Observations of Indian Ocean tropical cyclones by 85 GHz channel of TRMM Microwave Imager (TMI)

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Abstract:

Observations from TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) have been analysed for 18 tropical cyclones and depressions over Indian Ocean. Polarization Corrected Temperatures (PCT) of 85 GHz were used to define the convective elements within the tropical storms. Our analysis indicates that the relative population of convective elements is crucial to the intensification of tropical storms. As compared to the intense stage, the areal extent of convective pixels was seen to reduce significantly for systems decaying from intense to depression stage. For decaying depressions this area was even smaller. Also, during the developing and decaying stages, the convective elements show a larger spatial variability compared to mature stage of tropical cyclones.

1. Introduction

The convective rain bands of tropical cyclones can be treated as a highly organized multi-cellular convective system composed of numerous deep convective cells arranged along a spiral curve. Because the cirrus layer that forms over deep convection is opaque to infrared and visible sensors, the convection bands of cyclone appear on visible and infrared imagery to merge into larger, radiatively cold cloud clusters (Mapes, 1993, Mapes and Houze 1993). The longer wavelengths of the microwave band penetrate more deeply into convective cells than IR wavelengths. The microwave brightness temperatures upwelling from a cloud system are directly related to the types, size distribution and the density of hydrometeors within it (Wu and Weinman 1984). For large scattering coefficient and a high number density of scatterers, very little high frequency (> 30 GHz) microwave radiation is emitted into the field of view of a satellite sensor (Spencer et al., 1989). In some deep convective cores, 85 GHz brightness temperatures less than 100 K are observed due to ice scattering through long optical paths (Adler et al., 1990). Experiments with microwave radiative transfer models indicate that the ice layer above the main rain layer basically determines the 85 GHz brightness temperature (Adler et al, 1991, Mugnai et al., 1993). The ice layer in turn can act as a proxy for the convection. With the launch of first Tropical Rainfall Measuring Mission (TRMM) satellite in 1997, it has become possible to obtain observations of tropical convection and precipitation systems by a variety of sensors covering optical and microwave region of electromagnetic spectrum. A brief description of TRMM and its sensor package is given in the following section. One of the unique feature of TRMM Microwave Imager (TMI), a passive microwave radiometer, is the high resolution (~ 5 km) of its high frequency channel, 85 GHz. This feature is highly useful in resolving convective clusters and their spatial variation within the tropical cyclones. The eye-wall region of the tropical cyclone is an area of intense vertical motion, deep convection, and heavy precipitation, and in most cases this area is confined to a thickness of merely 20 km. Furthermore, the ability to resolve the features of eye-wall also ensures the correct determination of the location of the centre of the cyclone, a crucial information for the prediction of its future location. It is believed that the eye-wall convection shows the signs of decay about 1 hour before the maximum sustained winds start weakening. Thus the convection in the inner core of the cyclone is an important precursor to the intensification and decay of cyclone.

In the present study we have analysed the high resolution observations from 85 GHz channels of TRMM Microwave Imager (TMI) for the tropical cyclones over the Indian Ocean. As mentioned earlier, the 85 GHz brightness temperature patterns are reasonable proxy to the intensity of convection, and more so in an organized situation like tropical cyclones. In this study we have tried to include the observations for different intensification stages of the cyclones. One of the basic objectives of this study is to understand the spatial and temporal changes in the patterns of convection within the domain of a tropical cyclone with its intensification, or decay.

1.1. *The Tropical Rainfall Measuring Mission (TRMM:*

The Tropical Rainfall Measuring Mission (TRMM) is a joint venture of National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan. The objectives of TRMM are to measure rainfall and energy (i.e. latent heat of condensation) exchange of tropical and subtropical regions of the world. The primary rainfall instruments on TRMM are the TRMM Microwave Imager (TMI), the precipitation radar (PR) and the Visible and Infrared Radiometer System (VIRS). Additionally, the TRMM satellite carries two related EOS instruments in the Clouds and Earth's Radiant Energy System (CERES) and the Lightning Imaging System (LIS). The space segment of TRMM is a non-sun synchronous satellite in a 350 km circular orbit with a 35^{o} inclination angle. It was launched in the summer of November 1997. A comprehensive description of the TRMM sensor package has been provided by Kummerow *et al*. (1998).

The Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) is a passive microwave sensor and measures scattered radiation at frequencies of 10.7, 19.4, 21.3, 37.0, 85.5 GHz. All channels except 21.3 GHz channel are dual polarized. TMI quantifies the water vapor, the cloud water, and the rainfall intensity in the atmosphere. The TRMM satellite has a circular orbit with an altitude of 350 km, inclination of 35^{o} to the equator, and observes a swath width of 790 km are the earth's surface. Diffraction effects and the fixed antenna size of the TMI cause the instantaneous field of view (IFOV) to increase with decreasing channel frequency. For example, the 85.5 GHz channel IFOV is 4.4 km, while IFOV of the 10.7 GHz channel is 40 km. The satellite completes 16 orbits per day, and the TRMM orbit precesses such that the cyclones overpass times vary during the study period. The dimensions of effective field of view (EFOV) of 85.5 GHz channel of TMI are 6.9 km across-track and 4.2 km down-track, providing a resolution of about 5.3 km. Along a scan line the EFOVs of 85 GHz are separated by 4.6 km, while the distance between two consecutive scans is 7.0 km.

2. Data and Methodology

For the present study we have analysed TMI observations pertaining to 18 depressions and tropical cyclones occurring over the Arabian Sea, and the Bay of Bengal during the period 1998 to 2001. The data set covers the cyclones in different intensification stages e.g. depression, deep depression, cyclonic storms, and severe cyclonic storms. A total of 136 scenes from TMI were collected for this study. These scenes cover between 50% and 100% area of depressions and cyclonic storms. The mean value of the areal coverage by TMI was 90%. We used the Maximum Sustained Wind speed (MSW) available from the weather bulletins of India Meteorological Department (IMD) a measure of the intensity of cyclones. The TMI data set used in the present study covers the Indian Ocean tropical cyclones in different intensification levels. As per the definition of cyclone classification by IMD, 37 of 136 TMI scenes belong to the depression stage of the cyclones (17 Knots < MSW < 27 Knots), 32 to Deep Depression stage (28 Knots < MSW < 33 Knots), 27 to Cyclonic Storm stage (34 Knots < MSW < 47 Knots), 18 to Severe Cyclonic Storms (48 Knots < MSW < 63 Knots), 18 to Very Severe Cyclonic Storms (64 Knots < MSW < 119 Knots) , and 4 to Super Cyclones (MSW > 119 Knots).

In order to study the convective systems embedded in the environment of a tropical cyclone, it is necessary to distinguish between low brightness temperature caused by ice scattering and those resulting from the background effects (Mohr and Zipser, 1996). Surface water has low emissivity at 85 GHz resulting in brightness temperatures low enough to be confused with brightness temperatures depressed by scattering. For oblique viewing angles such as the TMI's, the emissivity of surface water is a strong function of polarization (Spencer et al., 1989). To eliminate the effect of surface water, a polarization corrected temperature (PCT) is required. The physical basis of the PCT is given in Spencer et al. (1989). The PCT is calculated from the 85-GHz horizontally and vertically polarized brightness temperatures by the following formula:

$$\mathrm{PCT} = 1.818\ \mathrm{T}_{BV} - 0.818\ \mathrm{T}_{BH}$$

PCT is effective in eliminating the differences of signals arising due to the surface effects e.g. land or water. Mohr and Zipser (1996) have suggested that a mesoscale convective system can be defined as an area of at least 2000 km^2 bounded by a PCT of 250 K with a minimum PCT $\leq$ 225 K occupying an area of at least 108 km^2. We have also used the above criteria to distinguish the multicellular systems composed of convective and stratiform elements, in the vicinity of tropical storms at different stages of their development.

3. Results

3.1. *Areal coverage of multi-cellular convection*

Convection is known to play important role in the intensification of tropical cyclones. Rodgers et al (2000) noted that a sharp increase in the maximum wind speed of cyclone generally follows the convective bursts within the inner core of the cyclone. This intensification may be attributed to the fact that the latent heating associated with convective bursts generates enough upward motion that compensates for the loss of cyclonic angular momentum due to surface friction and upper-tropospheric outward transport. In order to explore a possible relationship between the convection, and the tendency of intensification for the Indian Ocean tropical cyclones, we computed the fraction of convective elements in the cloud fields of cyclones of different intensities. Due to the limited swath of TMI, it is not always possible to obtain the complete coverage of cyclone in TMI scenes, and the area of cyclone covered varies from scene to scene. In this case the fraction of convective elements to total cloudiness serves as a normalization parameter that facilitates the comparison of the intensity of convection among different cyclones. Since the upwelling radiance at 37 GHz is sensitive to the emission from cloud liquid water, we used this channel of TMI for working out the cloud extent, while the measurements of 85 GHz PCT were used for the computation of the convective fraction. TMI pixels with 37 GHz (H) brightness temperatures (TB_{37H}) above 180 K were assumed to represent the clouds. In order to assess how well such TMI pixels compare with the cloudiness, we made a comparison of the observations by TMI and Visible Infrared Scanner (VIRS) for a few cases. Fig. 1 shows the scatter plot of fractional area covered by TMI pixels with $TB_{37H} >$ 180 K and that by VIRS pixels with Channel-4 (10.8µm) brightness temperature less than 275 K for 29 scenes over the Bay of Bengal and it indicates that TB_{37H} may be used as a reasonable proxy to the total cloudiness. A visual inspection of VIRS Channel-4 scenes (e.g. Fig.2) indicates that, the above threshold value of 275 K accounts for a large fraction of cloudy pixels including low and warm clouds. The mesoscale convective clusters were defined by the boundary of PCT=250 K, provided other conditions like the minimum areal coverage by PCT < 250 K, and PCT < 225 K are satisfied. The average area of mesoscale convective elements (MCC, defined by a boundary of PCT = 250 K) for intensifying systems was found to be 1060 pixels (~ 27000 km^2). For the systems decaying from cyclonic stage to depression stage, the area drastically reduced to 614 pixels (~ 15000 km^2), while for decaying depressions, the average area of MCC was only 390 pixels (~ 10000 km^2). Fig.3 shows the histogram of 85GHz PCT values for one intense cyclone and one decaying depression. This figure shows that the intense systems contain significantly larger number of convective elements (denoted by PCT < 250 K), compared to decaying systems.

Finally a ratio of convective to total cloud fraction was worked out for cyclones of different intensities and intensification tendencies. We have sorted the Indian Ocean cyclones as per their phase of evolution i.e. intensifying or decaying types. Figures 4-a and 4-b show the fractional contribution of convective elements in overall cloud coverage for a non-intensifying depression and a rapidly intensifying cyclonic depression. We have observed that the relative population of convective elements is crucial in determining the future course of intensification of a depression or a cyclone. The fractional coverage of convective elements was computed by dividing the number of pixels with PCT < 250 K by the number of pixels with BT_{37H} > 180 K within a radius of 1000 km from the reported centre of the system. Fig. 5 shows the fractional contribution of convective elements in total cloudiness for intensifying and decaying cyclones and depressions at different intensities. This figure indicates that there is a critical threshold of convective fraction (CF) that is necessary for the intensification of tropical cyclones. This critical convective fraction increases as the cyclone grows in intensity. The mean value of CF was 9.72% for intensifying systems (68 scenes) while the same for decaying systems (36 scenes) was 4.65 %. This is a significant difference that points to the importance of deep convection in maintenance and intensification of tropical cyclones. The observed scatter of CF in Fig. 5 can be attributed to the following reasons: (a) MSW values used in the present study are basically inferential in nature, i.e. these values are not measured directly, so there may be some uncertainties regarding the intensity of cyclone, and (b) we have not considered the rate of intensification or decay of the cyclone. The dependence of the intensification of cyclones on CF can be attributed to the fact that the convective elements are the pockets of intense precipitation and latent heat release within the cyclones, and thus are an important part of the energetics of these tropical systems (Charney and Eliassen, 1964)

3.2. *Inter-pixel variability of PCT*

As mentioned earlier, the areal coverage of multicellular convection increases with the intensification of tropical cyclone. However, our further analysis indicates that the spatial inhomogeneity, or the contrast of the PCT reduces with the intensification of the storm. This is particularly true in the areas of most intense convection (distinguished by lowest PCT values), normally found in the convective band. Fig. 6 shows the distribution of 85 GHz PCT for three different stages of life history of May-1999 Arabian Sea cyclone. During intensification (Fig. 6-a), and decaying (Fig. 6-c) stages, the minimum values of PCT are below 140 K and these belong to a few isolated pixels having much higher PCTs in immediate vicinity, while in the intense stage a large central area of the band shows a near uniform distribution of minimum PCTs. Within the domain that defines multicellular convection (PCT Threshold 250 K) the mean spatial variance of PCT is above 40 K per TMI pixel when the cyclones are in week stages, while in the intense stages it is found to be less than 10 K per pixel. This difference is significant and points towards some interesting physical mechanism behind the evolution and organization of multicellular convection in a situation dominated by strong circulation. Using available TMI scenes (N=136) we also noticed a negative correlation (r = -0.35) between the intensity of cyclones and the spatial variance of 85 GHz PCT in potentially convective regions, and this negative correlation was found to be statistically significant at 99% confidence level. It appears that in the situation of relatively weaker convergence, the convection bands are loosely organized. In addition to the main and large-scale cyclonic convergence, there are localized pockets of small-scale convergence and vertical updrafts /downdrafts within a convection band. In this situation some individual convective cells may grow at the expense of others if the vertical motion and moist mass flux are favorable. However, as the large-scale convergence gets stronger, the larger scale motions that are uniform over wider portions of the band replace the localized pockets of convergence. In this situation the convective cells may experience a uniform vertical motion, and the mass flux is more evenly distributed among various cells. In the decaying stage, the localized motions may again take over, redistributing the available mass flux and the convective available potential energy (CAPE). Furthermore, when tropical cyclones migrate over the land the dramatic shear in lowest 200 m (Powell 1988) may be spread through a deeper layer. The interaction of updraft may result in intensification of the cells within a rainband as it comes over land. Also, the relationship between PCT variance and the intensity of Indian Ocean cyclones seems to be reasonably robust, and may be considered as a tool for the estimation of cyclone intensity from satellite observations.

4. Conclusions

Polarization corrected temperature of 85 GHz channel of TMI which is an indicator of the convective activity has been shown to hold the potential for the study of Indian ocean tropical cyclones. Area covered by mesoscale convective clusters, (indicated by 85 GHz PCT < 250 K) which is linked with the magnitude of vertically transported cloud mass flux is critical to the growth and maintenance of the tropical systems. It appears from our analysis that for a given intensity of tropical cyclone, or depression, there is a minimum threshold amount of vertical mass flux that is required to maintain or accelerate the system, and below this value the system is likely to decay. These variations are indirectly indicated by areal coverage of mesoscale convective clusters inferred from 85 GHz polarization corrected temperatures. Also, our analysis indicates that spatial variance of PCT decreases as the cyclones intensify, suggesting that in intense stages of cyclone, the convective elements organize themselves in larger and uniform units compared to the cases when the cyclones have weak intensities. This interesting aspect needs to be analyzed in detail using more observational and modeling studies.

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References

ADLER, R.F., MACK, R.A., PRASAD, N., YEH, H.- Y.M., and HAKKARINEN, I.M., 1990, Aircraft microwave observations and simulation of deep convection from 18 to 183 GHz. Part-I: Observations. *J. Atmos. Oceanic Technol.*, **7**, 377-391.

ADLER, R.F., YEH, H.-Y.M., PRASAD, N., TAO, W.K., and SIMPSON, J., 1991, Microwave simulations of a tropical rainfall system with a three-dimensional cloud model. *J. Appl. Meteor.*, **30**, 924-953.

CHARNEY, J.G., and ELIASSEN, A., 1964, On the growth of the hurricane depression. *J. Atmos. Sci.*, **21**, 68-75.

IGUCHI, T., and MENEGHINI, R., 1994, Intercomparison of single frequency methods for retrieving a vertical rain profile from airborne or spaceborne data. *Jour. Ocean. Atmos. Technol*, **11**, 1507-1516.

KUMMEROW, C., BARNES, W., KOZU, T., SHINE, J., and SIMPSON, J., 1998 , The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.* , **15**, 809-817.

MAPES, B.E., 1993 , Gregarious Tropical Convection. *J. Atmos. Sci.*, **50**, 2026-2037.

MAPES, B.E., and HOUZE Jr., R.A., 1993 , Cloud clusters and superclusters over the oceanic warm. *Mon. Wea. Rev.*, **121**, 1398-1415.

MOHR, K.I., and ZIPSER, E.J., 1996 , Defining mesoscale convective systems by their 85- GHz ice-scattering signatures. *Bull. Amer. Meteor. Soc.*, **77**, 1179-1189

MUGNAI, A., SMITH, E.A., and TRIPOLI, G.J.,1993 , Foundations for statistical-physical precipitation retrieval from passive microwave satellite measurements. Part-II : Emission-source and generalized weighting function properties of a time dependent cloud radiation model. *J. Appl. Meteor.*, **32**, 17-39.

RODGERS, E., OLSON.,W., HALVERSON.,J., SIMPSON,J., and PIERCE, H., 2000, Environmental forcing of supertyphoon Paka's (1997) latent heat structure. *J. Appl. Meteor.*, **39**, 1983-2006.

SPENCER, R.W., GOODMAN, H.M., and HOOD, R.E.,1989, Precipitation retrieval over land and ocean with the SSM/I : Identification and characteristics of the scattering signal. *J. Atmos. Oceanic Technol.*, **6**, 254-273.

WU, R., and WEINMAN, J.A., 1984 , Microwave radiance from precipitating clouds containing atmospheric aspheric, combined phase, and liquid hydrometeors. *J. Geophys. Res.*, **89**, 7170-7178.

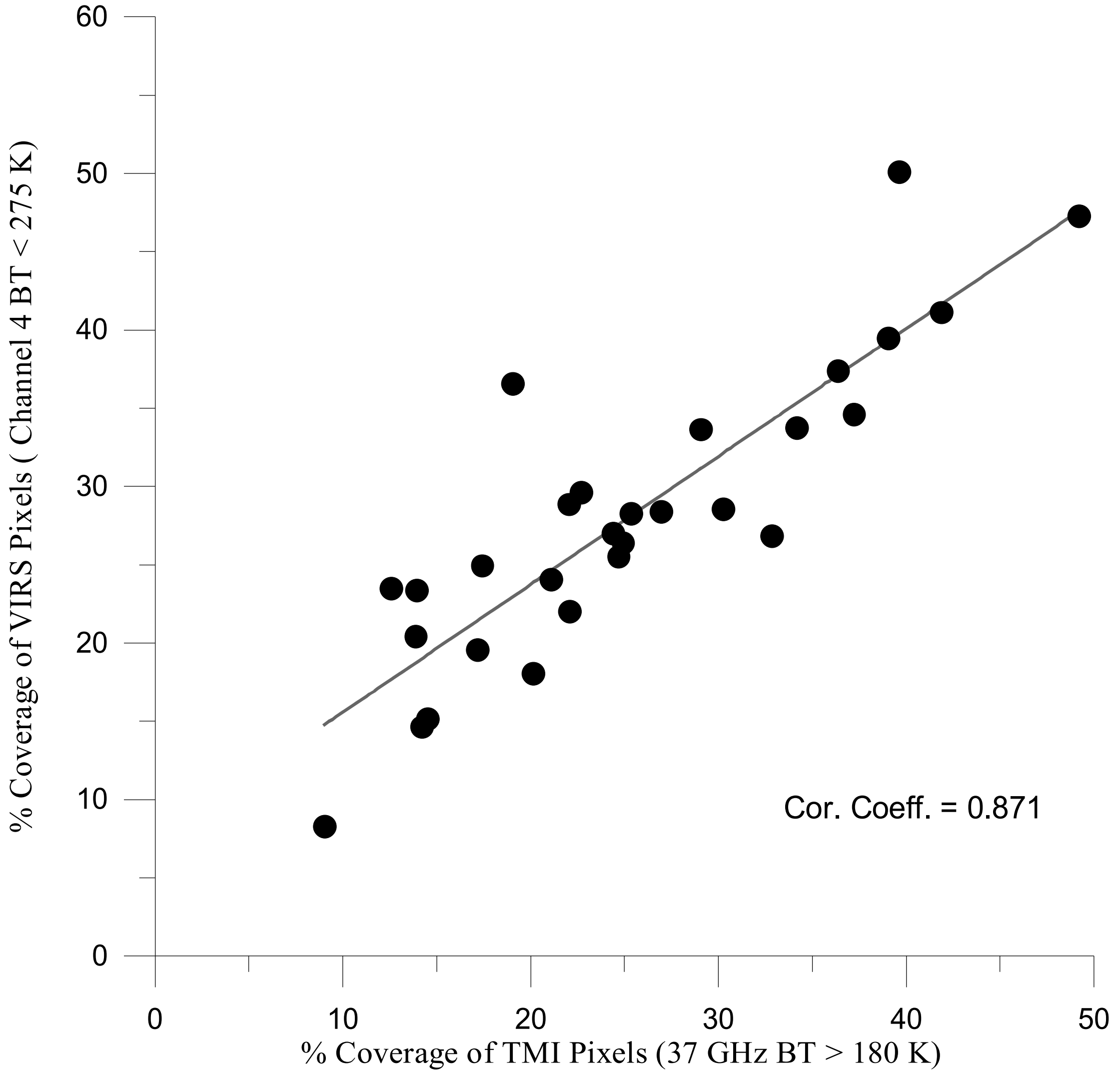


Fig. 1 : Scatter plot showing the fractional coverage by TMI pixels with $TB_{37H} > 180$ K , and VIRS-Channel-4 pixels with brightness temperature < 275 K. The quantities in this figure represent the fractional coverage of a subsection of orbital swath of TRMM.

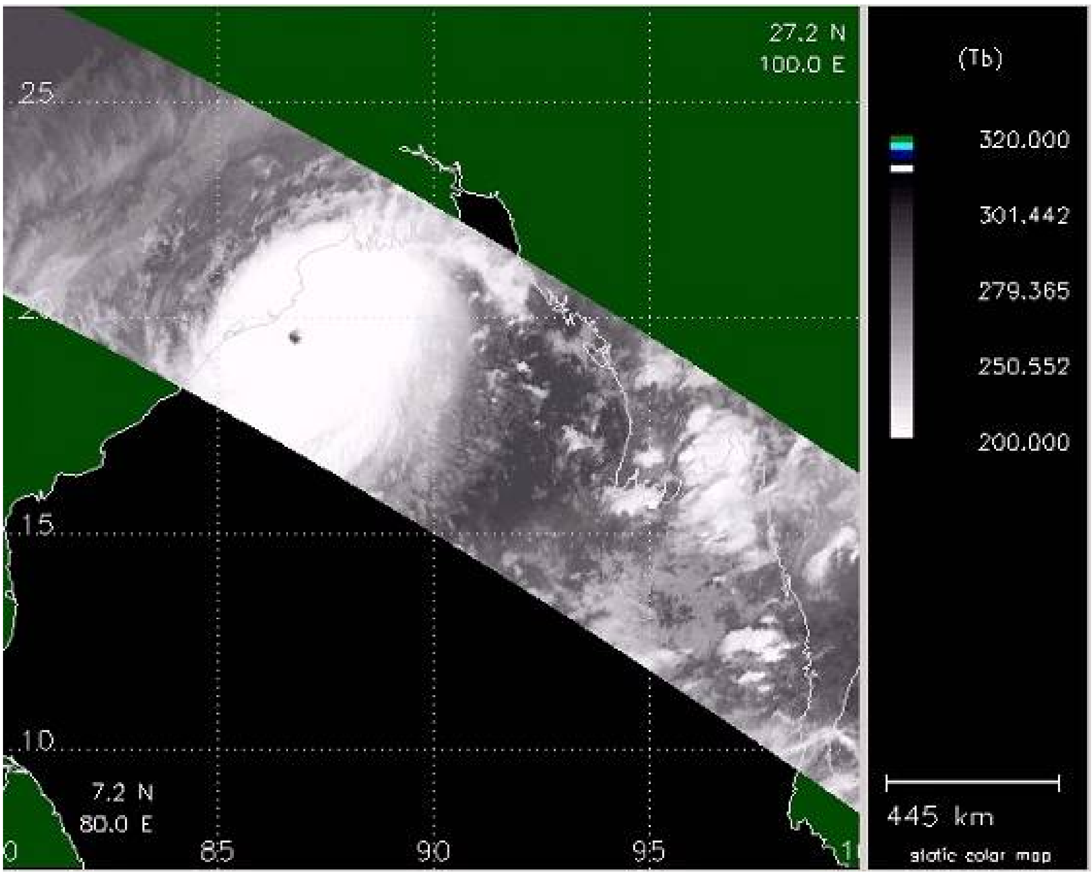


Fig. 2 : VIRS-Channel-4 brightness temperature image for Orissa Supercyclone (29-Oct-1999)

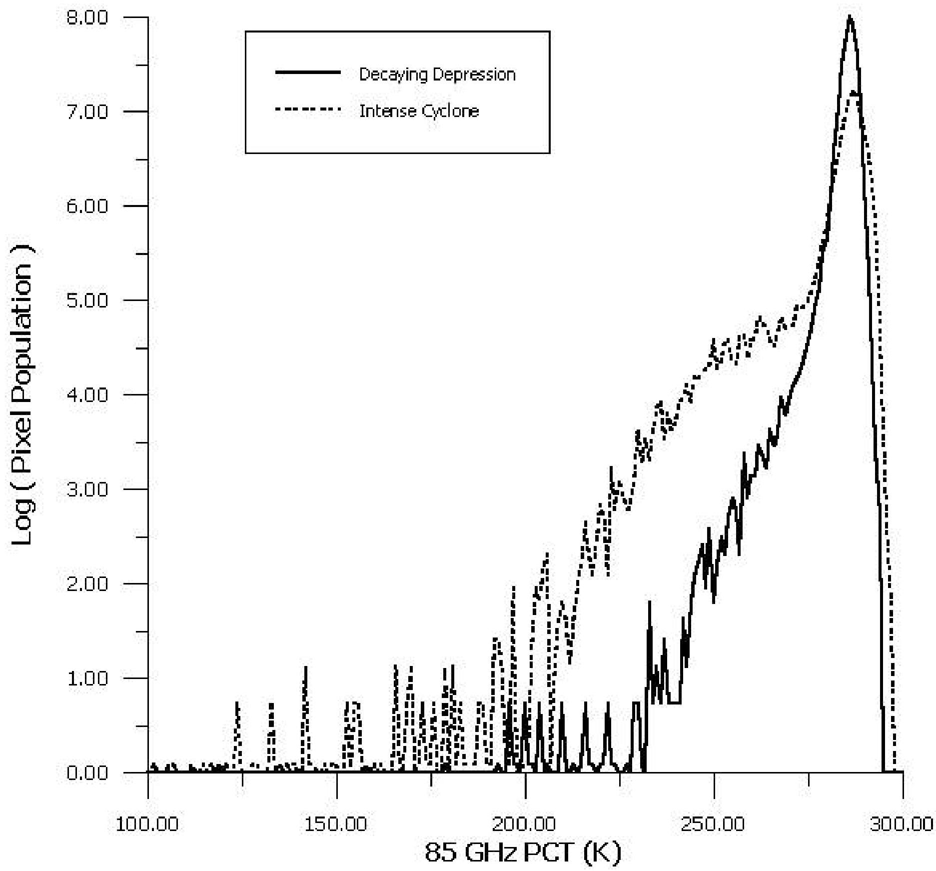
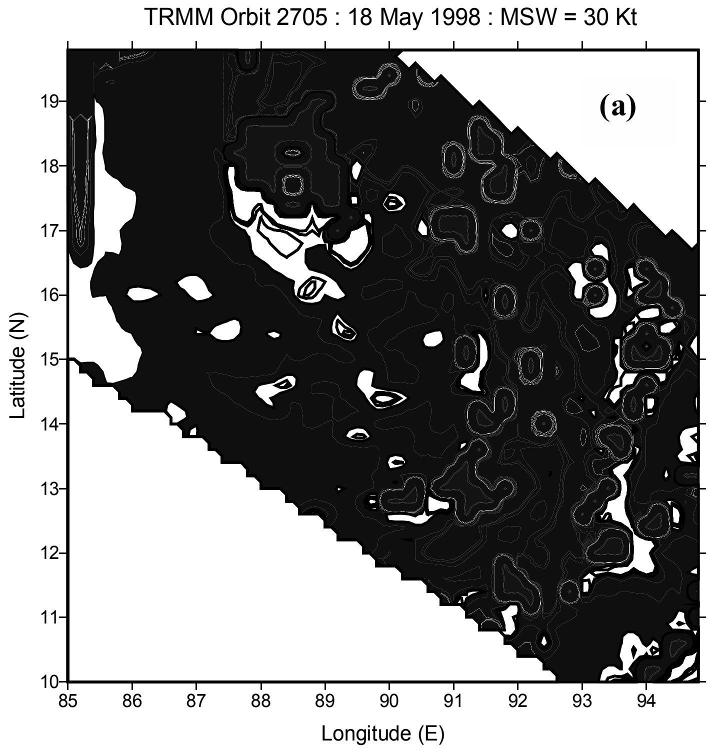


Fig. 3 : Histogram of 85GHz PCT values for one intense cyclone and one decaying depression.



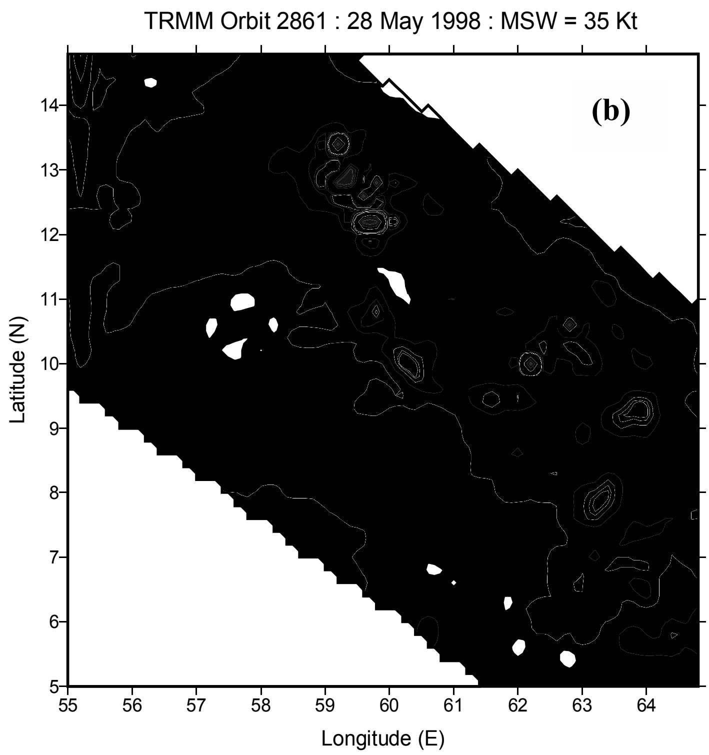


Fig. 4 : Distribution of 85 GHz PCT for (a) 18 May 1999 Rapidly Intensifying Cyclonic Depression (b) 28 May 1999 Decaying Cyclonic Depression. Hatched areas indicate cloudy region while dark regions show convective elements (85 GHz PCT < 250 K).

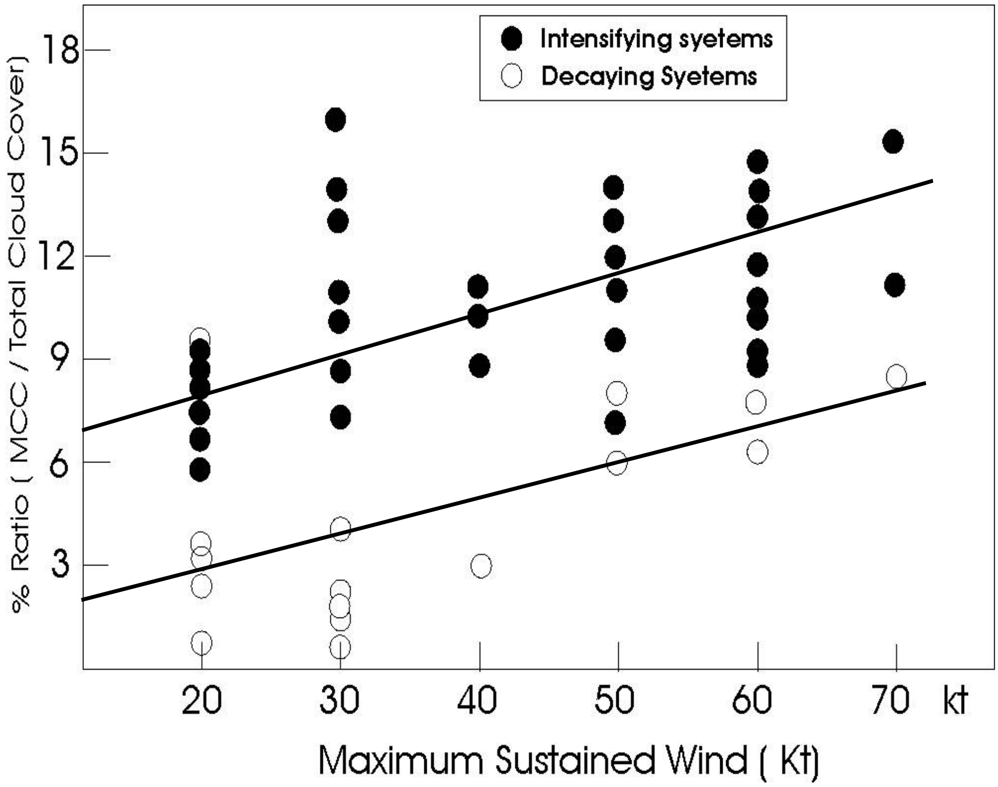


Fig. 5 **Ratio of areal coverage of convective elements to total cloudiness for intensifying (filled circles) and decaying systems (open circles)**

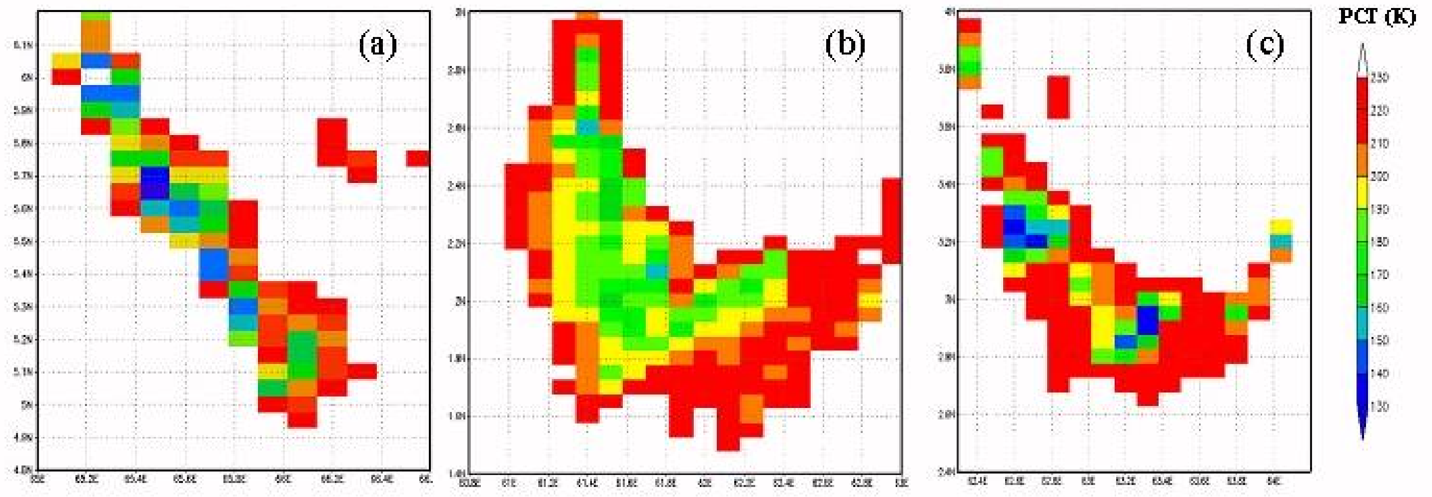


Fig. 6 : Distribution of 85 GHz PCT in the convective bands of three different stages of life history of May-1999 Arabian Sea cyclone (a) developing (17/05/99) (b) intense (19/05/99) and (c) decaying stages (21/05/99).