FACE Rainfall Results: Seeding Effect or Natural Variability?

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ABSTRACT

An examination of hourly rainfall within areas designated small outside (SO) and large outside (LO) reveals that prior to the introduction of a new seeding device (NEI) in 1975, average peninsular rainfall on seed (S) days outside the Florida Area Cumulus Experiment (FACE) target area was slightly less than rainfall on no-seed (NS) days. However, during the NEI period, average station rainfall within the SO area yields S/NS ratios as high as 3 for the 6 h period following the release of the first flare. Moreover, during the 3 h period prior to the time of the first seed, average SO station rainfall on seed days exceeded the rainfall on no-seed days by approximately 60%.

The large S/NS ratios that occurred outside the FACE target area during the NEI period were not associated with anomalously high rainfall on seed days, but rather with anomalously low rainfall on no-seed days. For the SO area, differences between seed and no-seed samples are highly significant, with one-tailed P values as low as 0.001 as determined from a Wilcoxon (Mann-Whitney) test. Natural variability therefore appears to account for statistically significant differences between area-wide rainfall on seed and no-seed days.

1. Introduction

The Florida Area Cumulus Experiment (FACE) was designed to test the hypothesis that area-wide rainfall would be increased if individual cumulus clouds could be induced to merge into larger, more organized systems that are typically associated with heavy rainfall events[1] (Simpson and Woodley, 1971). Preliminary results from the 1970–76 experiment show an overall seeding effect of 20% in the 1.3×10^4 km^2 FACE target.[2] However, statistically significant results are obtained only after a partitioning of the data according to echo motion, mean layer wind speed and type of seeding flare.

Sax *et al.* (1979a) documented the increased effectiveness of a new seeding device (hereafter designated NEI) introduced during the summer of 1975. Their laboratory analysis suggests that the presence of small amounts of chlorine may be responsible for the higher efficiency of the NEI flare. Moreover, an analysis of cloud microphysical data gathered during the 1975 and 1976 FACE experimental period led Sax *et al.* (1979b) to conclude that there exists a physical basis for partitioning the FACE rainfall results according to flare type. The increased efficiency of the NEI flares *appeared* to be manifested in a 70% seeding effect observed over the FACE target area during the NEI period.[2] This apparent 70% seeding effect, if confirmed in a subsequent experiment, would represent a major breakthrough in weather modification technology. The concept of dynamic seeding, which Simpson *et al.* (1975) invoked to explain factor-of-3 increases in rainfall from individual convective clouds, and which formed the physical basis for FACE, would then appear to be a viable mechanism for increasing area-wide rainfall.

Horizontal convergence associated with the Florida sea breeze has been shown to be an essential ingredient in convective rainfall activity over the Florida Peninsula (Byers and Rodebush, 1948). Three-dimensional numerical simulations of the Florida sea breeze (Pielke, 1975) have confirmed the importance of the sea breeze in supporting low-level convergence, thereby providing the dynamic forcing that produces rising motion above the planetary boundary layer. It was pointed out by Riehl (1949), however, that synoptic-scale forcing is equally important for the generation of peninsular rainfall.

Selection criteria were established for FACE operational days which sought to eliminate both the very disturbed and the very suppressed days from inclusion in the data set. Nevertheless, mesoscale and synoptic-scale influences were observed to have major impacts on target rainfall (Pielke and Cotton, 1977). The presence of large-scale meteorological systems during the course of an experimental day represents a major opportunity

[1] Woodley, W. L., and R. I. Sax, 1976: The Florida Area Cumulus Experiment: Rationale, design, procedures, results, and future course. NOAA Tech. Rep., ERL 354-WMPO 6.

[2] A preliminary presentation of FACE rainfall data by Woodley, Simpson, Biondini and Jordan may be found in the *Preprints of the 6th Conference on Planned and Inadvertent Weather Modification*, Urbana, Amer. Meteor. Soc., 206–209.

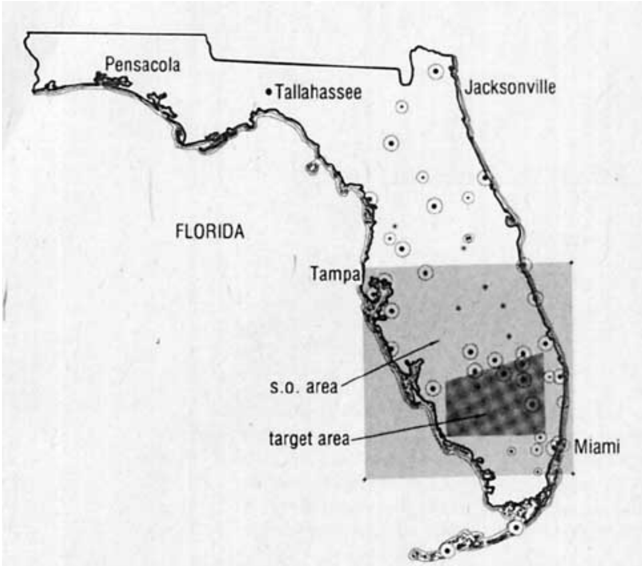

FIG. 1. Location of stations reporting hourly rainfall during the Florida Area Cumulus Experiment. See the text for a discussion of symbols used.

for bias if heavy, naturally occurring rainfall were incorrectly attributed to a seeding effect. For example, Gelhaus *et al.* (1974) showed that differences in target area rainfall between seed and no-seed samples in a South Dakota cloud seeding project occurred over a large area outside the target area, and that those differences were apparent prior to the commencement of seeding. A determination of the FACE seeding effect therefore requires not only a comparison of seed and no-seed samples of target rainfall, but also an assessment of the contribution of large-scale meteorological phenomena which extend beyond the target area. In this paper, hourly rainfall data are examined in order to determine whether area-wide rainfall on seed days was significantly different from rainfall on no-seed days outside the FACE target area.

2. Basic data set

a. Station network

Hourly rainfall data for the state of Florida were obtained from the National Climatic Center for the years 1970–76. Locations of the stations used in subsequent calculations are shown in Fig. 1. The size of the station designator indicates the percent of data actually available for analysis. Stations with the largest designator have data for more than 95% of the experimental days, while stations with the smallest designator have data for less than 20% of the experimental days. The effects of missing data on rainfall averages are examined in a later section.

Rainfall statistics for various groupings of stations have been constructed for periods of 1, 3, 6, 12 and 24 h for each experimental day. Rainfall amounts following a missing data accumulator are included in the calculations only if all missing data and the accumulated amount fall within the particular time period. Accumulated rainfall therefore is not included in the diurnal rainfall curves.

The shaded area designated small outside area (SO) in Fig. 1 consists of 27 stations outside the FACE target area. A large outside area (LO) is also defined consisting of the SO stations plus an additional 17. However, missing data reduce the average number of stations on a typical experimental day to 22 for the SO area and 35 for the LO area. Rainfall data are also available for five stations within the target area.

b. Network representation of area-wide rainfall

The effect of gage density on the accuracy of rainfall estimates over the FACE target area has been investigated by Woodley *et al.* (1975). On the basis of that analysis, it would be unlikely that the number of stations contained within the SO area could provide a meaningful estimate of area-wide rainfall. The interpretation of average station rainfall within the SO area as an area-wide rainfall estimate therefore requires supporting documentation. Fortunately, the horizontal scale of the convective systems that produce the bulk of the rainfall over south Florida is much larger than an individual convective cell. The location of the individual reporting stations with respect to the dominant terrain-induced mesoscale forcing may therefore be more important than the number of stations used to construct area-wide rainfall averages.

In order to determine whether or not average station rainfall is representative of the "true" area-wide rainfall, SO rainfall data have been correlated with radar estimates of rainfall over the FACE target area. Comparisons have been made using both the unadjusted and gage adjusted radar measurements of target rainfall. The radar estimates of rainfall (which encompass a 6 h period during each experimental day) have been correlated with SO area rainfall amounts averaged over 12 and 24 h in order to allow sufficient time for detection over an area more than three times the size of the FACE target area.

The correlation coefficient between noon-to-midnight SO rainfall and the FACE unadjusted (adjusted) target rainfall is 0.68 (0.57) for the 36 no-seed days, and 0.54 (0.55) for the 39 seed days. Correlations for particular subsets of the data are even higher. For example, the correlation coefficient between the 0800 to 0800 SO rainfall and the FACE unadjusted target rainfall is 0.85 for the 18 no-seed days that occurred during the pre-NEI period. The overall correlation coefficient between the 0800 and 0800 SO rainfall and the FACE target rainfall for all 75 experimental days is 0.59 using the unadjusted radar data, and 0.55 using the adjusted data. Moreover, both parametric and non-parametric (i.e., Spearman) tests of these correlation coefficients yield one-tailed significance values less than 0.005. However, the NEI NS period

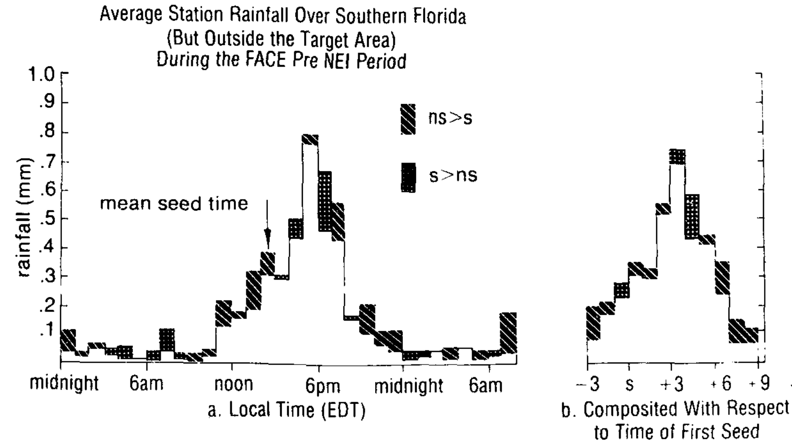

FIG. 2. Average station rainfall distribution for the SO area: pre-NEI period. (a) Diurnal distributions for the period midnight prior to seed until 0800 the next morning. (b) Distribution composited with respect to time of first seed.

probably is the most important from the standpoint of evaluating the relationship between area-wide rainfall and FACE target area rainfall. For that period, the correlation between 0800 and 0800 SO rainfall and FACE target area adjusted radar estimated rainfall is 0.67 (with a one-tailed significance level of 0.01). Therefore, it is concluded that despite an apparent deficiency in the number of reporting stations, the station network shown in Fig. 1 *is* capable of providing useful estimates of area-wide rainfall, especially during the very important NEI NS period.

3. Small outside diurnal rainfall distribution

a. Pre-NEI period

Mean diurnal rainfall distributions during the pre-NEI period for stations within the SO area are shown in Fig. 2a. The time period extends from midnight prior to seed (or release of placebo for no-seed days) until 0800 the following morning. Although there are times when either the seed or no-seed value exceeds the other, the two distributions are not significantly different.

Fig. 2b shows the seed and no-seed rainfall distributions composited with respect to time of first seed. (FACE seed times were supplied by Woodley, personal communication.) An examination of the distributions which extend from 3 h prior to seed until 9 h after seed again shows two samples that are apparently from the same population. Maximum average station rainfall rates in Fig. 2 are ~0.8 mm h^{-1}.

Average rainfall statistics computed over 6, 12 and 24 h periods (Fig. 3) show that the pre-NEI seed and no-seed rainfall rates were not significantly different. Average station rainfall rates range from 0.5 mm h^{-1} during the 6 h period following seeding, to 0.2 mm h^{-1} over a 24 h period. Ratios of seed to no-seed rainfall are all very close to 0.9.

b. NEI *period*

Diurnal rainfall distributions for the NEI period are shown in Fig. 4. In contrast to the pre-NEI period, NEI seed rainfall exceeds no-seed rainfall by an appreciable amount. However, a comparison of the distributions in Figs. 2 and 4 shows that the differences between the seed and no-seed distributions are not due to anomalously high rainfall on seed days, but rather to anomalously low rainfall on no-seed days. Moreover, not only does seed rain exceed no-seed rain by an appreciable amount, but the differences begin to appear several hours prior to the injection of seeding material into the clouds.

Mean rainfall rates for 6, 12 and 24 h time periods are shown in Fig. 5. The ratio of seed to no-seed rainfall varies from 3.1 for the 6 h period following seeding, to 1.7 for the 24 period 0800–0800. The one-tailed P values computed from a Wilcoxon test are as low as 0.001, and indicate that a very high level of significance can be ascribed to the differences between the seed

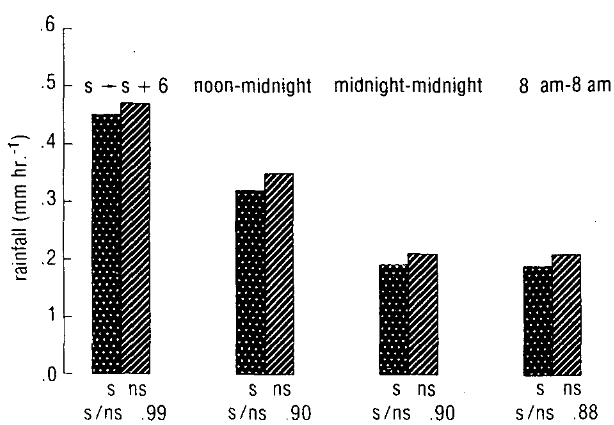

FIG. 3. Average station rainfall rates for the SO area: pre-NEI period.

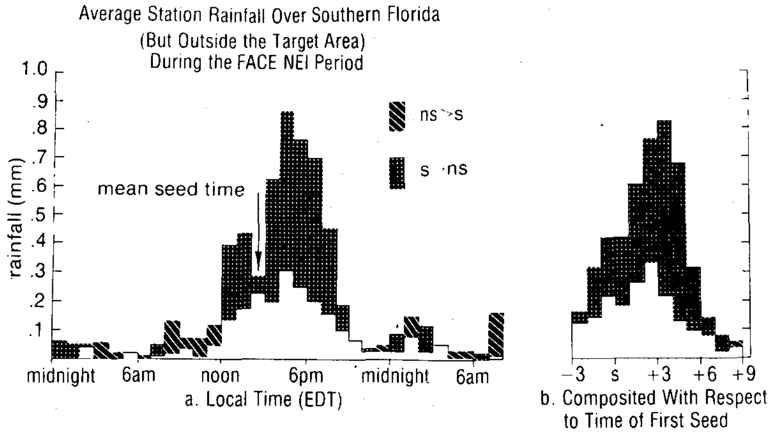

FIG. 4. As in Fig. 2 except for the NEI period.

and no-seed populations. The 95% confidence limits for the 12 h/seed mean are 0.27 and 0.54, while the corresponding confidence limits for the no-seed mean are 0.25 and 0.08. The sample mean estimate of the S/NS ratio is 2.5, corresponding to 95% confidence limits of 1.1 and 6.9 for the true S/NS mean. The S/NS ratio is smaller for the period 0800–0800 than for the period midnight to midnight, although the P values are nearly the same. This difference between the two 24 h averages occurs during both the pre-NEI and NEI periods.

4. LO diurnal rainfall distribution

a. *Pre*-NEI *period*

The stations for the LO area extend from Key West in the south to Jacksonville in the north. Just as was the case for the SO area, pre-NEI rainfall distributions for stations within the LO area (Fig. 6) indicate that the seed and no-seed samples come from the same population. Rainfall rates for the 6, 12 and 24 h time periods (Fig. 7) are similar to those found for the SO area, and the S/NS ratio for the peninsula is ~0.9.

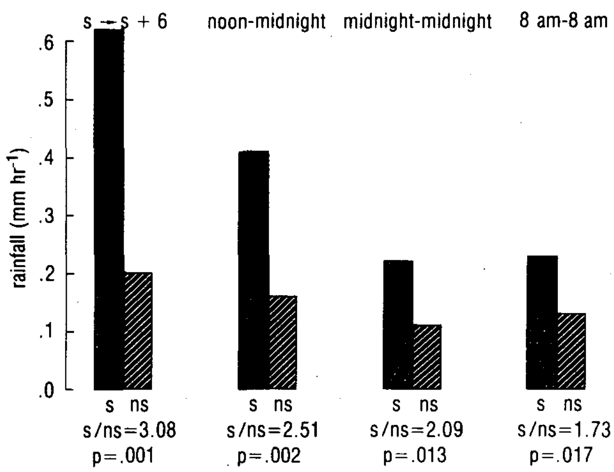

FIG. 5. As in Fig. 3 except for the NEI period.

b. NEI *period*

The substantial differences between seed and no-seed rain distributions that were found for the SO area are also observed for the LO area. This is to be expected, however, since the LO area includes the SO stations. Seed rainfall exceeds no-seed rainfall by an appreciable amount, although the differences do not appear until several hours following the time of first seed (Fig. 8).

Mean rainfall rates for stations within the LO area are shown in Fig. 9. A S/NS ratio of 2 and associated P value of 0.005 were found for the 6 h speed period. The S/NS ratio is less than that observed over the SO area because there was no significant difference between seed and no-seed rainfall outside the SO area.

5. SO total experimental period rainfall statistics

Average station rainfall rates for the SO area during the entire FACE period are shown in Fig. 10. Mean rainfall rates vary from 0.5 mm h^{-1} for the 6 h period following the time of seed, to 0.2 mm h^{-1} for a 24 h period. The 6 h S/NS ratio is 1.58 and the associated P value is 0.010. Moreover, as was the case for the NEI period, the 0800–0800 time period has a lower S/NS ratio and a higher P value than the midnight-to-midnight time period.

6. SO rainfall prior to seeding

Average rainfall rates for the 3 h period prior to the mean seed time of 1430 and prior to the actual seed times are shown in Table 1. During the NEI period,

TABLE 1. Average station rainfall rates (mm h^{-1}) over the SO area.

	11 a.m.–2 p.m. S	NS			S−3 → S S	NS	
Pre-NEI	0.16	0.24	S/NS = 0.67	Pre-NEI	0.18	0.24	S/NS = 0.79
NEI	0.30	0.15	S/NS = 2.00	NEI	0.30	0.18	S/NS = 1.63

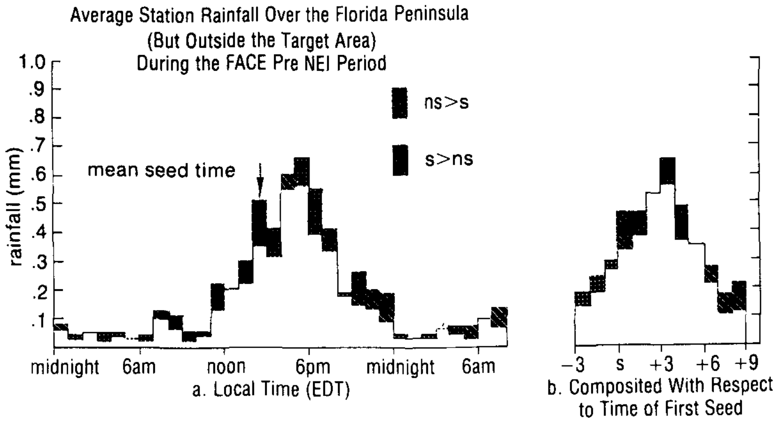

FIG. 6. As in Fig. 2 except for the LO area.

the S/NS ratio is 1.63 ($P=0.06$) for the 3 h prior to the time of first seed. However, when those rainfall totals are computed without the seven nearby stations designated I in Fig. 11, the S/NS ratio becomes 0.89. Those nearby stations are apparently responsible for the area-wide differences in rainfall on seed and no-seed days prior to the time of first seed.

During the pre-NEI period, 28% of the no-seed days and 23% of the seed days had no rain for the 3 h period prior to seed. However, during the NEI period, 50% of the no-seed days and 18% of the seed days had no rain prior to seed. The correlation coefficient between the rainfall 3 h prior to seed and the rainfall during the periods noon to midnight and 0800–0800 ranges between 0.53 and 0.59 for both seed and no-seed samples.

Evidence of a bias in rainfall prior to seed also appears in the FACE radar data. Table 2 contains average 1400 EDT radar echo coverage in square kilometers for both seed and no-seed days within a 100 m radius of Miami. The areal coverage therefore includes not only the FACE target area, but a considerable amount of ocean area as well. Although caution must be exercised in comparing the echo area coverage in Table 2 with the average station rainfall rates in Table 1, there appears to be a negative bias in echo area during the pre-NEI period and a positive bias during the NEI period. Synoptic and/or mesoscale forcing has apparently provided a favorable environment for the development of convective rainfall on seed days. The predisposition of rainfall on seed days to exceed rainfall on no-seed days prior to the release of the seeding agent indicates that substantive differences in the thermodynamical or dynamical state of the atmosphere were present on seed and no-seed days.

TABLE 2. 1400 EDT echo coverage (km^2).

	S	NS	
Pre-NEI	4980	7171	S/NS=0.69
NEI	5650	3881	S/NS=1.46

7. Target area influences on SO rainfall

The rainfall statistics presented in this study are strongly affected by the location of the reporting stations. Therefore, it is possible that stations close to the target area might be affected by seeding within the target area, thereby giving rise to extra-area effects. In order to assess the contribution of nearby stations to the rainfall statistics, new averages for the SO area were formed by eliminating seven nearby stations (designated I in Fig. 11). A comparison between 6 and 12 h SO rainfall averages with and without those stations appears in Table 3. The elimination of nearby stations resulted in lower average rainfall rates and S/NS ratios during the NEI period, implying that rainfall at those nearby stations was heavier than the rainfall at the remainder of the stations within the SO area. The 0800–0800 S/NS ratio, however, was only reduced by about 6% to a value of 1.62. The reduction in statistical significance between seed and no-seed samples may be due simply to a reduction in

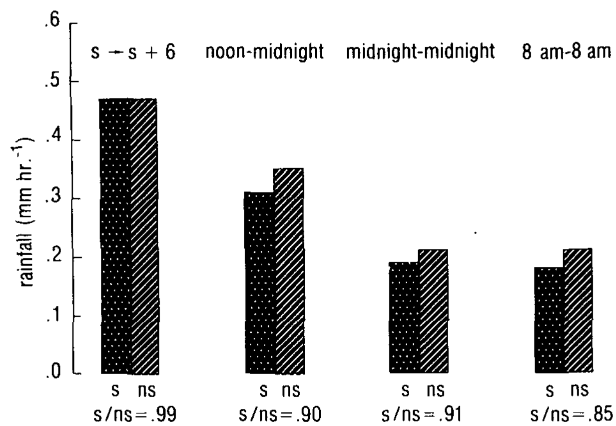

FIG. 7. As in Fig. 3 except for the LO area.

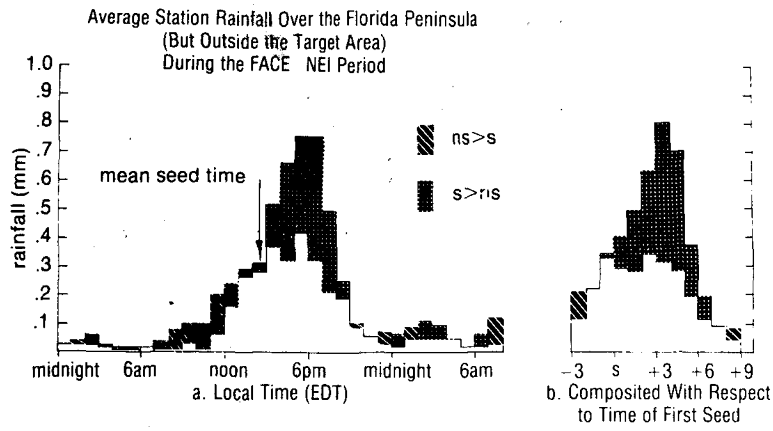

FIG. 8. As in Fig. 4 except for the LO area.

the number of stations used to compute the new SO rainfall averages.

Although the propagation of a seeding effect beyond the FACE target area cannot be ruled out as a contributing factor in the nearby station rainfall totals, the previously documented prewetness effect suggests the existence of an initial positive bias on NEI seed days. Nearby stations apparently make a substantial contribution to the SO rainfall totals not only before the onset of seeding, but also in the hours following the time of first seed.

8. The effects of missing data

Hourly convective rainfall data typically consist of a few values interspersed among many zeros. In order to obtain an estimate of the effects of missing data, rainfall statistics were computed using all the available data, and again using only those stations that had complete records. The results presented in this paper use all available data, but it is important to compare those rainfall averages and S/NS ratios with similar averages computed using only those stations with complete records. From Table 4 it is seen that the S/NS ratios are lower when only the stations with complete records are used. All available data were used rather than just those stations with complete data sets because the former are better correlated with the FACE target rainfall data. The correlation coefficient between 1975 FACE rainfall data (Woodley *et al.*, 1977) and noon-to-midnight SO rainfall data is 0.54 when all data are used, but drops to 0.35 when only those stations with complete data sets are used.

9. Rainfall variability across the Florida peninsula

Mesoscale meteorological features such as the east coast sea breeze, west coast sea breeze, and Okeechobee Lake breeze have a major impact on Florida rainfall distributions. Results presented in the previous sections have referred to the SO and LO areas wherein such mesoscale features are lumped together. Fig. 11 identifies four small regions which will be useful in examining the spatial variability of area-wide rainfall during FACE: west coast (W), central (C), target (T)

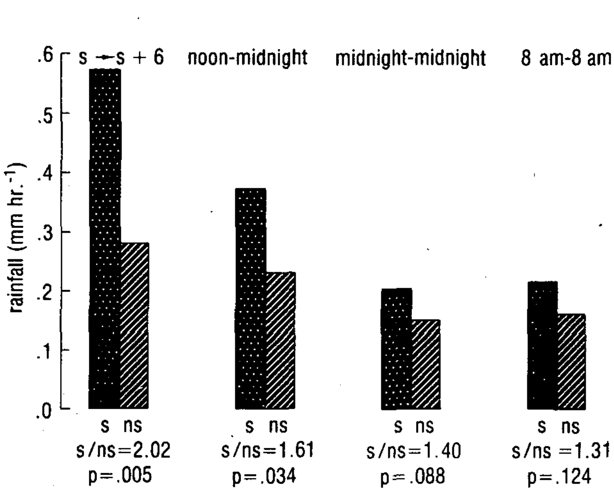

FIG. 9. As in Fig. 5 except for the LO area.

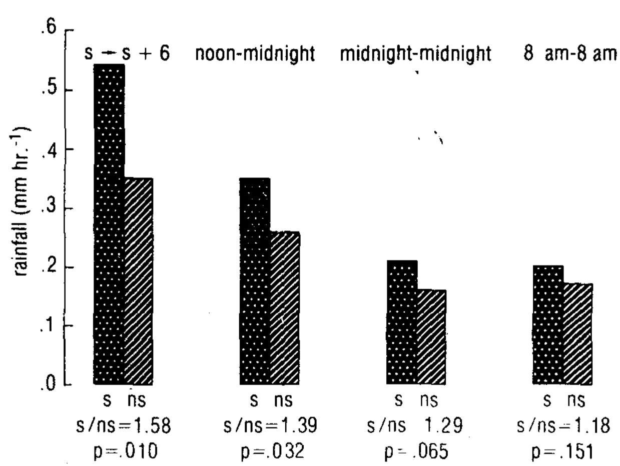

FIG. 10. As in Fig. 3 except for the entire FACE experimental period.

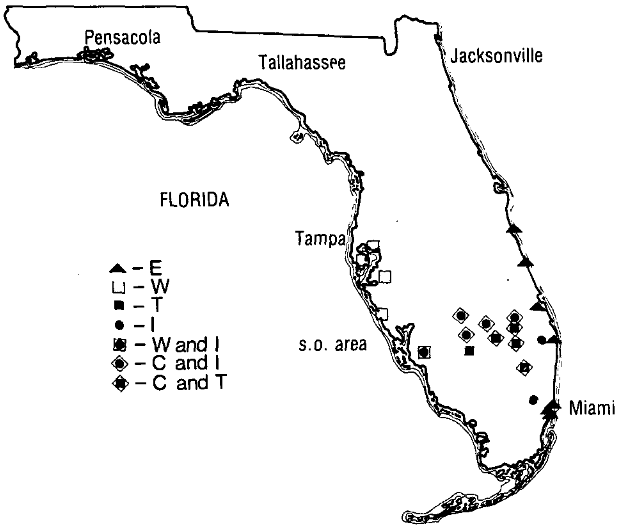

FIG. 11. Location of stations used to construct regional averages. E—east coast, W—west coast, T—target, I—interior.

and East coast (E). While the east and west coast regions lie entirely outside the FACE target area, the central region includes four target area stations. It is recognized that the number of stations contained within each area may not be sufficient to provide reasonably accurate rainfall estimates. Nevertheless, it will be useful to obtain an indication of rainfall variability across the Florida Peninsula.

Average station rainfall rates for the noon-to-midnight period are shown in Table 5. In general, rainfall is lightest on the east coast, heaviest over the center of the peninsula, and moderately heavy over the west coast. During the pre-NEI period, seed to no-seed ratios for all but the target region are ~0.9. During the NEI period, however, a considerable disparity exists between the regions. The S/NS ratio ranges from 1.3 ($P=0.36$) in the east, to 1.7 ($P=0.04$) in the central region, to 2.8 ($P=0.05$) in the west. Within the target area itself, the S/NS ratio is very close to unity during both the pre-NEI and NEI periods.

TABLE 3. Average station rainfall rates (mm h^{-1}) over southern Florida (but outside the target area).

	S → S+6						
	(a) SO area S	NS			(b) SO area without nearby stations S	NS	
Pre-NEI	0.47	0.50	S/NS−0.94	Pre-NEI	0.39	0.33	S/NS=1.18
NEI	0.62	0.20	S/NS=3.08 (P=0.001)	NEI	0.51	0.18	S/NS=2.88 (P=0.011)
	Noon–midnight						
	(c) SO area S	NS			(d) SO area without nearby stations S	NS	
Pre-NEI	0.31	0.35	S/NS=0.89	Pre-NEI	0.26	0.24	S/NS=1.09
NEI	0.41	0.16	S/NS=2.51 (P=0.002)	NEI	0.34	0.17	S/NS=2.04 (P=0.020)

TABLE 4. Effects of missing data on area-wide rainfall rates (mm h^{-1}).

			All data			Complete data only		
Category	Area	Time period	S	NS	S/NS	S	NS	S/NS
NEI	SO	S → S+6	0.62	0.20	3.08	0.52	0.21	2.50
NEI	SO	N–M	0.41	0.16	2.51	0.33	0.16	2.06
NEI	SO	8 am–8 am	0.23	0.13	1.73	0.19	0.12	1.63
NEI	LO	S → S+6	0.57	0.28	2.02	0.49	0.28	1.72
Pre-NEI	SO	S → S+6	0.47	0.47	0.99	0.44	0.54	0.81

10. Mean diurnal rainfall distributions over south Florida

FACE operational days constitute a special subset of summer rainfall activity over south Florida. Fig. 12 shows the average summer rainfall distributions for stations within both the SO and LO areas. Maximum rainfall occurs between 1500 and 2100 EDT, but both distributions begin to rise before noon, and attain $\frac{2}{3}$ of their maximum value by 1430 EDT, the mean FACE seed time. The 24 h average rainfall rate of 0.24 mm h^{-1} is higher than either the pre-NEI seed or no-seed values of 0.18 and 0.20, or the NEI seed and no-seed values of 0.22 and 0.11.

Fig. 13 shows that the west coast rainfall distribution is very similar to the SO distribution shown in Fig. 12. However, afternoon convective rainfall at the east coast stations is not nearly as strong. and occurs approximately 1 h earlier. The 24 h west coast rainfall rate of 0.27 is nearly 30% larger than the east coast rainfall rate.

Average rainfall distributions for stations within the FACE target area and in the south central portion of Florida are shown in Fig. 14. The heaviest afternoon rainfall rates occur at these inland stations, but a lack of nighttime rainfall reduces the 24 h rates to those found over the SO area. As was the case for the SO area, convective rainfall at the interior stations begins prior to noon and attains $\frac{2}{3}$ of its maximum value by the mean FACE seed time.

An important departure from the rainfall distributions previously presented occurs for the reporting

TABLE 5. Rainfall variability over south Florida (mm h^{-1}).

	West coast S	NS			East coast S	NS	
Pre-NEI	0.32	0.38	S/NS=0.84	Pre-NEI	0.20	0.22	S/NS=0.90
NEI	0.36	0.13	S/NS=2.84	NEI	0.19	0.15	S/NS=1.31
	Central S	**NS**			**Target S**	**NS**	
Pre-NEI	0.44	0.46	S/NS=0.96	Pre-NEI	0.43	0.40	S/NS=1.08
NEI	0.41	0.24	S/NS=1.70	NEI	0.31	0.32	S/NS=0.97

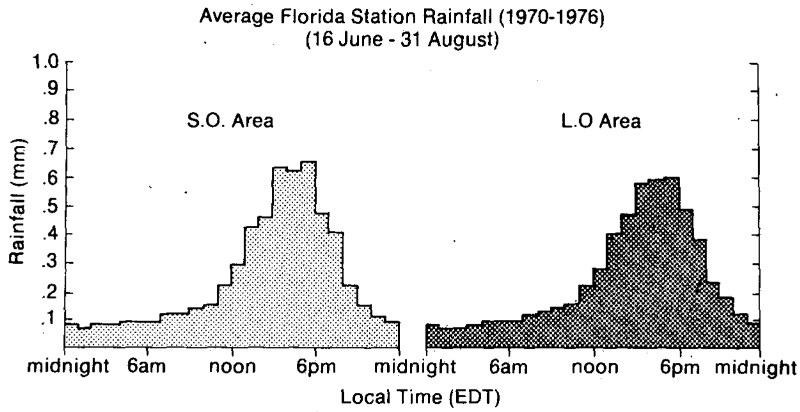

FIG. 12. Mean diurnal rainfall distributions for the SO area and the LO area.

stations in the Florida Keys. The maximum rainfall rate in that area occurs at approximately 0800 and the minimum at 1800. However, the distribution is relatively flat and yields a 24 h rainfall rate of 0.18 mm h^{-1} the lowest found in this study.

Rainfall over the FACE target area represents a combination of west coast, interior east coast precipitation regimes. The variations in the diurnal rainfall distributions shown in Figs. 12–14 demonstrate the importance of local surface heating and convergence in modulating summer rainfall patterns over south Florida. Under certain meteorological conditions, rainfall over a particular area or over a particular grouping of reporting stations might be well correlated with FACE target area rainfall. It remains to be demonstrated, however, that a predictor or covariate developed on the basis of such a correlation would be applicable to other meteorological conditions that may occur during an experimental period.

11. Conclusions and discussion

During the Florida Area Cumulus Experiment, significant differences were found to exist between seed and no-seed samples during the NEI period over a substantial area exterior to the target. An excess of rainfall on seed days relative to no-seed days during the NEI period prior to the injection of seeding material into the clouds provides a built-in bias and a predisposition for an apparent seeding effect.

If natural variability can account for statistically significant differences between rainfall on seed and no-seed days over an area more than three times the size of the FACE target area, then the measurement of statistically significant differences within the target area itself is not sufficient to establish the efficacy of a cloud seeding program. The relationship between target area rainfall and the larger scale meteorological state of the atmosphere must first be thoroughly understood in order to assess the natural contribution to rainfall totals from synoptic or mesoscale systems both prior to and after the commencement of seeding. An ability to predict natural rainfall accurately is especially important when, as in the case of FACE, a few outlyer days are responsible for the bulk of the apparent seeding effect. The areawide rainfall analysis presented in this paper does not preclude the existence

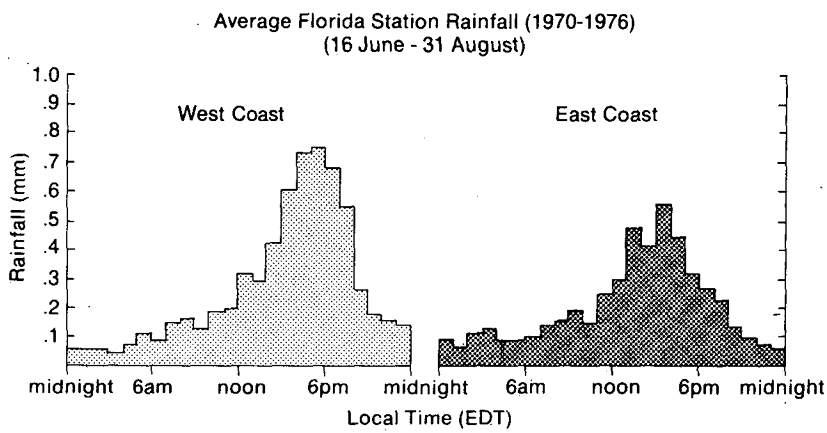

FIG. 13. Mean diurnal rainfall distributions for the west coast and east coast stations identified in Fig. 11.

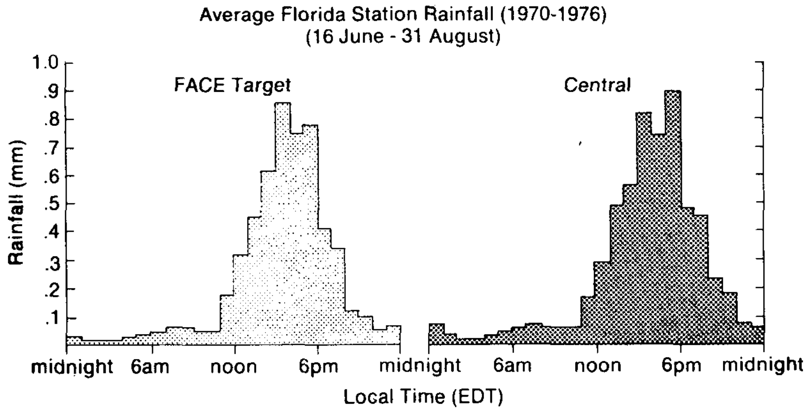

FIG. 14. Mean diurnal rainfall distributions for the FACE target and central stations identified in Fig. 11.

of either a positive or negative seeding effect, but it does suggest that variations in the larger scale meteorological state of the atmosphere are reflected in the apparent FACE seeding effect.

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