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Radar estimation of precipitation around Madras

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सार — मद्रास के समीप, चुने हुए 2000 वर्ग कि० मी० के लक्ष्य क्षेत्र के रेडार प्रेक्षणों की तुलना अभिलेखी वर्षामापी संजाल से की गई है। चक्रवातों से असम्बद्ध उत्तर पूर्व मानसून की वर्षा के लिये रेडार परावर्ती गुणक (Z) तथा वर्षणदर (R) के बीच माध्य सम्बन्ध का हल निकाला गया है। Z-R सभीकरण के स्थिरांक, मार्शल पामर मानों से काफी कम पाये गये।

प्रत्येक वर्षण के अवसर के लिये यह माध्य सम्बन्ध हो सकता है कि ठीक न हो। इसलिये छोटे वर्षामापी संजाल द्वारा प्रत्येक अवसर के रेडार अनुमान अनुपात के लिये जाल बनाया गया है और बड़े क्षेत्रों के रेडार अनुमानों के ऐसे समायोजन के लिये इस अनुपात का प्रयोग किया गया है। 17000 वर्ग कि० मी० के क्षेत्र में, पूर्णवर्षण के समायोजित अनुमान, 50 अनाभिलेखी वर्षामापियों के संजाल से द्विगुने गुणकों से सहमत होते हैं। रेडार तथा वर्षामापी द्वारा प्रदर्शित वर्षा के स्थानिक आवंटन भी काफी हद तक सहमत होते हैं। लेकिन बिन्दु अनुमान पर्याप्त सहमति प्रदर्शित नहीं करते।

यह निष्कर्ष निकाला गया है कि पूर्ण क्षेत्रीय वर्षण एवं वर्षा के स्थानिक आवंटन का अनुमान बड़े पमाने पर, माध्य मौसमी सम्बन्ध द्वारा किया जाता है और प्रत्येक छोटे वर्षामापी संजाल के लिये समायोजन गुणक का परिकलन किया जाता है। बड़े क्षेत्रों में उपग्रह अनुमानों के समायोजन के लिये रेडार अनुमानों का प्रयोग प्रारंभिक मानों के लिये किया जा सकता है।

ABSTRACT. Radar observations over a selected target area of 2000 sq km near Madras were compared with data from a recording raingauge network. A mean relationship for northeast monsoon rains not associated with cyclones between radar reflectivity factor (Z) and rainfall rate (R) was derived. The constants in the Z-R equation are found to be appreciably lower than the Marshall-Palmer values.

This mean relationship may not hold good for each individual occasion of rainfall. A gauge to radar estimate ratio was therefore determined for each occasion over this small raingauge network and this ratio used to adjust radar estimates over larger areas. Such adjusted estimates of total areal rainfall over 17000 sq km area were found to agree within a factor of two with a net work of 50 non-recording raigauges. Spatial distribution of rainfall indicated by radar and by raigauges also agree well but point estimates do not show good agreement.

It is concluded that total areal rainfall and spatial distribution of rainfall can be assessed over large areas by using a mean seasonal relationship and an adjustment factor derived for each occasion from a small raingauge network. The radar estimate can in turn be used as ground truth to adjust satellite estimates over larger areas.

1. Introduction

A study has been taken up at Madras to establish a methodology for radar estimation of rainfall over large areas. The first step in such estimation is to have a working relationship between equivalent radar reflectivity factor Ze (mm^6/m^3) and rainfall rate R (mm/hr).

Marshall and Palmer (Atlas 1964) first obtained a relationship between reflectivity factor Z and rainfall rate R of the form:

$$Z = AR^b \quad \text{where, } A=200 \text{ and } b=1.6$$

for temperate latitude rains. It is to be expected theoretically that the exponent b in the equation should be around 1.6 or 1.7. In practice, however, *Z-R* relationships have been found to vary widely with place and type of rainfall. Fujiwara (1965) and Stout and Mueller (1968) among others have given comprehensive surveys and discussion of *Z-R* relationships.

Notable among the early works in India on rain drop size distribution and *Z-R* relationships are those of Kelkar (1945, 1959, 1960, 1962 and 1968), Ramanamurthy and Gupta (1959), Sivaramakrishnan (1961) and Sivaramakrishnan and Selvam (1967). Kelkar as well as Sivaramakrishnan have computed *Z* and *R* from measurements of rain drop sizes at the ground. The results of Ramanamurthy and Gupta (1959) are also based on drop size measurements but have been applied by Ramanamurthy *et al.* (1960) and Biswas *et al.* (1962) to obtain radar estimates of rainfall at Delhi on some occasions. Chatterjee and Mathur (1966) made a limited comparison of radar and raingauge derived isohyets for monsoon rain around New Delhi but they have assumed the Marshall-Palmer constants to hold. In general it is difficult to expect the radar determined *Ze* or *Z** to yield a constant *Z-R* relationship with the rainfall measured at the ground. The reasons are not discussed here as they are available in the literature (*e.g.*, Stout and Mueller 1968).

It has been therefore considered by several scientists (Hitschfeld and Bordan 1954, Atlas 1964) that for practical rainfall measurement by radar it is better not to rely exclusively on *Z-R* relationships derived from theory or from drop size measurements. They have suggested starting with a reasonable *Z-R* relationship and adjusting the resulting radar estimate of precipitation with reference to a calibrating network of raingauges. The basic assumption here is that the radar measures the spatial and temporal variability of precipitation with adequate accuracy but requires a *fiducial* adjustment to get a realistic absolute value for each occasion of observation. Wilson (1970) successfully demonstrated this methodology in Oklahoma USA and several other scientists (*see e.g.*, Horrold *et al.* 1974, Herndon *et al.* 1973) have subsequently used it. This methodology has been adopted in in our present study with the following steps :

(1) Obtain a *'reasonable' Z-R* relationship for each season for the particular region of interest.

(2) Evaluate a radar estimate of rainfall amount *R'* for an extended period of time with this *Z-R* relationship over a small target area with a network of recording raingauges.

(3) Obtain a ratio (G/R') of gauge measured (G) to radar estimated (R') rainfall for this target area for each occasion.

(4) Adjust the radar estimate over larger areas of interest by multiplying the radar estimate by the G/R' value for that occasion.

2. Evaluation of Ze from radar observations

The specifications of the radar used for this study are as given by Raghavan (1975). Photographs of the echoes upto 100 km range on the PPI scope were taken at regular intervals (usually once in 15 min) at the successive isoecho levels, which correspond to receive power (P_r) values in steps of 5 dB above a preset threshold. The photographs are projected over a grid map divided into 5 km $\times$ 5 km squares. The maximum isoecho level numbers at which echoes appear in each square in a selected target area are noted. The 2000 sq km target area (Fig. 1) selected is free from ground clutter and radar shadows. From Probert Jones' equation (Raghavan 1975), the P_r values are converted into equivalent reflectivity factor (*Ze*) values. Thus one map of instantaneous distribution of *Ze* for each set of pictures is obtained and this is taken to represent the 15 minute period around the time of observaion.

The radar parameters — peak transmitted power, frequency pulse width and pulse repetition frequency — are monitored every week. The other radar parameters (antenna gain, beamwidth head losses) are assumed from initial measurements. Attenuation due to intervening precipitation and due to water film on radome are neglected at 10 cm wavelength. A range normalisation and correction function for attenuation by atmospheric gases is available through the same 'PIN' modulator which provides the 'isoecho' function. The calibration of the PIN Modulator circuit is carried out once a week and it is found that this circuit is reasonably stable from week to week and is accurate to within about $\pm$ 1 dB of received power in the range of signals dealt with.

The radar was operated at an antenna elevation of either 0 deg. or 2 deg. At a range of 100 km the mean height of the radar beam in normal propagation conditions is 0.6 km for zero degree elevation and 4.2 km for 2 deg. elevation. At both these elevations, therefore, the beam does not cut the melting band within this range. Although theoretically the beam should be as close to ground as possible to get a good correlation with rainfall measured at the ground, there are problems due to obstructions and absorptions by the ground surface at low elevation of 0 deg. at short ranges. As will be

* Since Rayleigh scattering is assumed to hold at least at the 10 cm wavelength which is large in comparison with raindrop sizes, the symbols *Z* and *Ze* are being used interchangeably in this paper, although strictly only *Ze* is obtained from the radar.

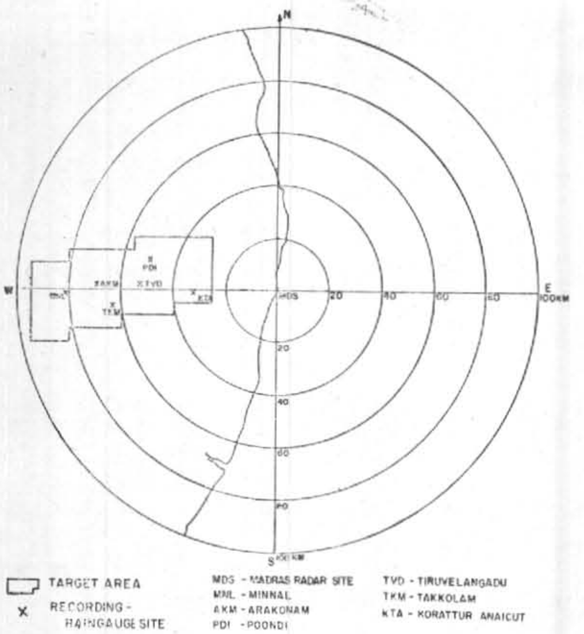

Fig. 1. Target area (2000 sq km) and raingauge network used in the study

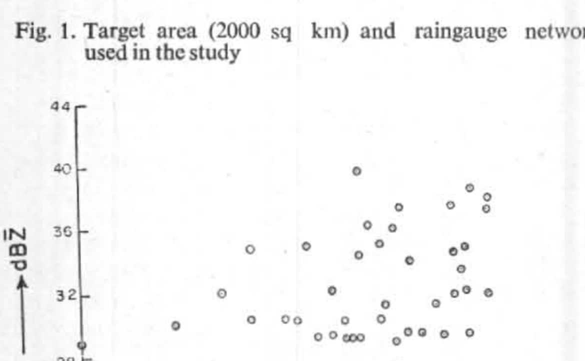

Fig. 2

demonstrated presently, operation at 2 deg. elevation gives better results at ranges upto 100 km. Observations at other elevations are also planned for subsequent seasons.

A small network of self recording raingauges was set up in a target area of 2000 sq km at distances of 40 to 80 km west of the radar site to obtain rainfall rates for comparison with the radar (Fig. 1).

In these conditions of operation the *Ze* value refers to a sampling volume of upto six cubic km which is very large in comparison to the sampling volume of a raingauge or of any drop size measurement at the ground. This difference as well as the wind drift and other factors make *point* rainfall comparison unlikely to be successful. Fig. 2 for example shows a plot of dBZ *vs* dBR values (*i.e.,* values of Z and R in dB above unity) computed for individual raingauge sites (Z averaged over a 10 km $\times$ 10 km area) for a number of occasions of typical northeast monsoon rainfall in November 1979. The plot exhibits a very wide scatter of points from which it is not possible to draw a regression line to obtain A and b. An *areal* rainfall comparison with the entire network of raingauges and over a longer period of time was therefore tried. Since it is not meaningful to average *Ze* values over a large area or over a period of time the *Ze* values for each square for each observation had to be converted to a radar estimated R assuming arbitrary values of A and b, before making an areal integration. These R values were then added up over the entire target area and over a period of several hours to yield a radar estimated areal rainfall amount (R'sq km mm).

A corresponding raingauge estimated areal rainfall amount (G sq km mm) for the same period was derived from the recording raingauges. For obtaining the average from six raingauges over this flat terrain, simple averaging was considered preferable to drawing of isohyets or of Thiessen polygons. The ratio G/R' for each occasion was then calculated. Ideally this should be unity. The actual results for various assumed values of A and b are shown in Tables 1, 2 and 3. The occasions considered were all typical northeast monsoon rainfall without any intense system (depression or cyclone) being present.

3. Discussion of G/R' ratios

In a recent paper Raghavan and Varadarajan (1981) working with the same radar have assumed the standard Marshall-Palmer relationship (hereafter referred to as M-P).

$$Z = 200\ R^{1.6}$$

and computed areal rainfall associated with a tropical cyclone. They compared it with an isohytetal map from a dense network of raingagues and obtained close agreement. On this basis they made *order-of-magnitude* estimates of rainfall distribution in other cyclones. While this approach is probably adequate for *order-of-magnitude* estimates of areal rainfall, absolute values of areal rainfall obtained from the M-P relation do not compare very well with raingauge data in non-cyclone situations as can be seen from Table 1.

As distinct from cyclones, northeast monsoon rain in non-cyclone situations is characterised by relatively low cloud heights and may have relatively smaller drop sizes. Further, among the factors considered by Mason and Ramanadham (1954) as responsible for modification of the drop size spectrum before the rain reaches the ground, evaporation below cloud base is the only one which can cause reduction in size as

TABLE 1

Ratio of gauge and radar estimated areal rainfall values for various assumed values of exponent *b*. Coefficient *A* assumed as 200

Date of exp. (Nov-1979)	Duration of obsn. (IST)	G/R′ values for b=					
		1.0	1.1	1.2	1.3	1.4	1.6
8	1230-1530	0.7 (2.8)	1.0 (3.7)	1.3 (4.7)	1.6 (5.7)	1.9 (6.7)	2.6 (8.7)
9	0900-1230	2.1	2.6	3.1	3.6	4.1	5.1
10	0515-1000	1.2	1.4	1.6	1.8	2.1	2.4
11	0715-1315	1.0	1.1	1.4	1.6	1.8	2.2
12	0545-0945	2.9	3.8	4.6	5.4	6.2	7.8
16	1045-1530	1.1 (4.3)	1.4 (5.1)	1.7 (16.2)	2.1 (7.1)	2.4 (8.1)	3.2 (9.7)
18	0815-1115	0.6 (2.1)	0.8 (2.7)	1.0 (3.2)	1.3 (3.4)	1.5 (4.3)	1.9 (5.2)
18	1430-1730	1.3 (2.9)	1.8 (3.9)	2.3 (4.9)	2.4 (5.6)	3.3 (6.8)	4.4 (8.6)

Values indicated are for operation at antenna elevation of 2 deg. except those in brackets which correspond to an elevation of zero deg.

TABLE 2

Ratio of gauge to radar estimated values of areal rainfall for various assumed values of coefficient *A*. Exponent *b* assumed as 1.1

(operation at antenna elevation of 2°)

Date (Nov 1979)	*G/R′* for *A*=				
	50	100	150	200	250
8	0.3	0.5	0.7	1.0	1.2
9	0.7	1.4	2.0	2.6	3.2
10	0.4	0.7	1.1	1.4	1.7
11	0.3	0.6	0.9	1.1	1.4
12	1.1	2.0	2.9	3.8	4.7
16	0.4	0.7	1.1	1.4	1.4
18 (F.N.)	0.2	0.6	0.7	0.8	0.9
18 (A.N.)	0.5	0.9	1.3	1.8	1.9

TABLE 3

Ratio of gauge to radar estimated values of areal rainfall for various assumed values of coefficient *A*. Exponent *b* assumed as 1.2

(operation at antenna elevation of 2°)

Date (Nov 1979)	*G/R′* for A=				
	50	100	150	200	250
8	0.4	0.7	1.0	1.3	1.5
9	1.0	1.7	2.4	3.1	3.7
10	0.5	0.9	1.3	1.6	1.9
11	0.4	0.8	1.1	1.4	1.6
12	1.4	2.6	3.6	4.6	5.5
16	0.5	1.0	1.4	1.7	2.1
18 (F.N.)	0.3	0.6	0.8	1.0	1.3
18 (A.N.)	0.7	1.3	1.8	2.3	2.8

the drops come to the ground, all other factors result in increase of dropsize at the ground as compared to the radar sample aloft. In northeast monsoon situations of widespread rainfall, the ambient humidity below cloud base is quite high and evaporation may be less important in comparison to the other factors. Hence a conversion of *Ze* values measured aloft to *R* values using the M-P formula should yield low *R* values as compared to the raingauge data. The beam height and related factors are also likely to result in under-estimation of rainfall by radar. Agreement between the measured *Ze* and gauge measured rainfall rate may therefore be expected with lower values of the constants *A* and *b* than the M-P values. Though the adjustment of *A* and *b* on a purely statistical basis as is attempted in Tables 1, 2 and 3 is not elegant from a physicist's point of view, constants obtained by this method provide a practical way of getting reasonably correct estimates at least for a given radar site.

Table 1 gives the G/R' ratios as defined above for eight occasions in November 1979 for various assumed values of the exponent keeping *A* constant at the M-P value of 200. Values of *b* higher than 1.6 were not considered for the reasons discussed above. On each occasion the observation extended over a period of several hours with sampling at 15 minute intervals. In each case the radar antenna was operated at 2 deg. elevation, but on three occasions the observation was taken at zero deg. elevation also and the corresponding G/R' values are shown in brackets in Table 1.

The following is evident from the Table :

(*i*) With a 0 deg. elevation observation, it is not possible to get a G/R' value close to unity with any value of *b* between 1.0 and 1.6.

(*ii*) With 2 deg. elevation, G/R' values within 3 are obtainable on most occasions by adjusting *b*. Hence it seems reasonable to assume that 2 deg. elevation gives a better radar estimate free from ground effects, at ranges upto 100 km.

(*iii*) A value of *b* in the range 1.1 to 1.2 yields G/R′ values closest to unity.

The effect of varying *A*, keeping *b* constant at 1.1 or 1.2 is shown in Tables 2and 3 respectively. It is seen from these tables that a combination of $A=150$, $b=1.1$ or $A=100$, $B=1.2$ gives G/R' ratios within 2.0 (except on one occasion — 12 November 1979), *i.e.*, on most occasions of northeast monsoon rain, the relationship:

$$Z = 150\ R^{1.1}$$

or

$$Z = 100\ R^{1.2}$$

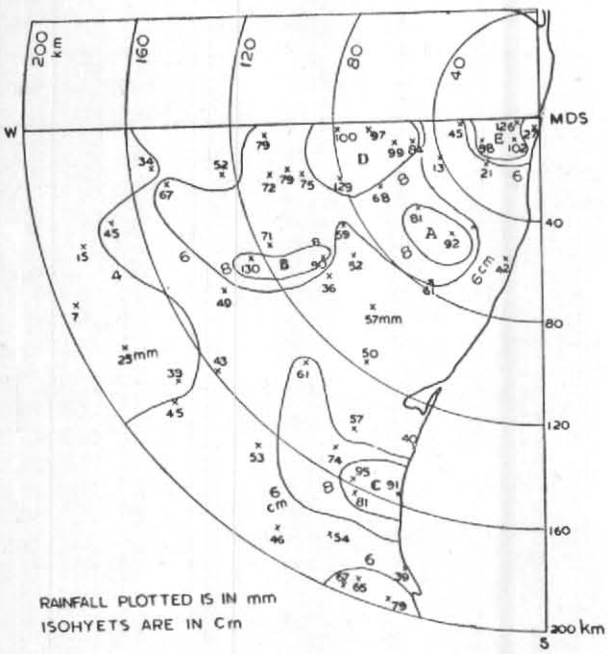

Fig. 3. 24 hours isohyetes based on raingauge data

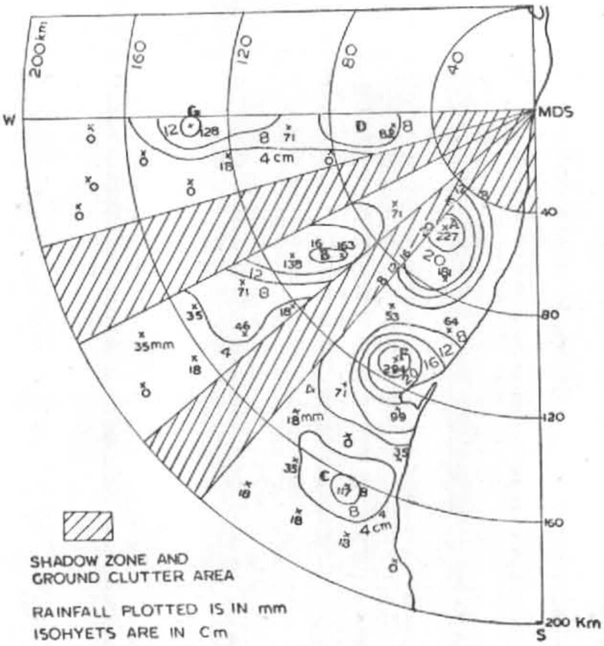

Fig. 4. 24 hours radar isohyetes

gives a radar estimate of areal rainfall within a factor of two. Any one of these two formulae can be chosen as a mean relationship for the northeast monsoon season for this area.

4. Estimation of areal rainfall over larger areas

It is seen from the Tables 1, 2 and 3 that the mean relationship derived above does not hold good for 12 November 1979. On this occasion there was heavy rainfall at one station at the western end of the target area and relatively light amounts at other gauges. The areal average G was influnced by this high point value, thus leading to a high G/R' ratio. Tests of these Z-R relationships with some data of earlier years also shows that the G/R' ratios often depart appreciably from unity. Hence to obtain a valid estimate of areal rainfall on any given occasion the R' value obtained from the above Z-R relation has to be further adjusted using the G/R' value appropriate to that particular occasion.

The above approach presupposes the availability of data from a small raingauge network on every occasion to adjust the radar estimate. If the estimation is to be made in realtime, the raingauge data should also be available in realtime. Then what is the advantage of attempting a radar estimate? The advantage is that some G/R' ratio can be assumed to be valid over a larger area and radar used to determine the areal rainfall over the larger area which may not have an adequate raingauge network. Rainfall estimates over the sea can also be made in the same way. It is assumed that the radar assesses the variability of rainfall in space and time correctly and needs only a *fiducial* adjustment against a small raingauge network. For this purpose the radar estimate taken over an area of 17338 sq km within 200 km of Madras was compared with data from a network of about 50 raingauges over the same area. Further, the spatial variability of rainfall as indicated by radar was compared with that indicated by the raingauge network. Considering the radar specifications, 200 km is taken to to be the largest range upto which reasonably accurate rainfall estimate can be made. At this range the mean height of the radar beam at 0 deg. elevation of the antenna is 2.4 km and at 2 deg. elevation it is 9.3 km. Hence a beam at the latter elevation will see only the tops of clouds and will also cut the melting band. An elevation of 0 deg. therefore is more suited for hydrological measurements upto 200 km. It was shown earlier that at short ranges of 40 to 80 km in which the calibrating raingauge network was situated, observation at 2 deg. elevation was preferable. Since the mean heights of the 2 deg. beam at 40 to 80 km range and those of the 0 deg. beam at 100 at 200 km are comparable, the Z-R relationship obtained with the 2 deg. elevation at close-range is taken as applicable to data collected at 0 deg. elevation at larger ranges. Use of different elevations for different range intervals has been found to give satisfactory results in the UK (Ball *et al.* 1976). Hence radar photographs were taken for 24 hours at frequent intervals on two occasions of widespread rainfall in November 1979 at an elevation setting of zero degree. An area in Tamilnadu where a network of 50 ordinary raingauges was available within 200 km radius (Fig. 3) was selected. The shadow zones and an area of 40 km radius around the radar site where there is excessive bloom in the radar pictures were excluded. The net area considered(shown in Fig. 4) is 17338 sq km. Since most of the gauges are read only once in 24 hours, the observations had to be taken for 24 hours at a time and only the cummulative 24 hours total radar estimate could be compared with gauge data.

The isohyetal map derived from the gauge data for the 24 hour period ending at 0830 hours of 13 November 1979 is shown in Fig. 3. This occasion was characterised by widerspread and sustained rainfall throughout the area in association with a low pressure area over the Bay of Bengal. The total areal rainfall (G_T) in 24 hours was computed from the isohyetal map. The radar pictures were digitised over a 10 km × 10 km grid, and the radar-estimated total areal rainfall (R_T) computed using the relationships :

$$Z=100\ R^{1.2} \quad \text{and} \quad Z=150\ R^{1.1}$$

and then summing over 24 hours. The G_T and R_T thus obtained for two successive 24 hours periods are shown in Table 4. The G/R' ratios for the small recording raingauge network of 2000 sq km area for 12 November 1979 were 2.6 and 2.9 respectively (Tables 2 and 3) for these two *Z-R* relationships. These (G/R') ratios were used to multiply the R'_T in Table 4 to get an adjusted radar estimate R'_A for the area of 17338 sq km. The R'_A values, also shown in Table 4, agree well within a factor of *two* with the G_T values. Thus the adjustment procedure employed gives areal rainfall estimation within a factor of two over the larger area.

The reader would have noticed that in these cases even the unadjusted radar estimate R'_T in Table 4, shows agreement with the gauge total (G_T) within a factor of two. However, it was shown earlier that the mean *Z-R* relationship by itself need not necessarily hold in each individual case; hence an adjustment is needed. In this case the adiustment is based on a G/R' ratio obtained from the small recording raingauge network for a four hour period on the morning of 12 November 1979. In this period the rainfall was high at the western end of the small network

TABLE 4

Gauge (G_T) radar estimated (R'_T) and adjusted (R'_A). Total areal rainfall over an area of 17338 sq km

24-hr period Dates (Nov 1979)	G_T (sq km mm)	for $Z=100\ R^{1.2}$		for $Z=150\ R^{1.1}$	
		R'_T (sq km mm)	$R'_A=(G/R')\times R'_T$ (sq km mm)	R'_T sq km mm)	$R'_A=(G/R')\times R'_T$ (sq km mm)
12 to 13	8.3×10^5	5.3×10^5	13.7×10^5	4.7×10^5	13.7×10^5
13 to 14	4.4×10^5	3.1×10^5	8.1×10^5	2.8×10^5	8.1×10^5

with relatively less rainfall in the other gauge sites. Due to arithemetical averaging of the gauge data, this has apparently resulted in a high '*G*' values and, therefore, also a high G/R' value of 2.6 or 2.9. This may explain the rather high value of R'_A in Table 4.

Another interesting result brought out in Table 4 is that areal rainfall estimate by radar is almost unchanged when the *Z-R* relationship is changed from $Z=100\ R^{1.2}$ to $Z=150\ R^{1.1}$. Hence one single relationship for the entire season can be used provided adjustments as above with the gauge network are made for each occasion.

5. Spatial distribution of rainfall as assessed by radar

The above analysis establishes only that the precipitation integrated over the entire area is reasonably estimated by radar. To establish clearly whether the spatial *distribution* of rainfall is also correctly assessed, point rainfall estimate for 24 hours for a large number of individual grid squares (each 10 km × 10km) were derived using the $Z=100R^{1.2}$ relationship. These were adjusted with the same G/R' ratio of 2.6 and are plotted in Fig. 4. Grid points falling in radar shadow zones and in the central bloom area were excluded. "*Radar Isohyets*" based on these grid points are also shown in Fig. 4. A comparison of these with the gauge isohyets in Fig. 3 shows the following :

(*i*) The point values of rainfall estimated by radar closely agree with the gauge values in some cases but diverge upto a factor of three in others. This confirms the conclusion that point rainfall estimation with radar is not very reliable.

(*ii*) The spatial distribution of rainfall indicated by radar agrees quite closely with that given by the gauge network. The latter shows five maxima at the locations marked A, B, C, D, E, in Fig. 3. The first four of these occur in approximately the same locations in the radar map (Fig. 4). The maximum at E fall in the ground clutter area of the radar which therefore cannot detect it. The radar map shows two more maxima (F and G) in areas where there are no raingauges. Hence the gauge network does not exhibit these maxima.

(*iii*) Even on an occasion of widespread rainfall associated with a well-defined synoptic system such as that of 12/13 November 1979, both the gauge network and radar show the existence of considerable spatial gradients in the rainfall map. This would mean that extrapolation or interpolation of rainfall for the areas lacking in radar observations may not be accurate.

6. Realtime estimates of areal rainfall by radar

The above discussion establishes that total areal rainfall over large areas as well as spatial distribution can be correctly assessed by radar provided that an adjustment factor can be derived from a small guage network for each occasion. Hence for *realtime* radar estimation of precipitation it is necessary that the gauge data at least from a few gauges should be available in realtime and radar data have to be processed in realtime. For the latter purpose a digital video processor and rainfall computer is being installed at Madras and when this becomes operational realtime printout of rainfall by radar may be possible. The procedure for adjustment with reference to raingauge data will then have to be incorporated in the computer software. Telemetering raingauges capable of feeding the data from the calibration points directly to be computer would also be necessary.

7. Estimation of rainfall over sea

The methodology described above makes it possible to compute total areal rainfall and rainfall distribution over the sea around Madras upto a range of at least 200 km by assuming the *Z-R* relationship derived on land to be valid over the sea. This should be useful for studies of low pressure systems over the sea including depressions and cyclones (Raghavan and Varadarajan 1981). As, however, such systems are usually larger in diameter than 200 km it is desirable to extend rainfall estimates to still larger areas. The estimates within 200 km can be used as ground truth to calibrate satellite estimates by visible, infared or microwave sensors (*see, e.g.*, Griffith *et al.* 1978; Wilheit *et al.* 1977) and the satellite estimate of precipitation can be obtained over very large areas.

8. Conclusions

A mean relationship for the northeast monsoon season at Madras between radar reflectivity factor (Z) derived from radar measurements and raingauge derived rainfall rate (R) has been determined. The relationship is $Z = 100R^{1 \cdot 2}$ or $Z = 150R^{1 \cdot 1}$. Radar estimates thus derived have, however, to be adjusted on each occasion using a Gauge Radar ratio obtained from a small network of calibration gauges. The adjusted radar estimates give the total areal rainfall over a large area within a factor of two and also correctly represent the spatial distribution of rainfall.

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