-2018		
	All	BD	Cat. 4	All	BD	Cat. 4
Overall						
Jan	-0.2057			-0.2214		
Feb				0.4411		
Mar						
Apr	-0.0893	0.2019	-0.2538	0.7732		
May	-0.2138	0.4120		-0.3091	0.0106	
Jun	0.1412	0.4644		0.6646	0.5370	
Jul	0.1253			0.1829		
Aug	0.5867			-0.7841		
Sep	-0.0388					
Oct	-0.4756	0.0833	-0.3863	-0.2901	0.1417	-0.3149
Nov	-0.1057	0.1018	0.1018	-0.4081	-0.7357	
Dec	-0.1230			-0.5965		
Pre-Monsoon	-0.1266	0.2586	-0.0865	-0.0317	-0.0171	
Post-Monsoon	-0.1954	0.1054	-0.1283	-0.2115	-0.0551	-0.0622

4.1.2. Decade-wise DMI vs TC Frequencies in Bay of Bengal

Boxplot of decade-wise DMI (shown in Figure 16(b)) have been followed with Figure 16(a). Point to be noted that each decade number 1-14 is assigned like [1:1877-1890; 2:1891-1900; 3:1901-1910; 4:1911-1920; 5:1921-1930; 6:1931-1940; 7:1941-1950; 8:1951-1960; 9:1961-1970; 10:1971-1980; 11:1981-1990; 12:1991-2000; 13:2001-2010; 14:2011-2018]. Maximum, minimum and mean values of each decade have been added with the boxplot (Figure 16(b)) so that each of the components can be followed with Figure 16(a) to find a good correlation point.

(a)



(b)

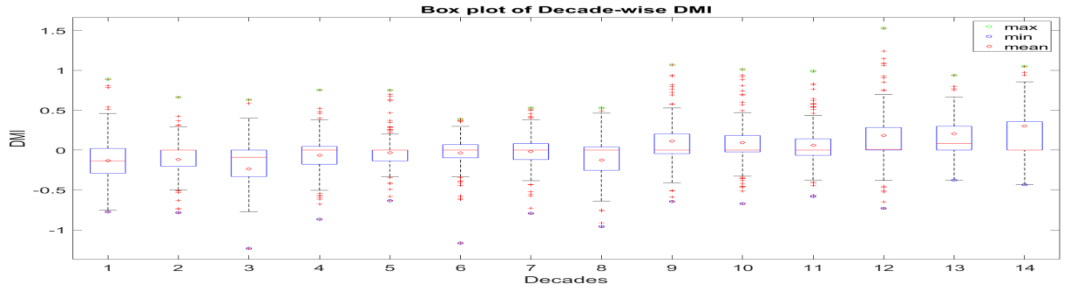
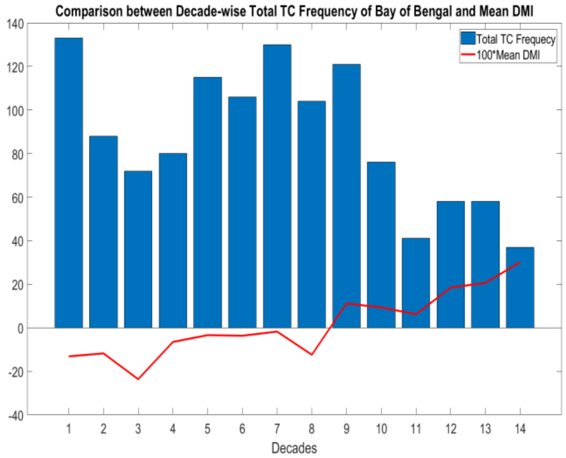
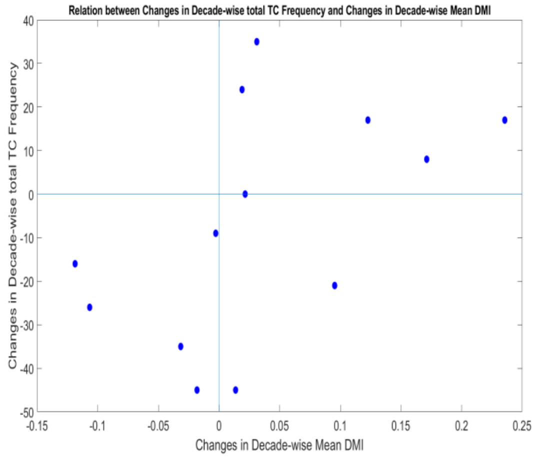


Figure 16. (a) Decade-wise total TC frequency in BoB for (1877-2018) era; (b) Boxplot of Decade-wise DMI for (1877-2018) era.

Most of the changes of two consecutive decades mean DMI are similar with the changes of those decades total TC frequency (Figure 17(a)). From Figure 17(b), it is clear that positive changes of DMI induced increase in total TC frequency and negative changes of DMI induced decrease in total TC frequency in most of the cases. Therefore, Decade-wise mean DMI is closely related to total TC frequency.

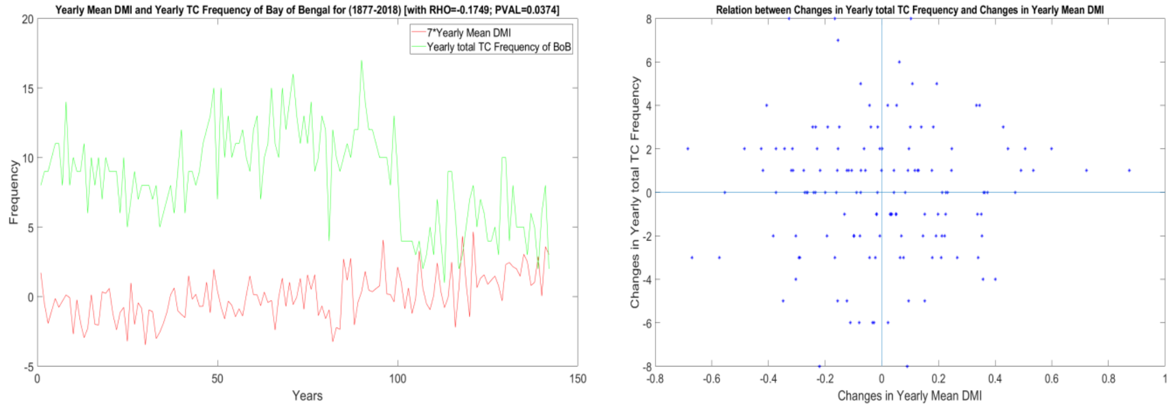




(a) (b)

Figure 17. (a) Comparing decade-wise mean DMI line (red) with decade-wise total TC frequency (blue); (b) Changes of decade-wise total TC frequency against the changes of decade-wise mean DMI.

Moreover, the relation between yearly mean DMI and yearly total TC frequency has been investigated (Figure 18(a)). But, Changes of yearly total TC frequency against the changes of yearly mean DMI are robust enough to reject our claim (shown in Figure 18(b)).



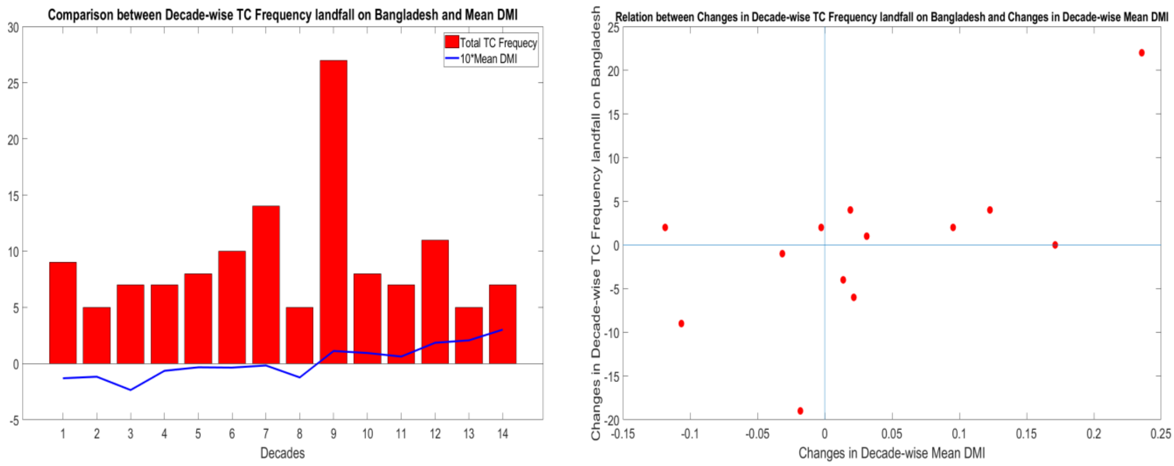
(a) (b)

Figure 18. (a) Yearly mean DMI (red) vs. yearly total TC frequency in BoB (blue); (b) Changes of yearly total TC frequency against the changes of yearly mean DMI.

The same approach has been followed for decade-wise TC frequency that landfall on Bangladesh and decade-wise mean DMI. They have good correlation since most of the cases where positive changes of decade-wise mean DMI induces increase of decade-wise TC frequency that landfall on Bangladesh and negative changes of decade-wise mean DMI induces decrease of decade-wise TC frequency that landfall on Bangladesh (see Figure 19).

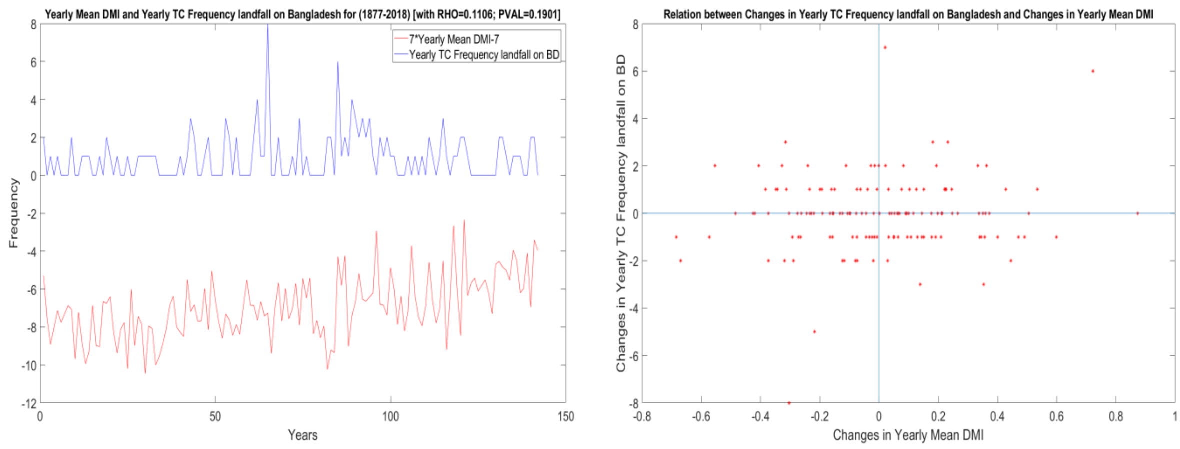
But there is no such trend in yearly counts of mean DMI and TC frequency that landfall on Bangladesh (Figure 20). It seems that the change of mean DMI value from negative to positive in 1960's may affect TC frequency of those TCs landfall on Bangladesh.

Due to lack of data of very few decades of having category 4 TCs, these approaches (Figure 21 – 22) got no logical evidence on support of the relation between decade-wise mean DMI and decade-wise category 4 TC frequency and so for yearly mean DMI and yearly category 4 TC frequency.



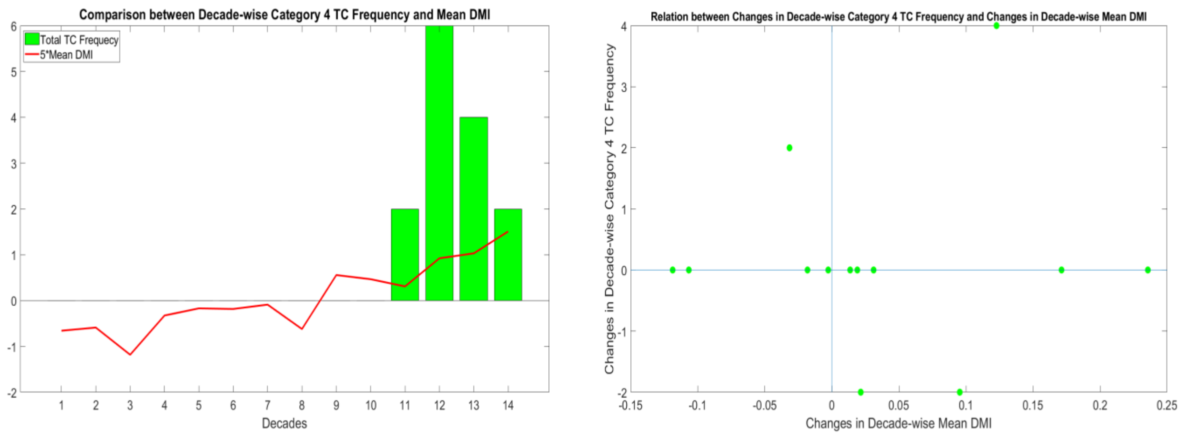
(a) (b)

Figure 19. (a) Comparing decade-wise mean DMI line (blue) with decade-wise TC frequency that landfall on Bangladesh (red); (b) Changes of decade-wise TC frequency that landfall on Bangladesh against the changes of decade-wise mean DMI.



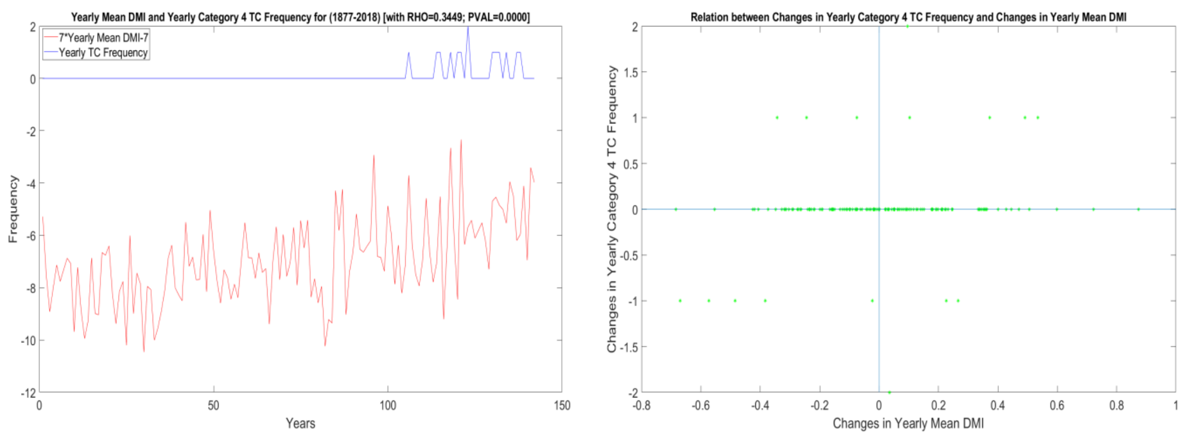
(a) (b)

Figure 20. (a) Yearly mean DMI (red) vs. yearly TC frequency in BoB that landfall on Bangladesh (blue); (b) Changes of yearly TC frequency that landfall on Bangladesh against the changes of yearly mean DMI.



(a) (b)

Figure 21. (a) Comparing decade-wise mean DMI line (red) with decade-wise category 4 TC frequency (green); (b) Changes of decade-wise category 4 TC frequency against the changes of decade-wise mean DMI.



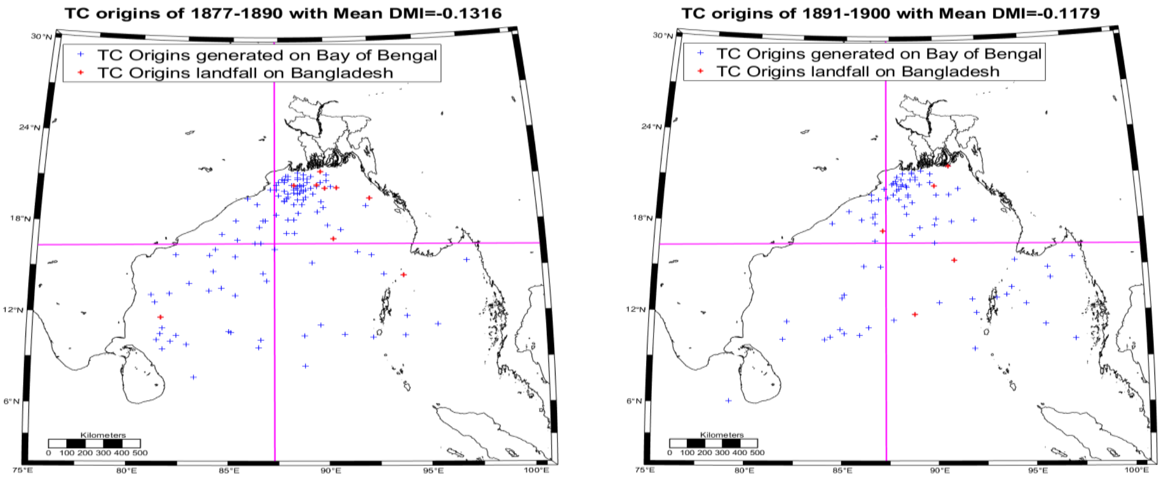
(a) (b)

Figure 22. (a) Yearly mean DMI (red) vs. yearly category 4 TC frequency in BoB (blue); (b) Changes of yearly category 4 TC frequency against the changes of yearly mean DMI.

According to the study of [3], TCs intensity is increasing during positive IOD events (the years having positive DMI values). Figure 21 is showing similar result that category 4 TCs are producing after 1981 while decade-wise mean is positive since 1960s. Also, most of the category 4 TCs are from 1990s when DMI had its maximum than ever recorded.

4.2. Behavior of TCs Origins of Genesis of Bay of Bengal with respect to Decade-wise Mean DMI

By follow Figure 23a – 23c with Table 8, TC origins have been mostly generated in 1st, 2nd and 3rd quadrants for negative decade-wise mean DMI values and more the mean DMI increases number of TCs origins of genesis increases in 4th quadrant. For negative decade-wise mean DMI values, very few TCs origins of genesis that landfall on Bangladesh have generated in 4th Quadrant.



(a) (b)

Figure 23a. Distribution of TCs origins of genesis of BoB in the Quadrant frame for (a) (1877-1890) and (b) (1891-1900).

For positive decade-wise mean DMI values, most of TCs origins of genesis have generated in 4th, 1st and 3rd quadrants. For positive decade-wise mean DMI values, most of the TC origins that landfall on Bangladesh have generated in 4th Quadrant and only few have been generated in 1st and 3rd. Therefore, it seems that TC origins have tendency to generate more from middle or eastern part of Bay of Bengal in a decade with positive mean DMI and on the other hand, have tendency to generate more from western part of Bay of Bengal in a decade with negative mean DMI. These tendencies can be found within one decade also. Since decade-wise mean DMI of 1960s have been changed from negative to positive within this decade, both positive and negative effects work. Therefore, having both tendencies may be the reason of having TCs origins generated from 1st, 3rd and 4th quadrants more than any other decades (see Figure 23c).

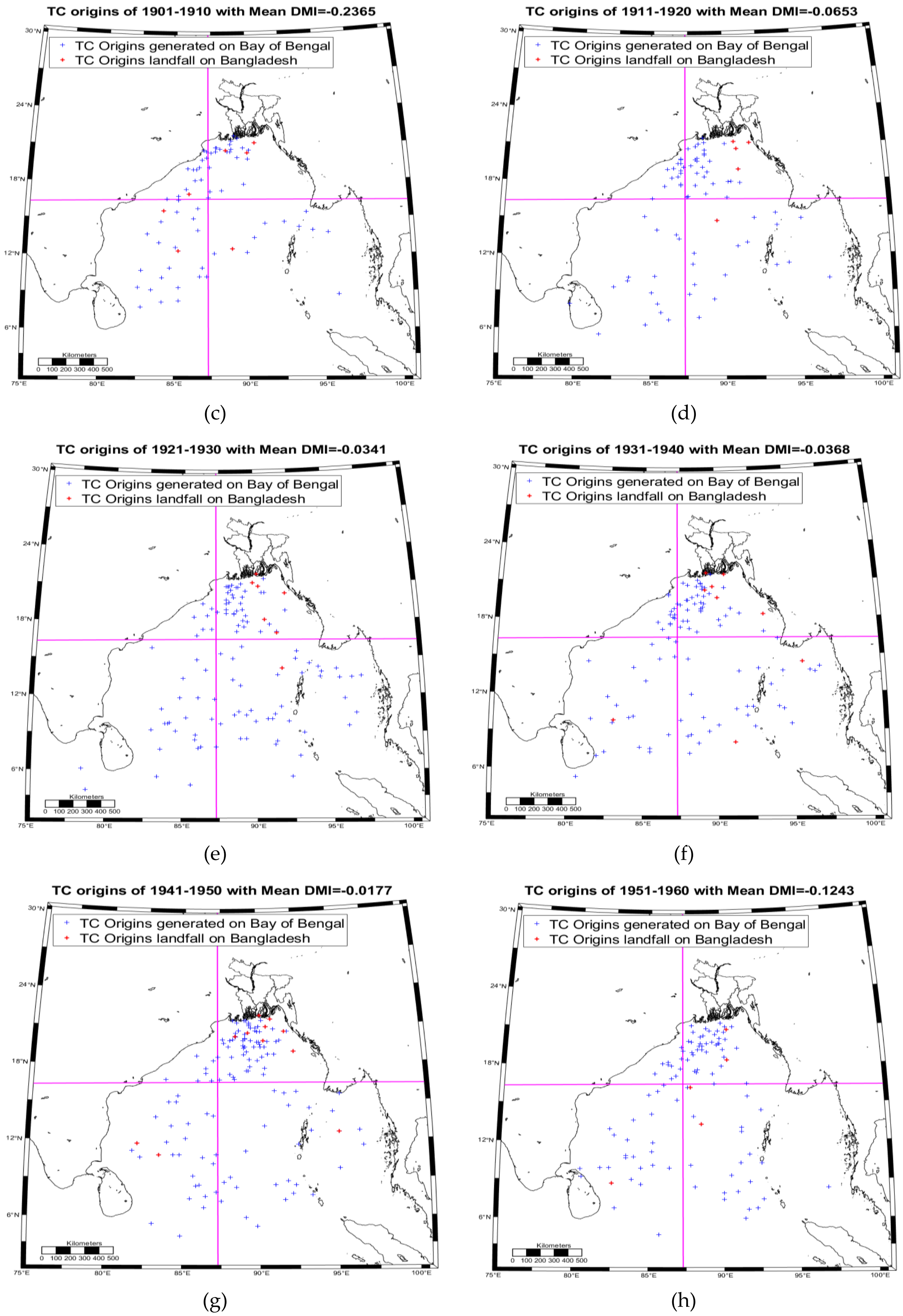


Figure 23b. Distribution of TCs origins of genesis of BoB in the Quadrant frame for (c) (1901-1910); (d) (1911-1920); (e) (1921-1930); (f) (1931-1940); (g) (1941-1950); (h) (1951-1960).

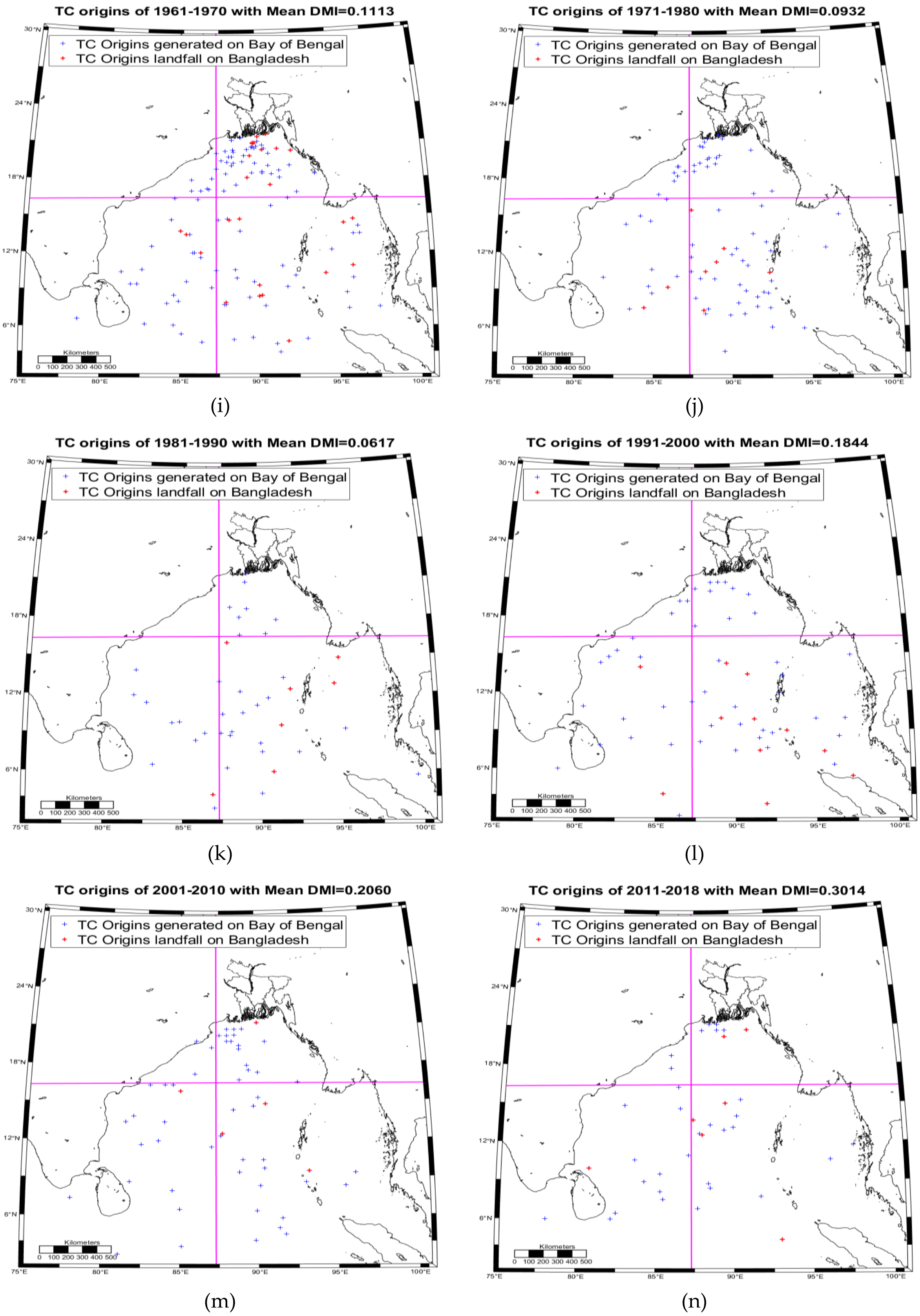


Figure 23c. Distribution of TCs origins of genesis of BoB in the Quadrant frame for (i) (1961-1970); (j) (1971-1980); (k) (1981-1990); (l) (1991-2000); (m) (2001-2010); (n) (2011-2018).

Table 8: Distribution of TCs origins of genesis (All: for all TCs; BD: for TCs that landfall on Bangladesh) of BoB in the reference Quadrant

Decades	Decade-wise Mean DMI	No. of TCs origins of genesis in 1st Quadrant		No. of TCs origins of genesis in 2nd Quadrant		No. of TCs origins of genesis in 3rd Quadrant		No. of TCs origins of genesis in 4th Quadrant	
		All	BD	All	BD	All	BD	All	BD
1877-1890	-0.1316	80	7	12	0	27	1	14	1
1891-1900	-0.1179	46	2	12	1	13	0	17	2
1901-1910	-0.2365	24	3	15	1	22	2	11	1
1911-1920	-0.0653	33	5	15	0	15	0	17	2
1921-1930	-0.0341	44	7	7	0	25	0	39	1
1931-1940	-0.0368	45	7	14	0	20	1	27	2
1941-1950	-0.0177	67	11	7	0	29	2	27	1
1951-1960	-0.1243	47	2	11	0	25	1	21	2
1961-1970	0.1113	50	12	8	0	24	3	39	12
1971-1980	0.0932	18	0	8	0	11	2	39	6
1981-1990	0.0617	8	0	0	0	11	1	22	6
1991-2000	0.1844	11	0	4	0	15	2	28	9
2001-2010	0.2060	19	1	6	0	13	1	20	3
2011-2018	0.3014	7	2	3	0	12	1	16	4

4.3. Trends of TCs Origins of Genesis Landfall on the Coast of Bangladesh

In (1971-2018) period, decade-wise mean DMI is positive (Figure 16(b)). For positive Decade-wise Mean DMI, TC origins landfall on Bangladesh are generating from Middle or Eastern part of Bay of Bengal and Most of them are from 4th Quadrant (Southeast part of BoB) and landfall on the coasts of Barishal and Chittagong (Chattogram) (see Figure 24). Almost all Category 4 TCs have been generated on 4th Quadrant (Figure 24-25). Most of the TCs that landfall on the coast of Sundarban were generated during decades having negative mean DMI (Figure 25).

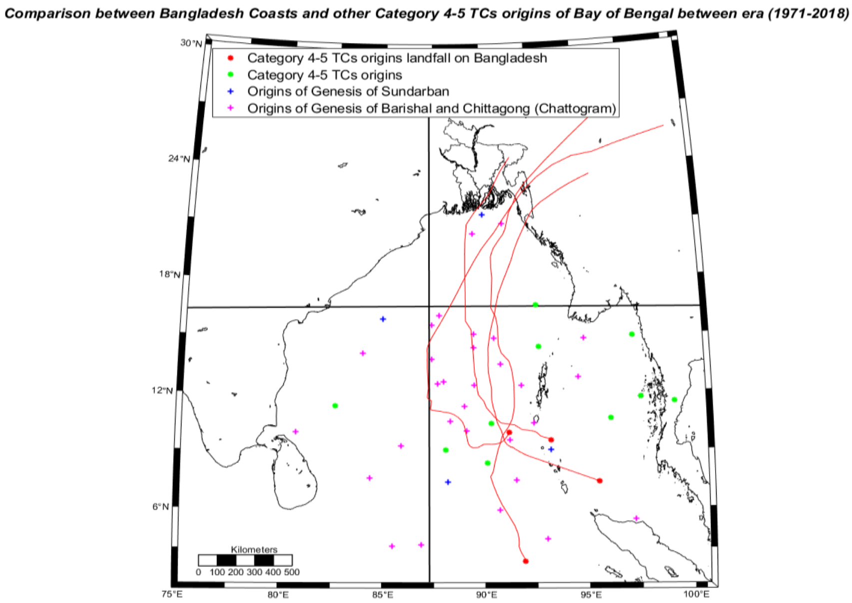


Figure 24. Comparison between TCs origins of genesis that landfall on Bangladesh and category 4-5 TCs origins of genesis of BoB for (1971-2018) era.

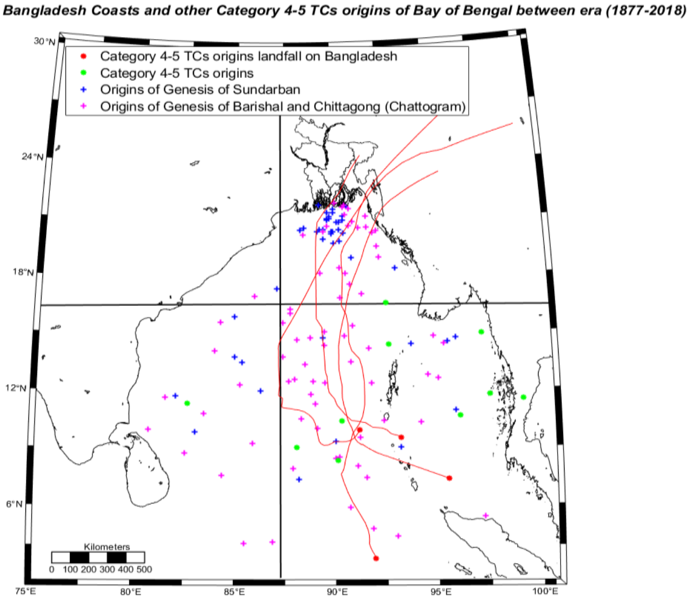


Figure 25. Comparison between TCs origins of genesis that landfall on Bangladesh and category 4-5 TCs origins of genesis of BoB for (1877-2018) era.

5. Discussion

In this study, a better correlation has been found of TC frequencies with DMI on two cyclone seasons (April-May and September-October). Then, correlation between IOD and TC frequency is very significant in decadal scale than yearly. Decade-wise positive changes in TC frequencies (both of total TC frequency and TC frequency landfall on Bangladesh) of BoB is identified due to decade-wise positive changes in DMI and also decade-wise negative changes in TC frequencies (both of total TC frequency and TC frequency landfall on Bangladesh) of BoB is identified due to decade-wise negative changes in DMI. Positive decade-wise mean DMI values may affect the TC intensity as category 4 TCs are happening since 1980's and for higher Maximum peak of DMI within (1991-2000) category 4 TCs frequency increased. The change of decade-wise mean DMI value from negative to positive in 1960's may affect TC frequency of those TCs landfall on Bangladesh. The decade might have both negative IOD and positive IOD effect.

TC origins of genesis have tendency to generate more from middle or eastern part of Bay of Bengal in a decade with positive mean DMI and on the other hand, have tendency to generate more from western part of Bay of Bengal in a decade with negative mean DMI. Almost all category 4 TCs have been generated on 4th quadrant (southeastern part of BoB).

Since decade-wise mean DMI is holding positive values in this current decade (2011-), continuation of similar approaches are expected from TCs as it was for last few decades (1971-2018). That is, most of the nearest future TCs might generate from Middle or Eastern part of Bay of Bengal. More category 4-5 TCs might generate frequently. Most of the TCs that landfall on Bangladesh might hit the Coast of Barishal and the Coast of Chittagong (Chattogram). This research can be extended using predicted DMI values to figure out decadal scenario of TCs of BoB that landfall on the coast of Bangladesh.

Bangladesh Meteorological Department (BDM) is the responsible authority to issue cyclone warnings and weather forecasting of Bangladesh. Cyclone Preparedness Program (CPP) usually receive those warnings from BMD and have responsibilities to warn people in different ways, call them to evacuate for shelters, give first aids, search and rescue and more interactive steps between BMD and people of the coast of Bangladesh since 1972 [14]. To implement 6th National Disaster Management Plan 2010-2015 (NDMP 2010-2015) of Bangladesh [2], a new division named Division of Disaster Management (DDM) has been made by using Act-2012 [15]. Now-a-days, DDM is playing a major role to reduce risk from cyclones under the Ministry of Disaster Management and

Relief of the government of Bangladesh. Building new cyclone and flood shelters, bridges and culverts etc. are some preparedness of DDM. A group of researchers are working with DDM to assess risks of different disasters and collaborate with policy makers. In the 7th National Disaster Management Plan 2016-2020 (NDMP 2016-2020) [10], understanding disaster risk has been given the highest priority to build resilience in all sectors of disasters. To understand risks from different disasters, national and international researchers have been called to collaborate.

Our study is basically indicating higher risk of having more frequent category 4-5 cyclones in upcoming decades and may landfall on the coast of Bangladesh since TCs that landfall on Bangladesh have the trend of generating from the same part of BoB from where category 4 TCs are generating historically. Also, the coast of Barishal and the coast of Chittagong are more vulnerable than the coast of Sundarban from TCs in upcoming decades. These understandings of risks from cyclones might be a good source for the authority of Bangladesh for taking necessary steps to reduce the risk in near future. Of course, reliable prediction of DMI is recommended before taking upcoming decade's scenario of this research.

Further, other climate driver's correlation with TCs genesis on BoB should also be investigated. Climate changing effects on different climate drivers can be counted and thus climate change effect can be followed on TCs that landfall on the coast of Bangladesh. To assess the climate change effect on tropical cyclones the whole Indian Ocean basin should be investigated including South Indian Ocean, Arabian Sea and Bay of Bengal. Different reference framework should also be investigated instead of quadrant framework to follow changes of origins of TCs genesis. More study needed for physical explanations mentioning relation between Indian Ocean Dipole (IOD) and Bay of Bengal.

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Conflicts of Interest: The authors declare no conflict of interest.

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