A Study of Urban Effects on Radar First Echoes

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ABSTRACT

The properties of 3 cm radar first echoes are used to study the effects of the St. Louis, Mo., metropolitan area on precipitation initiation in summer convective clouds. Based on a sample of 4553 first echoes, obtained on 82 echo-producing days of 1972–75, it is shown that the area-normalized frequency of first echo formation over the city and in the "near" downwind region is approximately a factor of 2 greater than for nearby rural regions. The maximum enhancement in first echo formation occurs over the downtown area and along the Mississippi River, which separates St. Louis from industrial suburbs to the east. The downwind extent of the region of first echo enhancement appears to be limited to about 1 h of wind travel. The enhancement occurs mainly on weekdays.

Temperatures of first echo tops and bases indicate that precipitation initiation is most frequently through drop collection, though there is evidence that ice processes may contribute a small fraction of the first echoes. Urban first echoes have lower and warmer bases and greater vertical thickness than rural first echoes.

1. Introduction

The locations and characteristics of radar first echoes (FE's) have been used to study the effects of St. Louis on precipitation initiation in summer convective clouds. This study was conducted by the University of Chicago Cloud Physics Laboratory, as part of METROMEX (Braham, 1974; Dungey, 1977). It is based on a sample of 4553 FE's obtained on 82 echo-producing days during the summers of 1972–75 using a TPS-10, 3 cm height finding radar located at Greenville, Ill. The location of the radar relative to St. Louis and other places mentioned in the text is shown in Fig. 1. Table 1 gives numbers of sample days, hours and echoes used in this study.

Radar first echoes are useful for studies of urban effects because they represent the earliest stage at which precipitation regions in clouds can be located by ordinary weather radars. Their characteristics reflect the nature of the initial precipitation regions and can be used to gain insight into precipitation mechanisms. In addition, with a radar like the TPS-10, it is possible to obtain large and representative samples from both urban and rural areas.

TABLE 1. First echo data set: days, hours and number of first echoes.

Year	June	July	August
1972	3 (18) 222	6 (20) 495	10 (41) 585
1973		12 (47) 696	6 (21) 304
1974	1 (1) 4	11 (32) 466	9 (29) 647
1975	4 (10) 178	13 (45) 708	7 (19) 248

Totals: 4553 first echoes from 283 h of 82 days.

A radar first echo is defined as the initial radar signal, above some defined threshold level, from a region of cloud undergoing precipitation *initiation.* To be useful in studies of precipitation initiation an equivalent reflectivity of about 10 dBZ is appropriate. The FE also must be sufficiently removed from previously existing echoes to allow one to rule out a simple propagation of existing precipitation. In most FE studies, the radar is programmed to scan a certain volume of space and then return to the starting point and repeat. In this case the definition of an FE becomes the first detected return from a region of developing precipitation. For studies of precipitation initiation, the time required for the radar to scan the FE volume must not exceed a few seconds, preferably be less than 1 s, and the radar return time to the same volume must be less than 5 min, preferably less than 2 min.

In spite of its age and its use of film for data recording, the TPS-10 is still one of the best radars for observing large numbers of FE's occurring over large areas. Its time to scan an FE is less than 1 s, and the return time is 3 min, assuming one scans the entire 360° in azimuth between 10 and 60 mi range, as was done in our study. In our data an FE corresponds to an echo of 3 dBZ at 10 mi and 20 dBZ at 60 mi. No FE data were evaluated for ranges <10 mi because of the reduced ability of the radar to scan tall echoes at close range.

Since our objective was to study urban effects, it was necessary to sample uniformly over the entire radar field

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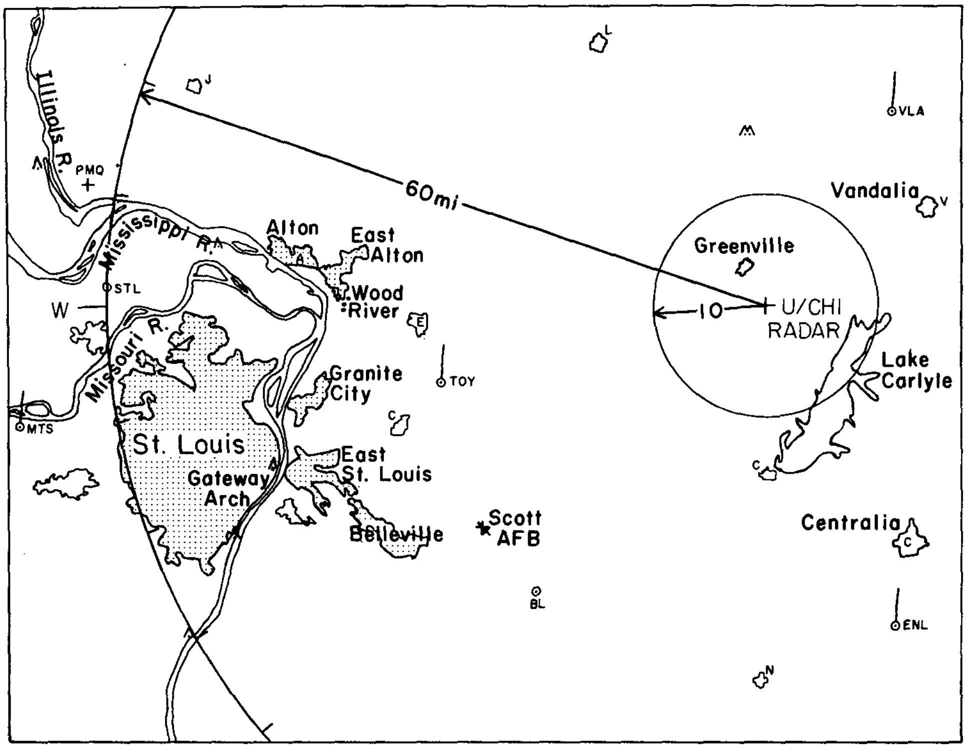

FIG. 1. Map showing the location of the University of Chicago radar relative to St. Louis, Mo., and other cities. Only a portion of the complete radar circle is shown.

of 10 996 mi² lest conclusions about relative frequencies or comparative characteristics of urban and rural echoes be biased by the times or areas selected for analysis. This requirement restricted our FE data reduction to days of scattered convective clouds, or to the early parts of periods of intense echo development.

Four data sets have been used in the analysis. These are as follows:

1) The total set of 4553 FE's from 82 days.

2) A set of 4175 FE's having the property of initial bases 3000 ft or more above ground level. This restriction helps to eliminate the possibility of misidentified second-sweep echoes and ground targets and weak echoes that may have been missed on the previous radar scan.

3) A set of 1950 FE's from 44 days having observed cloud and weather conditions such as to make it highly probable that FE's formed in new convective clouds having their roots near the earth's surface *and* that FE's were not influenced by particles falling from higher clouds. These days typically have no low or middle clouds at sunrise. By mid-morning they develop scattered clouds with bases 2000–5000 ft and the weather sequences report a progression from few cumuli, to towering cumuli, to scattered rainshowers. The presence of extensive middle or low cloud layers, or large convective storms, or of precipitation of *any* kind other than isolated convective showers, disqualifies a day from this sample since one cannot be sure that FE's have not developed from "seeding from aloft." We believe that this data set is most likely to show any influences from the city, either dynamical (say from the heat island or friction-induced convergence) or microphysical (due to urban aerosols and nuclei, or

TABLE 2. Average characteristics of first echoes.

Data set	Base Height (10^3 ft)	Base Temperature (°C)	Top Height (10^3 ft)	Top Temperature (°C)	Thickness (10^3 ft)
Complete sample $N=4553$	7.7	11.0	15.0	−2.1	7.3
Bases $\geqslant 3000$ ft $N=4175$	8.3	9.9	15.4	−2.7	7.1
44-day restricted $N=1950$	8.3	9.8	15.3	−2.8	7.0
Thickness $\leqslant 3000$ ft; valid second observations; $N=486$	9.9	6.4	12.3	−2.0	2.5

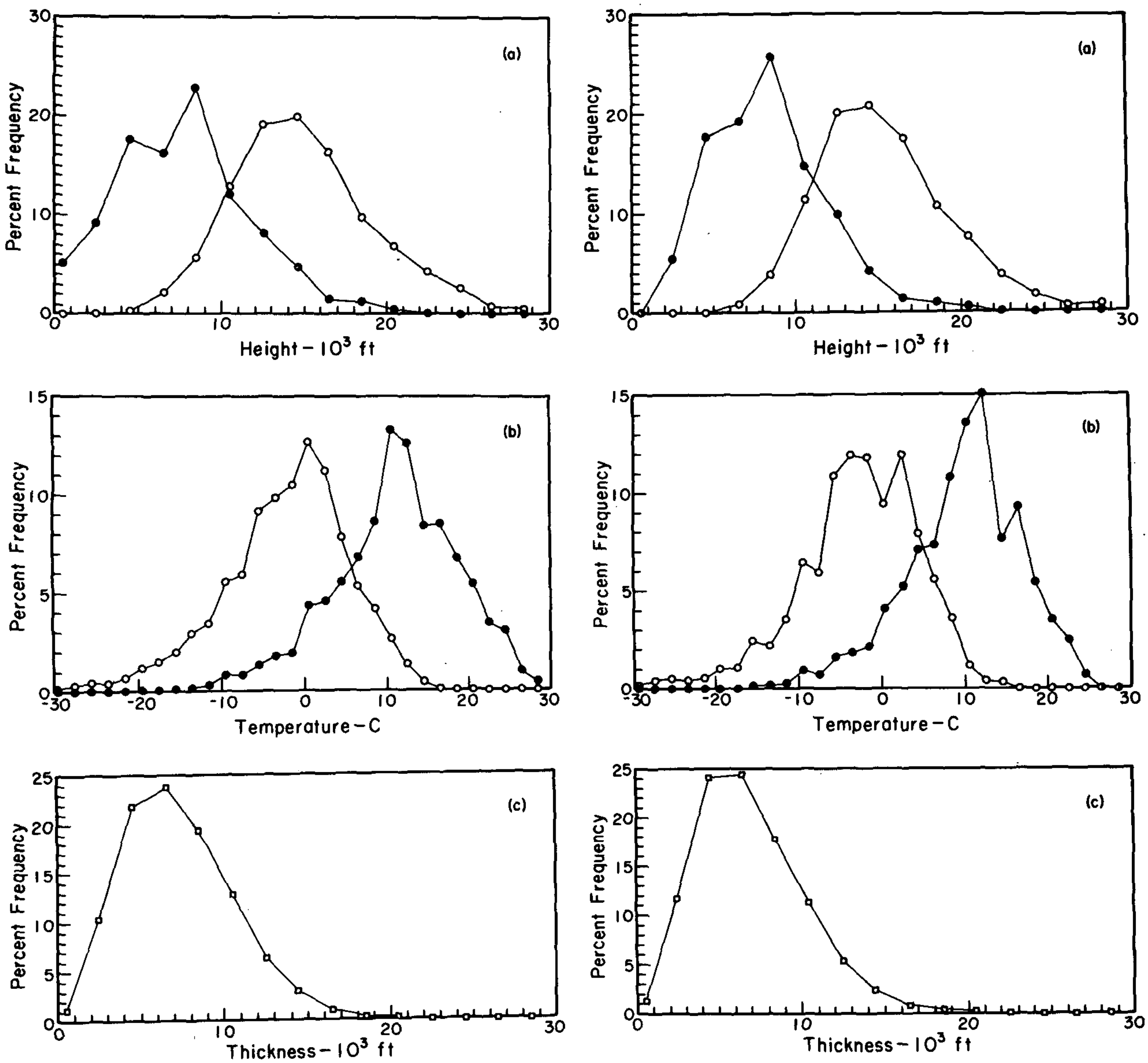

FIG. 2. Characteristics of first echoes: (a, left) height distribution of tops (open circles) and bases (solid circles) in total sample of 4553; (a, right) height distribution of tops in 44-day restricted set ($N = 1950$); (b, left) temperature distribution for tops and bases in total sample; (b, right) temperature distribution of tops and bases in a 44-day restricted date set; (c, left) thickness distribution in total data set, (c, right) thickness distribution in 44-day restricted data set.

urban-related moisture releases). This data set also was restricted to FE's with bases ⩾3000 ft.

4) A set of 486 FE's having initial thicknesses ⩽3000 ft and on which we have valid observations from the radar scan 3 min after first detection. Presumably these echoes were detected very early in their development and contain the greatest amount of information as to conditions associated with precipitation initiation.

2. Average characteristics

Average characteristics of the four data sets are given in Table 2. Frequency distributions of FE top and base heights and temperatures and thicknesses for the total data set and the 44-day restricted data set are given in Fig. 2. Several general conclusions can be drawn from this table and figure. The first three sets show FE tops to be about 15 000 ft AGL with temperatures of about −2°C. The average base was about 8000 ft with a temperature of +10°C. The average thickness was about 7000 ft. The fourth set, with different characteristics, is discussed later.

In the total data set we found that 40% of the FE's (1825) had tops warmer than 0°C, 53% (2402) had tops colder and bases warmer than 0°C and the remaining 7% (326) were entirely colder than 0°C. Corresponding values for the 44-day restricted data set are 39% (767), 53% (1021) and 8% (162). These data suggest drop collection, over ice nucleation, as the dominant mechanism of precipitation *initiation* in summer cumulus clouds in central Illinois.

We find considerable between-day and within-day variability in FE characteristics. The former apparently reflects day-to-day variations in regional meteorological conditions—a subject we hope to study further. Within-day variations appear to be related to cloud-to-cloud differences as well as to the range-related detection threshold and the 3 min azimuthal scan time of the radar. Our FE's may have grown anywhere between 0 and 3 min, after reaching detection threshold, before being illuminated and detected by the radar. It is well established, both theoretically and observationally (e.g., Battan, 1953; Saunders, 1965; Dytch and Johnson, 1977), that the process of drop collection and drop sedimentation in convective clouds brings about a very rapid increase in reflectivity and expansion of the volume within any given reflectivity level, once conditions are favorable for collection. It is this property of convective echoes that makes it possible to study FE location with the TPS-10. But it raises questions about the interpretation of FE top and base heights because of the 0–3 min variable growth intervals before detection. To reduce the effect of this radar variable we have examined separately those FE's with initial thicknesses ⩽3000 ft. Presumably these were detected very early in their development and contain the most useful data on FE top and base characteristics.

Top Growth First Three Minutes – 10^3 ft

Top Temperature – C	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9+	
-20 to -18	1																1
-18 to -16							1		1								2
-16 to -14					1	1	4	3			3						12
-14 to -12							1	2	2	1					1		7
-12 to -10					1			1							1	1	4
-10 to -8			1	2	2	1	4	5	2	2		2	1	1		2	25
-8 to -6			1		1	1		2	3	1	1	1			1		12
-6 to -4				2	2	2	5	1	3	3	3		2				23
-4 to -2	1				5	2	3	4	2	1	3		1		2		24
-2 to 0					2	4	13	4	6	4	3	2	2	1		1	42
0 to 2			2	1	2	7	10	12	9	9	2	4	1	3		1	63
2 to 4		1	1	3	5	2	13	8	5	4	7	8	4	2	3	2	68
4 to 6		1		2	2	6	6	7	10	6	4	6	6	1	1	2	60
6 to 8		1			6	1	6	3	8	4	4	6	1	1	1	3	45
8 to 10					1	2	5	10	4	5	6	4				1	38
10 to 12					1	2	3	10	6	5	6	2					35
12 to 14								5	2	3	2	1		1	1		15
14 to 16						1		1	2			1	1	1	1		8
16 to 18													1			1	2
	2	3	5	10	31	32	74	78	65	48	44	37	20	11	12	14	486

FIG. 3. Distribution of first echo top temperatures and amount of top growth during the first 3 min.

Average characteristics of these FE's are given in Table 2. Fig. 3 presents these data as a matrix of FE top temperatures and amount of top growth in the first 3 min after detection.

The marginal totals show a secondary maximum near −8°C which could be associated with ice phase initiation. The marked increase in frequencies between about −2 and +2°C suggests that some of the FE's might have involved melting of snow pellets. However, the broad major maximum in FE top temperatures between about 0 and +6°C, plus the fact that 69% of these FE's had top temperatures warmer than 0°C, reinforces our view that the drop collection process strongly dominated precipitation initiation in these data.

The dashed line in Fig. 3 is the linear regression of top temperature on top growth, indicating a weak association between these variables. The linear correlation coefficient is 0.18, a statistically significant value in view of the large sample size of 486, but one indicating that very little of the population variance is explained by this association. It may, however, provide a clue for future studies.

3. First echo locations

The actual locations at which the 4553 FE's were observed are plotted in Fig. 4. Fig. 5a is an analysis of these data based upon averages from overlapping rectangular grid cells of 100 mi² each. Map units are numbers of FE's per 100 mi² observed during 283 h of observations (hours having FE's somewhere in the radar area).

This map clearly shows a major anomaly in FE frequencies immediately over and just to the east of St. Louis. This anomaly is attributed, at least in large measure, to the presence of the city. Fig. 3 also shows a tendency for higher values to occur in a zone around the radar roughly at 20–30 mi range. This tendency suggests a range bias in our ability to detect FE's. Such an effect is not surprising. Both beam-filling considerations and the range-dependent minimum detectable signal act to decrease the probability of FE detection at the longer ranges. (However, as mentioned earlier, the second of these factors is thought to be of minor importance because of the rapid growth in reflectivity once drop collection becomes established.) In opposition to these effects, and tending to increase FE detection with increasing range, is a factor associated with the antenna vertical scan rate. In the RHI mode the antenna nods up and down every second while turning in the horizontal 2°, i.e., one horizontal beamwidth. The antenna comes to a complete stop at −2° and +26° and travels at the maximum rate at the middle elevation, 12°. Because the vast majority of FE's in this study occurred at elevation angles <12°, the number of radar pulses contributing to radar return from FE targets increases with range. Thus this effect

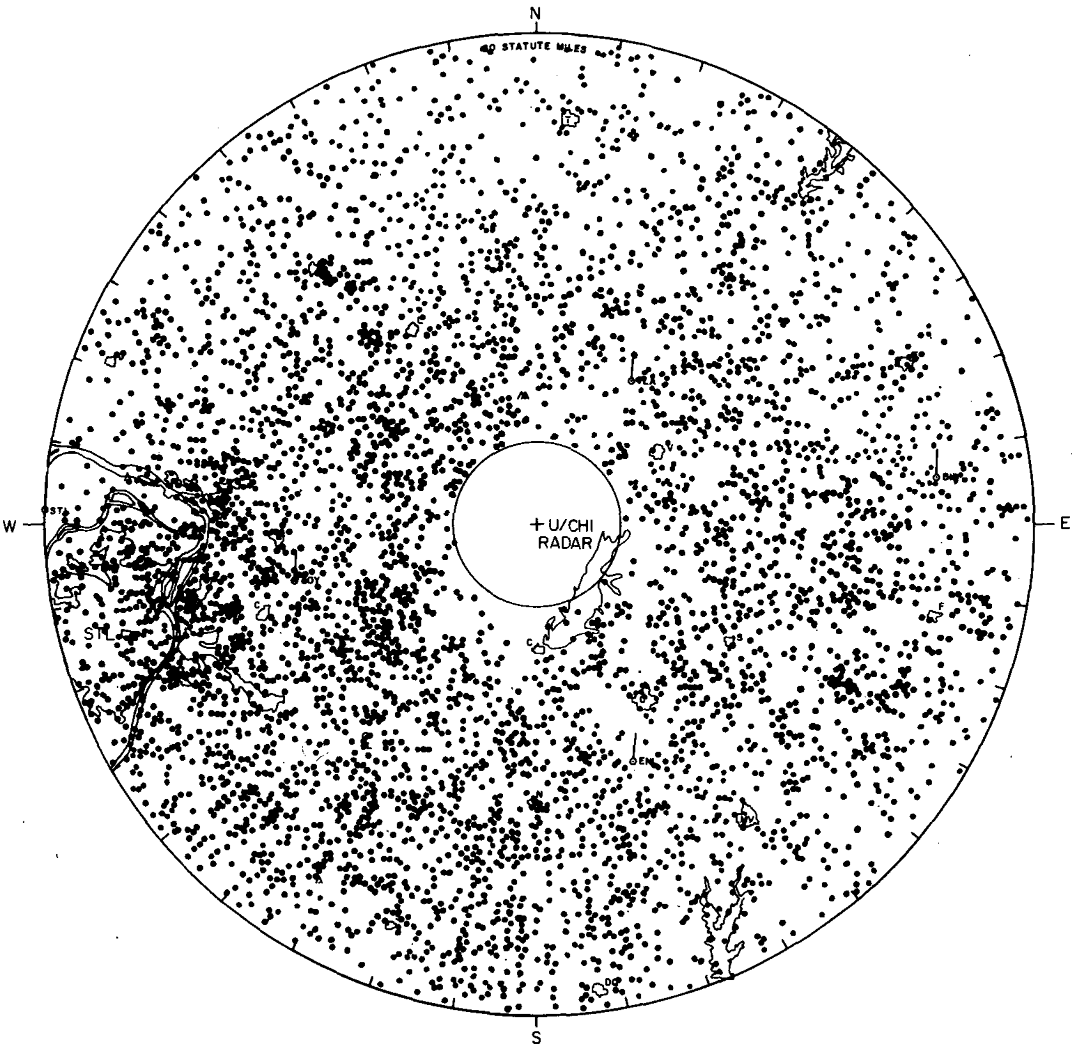

FIG. 4. Locations of 4553 first echoes.

tends to oppose effects of beam-filling and the range-dependent minimum detectable signal to give a region of maximum FE detectability around 20–30 mi range. One can note in Fig. 5a that beyond 40 mi the number of detected FE's drop to about half that in the 20–30 mi range.

It is important to realize that the "St. Louis" maximum occurs mainly between 30 and 60 mi where the radar has reduced ability to detect FE's.

Figs. 5b and 5c show isolined location frequencies for the 4175 FE's with bases $\geqslant$3000 ft, and the 1950 FE's from the 44-day restricted day set. Recall that the latter was restricted to days having meteorological conditions most favorable to showing subcloud influences, such as those from the city. We note an area of maximum FE frequencies directly over St. Louis and extending north-south along the Mississippi. The point maximum of 56 units is 50% higher than the next largest point maximum and 295% of map average. Fig. 5c is considered to be a clear indication of the effect of St. Louis in increasing the frequency of FE's.

4. First echo locations in partitioned data

Recognizing that effects of St. Louis on FE's could extend beyond the borders of the city and that the wide range of wind directions represented in the total data set could tend to "smear" the location mappings, it was desirable to partition the data upon wind direction. There was, however, some question as to which wind would be most appropriate for this purpose. The primary city factors, such as thermal and pollutant plumes, are generated near the surface and advect with winds of the boundary layer. On the other hand, urban effects on cumulus clouds could represent a response to some secondary city factor such as a dynamical one related to winds and stability over the entire subcloud layer. Once formed, these clouds would be expected to move with a mixture of winds throughout their vertical depth.

A study by Haagenson and Morris (1974) showed that the pollutant plume 80–120 km downwind of St. Louis, during daytime conditions, was effectively forecast using gradient level winds. Low-level wind measurements, other than for the surface, are available only for a limited number of dates and times within the extent of our study. Therefore, we decided to use a mean echo movement vector (EMV) obtained for each data period by tracking three or more widely separated small echoes. These have been used to partition the FE data. Cases with EMV$\leqslant$3 m s^{-1} regardless of direction were put into a single "light wind" category. Cases with stronger winds and 202°$\leqslant$EMV$\leqslant$360° were divided into four groups. Data for the other directions were too few and too scattered to permit useful partitioning.

Figs. 5d–6d give FE location mappings for the five EMV partitions. Three of the five maps, i.e., the "light wind" days, and days with south–southwest and west–northwest echo movements, show a region of markedly above average FE frequencies directly over St. Louis. All maps, other than for "light wind" days, show above-average frequencies downwind of the St. Louis Metropolitan area. These obviously suggest some sort of urban influence on precipitation initiation.

Analysis of partitions based upon 25 weekend and holiday days and 57 weekday days are given in Figs. 6e and 6f. The weekday map clearly contains most of the pattern information of FE locations found in the complete data set. The weekend day and holiday map is quite flat with six local maxima mostly around the same range circle previously noted for the range bias effect. Although comparison between Figs. 6e and 6f is made difficult by the differing sample sizes, it appears that most of the influence of the city on FE initiation comes mainly from weekdays.

5. Urban-rural comparisons of first echoes

Urban-rural differences in FE frequencies and characteristics have been quantized by applying the following analysis device. We accept a simplified outline for the city consisting of a compact polygon encompassing St. Louis and nearby surburban areas in Missouri, in addition to Alton, East St. Louis, Granite City and nearby Illinois suburbs as shown in Fig. 7. This area coincides roughly with the St. Louis Metropolitan area. It includes substantially all of the major sources of

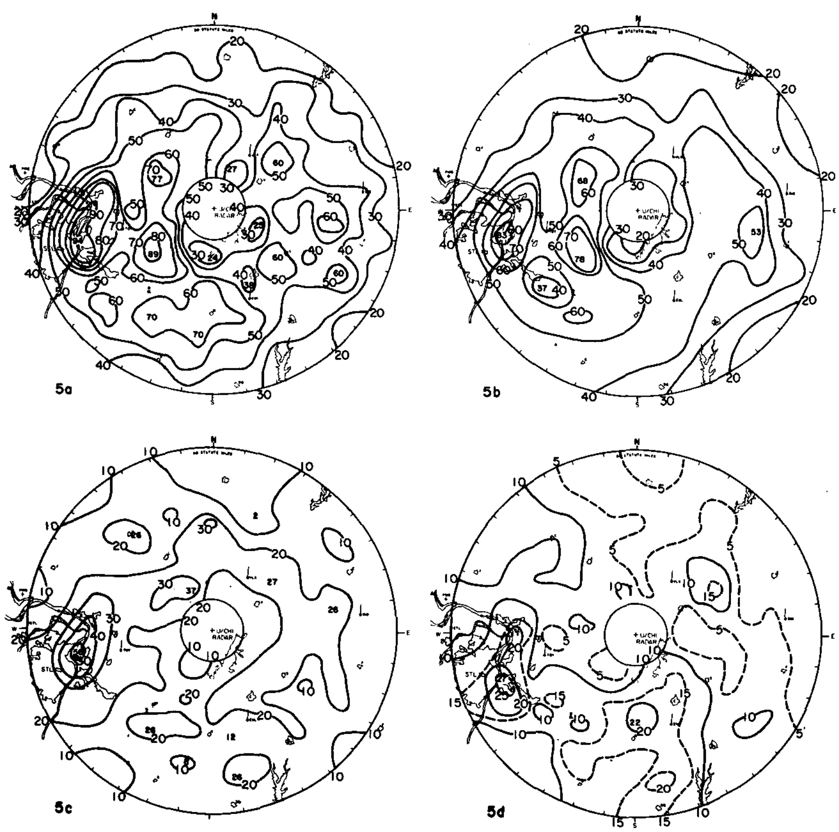

FIG. 5. Maps of first echo densities (for units see text): (a) analysis of data in Fig. 4; (b) set of 4175 first echoes having bases $\geqslant$3000 ft; (c) set of 1950 first echoes from 44 days selected to insure ground-based convective clouds; (d) data for days with light winds.

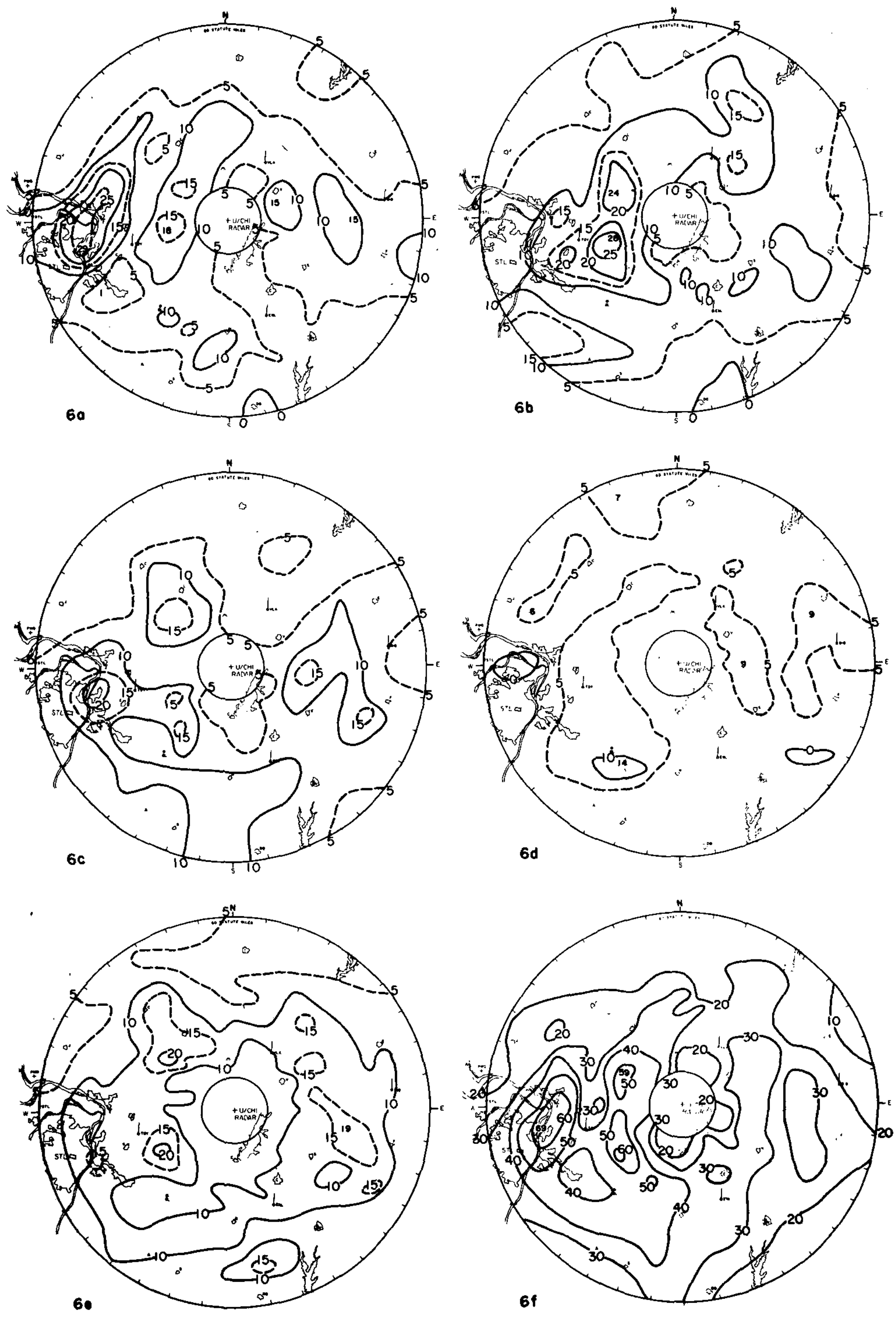

Fig. 6. Maps of first echo densities in wind direction partitions: (a) EMV from 202° to 249°; (b) EMV from 250° to 269°; (c) EMV from 270° to 304°; (d) EMV from 312° to 350°; (e) weekend days and holidays; (f) weekday days.

atmospheric pollution, as determined by the Environmental Protection Agency emissions inventory. It rejects as much as possible of the nearby rural areas while keeping a simple compact shape. The EMV for each day was applied to this City boundary, thereby defining areas corresponding to 1, 2 and 3 h of small echo advection downwind of the city, but within the 10–60 mi radar range annulus. The remainder of the radar field, outside the combined city and three advection areas, we call Rural. First echoes in the first four areas are compared with those in the rural area as a measure of urban effect. An example of the three 1 h areas on a day with an EMV of 211°, 5.3 m s^{-1} is given in Fig. 7. The city area remained the same on all days (588 mi^2) but the three 1 h advection areas may be different on any one day and, along with the Rural area, differ from day to day depending on the EMV. Average sizes of these areas for the 82 days used in FE analysis are 1 h area, 615 mi^2 (1593 km^2); 2 h area, 540 mi^2 (1399 km^2); 3 h area, 487 mi^2 (1261 km^2); rural area 8766 mi^2 (22 703 km^2).

Definition of these areas, and measurement of their sizes on each day, provides the information needed to normalize first echo frequencies to Rural values. Relative frequencies are computed in the following manner:

$$\text{relative frequency} = \frac{[\text{number/area}]_{\text{City, 1, 2, 3, h}}}{[\text{number/area}]_{\text{Rural}}}.$$

First echo frequencies, normalized on area and expressed relative to Rural values, for the City and three 1 h advection areas, for the total data set and the 44-day restricted set, are given in Tables 3 and 4. Values are given for the individual years and for all years as a single sample. We find a strong tendency for FE frequencies over the City and in the 1 h advection area to be about twice that of the Rural region. This indication is seen in the individual year's result as well as in the overall average. Frequencies in the 2 and 3 h areas are only slightly above rural values and show about as many individual yearly values above as below Rural values.

Table 3. Comparison of first echo frequencies in the urban area relative to rural values for 4533 echoes.

Year	City	Advective areas 1 h	2 h	3 h
1972	3.26	2.10	1.20	1.40
1973	1.55	1.29	1.45	1.02
1974	1.42	1.55	0.62	0.95
1975	1.48	2.23	1.07	0.91
Overall average	1.94	1.84	1.11	1.11

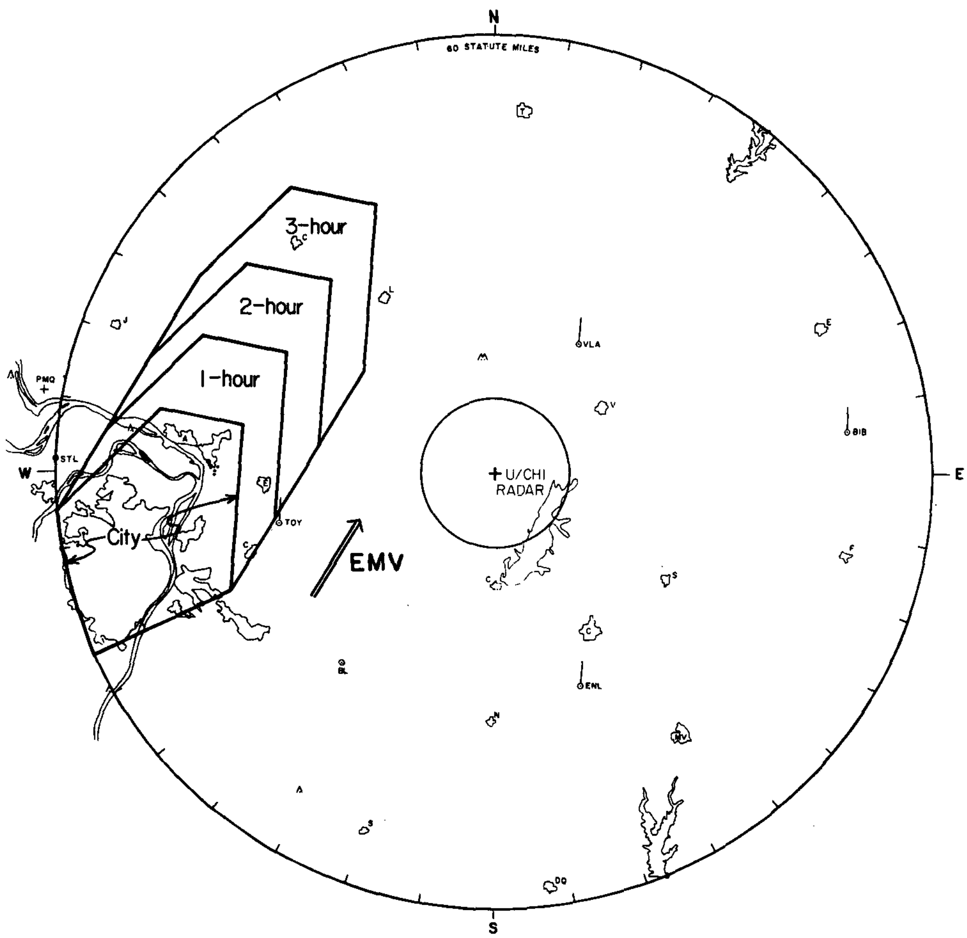

Fig. 7. Example of scheme used to designate City, Rural and three 1 h advection areas downwind of the City.

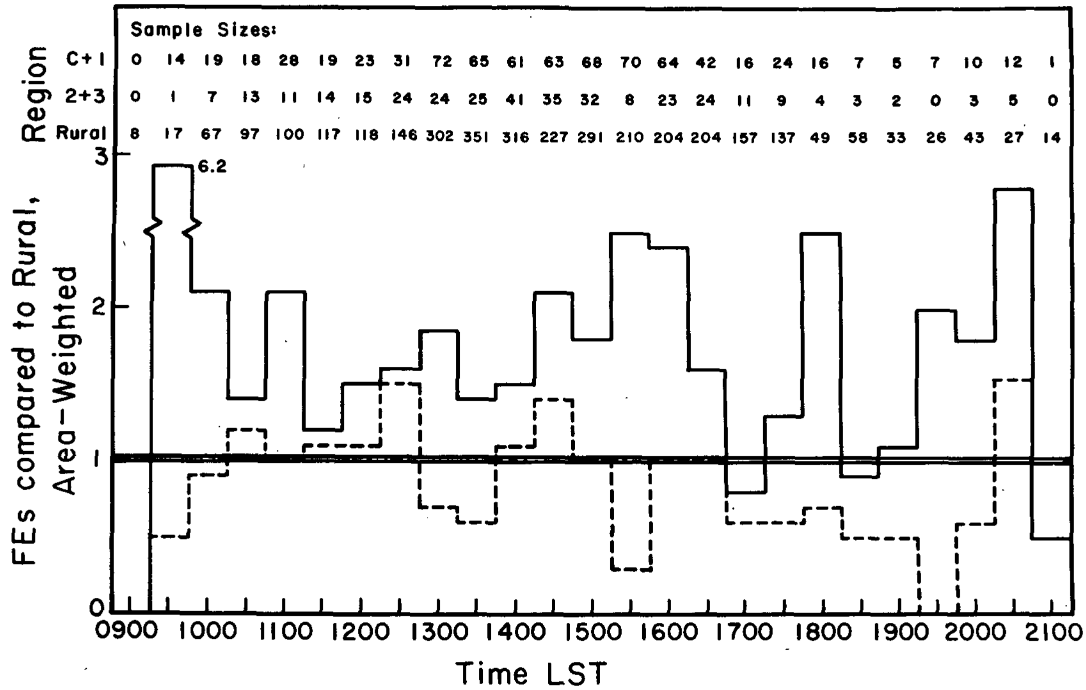

FIG. 8. Area-normalized frequency of first echoes, City plus 1 h area (solid line), and 2 h plus 3 h (dashed line) relative to Rural values, as a function of time of day.

We have attempted to assess the likelihood that the suggested urban effects shown in Table 4 might have resulted from sampling biases. This question is complicated by two factors. Our data show that FE's are seldom randomly distributed; they tend to occur in "clusters" of "lines," probably in association with some mesoscale feature in the boundary layer. In addition, the four analysis areas (City, 1, 2 and 3 h) are much smaller than the Rural area, typically about 5% as large. The result is a large number of "zero" cases for the City and downwind areas. Under the assumption that, on average, the density of FE's within any given day is related only to the size of an area we applied the signed-rank test to the differences in FE density between the City and downwind areas and the Rural area. The results are given in Table 4 in the form of unit normal deviates. We note that for the City and 1 h areas we reject the null hypothesis of equal ranks at better than the 5% level. However, we also note that most of the statistical strength came from 1972. This first year of the data has the largest sample size and the fewest days with zero counts in the city. It also had the fewest "light wind" days on which the downwind areas are taken as zero area. Data from the "light wind" days only, for all four years, gives a City effect of 1.87 times Rural with unit normal deviate of 1.96 (signed-rank test).

TABLE 4. Comparison of first echo frequencies in the urban area relative to rural values from 44 days with good ground-based convection for 1950 echoes. Results of signed rank tests (unit normal deviates) are given in parentheses.

		Advective areas		
Year	City	1 h	2 h	3 h
1972	3.85	1.96	1.22	1.76
	(2.62)	(2.34)	(0.71)	(0.51)
1973	1.75	2.46	0.90	0.45
	(0.36)	(1.47)	(−0.84)	(−0.42)
1974	1.61	1.20	0.13	0.15
	(0.59)	(−0.27)	(−1.87)	(−1.87)
1975	1.61	2.46	1.10	0.91
	(0.28)	(−0.13)	(−0.58)	(−1.11)
Overall average	2.28	2.14	1.00	1.07
	(2.96)	(2.12)	(−0.91)	(−0.74)

Fig. 8 shows the urban effect as a function of time of day. Area weighted values for the City plus 1 h area are above rural from 0930 LST (essentially the beginning of the data) until 1700. Between 1700 and 1930, two periods of below Rural values are found; these may simply reflect sampling variations. From 1930, until the end of the day at 2100, values are well above Rural. The enhanced urban effect during the mid-morning probably reflects the fact that the urban boundary layer over cities destabilizes and deepens faster than does the nearby rural boundary layer (Russell *et al.*, 1974). Throughout the middle of the day, when we have the largest sample sizes, the indicated urban effect over the city and 1 h of small echo travel downwind from the city varies from about 1.5–2.5 times that of the rural area.

The average top and base characteristics of FE's forming over the City, Rural and the three 1 h advection areas are given in Table 5 along with unit normal deviates obtained in a Student's t test for independent samples, comparing various values from the City and downwind areas with corresponding Rural values. We note that City FE's have lower bases than Rural with intermediate values in the downwind areas. These differences have strong statistical support. Corresponding values for FE tops are less clear cut, though there is a suggestion that tops of urban-affected FE's may be slightly lower than tops of Rural FE's. The evidence is strong that City FE's have greater thicknesses than Rural FE's.

6. Conclusions and discussion

Through a comparison of 3 cm, "10 dBZ" first echo frequencies over and downwind of St. Louis, Mo., with those of a large area of nearby rural Illinois, it has been shown that there is an increase, by a factor of about 2, in the number of FE's over the city and in the area representing 1 h of wind travel downwind from it. The evidence suggests that this is a real effect and not due to sampling variability, but inconsistent yearly effects suggest caution in applying this conclusion.

The region of enhanced first echoes is roughly an elongated oval with its major axis approximately along the Mississippi River and maximum point frequencies between Gateway Arch in downtown St. Louis and the mouth of the Missouri River. Partitioning of days on direction of movement of small echoes shows a distinct tendency for the downwind maximum to shift correspondingly. A partitioning of weekday echoes versus holiday and weekend day echoes suggests that the urban effect occurs mainly on weekdays. Earlier studies have shown urban rainfall and visibility anomalies to show weekend-weekday modulation (Summers, 1966; Dettwiller, 1968, 1970; Landsberg, 1974).

Urban first echoes have lower bases and greater thicknesses than corresponding echoes in nearby rural areas. The most probable explanation for the observed urban effects on base heights and thicknesses is accelerated drop collection coupled with drop sedimentation. Johnson (1976) measured the presence over the city of wettable, but largely insoluble, particulates up to 55 μm diameter and in concentrations up to twice rural values. By combining these large particle data with previously measured CCN spectra upwind and downwind of St. Louis (Spyers-Duran, 1974) in a numerical model of particle activation, condensation, and sedimentation, Dytch and Johnson (1977) were able to compute first echo characteristics very similar to those observed here. The enhanced frequency of FE's over the City and over the near-downwind areas is not obviously related to the presence of the large particulates; more probably it is related to changes in the urban boundary layer brought about by surface thermal and frictional forcing.

In keeping with earlier studies for the Midwest, we find summer convective first echoes to be dominated by the drop collection process although the data admit a minor role for initiation through the ice phase.

TABLE 5. Summary of first echo characteristics in the areas indicated. Results of Student's t test (unit normal deviates) are given in parentheses.

Region	Sample number	Daily average: Base height (10^3 ft)	Base temperature (°C)	Top height (10^3 ft)	Top temperature (°C)	Thickness (10^3 ft)
City	432	7.1	12.6	14.9	−1.9	7.9
		(3.58)	(− 4.67)	(0.46)	(−1.04)	(−3.31)
1 h	358	7.4	11.4	14.4	−1.5	6.9
		(1.71)	(− 1.34)	(2.76)	(−1.69)	(2.25)
2 h	192	7.7)	11.4	14.8	−1.5	7.0
		(0.40)	(− 1.25)	(1.05)	(−1.53)	(1.17)
3 h	158	7.3	11.9	15.0	−1.9	7.0
		(2.68)	(− 2.05)	(0.29)	(−0.64)	(1.19)
Rural	3413	7.8	10.8	15.1	−2.3	7.3
Single sample	4553	7.7	11.1	15.0	−2.2	7.3

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