A Study of the Threshold Method Utilizing Raingage Data

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ABSTRACT

The threshold method for estimation of area-average rain rate relies on determination of the fractional area where rain rate exceeds a preset level of intensity. Previous studies have shown that the optimal threshold level depends on the climatological rain-rate distribution (RRD). It has also been noted, however, that the climatological RRD may be composed of an aggregate of distributions, one for each of several distinctly different synoptic conditions, each having its own optimal threshold.

In this study, the impact of RRD variations on the threshold method is shown in an analysis of 1-min rain-rate data from a network of tipping-bucket gauges in Darwin, Australia. Data are analyzed for two distinct regimes: the premonsoon environment, having isolated intense thundersetorms, and the active monsoon rains, having organized convective cell clusters that generate large areas of stratiform rain. It is found that a threshold of 10 mm h$^{-1}$ results in the same threshold coefficient for both regimes, suggesting an alternative definition of optimal threshold as that which is least sensitive to distribution variations. The observed behavior of the threshold coefficient is well simulated by assumption of lognormal distributions with different scale parameters and same shape parameters.

1. Introduction

The area coverage and total rainfall from convective storms have been noted to be highly correlated since the early days of radar meteorology (Byers 1948). Area–rainfall correlation is due to the tendency of convective cells to produce similar life histories of rain rate when found within similar synoptic settings (Lopez et al. 1989, Atlas et al. 1990, and Short et al. 1993 give further references). As a result, when a large number of asynchronously evolving storms are observed within a given area, a high degree of correlation also exists between the area-average rain rate and the fractional area where rain occurs. The threshold method, first explored systematically by Chiu (1988), seeks to maximize area–rain-rate correlations by finding the optimal threshold. The optimal threshold is generally a bit higher than the conditional mean rain rate.

The threshold method is of particular interest in satellite remote sensing studies where area-average rain-rate estimates are useful for large-scale climate monitoring and input to numerical forecast models. It is perhaps fortuitous that optimal thresholds are near the conditional mean rain rate (Kedem and Pavlopoulos 1991; Short et al. 1993), roughly between 5 and 20 mm h$^{-1}$ in convective environments, because satellite estimation of very light rain rates is made difficult by signal-to-noise problems associated with cloud ice, cloud liquid water, atmospheric water vapor, and surface conditions. At the other extreme, high rain rates usually occur at spatial scales smaller than the resolution of satellite instruments, resulting in additional retrieval problems (see, for example, Chiu et al. 1990; Short and North 1990; Nakamura 1991). While the increased spatial resolution and complexity of future satellite instruments will increase the dynamic range

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of rain-measurement capabilities, the threshold method offers a simple, yet powerful, approach that can enhance the utility of measuring systems with limited dynamic range.

An idealized conceptual model for application of thresholding techniques to satellite observations would be a globally optimized threshold algorithm, reducing large-scale estimations to measurement of area coverage by rain rates exceeding the optimal threshold. Because the threshold coefficient depends on the RRD, documentation of regional variations in RRDs is a necessary first step toward evaluation of a global algorithm. The present observational study is intended to contribute toward that goal. In addition, we expand upon some previous exploratory analyses of thresholding alternatives.

Rosenfeld et al. (1990; hereafter RAS) have presented a survey of radar observations from several sites, demonstrating remarkably high correlations between area-average rain rates $\langle R \rangle$ and $F(T)$, the fractional coverage by rain rates exceeding the threshold $T$. A threshold algorithm of the form

$$\langle R \rangle = S(T_{\text{optimum}}) F(T_{\text{optimum}}),$$

where $S(T)$ is the coefficient of the method, is suggested by the high correlations and near-zero intercepts.

RAS have also shown that high correlations are achieved when the averaging area is large enough, about $10^4$ km$^2$ or greater, to contain numerous convective cells in various stages of their life cycles. Further studies have indicated that the area coverage (km$^2$) by rain, not necessarily the size of the averaging domain, is the determining factor in the accuracy of the method. These findings hold great promise for our ability to infer area-average rain rates from satellite by measuring accurately at a moderate, optimal threshold, provided that the slope of the $\langle R \rangle$, $F(T)$ relation; namely, $S(T)$ is known.

Atlas et al. (1990), Kedem et al. (1990a), and Kedem et al. (1990b) have shown that $S(T)$ is determined by the RRD, conditional on rain. A derivation of their result is given in section 3. The $S(T)$ dependence on the RRD holds when $R$ is averaged over space and time, as with the area–time integral of Doneaud et al. (1984) and Lopez et al. (1989), or space only, as with the area integral used by Chiu (1988) and RAS. Because previous empirical studies of the threshold method have been based on rain rates retrieved from radar reflectivity observations $Z_r$, there is some uncertainty in the retrieved RRD, and consequently $S(T)$, related to uncertainties in the $Z_r$–$R$ retrieval algorithm. More recently, Rosenfeld et al. (1993) have developed empirical $Z_r$–$R$ relations that are designed to produce retrieved RRDs identical to those determined from raingage measurements. Thresholding studies utilizing these techniques have not yet been undertaken.

Fig. 1. The Darwin area raingage network. Rainfall totals (mm) are for November 1987–April 1988. For comparison, the Darwin airport, about 8 km northwest of the Berrimah radar site, reported 1308 mm during the same time interval (NOAA 1987–88). The November–April wet season includes, climatologically, over 90% of the annual rainfall at Darwin.

In this paper, we explore the $\langle R \rangle$, $F(T)$ correlation and $S(T)$ with data from a network of raingages in Darwin, Australia. Section 2 describes the data and RRD characteristics for the premonsoon and active monsoon environments. Two seasons are included to demonstrate reproducibility of the RRDs. Section 3 describes application of the threshold method to the raingage observations. In section 4, a comparison of empirical results with the lognormal distribution is presented. A discussion and conclusions are presented in section 5.

2. The Darwin area raingage network

The rain rate data analyzed here come from a network of 22 tipping-bucket raingages (see Fig. 1) located within 120 km of the National Oceanic and Atmospheric Administration (NOAA)–Tropical Ocean Global Atmosphere (TOGA) C-band meteorological radar at Darwin, Australia. Six of the gauges and the radar were used during the Bureau of Meteorology Research Centre (BMRC) Australia Monsoon Experiment (AMEX; Holland et al. 1986). Radar and raingage observations have been continued for the 1987–91 rainy seasons in a joint effort by NOAA, BMRC, and NASA to investigate statistics of tropical rainfall. These studies will be useful in determining rain-rate climatologies, defining satellite-sampling requirements, and developing ground-truth strategies for the Global
Table 1. Latitude and longitude of the gauges in the Darwin network, as well as their respective locations relative to the radar [direction $\theta$ (deg) and distance $r$ (km)]. Station DAR was used only for the first season and station LAB only for the second.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (S)</th>
<th>Longitude (E)</th>
<th>$\theta$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annaburroo (ANN)</td>
<td>12°54'50&quot;</td>
<td>131°40'24&quot;</td>
<td>122</td>
<td>96</td>
</tr>
<tr>
<td>Batchelor Airstrip (BATC)</td>
<td>13°03'20&quot;</td>
<td>131°01'24&quot;</td>
<td>171</td>
<td>67</td>
</tr>
<tr>
<td>Bathurst Island (BATH)</td>
<td>11°46'18&quot;</td>
<td>130°37'12&quot;</td>
<td>336</td>
<td>83</td>
</tr>
<tr>
<td>Bellville Park (BEL)</td>
<td>12°45'30&quot;</td>
<td>130°52'48&quot;</td>
<td>188</td>
<td>34</td>
</tr>
<tr>
<td>Berreymah (Radair) (BER)</td>
<td>12°27'26&quot;</td>
<td>130°55'31&quot;</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Charles Point (CHA)</td>
<td>12°25'00&quot;</td>
<td>130°37'30&quot;</td>
<td>278</td>
<td>33</td>
</tr>
<tr>
<td>Darwin River Dam (DAR)</td>
<td>12°49'50&quot;</td>
<td>130°58'15&quot;</td>
<td>173</td>
<td>42</td>
</tr>
<tr>
<td>Dum In Mirie (DUM)</td>
<td>12°38'18&quot;</td>
<td>130°22'18&quot;</td>
<td>251</td>
<td>63</td>
</tr>
<tr>
<td>Garden Point Airstrip (GAR)</td>
<td>11°24'12&quot;</td>
<td>130°25'00&quot;</td>
<td>335</td>
<td>130</td>
</tr>
<tr>
<td>Goodall Mine (GOO)</td>
<td>13°13'00&quot;</td>
<td>131°22'30&quot;</td>
<td>150</td>
<td>97</td>
</tr>
<tr>
<td>Gunn Point Prison (GUN)</td>
<td>12°09'30&quot;</td>
<td>131°01'06&quot;</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>Humpty Doo Navy (HUM)</td>
<td>12°36'36&quot;</td>
<td>131°17'24&quot;</td>
<td>113</td>
<td>43</td>
</tr>
<tr>
<td>Kooolpinah (KOO)</td>
<td>12°23'24&quot;</td>
<td>131°10'30&quot;</td>
<td>75</td>
<td>28</td>
</tr>
<tr>
<td>La Belle Airstrip (LAB)</td>
<td>13°06'54&quot;</td>
<td>130°29'30&quot;</td>
<td>213</td>
<td>87</td>
</tr>
<tr>
<td>Litchfield (LIT)</td>
<td>13°26'04&quot;</td>
<td>130°29'00&quot;</td>
<td>204</td>
<td>119</td>
</tr>
<tr>
<td>Mandorah Jetty (MAN)</td>
<td>12°26'36&quot;</td>
<td>130°45'50&quot;</td>
<td>275</td>
<td>18</td>
</tr>
<tr>
<td>McMinn's Lagoon (McM)</td>
<td>12°32'30&quot;</td>
<td>131°04'57&quot;</td>
<td>119</td>
<td>19</td>
</tr>
<tr>
<td>Mount Bundy (MTB)</td>
<td>13°13'50&quot;</td>
<td>131°07'54&quot;</td>
<td>165</td>
<td>89</td>
</tr>
<tr>
<td>Old Point Stuart (OPS)</td>
<td>12°21'30&quot;</td>
<td>130°48'48&quot;</td>
<td>83</td>
<td>97</td>
</tr>
<tr>
<td>Pickertaramoor (PIC)</td>
<td>11°46'11&quot;</td>
<td>130°52'42&quot;</td>
<td>356</td>
<td>77</td>
</tr>
<tr>
<td>Point Stuart Abattoirs (PTS)</td>
<td>12°35'12&quot;</td>
<td>131°45'30&quot;</td>
<td>99</td>
<td>91</td>
</tr>
<tr>
<td>Snake Bay Old (SNA)</td>
<td>11°25'18&quot;</td>
<td>130°40'18&quot;</td>
<td>346</td>
<td>118</td>
</tr>
<tr>
<td>Woolner (WOO)</td>
<td>12°22'30&quot;</td>
<td>131°28'00&quot;</td>
<td>81</td>
<td>59</td>
</tr>
</tbody>
</table>


Table 1 gives the coordinates of the gauges. For the 1990–91 season, a dense network of 25 gauges with 2-km spacing was installed around the Humpty Doo Navy station. Analysis of these data will be reported in future papers.

a. The premonsoon and first active monsoon periods

Figure 2 shows a time series of daily rainfall during the 1987–88 wet season for the Darwin area, calculated from an equally weighted average of daily totals from each of the 22 gauges. During the premonsoon, days 304–349, the rainfall occurred in widely scattered thunderstorms, yielding a network average of 3.4 mm day$^{-1}$ during the 46-day period. Radar echo heights frequently surpassed 15 km and locally heavy downpours from these storms, resulting in 40-mm accumulations per hour, were not uncommon.

Day 353 (18 December 1987) coincides with the onset of summer monsoon westerly winds at 850 mb (Keenan 1988, personal communication). The onset date is 6 days earlier than the average but well within the interannual variability, which has a standard deviation of 15 days (Holland 1986). During the first active phase of the monsoon, the network accumulation was 33.5 mm day$^{-1}$, resulting from less intense, but more persistent, maritime convective systems whose tops seldom exceeded 12 km. Area-average rainfalls of greater than 19 mm day$^{-1}$ have long been associated with the summer monsoon rainfall spells in Darwin (Troup 1961). The remainder of the wet season can be characterized by a variety of convective rainfall regimes (Rosenfeld et al. 1993) with occasional heavy (network average greater than 19 mm day$^{-1}$) rains.

Figure 3 shows the time series of area-average rainfall for the following 1988–89 wet season. During the premonsoon, days 300–330, the network average accumulation was 5.0 mm day$^{-1}$, whereas the first active monsoon period, days 331–338, had an average ac-

![Fig. 2. Daily rainfall totals (mm) averaged over the raingage network. Julian day 1 of 1988 is given as Julian day 366 of 1987. The network averaged accumulation for the entire period was 1206 mm.](image-url)
cumulation rate of 28.5 mm day$^{-1}$. The contrast in these distinct intervals is similar to the premonsoon and first active monsoon periods of the 1987–88 wet season (Fig. 2).

b. Rain-rate distributions (RRDs)

Further documentation of the significant change in rainfall characteristics from the premonsoon to the active monsoon environment is revealed by an analysis of 1-min rain rates. The tipping-bucket gauges recorded the time of each tip to the nearest second. The 1-min rain rates were derived from these records by interpolation and RRDs tabulated as in Jones and Sims (1978). Figure 4 contrasts the normalized distributions of cumulative rain depth and the number of observations versus rain rate for the premonsoon and active monsoon time intervals of 1987. Distributions for the 1988 premonsoon and active monsoon intervals are not shown since they were practically identical to the 1987 distributions (further details are given below).

Figure 4 shows that the percentage of rain rates observed below 10 mm h$^{-1}$ was 68% for the premonsoon and 80% for the active monsoon. Thus, the rain rate was below 10 mm h$^{-1}$ about two-thirds of the time that it actually rained during the premonsoon and four-fifths of the time during the active monsoon. These percentages will be used in the next section to calculate threshold coefficients. It can also be inferred from Fig. 4 that rain rates below 10 mm h$^{-1}$ accounted for 15% of the premonsoon accumulation and 30% of the active monsoon rain accumulation, indicating the increased importance of lighter rain rates during the active monsoon.

For the purposes of further discussion, it is useful to express the average rain accumulation rate as the product of the mean rain rate during rainfall events [R], and the average number of hours per day that rain occurs. Table 2 lists [R] along with the average number of hours of rain per day, the average accumulation rate per day, and the total number of minutes of rain observed by the network for the premonsoon and first active monsoon periods of the 1987–88 and 1988–89 wet seasons.

3. Relations between $\langle R \rangle$ and $F(T)$

The basic thresholding model (1) is derived by considering an idealized case where the averaging area is large enough that the climatological RRD is perfectly represented. Under such conditions, the area-average rain rate is given by the product of the conditional mean rain rate and the fractional coverage by rain:

$$\langle R \rangle = [R]F(0).$$  \hspace{1cm} (2)

For this basic model, variations in the area-average rain rate are driven by variations in the fractional coverage by rain. In order to derive the general thresholding model, the right-hand side is multiplied and divided by $f(T)$, the conditional fraction of rain rates exceeding $T$:

$$\langle R \rangle = \frac{[R]}{f(T)}F(0)f(T) = S(T)f(T).$$  \hspace{1cm} (3)

<table>
<thead>
<tr>
<th>[R]</th>
<th>Total minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(mm h$^{-1}$)</td>
<td>(h day$^{-1}$)</td>
</tr>
<tr>
<td>Premonsoon 1987</td>
<td>13.6</td>
</tr>
<tr>
<td>Premonsoon 1988</td>
<td>13.6</td>
</tr>
<tr>
<td>Monsoon 1987</td>
<td>8.6</td>
</tr>
<tr>
<td>Monsoon 1988</td>
<td>7.4</td>
</tr>
</tbody>
</table>
Here $S(T)$ is the thresholding coefficient and $F(T)$ is the fractional coverage by rain rates exceeding $T$.

In practice, a perfect correlation between $\langle R \rangle$ and $F(T)$ cannot be expected due to the highly variable nature of convective rain systems. This results in random sampling fluctuations in the RRD and in $S(T)$. In a theoretical study, Kedem and Pavlopoulos (1991) have shown that the variance in $S(T)$ due to random sampling fluctuations is minimized at an optimal threshold, $T_{optimum}$. In the present study, empirical optimal thresholds are determined for the premonsoon and monsoon periods separately, and then an alternative definition of optimal threshold is considered as that whose coefficient is least sensitive to meteorologically forced variations in the RRD.

In order to examine the relations between $\langle R \rangle$ and $F(T)$, the rain gauge network data were used to estimate statistics of the rain rate within a space (Darwin area network)–time (one day) volume. The daily rainfall totals shown in Figs. 2 and 3 were divided by 24 h to provide a space–time-averaged rain rate $\langle R \rangle$. Error bars on $\langle R \rangle$ are about ±30% for the premonsoon and ±15% for the active monsoon, based on covariance statistics of the daily totals and the average spacing of the gauges (Zawadzki 1973). The fraction of the space–time volume having rain rates that exceed a given threshold, $F(T)$, was estimated by examining the gauge records individually and averaging the results. Sampling errors in $\langle R \rangle$ and $F(T)$ are correlated since they are both estimated from the same data (Short et al. 1993).

a. Premonsoon

Figure 5 shows $F(10 \text{ mm h}^{-1})$ versus $\langle R \rangle$ for the premonsoon period of 1987 (first 46 days of the record shown in Fig. 2). The slope predicted from the ensemble distribution of 1-min rain rates observed during the premonsoon is given by the following:

$$S(10) = \frac{\langle R \rangle}{f(10)} = \frac{13.6 \text{ mm h}^{-1}}{0.32} = 42.5 \text{ mm h}^{-1},$$

(4)

where $f(10)$ denotes the fraction of rain rates, when raining, that exceed 10 mm h$^{-1}$. The value of $S(10)$ is 10%–20% higher than found by Rosenfeld et al. (1990) in their survey of radar data from numerous sites. The difference may be due to intrinsic differences in the statistics of temporally averaged rain rate at a point versus instantaneously observed rain rate over the radar-scattering volume or to the radar–rain-rate retrieval procedure.

Figure 6 shows $F(10 \text{ mm h}^{-1})$ versus $\langle R \rangle$ for the premonsoon period of 1988 (first 31 days of Fig. 3). Note the excellent agreement between the data points from the 1988 period and the slope predicted from the 1987 RRD. These results further validate the thresholding model (Atlas et al. 1990; Kedem et al. 1990a; Kedem et al. 1990b).

b. Active monsoon

Figure 7 shows $F(10)$ versus $\langle R \rangle$ for the first active monsoon period of 1987 (days 352–365). The slope predicted from the monsoon RRD is $\langle R \rangle/f(10) = 8.6 \text{ mm h}^{-1}/0.20 = 43 \text{ mm h}^{-1}$, again agreeing well with the observed day-to-day variability in $\langle R \rangle$ and $F(10)$. Note that the predicted premonsoon and monsoon slopes are very close to each other even though the rain-rate distributions are substantially different (Fig. 4). This is because the ratio $\langle R \rangle/f(10)$ is nearly constant for the two cases.

Figure 8 shows $F(10)$ versus $\langle R \rangle$ for the first active monsoon period of 1988 (days 331–338). Excellent agreement is again found, despite the small sample size, between the day-to-day variability in $\langle R \rangle$ and $F(10)$.
and the slope predicted from the RRD of the previous season.

c. Optimal thresholds

Scatter diagrams (giving rms errors) and \( S(T) \)'s (from RRDs) were examined for thresholds from 0 to 30 mm h\(^{-1}\) for the premonsoon and active monsoon periods of 1987. The results are summarized in Figs. 9 and 10.

Figure 9 shows \( S(T) \) for the premonsoon period of 1987 as calculated from (3) using the information from which Fig. 4 was plotted. Note that \( S(0) = E[R] = 13.6 \text{ mm h}^{-1} \) and that \( S(T) \) shows a monotonic increase with \( T \) as expected. Also shown is the ratio of \( S(T) \)'s for the premonsoon and monsoon time periods.

For \( T = 0 \), the ratio is equal to \( E[R_{\text{premonsoon}}]/E[R_{\text{monsoon}}] = 13.6/8.6 = 1.58 \). The ratio curve indicates, for example, that if the premonsoon \( S(2) \) was applied to the active monsoon period, average rain rates would be over estimated by a factor of 1.5. On the other hand, the ratio reaches 1.0 between 9 and 10

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**Fig. 7.** As in Figs. 5 and 6 but for days 352–365 (1987), including the active monsoon period. The cluster of points near the origin are from a 6-day lull period, days 358–363.

**Fig. 9.** Thresholding \( S(T) \) as calculated from Eq. (2) for the premonsoon period and the ratio of \( S(T) \)'s for the premonsoon and monsoon periods. The ratio of 1.0 near 10 mm h\(^{-1}\) indicates a minimum sensitivity of the threshold method coefficient to distributions variations encountered in this study.

**Fig. 8.** As in Figs. 5, 6, and 7 but for days 331–338 (1988), the first active monsoon period of the 1988–89 wet season.

**Fig. 10.** Root-mean-square error in the regression of \( F(T) \) and \( \langle R \rangle \) versus threshold for the premonsoon and active monsoon periods of 1987.
mm h$^{-1}$, indicating this range is least sensitive to changes in the RRDs between the premonsoon and active monsoon time periods. The ratio of just under 1.0 at a threshold of 10 mm h$^{-1}$ can also be inferred from the theoretical slopes shown in Figs. 5 and 7.

4. Comparison with the lognormal distribution

The two-parameter lognormal probability density function (pdf) is useful for approximating RRDs and also for examining characteristics of the threshold method (Kedem et al. 1990a; Short et al. 1993). This section expands on the empirical findings of Atlas et al. (1990), who present evidence for natural variations in rain-rate distributions that result in an optimal threshold, described as that which results in a minimum variability of $S(T)$. The natural variation referred to is a positive correlation between the mean and standard deviation of rain rate, conditional on rain rate greater than zero. This property is readily described by two parameter distributions. An alternative perspective on minima in the dispersion of $S(T)$ for the lognormal, gamma, and inverse Gaussian pdf's presented by Kedem et al. (1990a) has inspired the present development.

A correlation between the mean and standard deviation of conditional RRDs and its impact on area-average rain-rate retrieval techniques has been reported by Short (1988), Short et al. (1989), Short and North (1990), and Atlas et al. (1990). Figure 11 shows data from the present study and previous studies that emphasize this characteristic. The correlation evident in Fig. 11 applies to rain-rate samples obtained from large area–time domains and thus is relevant to the threshold technique.

Because the mean and variance of the lognormal pdf are given by

$$E[R] = \exp \{ \mu + \frac{1}{2} \sigma^2 \}$$

$$\text{var}[R] = \exp \{ 2\mu + \sigma^2 \} \left( \exp \{ \sigma^2 \} - 1 \right),$$

the assumption of a constant ratio between the mean and standard deviation is equivalent to fixing $\sigma$, the shape parameter. For a standard deviation equal to five-thirds mean, as indicated in Fig. 11, a shape parameter of 1.153 is found. Shimizu (1993) has also reported a tendency for lognormal fits to rain-rate distributions to have a constant shape parameter with a value near 1. Figure 12, to be compared with Fig. 10, shows $S(T)$ and the ratio of $S(T)$'s for lognormal pdf's having means matched to the premonsoon and active monsoon periods of 1987 and standard deviations equal to five-thirds of the means. The similarity of Fig. 12 to Fig. 10 suggests that the lognormal approximation can be used to gain further insight into the performance of the threshold technique.

In the RAS study of the height–area rainfall threshold method it is evident that the climatological RRD may be composed of a family of distributions, dependent on some dynamic variable, such as vertical development. Each member of the family has its own optimal threshold and the threshold method can be improved when supplementary information is available to iden-
tify the relevant member. The present study considers the impact of distribution changes that may not be readily discernible or coexist in the region of interest. Figure 13 shows $S(T)$ curves and their dispersion (standard deviation at fixed $T$) for three lognormal pdf's having means of 4, 8, and 12 mm h$^{-1}$ and standard deviations equal to five-thirds mean. The minimum in the dispersion near 6 mm h$^{-1}$ suggests this threshold as being near optimum for an equally weighted mixture of the distributions.

From Fig. 13, it is evident that the minimum in the dispersion of $S(T)$ near 6 mm h$^{-1}$ is due to the crossing of the $S(T)$ curves. Crossings are guaranteed by fixing the shape parameter because the lowest conditional means start lowest (at $[R]$ when $T=0$) and rise fastest due to their rapidly decreasing probability of high rain rates \{ recall $S(T) = [R]/F(T)$ \}.

5. Discussion

The threshold method for estimation of area-average rain rate is an attractive alternative algorithm for satellite- and ground-based systems because requirements for the accurate measurement of instantaneous rain rate are confined to a moderate threshold level. The method does require, however, a priori knowledge or assumptions about the climatological rain-rate distribution for the region in question. This information may be available from ground-based observations, or in the case of remote oceanic regions, it may come from a spaceborne radar. Rosenfeld et al. (1990) have presented a variation of the threshold method that utilizes echo-height information to identify distribution variations and improve the accuracy of the method. There may be cases, however, where supplementary information is insufficient to uniquely identify the appropriate distribution or a mixture of distributions may coexist within the area of interest. In these cases, the threshold method offers the alternative strategy of choosing a threshold that is least sensitive to distribution variations.

From the preceding analysis, it is evident that 10 mm h$^{-1}$ is near the threshold of minimum sensitivity to distribution variations as found in this study of 1-min rain rates from the premonsoon and active monsoon environments in Darwin, Australia. In future studies, it will be important to reexamine these findings on the basis of rain-rate distributions applicable to the spatial resolution of satellite instruments.

The RRD applicable to a satellite field of view (FOV) is determined by both spatial averaging over rainy areas and the occurrence of nonrainy areas within FOV's. Empirical estimates of the resolution dependence of RRDs could be obtained from dense raingage networks, time-averaged rates from single gauges, or radar observations (as the two GATE points in Fig. 11). Theoretical modeling studies of resolution dependence on RRDs would also have to include the mixed-distribution properties of spatially averaged rain rate.

The present study of raingage data from the Darwin, Australia, network has shown that large-scale averages of convective rainfall are highly correlated with the fraction of rain rates exceeding a preset threshold, corroborating previous studies of the threshold method (Braud et al. 1993), including those that used radar-derived rain rates from Darwin and other locations (Chiu 1988; Rosenfeld et al. 1990; Meneghini and Jones 1993). Radar and raingage data from several tropical sites are being collected by NASA at Goddard Space Flight Center for TRMM definition studies. These data will be useful for further studies of threshold methods and strategies.

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