Mausam, (1987), **38**, 3, 335-340

551.508.7 : 551.553.21 (548.1)

A radar reflectivity-rainfall rate relationship for the southwest monsoon season for the Madras area

S. RAGHAVAN, T. R. SIVARAMAKRISHNAN*,
S. RENGARAJAN and S. W. PREM KUMAR
Cyclone Detection Radar, India Met. Dep., Madras

(*Received 30 July 1984*)

सार — राघवन एवं शिवरामकृष्णन (1982) की पद्धति का अनुसरण करते हुए रिकार्ड करने वाले वर्षामापियों के एक समुच्चय के साथ एक तुल्यरूप (अनालौग) समप्रतिध्वनि (आईसोइको) परिपथ तथा आंकिक (डिजिटल) वीडियो संसाधन, दोनों का उपयोग करते हुए मद्रास क्षेत्र के लिए दक्षिणपश्चिम मानसून ऋतु के लिए माध्य Z-R सम्बन्धों को व्युत्पति किए गए थे। पहले उपयोग में लाए गए तुल्यरूप परिपथ, जो कि प्राप्त की हुई शक्ति का अधिक मान बताते थे, की अपेक्षा आंकिक संसाधन संकेत औसतन की एक पद्धति का उपयोग करते हैं। आंकिक रडार की सहायता से प्राप्त माध्य सम्बन्ध का उपयोग वर्षा के व्यवहारिक आकलन के लिए तथा वास्तविक समय और इसके क्षेत्रीय वितरण में जलवायुविज्ञान सम्बन्धी प्रयोगों के लिए किया जा सकता है। किन्तु अंशांकित वर्षामापी के उपयोग में लाने के प्रत्येक अवसर पर आकलन के परिमाण का एक समंजन आवश्यक है।

ABSTRACT. Following the methodology of Raghavan and Sivaramakrishnan (1982), mean Z-R relationships were derived for the southwest monsoon season for the Madras area using both an analog isoecho circuit and digital video processor along with a set of recording raingauges. The digital processor uses a better method of signal averaging than the analog circuit used earlier which tended to overestimate the received power. The mean relationship obtained with the digital radar can be used for practical estimation of rainfall and its spatial distribution for realtime and climatological purposes. However, an adjustment of the magnitude of the estimate on each occasion using calibrating raingauges is necessary.

1. Introduction

In a recent paper, Raghavan and Sivaramakrishnan (1982), hereafter referred to as R-S, discussed the methodology for areal estimation of precipitation by radar. They also obtained a mean radar reflectivity factor (Z mm^6. m^{-3}) *vs.* rainfall rate (R mm. hr^{-1}) relationship for the northeast monsoon season for the Madras area based on radar-raingauge comparisons using a 10 cm radar with analog isoecho circuits. In the present paper a mean Z-R relationship for the southwest monsoon season has been obtained from a similar experiment in 1981 using analog radar data. Subsequently a digital video processor has been added to the radar capable of yielding a better averaging of the radar signal intensities. Data were available for some occasions during the monsoon season of 1982 and 1983. This gave an opportunity to recheck and revise the result obtained in 1981 and provide a new mean relationship which can be used on the digital system to give realtime printouts of rainfall distribution.

2. Methodology

The method of evaluation of analog radar data and their comparison with raingauge data has been discussed by R-S and will only be briefly recapitulated here.

The radar is operated at 15 minute intervals of time and photographs of the PPI scope are taken at preset thresholds of received power at intervals of 5 dB, after normalising the signal to 200 km range and integrating 5 successive video pulses by the analog isoecho circuits. The pictures are digitised manually by projecting over a 5 km×5 km or 10 km×10 km grid. The 'isoecho' thresholds are allotted rainfall rate values according to various assumed Z-R relationships of the form :

$$Z = AR^b \tag{1}$$

For values of A=100, 150, 200 and b=1.1 to 1.6, the total rainfall R' (km^2. mm) is computed over the experimental period over a target area of 2000 km^2. The target area which is in flat terrain about 40 to 100 km

---

*Present address : Meteorological Office, Mohanbari Airport, Dibrugarh-786 012, Assam.

TABLE 1

Ratio of gauge (G) to radar (R') estimated values of areal rainfall for various assumed values of coefficients, A and b using analog data for 1981. Antenna elevation one degree

Date of experiment (1981)	Duration of observation (IST)	G/R' values for																	
		A=100						150						200					
		1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6
										b									
25 Jun	1604-1959	0.4	0.5	0.6	0.7	0.8	1.0	0.6	0.7	0.8	1.0	1.0	1.2	0.7	0.9	1.0	1.2	1.2	1.5
17 Aug	1748-1948	0.7	0.9	1.1	1.3	1.7	1.8	1.1	1.3	1.5	1.8	2.2	2.3	1.3	[illegible].6	1.9	2.2	2.7	2.8
19 Aug	1656-1940	1.1	1.5	2.1	2.6	3.3	3.8	1.6	2.1	2.8	3.4	4.3	4.8	2.0	2.7	3.5	4.2	5.2	5.8
22 Aug	1704-1932	0.5	0.7	0.8	0.9	1.1	1.1	0.8	0.9	1.1	1.2	1.4	1.4	1.0	1.2	1.4	1.5	1.7	1.8
25 Aug	1930-2150	0.3	0.3	0.5	0.6	0.8	0.9	0.3	0.5	0.7	0.8	1.0	1.1	0.4	0.6	0.8	0.9	1.1	1.3
7 Sep	1800-1915	0.3	0.4	0.7	0.9	1.1	1.3	0.3	0.6	0.8	1.0	1.4	1.5	0.4	0.5	0.7	0.9	1.1	1.3
8 Sep	1558-1837	0.3	0.4	0.6	0.8	1.0	1.1	0.4	0.5	0.7	0.9	1.3	1.5	0.6	0.8	1.0	1.3	1.6	1.8

TABLE 2

Ratio of gauge (G) to radar (R') estimated values of areal rainfall for various assumed values of coefficients A and b using analog data for 1981. Antenna elevation two degrees

Date of experiment (1981)	Duration of observation (IST)	G/R' values for																	
		A=100						150						200					
		1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6
										b									
17 Aug	1748-1948	0.7	1.0	1.2	1.4	1.7	1.8	1.2	1.4	1.6	1.9	2.3	2.3	1.4	1.7	2.0	2.3	2.8	2.8
19 Aug	1656-1940	0.8	1.2	1.6	2.1	2.7	3.1	1.2	1.6	2.1	2.6	3.5	4.0	1.5	2.1	2.7	3.4	4.2	4.7
22 Aug	1704-1932	0.8	1.1	1.3	1.4	1.7	1.8	1.2	1.4	1.7	1.8	2.2	2.3	1.6	1.8	2.1	2.3	2.6	2.8
25 Aug	1930-2150	0.3	0.3	0.5	0.6	0.8	0.9	0.4	0.6	0.7	0.8	1.0	1.1	0.5	0.6	0.8	1.0	1.2	1.4
8 Sep	1558-1837	0.3	0.4	0.5	0.7	0.9	1.1	0.4	0.5	0.6	0.8	1.2	1.4	0.5	0.7	0.9	1.2	1.5	1.7

west of Madras has a number of recording raingauges some of which are installed for this purpose by the India Meteorological Department and the rest by other agencies for their own use. The areal rainfall for the target area for each experimental period is obtained by averaging these raingauge readings (G km^2 mm). The G/R' ratios vary considerably from the ideal value of unity. The A-b combination which consistently gives G/R' ratios closest to unity is used for the mean Z-R relationship.

A similar experiment was carried out in the southwest monsoon season of 1981, using on the average 5 raingauges in a target area of 2100 km^2. The G/R' values are presented in Tables 1 and 2.

R-S have discussed the relative merits of using different radar antenna elevations. An elevation of two degrees is suitable for short ranges where radar beam height is low while for longer ranges R-S have used a zero degree elevation beam to keep the beam height low. In actual practice if radar is to be used for all ranges upto 200 km, it is necessary to choose a compromise elevation of one degree (half the radar beamwidth) or combine data at different elevations for different ranges. In this study most of the data have been acquired at an elevation of one degree. However, some data relating to a 2-degree elevation are also presented (Table 2).

3. Mean Z-R relation for southwest monsoon season

From Table 1 it appears that the equations :

$$Z=100\ R^{1.5} \tag{2}$$

or

$$Z=150\ R^{1.4} \tag{3}$$

fit the data best as these combinations of constants give G/R' ratio in the range of 0.8 to 1.2 in the maximum number of cases of observation at one degree elevation. Before accepting a particular equation as typical for southwest monsoon season, we may consider the nature of precipitation in the southwest and northeast monsoon seasons at Madras. Raghavan *et al.* (1983) found that while the bulk of precipitation in both these seasons is of convective origin, the convective cells tend to develop large mesoscale stratiform anvils which contribute almost half the total precipitation. Similar findings have been made for tropical ocean and coastal areas in other parts of the world (see, *e.g.*, Houze and Hobbs 1982). The rate of rainfall in the anvil is small in comparison with that in the convective cores. Corresponding differences in the dropsize spectra and in the Z-R relationships are to be expected between the convective and stratiform regions of precipitation. Any mean Z-R relationship derived statistically from raingauge comparisons will average out of these differences besides including in itself all the experimental errors. During the southwest monsoon, convection near Madras develops mainly over land while in the northeast monsoon most of the development occurs over the sea and the rain area moves inland. Hence, the relative proportions of convective core rainfall with large drop-sizes and stratiform rainfall with small drop-sizes is likely to be different in the southwest and northeast monsoons. This is reflected in the value of b in the above equation being higher than in the corresponding relation given by R-S for the northeast monsoon. However, it is to be noted that the constants for both the seasons are distinctly lower than the Marshall-Palmer values.

4. Use of a digital processor

A digital radar video integrator and processor was commissioned in 1981 at Madras and for the first time several advantages over the relatively simple analog isoecho system could be gained. The digital processor digitises the logarithmic video output of the radar and integrates it over each bin of range of 1 km and azimuth one beamwidth while the antenna scans at a rate of 3 revolutions per minute. This is done by averaging all the pulses received during the passage of the antenna over one beamwidth (about 16 pulses). The number of samples integrated radially is approximately 2 and the total number of samples integrated is, therefore, 32. The number of independent samples is about 0.4 times (*see* Atlas 1964, p. 404) this value, *i.e.*, about 13. The standard deviation of the measured output is reduced by a factor of $13^{0.5}$, *i.e.*, about 3.5 by this averaging. By contrast the analog system integrates 5 pulses only by passing them through an R-C filter and then amplifies the signal above a certain threshold to saturation. The R-C filter converts a square pulse into an exponential waveform and in the process causes a spurious extension of the echo to a larger range. Hence, the estimated received power is likely to be higher than in the case of averaging by the digital processor and the area of precipitation may also be slightly exaggerated. Thus, the digital processor is expected to give a systematically lower but more accurate estimate of received power than the analog circuit. The processor also applies a correction for averaging of the logarithms and normalises the signal to 200 km range before converting into rainfall rate assuming a Z-R relation fed by the operator. A further area-weighted averaging over 10 km × 10 km squares is then carried out. Instantaneous rainfall rates for each square in an area of 200 km radius are printed out in realtime on a scale of eight thresholds

(1, 2, 4, 8, 16, 32, 64 and 128 mm. hr^{-1}). The processor also stores rainfall rate value for each square in the selected target area and prints out a cumulative rainfall value for each square assuming constant rainfall rate till the next data acquisition. It also updates this value after every new acquisition.

As part of a field trial carried out in 1980 the analog and digital maps were compared on eight occasions. The spacing of the thresholds at 5 dB intervals of reflectivity in the analog system and in powers of two in terms of rainfall rates in the digital processor, means that rainfall rates have to be categorised into wide slabs and not assigned any precise values. Hence, only a gross comparison was possible. The result is given below:

Comparison of analog and digital radar estimates of rainfall rates on 8 occasions in 1980

(Assuming $Z=200\ R^{1\cdot 6}$)

Total number of 10 × 10 km squares in which precipitation was recorded by analog system	3322
Percentage of squares in which analog and digital systems yielded rainfall rate in same slab	60
Percentage of squares in which analog system yielded rainfall rate one level higher than digital system	21
Percentage of squares in which digital system yielded rainfall rate one level higher than analog system	6
Percentage of squares in which the two systems differed by more than one level	13

In general, the digital system tended to yield a lower value of rainfall rate than the analog system. Since the same (arbitrary) Z-R relationship was used in both cases, the implication is that a lower estimate of reflectivity factor Z is obtained by the digital processor as compared to the analog processor. This is to be expected from the processing methods described above. Hence, it should be expected that in a fresh hydrological experiment with the digital processor a lower mean value of b should be obtained as compared to that yielded by the analog system.

5. Determination of Z-R relationship using the digital processor

Using the digital system a fresh comparison of radar and raingauges was attempted in the 1982 and 1983 seasons. The cumulative rainfall printout facility was utilised for computing the total areal rainfall over the target area during each experimental period. As the cumulative printout uses the actual computed rainfall rates instead of the threshold values, it avoids the grossness mentioned above. Unfortunately, due to frequent hardware malfunctions of the digital processor, the data available was limited to a few occasions only.

The G/R' ratio arrived at for seven occasions in the southwest monsoon seasons of 1982 and 1983 are presented in Table 3. In all the cases the antenna elevation is one degree. The data of seven raingauges were available in most of the cases. From the table it may be seen that to get a G/R' ratio close to unity a lower value of b is required than in the case of the analog processed data as anticipated in the previous section. The new mean relation that appears to give best G/R' ratios is :

$$Z=100\ R^{1\cdot 3} \tag{4}$$

6. Limitations of the method

The method of derivation of the Z-R relationship relies on a small number of raingauges, the data of which are not available in realtime. The mean Z-R relation gives the rainfall on any other occasion within about a factor of two only (*see* R-S), pointing to the need for realtime adjustment of magnitude of the estimate. Hence, in any operational scheme for estimation of precipitation by radar a few telemetering calibrating gauges are essential. It was also noted during the study that the time of occurrence of precipitation as recorded by the raingauges was not accurate. This may be due to errors in setting the chart, fluctuations in clock rate and lack of synchronisation with the radar station. This problem can probably be solved only by having telemetering gauges which have continuously running electronic clocks.

The other problems are the accuracy (*see* Sevruk 1982) and representativeness of each gauge and the time averaging of the rainfall rate. There is often some difference between the data of two raingauges located at the same place. When we consider 5 or 6 raingauges to represent the rainfall over an area of 2100 km² there will evidently be considerable error in the areal estimate G from the gauges. This is especially so for showery precipitation as in the southwest monsoon over Madras. The radar estimate R' is relatively free from such error and represents the spatial distribution better (Collier and Murray 1978). However, since G is used to adjust the magnitude of R', the error in the gauge estimate will also appear in the final radar estimate. Thus, the apparent result that the radar estimates the areal rainfall within a factor of two, is partly due to the error in the raingauge estimate itself. Hence from an operational point of view

TABLE 3

Ratio of gauge (G) to radar (R') estimated values of areal rainfall for various assumed values of coefficients A and b, using digital data
(Antenna elevation one degree)

Date of experiment	Duration of observation (IST)	G/R' values for																	
		A=100						150						200					
		b 1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6	1.1	1.2	1.3	1.4	1.5	1.6
14 Jul '82	1858-2053	0.5	0.7	0.9	1.1	1.4	1.7	0.7	0.9	1.2	1.5	1.8	2.0	0.9	1.2	1.5	1.9	2.2	2.6
14 Jul '82	2107-0009	1.2	1.7	2.1	2.5	2.8	3.3	1.7	2.3	2.9	3.4	3.7	4.3	2.3	3.0	3.6	4.2	4.8	5.3
7 Aug '82	1607-1752	0.9	1.4	1.8	2.3	2.9	3.4	1.4	1.9	2.5	3.1	3.8	4.4	1.8	2.4	3.1	3.8	4.6	5.3
16 Jul '83	2230-0017	0.6	0.9	1.1	1.3	1.5	1.7	0.9	1.2	1.5	1.7	2.0	2.3	1.2	1.5	1.9	2.2	2.5	2.8
26 Jul '83	2031-2348	0.7	0.8	1.0	1.2	1.3	1.5	0.9	1.2	1.4	1.6	1.8	1.9	1.3	1.5	1.8	2.0	2.2	2.5
1 Aug '83	2100-2146	0.4	0.6	0.8	1.1	1.4	1.6	0.6	0.9	1.1	1.5	1.8	2.1	0.8	1.1	1.4	1.8	2.2	—
1 Aug '83	2201-2316	1.0	1.2	1.8	1.5	1.7	1.8	1.3	1.6	1.8	2.0	2.2	2.3	1.9	2.3	2.5	2.7	2.9	—

the radar estimate of areal rainfall is at least as good as any areal estimate obtainable from existing raingauge networks in this country. In addition, the radar gives a very good picture of the spatial distribution.

The time averaging of rainfall rates with conventional recording raingauges is over a period of 15 minutes. This is being compared with the 'radar' rain rate assessed over a period of about 0.1 second and assumed constant over a 15 minutes period. This procedure is open to objection especially in showery precipitation in which rain rates may vary rapidly with time. The 15 minutes averaging of the raingauge record flattens the peaks while the period sampled by the radar may not be representative of the entire 15-minute period. It is possible to improve the rate of radar sampling, if realtime processing is not needed. As for the raingauge an electronic intensity raingauge capable of recording rain rates every minute has been installed at one station in the target area. The rain rates recorded by this gauge should be more suitable for comparison with radar-estimated rain rates in future experiments.

7. Climatological use

Apart from their realtime value, the gauge-adjusted radar data provide the equivalent of a very dense network of raingauges for climatological and non-realtime hydrological purposes. A technique for integrating the radar data into raingauge network data for climatological purposes has been developed by Palmer *et al.* (1983) in the U.K.

8. Conclusion

A mean Z-R relation for southwest monsoon rainfall around Madras is :

$$Z=100\,R^{1.3} \tag{5}$$

For radar estimation of areal precipitation adjustment of the magnitude by using a few calibrating gauges is necessary on each occasion. The gauge-adjusted radar estimate provides the equivalent of a dense network of raingauges for realtime as well as climatological use. However, the mean Z-R relationship has been obtained from a very limited data base. It is necessary not only to test the mean relation in more situations but to collect more extensive data over several seasons and over larger durations before the methodology can be put on a sound operational basis. A more quantitative assessment of the errors in gauge and radar data will also be necessary. Further studies with these aims are in progress.

Acknowledgements

The authors are thankful to the reviewer of this paper for several suggestions for its improvement and for further study.

It is a pleasure to thank a number of colleagues in the Cyclone Detection Radar Unit, Madras who assisted in the data acquisition and analysis. We also thank Shri A.M. Sukumaran who has prepared the typescript for publication. We are also grateful to the Institute of Hydraulics and Hydrology, Poondi, for their rainfall data.

References

Atlas, D., 1964, "Advances in Radar Meteorology" *Advances in Geophysics*, 10, Academic Press, pp. 318-478.

Collier, C.G. and Murray, R., 1978, Casebook on Hydrological Network Design Practice, WMO No. 324, Suppl. 1, Section VI-2.3.

Houze, R.A. (Jr.) and Hobbs, P.V., 1982, "Organization and structure of precipitating cloud systems", *Advances in Geophysics*, 24, Academic Press, pp. 225-315.

Palmer, S.G., Nicholass, C.A., Lee, M.J. and Bader, M.J., 1983, *Met. Mag.*, 1336, 112, pp. 333-346.

Raghavan, S. and Sivaramakrishnan, T. R., 1982, *Mausam*, 33, 1, pp. 21-28.

Raghavan, S., Sivaramakrishnan, T.R. and Ramakrishnan, B., 1983, *J. atmos., Sci.*, 40, pp. 428-434.

Sevruk, B., 1982, Operational Hydrology Report No. 21, WMO No. 589, 91 pp.