NOAA Technical Memorandum ERL WMPO-18

DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

OPTIMIZING THE MEASUREMENT OF CONVECTIVE RAINFALL IN FLORIDA

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ABSTRACT

The optimum methods of convective precipitation measurement as a function of specified accuracy, and area size over which the measurements are to be made, are discussed. These methods involve gages or S-band radar or a combination of the two. The various methods are compared in the context of the continuing multiple cloud seeding experiment of the Experimental Meteorology Laboratory.

The nature of the Florida convective rainfall to be measured is documented using measurements from a dense raingage mesonetwork (about 1 gage/mi^2 over 220 mi^2) that was operated for a total of 93 days in 1971 and 1973. The rainfall during this period was highly convective with large temporal and spatial gradients of rainfall that usually occurred from tall thunderstorms during the late afternoon. On 86 of the 93 days, the areal mean rainfalls exceeded 0.01 inch with a maximum of 2.59 inches. The mean rain gradient from the 24-hour rain maxima outward was 0.45 inch. The maximum rain difference noted on any day and for the entire period of network operation was 4.00 inches in one mile and 14 inches in four miles, respectively. Rain-time and rain-area relationships are also presented.

The gaging requirements for detection and measurement of 24-hour rainfalls in the mesonetwork were determined using the full complement of gages as the standard. A requirement of 99 percent detection of 24-hour rain amounts greater than 0.01 inches necessitates a gage density of approximately 20 mi^2/gage. For the measurement of areal convective rainfall greater than 0.01 inches within a factor of two on 90, 70 and 50 percent of the days, gage densities of 12, 35 and 80 mi^2/gage, respectively, are required.

Radar performance in estimating convective rainfall over south Florida was determined during the summers of 1972 and 1973. Two, collocated, calibrated 10-cm radars (UM/10-cm of the University of Miami and WSR-57 of the National Hurricane Center) were operated in 1972 and only the latter in 1973. In all cases, the radar estimates of rainfall were compared with the rainfall as determined by raingages (densities 1 to 3 mi^2/gage) in cluster arrays.

On a daily basis in 1972, the mean absolute percentage difference between gage and radar rainfalls for the periods of operation of the two radars ranged between 35 and 40 percent. The radars were within a factor of two of the cluster standard 70 percent of the time. The correlations between gage and radar rainfalls were 0.87 and 0.84 for the

UM/10-cm and WSR-57 radars, respectively. The correlation between radar rainfalls for 46 showers common to UM/10-cm and WSR-57 was 0.94.

In 1973, WSR-57 radar-derived rainfalls were computed by hand as in 1972 and by computer using taped radar observations. The new radar digitizer system is described. Upon comparison, no systematic differences between the rainfalls generated manually and by computer were noted. The mean gage and radar correspondence improves with heavier rain, with a larger time frame for the radar-rain estimates and with an increase in the area size over which the estimates are made. On a daily basis, 80 percent of the radar estimates were within a factor of two of the cluster standard. The mean factor of difference was 1.51. The combined accuracy of the WSR-57 radar in 1972 and 1973 in estimating convective rainfall approximated that which one would obtain with a gage density of 25 mi^2/gage over an area the size of the mesonet.

The daily representation of rainfall by the radar improves if one adjusts it using gages. The radar estimates of rainfall for the mesonet were compared to mesonet gages before and after the radar representation of rainfall had been adjusted by the ratio of the summed gage to radar rainfalls for peripheral gage clusters. In the mean, this adjustment produced a statistically significant 15 percent improvement (< one percent level with two-tailed "t" test) in radar accuracy. The adjusted radar measurements then had an approximate gage density equivalence of 10 mi^2/gage. The relative precentage improvement would have been greater if the radar performance for the mesonet had been poorer than it was (mean factor of difference of 1.53 before adjustment).

The gaging requirements for the estimation of area mean rainfall for an area the size of the EML target (4800 mi^2) are decreased relative to those for the mesonet (220 mi^2). Employing a method of indirect inference using the digitized radar observations, the gage requirements to meet a specified accuracy are determined. To meet a specification that the area mean rainfall be measured within a factor of two 99 percent of the time requires 55 mi^2/gage for the EML target but at least 5 mi^2/gage for the mesonet.

The optimum method of rain measurement as a function of prescribed accuracy and such practical considerations as budget, available personnel and terrain is specified. For the measurement of the rainfall from individual showers the gage-adjusted radar is far superior to gages alone unless one can afford to wait for the subject showers to pass over a limited, dense raingage network. For measurement in a fixed area the size of the mesonet, gages are superior to the radar. For measurement of rainfall over an area the size of the EML target either gages alone, or a radar adjusted by gages, can accomplish the task. In the former instance, about 90 evenly spaced gages in the EML target should provide area rain measurements within a factor of two of the true value 99 percent of the time. In the latter instance, the radar estimates adjusted by gages should be as accurate as those provided by the network of 90 gages. The final choice as to the measurement system will probably be determined by other considerations. As an example, EML will probably continue with a radar system adjusted by gages because of the difficulty of installing 90 gages evenly over an area that is partially covered by water by late summer.

It is concluded that the Z-R relationship in this study is the best currently available for south Florida. Any further fine tuning of this relationship does not appear warranted because of beam filling uncertainties and false echo due to anomalous propagation. The latter was a serious obstacle in this study that must be removed before radar rain estimation will be possible on all days.

The gage and radar comparisons are compiled herein in their entirety for use by other scientists.

OPTIMIZING THE MEASUREMENT OF CONVECTIVE RAINFALL IN FLORIDA

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and Victor Wiggert

1. INTRODUCTION

This paper represents the completion of a three-year study of the nature of Florida convective rainfall and its measurement. It combines the work reported by Herndon et al. (1973) with new observations and calculations from the Florida Area Cumulus Experiment of 1973 (FACE 1973). For simplicity, the Herndon paper is hereinafter referred to as H. All results are interpreted in the context of the continuing series of seeding experiments that are being conducted by the Experimental Meteorology Laboratory (EML) in Florida.

This report has five major sections. These include: 1) definition of the nature of Florida convective rains to serve as a basis for determining the magnitude of the measurement problem, 2) calculation of area-mean rainfall using gages deployed over an area of 220 mi^2 (570 km^2), errors are determined as a function of gage density, 3) estimation of area rainfall using S-band (10-cm wavelength) radar with gages in small, dense arrays serving as the basis for comparison, 4) definition of the gaging requirements to measure area-mean rainfall within a specified accuracy over large areas ($13.0 \times 10^3 km^2$) using gages (the gaging requirements are actually inferred from digitized radar observations in the manner to be described), and 5) specification of the accuracy of a combined gage and radar system for the measurement of areal convective precipitation.

In all sections, errors for the various systems of rain measurement are determined for the day (24 hours) because this is the time frame for the evaluation of most cloud seeding experiments. In practice, the EML evaluates its seeding experiments for a six-hour period after the time of initial seeding. On most days of experimentation, the rain has ceased by the end of this period so rainfall for the six hours differs little from that for the entire day. Consequently, the results presented here are pertinent to the evaluation of EML's seeding experiments.

2. THE NATURE OF FLORIDA CONVECTIVE RAINFALL

2.1 The Raingage Observations

The raingage observations were collected during the summers of 1971 and 1973 as a part of the EML Florida Area Cumulus Experiment (FACE). The network containing the gages deployed is shown in figure 1. In 1971, the network contained 186 separate gage locations (24 of the 186 locations had two or more gages) spread over 220 mi^2 (570 km^2) of flat agricultural land, most of it devoted to sugar cane and cattle grazing (fig. 1). Recording raingages were in operation at 68 of the 186 gage sites. In 1973 the network was expanded to 253 mi^2 (655 km^2) containing 229 gage sites (22 of the sites had multiple gages).

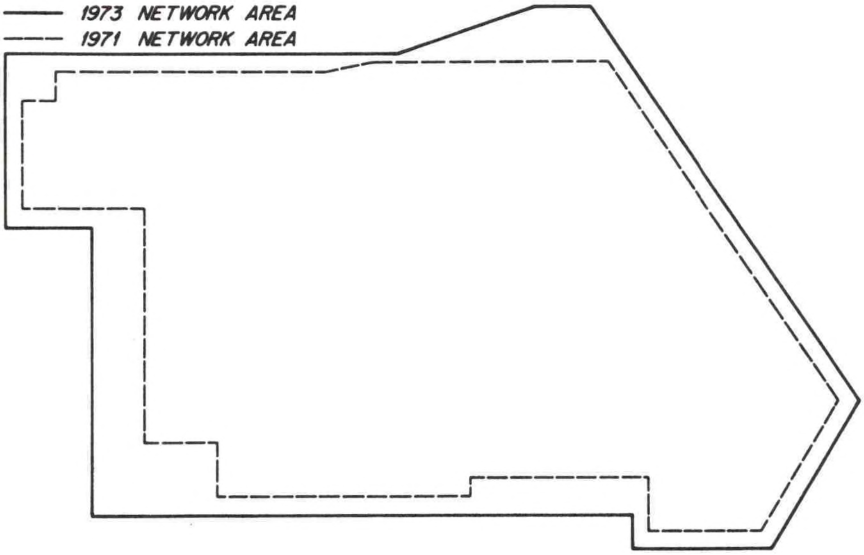

Figure 1. Outline of Mesonet in 1971 (dashed line) and in 1973 (solid line).

At 22 of the gage sites, recording (tipping-bucket) and non-recording gages were collocated. In 1971 and 1973, network operation was 15 June to 15 July and 14 June to 14 August, respectively, for a total of 93 days. Gage density averaged 1 mi^2/gage (2.6 km^2/gage) in both years.

2.2 Results

It rained somewhere in the network on 92 of the 93 days of network operation in 1971 and 1973, and on 86 days $R \geq 0.01$ in. (0.25 mm). The area-mean rainfall was 26.48 in.

(673 mm), 6.53 in. (166 mm) in 1971 and 19.95 in. (507 mm) in 1973 for an area average of 0.28 inches (7.1 mm) for the 93 days of network operation in the two years. In the 1973 period, it was rainy and disturbed much of the time. As an example, summation of the greatest single gage values for the 62 days of network operation provided an extraordinary total of 103.87 inches (2638 mm), or an average maximum 1.68 inches (43 mm) per day. Tabulation of network rainfall statistics for 1971 and 1973 is provided in table 1.

The spatial distributions of rainfall within the network for the periods in the two years individually and then combined are presented in figures 2a, b and c. (The boundaries of the network for the 1971 presentation have been expanded to match those in 1973.) Rather great point rainfalls and intense rainfall gradients characterize all presentations. The solid lines across the isohyetal analyses represent the cross sections for the rain profiles that are illustrated in figure 3. Profile distances are referenced to the position of the maximum rainfall along each line; distances southwest and northeast of the maximum are negative and positive, respectively. The most pronounced gradient for the profiles is the 14 inches in four miles for the combined 1971 and 1973 profile. Rain gradients are treated more extensively later in the text.

Table 1. Rainfall Statistics for Meso-Area 1971 & 1973

Date	# Gages Available	$\bar{R}$	σ	R_{max}	R_{min}	Median
15 June 1971	164	0.114	0.259	1.250	0	0
16	173	0.037	0.114	.710	0	0
17	180	0.017	0.064	.560	0	0
18	179	0.300	0.446	1.800	0	0.070
19	180	0.041	0.122	0.670	0	0
20	181	0.041	0.104	0.620	0	0
21	182	0.01	0.028	.170	0	0
22	182	0.295	0.463	1.920	0	0.080
23	183	0.052	0.085	0.560	0	0.020
24	181	0.382	0.407	1.830	0	.220
25	179	1.013	0.719	2.69	0	.960
26	180	0.054	0.135	0.790	0	0.005
27	180	0.499	0.562	2.100	0	0.270
28	181	0.254	0.397	2.000	0	0.070
29	178	0.124	0.232	1.450	0	0.010
30	182	0.001	0.003	0.020	0	0
1 July 1971	184	.011	.043	.370	0	0
2	181	.220	.309	1.400	0	.100
3	181	.076	.157	.970	0	.010
4	181	.269	.415	1.690	0	.020
5	183	.017	.047	.440	0	0
6	177	.324	.222	1.340	0	.300
7	179	.604	.325	1.800	0	.600
8	178	.078	.168	.820	0	0
9	181	.104	.135	.660	0	.050
10	179	.035	.084	.560	0	0
11	179	.185	.373	1.800	0	0
12	176	1.210	1.200	5.600	0	.980
13	178	.142	.290	2.430	0	.020
14	180	.018	.084	.840	0	0
15	177	.001	.003	.030	0	0
14 June 1973	181	.061	.192	1.650	0	0
15	177	.557	.641	2.810	0	.300
16	177	1.019	.797	4.000	0	.780
17	180	.004	.007	.040	0	0
18	181	.424	.321	1.820	0	.340
19	156	.627	.659	3.750	0	.385
20	114	.720	.266	1.850	270	.685
21	140	.013	.015	.150	0	.010
22	177	.510	.482	2.250	0	.380
23	183	.214	.323	1.560	0	.070
24	184	.320	.341	1.600	0	.210
25	184	.005	.014	.150	0	0
26	184	.607	.603	2.590	0	.475
27	184	.053	.128	.700	0	.010
28	180	.374	.640	3.100	0	.040
29	184	.123	.209	1.000	0	.010
30	184	0	0	0	0	0
1 July 1973	183	.188	.345	1.620	0	0
2	183	.690	.798	4.000	0	.380
3	184	.184	.243	1.100	0	.060
4	184	.661	.724	2.900	.010	.415
5	184	.005	.007	.030	0	0

Table 1. Rainfall Statistics for Meso-Area (cont.) 1971 & 1973

Date	# Gages	$\overline{R}$	σ	R_{max}	R_{min}	Median
6 July 1973	184	.357	.364	1.700	0	.245
7	184	.095	.218	1.430	0	.010
8	183	.136	.309	1.970	0	.010
9	183	.067	.238	1.800	0	0
10	181	.588	.681	4.600	0	.220
11	181	.084	.097	.500	0	.050
12	183	.247	.233	1.380	0	.190
13	184	.031	.061	.300	0	0
14	184	.140	.232	1.300	0	.030
15	184	.189	.315	1.560	0	.055
16	182	.044	.147	1.230	0	.010
17	184	.110	.211	1.460	0	.020
18	183	.042	.116	.820	0	0
19	182	.321	.489	2.430	0	.065
20	181	.041	.079	.500	0	0
21	183	1.131	.256	2.050	.020	1.150
22	181	2.798	1.509	6.000	.030	2.450
23	182	.027	.040	.220	0	.020
24	183	.038	.080	.510	0	0
25	184	.045	.128	.700	0	0
26	183	.328	.423	1.770	0	.140
27	184	.105	.190	1.170	0	.020
28	182	.628	.611	2.500	0	.400
29	183	.644	.518	2.130	0	.570
30	184	.033	.118	.960	0	0
31	183	.149	.224	1.100	0	.050
1 August 1973	183	.357	.411	1.740	0	.150
2	181	.130	.190	.940	0	.040
3	179	.358	.471	1.760	0	.100
4	177	.731	.637	2.590	0	.620
5	182	.050	.106	.620	0	0
6	181	.406	.414	1.650	0	.210
7	182	.161	.232	1.080	0	.075
8	181	.396	.534	2.540	0	.130
9	182	.734	.798	3.940	.030	.365
10	180	.284	.332	1.960	0	.150
11	181	.005	.025	.300	0	0
12	180	.119	.157	1.300	0	.050
13	183	.030	.043	.210	0	.010
14	181	.427	.492	2.480	0	.220

Isohyetal Analyses for Periods in 1971 and 1973

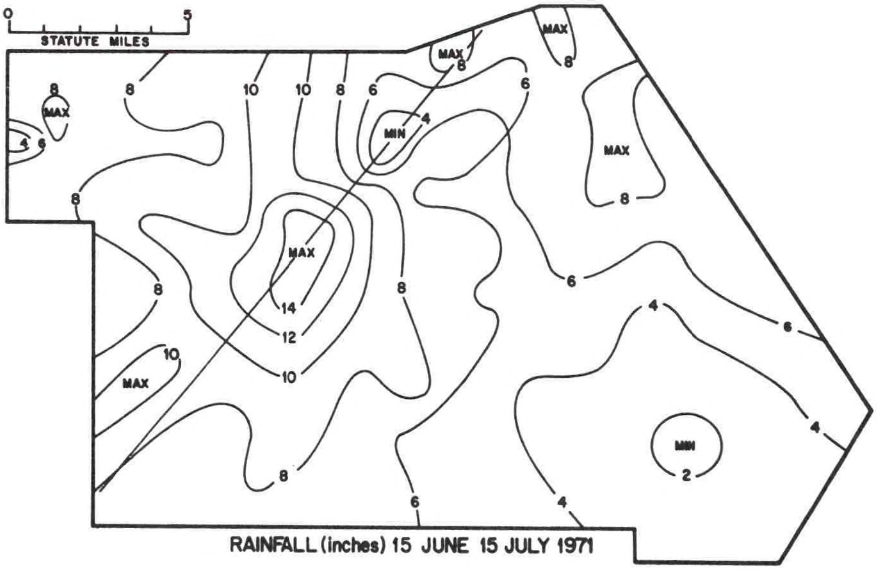

Figure 2a. Isohyetal analysis for 15 June to 15 July 1971.

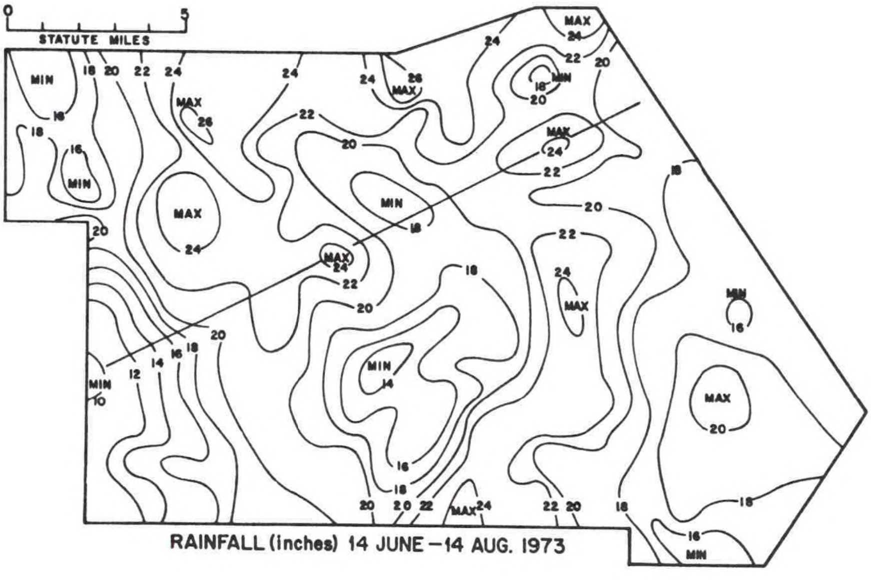

Figure 2b. Isohyetal analysis for 14 June to 14 August 1973.

Isohyetal Analyses for Periods in 1971 and 1973
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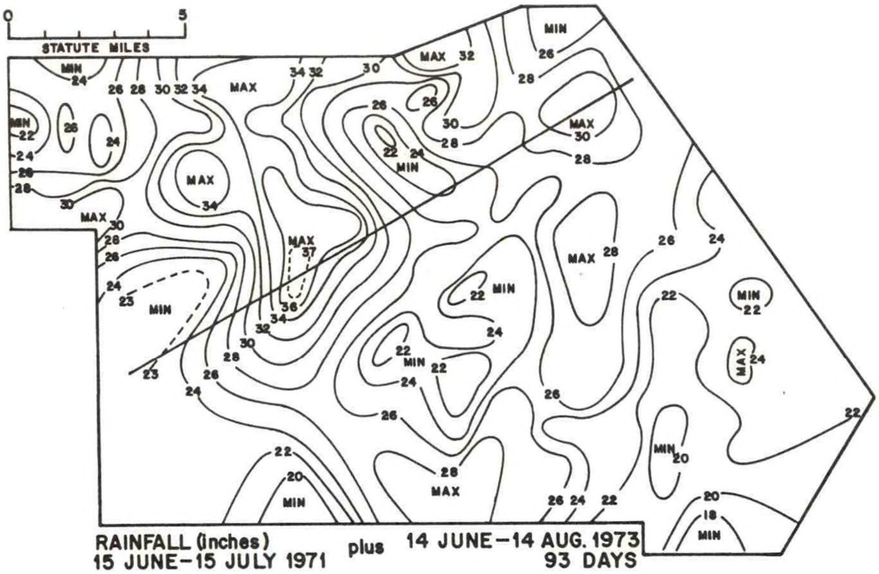

Figure 2c. Isohyetal analysis for 1971 and 1973 combined.

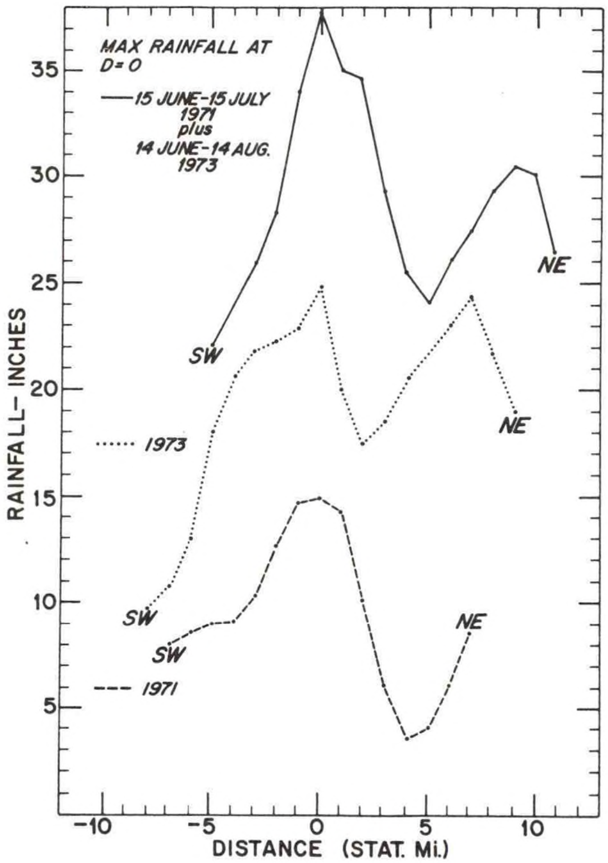

Figure 3. Rain profiles for lines shown in figure 2. Profile distances are referenced to the position of the maximum rainfall along each line.

The persistence of the rain maximum in the west-center of the network even after 93 days in two years may not be due to chance. It may represent a real area of preferred convection due to a complicated interaction of the sea breezes from the Gulf and Atlantic with that of Lake Okeechobee. The Florida sea breeze model developed by Pielke (1972) is being used to investigate this problem theoretically.

As shown in H, the greatest shower activity in terms of frequency and amount occurred in the afternoon and early evening hours. Most of the showers were from very tall clouds. Maximum, daily, radar-observed cloud tops within 25 n mi of the network for the 93 days of its operation are shown in figure 4. The radar tops were measured at approximately 40 minutes past the hour by operators of the National Hurricane Center (NHC) WSR-57 radar. Continuous radar monitoring of cloud tops would have yielded somewhat higher values. Using essentially the same radar equipment, Saunders and Ronne (1962) found that the height of the visible tops exceeded that measured by the NHC WSR-57 radar by 200 to 3000 feet for the 32 clouds that were studied. For the 1971 and 1973 observations, one should note that it is a rare day indeed when the maximum radar-measured cloud top does not exceed 40,000 feet.

The daily rainfall patterns are most interesting. Extraordinary gradients in daily rainfall were documented in both years of network operation. An isohyetal analysis of one of the most exceptional days is presented in figure 5 for 22 July 1973. Three point maxima near 6.00 inches are

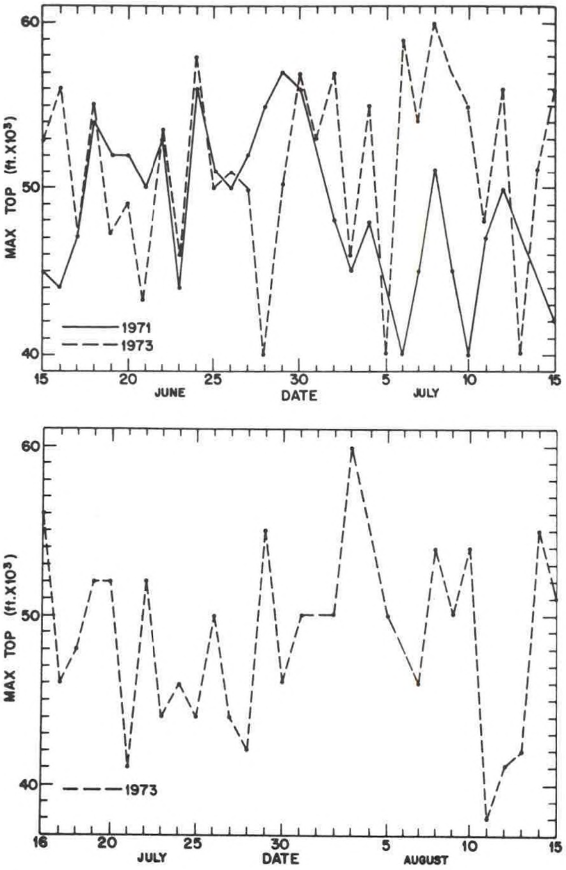

Figure 4. Maximum radar-measured echo tops within a 25 n mi radius of the center of the mesonetwork.

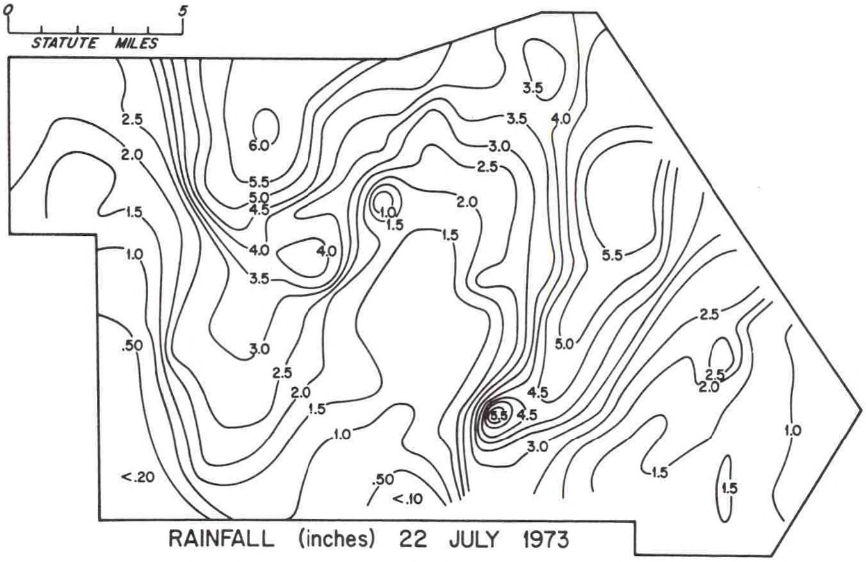

Figure 5. Isohyetal analysis for 22 July 1973.

evident; the one in the northwest portion of the network exceeded this value, but was unmeasured because of gage overflow. Amazingly, there are several areas in this small network where there was nearly no rainfall. The maximum rain gradient is 4.00 inches in one mile in the south part of the network. This is more easily appreciated by reference to the photograph in figure 6 that was taken from central site on this day. An area of extreme rain gradient is evident in the left background of the photograph.

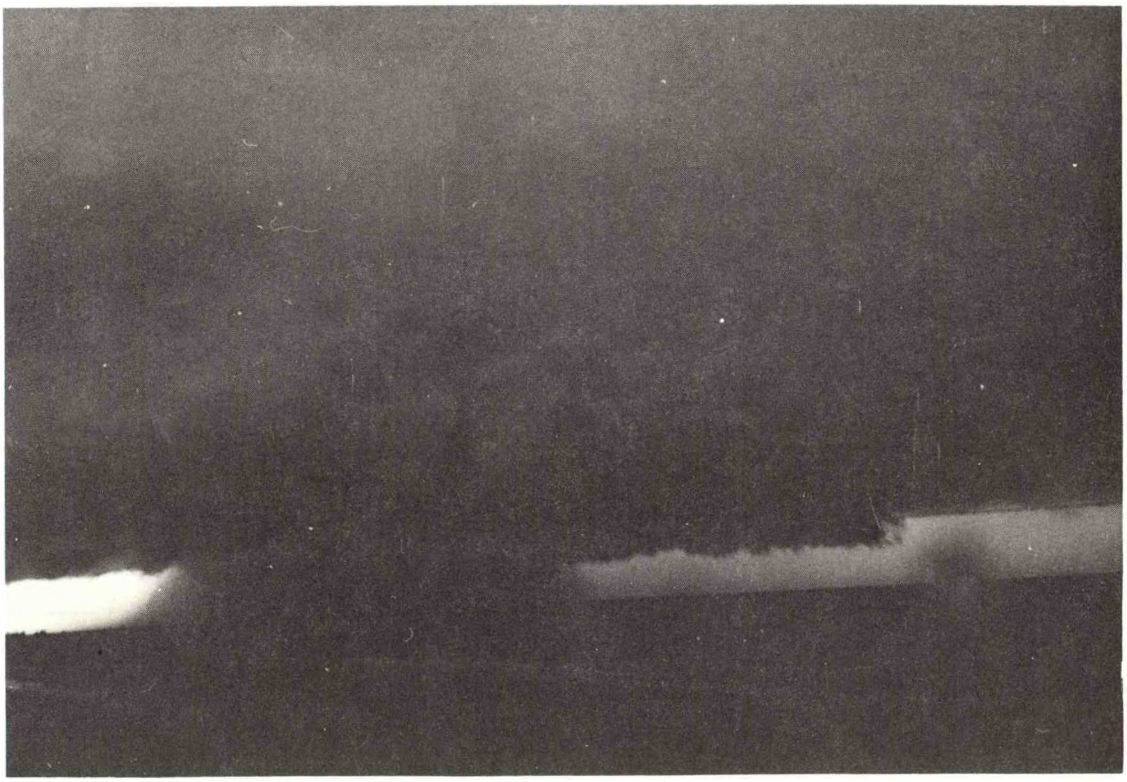

Figure 6. Photograph taken from central site in the mesonetwork at 2300 GMT on 22 July 1973.

A measure of rain gradients referenced to the core maxima was made for each day of network operation in 1973. An orthogonal grid, oriented north-south and east-west, was centered on the individual rain maxima on the network isohyetal analyses. Point rainfalls at mile intervals were interpolated along the intersecting lines as long as the readings decreased from the central maximum. The recordings were normalized to the maximum value and the mean values and ratios were calculated for each grid point. The average of the 127 core maxima used in this study was 1.79 inches.

Results are presented in figure 7. The lines represent mean normalized rain profiles for individual 24-hour rain maxima used in the study. The normalized profiles suggest symmetry in all directions. The point 24-hour rainfalls decrease to one-half the core maximum in roughly two miles; beyond this rate of decrease is much less. This characteristic shower profile has implications for the radar measurement of precipitation with respect to filling of the radar beam. This is discussed later in this report.

During the period of network operation nearly 50 percent of the total rainfall was measured on 14 days or 15 percent of the 92 days with rain. This is consistent with the findings of Riehl (1954) and Garstang (1972) that roughly 50 percent of the rain falls in 10 percent of the time with rain. Further, this rain-time relationship is

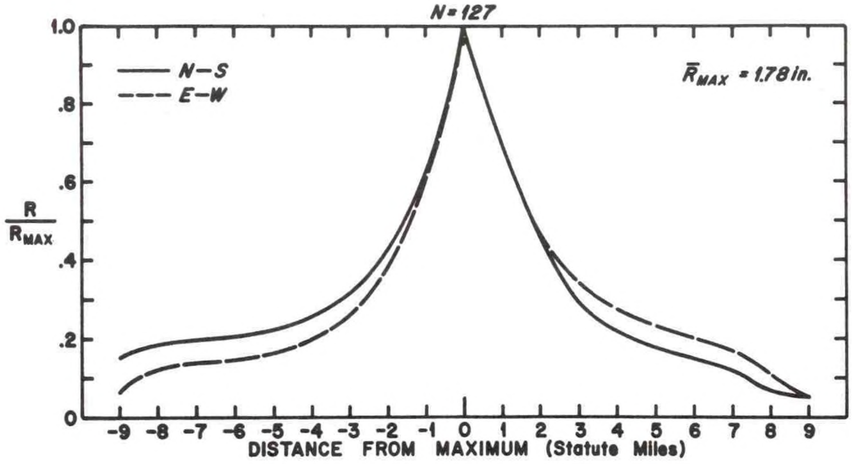

Figure 7. Mean normalized rain profiles for individual 24-hour rain maxima

apparently transferable to a rain-area relationship over the course of a day as shown in figure 8. In the mean for all days with rain, 50 percent of the rain volume is contained within about 17 percent of the area with rain. Examination of figure 8 reveals a few glaring, and as yet unexplained, exceptions to this mean relationship.

The transference of cumulative rain-time relationships to cumulative rain-area may be explained by a radar study by Woodley et al. (1971) from which it can be inferred that a cloud is structured such that 10 to 20 percent of the cloud volume contains about 50 percent of the rainwater (see fig. 9).

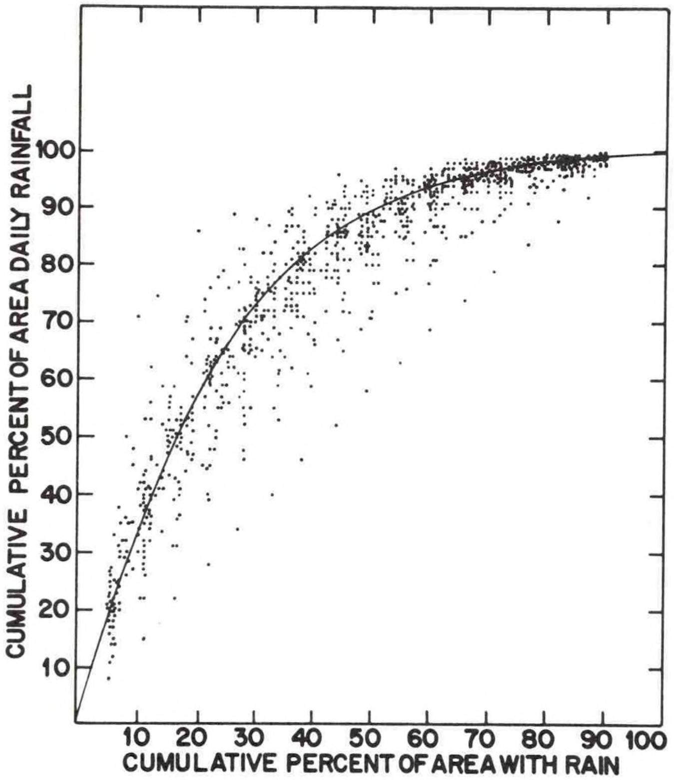

Figure 8. Cumulative percent of area daily rainfall versus cumulative percent of area with rain.

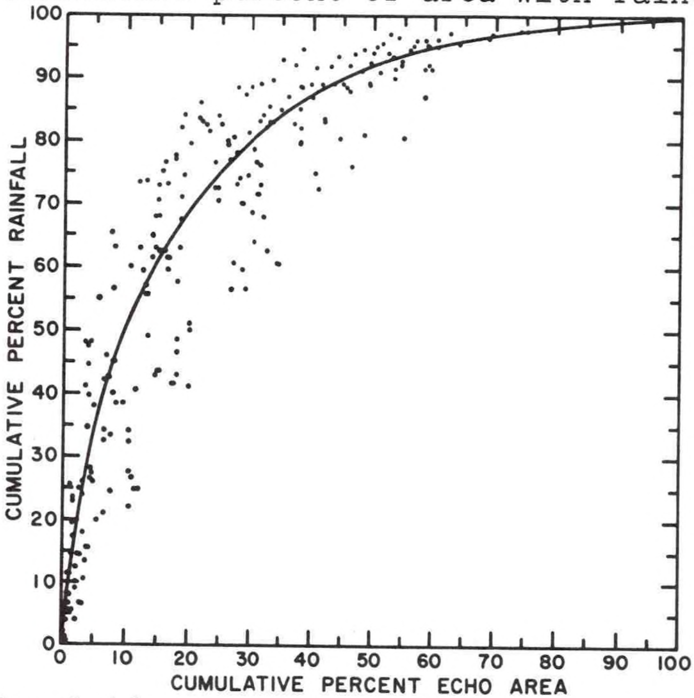

Figure 9. Cumulative percent rainfall versus cumulative percent of echo area producing the rainfall.

If this inference is correct, a stationary cloud should produce 50 percent of its rainfall 10-20 percent of the time with rain and over 10-20 percent of the area with rain -- in agreement with what is observed. With cloud movement or with many clouds over a longer time frame, the rain-area relationship should change because the same rainwater is spread over complicated, interacting areas. This time smearing was found for the 1971 and 1973 periods of network operation (fig. 10).

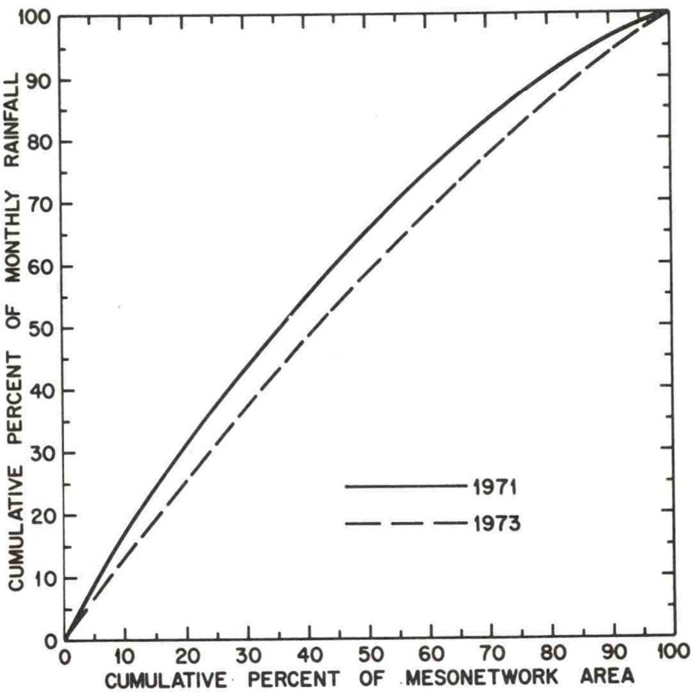

Figure 10. Cumulative percent of period rainfall versus cumulative percent of network area with rain. For 1971 and 1973, the periods are 31 and 62 days, respectively.

In 1971 and in 1973, 50 percent of the network rain was contained in 36 and 42 percent of the network area with rain.

3. MEASUREMENT ERRORS AS A FUNCTION OF GAGE DENSITY

3.1 Preliminaries

Before discussion of the use of raingages for the derivation of areal rainfall, one must first determine the accuracy of point rainfall measurements. This was investigated using observations from the meso-area during FACE 1971. At 24 of the 186 network gage sites, two and sometimes three gages were collocated. Three types of gages were used: 1) plastic, wedge-shaped gages that were affixed to stakes or fence posts, 2) standard dipstick gages with orifices of eight-inch diameter and 3) recording raingages of the tipping bucket variety.

The daily rain measurements were examined for systematic trends because of gage type, but none of consequence were found. The largest trend was a two percent underestimate of the mean point rainfall by the tipping bucket gages when referenced to the check or dipstick gages.

Assuming no systematic bias because of gage type, the daily rain readings were combined and examined for random variability. The maximum rainfall at each gage site was tabulated and rain differences were formed by subtracting the readings of the collocated gage or gages from the maximum reading. Maximum rainfalls less than 0.05 inch were not considered. Mean results are presented in table 2. The mean maximum rainfall was 0.57 inch and the mean difference was 0.05 inch, or approximately nine percent of the mean maximum rainfall.

Table 2. Comparison of Readings of Collocated Raingages

N = 221	Maximum Rain at Site (inches)	ΔR (inches)	$\frac{\Delta R}{R} \times 100(\%)$
Mean	0.57	0.05	8.6%
δ	0.62	0.07	--

The difference between the maximum rainfall and the other readings is a function of the amount of rain as shown in figure 11. The best fit line to the 221 points is a logarithmic least squares fit. The percentage variability or uncertainty is near five percent for maximum rainfalls near 1.00 inch increasing to 12 percent for rainfalls of 0.10 inches. These results should be compared to those of Huff (1955) for Illinois. He used eight-inch gages six feet apart and found a variability of six percent for mean rainfalls of 0.01 and 0.09 inches and one to two percent for rainfalls greater than 0.50 inches.

The reason for the variability among gages in Florida is not known. A small portion of it is explained by the

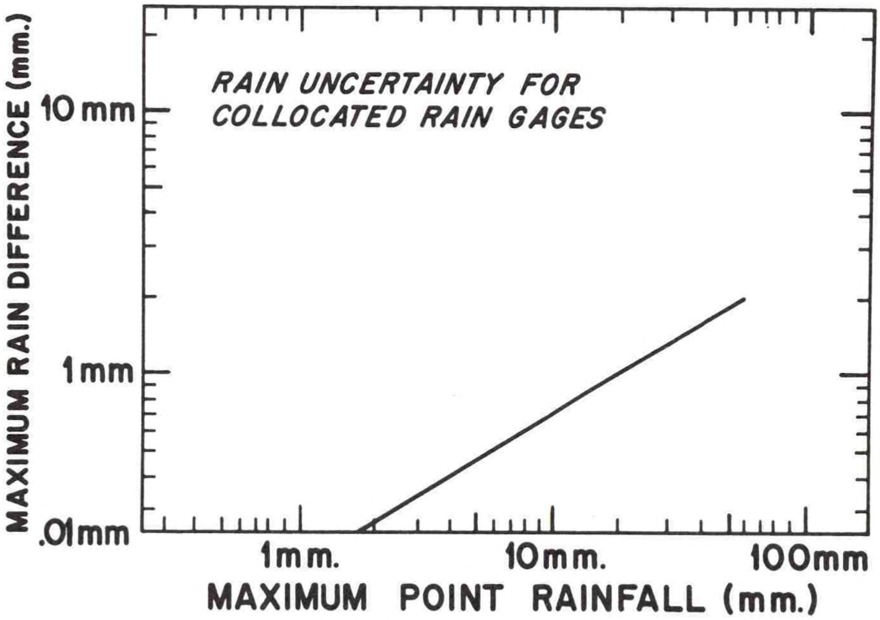

Figure 11. Rain uncertainty for collocated raingages.

nature of gages (e.g. the two percent difference between the dipstick and tipping bucket gages). The balance of the variability is probably random due to subtle differences in gage exposure and perhaps due even to the nature of the rain itself.

These results suggest that it is unreasonable to expect to measure point rainfall to an accuracy of better than five to ten percent. The researcher should recognize this when using gages as standards for comparing radar methods of percipitation estimation, as in section 4 of this report.

3.2 Area Rain Estimates Using Gages: Small Area ($220\ mi^2$ or $570\ km^2$)

It is important to know the accuracy of gage estimates of areal mean rainfall as a function of gage density in order to design intelligently a system of rain measurement. Discussion in this section is limited to results for an area covering 253 mi^2 (655 km^2) because this is the largest area the EML could afford to instrument adequately. Results are continually contrasted and compared with a similar study by Huff (1971) for Illinois. In a later section, the gaging requirements for a much larger area ($13.0 \times 10^3 km^2$) are inferred using radar observations.

Throughout this section, daily mean area rainfall as defined by the most dense gage array (1 mi^2/gage or 2.6 km^2/gage) is the standard for comparison. It is hereinafter referred to as the "true" rainfall even though the errors in area rainfall inherent with this gage density are not known. This true mean was compared to those derived from a number of subnetworks that were defined for various densities (table 3). A multiplicity of subnetworks were defined for each density to increase the sample size. For each density, gages included in one subnetwork were not repeated in another. To combine observations from 1971 and 1973, only the 184 gage sites common to both years of network operation were used. Several days were not included in this study because either (1) $\overline{R} < 0.01$ inch (0.25 mm) or (2) a large number of gages were not read because of logistic difficulties. Out of a possible 93 days, 78 met the acceptability criteria.

Table 3. Gage Subnetworks Used to Quantify Error as a Function of Gage Density

Gage Density (mi^2/gage)	No. of Subnetworks per day	Total Number of days = 78
3	3	
6	5	
12	11	
24	11	
55	11	
110	11	
220	11	

Before rain can be measured it must be detected. Precipitation detection probabilities versus gage density as a function of area mean rainfall is presented in figure 12. The number of days per rain category is indicated in parentheses. For area-mean rainfalls exceeding 0.50 inches, only one gage in this 220 mi^2 area is sufficient to detect virtually all of the rain days. On the other hand, approximately 25 mi^2/gage is necessary if one can accept nondetection of no more than ten percent of the rain cases with area means between 0.01 and 0.05 inches. Comparison of these results with the relevant results presented by Huff (1971) for Illinois reveals comparable detection requirements.

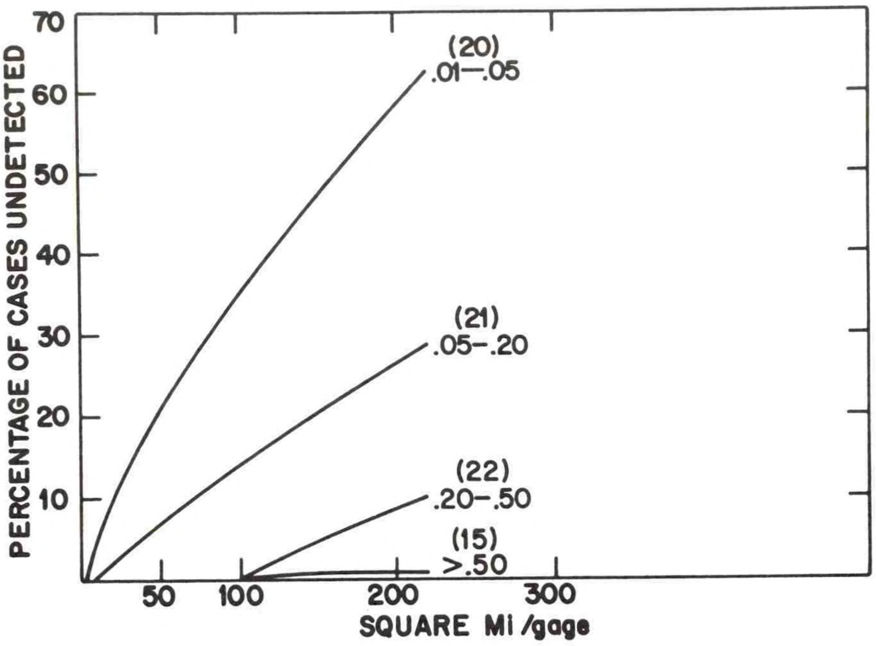

Figure 12. Detection of convective showers as a function of gage density and area-mean rainfall. As an example, for 0.01 in. $\leq \overline{R} \leq 0.05$ in. A network with 25 mi^2/gage will leave ten percent of the showers undetected.

Sampling error, defined as the absolute difference between subnetwork mean and "true" mean rainfall, was determined for the rain observations. Sampling errors were related to areal mean rainfall by linear regression and results compared with those in Illinois (Huff, 1971) as illustrated in figure 13. The Florida curves are for showers over 24 hours while the Illinois curves are for showers that lasted one hour. This time discrepancy is not as great as it might seem at first, because most of the Florida rains

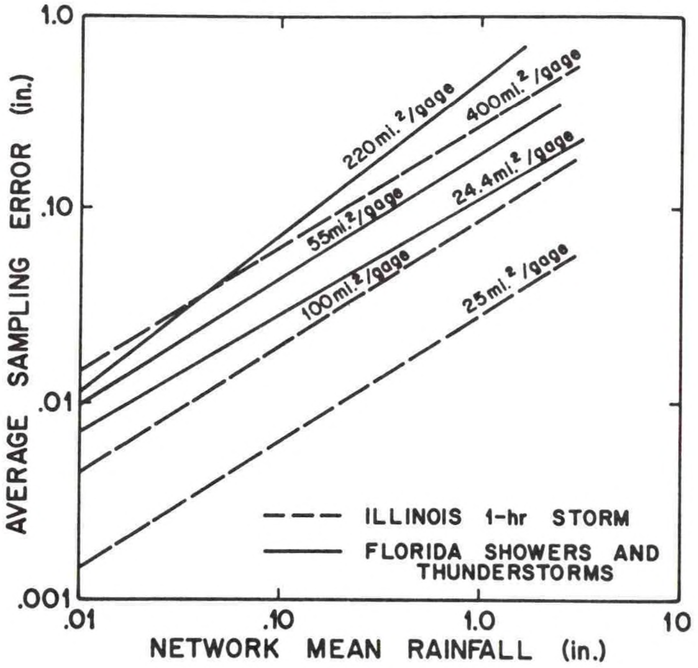

Figure 13. Average sampling error versus network mean rainfall. The lines are logarithmic least squares fits. The Illinois curves are from Huff (1971).

occurred in a six-hour period during the afternoons. Examination of the Illinois and Florida curves suggests that the gaging requirements are more stringent (by a factor of two to four) in Florida than in Illinois. However, there are two interpretations. The measurements in Illinois were made in an area of 400 mi^2 while those in Florida were made in an area of 220 mi^2. As we shall see in a later section, the gaging requirements for the measurement of areal rainfall decrease with an increase in area size, so the requirements in Florida for a 400 mi^2 area would certainly be reduced relative to the area covering 220 mi^2. Thus, the Florida and Illinois results would be in better agreement if the areas were of the same size. A second explanation for the discrepancy is the differing standards for comparison in the two studies. In Illinois, the standard densities were eight to 11 mi^2/gage. Consequently, it is likely that sampling errors for a given gage density are greater in Florida because of 1) the difference in area size for the calculations and, more importantly, 2) a more stringent basis for comparison in Florida than in Illinois. Because of these two variables, one cannot use figure 13 as evidence that the convective systems are inherently different in the two regions.

A useful presentation of measurement errors as a function of gage density is a factor-of-difference (FD) representation. The FD is defined as:

$$G_i/G_F \text{ when } G_i \geq G_F \text{ or } G_F/G_i < G_F \text{ when } G_i < G_F \qquad (1)$$

where G_F represents the mean rainfall as measured by the full network density and G_i represents the mean rainfall as determined by subnetwork with a lesser density of gages. FD distributions as a function of gage density are presented in figure 14 from which it can be seen that the accuracy of rainfall measurement degrades with decreasing gage density. As examples, the measured area mean rainfalls are within a factor of two of the true mean 90 percent of the time for a

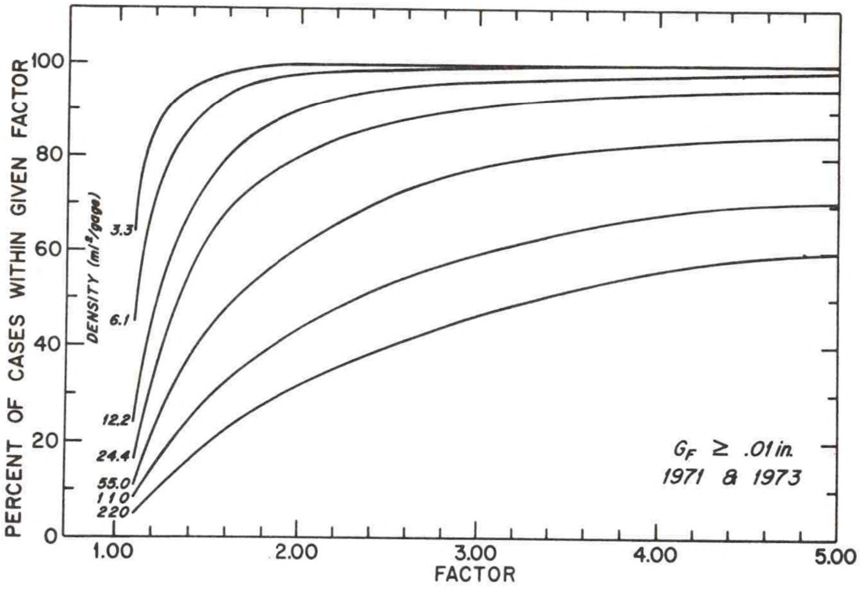

Figure 14. Factor of difference (as defined in text) versus percentage of comparisons within specified factor of difference as a function of gage density. Rainfall measured by full network density (G_F) with 1 mi^2/gage is the standard for comparison.

gage network density of 12 mi^2/gage and 50 percent of the time for a gage network density of approximately 90 mi^2/gage (obtained by interpolation). This type of presentation has great utility because it allows specification of gage density depending on the error and its frequency that one is willing to accept.

If the sole interest were the measurement of convective events on the scale of 220 mi^2, the gaging effort that must be expended to measure these rainfalls within a specified accuracy would now be determined. In most cases, however, one is interested in areas such as hydrologic basins many times this size. An example would be the target area for EML's continuing series of multiple cloud seeding experiments that covers 4800 mi^2 ($\sim 13.0 \times 10^3 km^2$). Because the scale of the convection changes drastically with this large increase in area size, mere extrapolation of the results for the smaller area to the larger is not valid. A separate effort is required to determine the gaging requirements for the larger area.

Until the advent of a digitized radar in Florida, there was really no hope of solving this problem using gages as the standard because the expenditure of time, effort and money necessary to instrument an area of this size were totally unacceptable. With the radar, the problem is now quite tractable as seen in section 5 of this report. But first, the characteristics of the Miami radars and their capabilities for the estimation of convective precipitation must be discussed.

4. RADAR MEASUREMENT OF PRECIPITATION

Weather radar is receiving increased attention for the measurement of rainfall, especially so, now that a computer processing capability is a reality at many radar installations. Radar provides the equivalent of an infinitely dense raingage network which would make it a near perfect tool for a convective precipitation measurement if the magnitude of the radar precipitation estimates were without error. Unfortunately, this is frequently not the case. Radar calibration is always an uncertainty to some extent and the radar beam is usually not uniformly filled with precipitation. Further, the relationship of radar reflectivity (Z) to rainfall rate (R) is variable between storms and within storms even in the same geographical location and season (Stout and Mueller, 1968). One can also not count on "normal" refractive conditions; with anomalous propagation, there is false echo and uncertainty as to what is being measured. All of these considerations produce error in the radar estimation of rainfall. Rather than attempt a quantitative correction for calibration and beam filling uncertainties, anomalous propagations and Z-R variability, it now appears more practical to calibrate the radar against a few raingages. Radar defines the spatial variability and provides a first estimate of the magnitude of the precipitation and the calibrating gages allow for its adjustment (Wilson, 1970). This is treated in more detail later in the text. For a more comprehensive discussion of the measurement of rainfall with radar, the reader is referred to a review paper by Atlas (1968).

The EML used the UM/10-cm radar of the Radar Meteorology Laboratory of the University of Miami to evaluate its series of seeding experiments between 1968 and 1971. The UM/10-cm and WSR-57 radar of the National Hurricane Center (NHC) were used concurrently in 1972 and by 1973 EML's primary research radar was the NHC WSR-57. The EML chose radar for the evaluation of its single cloud seeding experiments because gage measurement of rainfall from individual clouds (base echo areas generally ∿ 250 km^2) could not have been accomplished without a totally unacceptable expenditure of money and logistic effort. Further, seed and control clouds were obtained on each day of experimentation so, despite radar inaccuracies, intraday relative differences (seed vs control) should still have been valid. With the advent of the area experiment and interday randomization instead of intraday randomization cloud by cloud, radar is not as obvious a choice, particularly if the radar exhibits great interday variability. This section of this report treats this problem; it represents the most complete discussion to date of the radar estimation of convective rain in Florida. It builds on the earlier work in this region (Woodley and Herndon, 1970; Herndon et al., 1971 and 1973).

4.1 The S-Band Radars

Two S-band (10-cm) radars were used in this study of convective rainfall during portions of the summers of 1972 and 1973. In 1972 both the UM/10-cm (Senn and Courtright, 1971) of the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences and the WSR-57 (Rockney, 1958) of NOAA's National Hurricane Center operated concurrently from a common location (∿100 m separation) from 5 to 31 July. Only the WSR-57 radar made reflectivity observations from 1 to 20 August 1972. Both radars are capable of iso-echo contouring; the UM/10-cm uses a four-level device (Senn and Andrews, 1968) and the WSR-57 is equipped with a six-level video integrator and processor (VIP) (Shreeve, 1969).

In 1973, the EML used the NHC WSR-57 radar exclusively for its research without compromising the operational requirements of the NHC. Although the basic radar remained the same as in 1972, the radar output was digitally quantized and tape recorded. This major step was made possible by the cooperation of NHC in conjunction with the collaborative expertise of scientists from the National Severe Storms Laboratory (NSSL), Norman, Oklahoma, the Radar Meteorology Laboratory of the University of Miami and the EML. Sirmans and Doviak (1973) provide a comprehensive theoretical analysis of the integration and processing techniques necessary to digitize and record the power returned to the WSR-57 radar. Wiggert and Andrews (1974) provide specific details on the EML-NHC digitized radar system including a description of hardware and a description and listing of the software programs for reading and processing the taped data. Calibration of the radar and digitizer are also treated.

The combined radar and digitizer system provides range normalized average power (in dbm) in each bin. These observations are the data source of those programs designed, described and listed by Östlund (1974) to process the radar observations to meet specific needs within EML.

Radar performance in estimating Florida convective rains was determined by making comparisons of gage and radar-derived volumetric rainfalls for gage clusters. In 1972, 40 recording raingages were installed in five clusters each having a gage density of one to three mi^2/gage (fig. 15). In 1973 the Big Cypress cluster replaced the Talisman cluster, and the mesonet, installed under contract with the University of Virginia, was also added. In all cases cluster rainfall is the standard against which the radar-derived rainfall is compared, even though there is a five to ten percent uncertainty for collocated gages and an unknown error for gages deployed in arrays with a finite gage density. The gage-derived water volume and area-averaged rainfall was obtained for each time it rained in a cluster. The former was obtained by integration of an isohyetal analysis for the length of time it rained in the cluster; the latter was obtained by dividing the water volume by the cluster area.

The radar-derived rainfall for the clusters was obtained manually in 1972, and both manually and by computer in 1973. In the manual method of obtaining radar estimates of cluster rainfall, the radarscope photographs were

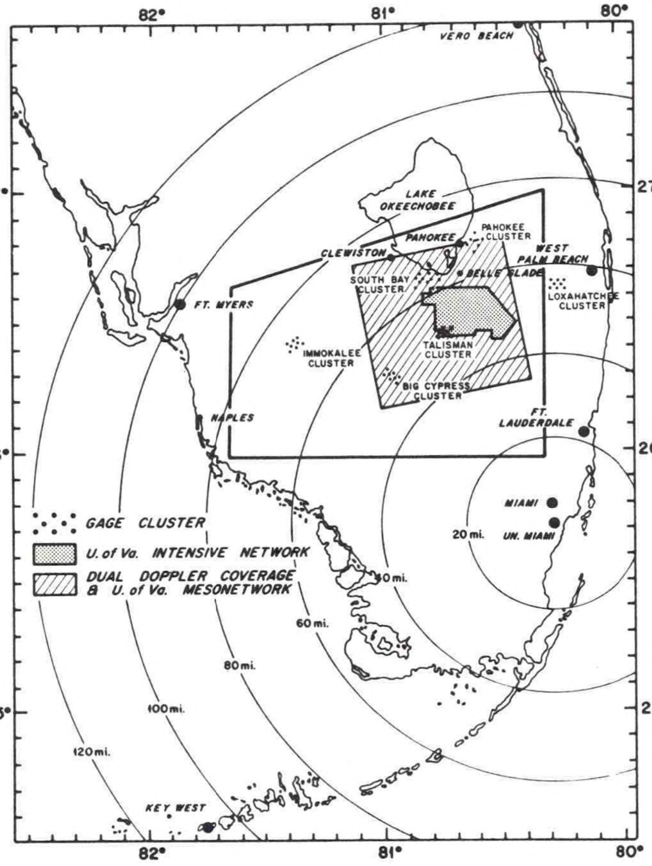

Figure 15. Field design for the Florida Area Cumulus Experiment (FACE). The largest quadrilateral is the EML target area. Contained within are the areas covered by the dual doppler radars, the mesonet (FACE intensive network) and the gage clusters. In the 1972 gaging effort, the mesonet and the Big Cypress cluster were not operative and in 1973 only the Talisman cluster was not operative.

projected onto a map of the gage clusters and the echoes over the clusters were traced at five-minute intervals. The echo contour areas were measured with a planimeter, plotted versus time and integrated. Water volume was obtained by multiplication of each integrated area-time value by a mean rainfall rate and an appropriate constant and then summation. Contour rainfall rates were derived from the Miami Z-R relationship

$$Z = 300\ R^{1.4} \qquad (2)$$

that has been used throughout the EML experiments (Woodley, 1970). The mean rainfall rate between any two successive contours is one-half the sum of the contour values.

In principle, the method of obtaining the radar estimates of rainfall by computer is the same as that for the manual method, but mechanically the two methods are quite different. Wiggert and Andrews (1974) and Ostlund (1974) describe the computer processing of the taped radar output to obtain rainfall. In unpacking the taped radar data, the digitizer response in each bin is converted to power using the transfer curve from the digitizer calibration run. Range normalization to correct for decreased power density with range is done at this time. These range normalized average powers in bins 2° by 1/2 n mi are then used with the KART and RSUM programs to compute rainfall in areas of interest. KART takes the average power per bin, converts power to reflectivity and then to rainfall rate using (2) and then interpolates the bin rainfall rates into a cartesian grid system of one nautical mile squares. (This is somewhat artificial because at ranges beyond 30 n mi the radar beam exceeds one nautical mile in diameter.) KART then writes a tape and displays the rainfall rates in one n mi squares for each scan. The RSUM program uses the tape created by KART and calculates the total rain depth over selected areas and for selected time periods within the day. For more details, the reader is referred to Östlund (1974).

In calculating the cluster rainfall from the digitized radar observations, the mean rain depth was calculated for the grid that encompassed the cluster by summing the depths for each square in the grid and dividing by the number of squares. The mean rain depth for the cluster contained within the grid is assumed equal to the mean rain depth for the grid itself. The cluster rain volume is then the product of the mean rain depth and the area of the cluster. Four of the cluster grids used for these calculations are shown in figure 16.

4.2 Results of Gage and Radar Comparisons

Comparisons between gage and radar-derived cluster rainfalls were made for individual showers and for summed shower rainfalls for the day. Hereinafter, the latter

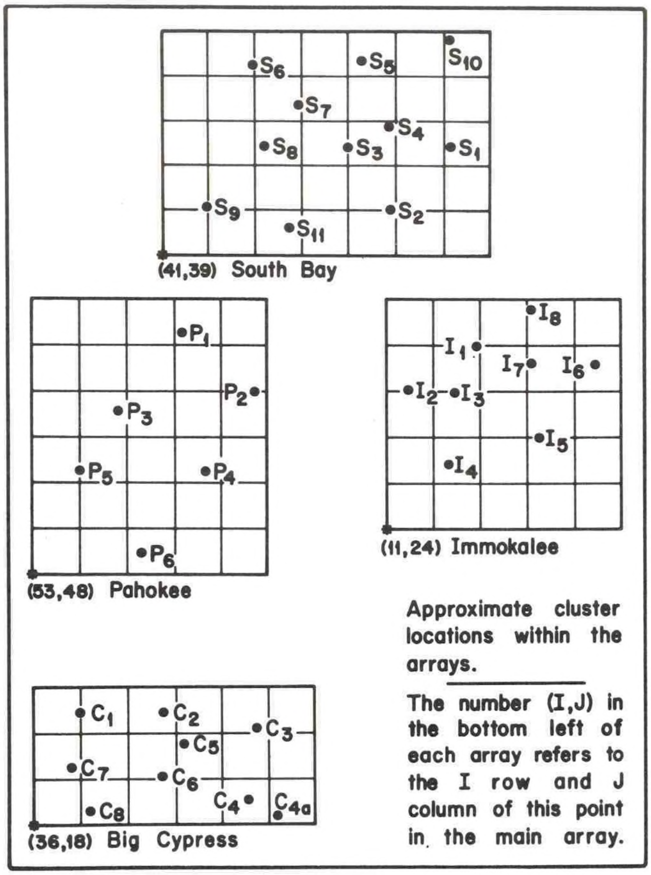

Figure 16. An example of the cluster grids for the calculation of radar-derived rain volumes and depths. These radar measurements are then compared with the corresponding measurements obtained from the gage observations at the indicated locations. The Loxahatchee cluster and the mesonetwork are not shown.

is referred to as the daily comparison. Tabulation of the individual shower comparisons for the UM/10-cm and the WSR-57 radar in 1972 and for the WSR-57 in 1973 are presented in Appendix B. Presentation of the daily comparisons for both years is found in table 4. In 1972 there were 69 individual and 16 daily gage-radar comparisons using

Table 4. Daily Gage and Radar Comparisons Using Gage Clusters

(WSR-57 Radar Observations in 1972 and 1973)

Date	# Cluster Showers	$G_V(m^3 \times 10^3)$	$R_V(m^3 \times 10^3)$	G/R	R/G	F.D.
5 July 1972	2	129.0	177.2	0.73	1.37	1.37
6	3	280.9	306.7	0.92	1.09	1.09
7	1	50.7	121.5	0.42	2.38	2.38
8	1	41.7	119.8	0.35	2.86	2.86
9	3	76.4	65.5	1.17	0.86	1.17
10	3	590.3	238.5	2.48	0.40	2.48
13	4	1421.3	862.9	1.65	0.61	1.65
14	4	82.0	191.3	0.43	2.33	2.33
15	1	34.9	75.5	0.46	2.17	2.17
16	8	627.1	453.4	1.38	0.72	1.38
17	11	1345.3	718.9	1.87	0.53	1.87
18	7	271.0	307.7	0.88	1.14	1.14
19	6	236.6	215.6	1.10	0.91	1.10
20	12	449.8	313.1	1.44	0.69	1.44
21	1	30.6	14.2	2.16	0.46	2.16
23	7	119.3	142.6	0.84	1.20	1.20
24	6	926.4	1110.6	0.83	1.20	1.20
31	5	858.0	562.9	1.52	0.66	1.52
4 Aug. 1972	1	1.6	2.8	0.57	1.75	1.75
5	1	140.3	66.4	2.11	0.47	2.11
6	2	32.6	67.6	0.48	2.07	2.07
9	3	299.5	310.0	0.97	1.03	1.03
11	1	88.4	58.7	1.51	0.66	1.51
12	4	300.7	205.1	1.47	0.68	1.47
13	2	328.5	323.1	1.02	0.98	1.02
14	1	108.7	151.7	0.72	1.39	1.39
15	2	39.9	10.9	3.66	0.27	3.66
17	3	426.3	231.7	1.84	0.54	1.84

Table 4. Daily Gage and Radar Comparisons Using Gage Clusters (cont.)

(WSR-57 Radar Observations in 1972 and 1973)

Date	# Cluster Showers	G_V(m^3 x 10^3)	R_V(m^3 x 10^3)	G/R	R/G	F.D.
18 Aug. 1972	1	12.7	115.7	0.11	9.09	9.09
19	2	111.8	54.9	2.03	0.49	2.03
20	1	61.6	126.9	0.49	2.04	2.04
15 June 1973	1	244.69	243.24	1.01	0.99	1.01
16	6	1884.91	640.68	2.94	0.34	2.94
17	1	11.57	12.05	0.96	1.04	1.04
18	3	1222.20	573.77	2.13	0.47	2.13
20	5	1338.18	1200.92	1.11	0.90	1.11
22	4	1813.05	983.0	1.84	0.54	1.84
24	3	619.41	440.4	1.41	0.71	1.41
25	1	177.86	222.68	0.80	1.25	1.25
26	3	215.64	168.25	1.28	0.78	1.28
27	1	173.66	101.28	1.71	0.58	1.71
28	4	483.83	187.15	2.58	0.39	2.58
29	3	153.88	100.06	1.54	0.65	1.54
30	1	311.44	193.76	1.61	0.62	1.61
1 July 1973	3	777.20	344.69	2.25	0.44	2.25
2	7	612.02	1004.77	0.61	1.64	1.64
3	5	605.00	470.91	1.29	0.78	1.29
4	4	916.72	540.93	1.69	0.59	1.69
5	1	96.11	37.19	2.58	0.39	2.58
6	2	212.38	136.41	1.56	1.79	1.56
7	1	497.86	422.04	1.18	0.85	1.18
8	3	604.80	336.88	1.80	0.55	1.80
9	1	46.56	233.70	0.19	5.26	5.26
10	3	396.84	621.97	0.64	1.56	1.56
11	6	475.52	243.78	1.95	0.51	1.95

Table 4. Daily Gage and Radar Comparisons Using Gage Clusters (cont.)

(WSR-57 Radar Observations in 1972 and 1973)

Date	# Cluster Showers	$G_V(m^3 \times 10^3)$	$R_V(m^3 \times 10^3)$	G/R	R/G	F.D.
12 July 1973	6	1945.58	1284.98	1.51	0.66	1.51
15	5	3153.30	2724.70	1.16	0.86	1.16
16	2	120.22	192.83	0.62	1.61	1.61
17	4	786.30	1032.68	0.76	1.32	1.32
18	3	278.93	375.83	0.74	1.35	1.35
19	1	152.67	104.80	1.46	0.68	1.46
20	5	1003.96	1005.49	1.00	1.00	1.00
21	5	565.82	284.93	1.99	0.50	1.99
22	3	3407.45	2571.22	1.32	0.76	1.32
23	3	82.20	253.50	0.32	3.13	3.13
24	4	198.10	409.34	0.48	2.08	2.08
25	2	59.06	89.09	0.66	1.52	1.52
26	3	235.06	347.83	0.68	1.47	1.47
27	4	496.81	404.92	1.23	0.81	1.23
28	2	792.05	486.98	1.63	0.61	1.63
29	7	2187.84	1354.48	1.62	0.62	1.62
30	3	310.88	375.98	0.83	1.20	1.20
31	3	867.98	628.96	1.38	0.72	1.38
1 Aug. 1973	3	97.17	185.87	0.52	1.92	1.92
2	5	909.18	915.93	0.99	1.01	1.01
3	5	2819.15	2209.0	1.28	0.78	1.28
4	6	3008.13	2900.83	1.04	0.96	1.04
5	2	61.98	52.54	1.18	0.85	1.18
6	4	1379.84	655.6	2.10	0.48	2.10
7	3	125.32	83.20	1.51	0.66	1.51
8	2	205.14	175.05	1.17	0.85	1.17

Table 4. Daily Gage and Radar Comparisons Using Gage Clusters (cont.)

(WSR-57 Radar Observations in 1972 and 1973)

Date	# Cluster Showers	$G_V(m^3 \times 10^3)$	$R_V(m^3 \times 10^3)$	G/R	R/G	F.D.
9 Aug. 1973	3	595.91	658.71	0.93	1.07	1.07
10	5	635.51	923.40	0.69	1.45	1.45
11	1	147.65	152.03	0.97	1.03	1.03
12	2	36.84	59.15	0.62	1.61	1.61
13	2	219.36	187.47	1.17	0.85	1.17
14	7	1320.08	2459.25	0.54	1.85	1.85
16	5	579.99	553.16	1.05	0.95	1.05
18	2	174.67	191.91	0.91	1.10	1.10
19	4	3251.81	2518.69	1.29	0.78	1.29
20	3	614.51	613.41	1.00	1.00	1.00
21	2	1310.73	779.61	1.68	0.60	1.68
22	2	260.39	230.89	1.13	0.88	1.13
24	6	1730.01	1997.38	0.87	1.15	1.15
25	1	490.25	673.03	0.73	1.37	1.37
26	2	609.69	621.54	0.98	1.02	1.02
27	1	15.30	18.37	0.83	1.20	1.20
28	1	34.00	21.01	1.62	0.62	1.62
29	4	469.79	244.79	1.92	0.52	1.92
30	3	448.70	336.67	1.33	0.75	1.33
31	5	846.99	534.43	1.58	1.72	1.58
1 Sept. 1973	4	260.04	146.93	1.77	0.56	1.77
2	3	201.25	131.58	1.53	0.65	1.53
3	4	764.90	554.30	1.35	0.74	1.35
4	2	137.32	95.54	1.44	0.69	1.44
5	1	147.82	69.69	1.33	0.75	1.33
6	2	524.86	440.31	1.19	0.84	1.19
7	1	98.72	85.81	1.15	0.87	1.15
10	1	692.61	423.89	1.63	0.61	1.63

UM/10-cm radar observations and 101 individual and 31 daily gage-radar comparisons with the WSR-57 radar. In 1973 with only the WSR-57 in use, there were 245 individual and 77 daily gage-radar comparisons. On 62 days the mesonet was in operation with the gage clusters. The Immokalee cluster was terminated on 22 August 1974.

One should keep in mind that the comparisons in 1972 were done manually using filmed radar VIP video while those in 1973 were made using taped digitized output. Even though both depend on the same radar, the two systems have independent electronic circuitry that requires its own calibration. Thus, it is possible that the gage-radar comparison for a particular shower will differ depending on the method of calculating the radar-derived rainfall. This is treated in more detail later in the text.

A statistical summary of the gage and radar comparisons for individual showers and for summed shower rainfalls within the day are presented in tables 5 and 6, respectively. The mean results are stratified depending on whether the cluster rain volume as determined by the gages was $<10^5 m^3$ or $\geq 10^5 m^3$. Shower volumes $<10^3 m^3$ are not considered in these tables. If desired, one can convert the rain volumes to mean depths by dividing by the cluster areas provided in Appendix A. Examination of tables 5 and 6 reveals that the mean gage and radar correspondence in terms of the factor of difference (F.D.)

Table 5
Gage and Radar Comparisons for Individual Showers

Shower Classification	1972			1973			1972 and 1973		
	n	$\overline{F.D.}$	σ	n	$\overline{F.D.}$	σ	n	$\overline{F.D.}$	σ
$<10^5 m^3$	79	2.46	2.15	118	2.52	2.24	197	2.49	2.20
$>10^5 m^3$	22	3.05	3.98	127	1.69	0.73	149	1.89	1.71
All Showers	101	2.59	2.65	245	2.09	1.69	346	2.23	2.02

Table 6
Daily Gage and Radar Comparisons

Rains Volume Classification	1972			1973			1972 and 1973		
	# Days	$\overline{F.D.}$	σ	# Days	$\overline{F.D.}$	σ	# Days	$\overline{F.D.}$	σ
$<10^5 m^3$	13	2.72	2.01	11	2.02	1.25	24	2.40	1.71
$>10^5 m^3$	18	1.46	0.39	66	1.50	0.39	84	1.49	0.39
All	31	1.98	1.45	77	1.51	0.61	108	1.69	0.94

is better if: 1) the rain volume exceeds $10^5 m^3$, 2) the comparison is for the day rather than for an individual shower and 3) the comparison is for 1973 rather than 1972.

The poorer radar performance for light showers is readily explained. For light showers even a small absolute error produces a rather large error in terms of F.D. If the mean results had been presented in terms of volumetric differences, then the mean error would be less for light showers than for heavy showers.

The better agreement between gage and radar for the day than for individual showers was expected. Random errors are inherent in the analysis procedures. Further, the Z-R relation is known to vary within a shower and with time as well as among showers. Thus random errors combined with a varying Z-R might result in a radar overestimate for one shower and an underestimate for another. Upon shower combination in the formation of the daily comparison, however, these errors tend to compensate resulting in better gage-radar correspondence. As an excellent example of further compensation, the ratio of summed daily gage to radar rainfalls for all days in 1973 was 1.21 which is a 30 percent improvement over the mean daily ratio expressed as a factor of difference.

The better radar performance in 1973 than 1972 has two possible explanations. First, the obstacles to radar estimation of rainfall may have been less serious in 1973 than in 1972. Second, it is possible that there was no real difference in radar performance in the two years, rather the apparent better performance was due to the change to computer processing of the radar observations. At present, it is not known which of these possibilities was operative with this set of observations.

The individual and daily gage and radar comparisons for 1972 and 1973 are presented in F.D. format in figure 17; its interpretation is analogous to that in the gaging section (section 3.2). One can see that the radar estimates are within a factor of two of the true individual shower and daily rainfall in about 66 and 80 percent of the comparisons, respectively. Comparison of the plots in figure 17 with those in figure 14 (section 3.2) permits an evaluation of radar performance in terms of an equivalent gage network covering 220 mi^2. The accuracies of radar measurements of individual showers in 1972 and 1973 are equivalent to that which one might obtain with a gage network having a density of about 50 mi^2/gage. The accuracy of radar measurements of all showers combined over the course of the day (the daily comparison) is roughly 25 mi^2/gage.

This result suggests that if one is concerned with the measurement of convective events over a fixed gage network, such as the mesonet covering 253 mi^2 (in 1973), then a

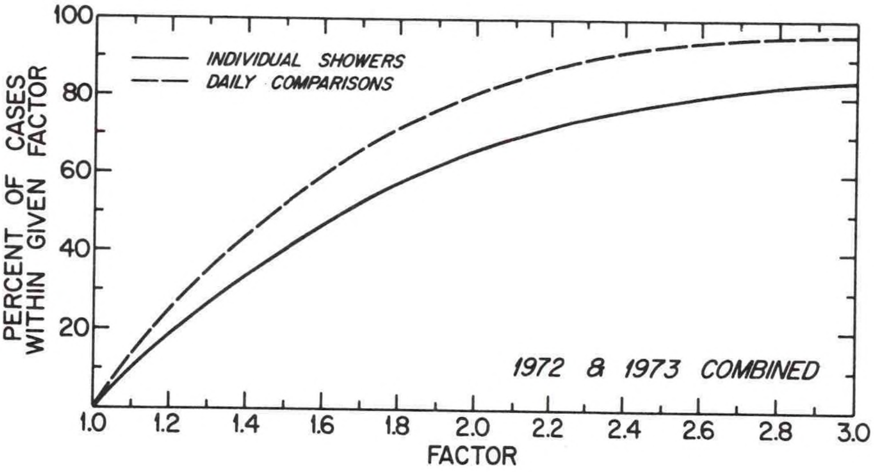

Figure 17. Factor-of-difference (FD) representation for individual showers and for all showers within the day (the daily comparison) as obtained by radar.

rather small number (10 to 20) of gages will do a better job than the radar. If one is concerned with the measurement of rainfall over an area that is one to two orders of magnitude larger, the choice is not so obvious, particularly so, if one can devise some means of adjusting the radar-rain estimates, as is described later in this section.

We have seen that the accuracy of radar-rain estimates improves as the time frame for estimation is increased. It is also interesting to see whether this accuracy might improve with area size over which the estimates are made. The radar estimates of rainfall in 1973 over the clusters, the mesonet, and the clusters plus the mesonet are summarized in table 7. There is some evidence for improved radar performance for rains over the mesonet as compared with the clusters; the mean factor of difference and the standard deviations improve with area size. The difference between the mean cluster factor of difference and the cluster plus mesonet factor of difference (1.57 - 1.47) is significant at about the 15 percent level using a one-tailed "t" test, assuming equal but unknown variances, so it is likely that the improvement with area size is real.

Table 7

Daily Gage and Radar Comparisons Versus Area Size (1973)

	Clusters	Mesonet	Clusters* plus Mesonet
n	77	40	40
$\overline{\text{F.D.}}$	1.57	1.52	1.47
σ	0.61	0.42	0.35

* Only clusters on days with useful mesonet data were used.

Some further improvement in radar performance might be expected for the EML target, but it can not be quantified here. It remains to be seen how the accuracy of gage measurements of areal rainfall changes with the size of the measuremean area and the density of the gages. This is investigated in section 5.

4.3 Gage Adjustment of Radar-Rain Estimates

Because of the problems in the radar estimation of rainfall, it is risky to accept radar estimates of rainfall without some check of their accuracy. This proviso can be relaxed somewhat for measurements within the day with a stable radar without anomalous propagation.

These conditions were probably met in EML's series of single cloud seeding experiments (Woodley, 1970; Simpson and and Woodley, 1971), but all of them are not met for its continuing series of multiple cloud seeding experiments. The experiments are randomized by day and anomalous propagation runs rampant on some days. This is why effort must be put into documentation of radar performance when used to estimate rainfall. Having obtained this documentation, one then might logically ask whether it might be used to improve the accuracy of the radar-rain measurements.

The value of gage adjustment of the radar estimates of rainfall was tested using the gage and radar estimates of rainfall in the clusters and the mesonet. Thirty-nine days in 1973, when all systems were operating properly without obstacles such as anomalous propagation, were used in this test. The adjustment of the radar estimate of rainfall in in the mesonet for each day was accomplished by: 1) determining the ratio of daily gage to radar rainfall for the clusters 2) applying the cluster ratio to adjust the radar estimate of rainfall in the mesonet and 3) comparing radar performance for mesonet rain estimation before and after adjustment with the cluster ratio. If gage adjustment has any validity, the radar measurements should be more accurate after adjustment. The results by day are tabulated in table 8 and summarized in table 9. Instances where the cluster adjustment actually changed the sense of the radar-rain estimate in the mesonet are indicated by an asterisk in table 8. Results are also plotted in the usual F.D. format in figure 18.

In examining these products it is obvious that the radar performance before adjustment was rather good in 1973 with a daily mean factor of difference of 1.53 and a standard deviation of less than one-third this figure. However, adjustment using the cluster ratios produces a statistically significant improvement (better than one percent level with two-tailed "t" test) in radar accuracy, decreasing the mean daily factor of difference to 1.38 and the standard deviation to 0.36. The adjusted radar measurements now have an approximate gage density equivalence of 10 mi^2/gage, which is a considerable improvement over unadjusted radar measurements. The relative improvement would have been more impressive if the radar performance for the mesonet had been poorer than it was.

In examining table 8, one should note that on 31 of the

Table 8. Radar Representation of Rainfall in Mesonet 1973

Date	Cluster Adjustment			M E S O N E T			
				Before Adjustment			After Adjustment
	n	ΣG (m^3 x 10^5)	$\frac{\Sigma G_V}{\Sigma R_V}$	G_V (m^3 x 10^5)	G/R	F.D.	F.D.
June 16	6	18.85	2.94	174.92	1.61	1.61	1.83*
17	1	0.12	0.96	1.66	0.73	1.37	1.32
18	3	12.22	2.13	74.88	1.85	1.85	1.15*
22	4	18.13	1.84	93.16	1.57	1.57	1.17*
24	3	6.19	1.41	48.26	1.96	1.96	1.39
25	1	1.78	0.80	1.64	0.50	2.00	1.60
26	3	2.16	1.28	86.48	1.20	1.20	1.07*
27	1	1.74	1.71	8.32	1.41	1.41	1.21*
28	4	4.84	2.58	56.60	1.89	1.89	1.37*
29	3	1.54	1.54	16.64	1.56	1.56	1.01
July 1	3	7.77	2.25	43.24	1.73	1.73	1.30*
3	5	6.05	1.28	28.30	0.93	1.08	1.38
4	4	9.17	1.69	99.84	1.45	1.45	1.17*
6	2	2.12	1.56	71.54	1.19	1.19	1.31*
7	1	4.95	1.17	14.98	0.86	1.16	1.36
11	6	4.76	1.95	15.00	2.01	2.01	1.03
12	6	19.46	1.51	39.94	0.83	1.20	1.83
15	5	31.53	1.16	26.60	0.57	1.75	2.04
16	2	1.20	0.62	15.66	0.57	1.75	1.09*
17	4	7.86	0.76	16.64	0.97	1.03	1.28*
18	3	2.79	0.74	6.68	0.45	2.22	1.64
19	1	1.53	1.46	51.56	1.73	1.73	1.19
20	5	10.04	1.00	8.84	1.19	1.19	1.19
22	3	34.07	1.32	431.00	1.10	1.10	1.20*
23	3	0.82	0.32	4.98	0.65	1.54	2.04*
24	4	1.98	0.48	6.68	0.40	2.50	1.20
25	2	0.59	0.66	7.99	1.84	1.19	1.27*

Table 8. Radar Representation of Rainfall in Mesonet 1973 (continued)

Date	Cluster Adjustment n	Cluster Adjustment Σ ($m^3 \times 10^5$)	Cluster Adjustment $\frac{\Sigma G_V}{\Sigma R_V}$	MESONET Before Adjustment G_V ($m^3 \times 10^5$)	MESONET Before Adjustment G/R	MESONET Before Adjustment F.D.	MESONET After Adjustment
July 26	3	2.35	0.68	48.28	0.94	1.06	1.39*
27	4	4.97	1.23	18.28	1.03	1.03	1.19*
28	2	7.92	1.63	101.48	1.33	1.33	1.23*
29	7	21.87	1.62	121.46	1.37	1.37	1.18*
Aug. 2	5	9.09	0.99	19.97	1.18	1.18	1.19
3	5	28.19	1.28	63.22	0.96	1.04	1.33
4	6	30.08	1.04	124.80	0.78	1.28	1.33
5	2	0.62	1.18	8.32	0.57	1.75	2.07
6	4	13.80	2.10	59.09	1.73	1.73	1.21*
10	5	6.35	0.69	63.22	0.86	1.16	1.25*
11	1	1.48	0.97	0.66	0.35	2.88	2.77
14	7	13.20	0.54	61.71	0.56	1.79	1.04*

* Indicates a change in the sense (e.g. overestimate to an underestimate or vice versa) of the radar-rain estimate for the mesonet after adjustment using the cluster ratio.

Table 9

Radar Estimate of Rainfall in Metronet

Before Cluster Adjustment			After Cluster Adjustment		
n	$\overline{F.D.}$	σ	n	$\overline{F.D.}$	σ
40	1.53	0.43	40	1.38	0.36

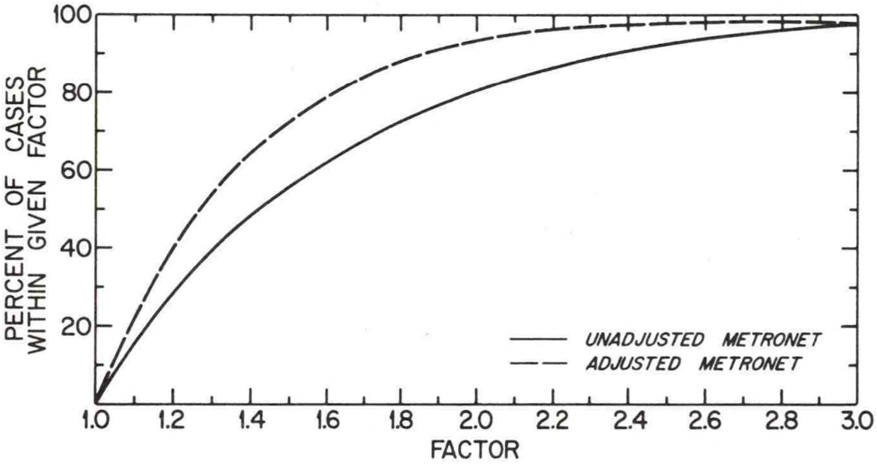

Figure 18. Factor-of-difference (FD) representation for rain estimation in the mesonet by radar. The adjusted FD curve was obtained after the radar-rain estimates had been adjusted by gages as described in the text.

39 days, the clusters caught the sense (underestimate or overestimate) of the gage to radar ratio for the mesonet. However, on 21 of these 31 days, adjustment with the cluster ratio actually changed the sense of the mesonet ratio. As an illustration, on 14 days a radar underestimate of the rainfall for the mesonet was changed to a radar overestimate for the mesonet after cluster adjustment. It was noted that adjustment by one-half of the cluster adjustment eliminated the change in sense of the gage to radar rainfall for the mesonet and further improved the mean adjusted F.D. to to 1.31. At present, it is not known why adjustment with one-half of the suggested cluster adjustment instead of the full adjustment ratio gives better adjusted radar rain estimates.

4.4 The Use of Raingages in the Radar Evaluation of EML Multiple Cloud Seeding Experiments

In the previous section, we have seen that adjustment of radar estimates using gages improves radar accuracy. In future experiments, scientists at EML may adjust total target rain estimates using a variation of the cluster technique described herein. In FACE 1973, however, all available gage data was used to accomplish the adjustment. Consequently, when all systems were operating properly, the adjustment factor was formed as the ratio of gage-derived rain volume in all areas including the mesonet to the corresponding radar estimates for the same areas. When the mesonet could not be used, only cluster volumes formed the adjustment ratio. No adjustment was attempted on days on which only one cluster had rain. No volumetric threshold for adjustment was invoked. An hourly tabulation of total target unadjusted rainfalls with suggested gage adjustments during FACE 1973 is provided in Appendix C. Hourly rainfalls that are doubtful because of AP are indicated with a double asterisk (**). Caution is urged in using the doubtful hourly rainfalls. A re-examination of the radar film in these periods to determine the extent and intensity of the AP is recommended.

In the course of evaluating the target rainfalls on days of experimentation in FACE 1973, the gages proved valuable in comparing the two methods of rain estimation. Prior to 1973 the target rainfalls were calculated manually as was described for the clusters, but in 1973 the transition to computer calculation of target rainfalls was made using taped radar observations. Before making the transition to computer processing of the radar observations exclusively, target rainfalls in 1973 were calculated manually and by computer so that they could be compared.

Unadjusted total target rainfall results in the six hours after real or simulated seeding using the two methods are presented in figure 19a. Results from August 9 and

September 10 are not plotted because false echo due to anomalous propagation precluded computer calculation. AP also wreaked havoc in the last two hours of the six-hour period of calculation on July 9 and September 9, 1973. On these days the two methods of rain calculation were compared for only four hours after initial seeding. AP was certainly a problem for brief periods on other days but no adjustments to the computer calculations have been made.

Despite problems with AP, there is reasonable agreement between the computer and planimeter calculations of total target rainfall before gage adjustment. All comparisons are within a factor of two, although there are two disturbing outliers (20 July and 14 August). The correlation between the two methods of calculation is 0.83. No systematic bias of one method with respect to the other is in evidence, suggesting that if one corrects for AP, in most instances the rain results generated by computer are comparable to those generated by hand in past years. Because of this no adjustment to the manual rain calculations from past years appears warranted before switching to computer processing.

The outliers are a problem with no ready explanation. On 14 August the computer calculation of rainfall exceeded that derived with the planimeter by nearly a factor of two and AP is not the cause of the discrepancy. On 20 July, the situation is reversed and the manual rain estimate exceeds that from the digitizer by a factor of 1.6. This is still unexplained. On both days it is obvious that only one of the two values is the better approximation of the rain that actually fell on that day, but it is impossible to select the more accurate value without additional information. Raingages are the key for resolving this dilemma.

The rainfall results generated by each method were adjusted using the cluster adjustment method discussed earlier in this report. The adjusted rain results appear in figure 19b. The results from five days that appear in figure 19a do not appear in 19b, because on these days at most one cluster had rain. No adjustment of the radar-derived rainfall is attempted unless more than one of the adjustment clusters has rain.

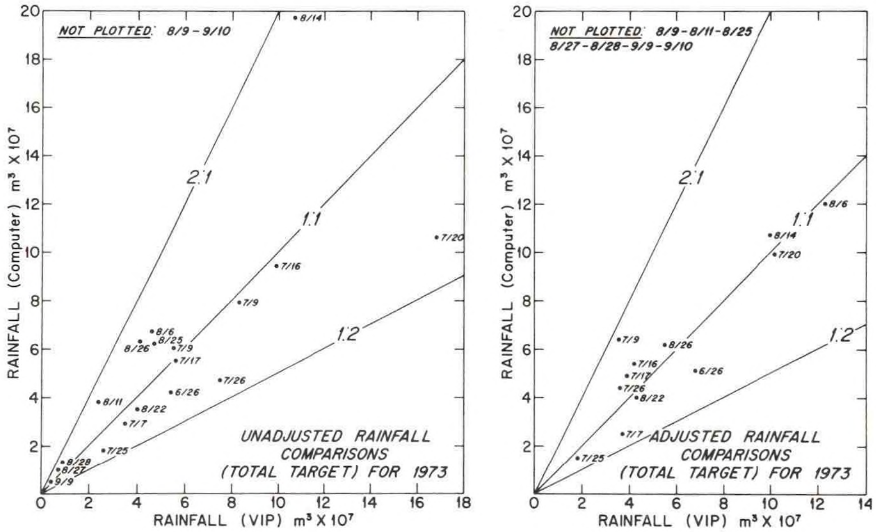

Figure 19. Comparison of manual and computer methods of radar-rain estimation. On the left are plots of the values before gage adjustment and on the right are the plots after gage adjustment. The month and day are indicated next to each plotted point.

The use of gages improves the agreement between the two methods of radar-rain estimation, particularly so for the outliers of 20 July and 14 August (compare the plots in figure 19a with those in figure 19b). The correlation between the methods improves from 0.83 to 0.95 after adjustment. The gages suggest that both manual and computer processing resulted in overestimates of the radar rainfall on 20 July with the former overestimating more than the latter. On 14 August, the gages indicate that the manual method was very nearly correct and that the computer processing resulted in a gross overestimate of the total target rainfall. The radar estimates of rainfall for 6 August are also changed by the gage-radar comparisons. With adjustment upward, the two methods are brought into better agreement. This day (a random control) is then the wettest day in FACE 1973 (a paper dealing with the results of the Florida Area Cumulus Experiment is in progress).

The general improvement of the rain calculations by the two methods after gage adjustment is a significant finding. It suggests that the adjustment ratios that were generated for rather small areas are useful as adjustors for rainfall over the entire target as well. This is most gratifying when one considers that the EML target is over an order of magnitude larger than the combined cluster areas. Thus, raingages are valuable for the improvement of the accuracy of radar-rain measurements over areas of varying size. It is likely that other schemes for gage adjustment of radar measurements will be more useful than the rather simple one currently operative at EML. The method suggested by Brandes (1974) at NSSL may prove to be of value for adjustment in Florida, although the strong rain gradients here will almost certainly preclude its use without alteration.

4.5 Comparison of Rain Representation by UM/10-cm and NHC WSR-57 Radars

As stated in section 4, both the UM/10-cm and the NHC WSR-57 radars were used concurrently to estimate rainfall over gage clusters in 1972. For all practical purposes these radars are collocated (separate by ∿100 m) and it is interesting to compare the performance of these radars in estimating rainfall using the gage clusters as a common system of groundtruth.

During its 27 days of operation in 1972, the UM/10-cm obtained 4166 min of shower observations. Individual shower durations ranged from 10 to 210 min with an average duration of 60 min. During its 45 days of operation, the WSR-57 obtained 8441 min of shower information. Shower durations for this period averaged 74 min with a range of 10 to 360 min.

Both calibrated radars underestimated the rainfall for the periods of their operation; the ratio of gage to radar derived rainfalls was 1.41 for the UM/10-cm and 1.23 for the

WSR-57. (As mentioned earlier, the factor for the WSR-57 in 1973 was 1.21.) The daily mean absolute percentage differences, defined as the absolute difference between gage and radar estimates of areal cluster rainfall divided by the gage cluster rainfall, for the same periods were 37 percent and 39 percent for the UM/10-cm and the WSR-57 radars, respectively. Correlation between gage and radar rainfalls on an individual shower basis gave values of 0.87 and 0.84 for the UM/10-cm and the WSR-57 radars, respectively.

Over 70 percent of the UM/10-cm daily radar comparisons were within a factor of two of that measured by the gage clusters. The corresponding figure for the WSR-57 radar was 63 percent. Both radars tended to underestimate convective rainfall with the UM/10-cm showing the greater tendency. This relative difference was noted mainly for light rain which might be explained by a less sensitive minimum detectable signal for the UM/10-cm.

The estimates of shower rainfall by the UM/10-cm and the WSR-57 radars were correlated for 46 showers that were observed concurrently by both radars. The resulting correlation coefficient was 0.94, suggesting that the radars were consistent in their estimation of shower rainfall.

The tendency of the radars to underestimate the convective rainfall is readily explained by reference to figure 16. Because a large fraction of the rainfall is contained in the shower core, it becomes increasingly unlikely that such cores will fill the radar beam with increasing range from the radar. When the beam is not filled by the shower core, the core is not represented by its true value but at a lesser rain value, resulting in an underestimate of the rainfall.

As we have seen, the Miami radars tended to underestimate the convective rainfall when used with the Miami Z-R relation. In H, two other relationships were examined to determine whether they would have provided better rain representation. The relation ($Z = 200 R^{1.6}$) used by Wilson (1970) in Oklahoma and the equation for thunderstorm rainfall in Illinois ($Z = 486 R^{1.37}$) were compared to the Miami equation ($Z = 300 R^{1.4}$). Use of either relation for Miami convective rains would have resulted in an even greater mean rain underestimate than was the case with the Miami Z-R relation. This result suggests that one should make some attempt to determine the most appropriate Z-R for a region. However, fine tuning of the equation beyond this appears unwarranted and is probably a waste of time, because of beam filling uncertainties and anomalous propagation. Only comparison of the radar rain representation with ground standard can correct in some measure for these uncertainties.

5. INFERENCE OF THE GAGING REQUIREMENTS FOR THE EML TARGET

Scientists at EML routinely make adjusted radar measurements of target rainfall. Until now, gage measurements were not considered because there was no way of knowing the number of gages required to meet a specified accuracy in an area of this size. Ironically, it is the digitized radar that may make this specification possible.

As stated in section 4, the EML computer software for processing the digitized radar observations permits the calculation of radar-derived rainfall in bins one nautical mile on a side. If one assumes that each bin represents a raingage, it is possible, in principle at least, to determine the target gage requirements by comparing the area mean rainfalls from the subnetworks of bins to that derived from the full bin density.

Unfortunately, this problem is not resolved that easily because bins are not gages. The bin information represents an integration of the rainfall within the radar beam, while that from the gages is representative of point rainfall. There is great disparity between sample volumes. Thus, in order to use the digitized radar to infer the gaging requirements for the large area, one must calibrate the bins in terms of the gages. This was done for the mesonet and the calibration was used to adjust the bin representation of gages for the entire target.

It is fortuitous that there are roughly the same number of bins in the mesonet as there are gages. Realizing this, it was a relatively simple matter to repeat the generation of mesonet F.D. curves for the bins in the same manner it was done for the gages (section 3). A computer program was written to calculate the radar representation of rainfall for the mesonet using all the bins and then subnetworks of the full bin density. Ratios of subnetwork area mean rainfall to full density area mean rainfall were formed to generate the F.D. curves for the bins. These F.D. curves, calculated as a function of bin density, are shown superimposed on the gage F.D. curves (from fig. 14) in figure 20. Sixty-eight days were used to generate the bin F.D. curves; 47 of them were common to the generation of the gage F.D. curves. Care

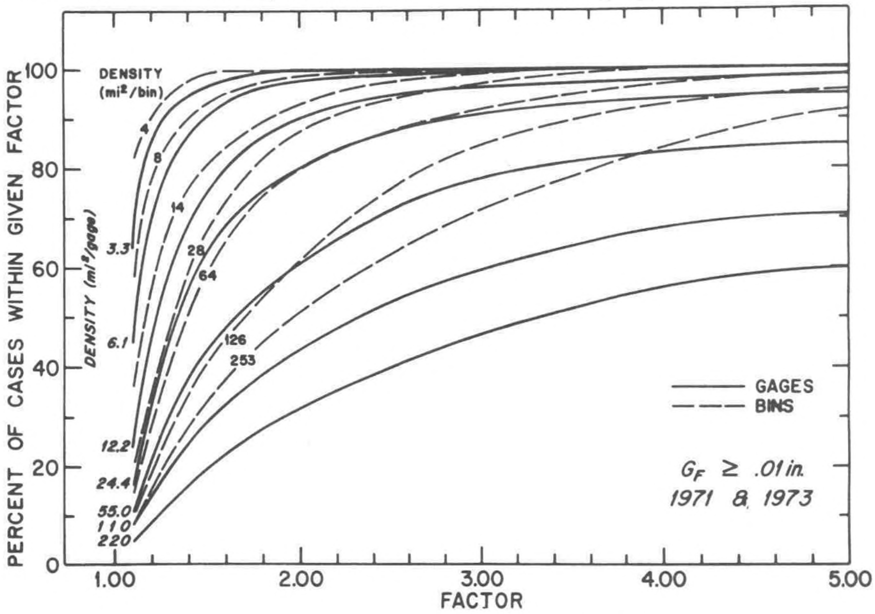

Figure 20. Superposition of Factor of Difference curves for the mesonet. The solid line (reproduced from fig. 14) is the F.D. for the gages and the dashed line is for the bins. For interpretation, see text.

was taken to avoid days on which AP was a problem.

The mesonet results suggest that for the same relative accuracies one needs a lesser density of bins than gages. For example, a gage density of 55 mi^2/gage is less accurate when compared to the full gage density than is a bin density of 126 mi^2/bin when referenced to the full bin density. Note well that absolute accuracies are not in question here; rather relative accuracies are obtained to serve as an adjustment for the bin results for the entire target.

The computer procedure of generating F.D. curves as a function of bin density was repeated for the entire target. The full bin complement of 3714 bins defined the reference rainfall. Once the total target F.D. curves were obtained they were adjusted based on the relationship between the bin and gage F.D. curves for the mesonet. This adjustment results in a F.D. representation for the entire target in terms of raingage density instead of bins. The adjustment used ranged between two and four as determined by curve superposition for the mesonet. For example, the mesonet calibration of the bin results in terms of gages suggests that a bin density of 83 mi^2/bin is actually equivalent to a gage density of 28 mi^2/gage. All total target bin densities were adjusted by the appropriate factors as obtained from figure 20. Calibrated gage results for the total target in the usual F.D. format are presented in figure 21 superimposed on the gage F.D. curves for the mesonet (from fig. 14).

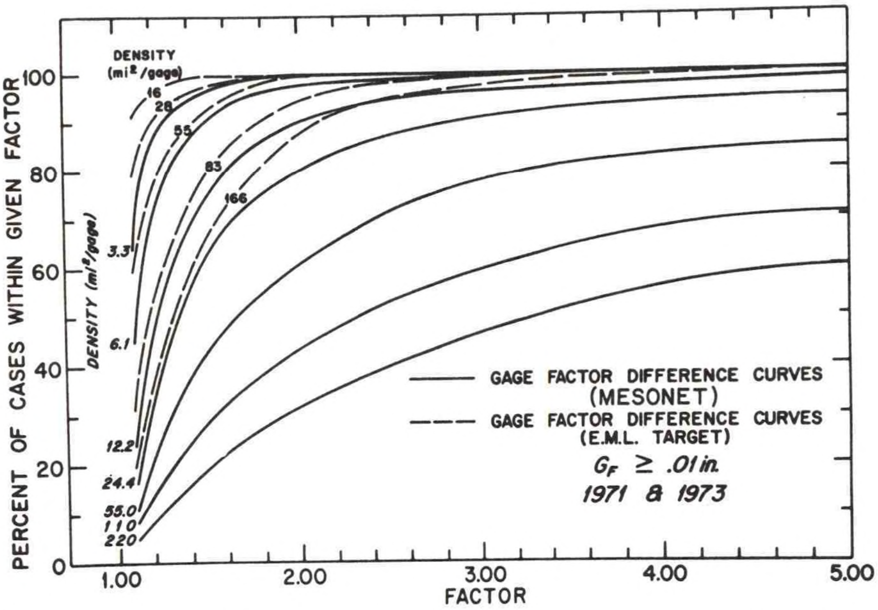

Figure 21. Superposition of gage Factor of Difference curves for the mesonet (reproduced from fig. 14) and for the entire EML target. For the interpretation, see text.

Comparison of the gage F.D. curves for the mesonet with the gage curves for the entire target suggests that for the same accuracies in the gage measurement of area mean rainfall, fewer gages are necessary in the entire target than are necessary in the mesonet. For example, a gage density of 28 mi^2/gage in the full target should provide the same accuracy for the estimation of areal rainfall for this area as a gage density of 3 mi^2/gage will provide for the estimation of areal rainfall in the mesonet.

The gage F.D. curves for the target were generated as a function of gage density until the gage calibration densities from figure 20 were exceeded. The minimum gage and density here is 253 mi^2/gage and this is the last bin density that can be calibrated in terms of gages. Thus, we are not forced into the logical absurdity that the larger the area, the fewer the gages that are necessary to meet a prescribed accuracy. The results here are valid for an area the size of the EML target for bin densities that could be calibrated in the mesonet. Extrapolation to larger areas and lesser gage densities should be done with caution.

We are now in a position to investigate the magnitude of the gaging problem for the EML target to meet a prescribed accuracy. If one were to require that the target area-mean rainfall measurements be within a factor of two of the true rainfall (obtained from 1 mi^2/gage) 99 percent of the time, the results in figure 21 suggest that a gage array of 55 mi^2/gage will meet this requirement. This implies that approximately 90 evenly spaced gages are necessary for the EML target (recall that this EML target covers 3714 n mi^2 or 4828 mi^2). This is a considerable relaxation of the gaging requirements for the same accuracy in the mesonet. If the decision to use gages in the EML target were made, one must contend with the difficulty of installing a uniform gage array in a region where a significant portion of the terrain is under two to three feet of water by late summer.

One can now make a cautious comparison of the relative merits of gage and radar systems for the measurement of the rainfall in the EML target. In this discussion, the necessity of adjusting the radar representation of rainfall with gages is recognized and no consideration is given to a radar system of rain measurement without a check of its accuracy. The comparison is then between a system of gages alone versus radar adjusted by gages in small dense arrays as described in section 4.

In the radar section it was determined that gage-adjusted radar measurements provide an accuracy equivalent to that obtained with a gage array of 10 mi^2/gage over an area the size of the mesonet. Simple extrapolation of this finding to the EML target results in the uncomfortable position that the radar makes virtually no errors here at all because a real gage network of this density in the EML target should provide area mean rain measurements of extraordinary accuracy. Beam filling problems and AP make it certain that this expectation could not be realized. On the other hand, we have seen some evidence that radar performance improves with area size so some improvement in performance for the EML target is expected. The most comfortable position to take at the present time is that radar, when adjusted by gages, will do as well as the uniform gage array of 90 gages spread over the entire target. There is reason to argue that the radar will do better than this, but it is difficult to determine this improvement quantitatively.

6. SUMMARY AND CONCLUSIONS

Nature of Convective Rains in Florida. Florida convective showers are typically tall (>40,000 ft) producing heavy rain (mean 24-hr maxima of 1.78 in) with sharp rain gradients. Typically, the 24-hr rainfall decreases to one-half the core maximum at a distance of two miles from the core center, implying a mean rain gradient of 0.45 in per mile. Even after three months of rain measurement, the rain gradients were surprisingly large amounting to 14 in four miles in one instance.

Area and time rainfall relationships are also of interest. In Florida, as elsewhere, about 50 percent of the rain falls in 10 to 20 percent of the time with rain. It was also noted that about 50 percent of the rain volume is contained in 10 to 20 percent of the area with rain. These observations are tentatively explained by radar studies of cloud echoes which reveal that a convective cloud is structured such that 10 to 20 percent of the echo volume contains one-half of the rainwater.

Measurement of Rainfall in a Small Area Using Raingages. The readings of collocated raingages differ by a mean of 10 percent -- 5 percent for maximum rainfalls near 1.00 in increasing to 12 percent for rainfalls of 0.10 in. In order for the gage-derived area mean rainfall to be within a factor of two of the true area mean rainfall 99 and 50 percent of the time, gage densities of 5 mi^2/gage and 80 mi^2/gage respectively, are required.

Radar Representation of Rainfall. The radar representation of rainfall improves with time of rain estimation and with the size of the area over which the estimates are made. In terms of percentage, the radar performance is best for the heavier showers. The mean factor of difference ($\overline{F.D.}$) for individual showers is 2.23 with 66 percent of the comparisons within a factor of two of the gage-cluster standard. The mean factor of difference for the daily comparisons was 1.69 with 80 percent of the comparisons within a factor of two of the standard. The radar performance on a daily basis in 1972 and 1973 was equivalent to that which one would obtain with a gage density of 25 mi^2/gage over an area the size of the mesonet.

Adjustment of the radar representation of rainfall with gage clusters produced a statistically significant 15 percent improvement (better than one percent level with two-tailed "t" test) in radar accuracy. The percentage improvement in the radar estimation of rainfall after adjustment would have been greater if the unadjusted performance had been worse that it was. The gage-adjusted radar approximated a gage network with a density of about 10 mi^2/gage spread over an area the size of the mesonet.

The Miami Z-R relation appears to be the best available for estimation of convective rain in Florida. Any further fine tuning of the Z-R relation does not appear warranted because of beam filling uncertainties and problems produced by anomalous propagation.

Measurement of Rainfall Over the EML Target Using Raingages. It was impossible to determine the gaging requirements for the EML target directly; rather it was inferred using digitized radar observations as described in section 5. The gaging requirements for a specified accuracy in the measurement of area mean rainfall are relaxed considerably for the EML target compared to those for the mesonet. For example, a network with 83 mi^2/gage provides approximately the same accuracy in the estimation of area mean rainfall over the EML target as a network with 10 mi^2/gage does for the estimation of area mean rainfall over the mesonet. A gage density of 83 mi^2/gage in the EML target provides rain measurements that are within a factor of two of the gage standard approximately 95 percent of the time.

The Optimum Method of Rain Measurement: Conclusions. We are now in a position to weigh the relative merits of gage and radar systems of convective rain measurement. In most cases, the system chosen will depend on the budget and/or available personnel, the terrain over which the measurements are to be made and the prescribed accuracy. For this discussion, a requirement that the rain estimates be within a factor of two of the standard 99 percent of the time is prescribed. The gist of this discussion is summarized in table 10.

There is frequently a requirement to measure rainfall from individual clouds. Unless one can afford to wait for such clouds to form, grow and die over a dense gage network, radar adjusted by raingages is really the only practical method of evaluating their rain production. The gage-adjusted NHC WSR-57 radar approximates a gage density of 10 mi^2/gage which makes it far more preferable than the installation of this gaging density over large areas. Even so, the radar cannot meet the requirement that the shower rainfall be represented within a factor of two 99 percent of the time. If one can afford to wait for the convective events to occur in an area of 200 to 300 mi^2, then gages are the best choice. Over an area of this size, 25 to 30 raingages will consistently outperform the gage-adjusted radar, and a density of 4 mi^2/gage will provide the desired accuracy.

The results for the EML target are not as definite as those for the smaller area because: 1) the gaging requirements for an area of this size had to be inferred using an unconventional, but apparently valid, method, and 2) the degree of improvement of radar performance for a larger area is not known definitely. There is undoubtedly a critical area size beyond which beam filling uncertainties degrade

Table 10. Optimum Method of Rain Measurement

Requirement: Measurement Within a Factor of Two 99 Percent of Time

Type of Measurement	Gages (required gage density)	Radar Adjusted with Gages (best equivalent gage density)	Best and/or Most Practical Choice
Individual cloud rainfall anywhere	5 mi^2/gage	10 mi^2/gage	Gages, but radar far more practical
Area rainfall over 220 mi^2	5 mi^2/gage	10 mi^2/gage	Gages
Area rainfall over 4800 mi^2	55 mi^2/gage	55 mi^2/gage or better	Gages or radar depending on terrain, personnel and budget

radar performance. Despite these problems, it appears that 55 mi^2/gage in the EML target will do as well as 4 to 5 mi^2/gage will do in the mesonet and still satisfy the requirement prescribed at the outset of this discussion. There is every indication that the S-band gage-adjusted radar will do as well, if not better, than this gage density in the EML target. Thus, in Florida the choice for the measurement of area rainfall over the 4800 mi^2 target is radar adjusted by as many as 40 recording raingages in small accessible clusters versus 90 or more raingages spread evenly over the entire target. At present, it appears that the gage-adjusted radar will continue to be the main measurement tool in Florida because of the inhospitable terrain in the EML target. However, if AP should be an even greater problem than presently perceived, EML scientists may be forced into a massive gage effort.

These results are pertinent to the Florida convective environment. It is hoped that the convective situation in other areas is not too dissimilar. If not, the findings here may have more general applicability in guiding the design of the optimal rain measurement system for weather modification experimentation and for other purposes in these areas.

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APPENDIX A

Constants, Conversions and Other Relevant Data

1 in = 2.54 cm = 0.0254 m

12 in = 1 ft = 30.48 cm = 0.3048 m

5280 ft = 1 mi = 1609.344 m

1 $mi^2 = 2.60 \times 10^6 m^2$

1 n mi = 6080 ft = 1853 m

1 n $mi^2 = 3.43 \times 10^6 m^2$

Areas of Clusters

South Bay with S-11 (after 6/27/73)	$5.24 \times 10^7 m^2$
" " without S-11	$4.90 \times 10^7 m^2$
Big Cypress with old C4 position	$2.41 \times 10^7 m^2$
" " with new C4 positions (after 7/9/73)	$2.87 \times 10^7 m^2$
Pahokee	$2.76 \times 10^7 m^2$
Immokalee (not available after 8/22/73)	$2.60 \times 10^7 m^2$
Loxahatchee	$2.07 \times 10^7 m^2$
Talisman (1972 only)	$1.85 \times 10^6 m^2$

APPENDIX B

Table 1. Gage-Radar Comparisons (from Clusters)

UM/10-cm Radar with 4-level iso-echo-contouring

Date July 1972	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
5	L	2212	42	49.2	33.3	1.48	1.48
	T	1830	55	79.8	44.3	1.80	1.80
6	L	1815	47	37.8	25.2	1.50	1.50
	T	1954	52	18.3	7.7	2.40	2.40
	I	2139	80	224.7	306.8	0.73	1.37
7	T	1821	40	18.5	7.1	2.60	2.60
	T	1930	43	5.0	16.4	.31	3.23
10	L	1802	48	16.2	13.4	1.21	1.21
	L	1909	16	15.7	1.8	8.53	8.53
	T	2000	64	444.0	127.3	3.49	3.49
	S	2013	16	1.3	5.4	0.25	4.00
	I	2030	59	24.1	8.2	2.92	2.92
11	T	1810	42	55.7	35.3	1.57	1.57
12	S	2015	105	2900.3	1465.0	1.98	1.98
	T	2018	19	1.3	0.80	1.57	1.57
13	S	1845	42	1009.7	728.2	1.40	1.40
	T	1630	70	212.2	144.7	1.47	1.47
	I	2210	45	0.7	3.5	0.21	4.76
	P	1730	165	100.8	142.5	0.71	1.41

14	T	2200	48	60.6	76.9	0.79	1.27
	P	2044	80	19.4	7.3	2.63	2.63
	P	1435	41	1.4	0	∞	0
	I	2201	25	0.4	0	∞	0
17	L	1630	15	64.4	30.3	2.12	2.12
	L	1845	25	2.8	5.0	0.56	1.79
	P	2015	90	273.0	72.6	3.76	3.76
	P	1545	30	21.6	6.5	3.30	3.30
	T	1700	30	201.8	30.8	6.50	6.50
	T	2200	135	599.3	395.1	1.52	1.52
	S	1700	120	62.6	38.8	1.61	1.61
	I	1530	120	31.9	28.5	1.12	1.12
18	S	1545	30	94.7	66.6	1.42	1.42
	S	1845	210	130.6	237.8	0.55	1.82
	L	2028	74	20.6	25.1	0.82	1.22
	L	0030	26	33.7	7.8	4.28	4.28
	I	1745	75	15.0	16.3	0.92	1.09
	P	1945	31	12.1	8.2	1.48	1.48
	P	2245	57	52.7	15.2	3.50	3.50
	T	1645	100	40.7	17.0	2.38	2.38

Footnotes

L - Loxahatchee
T - Talisman
S - South Bay
I - Immokalee
P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 1. Gage-Radar Comparisons
(from Clusters)
UM/10-cm Radar with 4-level iso-echo-contouring

Date July 1972	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
19	I	1400	45	22.6	24.4	0.92	1.09
	L	2145	60	55.4	46.8	1.18	1.18
	L	2325	28	2.1	0	∞	0
20	P	1915	20	15.9	3.5	4.48	4.48
	P	1700	65	151.7	15.1	10.0	10.0
	P	2015	10	4.4	0.8	5.1	5.1
	L	1630	90	81.3	31.4	2.58	2.58
	T	1445	43	48.3	7.7	6.2	6.2
	T	2000	19	22.3	2.9	7.6	7.6
	S	1500	34	53.2	14.0	3.80	3.80
	S	1645	35	13.5	11.0	1.22	1.22
	S	1815	51	19.8	8.8	2.24	2.24
	I	1615	16	29.1	3.3	8.55	8.55
	I	1915	25	13.8	5.6	2.45	2.45
21	I	1700	30	30.6	8.9	3.41	3.41
	S	1530	40	37.7	6.7	5.56	5.56
	P	1510	10	1.4	1.8	0.80	1.25
24	P	1730	130	317.4	203.8	1.56	1.56
	P	2030	30	3.3	0	∞	0
	T	1530	34	5.6	16.2	0.35	2.86
	T	1730	120	7.8	36.1	0.22	4.55
	S	1645	185	508.6	498.6	1.02	1.02
	I	1900	65	87.9	32.9	2.67	2.67
	L	2030	20	1.23	10.0	0.13	7.69

25	S	1800	65	43.4	60.5	0.72	1.39
	S	1930	150	432.8	1157.4	0.37	2.70
	P	1815	160	462.6	213.0	2.17	2.17
	T	1845	39	53.7	38.2	1.41	1.41
31	I	2000	60	47.4	48.0	0.99	1.01
	I	2230	75	39.6	71.9	0.55	1.82

Footnotes

L - Loxahatchee
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P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 2. Gage-Radar Cluster Comparisons
WSR-57 Radar with VIP

Date July 1972	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
5	L	2212	42	49.2	68.9	0.71	1.41
	T	1830	55	79.8	108.3	0.74	1.25
6	L	1815	47	37.9	63.1	0.60	1.67
	T	1954	52	18.3	41.2	0.44	2.27
	I	2139	80	224.7	202.4	1.11	1.11
7	T	1820	109	50.7	121.5	0.42	2.38
8	L	1800	90	41.7	119.8	0.35	2.86
9	T	1430	60	6.8	5.0	1.36	1.36
	T	1645	45	7.5	35.7	0.21	4.76
	T	2045	75	72.1	24.8	2.90	2.90
10	L	1802	112	32.0	64.0	0.50	2.00
	I	1915	120	67.3	92.3	0.73	1.37
	T	1945	92	491.0	82.3	5.97	5.97
13	S	1845	165	1009.7	682.2	1.48	1.48
	T	1630	90	212.3	78.6	2.70	2.70
	P	1730	165	100.9	94.6	1.07	1.07
	I	2210	45	0.7	7.5	.10	10.00
14	T	2200	48	60.6	73.3	0.83	1.20
	I	2201	25	0.5	4.3	0.12	8.60
	P	2044	80	19.4	112.5	0.17	5.88
	P	1435	41	1.5	1.2	1.20	1.20

15	S	1700	57	34.9	75.5	0.46	2.17
16	S	0853	40	18.9	36.2	0.52	1.92
	S	1510	45	5.5	13.7	0.40	2.47
	P	1445	15	7.8	29.4	0.26	3.85
	P	1630	45	184.2	87.2	2.11	2.11
	L	1500	75	79.2	37.6	2.10	2.10
	L	1730	45	26.3	46.6	0.57	1.75
	T	1800	90	13.0	23.4	0.55	1.82
	I	1715	106	292.2	179.3	1.63	1.63
17	L	1300	32	7.4	3.4	2.17	2.17
	L	2245	45	45.5	16.6	2.75	2.75
	L	1445	15	51.0	25.5	2.00	2.00
	L	0015	24	2.2	3.3	0.67	1.49
	P	1415	20	5.3	6.3	0.84	1.19
	P	2015	90	273.0	64.1	4.22	4.22
	T	1504	29	2.1	7.4	0.28	3.52
	T	1700	30	201.8	67.6	2.99	2.99
	T	2200	135	599.3	254.3	2.36	2.36
	S	1445	45	89.8	200.9	0.45	2.23
	S	1700	120	62.6	69.5	0.90	1.11

Footnotes

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P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 2. Gage-Radar Cluster Comparisons (continued)
WSR-57 Radar with VIP

Date July 1972	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
18	L	2028	74	20.7	47.1	0.44	2.27
	L	0030	26	33.7	41.4	0.81	1.23
	P	1600	25	6.0	18.0	0.33	3.00
	P	1945	31	12.2	11.2	1.09	1.09
	P	2245	57	52.8	38.7	1.36	1.36
	I	1745	75	15.0	51.2	0.29	3.45
	S	1845	210	130.6	100.1	1.30	1.30
19	L	1400	360	136.3	107.0	1.27	1.27
	L	2145	60	55.5	85.0	.65	1.53
	L	2325	28	2.1	1.5	1.40	1.40
	I	1400	23	22.6	1.7	13.1	13.1
	P	1745		7.4	0	∞	0
	P	0030	67	12.7	20.4	0.62	1.61
20	P	2015	42	4.4	3.2	1.38	1.38
	P	1700	24	151.8	80.4	1.89	1.89
	P	1915	29	16.0	10.9	1.47	1.47
	T	1445	17	48.3	15.6	3.10	3.10
	T	2000	19	22.4	6.8	3.27	3.27
	I	1615	16	28.4	2.1	13.30	13.30
	I	1915	25	13.9	20.8	0.67	1.49
	I	1436	20	6.8	3.4	2.00	2.00
	L	1630	90	81.3	59.3	1.37	1.37
	S	1500	34	53.2	50.9	1.05	1.05
	S	1645	35	13.5	41.3	0.33	3.03
	S	1715	51	19.8	18.4	1.08	1.08
21	I	1700	30	30.6	14.2	2.16	2.16

23	L	1613	20	0.0	2.2	0.00	∞
	L	1945	12	0.0	0.7	0.00	∞
	I	1700	105	61.4	57.4	1.07	1.07
	I	1945	45	44.6	39.7	1.12	1.12
	S	1610	40	4.3	12.7	0.34	2.95
	S	1732	38	9.0	12.5	0.72	1.39
	S	1910	50	0.0	3.2	0.00	∞
24	S	1645	186	508.6	621.9	0.82	1.22
	T	1730	117	7.9	144.0	0.05	20.00
	P	1730	139	317.5	181.7	1.75	1.75
	P	2030	30	3.3	6.8	0.49	2.06
	I	1900	65	87.9	152.4	0.58	1.72
	L	2030	23	1.2	3.8	0.32	3.16
31	I	2000	45	47.4	29.3	1.62	1.62
	I	2230	75	39.6	65.8	0.60	1.67
	P	1355	110	68.5	85.2	0.80	1.25
	L	0745	210	243.5	99.3	2.45	2.45
	S	1250	130	459.0	283.3	1.62	1.62

<u>Footnotes</u>

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P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 2. Gage-Radar Cluster Comparisons
WSR-57 Radar with VIP

Date August 1972	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
4	T	1910	40	1.6	2.8	0.57	1.75
5	I	2230	90	140.3	66.4	2.11	2.11
6	I	1715	15	32.6	62.9	0.52	1.92
	T	1740	24	00.0	4.7	0.00	0.00
9	P	1915	60	69.9	37.6	1.86	1.86
	S	2000	30	21.5	72.3	0.30	3.33
	I	2210	140	208.1	200.1	1.04	1.04
11	L	1630	132	88.4	58.7	1.51	1.51
12	P	2215	44	76.5	37.0	2.07	2.07
	L	2330	95	5.2	14.6	0.36	2.85
	T	2300	76	144.6	35.1	4.13	4.13
	I	2315	135	74.4	118.4	0.63	1.59
13	L	1900	146	136.4	185.9	0.73	1.37
	T	1830	100	192.1	137.2	1.40	1.40
14	S	0045	60	108.7	151.7	0.72	1.39
15	L	1800	60	11.6	1.8	6.28	6.28
	S	1630	195	28.3	9.1	3.12	3.12

17	P	1645	75	269.9	97.4	2.77	2.77
	L	1700	90	31.6	57.1	0.55	1.82
	T	1930	135	124.8	77.2	1.62	1.62
18	P	1915	60	12.7	115.7	0.11	9.09
19	T	2300	15	6.2	0.0	∞	0.00
	P	2215	45	105.6	54.9	1.92	1.92
20	T	1830	90	61.6	126.9	0.49	2.04

<u>Footnotes</u>

L - Loxahatchee
T - Talisman
S - South Bay
I - Immokalee
P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973 WSR-57 Radar with Digitizer

Date June 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
15	I	1630	180	244.69	243.24	1.01	1.01
16	S	2100	105	843.48	263.62	3.20	3.20
	L	1815	45	71.13	44.68	1.59	1.59
	L	2300	45	476.89	98.53	4.84	4.84
	P	2145	120	118.68	37.0	3.21	3.21
	I	1900	75	87.46	19.71	4.44	4.44
	C	2030	195	287.27	177.14	1.64	1.64
17	C	2030	60	11.57	12.05	0.96	1.04
18	L	1630	75	29.49	36.67	0.80	1.24
	C	1900	105	1119.0	525.91	2.13	2.13
	I	1730	150	73.78	11.19	6.59	6.59
20	C	1600	180	134.60	143.82	0.94	1.07
	L	1445	165	286.08	171.75	1.67	1.67
	P	1615	180	272.34	372.99	0.73	1.37
	S	1630	165	645.16	512.36	1.26	1.26
22	C	1745	105	195.50	140.81	1.39	1.39
	P	1815	60	358.93	161.73	2.15	2.15
	P	2000	120	135.25	39.63	3.41	3.41
	S	1830	210	1123.37	640.85	1.75	1.75
24	C	1530	60	9.79	2.65	3.69	3.69
	I	2030	180	185.47	199.55	.93	1.08

24	S	2015	165	424.15	238.20	1.78	1.78
25	C	2115	75	177.86	222.68	.80	1.25
26	L	2145	60	53.97	38.71	1.39	1.39
	P	2030	30	16.00	14.70	1.14	1.14
	S	2215	60	145.67	114.84	1.27	1.27
27	L	1715	75	173.66	101.28	1.714	1.71
28	I	1745	285	175.44	110.28	1.59	1.59
	C	1815	90	155.08	31.00	5.00	5.00
	P	1915	75	32.92	12.55	2.62	2.62
	S	1845	120	120.39	33.32	3.61	3.61
29	P	1800	15	22.86	6.90	3.31	3.31
	S	1530	135	0.80	6.13	.13	7.66
	S	2145	75	130.22	87.03	1.50	1.50
30	C	2300	45	311.44	193.76	1.61	1.61

<u>Footnotes</u>

L - Loxahatchee
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P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date July 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
1	I	2215	45	41.38	19.43	2.1	2.1
	C	2100	60	8.89	22.65	.39	2.55
2	I	1645	255	423.95	584.27	1.38	1.38
	C	1830	75	40.79	170.16	.24	4.17
	C	2015	30	6.00	76.0	.08	12.67
	L	1600	15	0.25	8.37	.03	33.48
	P	1630	75	125.98	150.03	.84	1.19
	P	1815	75	14.52	24.31	.60	1.67
	P	2015	15	0.86	10.05	.09	11.69
3	C	1545	60	10.32	11.09	.93	1.07
	L	1430	105	15.42	5.15	2.99	2.99
	P	1615	75	98.50	197.77	.50	2.01
	P	1800	15	4.93	8.87	.56	1.80
	S	1615	90	475.83	247.33	1.92	1.92
4	I	2145	45	11.89	9.10	1.31	1.31
	P	1545	75	475.01	267.33	1.78	1.78
	S	1700	120	102.80	51.65	1.99	1.99
	C	1715	330	327.02	212.85	1.54	1.54
5	I	1400	195	96.11	37.19	2.58	2.58
6	C	1630	30	11.60	7.92	1.46	1.46
	S	1800	60	200.78	128.49	1.56	1.56

7	L	2015	135	497.86	422.04	1.18	1.18
8	L	1745	105	562.38	275.80	2.04	2.04
	P	1930	45	23.19	44.45	.52	1.91
	C	1830	30	19.25	16.63	1.16	1.16
9	I	2130	135	46.56	233.7	.20	5.02
10	I	1930	165	219.29	376.06	.58	1.71
	C	2115	120	152.42	139.48	1.09	1.09
	S	1415	225	36.13	106.43	.34	2.95
11	I	2015	90	284.76	84.24	3.38	3.38
	C	1900	75	21.80	15.50	1.41	1.41
	C	2115	135	41.90	37.00	1.13	1.13
	L	1945	90	21.97	20.96	1.04	1.04
	P	2030	15	4.14	3.81	1.09	1.09
	S	2000	90	100.95	82.27	1.23	1.23
12	I	1400	540	223.72	229.09	.98	1.02
	C	1430	540	553.80	341.83	1.62	1.62
	L	1615	255	180.98	115.53	1.57	1.57
	P	2045	60	262.18	130.44	2.01	2.01
	P	2245	60	14.02	13.08	1.07	1.07
	S	1600	135	387.18	248.25	1.56	1.56
	S	2030	165	303.80	206.76	1.47	1.47

Footnotes

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G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date July 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
15	I	1930	30	17.15	7.80	2.20	2.20
	C	1900	150	61.69	186.96	.33	3.03
	L	1815	15	0.05	26.60	.002	532.00
	P	1815	285	334.32	217.65	1.54	1.54
	S	1945	240	2740.09	2285.69	1.20	1.20
16	I	2100	75	107.08	177.88	.60	1.66
	L	2115	60	13.14	14.95	.88	1.14
17	I	1945	150	183.79	254.02	.72	1.38
	L	1600	90	7.39	6.83	1.08	1.08
	P	1730	270	463.96	573.53	.81	1.24
	S	1830	45	99.32	102.18	.97	1.03
	S	2145	45	31.84	96.12	.33	3.01
18	C	1645	45	9.60	20.49	.47	2.13
	L	1800	75	266.48	338.78	.79	1.27
	P	1745	30	2.85	16.56	.17	5.81
19	S	1930	30	39.67	13.86	2.86	2.86
	S	2215	45	113.00	90.94	1.24	1.24
20	C	2130	120	559.23	605.87	.92	1.08
	L	1545	60	139.72	112.69	1.24	1.24
	P	2145	15	2.32	12.55	.18	5.41
	S	2300	15	47.24	69.17	.68	1.46
	I	2045	270	260.45	205.21	1.27	1.27

21	C	1645	15	1.70	0	∞	0
	L	1630	75	92.44	44.94	2.06	2.06
	P	1715	15	70.23	41.27	1.70	1.70
	S	1645	45	357.45	164.41	2.17	2.17
	I	1700	30	44.00	34.31	1.28	1.28
22	C	1700	330	208.33	228.37	.91	1.10
	P	1400	585	1227.07	960.04	1.28	1.28
	S	1400	585	1962.82	1382.81	1.42	1.42
23	C	1530	45	2.47	43.05	.06	17.42
	C	1830	30	54.31	74.31	.73	1.36
	I	1945	150	25.42	136.14	.19	5.36
24	L	1530	15	3.43	0	∞	0
	P	1715	30	2.29	7.36	.31	3.21
	S	1545	195	113.08	272.15	.42	2.41
	C	1515	120	38.07	41.21	.92	1.08
	I	1615	150	41.23	88.62	.47	2.15
25	C	1700	270	26.04	48.21	.54	1.85
	L	1645	45	33.02	40.88	.81	1.24
26	P	2115	60	178.31	216.6	.82	1.21
	S	1700	30	7.68	14.93	.51	1.94
	C	2000	45	49.07	116.30	.42	2.37

Footnotes

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P - Pahokee

G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date July 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
27	C	1730	90	128.98	88.77	1.45	2.00
	S	1445	330	275.63	260.36	1.06	1.06
	P	1900	30	37.08	5.45	6.80	6.80
	I	1645	300	55.12	50.34	1.09	1.90
28	L	2230	90	335.42	124.72	2.69	2.69
	I	1730	180	456.63	362.26	1.26	1.26
29	S	1900	300	47.17	246.39	.19	5.22
	C	1915	60	50.67	84.87	.60	1.67
	C	2130	150	45.90	92.45	.50	2.01
	P	2045	180	1259.49	487.47	2.58	2.58
	L	1800	60	108.00	43.26	2.50	2.50
	L	2030	45	23.93	15.60	1.53	1.53
	I	1900	135	652.68	384.44	1.70	1.70
30	S	1530	330	22.75	103.40	.22	4.55
	C	1900	45	49.06	116.64	.42	2.38
	I	1815	75	239.07	155.94	1.53	1.53
31	L	1515	195	201.02	128.60	1.56	1.56
	S	1800	270	375.67	344.79	1.09	1.09
	I	1430	150	291.29	155.57	1.87	1.87

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date Aug. 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
1	L	2030	30	25.02	62.66	.40	2.50
	S	1600	165	40.14	104.36	.38	2.60
	C	1615	435	119.72	302.48	.40	2.53
	I	2200	45	32.01	18.85	1.70	1.70
2	S	1845	150	185.56	335.80	.55	1.81
	C	1945	120	122.82	172.10	.71	1.40
	P	1815	135	26.01	36.54	.71	1.40
	L	2015	105	10.87	46.35	.23	4.26
	I	2015	120	563.92	325.14	1.73	1.73
3	S	1430	420	1263.83	748.67	1.68	1.68
	C	1700	60	45.59	35.01	1.30	1.30
	P	1600	270	707.69	791.00	.89	1.12
	L	2045	60	217.22	181.90	1.19	1.19
	I	1815	135	584.82	452.40	1.29	1.29
4	C	1830	45	65.28	62.83	1.04	1.04
	C	2045	60	344.0	303.50	1.13	1.13
	S	1745	150	847.27	944.51	0.90	1.11
	S	2115	60	297.49	167.46	1.78	1.78
	P	1515	210	432.07	334.29	1.25	1.25
	I	1700	360	1022.02	1088.24	0.94	1.06
5	P	1715	15	35.46	24.64	1.44	1.44
	L	1515	255	26.52	27.90	0.95	1.05

6	L	1645	150	227.67	131.10	1.74	1.74
	S	1915	60	736.50	262.63	2.80	2.80
	C	1900	285	238.36	160.35	1.49	1.49
	L	2145	15	36.20	13.25	2.73	2.73
	I	1845	300	141.11	83.27	1.69	1.69
7	C	1745	90	91.73	72.90	1.26	1.26
	I	1930	15	15.24	7.54	2.02	2.02
	P	1430	150	28.35	2.76	10.27	10.27
8	P	1800	45	7.75	24.84	0.31	3.21
	L	1745	90	197.39	150.21	1.31	1.31
9	P	2100	150	24.49	71.43	0.34	2.92
	L	1930	120	266.63	205.07	1.30	1.30
	S	1715	180	138.32	164.62	0.84	1.19
	S	2230	90	79.90	150.0	0.53	1.88
	I	2015	60	74.12	24.16	3.07	3.07
	I	2215	60	17.95	43.43	0.41	2.42
10	C	1530	270	481.86	559.24	0.86	1.16
	P	1830	45	5.72	32.33	0.18	5.65
	L	1745	165	51.97	92.44	0.56	1.78
	S	1745	90	38.76	130.45	0.30	3.37
	I	1845	195	57.20	108.94	0.53	1.90

Footnotes

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G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date Aug. 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
11	I	2100	90	147.65	152.03	0.97	1.03
12	C	1815	105	6.00	4.88	1.23	1.23
	I	1900	135	30.84	54.27	0.57	1.76
13	I	1645	135	194.77	161.90	1.20	1.20
	I	2215	45	24.59	25.57	0.96	1.04
14	C	1945	60	134.94	141.55	0.95	1.05
	P	1900	300	550.49	974.5	0.56	1.77
	L	1700	60	0.81	5.79	0.15	6.67
	L	2045	105	58.28	19.71	2.96	2.96
	S	1745	165	382.00	680.87	0.56	1.78
	S	2100	165	160.90	491.58	0.33	3.06
	I	2100	75	32.66	142.93	0.23	4.38
16	P	1545	75	124.69	128.60	0.97	1.03
	L	1500	210	245.16	132.44	1.85	1.85
	S	1415	165	90.45	105.13	0.86	1.16
	I	1545	120	101.45	153.33	0.66	1.51
	I	2100	60	18.24	33.66	0.54	1.85
18	C	1945	15	50.79	85.24	0.60	1.68
	I	2145	105	118.29	106.67	1.11	1.11
19	C	1945	45	70.35	59.86	1.18	1.18

19	P	1715	105	279.72	193.69	1.44	1.44
	S	1600	450	2248.86	1622.65	1.39	1.39
	I	1815	270	652.98	642.49	1.02	1.02
20	P	1545	45	67.91	73.47	0.92	1.08
	L	1445	180	158.58	102.40	1.55	1.55
	S	1500	165	388.02	437.54	0.89	1.13
21	L	1715	135	689.36	411.49	1.68	1.68
	I	1415	240	621.37	368.12	1.69	1.69
22	P	2300	45	24.54	61.64	0.40	2.51
	S	2245	45	235.85	169.25	1.39	1.39
24	C	1400	105	386.81	264.45	1.46	1.46
	C	1845	15	95.35	23.37	4.08	4.00
	P	1515	90	196.34	318.19	0.62	1.62
	S	1430	105	360.73	483.25	0.75	1.34
	S	1945	180	340.44	363.85	0.94	1.07
	L	1630	105	350.34	544.27	0.64	1.55
25	S	1900	285	490.25	673.03	0.73	1.37
26	P	1845	255	179.71	200.36	0.90	1.11

Footnotes

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G_V = rain volume in cluster as determined by gages

R_V = rain volume in cluster as determined by radar

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date Aug. 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
26	S	1845	285	429.98	421.18	1.02	1.02
27	L	1745	75	15.30	18.37	0.83	1.20
28	L	2030	165	34.00	21.01	1.62	1.62
29	P	1415	105	48.23	31.81	1.52	1.52
	S	1400	105	329.00	163.97	2.00	2.00
	L	1430	30	8.32	6.95	1.20	1.20
	L	1615	135	84.24	42.06	2.00	2.00
30	P	2315	30	82.18	90.03	0.91	1.10
	S	1945	240	84.92	73.69	1.15	1.15
	L	1815	330	281.60	172.95	1.63	1.63
31	C	1800	135	21.81	8.41	2.59	2.59
	P	1445	75	15.43	7.89	1.96	1.96
	P	1915	60	88.29	23.72	3.72	3.72
	S	1930	435	279.93	275.64	1.02	1.02
	L	1400	585	441.53	218.70	2.02	2.02

Table 3. Gage and Radar Comparisons in 1973
WSR-57 Radar with Digitizer

Date Sept. 1973	Cluster	Rain Start Time (GMT)	Approx. Duration	G_V $m^3 \times 10^3$	R_V $m^3 \times 10^3$	G/R	F.D.
1	C	1715	420	73.98	39.03	1.90	1.90
	S	1815	150	86.93	51.42	1.69	1.69
	L	1400	75	31.00	25.92	1.20	1.20
	P	1400	600	68.13	30.56	2.23	2.23
2	P	1500	180	74.20	55.79	1.33	1.33
	S	1515	105	79.32	37.77	2.10	2.10
	L	1430	405	47.73	38.02	1.26	1.26
3	C	1730	60	43.91	48.22	0.91	1.10
	P	1545	390	240.68	61.18	3.93	3.93
	S	2015	180	219.48	374.00	0.59	1.70
	L	1500	180	242.83	70.90	3.42	3.42
4	L	1400	60	17.62	10.39	1.70	1.70
	S	1715	210	119.70	85.15	1.41	1.41
5	S	2030	105	147.82	69.69	2.12	2.12
6	P	1615	120	144.04	93.05	1.55	1.55
	S	1530	480				
7	S	1445	165	98.72	85.81	1.15	1.15
10	S	1845	210	692.61	423.89	1.63	1.63

APPENDIX C

Hourly Rainfall for FACE Target In 1973

(units: $m^3 \times 10^6$)

Date	G/R	0900 1000 R_V	0900 1100 R_V	0900 1200 R_V	0900 1300 R_V	0900 1400 R_V	0900 1500 R_V	0900 1600 R_V	0900 1700 R_V	0900 1800 R_V	0900 1900 R_V	0900 2000 R_V	0900 2100 R_V
June 14	-	**	**	**	27.96	33.17	47.78	54.23	62.84	69.18	76.69	107.08	114.88
15	1.01 (1)	.51	.85	2.77	11.25	19.92	34.95	59.71	78.63	94.16	142.63**	167.95 **	190.56 **
16	1.68	.23	.72	1.78	4.89	7.79	10.97	15.63	20.74	32.92	62.20	83.46 **	99.05 **
17	0.74✓(1)	.32	.82	2.33	4.52	5.48	7.03	9.63	13.66	17.33	22.88	**	**
18	1.89	1.17 **	1.72	2.94	3.88	7.72	20.03	41.53	63.27	77.00	105.59**	147.98 **	166.73 **
19	-	-	-	-	-	-	-	-	-	-	-	-	-
20	1.11*	10.46	10.87	19.23	41.29	62.39	70.91	74.35	80.72	90.86	103.01	108.44	110.53
21	-	-	-	-	-	-	-	-	-	-	-	-	
22	1.61	.64	1.01	1.39	3.01	11.34	27.70	51.34	70.05	78.41	80.45	82.17 **	97.32 **
23	-	-	-	-	-	-	-	-	-	-	-	-	-
24	1.88	.24	1.62	4.35	8.34	13.10	22.22	27.66	36.98	56.04	70.39	73.27	-
25	0.62	.45	.84	1.29	2.21	3.16	4.40	8.12	14.65	20.18	25.22	32.00	34.92
26	1.19	.42	.81	1.20	1.61	2.17	3.98	5.44	10.93	22.62	35.08	44.27	45.36
27	1.46	.35	.71	1.24	3.30	7.48	14.07	23.49	24.82	26.22	27.32	31.36	42.03
28	1.94	.89	2.18	2.77	11.47	14.84	23.86	32.10	41.17	45.43	45.88	46.03	-
29	1.56	.37	.78	1.24	3.87	3.31	3.95	4.18	4.33	4.88	6.12	8.40	13.96 **
30	1.61 (1)	.22	.68	1.43	2.59	4.86	8.36	13.88	15.88	17.10	18.67	26.00	31.07
July 1	1.80	.11	.52	.98	1.45	1.90	2.92	6.76	13.04	24.33	35.06	38.13	39.61
2	1.64*	.35	.71	1.99	12.25	41.93	74.14	133.69	181.85	-	-		
3	0.89	.33	1.09	4.44	13.65	21.62	41.37	50.79	52.57	55.74	57.21	58.73	60.72
4	1.47	.010	.42	2.26	7.49	18.80	48.63	88.84	111.81	117.57	120.80	122.08	125.09
5	2.58✓(1)	.18	1.52	2.07	2.49	2.94	3.74	5.02	6.10	8.03	18.38	31.55	-
6	1.20	.43	.83	4.06	5.73	13.19	33.93	46.69	48.32	49.34	54.69	56.38	58.46**
7	0.92	.47	1.05	1.48	2.17	5.32	11.83	17.64	24.35	28.93	30.35	33.07	34.49
8	1.80*	.038	.43	.87	4.09	14.08	37.46	82.15	110.49	132.87**	148.71**	180.34**	268.98**
9	0.32	.39	.77	1.18	1.61	2.05	3.80	14.81	27.36	41.03	64.28	78.40	87.80**
10	0.64	.20	1.02	2.23	7.85	22.66	36.56	55.64	85.31	108.12	140.38**	170.87**	232.00**
11	1.39	3.50	4.69	5.38	5.91	6.89	11.80	16.60	25.28	34.08	42.23	44.77	46.13
12	0.98	1.34	6.43	19.09	35.34	45.76	58.16	78.93	98.82	109.10	115.49	117.26	119.47
13	-	-	-	-	-	-	-	-	-	-	-	-	-

* Only clusters available; no mesonet

(1) Only one cluster available without mesonet

✓ Rainfall in clusters < $10^5 m^3$

\- Not available

** Rainfall unreliable due to AP

Hourly Rainfall for FACE Target in 1973 (continued)

(units: $m^3 \times 10^6$)

Date	G/R	0900 1000 R_V	0900 1100 R_V	0900 1200 R_V	0900 1300 R_V	0900 1400 R_V	0900 1500 R_V	0900 1600 R_V	0900 1700 R_V	0900 1800 R_V	0900 1900 R_V	0900 2000 R_V	0900 2100 R_V
July 14	-	-	-	-	-	-	-	-	-	-	-	-	-
15	0.79	.36	.92	2.86	4.53	8.14	22.01	47.51	77.67	95.55	107.49	121.99**	172.75**
16	0.57	.48	.96	1.45	3.04	11.37	27.72	52.08	74.17	90.72	99.57	117.38**	160.30**
17	0.89	.44	.90	1.66	3.56	7.79	14.64	28.63	52.10	63.29	66.84	69.46	-
18	0.51	.56	20.41	21.47	24.26	29.59	31.31	33.03	34.63	46.39	47.37**	52.96**	60.94**
19	1.72	.023	.029	.41	2.12	3.00	6.34	12.65	23.03	34.32	54.75	85.96	86.57
20	0.92	.38	.72	2.33	4.59	7.25	10.15	21.92	45.26	68.42	93.72	106.74	115.93
21	1.99*	.41	1.66	5.20	14.17	24.10	29.77	30.53	31.08	32.09	36.79	41.44	47.08**
22	1.02	.63	2.33	3.26	4.41	10.15	36.21	64.29	97.84	132.37	161.63	176.91	189.28
23	0.57	2.81	3.59	9.44	15.83	25.35	35.83	47.70	53.14	54.62	56.53	57.00	57.46
24	0.41	.48	1.00	3.44	12.83	26.34	34.04	36.88	38.93	41.69	43.46	44.19**	45.85**
25	0.82	.45	.87	1.29	2.36	4.76	7.60	9.87	14.71	17.82	20.50	24.04	28.18**
26	0.94	.41	.80	1.65	5.76	9.12	16.11	25.23	33.58	39.67	50.91	55.73	65.58
27	1.07	2.62	3.45	13.63	28.14	49.51	65.28	68.40	73.76	78.56	81.89**	90.43**	103.52**
28	1.35	.081	.51	.98	1.58	6.65	15.59	28.77	40.66	57.20	71.20	91.69**	107.94**
29	1.40	.14	.56	1.02	2.32	6.15	13.83	30.15	55.80	77.65	84.53	88.87**	105.19**
30	0.83*	.56	.70	2.41	5.03	8.27	15.70	24.81	30.80	32.05	32.83	35.63**	41.24**
31	1.38*	1.20	7.25	16.49	24.81	29.12	33.05	37.37	46.49	68.03	84.45	91.40	99.56
Aug. 1	0.52*✓	7.11	10.68	21.11	30.45	34.36	41.33	53.13	63.59	74.34	86.19	102.22	122.53**
2	1.11	-	-	.20	.99	15:09	33.44	50.12	61.79	68.12	69.44	71.11	83.61**
3	1.04	1.87	3.54	7.27	13.71	27.60	63.87	92.30	102.64	108.85	113.14**	127.58**	142.74**
4	0.82	3.98	4.01	6.90	12.00	24.11	62.20	114.40	140.97	150.97	154.34	158.77	162.87
5	0.59	.24	1.58	13.32	25.28	37.63	47.81	48.46	48.92	49.37	51.66	58.70	71.39
6	1.79	.062	1.72	1.80	2.20	5.55	10.47	16.00	24.38	44.68	69.31	88.55	98.11
7	1.51*	.13	.48	1.03	2.58	8.79	11.85	21.56	30.76	36.94	37.40	38.01	39.85**
8	1.17*	46.92	47.58	48.18	49.08	52.01	63.68	82.76	138.88	206.91	231.40	**	**
9	0.93*	.14**	.75**	1.94**	5.24**	9.80**	28.45 **	50.58**	67.41**	88.02**	109.07**	123.23**	125.69**
10	0.84	3.74	4.39	10.35	36.50	79.29	122.13	143.36	149.01	151.48	153.48	155.77	156.46
11	0.63	.53	1.00	1.49	2.11	3.50	7.82	22.82	32.98	39.44	41.59	48.41	49.80**
12	0.62✓	.30	.99	1.63	2.21	2.78	5.35	8.55	19.67	28.49	30.85	32.68	39.04**

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\- Not available

** Rainfall unreliable due to AP

Hourly Rainfall for FACE Target in 1973 (continued)

(units: $m^3 \times 10^6$)

Date		G/R	0900 1000 R_V	0900 1100 R_V	0900 1200 R_V	0900 1300 R_V	0900 1400 R_V	0900 1500 R_V	0900 1600 R_V	0900 1700 R_V	0900 1800 R_V	0900 1900 R_V	0900 2000 R_V	0900 2100 R_V
Aug.	13	1.17	1.01	3.53	3.61	4.59	10.45	15.22	19.97	23.82	28.33	32.32	33.99	35.77**
	14	0.55	.63	1.22	1.95	3.14	8.18	30.88	86.18	151.12	177.32	199.06	221.17	227.11**
	15	-	-	-	-	-	-	-	-	-	-	-	-	-
	16	1.05*	2.11	3.82	7.94	13.92	20.57	22.77	25.55	29.17	31.88	32.56	34.28	38.56**
	17	-	-	-	-	-	-	-	-	-	-	-	-	-
	18	0.91*	.84	2.05	2.85	3.72	6.90	10.73	15.37	24.42	35.33	52.79	63.80	73.43**
	19	1.29*	.31	2.58	6.66	15.36	22.71	58.96	120.97	136.52	151.31	168.88	180.41 **	198.46**
	20	1.00*	1.55	7.72	20.60	29.65	34.77	44.44	47.54	51.78	-	-	-	-
	21	1.68*	3.61	5.58	7.77	12.66	54.69	95.29	114.26	119.33	120.19	120.83**	123.62**	146.05**
	22	4.13*	124.84	125.52	126.27	127.03	128.52	132.20	138.05	140.82	146.44	155.23	163.99**	167.46**
	23	-	-	-	-	-	-	-	-	-	-	-	-	-
	24	0.87*	9.81	29.72	56.78	76.18	81.61	87.92	10.85	133.29	150.30	160.09	170.12	172.72
	25	0.73 (1)	.94	2.32	2.48	4.91	13.50	32.11	52.38	64.77	70.68	73.69	75.26	76.91
	26	0.98*	.94	2.19	4.14	7.31	19.39	45.30	57.66	63.50	66.51	70.48	75.56	77.30
	27	0.83✓(1)	.76	1.45	2.18	2.94	4.72	7.35	10.00	12.34	13.34	14.20	15.56	16.10**
	28	1.62✓(1)	.73	1.45	2.27	3.30	4.61	7.29	9.11	11.05	13.82	16.16	17.68	19.15
	29	1.92*	1.79	9.43	16.25	20.67	26.40	32.47	34.38	35.38	37.24	38.81	39.80	40.88
	30	1.33*	1.77	8.02	9.11	11.08	16.33	34.95	60.00	76.37	86.29	96.16	-	-
	31	1.58*	3.26	5.60	9.53	15.71	27.46	33.13	38.87	42.90	54.24	65.49	70.26	71.82
Sept.	1	1.77*	1.22	3.52	4.59	8.17	15.18	21.16	27.58	34.69	37.13	39.45	39.43	40.07
	2	1.53*	.58	2.16	7.95	11.15	15.66	17.39	19.14	20.50	22.00	23.33	24.65	25.62
	3	1.35*	.30	2.64	5.55	9.32	18.11	28.17	31.24	39.14	46.00	59.71	54.00	54.77
	4	1.44*	.48	1.02	1.96	3.75	7.07	10.37	14.48	21.29	27.36	30.47	31.37	32.10
	5	2.12 (1)	2.00	5.88	11.26	12.88	14.31	15.69	17.49	19.36	24.45	29.79	31.26	32.16
	6	1.19*	.58	2.29	6.85	11.73	18.23	30.93	53.38	64.27	65.35	66.42	67.35	68.46
	7	1.15✓(1)	1.05	4.32	7.92	8.57	9.03	10.15	13.26	15.17	16.13	16.52	17.09	17.72
	8	-	-	-	-	-	-	-	-	-	-	-	-	-
	9	-	.40	.86	1.37	1.86	2.34	2.97	4.12	5.74	6.99	8.48	12.08	14.54
	10	1.63 (1)	-	-	- **	- **	- **	6.57**	12.46	23.56	34.04	60.31**	74.63 **	77.19 **
	11	-	5.55	1.03	12.98	13.77	15.39	15.40	15.46	15.96	17.54	22.09	26.28	29.26
	12	-	.70	1.48	2.62	3.99	5.62	8.00	22.26	34.74	39.64	42.23	-	-

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