Mausam, (1981), **32**, **3**, 247-252

551.508.85 : 551.577 : 551.515

Radar estimate of rainfall and latent heat release in tropical cyclones of the Bay of Bengal

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(*Received 18 October 1979*)

ABSTRACT. Distribution of rainfall rates and latent heat release in three tropical cyclones of the Bay of Bengal has been estimated with a coastal radar. It is shown that the latent heat release (LHR) distribution and its changes appear well related to the intensity changes of the system and will be a valuable input for storm modelling. Attention is drawn to an asymmetrical distribution of LHR in one storm and the need to postulate a mechanism for transfer of the energy released to the large scale storm field in such cases.

The operational value of rainfall distribution estimates by radar for realtime warnings of flood and rain damage due to tropical cyclones is illustrated.

Radar is the only available tool in this area for continuous monitoring of cyclones in the absence of a geostationary satellite. Even when the latter becomes available radar can provide the ground-truth for rainfall and latent heat release determinations.

1. Introduction

Development of tropical cyclones is generally considered to be due to energy interactions between cumulus-scale convection and large scale synoptic motion field, leading to a self-amplification process or "conditional instability of the second kind" (Charney and Eliassen 1964, Kuo 1965). The release of latent heat in the convective processes and the distribution of such release appear therefore to be crucial factors in the development and intensification of tropical low pressure systems into mature cyclones. A knowledge of the latent heat release and its spatial and temporal variations in a cyclone should therefore help us to model its structure and perhaps predict its intensity changes. Determination of the rainfall rate and its distribution in a tropical storm will enable us to estimate the rate of latent heat release(LHR). Besides this, the rainfall distribution field is of course of direct operational interest as well.

In recent years techniques for estimation of rainfall from satellite visible and infrared pictures have been developed (*e.g.*, Martin and Scherer 1973 ; Griffith *et al.* 1978). The relationship between the brightness temperatures in such pictures and the rainfall is an indirect one. The advent of satellite microwave sensors very recently has enabled a more direct sensing of the liquid water and computation of latent heat release therefrom (*e.g.*, Wilheit *et al.* 1977, Adler and Rodgers 1977). The last mentioned authors working with NIMBUS-5 ESMR data have found that the total LHR in a tropical cyclone increases with the intensity of the system and that the contribution of higher rainfall rates to the LHR also increases likewise Griffith *et al.* (1978) who used visible and infrared geostationary satellite data are of the view that rather than the total LHR, the LHR in the core region of the storm is the one likely to yield a relationship with the system intensity. They have discussed also the operational application of rainfall estimation by satellite in determining the flood potential of hurricanes.

It is important to note here that the "ground truth"' for all satellite estimates of rainfall is obtained from *radar*. Over the sea there is no other means of obtaining areal rainfall data. Even

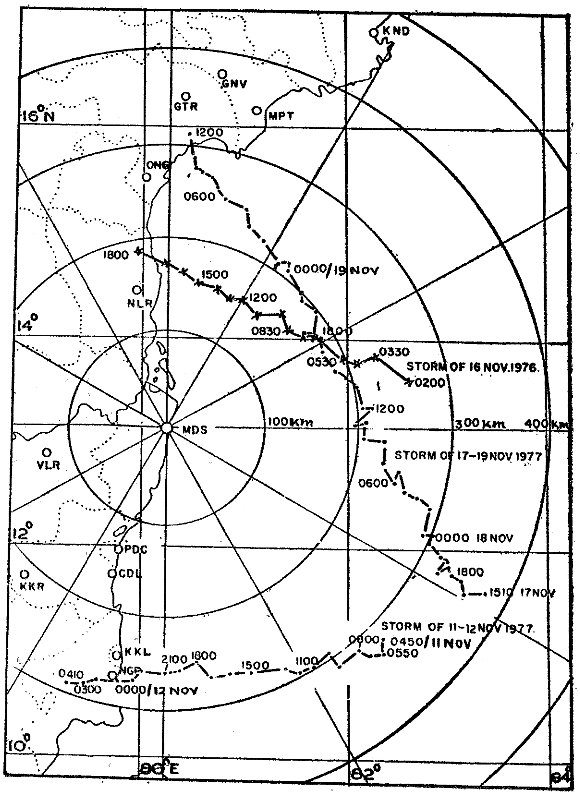

Fig. 1. Radar determined track of cyclones of 16 Nov 1976, 11-12 November 1977 and 17-19 November 1977 (time in GMT)

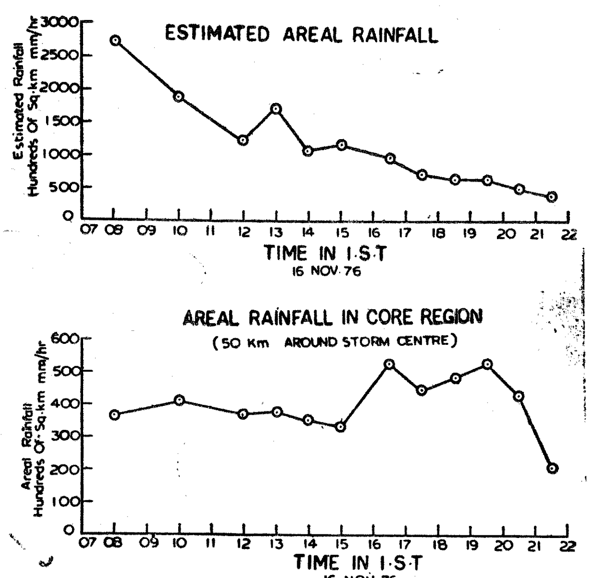

Fig. 2. Kavali cyclone of November 1976

over land, radar calibrated with a network of raingauges, is usually the only effective platform for quantitative estimation of areal rainfall rates over large areas. During "GATE", shipborne radars have been used for standardising the satellite estimates. Particularly in the Bay of Bengal region where geostationary satellite surveillance has not so far been available, radar provides the only means of continuous monitoring of a cyclone, although range limitations do constitute a significant handicap. Hence an attempt has been made in the present study for the first time in this region to estimate rainfall and latent heat release and their distribution in the case of three Bay Cyclones using an S-band radar at Madras, mainly with a view to assessing the validity and utility of such estimation.

2. Method of computation

The method used in this preliminary study is to digitise manually in a grid of 10 km $\times$ 10 km squares the radar* PPI photographs taken at discrete "isoecho" levels. With frequent monitoring of radar parameters and adjustments for their variations, this produces a map of radar reflectivity factor (Z mm^6/m^3) distribution. The conversion of this to a rainfall rate (R mm/hr) map requires a "ground truth" determination by calibration with a raingauge network. As no comprehensive radar-raingauge comparisons are available for this region, an earlier cyclonic storm which produced extensive rainfall on the 25-26 November 1975 in a land area within a radius of 200 km of Madras has been used for providing such a comparison.

In an area of 27500 km^2 having a raingauge density of one gauge per 275 km^2 the 24-hr areal rainfall upto 0830 IST of 26 November 1975 was computed by drawing isohyetal maps to be 1.400×10^6 sq km mm. The radar estimate by the manual digitisation method for the same area by using the standard Marshall-Palmer relation $Z=200R^{1 \cdot 6}$ was 1.396×10^6 sq km mm. The closeness of agreement is perhaps fortuitous, but may be considered to show that *Z-R* relationship assumed will give at least the *right order of magnitude* of the rainfall intensities. Hence this relationship has been used for the three cyclones, which being also November storms, may have the same *Z-R* relationship. Equipment for electronic realtime digitisation of the radar video is being added (at the time of writing) and in future this may enable more precise calibration with a raingauge network on a number of occasions large enough for application of statistical methods. A more refined estimate of the rainfall distribution in storms should thus become possible.

As the area of precipitation in the storm is usually greater than the 200 km radius of the isoecho system calibration of the radar, the digitisation was extended to a range of 300 km by applying suitable correction for range square

*The radar is a S-band radar of peak power 500 KW, beamwidth 2° pulsewidth about 4 us, located on the coast at Madras in nearly level terrain. An integrated range normalised analog isoecho presentation with 8 levels of echo intensity at 5 dB intervals is available.

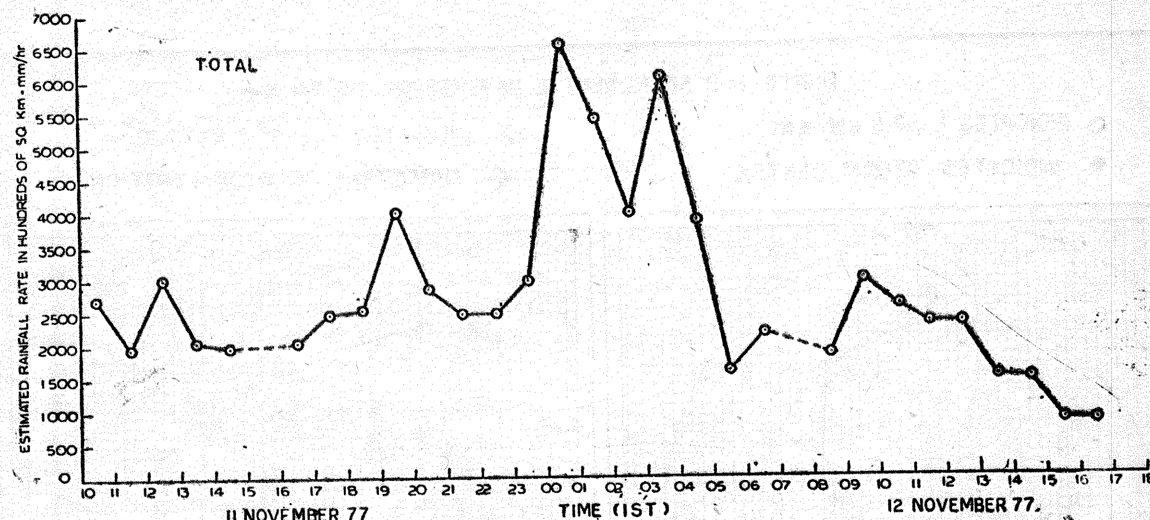

Fig. 3. Nagapattinam cyclone of November 1977 (Estimated areal rainfall.)

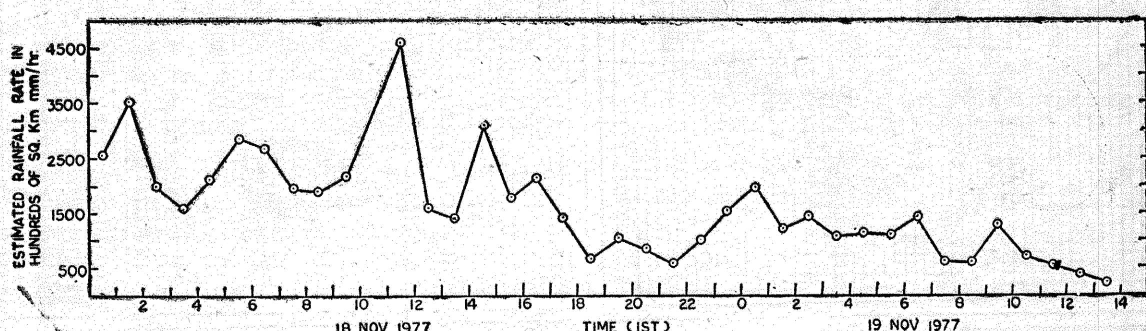

Fig. 4. Cyclone of 18-19 November 1977

and atmospheric attenuation. These two corrections were quite simple, but no realistic correction for the increasing altitude of the radar beam with range and for beamfilling errors could be carried out. With this limitation, digitisation of the PPI pictures have been carried out and rainfall rate in every 10 km × 10 km square computed over the area of the storm within 300 km of the radar for 3 storms, the tracks of which are shown in Fig. 1. The variation of the areal rainfall rates with time in these storms is plotted in Figs. 2 to 4. Fig. 2 also gives the variation of the rainfall rate in what may be considered as the core area (a radius of approximately double the eye radius) of the storm of 16 November 1976.

In a steady state system the condensation and precipitation inside the boundary are approximately equivalent to the boundary flux of latent heat. With this assumption Longley (1949), Watanabe (1963), and Adler and Rodgers (1977) among others have computed LHR in tropical cyclones by multiplying the mass of rainfall by the latent heat of evaporation per unit mass. Adler and Rodgers (1977) have discussed the assumptions involved in some detail. In the present study assuming that the rainfall estimated by radar viewing at zero degree elevation represents the entire LHR (L Gigawatts per sq km), the areal rainfall rate values have been converted to L values (1 sq km mm/hr corresponds to 0.7 GW/km^2). The areal distribution of L in 10 km × 10 km squares is presented in Fig. 5 for four selected hours for the storm of 11-12 November 1977. The values plotted are in fives of Gigawatts per square kilometre. Similar digital plots (not shown here) are available for the other two storms.

3. Discussion

The rainfall rate estimates presented are clearly under-estimates because (*i*) rainfall within 300 km of the radar site only has been considered, (*ii*) due to increase of beam height and sampling volume and uncertainty of propagation conditions, the radar estimate becomes increasingly inaccurate with increasing range and (*iii*) only the assumed *threshold* values for each isoecho level has been attributed to the digits. Yet if the storm position and extent is such that most of the precipitation occurs within the area of radar coverage, spatial and temporal distributions are at least likely to be representative of storm features even if the actual hourly values themselves are underestimates.

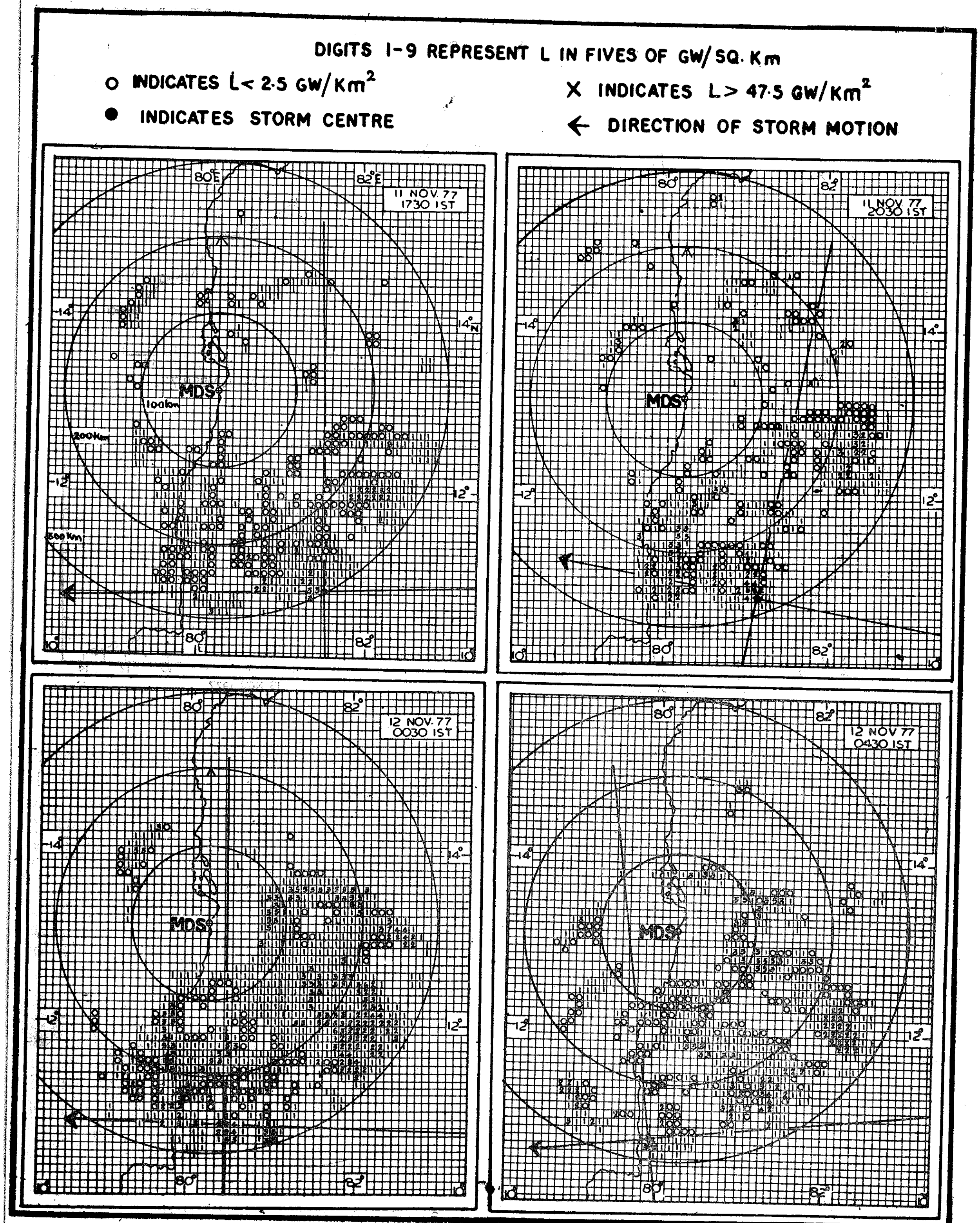

Fig. 5. Cyclone of 11-12 November 1977, digitized map of latent heat release (L)

3.1. *Storm of 16 November 1976*

This system was of small horizontal extent and the precipitation was confined most of the time well within the 300 km range. The eye as well as the entire radar echo coverage progressively shrank in size, as it approached the coast. From the eye size changes and from independent survey of storm damage, Raghavan *et al.* (1980 *a*) have shown that the storm was intensifying throughout the afternoon and evening of the 16th. Usually it is difficult to verify such intensification in the case of Bay cyclones from synoptic meteorological data, because wind and pressure data in the core area of the storm while at sea are almost non-existent. Hence reliance is placed on radar observed eye size changes which are generally accepted as related to storm intensity (Bell 1975). It is seen from Fig. 2 that the total areal rainfall rate was progressively *decreasing* during this period (due to the shrinking of the horizontal extent of the storm), but the core area rainfall rate *increased* simultaneously, probably in association with the intensification of the storm until it came very close to the coast. The time variation of latent heat release in this storm of course follows the rainfall rate variation curves, *i.e.,* the LHR in the core area increased, while the total LHR within radar range decreased, the order of magnitude of these two quantities being 35×10^{12} and 70×10^{12} watts respectively. Thus in this case increase of LHR in the core region is associated with intensification of the system, a result which agrees with the conclusion of Griffith *et al.* (1978).

3.2. *Storm of 17-19 November 1977*

This cyclone which was of unusually severe intensity was within 300 km of the radar from 00 GMT of 18 November to 06 GMT of the next day. The eye remained nearly constant in size during this period. The storm was already a mature one with a central pressure of 940 mb on the 18th. The rainfall rate (and LHR) were highest near the eyewall region. The total areal rainfall rate estimated by radar had a maximum value of 46×10^4 sq km mm/hr (*i.e.,* $L = 3.2 \times 10^{14}$ W) at 06 GMT of the 18th (Fig. 4). The contribution of rainfall rates over 18 mm/hr to the areal rainfall was 41 per cent at this time. The total areal rainfall as well as this percentage progressively decreased thereafter even though the storm was approaching the radar for several hours. Twenty four hours later these values were 5.8×10^4 sq km mm/hr and 8 per cent respectively. The core area rainfall rate (within 100 km of the centre) also *decreased* from 10.5×10^4 sq km mm/hr at 09 GMT of 18th to 3×10^4 sq km mm/hr at 06 GMT of the 19th. Thus there is a decrease in areal rainfall rate and in LHR from the 18th to 19th not only in the entire radar echo but in the core region as well. The contribution of heavy rainfall rates to the LHR also decreased. Following the findings of Adler and Rodgers (1977) and Griffith *et al.* (1978) there should have been some reduction of intensity of the system from the 18th to the 19th. Based on some other considerations also discussed in detail by Raghavan *et al.* (1980 b) it seems probable that the storm might have decreased to some extent in intensity from 18th to 19th.

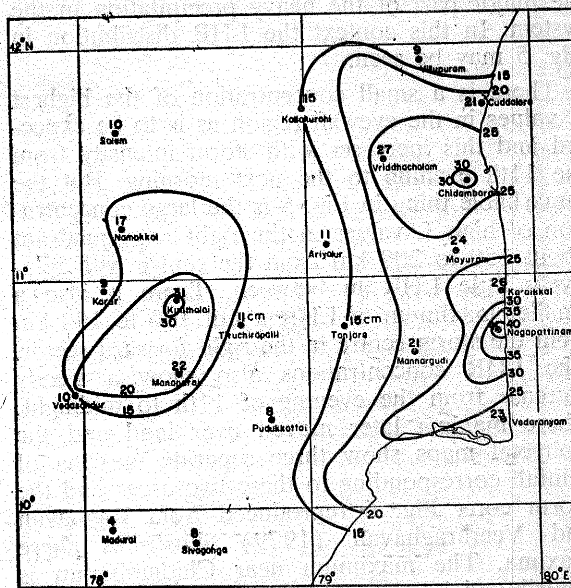

Fig. 6. Isohyetal map of 2-day rainfall (cm) of 12-13 November 1977

The areal distribution of LHR in this storm and the previous one discussed above invariably shows a maximum near the eyewall region and decreases with increasing distance from the core, *i.e.,* maximum energy liberation is occurring near the core region. This is an expected result and is in contrast with what follows in the case of the storm of 11-12 November 1977.

3.3. *Storm of 11-12 November 1977*

The apparent eye diameter of this storm as seen by radar was about 20 km on the 11th morning, but was only 5 km on the 12th morning. Even allowing for radar beamwidth errors, the eye was shrinking in size rapidly from 11th evening to 12th morning. From this and from independent evidence of rainfall distribution over land, surface wind speed, surface pressure and wind damage, Raghavan and Veeraraghavan (1979) concluded that the storm was intensifying during that period. They also established that while there was wind damage and heavy rainfall in the small core region and heavy rainfall in the right forward and rear quadrants of the storm, there was relatively little rainfall in the left quadrants of the storm outside the core region. Hence the radar which was seeing only the right quadrants was giving a coverage of the major part of the heavy precipitation in the system. In this context the LHR distribution in Fig. 5 may be seen.

There is a small concentration of the highest L values in the eyewall region as is to be expected and this increases with storm intensity from the 11th evening to the next morning. But the remarkable thing in Fig. 5 is the large concentration of high L values in the right *rear* quadrant about 150 to 200 km from the centre with relatively little LHR in between. There is also a smaller maximum of LHR about 100 to 150 km from the storm centre in the right forward sector. The LHR concentrations also show a steady increase from the evening of 11th to midnight. These maxima later moved over land and the isohyetal maps show three separate maxima of rainfall corresponding to these two areas and the storm core. Fig. 6 reproduced from Raghavan and Veeraraghavan (1979) illustrates these maxima. The maximum near Chidambaram is contributed by the right rear sector which came over land some hours after the storm landfall.

The concentration of LHR asymmetrically in the right rear sector well away from the core of this storm is a peculiar feature not seen in the other two storms considered above. This observation suggests that besides the LHR in the core, LHR in certain other locations in the system probably does contribute to the intensification of the cyclone. While thermodynamically it is possible to conceive of transfer of the localised convective energy release to the large scale storm field, it appears necessary to postulate a suitable mechanism for this purpose. More precise determination of LHR distribution in a number of storms may therefore constitute a valuable input for realistic modelling of tropical cyclone structure and understanding its intensification.

Figs. 5 and 6 also illustrate that besides contributing an input to the modelling of storm structure, the distribution of rainfall rate/LHR by radar, if estimated in realtime, can be used for more precise warnings of floods in particular areas, instead of giving a rather general warning for a large area as is the present practice.

4. Conclusions

The estimation of areal rainfall rate and latent heat release in tropical cyclones is possible with coastal S-Band radars subject to the limitation that rainfall within a range of at the most 300 km can be computed without the errors becoming unmanageable. Wherever satellite data are available, the radar data could be used as ground truth to extend the estimates over a larger area. Continuous monitoring of the rainfall rate/LHR distribution will provide an operational assessment of flood potential and rain damage. In addition it may be possible to relate the LHR distribution and its variation with time to changes in intensity of the system. This last relationship, if developed will be a powerful tool for assessment of intensity of tropical cyclones.

Acknowledgements

The authors are thankful to Dr. P. K. Das, Director General of Meteorology for going through the paper. It is a pleasure to acknowledge the assistance received in data collection and processing from a number of colleagues in the Cyclone Warning Radar group at Madras.

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