An Overview of Tropical Cyclone Formation over the Bay of Bengal

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Abstract

Tropical Cyclone is characterized by a warm-core low pressure system at the centre called eye. It is often accompanied with strong gusty winds, torrential rains and storm surges which create great damage to life and property. The outer rain bands of the eye are made up of convective cells embedded in straight form rain. The horizontal shape of an outer rain band is generally prominent with equiangular spiral geometry but in the Bay of Bengal the eastern side band of the cyclone Sidr (2007) was a long, quasi-straight shape in the meridional direction that remained stationary relative to the cyclone centre. In fact, the Bay of Bengal experiences many differences in forming tropical cyclone. The formation of TC is bimodal and the post-monsoon cyclone frequency is almost double than that of pre-monsoon cyclone. Again, pre-monsoon environments are more favourable for cyclogenesis. So, it is very important to improve the understanding of the cyclone characteristics and monitor their intensity in the Bay of Bengal.

Keywords: tropical, wind, surges, rain band, Sidr, cyclogenesis.

Introduction

Amongst major natural hazards, tropical cyclone (TC) accompanied with strong gusty winds, torrential rains and storm surges is considered as a severe threat to human life, property and ecosystem. TC is defined by a warm-core low pressure system at the centre, called eye, which is characterized by little or no wind. The diameter of eye varies between 10 to 100 km. Surrounding of the eye consists of a wall having intense convective cloud of almost 15 km in height. The distinctive pattern of convective cloud bands spiralling into the eye wall is known as outer rain band (Fig.1). Most of the previous studies have noticed that the outer rain bands are made up of convective cells embedded in stratiform rain in which convective cells are found in the concave (inner) side and stratiform on the convex (outer) side of the band. (e.g. Barnes et al. 1983; Willoughby et al. 1984; Powell 1990).

Fig. 1 Structure of tropical cyclone

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The horizontal shape of an outer rainband is generally prominent with equiangular spiral geometry (Senn et al. 1957). But, in the Bay of Bengal (BoB), exception was found for the cyclone Sidr (2007) in terms of spiral shape and length of band (Akter and Tsuboki 2012). The eastern side band of Sidr was a long, quasi-straight shape in the meridional direction that remained stationary relative to the cyclone center. The band was composed of intense convective cells and the length of the band gradually increased with time as the cyclone moved north, and reached to the maximum length of ~800 km (Fig. 2).

![Fig. 2 Radar and satellite images of cyclone Sidr (2007)](image)

According to global cyclone frequency data, only 7% of TCs occur in the North Indian Ocean (NIO), among them the BoB experiences five to six times more cyclones than in the Arabian Sea (Neumann 1993). The BoB, located in the north of the Indian Ocean between 5°N to 22°N and 80°E to 100°E, is roughly triangular, bordered in the west by the east coasts of Sri Lanka and India, on the north by Bangladesh and on the east by Myanmar peninsula extended up to the Andaman and Nicobar ridges. The BoB is not only responsible for the formation of different shaped and strongest TCs in the world; it plays pivotal roles in the seasonal wind reversal of South Asian monsoons. A strong south westerly (SW) prevailing wind transports enormous moist and warm air masses from the BoB to the land in the summer (June-September), while dry and cool north easterly (NE) flows occur in the opposite direction, i.e., from the land to the BoB, during the winter (January-February). The South Asian pre-monsoon (March-May) and post-monsoon (October-December) seasons, which are significant for cyclogenesis, are the transition periods between the summer and winter monsoons (Ramage 1971; Das 1995). It is mentionable that the BoB experiences the southwest monsoon in early May, earlier than monsoon onset in India (Wu and Zhang 1998; Mao and Wu 2007; Wu et al. 2012).
Cyclones occurring in the funnel-shaped BoB are particularly deadly, because they cause severe flooding of the densely populated low-lying coasts of Bangladesh, India, and Myanmar. During landfall of TC, it is enormously difficult task to evacuate population from the affected coastal regions due to socio-economic conditions of this region. The number of deaths caused by strong, destructive cyclone that hit Bangladesh in 1991 was at least 138,000, and for cyclone Sidr (2007) it was estimated more than 3400. Considering the intensity of severity and level of casualty, the main purpose of this paper is to discuss the characteristics and formation process of cyclones over the BoB.

Basic requirements for TC formation

The initiation of depression or deep depression over the ocean does not indicate the cyclone formation. The genesis of a TC, also known as a tropical storm, is characterized by a cyclonic vortex which is capable of self-intensification i.e. no external force is required for the growth of cyclone. By definition, TC is formed when surface wind speed around vortex is at least 17.5 m s$^{-1}$ (34 knots). Depression is the pre-existing disturbance that turns to a cyclone when background environments are favourable. The primary factor for initiating pre-existing disturbance (or tropical cloud cluster) is the location of the monsoon trough (monsoon-type inter tropical convergence zone). In addition, six climatological parameters are required to form a cyclone i.e. low-level relative vorticity, inverse of the tropospheric vertical wind shear, the Coriolis parameter, surface temperature (SST) exceeding 26°C, moist static instability and mid-tropospheric relative humidity (Gray 1975; 1979). Within these favourable environments, an external wind surge into regions containing a tropical cloud cluster can trigger cyclogenesis by causing the development of deep convection or an intense mesoscale convective system (MCS) (Zehr 1992; Gray 1998). The summary of the background necessities for cyclone formation is listed below, which are explained in details for the TCs formed in the BoB.

a. Monsoon trough location
b. Favourable six environmental parameters
c. Wind surge to the pre-existing disturbances
d. Intensification of mesoscale convective systems (MCSs) and associated mesoscale convective vortices (MCVs)

Monsoon Trough

The monsoon trough or shear line forms between the westerly or south westerly monsoon winds and the easterly trade winds. Where the westerly and easterly winds converge, a zero vertical wind shear produces with a westerly shear on the
pole ward side and an easterly shear on the equator ward side. Fig. 3 shows that during the pre-monsoon, especially in May, the monsoon trough is extended from western India to the eastern part of the BoB between 10°N and 25°N, whereas, it is over the ocean between 5°N and 15°N during the post-monsoon. In the pre-monsoon, the trough crosses the northernmost BoB, whereas during the post-monsoon, it passes the middle of the BoB (Akter and Tsuboki 2014). In summer, the location of monsoon trough is well inland; the prevailing southwesterly monsoonal winds and upper-level easterly winds create strong vertical shear that suppresses TC formation in the BoB (Jeffries and Miller 1993; McBride 1995; Li et al. 2013).

Fig. 3 Average zonal wind shear (color shades; m s\(^{-1}\)) between 850 and 200 hPa and streamlines at 925 hPa during 1990–2009. In each panel, the approximate location of the monsoon trough lines is shown by the dashed line (Source: Akter and Tsuboki 2014)

**Cyclone occurrence frequency**

The BoB offers a unique setting for TC activities. As the seasonal variation in the cyclone distribution is associated with the monsoon trough location, TCs over the BoB are confined within the monsoon transition periods, with a maximum frequency in October-November and second maximum in May (Akter and Tsuboki 2014). Whereas, in all other ocean basins, TCs generally occurs during the summer season (Neumann 1993).

Fig. 4a shows the cyclone formation locations for 20 years from 1990–2009. Within this time, 65 cyclones formed over the BoB, 32% during the pre-monsoon and 62% during the post-monsoon season. When the monsoon onset (withdrawal) is late (early) over the BoB, cyclones formed in June (September) are considered pre-monsoon (post-monsoon) cyclones. The cyclones are widely distributed across the BoB, however, more concentrated in the central region. Fig. 4b indicates the annual cyclone frequency distribution which is clearly bimodal; the
primary peak is in November (0.8 cyclones/year), and the secondary peak (0.5 cyclones/year) is in May.

Fig. 4 (a) Tropical cyclone formation over the Bay of Bengal (BoB) during 1990–2009 (dots): red, pre-monsoon; black, post-monsoon; green, other. (b) Annual cyclone occurrence frequency (Source: Akter and Tsuboki 2014)

Environmental parameters for cyclogenesis

The environmental dynamic and thermodynamic factors for cyclogenesis during pre- and post-monsoon seasons and their relative contributions were analyzed by Akter and Tsuboki (2014). Because of weak Coriolis effect, cyclones do not form near the equator. Fig. 5 indicates that in both seasons, relative vorticity was positive, with values on the order of $10^{-6}$ s$^{-1}$, SST exceeded the threshold of 26 °C, the mid-tropospheric humidity at 700 hPa was greater than 65%, and the equivalent potential temperature ($\theta_e$) gradient between the surface and 500 hPa was within the range of typical value (15–20K, Gray 1977), while vertical shear in the 850–200 hPa layer was less than the threshold of approximately 12.5–15 m s$^{-1}$ (Zehr 1992).

Fig. 5 Seasonally averaged values within 5°N–22°N, 80°E–97°E (rectangle in Fig. 4a, excluding the land area) during 1990–2009 (Source: Akter and Tsuboki 2014)
The values of these dynamic and thermodynamic parameters for TC genesis were found similar to values in the western North Pacific (Gray 1977). However, between the two seasons, the values of relative vorticity, vertical shear, SST, relative humidity, and $\theta_e$ gradient differed by 44%, 34.7%, 3.4%, 4.7%, and 12.9%, respectively. During the pre-monsoon season, the positive relative vorticity was smaller and the vertical shear was larger than during the post-monsoon values that support the less frequent cyclone activity being observed during the pre-monsoon.

**Suppression of TCs during pre-monsoon**

During pre-monsoon, especially in May, direct heating of the ocean by the sun increases SST, which in turn influences the vertical gradient of potential temperature and results in high possibility to form tropical convection during the pre-monsoon season (Sasamal 2007; Alappattu and Kunhikrishnan 2009). More convection favors the increase in cyclone frequency. Even though activities of convection are high during the pre-monsoon season, the question arises, however, as to why there are fewer TCs during the pre-monsoon than during the post-monsoon (Fig. 4b).

![Fig. 6 Seasonally averaged, vertically integrated (surface–700 hPa) moisture flux (color shades; kg m$^{-1}$ s$^{-1}$) and horizontal wind (vectors; m s$^{-1}$) at 850 hPa during the (a) pre-monsoon and (b) post-monsoon season during 1990–2009. Average relative humidity (color shades; %) and temperature anomalies (contours; contour interval, 2 K) at 850 hPa during the (c) pre-monsoon and (d) post-monsoon season. (Source: Akter and Tsuboki 2014)
Akter and Tsuboki (2014) have explained that during pre-monsoon, the position of trough in the northernmost bay and a strong south westerly wind shear helps to decrease the cyclone numbers in the southern bay. In addition, a dry (<60% humidity) and hot (~4 K above the average) air from north western India moves into the northern BoB during the pre-monsoon (Fig. 6). This deep layer, from around 950 to 600 hPa, prevents the warm, moist, near-surface air (>70% humidity and 298 K temperature at 925 hPa) from rising. This synoptic-scale forcing of dry, hot air from the northwest creates a cap which helps to suppress the convection as well as cyclone formation in the northern BoB. In contrast, during the post-monsoon, moisture advected from the east results in a relative humidity of ~80% over the entire BoB from the surface to the mid-troposphere. The absence of the horizontal transport of hot air toward the BoB causes the stable atmospheric layer to be weak. Therefore, the monsoon trough position and the environmental stable layer in combination can explain the lower frequency of cyclogenesis during the pre-monsoon compared with the post-monsoon season.

**Wind surge to the pre-existing disturbance**

The development of pre-existing disturbances, initiation of early stage convection and formation process of mature convective systems which are necessary for the bimodal cyclogenesis have been analyzed by Akter (2015) using the Advanced Hurricane WRF (AHW) model (version 3.3.1 (Skamarock et al. 2008). Two pre-monsoon TCs: Akash (2007) and Laila (2010) and two post-monsoon TCs: Sidr (2007) and Giri (2010) were simulated for this purpose. A Lambert projection map was utilized with two-way nested domains; the grid spacing was 12 km for the outer domain and 4 km for the innermost domain. Details of the model setup are available in Akter (2015).

The zero line of the average zonal vertical wind shear between 850-200 hPa in figure 7 indicates a monsoon trough passing over the BoB and within the trough region, cloud clusters are organized with length of at least ~700 km. Two types of synoptic flow patterns in the BoB are related to the seasonal development of TCs. In the pre-monsoon cases, a combination of SW and northwesterly (NW) winds appear at low levels within the BoB. The NW flow advects dry air from the arid regions of southwestern Asia and western India to the BoB up to 500 hPa; however, the equatorial SW flow from the Arabian Sea carries large amounts of moisture from the surface to 875 hPa over the BoB (also Akter and Tsuboki 2014). In the post-monsoon cases, the SW and NE winds coexist from low levels to the 600 hPa level. The SW wind surges in the pre-monsoon cases and the NE wind surges in the post-monsoon cases, supply low-level moisture and support for initiating mesoscale deep convection within the cloud clusters.
Fig. 7 Averaged moisture fluxes (shaded, m s\(^{-1}\)), reflectivities (green contours, 20-dBZ intervals), wind vector at 925 hPa and the zero zonal wind shear between 850-200 hPa (red line, m s\(^{-1}\)). The red circles are the positions of the depressions (max. wind speed of 15 kt) of each TC.

**Mesoscale convection and mesoscale vortex**

Many studies have acknowledged that large-scale or synoptic-scale flows are not the only major contributors to TC genesis. Individual MCSs that are associated with a pre-existing tropical disturbance and MCVs that develop in the stratiform precipitation region near the middle troposphere are also fundamental precursors for cyclogenesis (e.g., Zehr 1992; Harr et al. 1996; Gray 1998; Dunkerton et al. 2009; Houze 2010).

Akter (2015) studied the structure and characteristics of MCSs and the associated MCVs that form in the BoB during pre- and post-monsoon TCs. Fast-moving, long-lived quasi-linear convective systems with leading-edge convection were found as a common characteristic of MCSs associated with cyclogenesis in the BoB. In the pre-monsoon environment, severe MCSs were possible when the low-level moist SW winds converged with the dry NW winds along the dryline or non-organized convective systems produced when the confluence zone remained
outside the dryline. In the post-monsoon cases, when strong NE winds advected air over the BoB, a horizontal wind gradient or shear line formed, which assists in the development of the squall line MCSs that were oriented in a north-south direction.

All MCSs contained several mesovortices, which formed at low levels along the leading edge of the system; the intensities of the mesovortices increased through the mid-troposphere. The diameters of the vortices were found larger in the pre-monsoon cases than in the post-monsoon cases. The gradual movement of the systems and the formation of new mesovortices downwind created a mid-tropospheric environment with enhanced vorticity, which further assisted in the formation of an active cyclone.

![Fig. 8 Reflectivity at 925 hPa (shaded, dBZ). The geopotential height (shaded, m) along with the horizontal wind (vectors, m s⁻¹) at 500 hPa for TCs in 2007 (Source: Akter 2015)](image)

Fig. 8 shows the MCSs, the 500-hPa geo-potential heights and wind speeds for the pre- and post-monsoon TCs in 2007 at three times: the initial convection at t, the deep moist convection that gradually organizes within the MCV and an intensifying tropical storm that is represented by decreasing geo-potential heights. Latent heat released aloft due to convection results in low pressure at levels below, which increases the magnitude of the cyclonic surface winds around the TC center.

**Severity of TC**

The intensity of cyclone depends on warm ocean waters, boundary layer convergence, high relative humidity and accompanying convection (Laing and Evans 2011). As SST in the BoB is found almost 29°C which crosses the threshold value of 26°C and relative humidity is more than 65%, associated
Convective systems are significant for intensifying the TCs over BoB. Previous studies have reported about the severe convective systems known as supercells in many rainbands of TCs (Spratt et al. 1997; Lee et al. 2008; Eastin and Link 2009). Hurricane Katrina (2005) was one of them which had supercells in the rainbands and caused catastrophic devastation along the central Gulf coast of U.S.

Super cell is characterized by a deep, continuously rotating updraft which can produce large hail, damaging winds, deadly tornadoes, flooding, dangerous cloud-to-ground lightning and heavy rain. Many characteristics of the cyclone-spawned tornadoes still remain poorly documented, so improved understanding is required to enhance the ability to forecast of tornadoes and to provide timely warnings to the public (Spratt et al. 1997). In the coastal countries of the BoB, people do not even have any knowledge about the cyclone-spawned tornadoes to take actions for further awareness of its severity. However, Akter and Tsuboki (2010) have noticed several supercells with rotating updraft in the eastern band of cyclone Sidr (2007) shown in Fig. 9 and analyzed their characteristics by high resolution simulation. They found that supercells in the outer axis were more intense and well-structured and persisted for a longer period and their characteristics were similar to those of classical or high-precipitation type of supercell at midlatitude (Moller et al. 1994). Cyclone Sidr (2007) was highly destructive because of tornadoes along with the cyclone itself which caused severe wind and enhanced strong storm surge.
Conclusion

The cyclone activities in the North Indian Ocean or BoB are not very frequent compared to Pacific or Atlantic Ocean basins. However, the BoB experiences the differences in many aspects:

a. Formation of TCs in the BoB is perfectly bimodal with maximum frequency in October-November and second maximum in May. The monsoon trough positions over the BoB confine the TC distributions within pre- and post-monsoon seasons.

b. Pre-monsoon environments are more favorable for cyclogenesis than that in post-monsoon. However, post-monsoon cyclone frequency is almost double than the TCs occurred in pre-monsoon. Location of monsoon trough in the northernmost bay and stable atmosphere layer causing by dry north westerly reduce the TC frequency in pre-monsoon.

c. Both severe and non-severe quasi-linear convective systems are possible for pre-monsoon cyclogenesis but in case of post-monsoon, squall line convective systems are associated with cyclogenesis.

d. The structure of rain band of cyclone Sidr (2007) is found different from typical one. It is long and straight rather than spiral shape.

e. Classical super cells that are responsible for intense tornadoes are found in the squall line convective systems of the rain band of cyclone Sidr (2007).

Therefore, it is important to advance our understanding of individual cyclone characteristics and urges the necessity of monitoring tornadoes spawned by super cells and their intensity in land falling cyclones in the BoB.

References


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