Radar Rainshower Growth Histories and Variations with Wind Speed, Echo Motion, Location and Merger Status

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ABSTRACT

Data from rainshowers observed by the WSR-57 radar at the NOAA National Hurricane Center in Miami were tape-recorded during three recent summers as part of the Florida Area Cumulus Experiment (FACE). Past studies of convective clouds in the $10^3$ km$^2$ FACE target area have indicated that enhancement of rainfall, following silver iodide seeding, was favored on those days that had light winds in the lower troposphere, along with some movement of rainshowers echoes.

In this study, we investigated the effect of wind speeds above and below 3 m s$^{-1}$ and, alternatively, the effect of echo motion (or stationarity) on the behavior of radar-observed rainshower echoes that were over water or over land, that had undergone merger with other echoes or had never merged, as functions of time of day and of echo growth cycle. We ignored any alterations in echo behavior that may have been the result of cloud seeding activities that were conducted over the target area on half of the afternoons.

PPI radar scans were tape-recorded every 5 min from 0900 to 2100 LT. Individual rainshower echoes were isolated by computer and objectively "tracked" in a square domain of $10^3$ km$^2$ that was centered on Miami. Echo characteristics such as area, population, volumetric rain rate and area-average rain intensity were extracted from each of the recorded PPI scans during 16 days of the FACE program. Variations in the echo characteristics were studied from data that were composited into 8-day sets. The compositing was based on echo motion and, alternatively, mean speed of the lower tropospheric wind.

The 8-day averages of daytime echo areas and rain volumes were generally larger when echoes had resulted from the merger of preexisting echoes, or were over land, or stationary, or embedded in a lower tropospheric wind field with speed < 3 m s$^{-1}$. Unmerged echoes were 5–14 times more numerous and, per echo, had 12–42% of the rain volume of merged echoes in the same set of days. There were 15% more echoes over land than over water. Over land and over the total domain, total rain volume was 30–110% greater on days with stationary, rather than with moving, echoes and 70–200% greater on days with weak, rather than strong, mean winds at low levels.

Differences among the 16 days of the hour-by-hour averages of four parameters were tested for significance at the <5% level (one-tailed Wilcoxon-Mann-Whitney test). The parameters were average echo area, average volumetric rain rate, average population and echo-average rain intensity. For unmerged echoes, each parameter, except rain intensity, was shown to be significantly different from that of echoes that resulted from the merger of other echoes. This significance was found especially after noon and regardless of whether wind speed was weak or strong, or whether echoes were moving or stationary. After 1400 LT, echoes over land had significantly larger volumetric rain rates, areas and rain intensities than did those over water, but only when the echoes were stationary or embedded in light winds in the lower troposphere. When days with strong wind were compared to those with weak wind, unmerged echoes were found to have been affected more strongly by wind speed than were merged echoes, and echoes over land were more affected than were echoes over water.

Volumetric rain rate was significantly larger on days with stationary, rather than moving, echoes, for a greater number of hours, when echoes were unmerged rather than when merged. Thus, even before merger, the stationary rainshowers produced greater rain volumes for more hours than did moving echoes. This is a factor that underlies the lack in improvement of rain volumes by artificial means, which has been observed on days with stationary echoes.

Growth tendencies of rain intensity for the four 8-day composite sets were similar in that echoes at any given percentage of their maximum size, and while growing in area, had higher intensities than did drying rainshowers having the same relative size. Highest rain intensities preceded maxima in echo area.

Growth tendencies revealed that greater average rain intensities, over the ocean as well as over land, were found on the same kinds of days (i.e., with light winds but some echo motion) that provided the most favorable conditions for seeding cumuli in the FACE target area.

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Either of the covariates, echo motion/stationarity or $V_L$, could prove useful as a real-time hydrologic predictor during the summer in the subtropics because rainshower were found to have larger areas and greater volumes of water when $V_L < 3 \text{ m s}^{-1}$ or when there was little or no motion of the radar rainshower echoes.

1. Introduction

Tropical convective rainshower clouds undergo large variations in their rain intensity, areal extent, population spectrum and duration. Temporal and spatial variability make rainshower difficult to study. Weather search radar is one of the best tools for investigating showering cumuli.

Rainshower activity over South Florida was observed by radar and was tape-recorded and computer-processed to yield growth histories of rainshower echoes. Over a square domain (Fig. 1) of $11 \times 10^4 \text{ km}^2$ that was centered on Miami, the echo histories were derived as functions of time of day, location (over land or over water), and stage in growth cycle. The taped radar data were gathered as part of the Florida Area Cumulus Experiment (FACE).

The FACE program, as discussed by Woodley and Sax (1976), is a randomized seeding experiment that has sought to increase the volumetric rain output of cumuli under specified weather conditions in a fixed target area. Rain volumes were calculated (Woodley et al., 1974, 1975) over the trapezoidal target area, which was $13 \times 10^3 \text{ km}^2$ (Fig. 1), by use of an S-band radar. The radar's output was digitally quantified (Sirmans and Doviak, 1973), tape-recorded, and computer-processed (Wiggert and Andrews, 1974).

In the course of evaluating FACE rainfall results, Simpson and Woodley (1975) and Woodley et al. (1977b) noted that "... the most favorable [target area cumulus] seeding conditions [to promote cloud merger and enhance rain output] occur under Florida weather regimes with light winds [$<$3 m s$^{-1}$] in the lower troposphere that produce some echo motion." But this raised some questions: If it was true that the rain volume for any whole day in the FACE target area was found to depend upon the wind speed $V_L$ (defined by Woodley and Sax,

\[
V_L = \frac{1}{3} \left[ \frac{2}{3} |V_{850}| + \frac{1}{3} |V_{700}| \right]_{1200 \text{ GMT}} + \frac{2}{3} \left[ \frac{2}{3} |V_{850}| + \frac{1}{3} |V_{700}| \right]_{0000 \text{ GMT}},
\]

where $|V_{850}|$ is wind speed at 850 mb and $|V_{700}|$ is wind speed at 700 mb on the Miami radiosonde sounding at 1200 GMT (0800 EDT) and 12 h later at 0000 GMT (2000 EDT). Because convect-

![Fig. 1. Total domain of data rectification (square perimeter, enclosing $11 \times 10^4 \text{ km}^2$) and trapezoid FACE target area ($13 \times 10^3 \text{ km}^2$). Range circle is 90 n mi (167 km).](image)
or echo motion for that day, then was the behavior of individual rainshower echoes, hour by hour, over land or over water, merged or unmerged, also dependent on wind speed or echo motion? If so, was there any significance to the differences in behavior?

In response to these questions, the behavior of separately tracked rainshower echoes was studied. The echoes were observed by the WSR-57 radar at the NOAA National Hurricane Center (NHC) in Miami, digitally recorded during three recent summers, and objectively isolated and tracked over the square domain (Fig. 1) through computer programs that were developed for the FACE program (Wiggert and Ostlund, 1975; Wiggert et al., 1976a).

The goal of this echo study was to investigate the effects of echo motion, and alternatively, the effects of mean speed of the low-level wind, on the behavior of such rainshower variables as their area, rain intensity and population. The echoes were near and over South Florida during the daytime. The radar data did not include scans in vertical planes and, in fact, all data were rejected where the antenna tilt exceeded +1.5°. Therefore, no information on echo-top heights, vertical profiles of reflectivity or vertical growth rates was gathered as had been done in studies of summertime echo behavior by Changnon (1976) with data from the vicinity of St. Louis, Missouri and by Konrad (1978) with data from near Wallops Island, Virginia.

The four primary variables that were studied included 1) the population of radar rain shower echoes, 2) the average echo areas, and 3) the average, per echo, of rain volume per unit time—the volumetric rain rate (VR). The fourth variable is the ratio of average VR to average area and is the area-average rain intensity (depth per unit time). All four were derived from digitized radar reflectivity data (Section 2), with computer software and echo isolation techniques that are described in Section 3, and using 16 days whose vita are discussed in Section 4. Averages for 12 daytime hours (0900 to 2100 LT) of areas, rain intensities and populations are presented in the first part of Section 5; these daytime averages serve to illustrate general echo behavior and methods of comparisons. Averages of the echo variables on 8 days with “strong” winds ($V_L > 3 \text{ m s}^{-2}$) were compared with the counterpart averages from 8 days with weaker winds. Similarly, 8-day averages of the echo variables on days with moving echoes were compared with the counterpart averages for 8 days with stationary echoes. Within each of these two pairs of intercomparisons, the variables of unmerged echoes were compared with those of merged echoes, and the variables of echoes over land were compared with those of echoes over water. The comparisons involving merger status and location of echoes were made to enlarge on earlier work by Frank et al. (1967), Gerrish (1971) and Simpson et al. (1980), who indicated that geographic location and merger status affect the behavior of rainshower echoes near Miami.

Rainshower over land should behave differently from those over the ocean for a number of reasons. The temperature of the underlying surface, given the same solar heating, will increase faster and become higher over land than over the sea because of the ocean’s larger heat capacity. The higher temperature of a (dry) land surface should result in stronger convective overturning of the atmosphere and more vigorous cumuli over land than over water, all other factors being equal. In addition, the land/sea temperature contrast should result in a solenoidal field, which may produce a sea breeze that yields enhanced low-level convergence at some distance inland from the coastline (Frank et al., 1967). The strength and organization of this effect, especially when synoptic-scale pressure gradients and winds are weak, frequently results in a line of convective clouds and rainshowers growing parallel to and inland from the coast. Some of the rainshowers we studied were generated by this process. The counterpart effect at night is an offshore line of convective clouds that results from a land breeze. However, land breeze convection was not investigated because the FACE project did not tape-record radar data at night during the period of this study.

Echo behavior over land in the afternoon on days with strong winds may differ from that on days with weak winds, in part because the effective strength of any sea breeze tends to decrease with increasing speed of the synoptic-scale low-level wind (Pielke, 1974). If low-level convergence is weakened, less vigorous convective development results, and less rainfall is likely from convective clouds (Ulanski and Garstang, 1978 a,b). Over water, or at other hours of the day, the effect of wind speed on echo behavior, which is less well known, was also investigated with this data set and is discussed below.

The effect of echo motion on echo behavior, noted by Simpson and Woodley (1975) and Woodley et al. (1977a), is less readily explained and, moreover, the evaluation of echo motion is not a wholly objective process. For example, the echo motion/no motion categories used here were those listed in the FACE operational summaries (Staff, Cumulus Group, 1976, 1977) and by Woodley and Sax (1976). After our analysis was completed, however, Merceret et al. (1980) reexamined echo motion during FACE GO days, enlarged the number of classification categories and reclassified some of the days,
including some used in this study. Some of the differences between the new categorization of echo motion/stationarity and the old one, which we used, arose, for example, because echo motion is not always uniform everywhere in the radar’s field of view nor constant through the course of a day.

Echo stationarity can occur in a stagnant environment, but can also occur with significant vertical shear of the horizontal wind. Some of the storms in this study with largest areas, highest rain intensities, greatest rain volumes and longest durations occurred on days with moderately large wind shear, but with no echo motion. Since echo motion or stationarity was a useful covariate in earlier analyses of FACE target rainfall, we subjected it here to broader investigation.

Although the merger of clouds is not the same as the merger of rainshower echoes, the two processes are related; merger of radar echoes occurs after the visual merger of cumuli (Holle et al., 1977). Merger of convective clouds should result in systems having larger volumes of saturated cloudy air. These systems would have more volumetric bulk per unit surface area. As a result, the processes that tend to erode and destroy clouds, such as a dry environment or vertical shear of the horizontal wind, should have less effect on the more protected interiors of bulkier systems. Such clouds, then, should survive longer, process more water vapor and yield more rain volume than unmerged clouds, as noted by Simpson and Dennis (1974) and Changnon (1976). With rates of entrainment that are less than those found for smaller clouds, the bulkier clouds should have interiors that are warmer and more buoyant, and that, therefore, grow taller. The taller a convective cloud becomes, the more likely it is to attain altitudes in the troposphere where lower stability or stronger shear may interact with the cloud system (Newton and Newton, 1959; Browning and Ludlam, 1962; Browning, 1977) and result in a convective cloud complex that produces record-breaking rain volumes, hail or tornadoes. Such severe organized convective systems are less frequent but not unknown in the tropics; extreme examples include the rainbands and the eyewall of tropical cyclones. Regardless of their location, in the tropics or elsewhere, such systems of convective clouds owe their longevity and intensity to dynamical organization processes that include the merger of convective cells.

Rainshower echoes over South Florida that merged (or merged echoes that merged with other echoes) were found by Simpson et al. (1980) to produce 10–100 times more rain volume, to be about 5–30 times larger in area, and to persist about 2–6 times longer than unmerged echoes, based on an investigation of three days of Miami radar data gathered during FACE, 1973.

In our study, the behavior patterns of unmerged and merged echoes are compared even further, as functions of wind speed and echo motion.

In the last part of Section 5, our intention is to identify hour-by-hour variations in the daytime echo variables and to test the significance of the differences that are found. We ranked the 16 daily averages of areas, rain intensities, populations and volumetric rain rates for each hour and tested the rankings for statistical significance. We have suggested physical causes for some of the observed behavior.

Individual rainshower echoes, merged or not, usually grew in size, attained maximum area, dissipated and disappeared from view on the radar, typically within ~10 min to ~2 h. Simultaneously, the rain intensities averaged over the area of each echo, were found to vary during the course of a day. But because the average hour-by-hour rain intensities on days with moving echoes were not consistently lower than those on days with stationary echoes and because Ulanski and Garstang (1978b) implied that rain intensity was larger for moving, than for stationary echoes, we made use of an alternate method of analysis of rain intensity data to resolve these conflicts. The method is based on normalization of each echo’s behavior to that when the echo was at its maximum area. It has been used in analyses by Wiggert et al. (1976a,b, 1977), who found that area-average rain intensity depended on whether the echo was growing or decreasing, that is, depended on the echo’s ‘‘growth tendency.’’ In Section 6, growth tendencies of echo-average rain intensity are shown to be larger, even though echo-average volumetric rain rates are smaller, for days with moving echoes than for days with stationary echoes. Possible causes for these differences are suggested.

The acceptance, however, of quantitative statements, such as those below regarding rainshower behavior, requires some understanding of capabilities, limitations and past experience with weather radar data.

2. Weather radar data

The WSR-57 radar at NHC is an operationally dedicated and regularly calibrated weather surveillance radar with a conical 2° beam. It is a 10 cm radar. Thus its beam suffers much less attenuation than that from a shorter wavelength radar when the microwave energy traverses heavy tropical rainshowers. Because of Miami’s subtropical location, the NHC radar has been an important source of information on tropical cyclones and on the life cycles of sea-breeze-induced tropical cumulus convection.

In an earlier study of summer shower distribution
over and near peninsular Florida, researchers at NHC (Frank et al., 1967) used data gathered from the Miami WSR-57, as well as from similar radars at Tampa and Daytona Beach, during May through August in the early 1960's. Within 100 n mi (185 km) of each radar, the area was sectioned into squares 7.5 n mi (14 km) on a side. Every 3 h, day and night, the radar observers recorded the locations of those squares containing precipitation echoes. The console operator could identify true weather echoes and ignore echoes that resulted from anomalous propagation, nearby ground clutter or other non-meteorological targets. With these data, maps of rainshowers echo frequency were prepared by Frank et al. (1967). They concluded that the variations in space and time of rainshowers frequency were highly correlated with the daily onset of the sea breeze circulations on each coast of the peninsula. Also, they noted that a climatology of radar echoes for the entire Florida peninsula could be derived by these manual methods and could aid subsynoptic-scale forecasting. However, they did not evaluate echo motion or echo strength (rain intensity).

For the FACE program, only the Miami radar was used. It was needed to supply quantitative estimates of rain volume (intensity \times area \times time) in the FACE target area. However, rainfall rates calculated from returned radar power are almost never without error.

Some of the errors that detract from the reliability of radar estimates of rain intensity were discussed by Batten (1973), Wilson and Brandes (1979) and Woodley et al. (1974, 1975). For example, unless a radar is frequently calibrated, its transmitter and receiver performance are uncertain. Some degradation of signal power at 10 cm, and rather more at shorter wavelengths, results from the shell of water that can coat a radar dome during heavy rainstorms (Cohen and Smolski, 1966). Except for very narrow beamwidths, the pulse volume usually is not uniformly filled by precipitation. The relationship of radar reflectivity (Z) to rainfall rate (R) is variable among storms, even in the same geographic location and season and is variable within the same storm at different times in its life cycle (Stout and Mueller, 1968; Joss et al., 1968). Atmospheric index of refraction is dramatically variable in space and time, and if an appreciable fraction of the radar's power is refracted and reflected from earth, strong, but non-meteorological, anomalous echoes can occur.

In the rain volume calculations that are basic to the FACE program, some of the foregoing errors have been corrected through a comparison of the area-average radar rainfall estimates for each 12 h day with the average rain depth measured in a network of raingages. Woodley et al. (1974, 1975) detailed the techniques, and discussed the advantages and limitations of these comparisons of gage (g) and radar (r) measurements. In this study, the gage average rain depth was within 25% of the radar average rain depth during 11 of the 16 days; the remaining 5 days were included for other reasons, despite g/r ratios as low as 0.4 and as high as 2.6. However, as discussed in Section 4, the properties of individual radar echoes presented in this paper were not adjusted by gage measurements.

A constant radar antenna tilt of +0.5° was desired and was almost always the actual elevation angle while the radar data were tape-recorded during FACE, although other tilt angles occurred and angles as large as +1.5° were tolerated. If we presume a tilt of +0.5°, a smooth, spherical earth and standard conditions of refraction by the atmosphere, the beam's axis at 100 km range was ~1.5 km above the earth (essentially at cloud base, as desired); the pulse volume's diameter, to half-power points, was ~3.7 km. The maximum range at which radar data were gathered was 116 n mi (215 km). There, with an antenna tilt of +0.5°, the axis of the beam was almost up to the usual altitude (~4.5 km) of the 0°C isotherm and was an appreciable distance above the typical altitudes of cloud bases. At these maximum distances and altitudes, smaller showers probably did not fill the volume of the radar's pulse and were, perhaps, not even recorded. Moreover, part of the pulse volume was at subfreezing temperatures and precipitation particles might not have been composed only of water droplets. If the particles were all ice, their reflectivity would have been less than that of equal-sized water droplets (Batten, 1973). If hail were present, coated with a thin shell of water, then the reflectivity would have been much larger than that from equal volumes of liquid water. Reflectivity could have been reduced or enhanced by the presence of ice or ice-water particles, but whatever the case, only one relationship between reflectivity [Z (mm^8 m^-3)] and rainfall rate [R (mm h^-1)] was used throughout this study, even though such relationships do vary from one rain shower to another, as noted. We used Z = 300R^{1.4}, after Woodley (1970).

Microwave energy can be refracted by strong vertical gradients in temperature and moisture, which sometimes occur in the lowest 1 or 2 km over South Florida in summer. The anomalous propagation (AP) that results can yield intense reflectivities, even though the echoing regions contain no rainshowers. AP over South Florida is usually strongest and most durable during night and early morning hours when, however, convective shower activity is most often dying or absent. Currently, AP cannot be reliably eliminated, except by manual intervention at the radar's control console. Manual height scanning, or RHI investigation, can usually
Contents: Binary coded response to average, non-range normalized, radar power returned in 280 bins along each 2° wide radial. Bins ("gate length") are each 1/2 n mi (925 m) long. Each PPI scan thus is a polar coordinate array of about 36000 bins collected during approximately 20 s, with an antenna rotation rate of 3 min⁻¹. Recording interval usually is one PPI scan every 5 min. Tape is archived permanently unedited. Format details listed by Wiggert and Andrews (1974).

COMBI
Program intermeshes the UNPACK and KART programs discussed by Wiggert and Ostlund (1975).

Contents: Cartesian grid of 1 x 1 n mi squares of rainfall rates derived using $Z = 3000R^{4.4}$. Each grid is a rectified PPI scan, and is a square domain 180 n mi on a side. One 12 hour day is a record of about 150 PPI scans.

RSUM
Program calculates rain volumes over total domain and also over other arbitrarily chosen fixed geographic domains every half hour; program also accumulates rain volumes for 12 hour data day.

PEAKS
(Successor to TRACK) Program isolates echoes which exceed arbitrary size and rain rate thresholds, and tracks them through successive Cartesian grid PPI scans. Details listed by Wiggert et al. (1976a)

Contents: Tracked echo vita for every echo in every PPI scan: centroid coordinates, area, rain volume rate, integrated rain volume, time of origination and whether echo was result of merger of old echoes, or was new growth, or result of split up of an old echo.

STATS
Program provides end-of-hour and whole-day resumes of echo parameters (i.e., area, volumetric rain rate, rain intensity, population) as functions of genesis, geography, and quartile of growth cycle.

Contents: Summaries of echo area, volumetric rain rate, rain intensity and population for every echo observed and tracked.

SUMPRO/PROBAS
Programs calculate population distributions of maximum echo area, summed rain volume, echo duration and average echo area for each of 9 genesis/ geography combinations. To each of these spectra, objective fits by each of 9 distributions are calculated using criterion of maximum entropy.

FIG. 2. Computer program train.

discriminate between genuine rainshower and the false, shallow, highly coherent echoes of AP. RHI investigations were performed when the data used by Frank et al. (1967) were gathered, thus permitting nighttime as well as daytime echo information to be used. But RHI investigations were not performed and recorded when the data for this study were gathered. Because AP can yield erroneous PPI radar "rain rates," the absence of AP contamination is very desirable. The 16 days of FACE (NHC radar) data selected for this study were chosen in part because of their seeming lack of AP, as deduced from investigation of video displays seen on 35 mm film records of the radar scope. The FACE program minimized the gathering of AP-contaminated radar data by tape recording only from 0900 to 2100 LT. Also, the area within 25 n mi (46 km) from Miami, which contains some of the very strongest ground clutter, was excluded from conversion into "rainfall" by the computer code, in the COMBI program in Fig. 2.

Constant antenna rotation aids the gathering of data for research purposes. However, NHC's mandate, to detect potentially dangerous weather and
to warn the public, occasionally required the radar operators to perform RHI studies of the stronger or more rapidly intensifying rainshower echoes. In doing these studies, the operators stopped the steady rotation of the antenna. Intermittent antenna rotation sometimes deactivated our automatic tape recording of the radar output. Also, if manual intervention were at multiples of 5 min, interaction with the automatically timed tape recording could occur. In that case, a succession of PPI scans went unrecorded, which, in turn, complicated the subsequent automatic tracking of echoes. For the most part, this type of data problem was avoided because each of these particular 16 days of data suffered few, or no, long interruptions between recorded PPI scans.

3. Computerized echo isolation, tracking and tabulating

One full circle PPI scan was usually tape-recorded every 5 min. Each PPI scan was in the form of about 180 adjacent sectors, with every sector being 2° wide, containing 200 range bins 0.5 n mi (925 m) in size and lying within the annulus from 16 to 116 n mi (30 to 215 km) from NHC. The digitized responses to the radar power returned to all of the approximately 36 000 range bins in the polar coordinate array were converted to range-normalized rain rates (Wiggert and Andrews, 1974). The rain rates then were remapped, as described by Ostlund (1974), onto a geographically fixed Cartesian grid of squares 1 n mi on a side (3.43 km² per square) in the total domain (Fig. 1) by the COMBI program (Fig. 2).

Rainshower echoes were formerly isolated and tracked with a computer program named TRACK that was discussed by Wiggert and Ostlund (1975) and detailed by Ostlund (1974). TRACK described an echo with Fourier techniques, fit an ellipse to only the perimeter of an echo, and performed only over the FACE target area. It has been superseded.

The new program is called PEAKS (Fig. 2) and was detailed by Wiggert et al. (1976a). PEAKS isolates and tracks echoes anywhere in the square total domain (Fig. 1). An "echo" is a region that contains at least four grid squares (i.e., echo area \( \geq 4 \text{ n mi}^2 \)); and each of those squares contains a rain rate \( \geq 1 \text{ mm h}^{-1} (24.8 \text{ dBZ}) \). Every square is adjacent to at least one other square, either side-to-side or corner-to-corner.

PEAKS is functionally divided into three parts: the program analyzes a radar PPI scan so that it isolates and describes echoes found to exceed the 1 mm h⁻¹ rain rate threshold; it matches echoes between a pair of these scans; and it updates the tracked information and provides continuity between successive scans.

Each echo is isolated rapidly and unambiguously by means of the eight-surrounding-points search described by Ostlund (1974). Within each echo (as described in the Appendix) the zeroth, first and second moments of the spatial distribution of the grid rain intensities are calculated during the process of isolating the total area of the echo. Then, inside each echo, all local maxima ("cores") in rain intensity are also found and flagged for further analysis as described below. Local maxima occur at points where each of the eight neighboring grid squares has a lower value of rain intensity than the center point. When an echo contains two or more relative maxima, each of the latter is subjected to an analysis similar to that performed on the echo as a whole. That is, surrounding and associated with each maximum is a region, called a "fragment," that is analyzed to find its areal extent. This is done by searching from the "top of the hill" (the grid square with the maximum rain intensity) "downward" to the point where the grid rain intensities again increase, or where the 1 mm h⁻¹ echo boundary is found. The weight, centroid and second moments of the fragment's distribution of grid rain intensities are calculated during the process of assessing the extent of the fragment.

The use of moments to describe each echo is, in principle, superior to the old TRACK method (of Fourier analysis of only the echo perimeter), because the moment description better fits an echo's internal distribution of rain rate data and the moments provide a method of describing a bivariate normal (e.g., Wonnacott and Wonnacott, 1972, Chap. 14) distribution to the echo. Therefore, PEAKS can describe the interior and exterior of all the elliptical sections determined by the distribution. The result is a better mathematical description, which yields greater skill in automatic tracking of each echo, than was possible with TRACK.

For every echo in every PPI scan, the program calculates the summation of grid rain intensity for every grid square within an echo; the summation is the volumetric rain rate VR. The program also calculates the area and centroid position of each echo. After the bivariate normal distributions are described, matching is attempted between successive pairs of PPI scans. With all the echoes, fragments and their distribution parameters in the first scan, the PEAKS program determines whether any centroids in the second scan lie within any of the old echoes or fragments. If so, there is a match. The algorithm and procedure are similar to those described by Ostlund (1974). After comparing successive Cartesian-rectified PPI scans (usually 5 min apart), the "up-dating" section of the program tracks echoes by analyzing the results of the matching procedure. It labels the echoes as they move, grow, merge, split, dissipate or leave the radar's
Fig. 3. Rainshower echoes observed and tracked near Miami. (a) Echoes in area northwest of Miami during one PPI scan, (b) example of process of merger of two tracked echoes.

Field of view. Each echo is given a unique identifier based on time of origin and on whether the echo was the result of a split-up of an old echo, or was a merger of preexisting echoes, or was new growth.

Examples of Cartesian grid rain intensities that comprised some tracked radar echoes over land are displayed in Fig. 3a. Among the variables tallied for each echo are the identifier, the coordinates of each
centroid (nautical miles east of the west border and north of the south border), the area (square nautical miles), the volumetric rain rate TOT RT mm h⁻¹ n mi², and the lifetime rain volume. The last quantity is the sum of the products of volumetric rain rate (per scan) times the time interval between PPI scans, for all scans following the first record of the echo. The sum is denoted TOT RN (mm n mi²). Two echoes (boxed) undergo merger as seen in Fig. 3b. The total rain volume that is calculated for the resultant merged echo excludes the lifetime volumes of the predecessor “parent” echoes. Rain intensities in each grid square are scaled by “true value” at the top of the figure. Dots are intensities >1 mm h⁻¹, but <1 scale factor unit. Distance between “+” signs is 10 n mi.

The foregoing vital statistics, for every tracked rain shower echo in every PPI scan anywhere in the
TABLE 1. Echo areas, rain intensities and populations: averages for each of two 4-day sets. Set I: Moving echoes and $V_L > 3$ m s$^{-1}$; set II: stationary echoes and $V_L < 3$ m s$^{-1}$.

<table>
<thead>
<tr>
<th>Echo status/ location*</th>
<th>Average area (km$^2$)</th>
<th>Average rain intensity (mm h$^{-1}$)</th>
<th>Average population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>Unmerged/land</td>
<td>38</td>
<td>212</td>
<td>4.9</td>
</tr>
<tr>
<td>Merged/land</td>
<td>147</td>
<td>708</td>
<td>5.6</td>
</tr>
<tr>
<td>Both/land</td>
<td>46</td>
<td>285</td>
<td>5.1</td>
</tr>
<tr>
<td>Unmerged/water</td>
<td>49</td>
<td>61</td>
<td>5.3</td>
</tr>
<tr>
<td>Merged/water</td>
<td>245</td>
<td>144</td>
<td>8.7</td>
</tr>
<tr>
<td>Both/water</td>
<td>66</td>
<td>73</td>
<td>6.4</td>
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<tr>
<td>Unmerged/TD**</td>
<td>56</td>
<td>138</td>
<td>5.3</td>
</tr>
<tr>
<td>Merged/TD</td>
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<td>456</td>
<td>7.9</td>
</tr>
<tr>
<td>Both/TD</td>
<td>73</td>
<td>186</td>
<td>6.2</td>
</tr>
</tbody>
</table>

* Only those echoes with centroids no farther than 75 n mi (139 km) from the radar were separated into the “land” or “water” categories.
** TD = Total domain.

total domain, for an entire (~12 h) data-gathering period are stored and supplied to the STATS program (Fig. 2).

Summaries of echo characteristics are the product of the STATS program. The summaries are supplied at the end of each hour, as well as at the end of an entire day for echo population, echo area and volumetric rain rate, for every combination of merger status (unmerged echoes only; merged echoes only; both) and geography (echo centroid over land; centroid over water; anywhere in total domain). The area within 75 n mi of Miami is roughly half land and half water (on the presumption that swamps are land), and only within this circle are echoes separated into the “over land” or “over water” categories. The total domain, as seen in Fig. 1, is about double the size of the combined “land” and “water” areas, and most of it lies over water.

Summaries of tracked weather echo characteristics for just two days were compared by Wiggert et al. (1976a,b). The more disturbed day of the two had more numerous echoes, with larger average areas over land than over water during the convectively active hours of 1200 to 1900 LT, and the more normal day had larger echo populations and areas over water than over land. Both days had more unmerged echoes than merged ones, regardless of hour or locale. The average areas, average volumetric rain rates and echo-average rain intensities of merged echoes were always larger than for unmerged echoes.

Showers are believed to be influenced by a variety of factors, such as convergence of the low-level wind, mean wind speed, wind shear, thermal and moisture stratifications, orographic and terrain (frictional) effects, land-sea temperature contrasts and (in FACE) the enhancement of cumulus buoyancy by seeding with silver iodide flakes. But, because one particular factor, the movement (or stationarity) of rainshower echoes, was found to be a significant covariate by Simpson and Woodley (1975), in their study of the change in volume of rainfall that followed cloud seeding in the FACE target area, this covariate was subjected by Wiggert et al. (1977) to a broader investigation. Miami radar data from eight experimental days in FACE were selected for study. During four of the days, the radar echoes were stationary (but also, $V_L < 3$ m s$^{-1}$). On the other four days, echoes moved at an average speed of about 6 m s$^{-1}$ (but also, $V_L > 3$ m s$^{-1}$). Seeding operations in the target area occurred on three of the four days with moving echoes and stronger winds (set I, in Table 1), while seeding was done on only one of the four days with stationary echoes and weaker winds (set II; see also column 6, Table 2). Average echo areas and average rain intensities for the two 4-day sets, when intercompared, revealed that on days with moving echoes and stronger winds, smaller average echo areas and weaker average rain intensities were observed than on days with stationary echoes and weaker winds. Merged echoes over water were the only exception. Hour-by-hour trends (not shown) indicated that after noon, over land, the areas and rain intensities attained much larger values on days in set II than those in set I, despite the preponderance of “seeded” days in the latter set.

Seeded echoes were not removed from the data sample in this study, primarily because there is no objective method that would enable the automatic tracking program to exclude an echo or a part of an echo at and after the time that some part of it had been seeded. There is no question that seeding, under certain conditions, can result in enhanced vertical growth of individual tropical convective clouds (Simpson et al., 1965; Simpson and Wiggert, 1971), and that the seeded clouds tend to undergo merger with neighboring clouds earlier than control clouds do (Simpson et al., 1971; Simpson and Woodley, 1975).

The single cloud seeding program was enlarged into an area seeding experiment, as explained by Woodley and Sax, (1976). Using data from programs in the years 1970–75, Woodley et al. (1977a) found that, over the total target, 1) with no seeding, the mean rain volume on days with stationary echoes was about double that on days with moving echoes; 2) with moving echoes, mean rain volume on seeded days was about 113% of that on unseeded days; but 3) with stationary echoes, mean rain volume on seeded days was only 86% of that on unseeded days.
TABLE 2. Meteorological characteristics of 16 days of FACE.

<table>
<thead>
<tr>
<th>Set</th>
<th>Date</th>
<th>Day</th>
<th>$V_L$* (m s$^{-1}$)</th>
<th>Echo V deg/(m s$^{-1}$)</th>
<th>Seeding in target area</th>
<th>Echo cover (km$^2$) @1800 GMT</th>
<th>Mean V deg/(m s$^{-1}$) @1200 GMT</th>
<th>($V_{900} - V_{500}$) deg/(m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>27 Aug 1973</td>
<td>3239</td>
<td>6.9</td>
<td>070/6.2</td>
<td>S</td>
<td>2277</td>
<td>067/4.5</td>
<td>310/5.7</td>
</tr>
<tr>
<td></td>
<td>28 Aug 1973</td>
<td>3240</td>
<td>6.4</td>
<td>040/7.2</td>
<td>S</td>
<td>3860</td>
<td>094/7.5</td>
<td>305/10.3</td>
</tr>
<tr>
<td></td>
<td>25 Aug 1975</td>
<td>5237</td>
<td>5.8</td>
<td>080/7.2</td>
<td>S</td>
<td>3293</td>
<td>087/6.5</td>
<td>242/5.7</td>
</tr>
<tr>
<td></td>
<td>28 Aug 1975</td>
<td>5240</td>
<td>5.4</td>
<td>070/6.2</td>
<td>N</td>
<td>2778</td>
<td>068/5.6</td>
<td>098/1.5</td>
</tr>
<tr>
<td>B</td>
<td>07 Jul 1973</td>
<td>3188</td>
<td>4.0</td>
<td>00/0</td>
<td>S</td>
<td>3733</td>
<td>333/2.9</td>
<td>055/8.7</td>
</tr>
<tr>
<td></td>
<td>21 Jun 1975</td>
<td>5172</td>
<td>3.4</td>
<td>00/0</td>
<td>N</td>
<td>14482</td>
<td>135/1.1</td>
<td>310/3.1</td>
</tr>
<tr>
<td></td>
<td>24 Jun 1975</td>
<td>5175</td>
<td>3.3</td>
<td>00/0</td>
<td>S</td>
<td>4241</td>
<td>255/2.5</td>
<td>098/3.6</td>
</tr>
<tr>
<td></td>
<td>28 Jun 1976</td>
<td>6180</td>
<td>3.6</td>
<td>00/0</td>
<td>S</td>
<td>4681</td>
<td>095/2.0</td>
<td>350/14.9</td>
</tr>
<tr>
<td>C</td>
<td>09 Aug 1973</td>
<td>3221</td>
<td>2.4</td>
<td>070/4.1</td>
<td>N</td>
<td>24654</td>
<td>101/1.8</td>
<td>060/17.0</td>
</tr>
<tr>
<td></td>
<td>09 Sep 1973</td>
<td>3252</td>
<td>2.5</td>
<td>250/7.7</td>
<td>N</td>
<td>639</td>
<td>025/1.4</td>
<td>040/11.3</td>
</tr>
<tr>
<td></td>
<td>07 Jul 1975</td>
<td>5188</td>
<td>2.1</td>
<td>240/5.1</td>
<td>S</td>
<td>1315</td>
<td>203/2.4</td>
<td>275/11.8</td>
</tr>
<tr>
<td></td>
<td>29 Jul 1975</td>
<td>5210</td>
<td>2.4</td>
<td>200/5.1</td>
<td>S</td>
<td>7335</td>
<td>297/1.9</td>
<td>032/8.2</td>
</tr>
<tr>
<td>D</td>
<td>30 Jun 1975</td>
<td>5181</td>
<td>2.3</td>
<td>00/0</td>
<td>N</td>
<td>7462</td>
<td>296/1.6</td>
<td>135/13.9</td>
</tr>
<tr>
<td></td>
<td>19 Aug 1975</td>
<td>5231</td>
<td>2.9</td>
<td>00/0</td>
<td>S</td>
<td>7023</td>
<td>049/2.6</td>
<td>077/14.4</td>
</tr>
<tr>
<td></td>
<td>18 Jul 1976</td>
<td>6200</td>
<td>1.8</td>
<td>00/0</td>
<td>N</td>
<td>2634</td>
<td>159/2.1</td>
<td>260/4.6</td>
</tr>
<tr>
<td></td>
<td>31 Jul 1976</td>
<td>6213</td>
<td>1.4</td>
<td>00/0</td>
<td>N</td>
<td>6364</td>
<td>142/2.1</td>
<td>310/6.7</td>
</tr>
</tbody>
</table>

* Defined in footnote 1.

In the 8-day data set, as well as the 16-day set in Section 4, some individual echoes in the FACE target area may have had larger-than-average areas or rain volumes (or durations or top heights, although these were not studied) as a result of seeding with silver iodide; and some of the differences between echoes over land and those over water may have resulted from seeding rather than from geographical location. But seeding was not used as a covariate in this study because we believe that seeding had no substantial effect on the average rain volumes and areas that were derived in the “over land” domain.

The differences between the two 4-day sets in Table 1 raised questions. Was one of the covariates, $V_L$ or echo motion, more powerful than the other? If so, which one, when and why? In an attempt to resolve the ambiguities inherent in the 8-day sample of Wiggert et al. (1977), we doubled the number of days, so that two pairs of 8 day composites could be compared. Our intention, in the next section, is to study, separately, the effects that wind speed and that echo motion have upon the behavior of rain shower echoes.

4. The 16 days of FACE radar data and the multiday sets

The weather over South Florida during each of the 16 days was neither very dry (having scant, suppressed convective activity), nor very wet (having widespread around-the-clock rain storms); all the days were experimental (GO) days in the FACE program. As noted by Woodley and Sax (1976), GO days have good potential for enhancement of cumulus growth from cloud seeding, based on predictions from a one-dimensional model of a cumulus tower (Simpson and Wiggert, 1971). But GO days also have few or no forenoon hours with shower activity observed in the FACE target area. Usually, about half the days in each summertime FACE program qualify as GO days, and usually they are neither convectively overactive nor suppressed.

The days are identified in Table 2 and are grouped into four sets of 4 days each. The first 8 days had $V_L$ exceeding 3 m s$^{-1}$. Of these, the first 4 days had moving radar echoes over land and were denoted set A. The second set of 4 days had stationary rain-shower echoes and was labeled set B. Sets C and D had $V_L < 3$ m s$^{-1}$, but C had moving and D had stationary radar echoes. The data used by Wiggert et al. (1977) are again used in this study; these are identified as sets A and D, (and in Table 1 as sets I and II, respectively).

There were equal numbers of days with stationary echoes, moving echoes, strong winds and weak winds in this study. By comparison, the distributions of days within these categories were unequal in the 86 GO days contained in three summers of the FACE data from which our data sample was drawn. The conditions that defined set A were observed on 56 days, while those that defined sets B and C occurred, respectively, on 6 and 7 days. The limited number of candidates for sets B and C included many seed days, and because each set was to contain a sample of 4 days, neither of these two sets was devoid of seed days. The seeding action that occurred each day in the target area is indicated by S or by N in the sixth column. The S denotes a day when selected clouds were seeded with silver...
iodide flares, while the N denotes a control day, during which placebos or no flares were dispensed. The seeding action did not play any role in our selection of these 16 days and is listed for information only.

Echo area coverage underwent daily cycles. In the FACE program, a single index was needed that would objectively define a rainy day. That index was defined by Simpson et al. (1971) as the total areal extent of echoes, at or above the radar’s minimum detectable signal (~18 dBZ), within 100 n mi (185 km) of NHC at 1800 GMT, near the time of maximum solar heating and rainfall activity; a “rainy” day had echo coverage > 4000 n m² (13.7 \times 10^9 \text{ km}^2). Echo coverage is listed in the seventh column of Table 2. Echo coverage at 1800 GMT 9 August 1973 and 21 June 1975 exceeded the “rainy day” threshold and was about double that of any of the other days.

The mean vector wind in the layer from the surface to 700 mb and the vector shear between winds at the 850 and 200 mb levels, derived each day from only the 1200 GMT Miami sounding, are listed in the last two columns in Table 2. “Mean V” is approximately the mean planetary boundary-layer wind vector and is the average of the vector sum of the winds at altitudes of 1000 ft, 2000 ft, 3000 ft, 4000 ft, 850 mb, 6000 ft, 7000 ft, 8000 ft, 9000 ft and 70 mb. In general, these mean V had a northerly component with speeds > 2 m s⁻¹ on the days with \( V_L > 3 \text{ m s}⁻¹ \), while mean southerly components and speeds < 2 m s⁻¹ tended to be associated with the remaining 8 days.

We deduce from the last column that on the 8 days with \( V_L > 3 \text{ m s}⁻¹ \) the average shear was 6.7 m s⁻¹. By contrast, the average shear was 11 m s⁻¹ for the 8 days with weaker \( V_L \), although there were large daily deviations from each average. Nevertheless, if these 16 days had been grouped on the basis of either the mean layer wind or the wind shear in the middle troposphere, days would have been interchanged in some of the subsets compared to the days found with the \( V_L \) criterion.

Rainfall in the target area is used to assess the effectiveness of FACE cloud seeding operations. The radar rainfalls in the target area are used only after being “adjusted.” The adjustment factor is the ratio, each day, of area-average rain as measured by gages to that measured by radar. The gages are in a ~600 km² cluster (smaller rectangular area in Fig. 1), and the rain depth averaged over that area is denoted by \( g \). The rain depth derived from returned radar power from that same area and time span is denoted \( r \).

The gage adjustments (\( g/r \) ratios) used for the FACE target area rain volumes have been presented elsewhere (Woodley et al., 1974, 1975). However, in this study, the gage ratios were not applied to any of the individual rain volumes from tracked rain showers. The primary reason is that \( g/r \) can undergo large variation within a day so that the \( g/r \) value calculated from 12 h of gage and 12 h of radar rain volume (as was sometimes done for FACE) often disagree with one that is calculated from, for example, a particular 60 min (or smaller) interval within the same day. Second, the \( g/r \) is calculated from data that were gathered in a small area over land; its value over water is unknown and the total domain is predominantly water. Thus, no attempt was made to incorporate the \( g/r \) ratio into any of the characteristics of individual rainshowers treated in this study.

5. Echo areas, populations and rain intensities
   a. Twelve-hour average values for multiday sets

Four echo parameters were supplied by the STATS program. At the end of each hour of each day, from all recorded PPI scans, for every one of the nine combinations of echo centroid position (over land/water/total domain) and merger status (unmerged only/merged only/both), the following variables were summarized:

1) Total volumetric rain rate from all observed echoes
2) Total area of all recorded echoes
3) Total number of echo observations
4) Number of individually tracked echoes.

The hourly totals are used in Section 5b. Here, sums of all of the hourly totals for 1, 4 or 8 days in a set form the basis for the averages discussed in this section. Average rain intensity was the quotient of the first parameter (above) divided by the second one. Average echo area was the quotient of the second parameter divided by the third one. Echo population was the fourth parameter.

Eight-day averages of echo characteristics with \( V_L > 3 \text{ m s}⁻¹ \) were derived from the combined A and B sets (Table 2); these were contrasted to averages when \( V_L < 3 \text{ m s}⁻¹ \), the 8 days formed by combining sets C and D. Alternatively, echo characteristics on days with echo motion, set A plus set C, were compared with those for 8 days with stationary echoes, sets B and D combined.

The average area of unmerged echoes over land (Fig. 4) was least for set A, and was successively larger for sets B, C and D. The same ranking also held for merged echoes over land. Average echo areas for 8-day composite sets appear on the right side of Fig. 4. Echoes over land when \( V_L < 3 \text{ m s}⁻¹ \) were about double the area of those on days when \( V_L > 3 \text{ m s}⁻¹ \). The areas of stationary echoes averaged about 25% larger than those of moving echoes. This would imply that over land, increased echo area was better correlated with light winds than with echo stationarity. The 16-day average
area for all unmerged and merged echoes over land was 198 km².

Over water (Fig. 5) set B had the largest average area for all unmerged and merged echoes, with C being second largest. Among the 8-day composites, the differences were slight; average area for all stationary
echoes was larger than for all moving echoes. For the 16 days, average echo area over water was 86 km², or about half that over land.

When we compare Figs. 4 and 5, unmerged echoes are found to be larger over land than over water, except for set A. Most notably, stationary echoes with $V_L < 3$ m s⁻¹ (set D) over land were about four times larger than those over water. Regardless of echo location being over land or over water, the average area for merged echoes (with one exception) was always greater than the average area of unmerged echoes.

Daytime echo areas were averaged over the $1 \times 10^4$ km² total domain (Fig. 6). We found that the average for unmerged echoes in set A was less than half that of any of the other sets; the latter ranged from 161 to 186 km². The 8-day composites reveal that when $V_L > 3$ m s⁻¹, the average area of unmerged echoes was 88 km² and was similar to the area for echo motion days (90 km²). However, when $V_L < 3$ m s⁻¹, the 132 km² average area was similar to that for days with stationary echoes, 129 km². The average unmerged echo area within the total domain for the 16 days was 109 km². The average area of merged echoes was more than triple the area of unmerged counterparts.

Daytime echo population varied with echo centroid location, as seen in Fig. 7. For example, set A, over land, had an average of 527 tracked echo centroids that remained unmerged. One day in the set had only 297 unmerged echoes over land, while another had 840 such echoes. Echo populations varied among the component days of each set, and in three sets the interday differences exceeded in order of magnitude. Within each of the four sets, there was a greater range in population for echoes over water than for those over land; this was true for both unmerged and merged echoes. Over land, there were fewer moving than stationary echoes; over water, the converse was true.

Regardless of geography, there were about seven times as many unmerged as merged echoes. For the 16 days, over land, there were more unmerged echoes than over an equal area over water; the same can be said for merged echoes. The average number of tracked unmerged echoes over the total domain for a 12 h day exceeded 2000 in each of the four sets. The reason for the large number of tracked echoes is that many echoes neither grew very large nor persisted. In turn, the minimum thresholds of time, area and rain intensity that were imposed by the automatic tracking program interacted adversely with the actual behavior of young, small showering cumuli. There were many short-lived echoes. As seen in Fig. 8, half of all echoes on 19 August 1975 did not exceed the area and rain
intensity thresholds for more than one recorded PPI scan before they shrank below the 4 n mi$^2$ minimum in area. Smaller area thresholds (3, 2 or 1 n mi$^2$) and more frequent recording intervals probably would have resulted in a greater number of smaller echoes with, perhaps, greater durations. On the other hand, thresholds of some kind were unavoidable because of recording interval, spatial resolution, and the need to reject small nonweather echoes (e.g., from aircraft).

Average rain intensities as functions of echo centroid location are displayed in Fig. 9. These rain intensities at first may seem quite small for tropical convective showers. However, they are areally and temporally averaged values and the perimeter of every echo area in this study is the arbitrarily chosen 1 mm h$^{-1}$ isopleth. Therefore, each echo contained a region of very light rain intensities. The intensities for merged echoes over land always exceeded those for unmerged echoes there, within each of the four sets. Over water, merged echoes had higher average rain intensities than unmerged echoes for sets A, C and D. Set C (moving echoes, $V_L < 3$ m s$^{-1}$) had the highest average rain intensity in five of the six categories. However, rain intensity differences between days within a set often were larger than differences between sets. For the 16 days, average rain intensities over water, whether the echoes merged or remained unmerged, were less than the intensities from counterparts over land.

Ratios of parameters for unmerged echoes to those of merged echo counterparts appear in Table 3a. For example, there were about 5–14 times as many unmerged as merged echoes, as seen in the column labeled P. Because of this disparity in numbers, the ratio of total rain volume from all unmerged echoes to that from all merged echoes in a set, TRV, always exceeded unity and ranged from 1.3 to 3.1. TRV exceeded 2 for moving echoes over land as well as for stationary echoes over water. In the ARV columns are the ratios of the average rain volume per echo from unmerged echoes to those from merged echoes, as functions of centroid location, mean low-level wind speed and echo motion. The ratios were all <1. Thus (inversely) the average merged echo delivered from 2.4 to 8.3 times as much rain volume per unit time as did its unmerged counterpart. For moving echoes, ARV ratios over land were about double those over water, whereas for stationary echoes, ARV ratios were less over land than over water.

Total rain volume for days with light winds was compared with that from days with strong winds. Table 3b indicates that, regardless of merger status, echoes over land and over the total domain had larger TRV on light wind than on strong wind days. Similarly, the TRV on days with stationary echoes was somewhat larger than on days with moving echoes, except when echoes were over water.

These over land results are in contrast to those of Ulanski and Garstang (1978a,b). They studied 12 well-organized thunderstorm cells that originated, matured and decayed inside of a 33 km × 20 km
Fig. 9. Average rain intensity for each 4-day set as a function of centroid location, for unmerged echoes and for merged echoes.

The area was situated in the FACE target, near the rectangle in Fig. 1, and contained a grid of raingages (2.5 km² per gage). Ulanski and Garstang (1978b) found that the average moving storm, over land, was characterized by greater rain depth, duration, area and (by implication) rain intensity than the average stationary cell. We agree with their findings that moving storms have higher rain intensities; see Section 6, below. But, in general, we found that the average stationary storm had larger areas and produced larger rain volumes than the average moving storm; the sizes and locations of the storms that we studied may be crucial to these findings. For example, Fig. 10 illustrates the population distribution of areas of unmerged echoes over land on a day with stationary echoes; 10% of

<p>| Table 3a. Ratios of unmerged-echo to merged-echo populations (P), total rain volumes (TRV), and average rain volume per echo (ARV) for four 4-day composite sets. |</p>
<table>
<thead>
<tr>
<th>Set A</th>
<th>Set B</th>
<th>Set C</th>
<th>Set D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>13.3</td>
<td>3.1</td>
<td>0.23</td>
</tr>
<tr>
<td>Water</td>
<td>10.4</td>
<td>1.3</td>
<td>0.12</td>
</tr>
<tr>
<td>Total domain</td>
<td>10.1</td>
<td>1.5</td>
<td>0.15</td>
</tr>
</tbody>
</table>
these individual, unmerged echoes were larger than the total area of the rain gage network. Any rain from echoes with areas > 660 km² that fell outside the gage network escaped inclusion in the analysis of Ulanski and Garstang (1978b). We believe that their results differ from ours in part because of the small sample of storms and the small area of the raingage network that was used—about 3% of the land area in our study—and because the site of the raingage network may have been located far from some of the larger or more intense stationary rain systems, which were observed and recorded by the Miami radar.

Daytime echo behavior when \( \bar{V}_L > 3 \text{ m s}^{-1} \) was compared with that on days with weaker winds; similarly, echo behavior on days with moving echoes was compared with that on days with stationary echoes. As noted, we found that echoes had larger than average areas and volumetric rain rates if they were 1) the result of the merger of preexisting echoes, or 2) over land, or 3) stationary, or 4) embedded in light low-level winds. Unmerged echoes were larger in number, but had smaller echo-average rain intensities than merged echoes. There were more echoes over land than were situated over water.

b. Hour-by-hour variations and their statistical significance—a closer view and its reliability

For each day, end-of-hour averages of echo populations, rain intensities, echo areas and volumetric rain rates were calculated through procedures stated in Section 5a. The differences between midday sets of these variables were tested for statistical significance; this was done by ranking the values for the individual days for each hour. For example, populations of unmerged echoes in the total domain during the hour ending at 1000 EDT, for each of the 16 days (and regardless of \( \bar{V}_L \) being strong or weak), were placed in ascending order. Then, with respect to \( \bar{V}_L \), the probability that the observed ordering resulted from chance was calculated with the Wilcoxon-Mann-Whitney rank test (Wilcoxon, 1945; Mann and Whitney, 1947). This ranking and testing procedure was repeated for every parameter for each hour. *Significance* was defined to occur

\[
\begin{array}{cccccc}
\text{Time (EDT)} & \text{Pop.} & \text{RI} & \text{A} & \text{VR} & \text{Pop.} & \text{RI} & \text{A} & \text{VR} \\
10 & \bullet & 1 & \bullet & \bullet & \bullet & 1 & 1 & 1 \\
11 & \bullet & 1 & \bullet & \bullet & \bullet & 1 & 1 & 1 \\
12 & \bullet & 1 & \bullet & \bullet & \bullet & 2 & 1 & 1 \\
13 & \bullet & 1 & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
14 & \bullet & 1 & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
15 & \bullet & 1 & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
16 & \bullet & 1 & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\
17 & 1 & 2 & 2 & 2 & \bullet & \bullet & \bullet & \bullet \\
18 & \bullet & 2 & 1 & 1 & \bullet & \bullet & \bullet & \bullet \\
19 & \bullet & 2 & 2 & 3 & \bullet & \bullet & \bullet & \bullet \\
20 & \bullet & 2 & 2 & 3 & \bullet & \bullet & \bullet & \bullet \\
21 & \bullet & 2 & 2 & 3 & \bullet & \bullet & \bullet & \bullet \\
\end{array}
\]

* Significance = \( \alpha = \) one-tailed probability.

\( \bullet \): \( \alpha >= 10\% \)

1: \( 10\% > \alpha >= 5\% \)

2: \( 5\% > \alpha >= 1\% \)

3: \( \alpha < 1\% \)

Pop. Echo population
RI Echo-average rain intensity
A Average echo area
VR Echo-average volumetric rainfall rate

![19 AUGUST 1975 (523)]

- 302 Unmerged Echoes Over Land

**TABLE 4.** Significance* of differences between days with light winds and days with strong winds in total domain.
weak winds; Figs. 11–14 display 8-day averages of the hourly trends of echo populations, rain intensities and echo areas for these intercomparisons. Tables 8–11 show counterpart test results from a comparison of days that had moving echoes with days that had stationary echoes. Figs. 15–18 depict average hourly trends for those days.

In the tables, the α’s themselves are not displayed. Instead, α’s were encoded with the intention that the tables would present just the salient results. Thus a solid dot represents $\alpha \geq 10\%$; 1 represents $10\% > \alpha \geq 5\%$; 2 stands for $5\% > \alpha \geq 1\%$ and 3 means that $\alpha < 1\%$. The phrase “strong significance” is reserved for $\alpha < 5\%$.

Table 4 contains results from tests made of each hour’s data, between days with strong and days with weak winds, for unmerged and merged echoes in the total domain. For unmerged echoes (Fig. 11), the average rain intensities and average echo areas during every hour after noon were larger on days with light wind than on days with strong wind.

However, the differences were strongly significant (Table 4) only during 2 or 3 h in the late afternoon. Echo population differences were not significant, despite the dissimilarities in averages seen in Fig. 11a.

For merged echoes, only the rain intensities and volumetric rain rates on strong wind days differed strongly from those on weak wind days and not during a sequence of hours concentrated after noon, as was the case with unmerged echoes.

Table 5 contains results from each hour’s tests between unmerged and merged echoes, when $V_L > 3$ m s$^{-1}$ (solid lines, Figs. 11 and 12) and $V_L < 3$ m s$^{-1}$ (dashed lines). Unmerged echoes differed significantly from merged echoes, regardless of wind speed, according to Table 5. For example, with strong winds, echo population differed at the 99% confidence level for almost every hour, and echo areas and volumetric rain rates after 1300 EDT persistently had strong significant differences. But rain intensities during many hours were not significantly different. With weak winds, there was a tendency for significance to occur earlier and in the case of rain intensity, to also last longer, than with strong winds.

Significance test results in Tables 6 and 7 are from intercomparisons of all echoes over land (Fig. 13) versus all echoes over water (Fig. 14), for strong versus weak winds.

Echo area and volumetric rain rate (Table 6) after 1500 EDT differed between strong and weak winds to a significant extent over land, but almost never over water. Echo behavior over land differed significantly from that over water when winds were weak (Table 7, right half), after 1400 EDT. However, with strong winds, significant land/water differences were seldom found.

Thus, Tables 4–7 imply that lower wind speeds permit a larger effect, at low levels, by the sea breeze on the convergence of heat, mass and mois-
Fig. 11. Unmerged echoes within total domain: 8 day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for strong and weak $V_L$.

Fig. 12. Merged echoes, total domain: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for strong and weak $V_L$. 
Fig. 13. All echoes over land: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for strong and weak $V_L$.

Fig. 14. All echoes over water: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for strong and weak $V_L$.

As expected, the effect is most noticeable after noon, over land and on the smaller, unmerged, echoes.

Echo motion/stationarity was related to altered echo behavior in a fashion that paralleled that seen with strong and weak wind speed. But occasionally
Fig. 15. Unmerged echoes, total domain: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for stationary and for moving echoes.

Fig. 16. Merged echoes, total domain: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for stationary and for moving echoes.
Fig. 17. All echoes over land: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for stationary and for moving echoes.

Fig. 18. All echoes over water: 8-day average of (a) echo population, (b) rain intensity and (c) echo area for each daytime hour, for stationary and for moving echoes.
that parallelism failed. It is the failures in parallelism that are now examined.

In Figs. 15 and 16 and Tables 8 and 9 are comparisons between unmerged and merged echoes on days with moving and with stationary echoes. Rain intensity differences in Table 8 were less significant, but the differences in areas and volumetric rain rates were more significant and for a longer period, than found for the strong/weak wind counterparts in Table 4.

Strongly significant differences on days with moving echoes (Table 9, left half) were delayed, relative to those on days with strong wind (Table 5, left half). Strong significance on days with stationary echoes was found earlier and was more persistent than on days with moving echoes, according to the two halves of Table 9. Regardless of echoes being over land or over water, strongly significant differences were found, at an earlier hour, in the stationary/moving echo comparison (Table 10) than were found in the light/strong wind comparison (Table 6).

Echoes over land differed from those over water with stronger significance, at an earlier hour, on days with stationary echoes (Table 11, right half), than on days with weak winds (Table 7, right half). But there never were strongly significant land/water differences on days with moving echoes (Table 11, left half) as there were on days with strong winds (Table 7, left half).

Average populations for merged echoes (Fig. 16 and Table 8) and echoes over land, (Fig. 17 and Table 10) were persistently larger, although, for echoes over water (Fig. 18 and Table 10) populations were smaller, almost every hour, on days with stationary echoes compared with those having mov-

**Table 8.** Significance* of differences between days with moving echoes and days with stationary echoes in total domain.

<table>
<thead>
<tr>
<th>Time (EDT)</th>
<th>Unmerged echoes</th>
<th>Merged echoes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pop. RI A VR</td>
<td>Pop. RI A VR</td>
</tr>
<tr>
<td>10</td>
<td>1 2 2</td>
<td>2 1 1</td>
</tr>
<tr>
<td>11</td>
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<td>1 2 2</td>
<td>1 1 1</td>
</tr>
<tr>
<td>21</td>
<td>1 2 2</td>
<td>1 1 1</td>
</tr>
</tbody>
</table>

* As in Table 4.

**Table 9.** Significance* of differences between unmerged echoes and merged echoes in total domain.

<table>
<thead>
<tr>
<th>Time (EDT)</th>
<th>Days with moving echoes</th>
<th>Days with stationary echoes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pop. RI A VR</td>
<td>Pop. RI A VR</td>
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<td>1 1</td>
<td>3 1 1</td>
</tr>
</tbody>
</table>

* As in Table 4.
Fig. 19. All echoes over land: average rain intensity, as a function of quartile of maximum area, for echoes increasing in area, at maximum area, and decreasing in area, for stationary echoes and moving echoes.

Normalized values then are sorted and stored on the basis of percentage quartile of maximum area, and as part of the process, areas that were recorded at scan times before the time the echo attained maximum area are stored separately from those areas recorded after the echo’s maximum size occurred. The average rain intensity per echo, for all echoes in a particular quartile, is the ratio in that quartile of the summed rain volume per unit time (VR) to the summed echo area.

In every quartile, the average rain intensities of moving echoes were found to be larger than those of stationary echoes, whether over land (Fig. 19) or over water (Fig. 20). These results agree with some that were implied by Ulanski and Garstang (1978b). Similarly, for unmerged and merged echoes (not shown), average rain intensities of moving echoes exceeded those of stationary echoes for almost all quartiles. Therefore, average rain intensities of moving echoes exceeded those of stationary echoes at almost all stages in growth cycle and regardless of echo location or merger status. Growth tenden-

Fig. 20. All echoes over water: average rain intensity, as a function of quartile of maximum area, for echoes increasing in area, at maximum area, and decreasing in area, for stationary echoes and moving echoes.

6. Rain intensity growth tendencies

Echo behavior can be studied by a technique that focuses on tendencies of echo life cycle and that can be performed only after all echoes for an entire 12 h day have been isolated and tracked. These “echo growth tendencies” provide a way to study the behavior of growing echoes separately from that of dying echoes. The procedure is based on the fact that each tracked echo, during some individual PPI scan in the day, attained a maximum in its recorded area. That maximum recorded area is used to normalize all other areas recorded when the echo had the same merger status and geographic domain. The
cies as functions of $V_L$ (not shown) indicated that higher average rain intensities were found when wind speeds were below, rather than above, the 3 m s$^{-1}$ threshold, although rain intensity differed less as a function of wind speed than of echo motion/stationarity.

The highest average rain intensity almost always occurred before maximum area was achieved, as seen in Figs. 19 and 20. For any quartile when echo area was increasing, the rain intensities were higher than those for the same percent quartile when echo areas were decreasing. In general, this demonstrated that intense, growing convective shower cores rained first, but as showers matured they increased in area, yet decayed in intensity. There persisted a region of widespread light rain, which then slowly decreased in area and finally dissipated.

Growth tendencies of average volumetric rain rates (not shown) for stationary echoes were larger than for moving echoes, for the five central quartiles, which exclude echoes that were less than one-half their maximum areal extent.

Paradoxically, then, moving echoes whose size exceeded 50% of the greatest area that they were to attain, were found to have higher echo-average intensities but lower volumetric rain rates than stationary echoes during these 16 days. The smaller volumetric rates are related to the observed smaller areas of moving, than of stationary, echoes. Regarding the average rain intensities, we hypothesize that moving echoes have a greater percentage of the mass flux at cloud base with higher heat and moisture content than do stationary shower echoes. In turn, more vigorous convection with higher rain intensity may result. However, regardless of the causal mechanisms, higher average rain intensities but lower average volumetric rain rates were found with moving than with stationary echoes.

7. Summary, conclusions and future work

Radar data from showers observed by the WSR-57 at the NOAA National Hurricane Center in Miami were tape-recorded during three recent summers as part of the Florida Area Cumulus Experiment (FACE). The presence and strength of differences in behavior of tropical convective rain echoes, isolated at the $\sim 25$ dBZ contour, were sought for merged and unmerged echoes, over water and land, through the daytime hours. Sixteen days of computer-tracked echo data were composited into 4-day and 8-day sets. The compositing was based on what were intended to be two objective criteria, namely the movement or stationarity of the echoes and the time-weighted mean speed of the lower tropospheric wind ($V_L$). The latter was used for stratifying with a threshold of 3 m s$^{-1}$. Behavior of echoes on days with moving echoes was compared with that on days with stationary echoes. Similarly, echo behavior on days with $V_L > 3$ m s$^{-1}$ and on days with weaker winds was compared. Intercomparisons of these pairs of 8-day sets were made to find which of these covariates was more strongly correlated with changes in echo behavior.

The 8-day averages of daytime echo areas and rain volumes (but not rain intensities) were generally larger if the echoes were 1) the result of the merger of preexisting echoes, or 2) over land, or 3) stationary, or 4) embedded in light low-level winds. Unmerged echoes were 5–14 times more numerous, had marginally smaller rain intensities and had 12–42% of the rain volume of merged echoes. There were about 15% more echoes over land than were situated over water. Over water, total 12 h rain volumes were 25% greater on days with strong, rather than with weak, winds and 25–100% greater on days with moving, rather than stationary, echoes. But, over land and over the total domain, the converse was true in each comparison, with 30–110% more total volume of rain on days with stationary, rather than moving, echoes and with 70–200% more volume on days with light, rather than strong, winds.

Differences in hour-by-hour averages of echo areas, populations, volumetric rain rates and rain intensities were tested for significance with a rank test. For most of the day, but especially after noon, each characteristic of unmerged echoes, except rain intensity, was significantly different from that of merged echoes, regardless of whether wind speed was weak or strong or whether echoes were moving or stationary. With weak winds, significant differences were found earlier in the day than with strong winds. After 1400 EDT, echoes over land differed significantly from those over water, but only when echoes were stationary or embedded in light winds in the lower troposphere. Variations in mean low-level wind speed were more strongly correlated with the changed behavior of unmerged, rather than merged, echoes, and with the changed behavior of echoes over land, rather than of those over water. The lower wind speeds apparently permitted sea-breeze-induced convergence fields to be more effective than those with stronger winds; as a result, convective showers, especially those over land and those that had not merged, had larger areas and volumetric rain rates on days with light, rather than with strong, winds.

The comparison between moving and stationary echoes revealed stronger significance, at an earlier hour than seen in the strong/weak wind comparisons, 1) when echo areas and volumetric rain rates (VR) of unmerged echoes were investigated and 2) when areas, VR's and rain intensities of echoes over land or water were studied. The converse was true for rain intensity for both unmerged and merged echoes.
When parameters for unmerged echoes were compared with those of merged echoes, the significance of the differences was stronger on strong wind days than on moving echo days, but was essentially the same on weak wind days as on stationary echo days. Over land, echo areas and VR's differed from those over water with greater significance on strong wind days than on moving echo days, but with less significance on days with weak winds than on days with stationary echoes.

Therefore, while neither of the covariates, echo motion nor $V_L$, was uniformly superior to the other as a predictor of echo behavior, either covariate would aid real-time hydrologic forecasts.

Average rain intensity and volumetric rain rate were studied as functions of echo growth tendency. Growth tendencies of rain intensity for the 8-day composite sets were similar in that echoes at any given percentage of their maximum size, and while growing in area, had higher intensities than dying rain showers having the same relative size. Highest rain intensities preceded maxima in echo area. Growth tendencies indicated that greater average rain intensities generally occurred on days with moving echoes than on days with stationary echoes. Greater rain intensities also were found on days with light, rather than strong, winds, for most stages of growth tendency. Thus, greater rain intensities, from individually tracked rainshowers, tended to occur on days with moving echoes and on days with light winds, over the ocean as well as over land. These were the same kinds of days that provided the most favorable conditions, according to Simpson and Woodley (1975), for seeding cumuli in the FACE target area.

Rain volume in the total FACE target area on control (no seed) days with stationary echoes, according to Woodley et al. (1977a), was about twice that of control days with moving echoes. However, total target rain volume was greater on control days with stationary echoes, than on seed days with stationary echoes, although the difference was not statistically significant. Our results confirm and enlarge upon these observations. First, over a land area that is about double the size of the FACE target, the total rain volume on days with stationary echoes was 1.3–2.1 times larger than on days with moving echoes; over water, however, the converse was true. Second, volumetric rain rate was significantly larger on stationary, rather than on moving, echo days, for a greater number of hours, when echoes were unmerged, rather than when merged. This fact is interrelated to the lack of seeding-enhanced rain volume noted by Woodley et al. (1977a) because, even before merger, the stationary rainshowers produced more rain volume, for more hours, than did moving echoes. Thus, little artificial improvement in volume of rain was possible on days with stationary echoes. Basic processes in cumulus convection were amplified when the mean wind speed in the lower troposphere was <3 m s$^{-1}$; when echoes were stationary, total rain volumes were enhanced, but average rain intensities were reduced.

Showering cumuli studied here underwent changes in their dynamics and, perhaps, microphysics as a result of alterations in the strength and shear of the wind field in which they were embedded. The interactions between the kinematics of the flow field and the dynamics and microphysics of convective clouds are complex and require further study. This work is intended as an aid to that continuing study.

In a subsequent paper, population spectra of maximum echo area, summed rain volumes and echo durations, for the same 16 days of Miami radar data, will be studied by use of the last in the train of the programs in Fig. 2. In general, the spectra tend to be best fitted by a truncated log-normal distribution. The spectra should prove useful in parameterizations of cumulus convection within models of larger scale atmospheric processes.

Radar data from an independent set of days will be analyzed in a similar fashion to the above, to confirm (or refute) these results. Also, data gathered during Hurricane David (1979) (Wiggert et al., 1980) will be intercompared with the foregoing to gain a further understanding of tropical convective rainfall processes as revealed by tracked radar rainshowers.

Acknowledgments. The S-band radar information used in the FACE program is supplied gratis by the NOAA National Hurricane Center. We are indebted to NHC’s director, radar operators and electronics technicians for their sustained support, data supply, calibrations and technical assistance.

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APPENDIX

Radar Echo Description

The method that is used to fit a bivariate normal distribution, to each echo and each fragment, first
calculates the moments of the distribution of rain intensity:

1) The zeroth moment (weight = \( W \)) of the distribution in the echo (or fragment), of rain intensity \( r_{i,j} \) is

\[
W = \sum_{i,j} r_{i,j}.
\]  
(A1)

2) The first moment (the centroid) of the distribution of rain intensities in the echo (or fragment) is geographically located at coordinates that are the average \( \overline{X} \) and the average \( \overline{Y} \) values of the distribution, or

\[
\overline{X} = W^{-1} \sum_{i,j} i r_{i,j} = \mu_x, \tag{A2}
\]

\[
\overline{Y} = W^{-1} \sum_{i,j} j r_{i,j} = \mu_y. \tag{A3}
\]

3) The second moments of the distribution are \( \overline{X^2}, \overline{XY} \) and \( \overline{Y^2} \), where

\[
\overline{X^2} = W^{-1} \sum_{i,j} i^2 r_{i,j}, \tag{A4}
\]

\[
\overline{XY} = W^{-1} \sum_{i,j} ij r_{i,j}, \tag{A5}
\]

\[
\overline{Y^2} = W^{-1} \sum_{i,j} j^2 r_{i,j}. \tag{A6}
\]

In (A1)–(A6), the summation is performed over all the grid squares that lie within the boundary of the echo (or fragment). Using (A1)–(A6), the variance in \( \overline{X} (\equiv \sigma_x^2) \), the variance in \( \overline{Y} (\equiv \sigma_y^2) \), and the correlation coefficient \( \rho \) are

\[
\sigma_x^2 = \overline{X^2} - \overline{X}^2, \tag{A7}
\]

\[
\sigma_y^2 = \overline{Y^2} - \overline{Y}^2, \tag{A8}
\]

\[
\rho = \frac{\overline{XY} - \overline{X} \overline{Y}}{(\sigma_x \sigma_y)}^{-1}. \tag{A9}
\]

Thus the bivariate normal distribution (e.g., Wonnacott and Wonnacott, 1972, Chap. 14), which best fits the distribution of rain intensities in the echo (or in the fragment), is

\[
f(x, y) = \exp \left\{ -\frac{1}{2(1-\rho^2)} \left[ \frac{(x - \mu_x)}{\sigma_x} \right]^2 + \frac{(y - \mu_y)}{\sigma_y} - 2\rho \left( \frac{x - \mu_x}{\sigma_x} \right) \left( \frac{y - \mu_y}{\sigma_y} \right) \right\}. \tag{A10}
\]

REFERENCES


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