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Structure of tropical cyclones in the Bay of Bengal

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सार — इस शोध पत्र में, तटीय रेडार आंकड़ों और उपग्रह प्रतिबिम्बों के अध्ययनों से व्युत्पन्न किए गए बंगाल की खाड़ी के उष्ण कटिबंधीय चक्रवातों की पवन और वर्षा वितरण और प्रतिरूपी क्रोड संरचना पर अनुमान प्रस्तुत किए गए हैं तथा अन्य महासागरीय बेसिनों से प्राप्त परिणामों से तुलना की गई है। प्रचालन पूर्वानुमान और नावकास्टिंग के सन्दर्भ में इन परिणामों के आशयों की चर्चा की गई है।

ABSTRACT. Inferences on the typical core structure and wind and rainfall distribution of tropical cyclones (TCs) of the Bay of Bengal derived from studies of coastal radar data and satellite imagery are presented in the paper and compared with findings from other oceanic basins. The implications of these findings in the context of operational forecasting and nowcasting are also discussed.

1. Introduction

The Bay of Bengal is one of the most important basins in respect of occurrence of tropical cyclones (TCs). Although the frequency of occurrence of TCs is less than those in some of the other basins and the TCs themselves are usually of lower intensity owing to limited sea travel, Bay cyclones are among the deadliest. Although synoptic studies are available, studies of TC structure are unfortunately relatively few in this basin compared to those in the northwest Pacific and north Atlantic. In those oceans the main source of data has been from aircraft reconnaissance which has been almost absent in this basin. Another powerful method of study especially in the north Pacific has been rawinsonde compositing pioneered by Gray and his school. Even that has not been practicable in the Bay of Bengal area. Moreover, composite studies have the disadvantage of smoothening out the variability which is very necessary to take into account while issuing realtime warnings in respect of individual cyclones. In recent years, however, radar and satellite observations of cyclones have become available in this area and these are especially suited to study the core structure of individual TCs. This paper presents some findings on the core structure based on intensive radar observations of several cyclones and qualitative and semi-quantitative inferences from satellite imagery and a comparison of these with the findings reported from other basins. The implications of these for operational cyclone forecasting are also considered. It should be expected that the structure of the core region must be very similar in all basins although the outer region of the TC being subjected to more general synoptic influences could vary more from basin to basin. Still, it is interesting to find that while the core structure is broadly similar to that in other basins these studies reveal a few differences also.

2. Eyewall formation and structure

The majority of low pressure systems in the Bay do not achieve TC intensity (maximum sustained wind exceeding 33 kt). But even before any system reaches this stage it shows an organisation in the form of spiral rain bands. As the system intensifies into a TC a partial eyewall usually forms *as an extension* of the innermost spiral band. When the TC intensifies further the eyewall separates out from the spiral band into a ring or crescent. This kind of development has been observed on several occasions in the Bay of Bengal (*e.g.*, Raghavan and Veeraraghavan 1979, Raghavan *et al.* 1980, Raghavan and Rajagopalan 1980) but the concept of the eyewall developing out of the spiral bands appears to have found general acceptance in other basins only recently (*see*, *e.g.*, Holland 1987 who also mentions the mechanisms by which such development could occur). A model structure of the Bay cyclone is shown in Fig. 1.

All the systems which reached TC stage had at least a partial eyewall. Once an eye is formed the eyewall is the place "where the action is". We shall consider the eyewall region, an area with radius about twice the Radius of Maximum Winds (RMW) as the core of the TC, although some authors prefer to consider a larger area as the core. This region is dominated by moist convection and interchange of energy between convective and cyclone scale processes (Holland 1987). This should be viewed in contrast to the outer regions of the TC where external synoptic interactions have greater influence.

The spiral bands tend to have decreasing crossing angles, *i.e.*, they approximate more and more to a circle as one approaches the centre of the TC. The crossing angles also tend to be smaller in more intense cyclones (Raghavan *et al.* 1980). As the eyewall forms from a spiral band the spiral configuration tends to change to

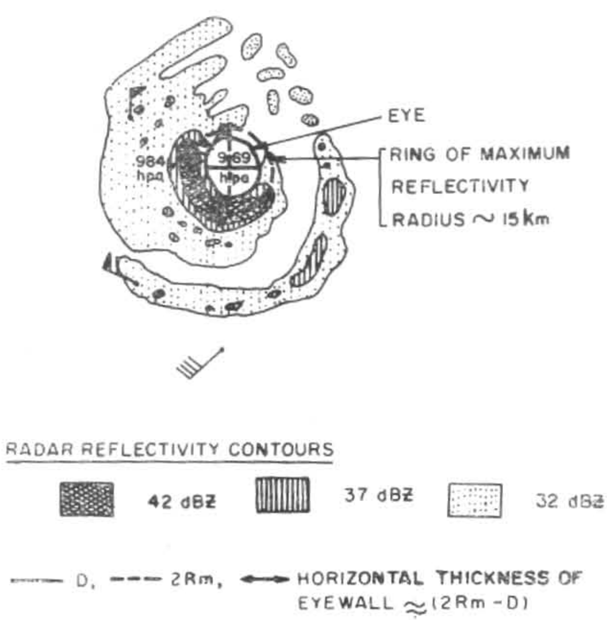

Fig. 1. Model of surface structure of Bay cyclone of November 1984

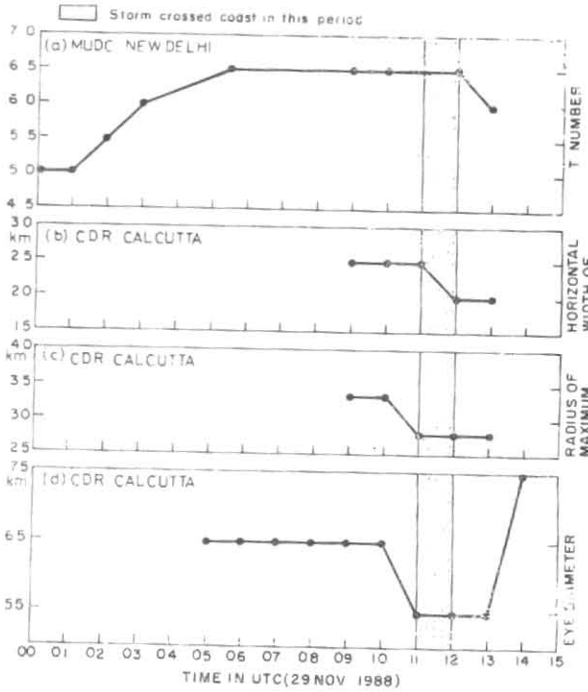

Fig. 2. Bay cyclone of 29 November 1988

a circular one and the eyewall becomes a nearly circular ring of convective precipitation. The convective nature of precipitation in the eyewall and in spiral bands is clearly brought out in radar RHI pictures. Stratiform precipitation occurs only in some places between spiral bands. Indeed very few cases of 'bright band' formation with horizontal orientation of radar reflectivity contours characteristic of stratiform precipitaton could be observed in association with Bay of Bengal TCs. This is contrary to the tendency of groups or lines of convective cells in the tropics to form large meso-scale stratiform anvils.

The formation of large meso-scale stratiform anvils in association with convective cloud clusters or squall lines (not associated with TCs) is well documented over several parts of the tropics including India. Houze (1982) has discussed the effect of the meso-scale stratiform anvil on the heat exchange and radiation processes, the mass flux and the large scale vertical motion. He has shown that one consequence is a warming in the mid and upper troposphere in the entire area covered by the meso-scale anvil. Houze and Hobbs (1982) think that similar meso-scale development should occur in TCs also. Jorgensen (1984) has reported stratiform precipitation just outside the eyewall as evidenced by bright band formation in three hurricanes in the Atlantic and Marks (1985) in one. However, no corresponding large scale warming in the upper levels has been reported by any of the reconnaissance missions (except of course for the warm core in the eye region itself). Hence, it appears doubtful that the mechanism outlined by Houze (1982) for cloud clusters applies to TCs. The near absence of bright bands in Bay of Bengal TCs suggests that at least in this basin the eyewall and spiral band rainfall is almost entirely convective and no large meso-scale anvils are formed. It needs to be considered whether the extensive stratiform precipitation observed by Jorgensen and by Marks in some Atlantic hurricanes is to be explained by some other process.

3. Eyewall structure changes and TC intensity

As intensification proceeds the eyewall ring has in many cases a tendency to contract. In the case of some deep cyclones an "asymmetric double eye" sometimes develops. This consists of the formation of an outer ring around the eyewall. The double eye is, however, shortlived and is different from the symmetric double eyes described by Willoughby *et al.* (1982) in some Atlantic hurricanes. The latter consist of a process of formation of the outer ring while the inner ring contracts and finally dissipates leaving the outer ring as the eyewall and this process may repeat in several cycles. While it should be noted that several authors have found statistically that eye size is inversely correlated with intensity of TCs, eyewall contraction with time in the same cyclone is more significant (Raghavan 1985, 1987). As the RMW lies in the eyewall ring, the eye contraction implies a decrease in RMW. By angular momentum considerations a decrease of RMW should result in an increase of the maximum sustained wind. Hence the progressive contraction by itself signifies intensification. Hence an eye contraction with time is an operationally useful indicator of TC intensification. That the radar determined eye contraction is accompanied by intensification is verified from independent satellite estimates of maximum wind speed. In the case of the cyclic process

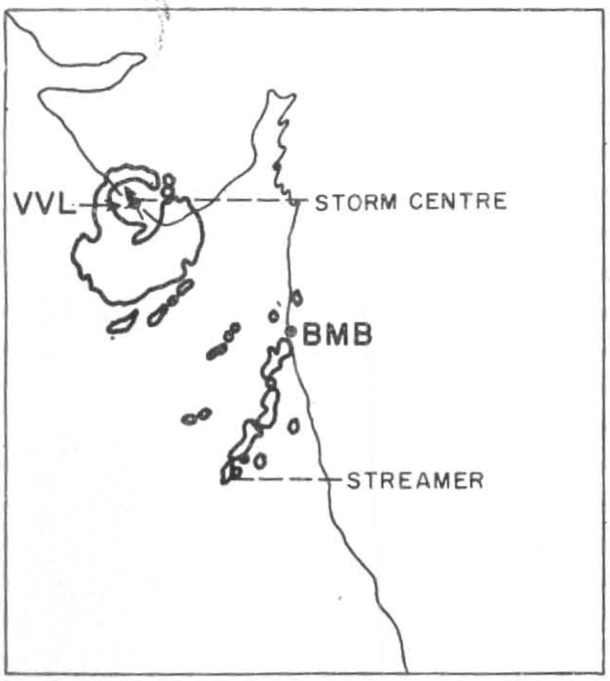

Fig. 3. Streamer bands near Bombay associated with a cyclone over Saurashtra coast

discussed by Willoughby *et al.* (1982) there are corresponding phases of intensification and weakening accompanying the effective changes in eye diameter (Fig. 2). However, there is usually a considerable time lag between the eye radius changes and the wind speed changes and therefore, caution should be exercised by forecasters while linking any increase in eye diameter with weakening of the TC.

The attributes of the eyewall which can be mapped by conventional landbased radar are echo top heights, radar reflectivity and precipitation rate. Latent Heat Release (LHR) distribution can also be derived (Raghavan and Varadarajan 1981). It has been observed that echo top heights in the eyewall are not necessarily higher than elsewhere in the TC but radar reflectivities and precipitation rates are higher in the eyewall than elsewhere. In all cases when an eyewall passed over land it has been verified by independent study of the wind damage and rainfall distribution that the maximum wind speed is co-located approximately with the points of highest radar reflectivity and the highest precipitation rate observed earlier in the eyewall over sea. This is particularly evident in the case of partial or unsymmetric eyewalls (Raghavan and Veeraraghavan 1979). More recently Jorgensen (1984) has established by airborne radar observations that the maximum radar reflectivity in the eyewall and the maximum horizontal and vertical winds occur in Atlantic hurricanes at about the same radial distance from the centre within a few kilometres of each other. Marks and Houze (1984) found from airborne Doppler radar observations that maxima of convergence, radar reflectivity and couplets of vorticity at 3 km level were juxtaposed in the hurricane (*Debby*) which they studied. This established the eyewall as the place where the RMW as well as the radius of maximum reflectivity (R_m) occur. In practice, therefore, the R_m observed on radar can be used to determine the RMW of the TC in realtime to a good degree of approximation. The RMW can also be estimated with somewhat less accuracy from satellite imagery if the eye is clearly seen. Such a determination has an operational value as apart from RMW changes being related to changes in TC intensity, RMW is also an input parameter for storm surge computation and prediction (Raghavan 1987). Changes of the R_m with time can also be evaluated from radar observations and the R_m variation appears to be a better indicator of TC intensification than the eye size.

It is important to emphasize, however, that "intensity" of a TC specifies only the central pressure and the maximum wind to be expected in the core. The rate of fall of the wind speed as one goes outward from the RMW may vary considerably in cyclones having the same intensity. This variation is taken account of by the concept of 'strength' which is operationally important. Strength is the average wind speed over the cyclone circulation. Weatherford found in the northwest Pacific that some typhoons had no eye even after they gained typhoon intensity. Typhoons which had no eye tended to have greater strength than typhoons with small eyes having the same central pressure and hence by definition the same intensity. Here it is relevant to mention the LHR computations in cyclones. The total LHR in the entire circulation does not seem to have much relation to TC intensity (Marks 1985). This result is to be expected as weak systems to give very heavy rainfall in peripheral areas. The core area LHR, however, seems better correlated with TC intensity (Marks 1985, Raghavan and Varadarajan 1981). Hence a distinction has to be made between the core region and the entire cyclone circulation while nowcasting weather effects over specific areas.

4. Asymmetries in wind and rainfall distribution

The eyewall development is unsymmetrical around the centre in most TCs. Even when a complete ring is observed on radar or satellite, it is unequally developed in different directions. This can be most readily observed by mapping the radar reflectivity or even the echo top heights. Corresponding asymmetries are observed in the rainfall rate and wind speed in the eyewall region when it goes over land. In southern Bay of Bengal storms the best developed portion of the eyewall is generally to the left of the track (Raghavan and Veeraraghavan 1979, Raghavan *et al.* 1980) and it has been established by wind damage surveys that the damage in these cases is a maximum where the left sector of the eyewall passed. Similarly there is a rainfall maximum immediately to the left of the track (*see e.g.*, Biswas *et al.* 1988). In fact such a rainfall maximum in the left sector has been noted by Ramakrishnan (1937) long before radar and satellite observations were available in the Bay of Bengal. This finding may seem contradictory to the general concept that the highest winds (and highest precipitation rates) should be in the right sector (in the northern hemisphere) where the cyclone flow and the environmental flow are in the same direction (Holland 1987). Indeed in an Arabian Sea cyclone at a latitude of about 20° N, Mukherjee and Sivaramakrishnan (1977) observed the maximum surface winds in the right rear sector. The explanation appears to be related to the speed of motion of the TC. Shapiro (1983) has studied the asymmetric wind field in relation to the speed of translation of a hurricane. From his model it appears that in a stationary or slow-moving hurricane the low level wind maximum should be expected in the left sector while in a fast-moving TC the maximum would shift to a more clockwise position, *i.e.*, the right sector. If this is the case, storms in the south Bay of Bengal which move slowly should have the core wind maximum in the left sector as noted above. TCs at more northern latitudes which move much faster should be expected to have the wind maximum in the right sector. The latter presumption has not yet been extensively tested for want of adequate data.

In the TC *as a whole* the rainfall has been observed to extend much farther to the right of the track than the left. *Outside* the core region the maximum low level convergence appears to occur in the right sector in all cases. One of the features which contributes to this maximum in the right rear sector is the formation of convective 'streamer' bands in the rear. This represents an area of high rainfall well separated from the core region maximum. This phenomenon appears to be responsible for the heavy rainfall which occurs over Bombay city (Fig. 3) when aTC hits the Saurashtra coast (Mukherjee and Padmanabham 1980, Raghavan and Ramakrishnan 1981). There is also heavy convective rainfall about 500 km ahead of the storm centre due to the pre-cyclone squall lines (Raghavan *et al.* 1980).

5. Landfall

When a storm goes over land it weakens rapidly but in some cases the eye can be tracked over land for several hours. However, the pattern of rainfall distribution appears to remain largely unchanged as a one to one correspondence could be established in most cases between the radar reflectivity distribution over sea and the subsequent isohyetal configuration over land (Raghavan and Veeraraghavan 1979). Thus, there is no appreciable effect on the structure of the TC immediately after landfall in the case of most Bay of Bengal TCs. This is probably because of the flat topography of most of the coastal belt on the east coast of India (The same may not necessarily be true in the case of TCs hitting the Arakan coast or the west coast of India). The preservation of the rainfall distribution pattern on landfall can be taken advantage of for nowcasting purposes if good realtime radar and satellite data are available immediately before landfall.

6. Conclusion

To sum up, these studies indicate a TC structure in the Bay of Bengal which is similar in most respects to those observed in other basins. There are some differences notably in the asymmetries encountered in the eyewall region and in the dominance of convective precipitation in the TC. The realtime determination of RMW derived from radius of maximum radar reflectivity has operational utility in intensity determination and storm surge prediction. The findings regarding wind and rainfall distribution will be useful in nowcasting.

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