individual radars and those from selected gages. Comparisons between radar estimates and gage catches also were made for shorter time periods; however, because the inherent noise in relating the point measurements from the single *in situ* sensors to the much larger volume measurements from the remote sensors increases with decreasing integration time, no attempt was made to dynamically adjust the radar fields for limited areas or times using gage calibrations. In fact, only time and space invariant bias adjustments, defined here as systematic bias adjustments, were applied to the data sets from the individual radars. In addition, attenuation corrections were applied as described in section 2.

Although it is difficult to relate rain estimates from radar to point estimates from isolated gages, some information can be gained about the accuracy of the radar estimates from such comparisons if the large spatial variabilities and the impreciseness with which the radar precipitation fields can be positioned are considered. Some of the factors that potentially limited the precision with which the shipboard rain gages could be absolutely positioned in the radar fields follow:

1. Uncertainties in the ships' estimated positions were sometimes 1-2 km.
2. Small, time-variant antennae azimuth errors may have occasionally become significant.
3. Data resolution prevented navigation of individual radar fields to an accuracy better than 2 km.
4. The navigation accuracy could further deteriorate for parts of the master array subsequent to the merging of fields from two or more radars (sec. 2).
5. Areas that were obstructed by the ships' superstructures in the individual NOAA radar scans sometimes were filled by data from the same radar, 15-min removed (Richards and Hudlow, 1977), or from another radar as part of the merging process.
6. Wind between beam level and the surface could cause the precipitation to drift laterally and reach the surface a significant distance from the point of radar observation.

None of the above six factors would have a significant impact on the accuracy of the rainfall estimates, except on those applications requiring extremely accurate absolute location of the radar data and/or gage data; for example, "point"[3] estimates are needed in order to make comparisons between radar observations and the individual gage catches.

### 4.4.2 Radar-Gage Comparative Analyses

Figures 10, 11, and 12 illustrate the scatter that is observed when comparing the refined radar rainfall estimates to individual gage catches for Phase, daily, and hourly periods, respectively. The plotted numbers give the frequency of radar-gage pairs falling within the classes delineated by the vertical and horizontal lines. The class intervals are normally 2 dBR, except 3 to 5 dBR classes are used below -5 dBR for the daily plot because of poor resolution in the rain-gage data at light rain rates. The rainfall rates, R, are averages over the various periods expressed in mm $hr^{-1}$ and in dBR, where dBR = 10 $\log_{10} R$.

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[3]"Point" radar estimates in the context of this report refer to the values for the elemental 4-km x 4-km data bins.

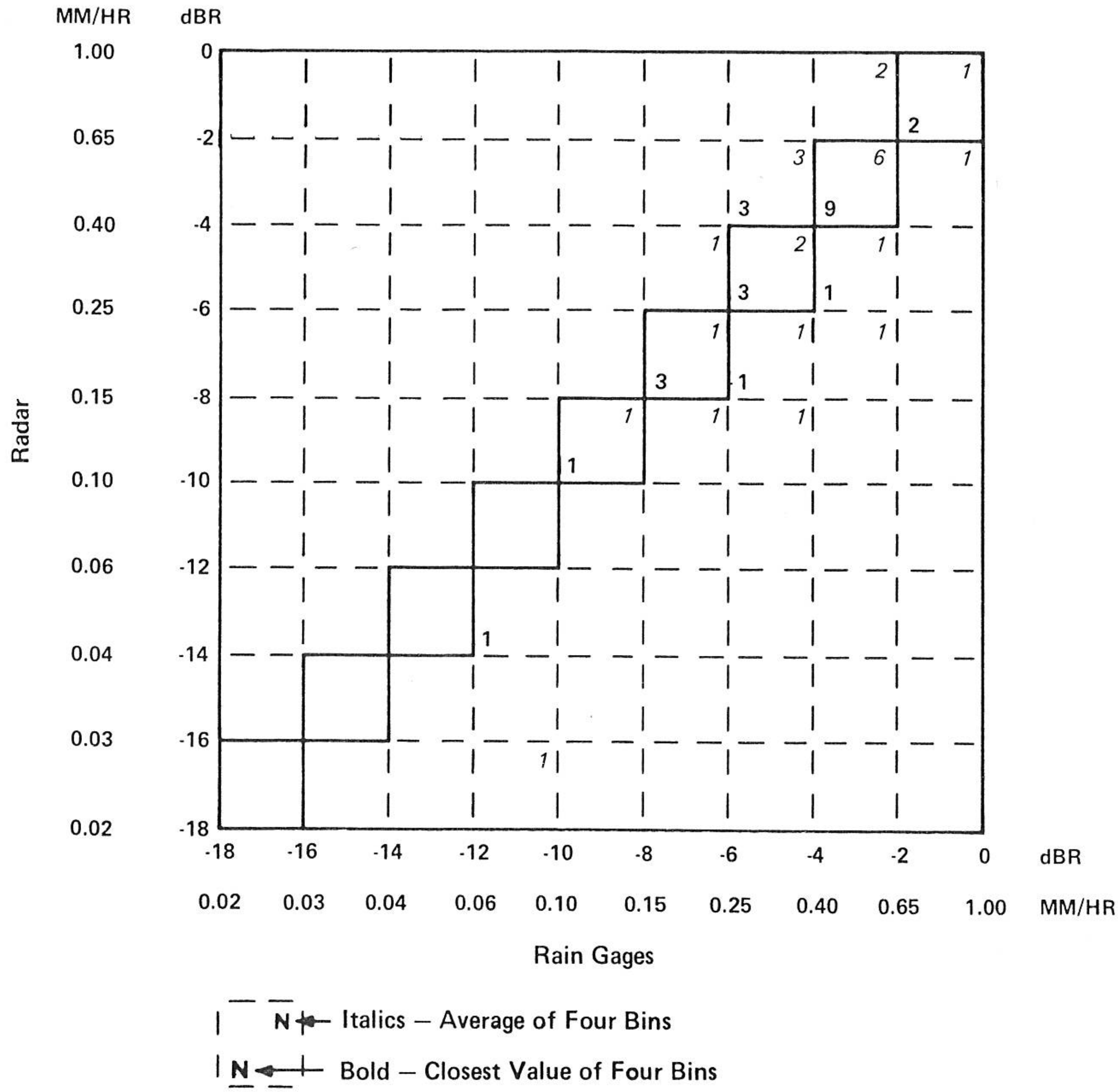


Figure 10.--Scatter diagram of Phase mean radar-rainfall estimates versus those from rain-gage measurements at all B-scale ship stations. The two groups of numbers give frequencies with which estimates fall within indicated classes for two methods of determining the radar values as described in the text.

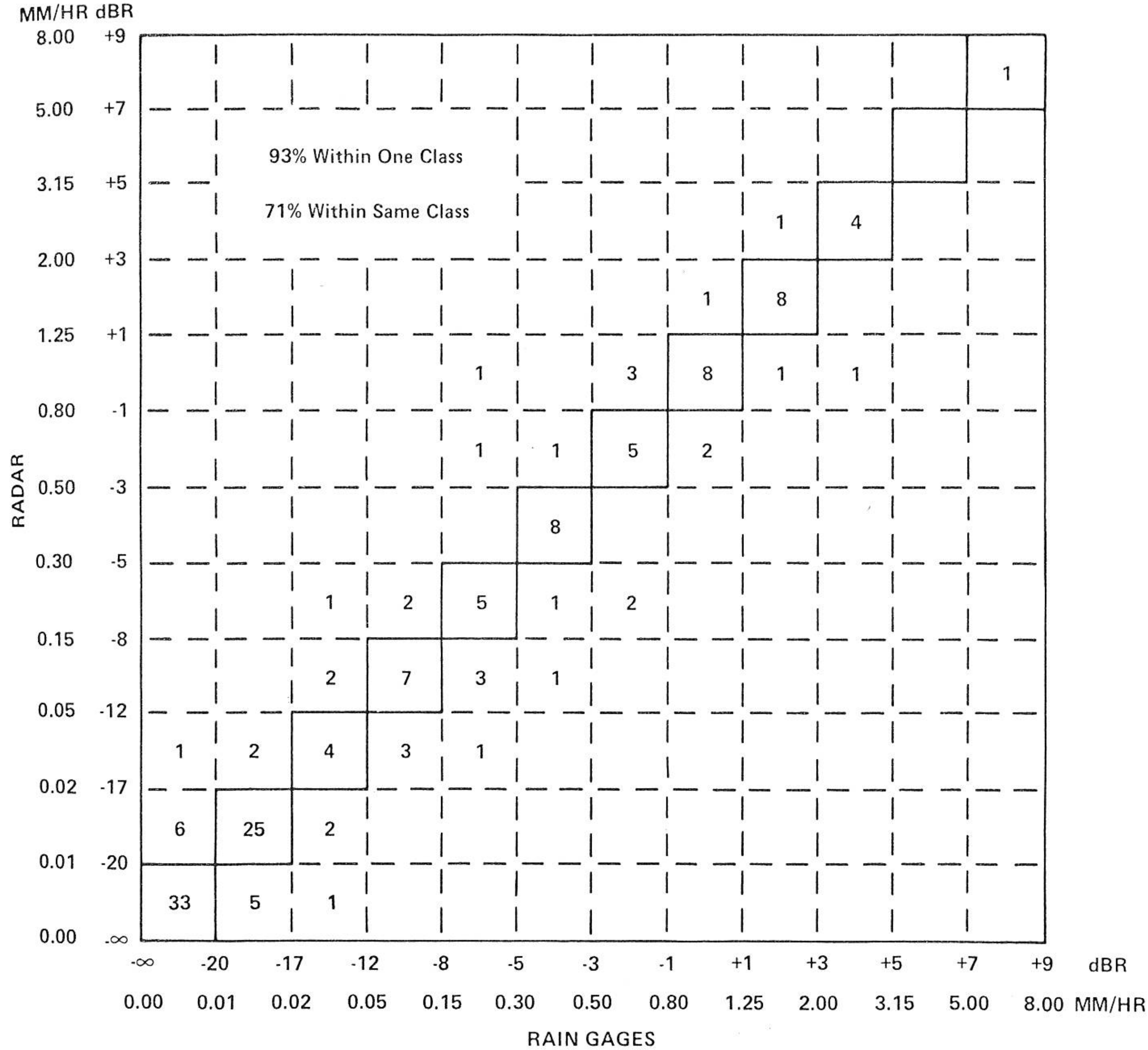


Figure 11.--Scatter diagram of daily mean radar-rainfall rate estimates versus those from rain-gage measurements for all days with data at stations maintained by the Gilliss, Oceanographer, and Meteor. Numbers give frequencies with which estimates fall within indicated classes, when each radar estimate is taken as the value from the set of nine, which minimizes the scatter. (See text.)

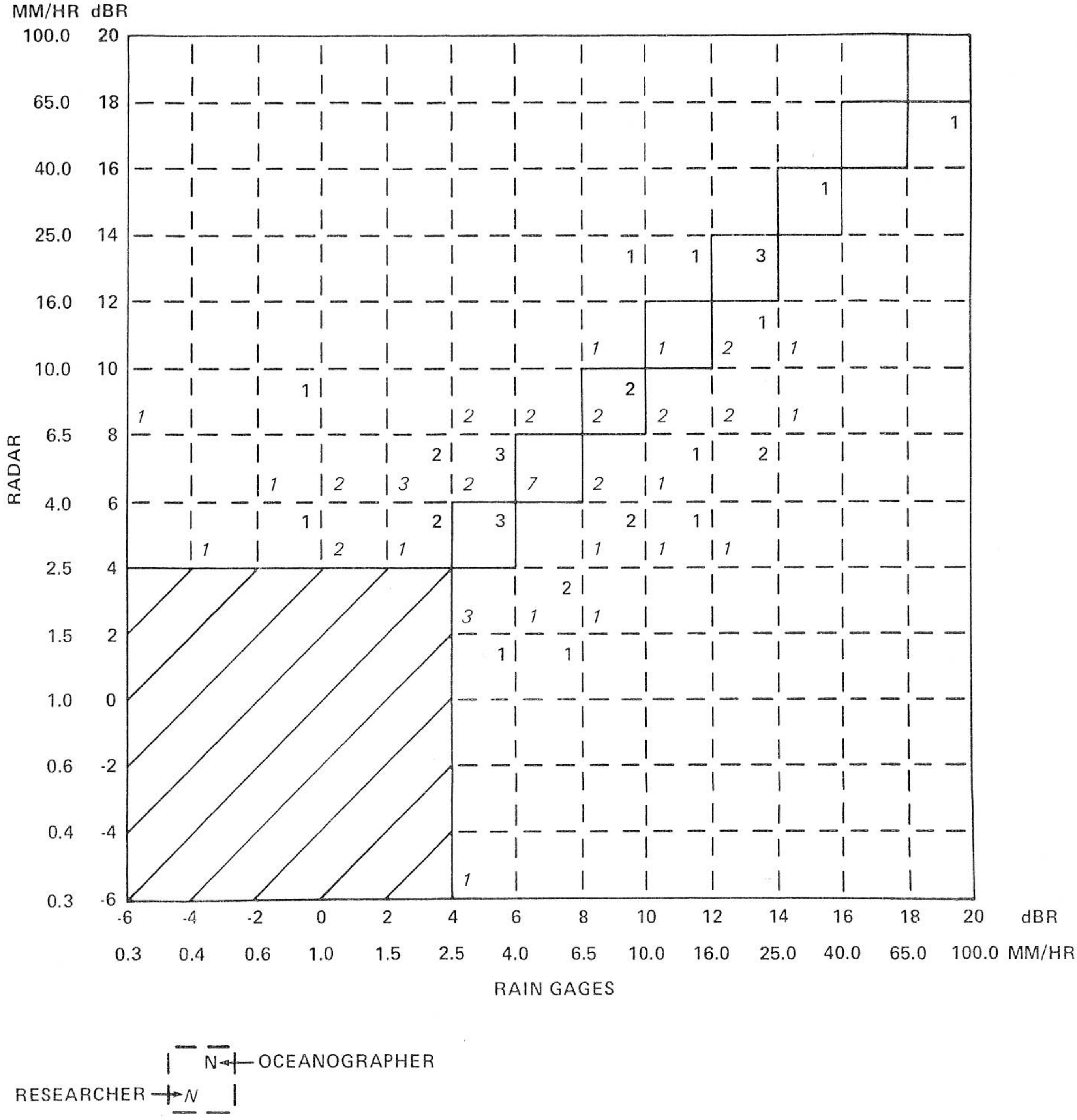


Figure 12.--Scatter diagram of hourly radar-rainfall rate estimates versus those from collocated rain-gage measurements for all hourly values exceeding 2.5 mm $hr^{-1}$ at the Oceanographer and the Researcher. Numbers give frequencies with which estimates fall within indicated classes. Radar estimates are at the respective radar origins as interpolated using an objective analysis model.

The gage values used for the Phase scatter diagram are those plotted on the Phase isohyetal maps. Data were available from two or more gages for some ships. For these cases, the maximum of the gage values was usually selected for comparison with the radar estimates, except that only the rain-gage data published by Seguin and Sabol (1976) were used for the daily comparisons. The data from the supplemental gages, which were subsequently published by Seguin and Crayton (1977), were incorporated for the Phase and hourly comparisons. Rain-gage data from gages aboard the Gilliss, Oceanographer, and Meteor[4] were used, for all days that radar and gage data were available, for the daily comparisons. Only collocated gage and radar data were used for the hourly comparisons. This was accomplished by using the objective analysis model described by Patterson et al. (1979) to obtain interpolated radar estimates at the radar origin, which could then be compared to the rain-gage data aboard the same ship.

The hourly collocated comparisons were made using the refined rainfall estimates from the Oceanographer and Researcher radars, individually, before the fields were navigated and merged. This approach virtually eliminated the positional errors, which may be significant for the daily and Phase comparisons of the remote radar and gage observations. However, the interpolation errors accompanying the hourly radar estimates can be large, since the closest observed data used in the objective analysis were 4 km from the radar origin. Hudlow et al. (1978) show that the mean correlation radius (distance at which the autocorrelation coefficient first diminishes to $e^{-1}$) is only approximately 4 km for GATE instantaneous rain-rate fields.

Comparison of figures 10, 11, and 12 shows that a significant increase in variability is encountered between the radar and gage observations as the averaging period decreases. No systematic biases are apparent from these plots, however, throughout the dynamic range of the rainfall rates for the three time scales.

An appreciation for the large spatial gradients that exist in the isohyetal patterns, even for averaging periods as long as a Phase, can be obtained by comparing the scatter of the two groups of numbers plotted in figure 10 (italics and bold). The radar estimates for the group exhibiting the most scatter were obtained by averaging the values in a set of four 4-km x 4-km data bins consisting of the one containing the Phase-mean ship (gage) position plus the three nearest neighboring bins. The second group was obtained by taking, for each "point" comparison, the value from the set of four in closest agreement with the gage, which reduces the scatter to the extent that one-third of the radar estimates fall one class closer to the gage values (fig. 10). Considering the large spatial variability and the six factors enumerated above that affect the precision with which the rain gages can be positioned relative to the radar fields, it seems likely that the positional error can be as large as 4 km. Therefore, the second group of numbers can be considered as being most appropriate for the Phase radar-gage comparisons.

Comparison of figures 11 and 13 emphasizes the substantial spatial variability and uncertainty encountered in relating the daily radar and gage estimates. Each radar estimate for the scatter diagram shown in figure 11

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[4]The Meteor maintained station D during Phases I and II and switched with the Oceanographer during Phase III (station A, see table 4 and figs. 4 and 5).

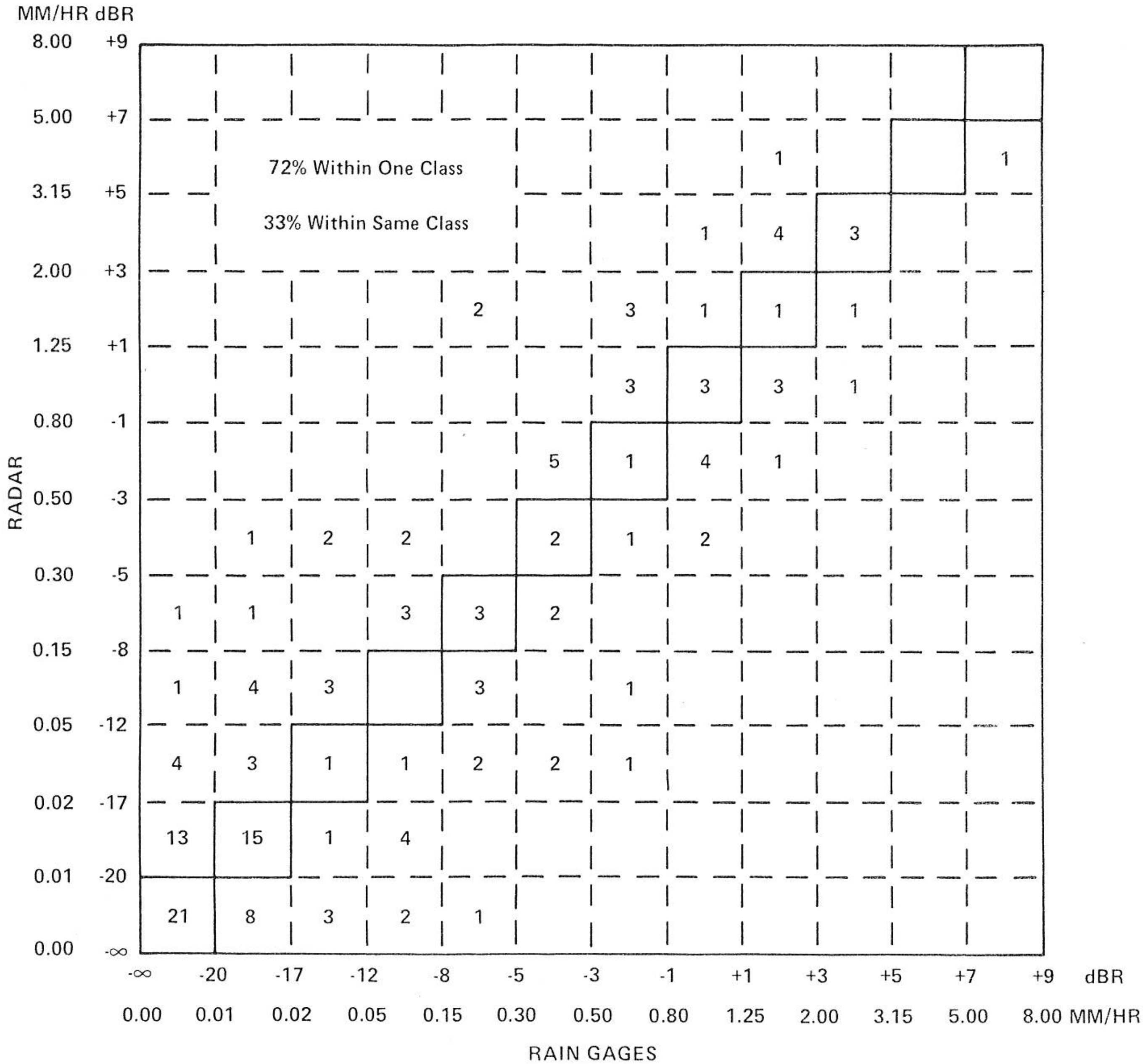


Figure 13.--Same as figure 11 except each radar estimate was taken as the value from the data bin containing the daily-mean ship (gage) position.

was taken as the value in closest agreement with the rain gage from the set of nine 4-km x 4-km data bins, which consist of a central bin containing the daily-mean ship (gage) position plus the eight surrounding bins. Each radar estimate for figure 13 was taken from the central bin, however. The increased scatter exhibited in figure 13, over that in figure 11, is summarized by the significant reduction in the number of radar estimates falling within the same class, and within one class, of the gage values (see annotations on figs. 11 and 13).

Figure 14 further illustrates the large gradients in the daily radar isohyetal maps that exist over distances less than 5.7 km ($\sqrt{4^2 + 4^2}$). The pairs of radar values for this scatter plot were obtained by taking, from the set of nine bins described above, the maximum and minimum values from the eight surrounding bins versus the central bin.

Because of the even larger spatial gradients existing in the daily isohyetal maps compared to the Phase maps, it seems likely that the errors resulting from positioning uncertainties of the rain gages relative to the radar fields would be somewhat greater for the daily scale. Consequently, daily comparisons were made by selecting the radar estimate in closest agreement with the rain gage from the set of nine bins (as opposed to the set of four used for the Phase comparisons).

Potential errors in the shipboard rain-gage data also should be considered when using gage data to assess the absolute accuracy of the daily radar estimates. Significant variability often is observed between measurements from different gages aboard the same ship. For example, the mean absolute percent difference in daily collections between the stern 1 gage and the bow gage on the Gilliss was 18 percent (Seguin and Crayton, 1977). Furthermore, the difference between the stern 1 and the stern 2 gages was 12 percent. As mentioned earlier, the maximum gage catch was normally used for comparison with the radar estimates, since most potential sources of gage error produce deficient gage catches (sec. 4.4.3). The observed variability among the various gage records does further support the appropriateness of matching the radar and gage pairs as described above for the radar-gage comparisons.

### 4.4.3 Summary of Expected Accuracies

Because the rain-gage observations can be in error and since significant variability (error) is encountered in relating the point measurements from the gages to the much larger volume measurements from the radar, it is difficult to assess the absolute errors in the radar estimates from comparisons with the sparse shipboard rain-gage catches. However, it is useful to summarize the observed differences between the radar and gage estimates, and if one assumes to a first approximation that the gage measurements represent "ground truth" at the point of observation and that the data positional uncertainties are largely eliminated by using the nearest radar value from the data bin sets as described in section 4.4.2, then these observed differences can be interpreted as estimates of the expected error for the radar "point" measurements.

An evaluation of any overall residual systematic biases in the final radar estimates can be obtained by computing the following statistic for each Phase:

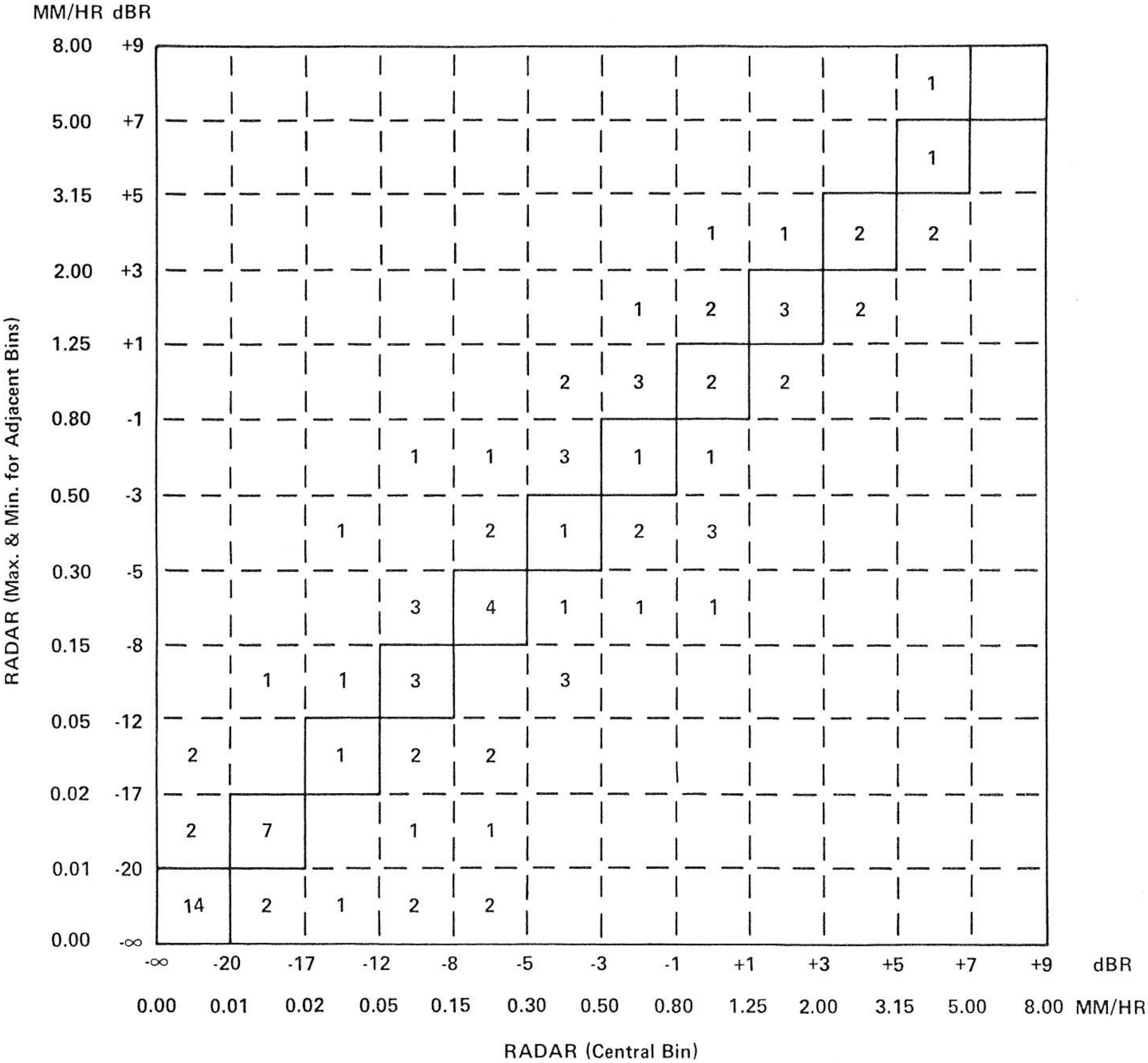


Figure 14.--Scatter diagram of maximum and minimum radar values versus value of the central bin, all from sets of nine data-bins as described in the text. Numbers give frequencies with which radar estimates fall within indicated classes using the same radar data-bin sets as described for figures 11 and 13, except only the first 16 days of Phase I are plotted here.

$$\frac{[\Sigma(\text{Gage})_i - \Sigma(\text{Radar})_i] \times 100}{\Sigma(\text{Gage})_i}$$

where the sum is for all B-scale ship stations (i), and the radar estimates are those corresponding to the second group of numbers in figure 10 (the bold numbers, see sec. 4.4.2). The results from this computation are given in table 5.

The estimated systematic biases (table 5) for the three Phases are probably not significantly different from zero when one considers the uncertainties that may accompany the estimates from both sensors. Although the estimated magnitudes of the biases are small, the change in sign of the bias for Phase III may be real, and could be explained by remembering that the data from the individual radars were merged differently during Phase III (sec. 2). Specifically, if systematic underestimates exist in the radar fields during Phases I and II, they probably are most significant over the northernmost part of the array since the estimates over this area were derived using the data coverage of only the Oceanographer radar (fig. 4). This was normally not a serious limitation because of (1) the Oceanographer's central position in the array, (2) the superior range performance characteristics of the Oceanographer radar (Hudlow et al., 1979), and (3) the generally smaller amounts of rain occurring in the northern part of the array.

It should be emphasized that the rain-gage records could contain systematic biases, which are not reflected in the percent differences given in table 5. In fact, most potential errors in shipboard rain-gage measurements tend to result in deficit catches (WMO, 1962). Laevastu et al. (1969) and Reed and Elliot (1977) suggest that the approximate magnitude of these deficits would be less than 10 percent for suitable shipboard installations. For those GATE ships that were equipped with two or more gages, the maximum gage value was normally selected for comparison with the radar estimate. This tended to minimize the effect of gage underestimates, resulting from bad gage exposure, in the assessment of systematic biases in the radar estimates (table 5). The difference between minimum and maximum gage values was frequently considerable. For example, the maximum deviation between gages was observed on the Gilliss, where there was consistently about a 20 percent greater Phase catch in one of the stern gages than in the bow gage (see gage values and deviations plotted on the Phase isohyetal maps). The stern gages on the GATE ships generally collected more rain than the mast or bow gages. This was probably due to the sheltering effect provided by the stern exposure. The standard operating procedure for the GATE ships was a drift and slow recovery mode, with the bow maintained into the wind when possible.

Assuming no systematic biases exist in the gage records, an estimate of the expected errors in the radar "point" rainfall estmates, for daily and Phase periods, is given by the mean absolute percent difference between the gage and radar values, i.e.,

$$\Sigma\Sigma \left| \frac{(\text{Gage}_{ij} - \text{Radar}_{ij})}{\text{Gage}_{ij}} \right| \times 100/N$$

Table 5.--Residual systematic bias evaluation between shipboard gages and final radar "point" measurements

| Observation period | Percent differences<br>plus: radar < gage<br>minus: radar > gage |
|---|---|
| Phase I | +5% |
| Phase II | +6% |
| Phase III | -4% |
| All GATE | +2% |

where the sums are for all B-scale stations (i) used in the analysis and for all Phases (j), or days (j), during GATE; N is the total number of gage-radar pairs. The first two lines in table 6 give this error statistic for the Phase and daily periods.

Because of the very large variability (scatter) observed in relating the hourly gage and radar values (fig. 12), it is not feasible to use these comparisons directly to assess the expected error for hourly "point" radar estimates. However, as mentioned in section 4.4.2 the scatter plot does show that no significant systematic biases exist between the radar and gage values throughout the dynamic range of the hourly rain rates.

The error estimate for the 1- to 3-hr time scale (third line, table 6) was subjectively determined by assuming that, although errors from such sources as variability in the Z-R relationship (sec. 1.2) are locally correlated for large enough space and time scales, the errors can be treated as random. Therefore, by averaging over more area, an equivalent accuracy to that for the "point" daily estimates can be achieved for the shorter (1- to 3-hr) time scale. Hudlow and Arkell (1978) experimentally show, using observed GATE reflectivity distributions, that changes in the exponent of the Z-R relationship, within realistic bounds, would not seriously affect the accuracy of the rainfall estimates for the space and time scales being considered for the atmospheric budget studies ($\geq$3 hr, $\geq$4000 km$^2$). They also arrive at the same conclusion for another potential source of error: inadequate temporal sampling. Hudlow and Arkell show that these two sources of error decrease steadily, or until they reach an asymptote, as the averaging area and/or time increases. While other potential sources of error exist, it is reasonable to assume that they too would behave in a similar manner; therefore, the error estimate for the 1- to 3-hr and 500- to 5000-km$^2$ scales should be realistic (table 6).

Analogous arguments can be made with regard to error estimates for other time and space scales. For example, if the correlation of errors in the Phase "point" estimates weakens with short spatial separations, then averaging in space would rapidly reduce the 14 percent expected "point" error. In fact, if the gage Phase totals, used as standards, contain no systematic biases, then the error in the Phase-mean radar estimates should approach zero as the estimates are averaged

Table 6. -- Summary of mean absolute percent differences between radar and shipboard rain-gage measurements

| Time scale | Space scale | Mean absolute percent difference (error) | Comments |
|---|---|---|---|
| Phase | 16 $km^2$ | 14% | Each radar estimate was taken as the value in closest agreement with the rain gage, from the set of four, 4-km x 4-km data bins consisting of the one containing the Phase mean ship position plus the three nearest neighboring bins. |
| Daily | 16 $km^2$ | 23% | Each radar estimate was taken as the value in closest agreement with the rain gage, from the set of nine, 4-km x 4-km data bins consisting of the one containing the daily mean ship position plus the eight surrounding bins. |
| 1-3 hours | $5 \times 10^2$ - $5 \times 10^3$ $km^2$ | 23% | Based on expected range of space scales over which the 4-km radar estimates must be averaged to obtain an accuracy equivalent to the daily estimates for time scales of 1-3 hours. |

over areas approaching the size of the total B-scale array. As described above, however, there could be systematic deficits in the gage collections, averaging as much as 10 percent.

In conclusion, it is encouraging to note that both Lord (1978) and Thompson et al. (1979) have found excellent agreement between the radar rainfall estimates and those based on B-scale moisture budget analyses. Lord has further demonstrated that the rainfall rates estimated from the Arakawa-Schubert convective parameterization model are also in excellent agreement with the radar estimates. These findings are extremely significant, since they reveal that the quality of the principal GATE data sets should be adequate to achieve the central objectives of the experiment.

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