

The relationship between sea surface temperature and formation of tropical cyclone in the Bay of Bengal

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Abstract: The influence of Sea Surface Temperature (SST) on tropical cyclone formed in the Bay of Bengal was examined, using 314 months (November 1981-December 2007) of National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation version 2 weekly mean SST data. The study area was from 5.5-21.5°N to 80.5-95.5°E; with a total 272 grid points at 1° × 1° grid spans were found. 162 disturbances were formed over the Bay of Bengal. 91 were cyclones, among these cyclones 38 were cyclonic storms (CS), 23 were severe cyclonic storms (SCS), 28 were very severe cyclonic storms (VSCS) and 2 were super cyclones (SC). More than 86% cyclones are formed in the observed months having positive SST anomalies. The average of the contemporaneous SST at the formation time of CS, SCS, VSCS and SC was 28.93, 29.08, 29.27 and 29.41°C, respectively. The most active zone for powerful cyclone (VSCS and SC) formation is located within area-3 (7.5°N ≤ latitude < 13.5°N) where the temporal average SST is high (around 28.70°C) and the rate of declining temperature with increasing latitude is nearly constant (0.01°C/latitude). The formation of SCS, VSCS and SC starts after 27.50°C and increases with increasing SST but discontinuously. The intensity of cyclone has a step-like rather than continuous relationship with SST.

Key words: Tropical cyclone, Sea surface temperature, Bay of Bengal and Seasons.

1. Introduction

Bangladesh, a South Asian country, is a densely populated country with 1099/km². The coastal area of Bangladesh is one of the most hazardous coasts in the world in terms of the number of people who suffer from various types of environmental hazards every year.

Among the diversity of environmental perils the cyclone is one of the most perilous types of disaster. Due to the scarcity of data, overall scientific research in Bangladesh particularly relating to cyclone is inadequate. 19 coastal districts, covering 32% area and about 33% of the total population of Bangladesh, are the cyclone prone area. The coastal area is flat low-lying land having altitude less than 3m from the mean sea level. The climate of Bangladesh is a part of the humid tropics with the Himalayas lying in the north and the funnel shaped coast touching the Bay of Bengal in the south. Owing to the funnel shaped coast of the Bay of Bengal, the cyclones formed in it frequently make landfall on the coastal area of Bangladesh. The cyclones formed in the Bay of Bengal also move towards the eastern coast of India, towards Myanmar and sporadically into Sri Lanka. The cyclones cause the maximum damage when they come into Bangladesh and north-eastern coast of India (Tahmeed et al. 2005). This is because of the low flat terrain, high density of population and mostly tin-shed and thatched houses.

The working and maintenance of the tropical cyclones (TCs), the most destructive of all the natural disasters, is still a puzzle. The genesis and development of this magnificent heat engine is being pondered by atmospheric scientists from many years. TC genesis is one of the few atmospheric processes that are poorly understood. The climatological conditions under which tropical cyclones occur have now been well established over decades of research. The importance of monsoon circulations in determining tropical cyclone characteristics is related to the six primary environmental factors defined by Gray (1968, 1975) to be favorable for tropical cyclone formation. These include (i) large values of low-level cyclonic relative vorticity, (ii) a location that is at least a few degrees pole-ward of the equator, (iii) weak vertical wind shear, (iv) large values of relative humidity in the lower and middle troposphere, (v) conditional instability throughout a deep tropospheric layer, and (vi) sea surface temperature (SST) above 26°C. The existence of such conditions is common in the tropics. Several recent publications (Emanuel 1987, 2000, and 2005) have shown that the intensity of TC is linked with rising SST. It is well established that SST greater than 26°C is a requirement for TC formation in the current climate (Palmen 1948). Webster et al. (2005) found an increase trend in tropical cyclone number, duration and intensity with increasing SST in North Indian Ocean basin. All these research have fueled the debate on whether warming environment is causing an increase in intensity of TC. Mark and Adam (2008) used a statistical model to disentangle the two main hurricane predictions - SST and near-surface trade wind speed. These two variables

together explain about 80% of the variance observed in tropical Atlantic hurricane activity between 1965 and 2005. Their result indicates that 0.5°C increase of SST in August – September SST, an average 40% increase in hurricane activity, a measure including both number and severity of storms. Their study showed that if the SST increases by 2°C by 2100 AD, maximum wind speeds of hurricanes could increase by 63%, with damage from hurricanes rising in proportion to the cube of the wind speed. This is because the warm ocean water provides sensible heat and water vapor that fuels the intense convection of a hurricane, and assists the conversion of a depression to a cyclone.

Jadhav and Munot (2008) examined the intensity as well as duration of low pressure system (LPS) in association with the increasing SST in the Bay of Bengal. They classified LPS into two categories, viz.: (1) only low-pressure areas (LPA) and (2) more intense systems like depressions/storms (DDS). They found that the frequency and duration of LPA (DDS) during the monsoon season are positively (negatively) correlated with SSTs of the Bay of Bengal during winter, pre-monsoon and monsoon season indicating warmer SST of the Bay of Bengal may not be favorable for intensifying lows into depressions. Sujata and Bhide (2003) found decreasing trend of storm frequency on decadal scale with the increase of SST during monsoon season over Bay of Bengal. They used monthly mean SST data which may obscure associations between tropical cyclone and the actual SST over which the storm exists.

Research has been done on the frequency of cyclones as well as intensity with SST of different oceans, such as Atlantic Ocean, Indian Ocean, North Indian Ocean etc. But the relationship between the SST of the Bay of Bengal and cyclones which were formed and made landfall around the coastal region of Bangladesh is investigated inadequately. The aims of this study were to see the relationship between SST and formation of tropical cyclone as well as to find the prone area of powerful cyclone formation.

2. Data and methods

In this study the tropical cyclone data during 1981-2007 have been taken from Bangladesh Meteorological Department (BMD) to assess the variability of tropical cyclone intensity. Initial location coordinates (latitude/longitude) for all the tropical disturbances developed in the Bay of Bengal during the above mentioned period are tabulated. The intensity of tropical disturbances is defined depending on the maximum wind speed. The tropical disturbances are subdivided into tropical depression (wind speed < 61 km/h), cyclonic storm (CS, 62 km/h \leq wind speed ≤ 88 km/h), severe cyclonic storm (SCS, 89 km/h \leq wind speed ≤ 117 km/h), very severe cyclonic storm (VSCS, 118 km/h \leq wind speed ≤ 220 km/h) and super cyclone (SC, wind speed > 220 km/h). The data of tropical disturbances as well as the SST are tabulated season wise, namely pre-monsoon (March, April and May), monsoon (June, July, August and September), post-monsoon (October and November) and winter (December, January and February). The weekly mean SST dataset are collected from the National Oceanic and Atmospheric

Administration Climate Data Center. SST has taken by matching the year, month, week and position (latitude and longitude) of the cyclone. The study area have been taken from 5.5 - 21.5°N and 80.5 - 95.5°E which is shown in the Fig. 1; from that area at 1° interval of latitude and longitude total 272 observation grid points for SST are obtained. Spatial and temporal averages of the SST data are prepared. To find SST anomaly, long term spatio-temporal average SST has deducted from contemporaneous (during the formation of cyclone) SST. For analysis purpose the study area has been subdivided into 3 areas (Fig.1), namely, area-1 ($17.5^{\circ}\text{N} \leq$ latitude $< 21.5^{\circ}\text{N}$), area-2 ($13.5^{\circ}\text{N} \leq$ latitude $< 17.5^{\circ}\text{N}$) and area-3 ($7.5^{\circ}\text{N} \leq$ latitude $< 13.5^{\circ}\text{N}$).

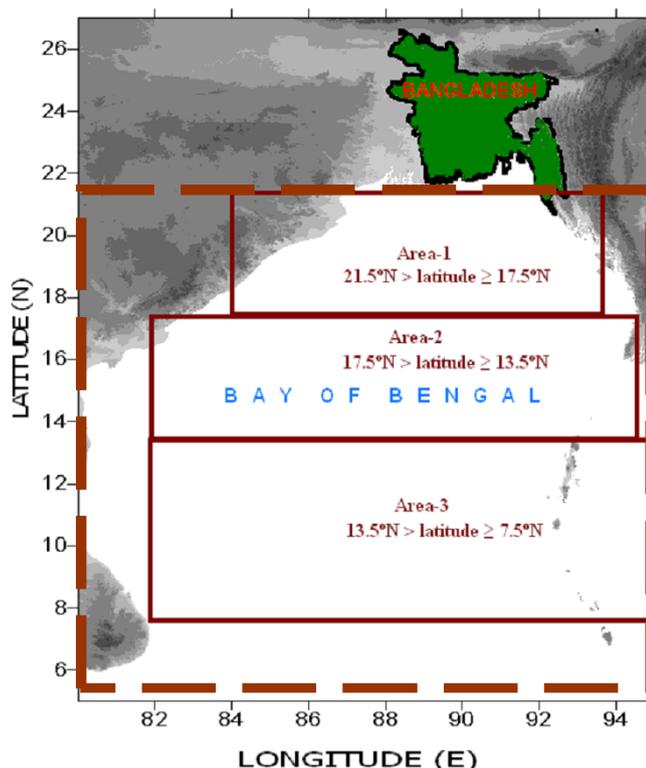


Fig. 1: Rectangular dash box in the regional map showing the study area of 5.5 - 21.5°E , 80.5 - 95.5°E . Three rectangular solid boxes in regional map showing the regions of interest.

3. Results and discussion

During the study period (1981-2007) 91 cyclones formed in the Bay of Bengal, among them 16 (18%) cyclones made landfall in the coastal region of Bangladesh. 12 (75%) of the land falling cyclones were life snatching. Fig. 2 shows the comparison of temporal average SST with the contemporaneous average SST at the formation location of CS, SCS and VSCS and SC. It is found that the average of the temporal average SST was 28.32°C with standard deviation 0.36°C at the formation location of CS. The average of the contemporaneous SST at the formation time of CS was 28.93°C . It is observed that the overall increase of SST during tropical cyclones was 0.60°C . At the time of CS formation the SST increased 0.61°C from the temporal average value of SST. Highest contemporaneous average SST, 29.28°C , was found at the time of formation of VSCS and SC which are most powerful cyclones. At this time the increment of SST was 0.63°C from the temporal average SST.

Fig. 3a shows the monthly distribution of SST anomalies of the Bay of Bengal. The positive anomalies were in the months from April to November. On the other hand, negative anomalies were in the months from December to March. In the positive anomalies there were two peaks, one major peak was in the month of May and another minor peak in October. In May and October the SST were 5% and 1% more than the average spatial SST, respectively. The highest negative anomaly was found in January. The value of SST was 6% less than the average spatial SST. Fig. 3b shows that the highest occurrence of cyclones was in the month of November. In this month cyclone formation was 33% (30 out of 91) of the total cyclones. In the Fig. 3b two peaks were found, one major peak was in the month of November and the other minor peak was in May.

From Fig. 3 it is found the percentage of cyclone formation in the month of minor positive peak SST anomaly (Fig. 3a) was 18% (16 out of 91) whereas 14% (13 out of 91) cyclones formed on the month of highest positive peak SST anomaly (Fig. 3a). On the other hand in the highest negative SST anomaly month which was in January, the number of cyclones formation was 1% (1 out of 91) of the total cyclones. There were 4 months (December, January, February and March) having negative SST anomalies. During that 4 months 14% (13 out of 91) of the total cyclones were formed and in last 3 months (January, February and March) only 3% (3 out of 91) cyclones were found.

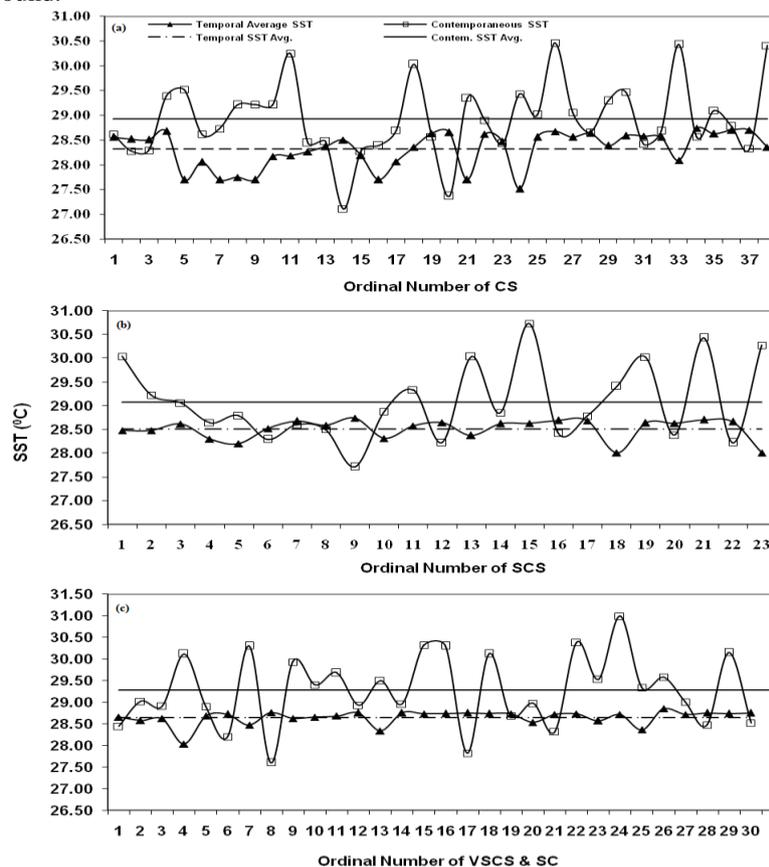


Fig. 2: Comparison of temporal average SST and contemporaneous average SST at the (a) Cyclonic Storm (CS) (b) Severe Cyclonic Storm (SCS) and (c) Very Severe Cyclonic Storm (VSCS) and Super Cyclone (SC) formation location.

Table 1 shows the seasonal distribution of tropical cyclones, their duration and average spatial SST. From this Table it is clear that the formation of SCS and VSCS were dominated during pre-monsoon and post-monsoon periods. The SST was 28.85°C (28.79°C) with standard deviation 0.21°C (0.22°C) in the pre-monsoon (post-monsoon) period. During pre-monsoon period 17 cyclones were formed, 3 of them were CS, 5 were SCS, 8 were VSCS and the rest 1 was SC. In the post-monsoon period 46 cyclones were formed, 17 of them were CS, 12 were SCS, 16 were VSCS and 1 was SC. The SST was the highest (lowest), 28.93°C (27.17°C) with standard deviation 0.26°C (0.25°C), in the monsoon (winter) season. During the monsoon period the number of total cyclones was 16, among them 13 were CS, 2 was SCS and 1 was VSCS. The number of tropical cyclone was the lowest in the winter season, 12 out of 91. In this season the number of CS was 5, SCS was 4 and VSCS was 3. The number of VSCS was the lowest, 4% (1 out of 28), during the monsoon period. From the Table 1 it is also found that the total cyclonic hours during the period 1981-2007 was 4858. In the post-monsoon period there were 53% (2909 hours out of 5449 hours) of the total cyclonic hours.

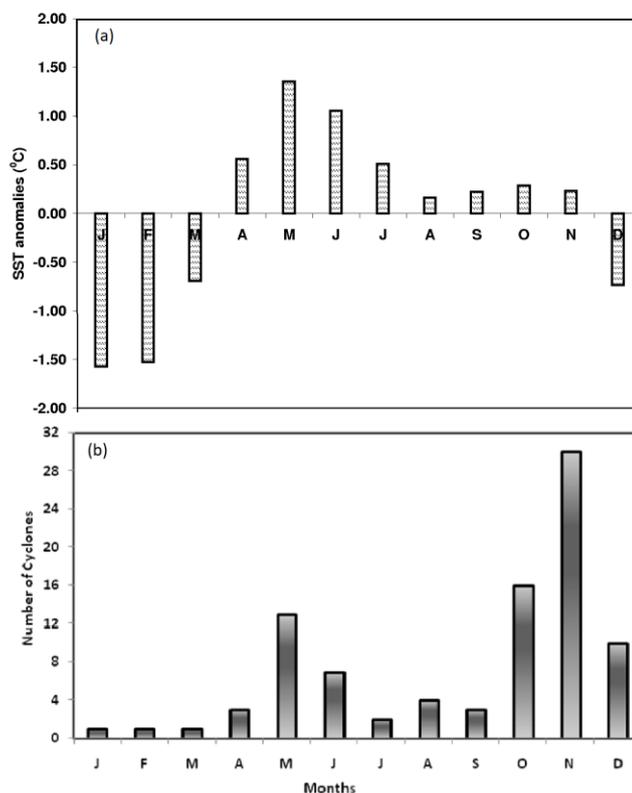


Fig. 3 (a) Monthly distribution of SST anomalies and (b) monthly distribution of 91 Cyclones formed over the Bay of Bengal during 1981-2007.

Table 1 Various types of tropical cyclones, formed in the four seasons within 1981-2007, their total number, duration, seasonal mean SST and standard deviation of seasonal mean SST

		Seasons				Total	
		Winter	Pre-monsoon	Monsoon	Post-monsoon		
Cyclones	CS	Number	5	3	13	17	38
		Duration (hour)	255	105	324	1042	1756
	SCS	Number	4	5	2	12	23
		Duration (hour)	201	351	150	615	1317
	VSCS	Number	3	8	1	16	28
		Duration (hour)	264	680	65	1147	2156
	SC	Number	0	1	0	1	2
		Duration (hour)	0	115	0	105	220
Total	Cyclone	12	17	16	46	91	
	Duration (hour)	720	1251	569	2909	5449	
SST (°C)		27.17	28.85	28.93	28.79		
Standard deviation of SST (°C)		0.25	0.21	0.26	0.22		

It is found that the formation of SCS, VSCS and SC were lower at the lowest (27.17°C in winter) and highest (28.93°C in monsoon) SST, than that of SST in between (28.85°C in pre-monsoon and 28.79°C in post-monsoon). Although SST was the highest in the monsoon period, tropical cyclones generally were less observed. This is due to the fact that the monsoon trough is generally located to the north over land during summer (Frank 1987). Hence, the required dynamical conditions, relative vorticity and vertical wind shear, for tropical cyclone formation (Gray, 1979) are not satisfied.

The temporal average SST within the study period is shown in Fig. 4a; the SST remained nearly constant along longitude but decreased towards the higher latitude. In the lower latitudinal area-3 ($7.5^{\circ}\text{N} \leq \text{latitude} < 13.5^{\circ}\text{N}$) 72% (21 out of 29) VSCS were found as shown in Fig. 4b. On the other hand 14% (6 out of 44) depressions were formed within the same region. The disturbances which were formed within the area-3 had much probability to convert into VSCS. Above the area-3, 86% (38 out of 44) depressions were formed. The disturbances which were formed above the area-3 had less probability to convert into VSCS. So it is found that the formation of VSCS was higher in area-3 where the SST was higher and the formation of VSCS decreased along the direction of higher latitude where the SST comparatively lower.

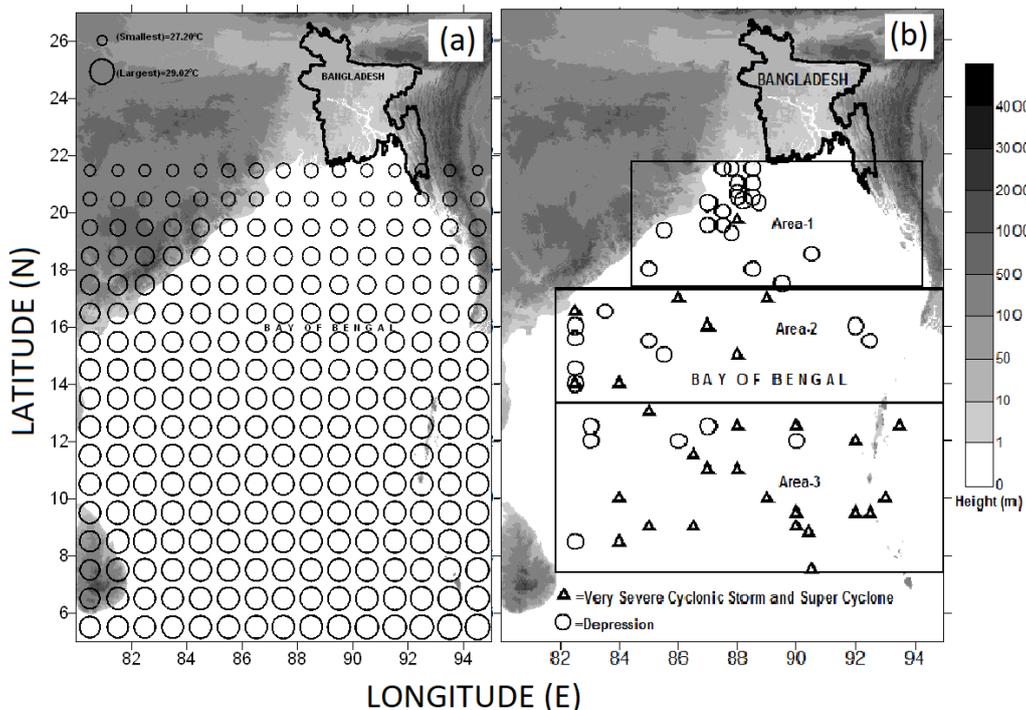


Fig. 4 (a): Temporal average sea surface temperature of 272 observation points (17 latitude points for each longitude points, i.e. $17 \times 16 = 272$). **(b)** Initial location of very severe cyclonic storm (triangle) and depression (circle). Gray shade indicates the topography in meter.

The behavior of SST did not change significantly with longitude (Fig. 4a), whereas the changing behavior of SST was found with respect to latitude (Fig. 5a). It illustrated that from higher to lower latitude, which is toward the direction of the equator, the SST increased. Within area-3 the average temporal SST remains nearly constant around the value of 28.70°C during the study period. It is found that there was no VSCS and SC before 7.5°N latitude; even though the SST was higher but may be due to the lack of Coriolis force there was no VSCS and SC (Fig. 4b). Moreover it is found that 45% (13 out of 29) VSCS and SC formed within 7.5°N – 10.5°N of area-3 and only 2% (1 out of 44) depressions formed in this region. After 12.5°N , the decreasing trend of SST was higher with respect to the higher value of latitude. Within area-2 there were 24% (7 out of 29) VSCS and SC and the percentage of formation of depressions were 23% (10 out of 44). Within area-1 only one VSCS (3%) was formed, on the other hand the formations of depression were 64% (28 out of 44). Hence area-1 with average temporal SST 27.75°C was favorable for the formation of depressions and the formation of VSCS and SC within the area-3 around the average temporal SST 28.70°C was favorable.

Within the study period there were 13 disturbances, whose duration was more than 100 hours. The total duration of the above mentioned 13 disturbances was 1589 hours, these disturbances spent 50% (801 h) of their lifetime within the area-3, where the rate of change of temperature was nearly constant ($0.01^{\circ}\text{C}/\text{latitude}$) with respect to increasing latitude. 42% (666 h) of their lifetime of the disturbances used up within area-2, where the declination of temperature with respect to increasing latitude was remarkably more, $0.22^{\circ}\text{C}/\text{latitude}$, than the area-3. Only 8% (122 h) of their lifetime consumed within area-1, the declivity of SST was the highest, $0.36^{\circ}\text{C}/$

latitude, inside this area. When the disturbance remained in area-3 it received nearly constant heat supply. When the cyclone forwarded toward the area-2 and area-1 the decreasing rate of temperature gradually increased.

It is found from Fig. 5b that 59% (17 out of 29) of VSCS and SC got highest wind speed in area-1. Within area-2, 28% (8 out of 29) of the VSCS and SC reached highest speed. Only 4 out of 29 (14%) achieved their highest wind speed within 11-12.5°N latitude of area-3. So area-3 was the region where the SST remained highest and nearly constant. The formation of VSCS and SC and the retention time (Table 2) of the disturbances were also highest within this area. At the initial stage the speed of the disturbance remains less, so the consumption of heat energy from the reservoir, of nearly constant and higher SST, remains lower. As the heat acts as fuel for cyclone, may be due to adequate heat energy the cyclone survives more time when it stays in area-3. As the disturbance moves to the higher latitudinal direction the speed gradually increases (Fig. 5b) but the SST declines (Fig. 5a). As the SST dwindles the heat energy also wanes. It may be due to the augmentation of wind speed the supplied energy does not cope up with the burning up of heat energy, for this reason highest numbers of cyclones die out within area-1.

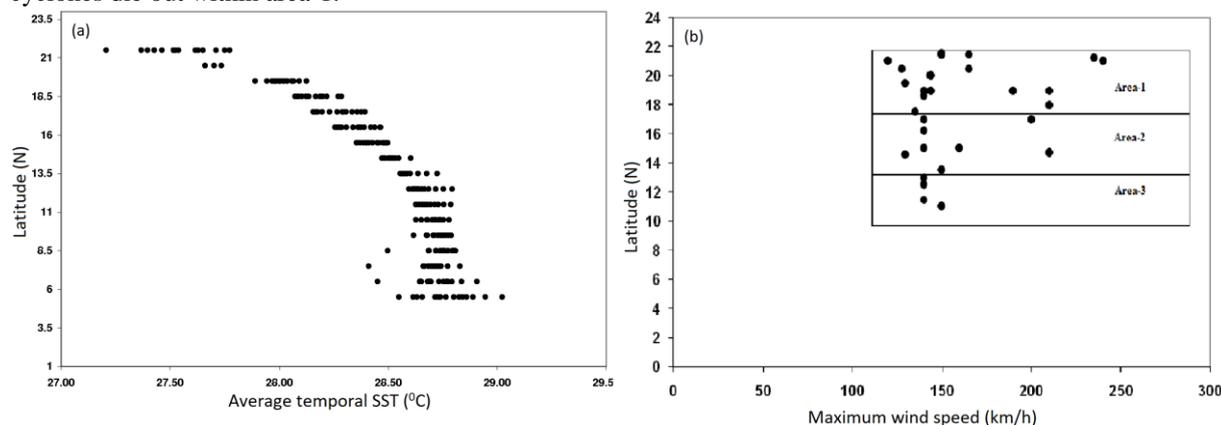


Fig. 5 (a): Variation of average temporal SST and **(b)** Variation of maximum wind speed of VSCS and SC with respect to latitude.

Table 2: Starting point, landfall or die out point and retention time in hour of the disturbances whose duration was more than 100 hours in three different regions

Starting		Disturbance duration (hours)	Duration in area-3 (hours)	Duration in area-2 (hours)	Duration in area-1 (hours)	Just before Landfall/Die out	
Lat(°N)	Lon(°E)					Lat(°N)	Lon(°E)
8.5	85.0	186	150	36	0	17.0	91.0
15.0	89.0	118	--	118	0	15.0	82.0
13.0	87.0	129	--	129	0	17.2	91.5
10.0	90.0	102	102	0	0	12.7	82.5
11.0	87.0	132	54	42	36	21.2	89.0
7.0	89.0	180	75	105	0	15.0	84.0
9.0	86.5	102	72	30	0	15.0	80.3
10.0	93.0	111	72	27	12	20.5	89.0
10.0	84.0	102	63	39	0	15.8	80.5
10.0	89.0	115	51	36	28	22.3	91.8
9.5	92.5	105	36	38	31	21.5	92.5
9.5	90.0	102	66	36	0	16.5	92.8
9.5	92.0	105	60	30	15	21.0	89.3

Scatter plots are compiled by matching the year, month, week and position of each cyclone first attained its maximum intensity with the corresponding SST. In this study the relationship between SST and intensity of cyclone is not straightforward, similar results also shown in a study of Patrick et al. (2006). But in studies of Evans (1990), Baik and Peak (1998) showed that the peak in intensity occurring below the maximum SST of the cyclones formed in the North Atlantic Ocean. It was found from the Fig. 6 that there was no VSCS below the SST of 27.44°C and after the SST of 30.34°C. Fig. 6 shows that the cent percent of the cyclones got their highest wind speed within the temperature range 28.00°C to 29.50°C. There were 7 tropical cyclones with maximum wind speed ≥ 200 km/h; 86% (6 out of 7) of them attained uppermost wind speed within the temperature range from 28.00°C to 29.50°C. After 29.50°C the intensity of the maximum wind speed depicted decreasing trend, except one cyclone got its maximum wind speed, 240 km/h, at 30.22°C. There were 20 cyclones within the temperature range 30.50°C \geq temperature > 29.50°C. 50% (10 out of 20) of those cyclones got the maximum

wind speed ≤ 100 km/h, 40% (8 out of 20) cyclones were within the speed range $150\text{km/h} \geq \text{wind speed} > 100\text{km/h}$ and only 10% (2 out of 20) cyclones crossed 150km/h at its maximum wind speed. This suggests the existence of a temperature dependency but not a continuous positive relationship between maximum storm intensity and SST.

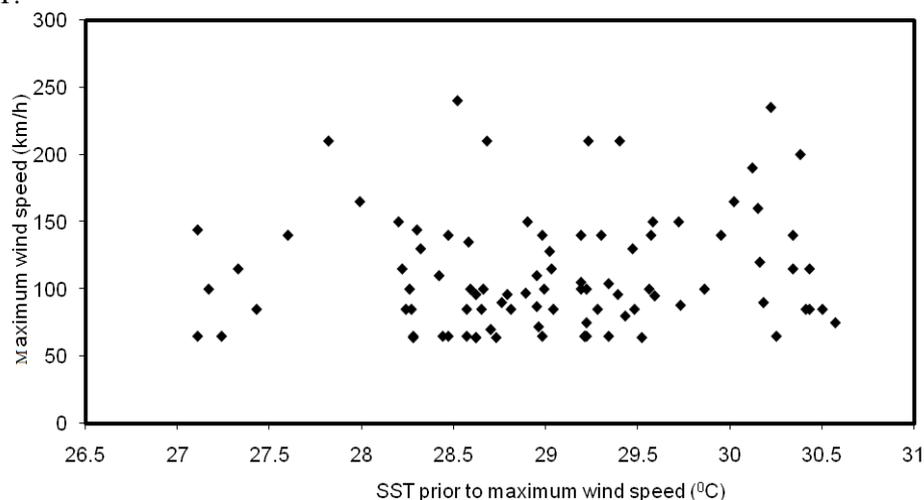


Fig. 6: The relationship between maximum wind speed and SST encountered prior to reaching the maximum wind speed.

From Table 3 it is clear that the formation of VSCS and SCS started after SST of 27.50°C and increased with SST. The formation of VSCS decreased for SST from 29.00°C to 29.50°C after that increased with SST. So it revealed that the intensity of cyclone has a step-like, rather than continuous relationship with SST.

Table 3: Comparison among the number of various types of cyclones at 0.5°C temperature bins (starting from 26°C) with the total number of weeks remaining within that temperature bin.

Temperature bin($^{\circ}\text{C}$)	No. of total week	CS	% of CS	SCS	% of SCS	VSCS	% of VSCS
$26 < T \leq 26.5$	14	0	0.0	0	0.0	0	0.0
$26.5 < T \leq 27$	152	0	0.0	0	0.0	0	0.0
$27 < T \leq 27.5$	132	2	1.5	0	0.0	0	0.0
$27.5 < T \leq 28$	105	0	0.0	1	1.0	2	1.9
$28 < T \leq 28.5$	196	9	4.6	6	3.1	4	2.0
$28.5 < T \leq 29$	344	10	2.9	6	1.7	8	2.3
$29 < T \leq 29.5$	247	11	4.5	4	1.6	4	1.6
$29.5 < T \leq 30$	128	1	0.8	0	0.0	4	3.1
$30 < T \leq 30.5$	42	5	11.9	5	11.9	7	16.7
$30.5 < T \leq 31$	5	0	0.0	1	20.0	1	20.0

4. Conclusions

The influence of sea surface temperature (SST) on tropical cyclone formed in the Bay of Bengal was examined, using 314 months (November 1981-December 2007) of National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation version 2 weekly mean SST data and historical cyclone data obtained from Bangladesh Meteorological Department. At the formation location of CS, SCS, VSCS and SC the averages of the temporal average SSTs were 28.32°C , 28.51°C , 28.64°C and 28.74°C (showing increasing trends), respectively. During the time of formation of CS, SCS, VSCS and SC the averages of the contemporaneous SSTs were 28.93°C , 29.08°C , 29.27°C and 29.41°C , respectively.

The formation of SCS, VSCS and SC started after 27.50°C and increased with SST but discontinuously. In the months of negative SST anomalies (December, January, February and March) the formations of cyclones were lower. The intensity of cyclone has a step-like, rather than continuous relationship with SST. The area-3 (within $7.5^{\circ}\text{N} \leq \text{latitude} < 13.5^{\circ}\text{N}$) with the average temporal SST 28.70°C was the favorable atmosphere for the formation of VSCS and SC. On the other hand the average temporal SST 27.75°C within the area-1 (within $17.5^{\circ}\text{N} \leq \text{latitude} < 21.5^{\circ}\text{N}$) was the salutary environment for the formation of depression (D). It is seen that the SST increased two to four weeks prior the formation of a tropical cyclone.

The intensification probability from D to VSCS and SC were fluctuating except in April, the depressions which were formed in this month 100% of them intensified into VSCS and SC. The retention time of the disturbances

was also highest within the area-3. Results showed that, although SST was the highest in the monsoon period, tropical cyclones generally were less observed. This is due to the fact that the monsoon trough is generally located to the north over land during summer.

Hence, the required dynamical conditions, relative vorticity and vertical wind shear, for tropical cyclone formation are not satisfied. So, the SST is not found to be the only prevailing factor in determining the maximum storm intensity and there are others possible influences. The full reasons behind the observed changes remain an area of active scientific inquiry. So it is urged a precautionous approach to assigning an underlying cause in this complex system by using SST data with improved time resolution because the use of weekly SST data here may have veiled an association between the formation of severe tropical cyclone and the actual SST over which the storm exists.

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