Effects of Urban Areas and Echo Merging on Radar Echo Behavior

STANLEY A. CHANGNON, JR.

Illinois State Water Survey, Urbana, 61801

(Manuscript received 2 September 1975)

ABSTRACT

The temporal histories of 702 convective echoes measured in the St. Louis area during the 1973 summer were studied to discern potential effects on echo behavior of the urban influences and those effects resulting from the merger of two or more echoes. The 190 echoes that merged grew faster (50%), became taller (52%), and lasted longer (122%) than non-merger echoes. The average echo top growth 10 min after a merger was 1500 m, and on any given day 80% of the heights of merger echoes at a given stage of echo life were higher than those of non-merger echoes. The 137 echoes that crossed the urban area were longer lasting (119%), faster growing (61%), taller (30%), and more merged (44% vs 23%) than the non-urban echoes. The 61 urban echoes that subsequently merged over or beyond St. Louis were demonstrably longer lasting (110 vs 44 min) and taller (4800 m at 10 min after entry into the urban area and 5900 m at urban exit) than 76 urban echoes that did not merge. The urban echo that merged was also measurably different than the rural merged echo. The average urban merged echo lasted 51% longer, grew 100% faster, and achieved a height 20 min after merger that was 133% higher. The urban area apparently affected nearly half (44%) of the echoes over it leading to larger, more vigorous, and longer lasting storms that always merged with one or more other storms. This dynamic process leads to more rain, short-duration rainstorms and hailstorms in and east of St. Louis.

1. Introduction

As part of METROMEX, a major program attempting to determine whether and how an urban area affects summer precipitation (Changnon *et al.*, 1971), a variety of radar echo studies have been pursued (Braham, 1974; Dungey *et al.*, 1974; Braham *et al.*, 1975; Huff and Schlessman, 1974a; Changnon, 1974). These have attempted both to document the precipitation anomaly and to help explain the processes producing observed changes.

Each of the previous radar studies have focused on the areal frequency of first echoes (a first echo is one which was not visible on the previous radar scan), but these studies have also investigated other echo aspects including the areal distribution of mergers of echoes, the tall echoes (single tallest echo found in each 30 min scan), and echo core characteristics. Dungey *et al.* (1974), using 1972–73 summer data for The University of Chicago 3 cm RHI radar, showed 1) a higher first echo frequency over and downwind of St. Louis than elsewhere within a 30 000 km² area in and east of St. Louis, and 2) more tall convective echoes occurred over and NE of St. Louis than elsewhere. They concluded there is "weak but compelling evidence for an urban effect at St. Louis tending to localize occurrences of precipitation formation and enhancing the height of convective clouds."

Braham *et al.* (1975) using 1972–73 data from the Illinois State Water Survey's 10 cm radar that only scanned near the ground (0° elevation) also found more first echo initiations over St. Louis, the isolated Wood River industrial area, and the Ozark Plateau SW of St. Louis. Huff and Schlessman (1974a) found that the most frequent location of echo (10 cm) mergers, which are frequently associated with the intensification of surface rainfall, was just E and NE of the St. Louis and Wood River areas. They also showed that echo cores exposed to urban effects had longer durations, longer paths and greater echo intensity than did unaffected (rural) echoes. All of these radar studies. largely through spatial analyses of a single event in an echo lifetime, have strongly suggested urban effects on convective precipitation initiation and its intensity, as reflected in maximum tops and merger frequency.

The goal of the echo study described in this paper was to investigate the effects of the urban area and echo mergers on the temporal behavior of individual echoes throughout their lifetimes. This was accomplished by studying and comparing the top histories of echoes sorted by urban vs non-urban classes and by merger vs non-merger classes. Echo top behavior was chosen for study for two reasons. First, echo tops reflect the convective strength and behavior of summer showers and thunderstorms. Second, since above surface radar data were available only with 3 cm radars, potential analyses of echo volumes and reflectivities would be undesirably biased by attenuation problems. Such is not the case with echo tops which are largely unaffected by signal attenuation. Furthermore, echo tops are indicative of the extent of precipitation development and of echo volume (Changnon, 1972).

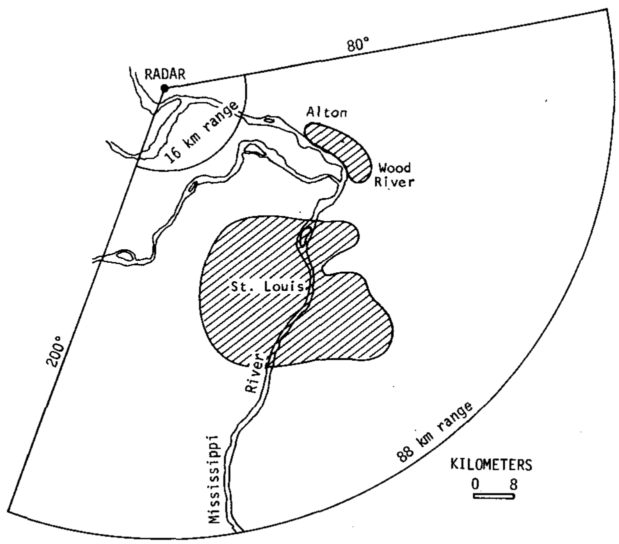

FIG. 1. Echo study area.

2. Data and analyses

The Illinois State Water Survey operated in 1973 a TPS-10 (3 cm wavelength) radar that has an RHI capability so that it displays two-dimensional (height-distance) aspects of echoes. Photographs were taken each second of the RHI display for a 2° beamwidth. Three-dimensional echo descriptions were developed from these data. Data collected in June–August 1973 were used. Most of the echoes occurred in a 120° sector centered on St. Louis (located 53 km SE of the radar) and in a range span (ring) of 16–88 km from the radar (Fig. 1). Since this radar is subject to attenuation problems, the only echoes included in this study were those considered to have little or no effects from intervening echoes. About half the detected echoes were deleted from the study because the lifetime of their tops could not be followed.

Data were from 19 discrete rain periods, most of which represented all the echoes on a given day. The average duration of these periods in the echo study area (Fig. 1) was 6.3 h, ranging from a low of 0.5 to a high of 11.8 h. The sampling period in 1973 was one of near-average summer rainfall throughout much of the echo study area, being greatest east of St. Louis and least west. This conforms to the last 20-year average pattern considered indicative of urban enhancement of local rainfall (Huff and Changnon, 1972).

A summary of the data sorted by echo-producing synoptic conditions appears in Table 1. This shows that tops of 702 echoes whose entire lifetime could be followed were studied. As shown, 27% merged and 20% were classed as urban echoes. Five synoptic weather types were sampled with sizeable numbers of echoes found in each type. The number that merged represented 21–26% of the total in most synoptic types, the largest (34%) consisting of cold front echoes. The frequency of potential urban echoes was more variable, being 13–16% of the totals of three types but with a much larger percentage for air mass (26%) and squall line with cold front (34%) totals. This agrees well with Vogel's (1974) synotpic analysis of 1972–73 METROMEX rain data showing that much of the enhancement occurred in squall line-cold front conditions.

Most of the radar operations were in the 0800–2400 CDT period which might bias the results. However, Huff and Schlessman (1974b) showed that 82% of the total 1973 rain fell in the radar sampling period. Although the echo sample was from one summer, these various comparisons with historical data and other METROMEX results indicate that the sampled echo conditions were typical and the results should be representative of long-period conditions.

There were no reduced-gain data available from the radar, and all echo definition was based on the minimum detectable reflectivity which was 27 dBZ. An echo was the entity defined by a first echo and was considered an "echo" until it dissipated even though it may have alter embraced one or more nearby echoes that grew up alongside it with less than 4 km separating them. The range resolution of the radar data was 0.8 km. If two echoes that had existed at least 10 min and had been more than 8 km apart moved together such that they meshed to form one or more cells for at least 5 min, the time of union was considered a "merger." The following behavior of the top of the merged echo was recorded for both of the original separate echoes.

TABLE 1. Summary of 1973 echo sample.

Synoptic weather type producing discrete periods of echoes in St. Louis area			Echo frequencies			
			Merged		Urban	
Type	Number of periods	Total number	Number	Percent of total	Number	Percent of total
Squall line	3	162	34	21	26	16
Squall zone	2	92	24	26	12	13
Squall line and cold front	4	148	36	24	46	31
Cold front	2	226	78	34	34	15
Air mass	8	74	18	24	19	26
Totals	19	702	190	27	137	20

Table 2. Diurnal distribution of echo initiations, sorted by 3 h periods and expressed as percent of total echoes in each class.*

Three-hour period ending (CDT)	Total sample	Echoes with vertical growth	Echoes of ⩾ 30 min	Merged echoes	Urban echoes
0300	1	0	0	0	1
0600	0	0	0	0	0
0900	2	2	3	2	2
1200	7	2	3	0	9
1500	23	22	28	25	26
1800	*39*	*43*	*38*	28	*38*
2100	26	29	27	*34*	22
2400	2	2	1	1	2

* Maximum values are italicized.

Data recorded for each echo included the time, height, and its locale as noted every 1–3 min during its lifetime. From these records, summaries were derived for each echo, including its 1) initiation time, 2) duration, 3) top heights at initiation and dissipation, 4) *maximum* growth in any 5 min period, 5) maximum height and the stage of echo duration when it occurred, and 6) average heights determined for the four stages of echo duration. Each stage was simply one-fourth (1st, 2nd, 3rd and 4th) of the duration, e.g., if an echo had a 32 min duration, the average echo top height for the first stage was determined from the height values measured during the first 8 min of its life. Use of stages was deemed necessary to allow meaningful comparisons between echoes of differing durations. In a conceptual sense, stage 1 was the growth stage of the storm, stages 2 and 3 were the mature stages, and stage 4 was the decay stage (Byers and Braham, 1949). No echo top motion (speed or direction) values were compiled because several turrets of a cell often became the top at different times which produced very erratic and meaningless patterns of motion.

Two other sets of values, if they had occurred, were recorded for each echo. If the echo merged with another echo, this was noted along with the identification of the merged echo, each echo's stage at that time, and the amount of change in echo top height 10 and 20 min after the merger. If an echo crossed above either the St. Louis and/or Alton-Wood River urban areas (Fig. 1), the information recorded included 1) the stage(s) of echo duration when it was over the urban area, 2) its duration over the urban area, 3) echo top height 5–10 min prior to reaching the urban boundary, 4) the echo height 10 and 20 min after entering the urban area, 5) the maximum height anytime over the city, 6) echo height at departure from the urban area, and 7) whether it initiated or dissipated over the city. An echo was classified as "urban" by its presence within a volume formed by the vertical extension of the metropolitan boundaries (see Fig. 1).

Echo data were initially analyzed by grouping the echoes according to five classes. First, the data from all 702 echoes were analyzed to review the entire data

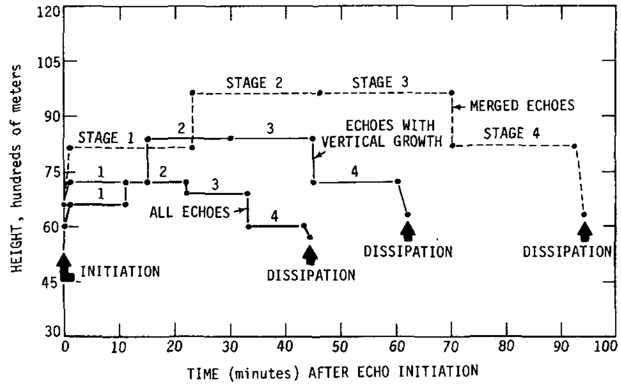

Fig. 2. Time-height profiles for selected echo classes, based on average values.

sample. Then to examine the characteristics of the more vigorous storms, all characteristics of two other echo classes were analyzed: those for all 414 echoes with vertical growth ⩾300 m (40% did not grow after inception), and those for all 33 echoes that lasted 30 min or longer (53% did not persist this long). However, most of the results of the analyses of these classes will not be presented, other than to support and contrast with the merged echo and urban echo data. A major analysis consisted of comparisons of characteristics of merged and non-merged echoes, and the other major analysis consisted of comparisons of characteristics of urban echoes and non-urban echoes. These two analyses were based partially on differences in echo top characteristics calculated for each day (since between-day differences were generally larger than in-day differences). The daily differences (merger vs non-merger, and urban vs non-urban) were then combined to get total sample averages and extremes for comparisons of of each subset.

3. Characteristics of merged echoes

All of the 190 merged echoes grew vertically, and 93% of the echoes that merged had durations ⩾30 min. Mergers occurred largely in the first *echo* stage (87 *of* the 190), while 57 merged in the second stage, 40 in the third, and only 6 mergers in stage 4. Their preferred 3 h period of occurrence was 1800–2100 (72 mergers or 38%), later than the distribution for all other echo classes (Table 2). All other classes peaked in the 1500–1800 period.

Table 3. Echo duration (min) for five classes of echoes.

	Average	Maximum	Minimum
All echoes	43	246	5
Echoes with vertical growth	62	246	7
Echoes ⩾ 30 min	76	246	30*
Merged echoes	94	246	28
Urban echoes	78	246	12

* By definition.

TABLE 4. Distribution of maximum echo top values by echo stages and for echo classes, expressed as percent of total for each class.*

	Percent per height interval (100 m)										
	15–30	30–45	45–60	60–75	75–90	90–105	105–120	120–135	135–150	150–165	165–180
Stage 1											
All echoes	8	11	*30*	22	14	8	5	2	0	0	0
Vertical growth	4	6	23	*24*	21	10	9	3	0	0	0
⩾30 min	2	3	24	*25*	23	11	10	2	0	0	0
Merger	0	2	18	24	*26*	13	12	5	0	0	0
Urban	3	9	*26*	18	13	13	*15*	3	0	0	0
Stage 2											
All echoes	7	11	*29*	16	13	9	8	5	1	1	0
Vertical growth	2	5	18	16	*19*	14	14	9	1	2	0
⩾30 min	1	2	17	18	*19*	15	14	10	2	2	0
Merger	0	2	8	15	18	19	*21*	11	2	4	0
Urban	1	9	*21*	12	10	*19*	13	9	1	5	0
Stage 3											
All echoes	8	11	*30*	19	7	7	8	6	3	1	1
Vertical growth	1	3	23	*23*	9	9	*15*	10	5	2	1
⩾30 min	0	2	21	*23*	10	9	*16*	11	5	2	1
Merger	0	1	14	*23*	5	12	*18*	15	9	2	1
Urban	3	10	*17*	13	9	13	*18*	10	3	3	1
Stage 4											
All echoes	10	20	*31*	14	9	7	7	2	0	0	0
Vertical growth	3	10	*28*	17	15	12	11	3	1	0	0
⩾30 min	4	5	*31*	17	14	12	*13*	3	1	0	0
Merger	4	5	*23*	14	*21*	14	*17*	2	0	0	0
Urban	7	*21*	18	7	*15*	13	*17*	2	0	0	0

* Italicized values are the largest in each class.

The average duration of the merged echoes was 94 min, nearly 20 min longer than the average for the ⩾30 min echo class (Table 3). As shown in Fig. 2, the merged echoes represented longer-lived and more vigorous convective entities than those in other classes. The average duration of each stage of the merged echoes was 24 min (94÷4) and commonly 6–9 measurements of each echo top were made in each stage. The later time of maximization in the day of the merged echoes may result from their longer echo lifetimes and it may also reflect the fact that big, long-lived echoes generally mature later in the day.

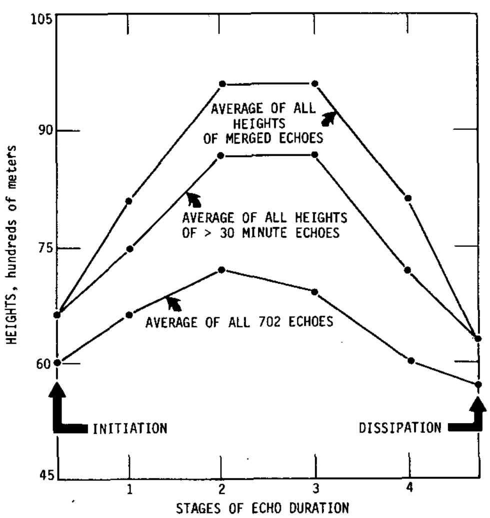

FIG. 3. Average heights of various echo classes.

The average heights of the merged echoes at various phases appear in Fig. 3. The averages for the four stages of the merged echoes are 600–1200 m higher than those for the ⩾30 min echo class, and they are also 1500–2700 m higher than those for the all-echo sample.

The maximum tops of the merged echoes in each stage were frequently higher than those achieved in the other echo classes (Table 4). Distributions of the tops for the merged echoes are unimodal in the first and second stages, but the modes are higher than those for most other classes. The distribution becomes bimodal in the third stage and shows three modes in the fourth stage. The distribution of the heights in stage 3 (Table 4) demonstrates striking differences between the merged echoes and all other echo classes. In the third stage, 28% of the merged echoes had heights above 12 000 m, as compared to 19% in the ⩾30 min class and 10% of all echoes.

The markedly higher values of merged echoes in longevity and height, both in the average and maximum

TABLE 5. Statistics on the maximum 5 min growth of echo tops for echo classes.

	All echoes	Echoes with vertical growth	Echoes of ⩾ 30 min	Merged echoes	Urban echoes
Average (m)	1500	2400	2400	2700	3000
Frequency of growth values per category expressed as percent of totals (m)					
<300	41	0	12	6	12
300–1500	23	38	25	18	16
1500–3000	18	31	27	36	18
3000–4500	10	17	19	22	28
4500–6000	6	9	12	9	16
6000–7500	2	5	5	9	10

values, are also reflected in the echo growth data (Table 5). The average of the maximum 5 min growth values of the 190 merged echoes is 2700 m, compared with lower values for all but the urban class. Of the total merged echoes, 40% had a maximum 5 min growth >3000 m, as compared with 18% for all echoes.

Another statistic specifically determined for the merged echoes was the amount of top change at 10 min after the merger, and at 20 min after the merger. These statistics help reveal the impact of merging on echo behavior and the strength of the storm dynamics. Table 6 presents the post-merger echo top statistics. The average echo top 10 min after merger was 1500 m higher than at merger, and 20 min after merger it was 1200 m higher than at merger. About 70% of the merged echoes grew in height during the 10 min after the merger, and 55% were higher 20 min later.

INTER-DAILY VARIATIONS

Echo mergers occurred on 14 of the 19 echo periods, and the daily differences between the characteristics of the 190 merger echoes and the 428 non-merging echoes on these periods were determined. The values of each merged echo were expressed as a percentage of the non-merger average values on each day, and these percentages were then combined to make comparisons. The results appear in Table 7. The durations were markedly different with the merger average being 322% of the non-merger values. Only 9% of the 190 merger echo durations were less than the daily non-merger average, and 33% had durations that were >350% of the non-merger echo daily value. Differences in initiation heights were slight with 51% below 100% and 49% above 100%. Differences for stages 2–4 were fairly consistent with only about 20% of all percentage differences below 100% (merger heights below the non-merger averages). About 80% of all values in the characteristics listed in Table 7 are above the 100% level, indicating that most merger echoes on any given day well exceeded the top characteristics of echoes that did not merge. Basically, merger echoes were bigger throughout their lifetimes, grew faster (and grew significantly after merger), and lasted much longer than echoes which did not merge.

TABLE 6. Statistics for change in echo heights after merger.

Time after merger (min)	Average top change (m)	Number of echoes expressed as percent of total			
		Increase in height	Decrease in height	No height change	Echo dissipated
10	+1500	74	12	14	0
20	+1200	55	20	12	13

4. Characteristics of urban echoes

There were 137 echoes which partially or totally developed or passed over the St. Louis and/or the Alton-Wood River urban areas (Fig. 1). These were classed as "urban" echoes, or potentially urban affected. This somewhat restrictive definition was based on findings by Schickedanz (1973) that raincells directly over the two cities were altered more than those in a variety

TABLE 7. Comparison of merged echoes and non-merged echo characteristics based on data from 14 periods with both types.

	Average percentage, merged ÷ non-merged values	Number of merged echoes in each merger ÷ non-merger percentage class, expressed as percent of total (190) merged echoes					
		50–100%	100–150%	150–200%	200–250%	250–350%	>350%
Duration	222	9	13	15	17	13	33
Height							
Initiation	104	51	40	8	0	1	0
Stage 1	125	28	48	20	2	2	0
Stage 2	140	21	37	36	5	1	0
Stage 3	144	22	38	37	0	3	0
Stage 4	139	21	42	31	6	1	0
Dissipation	117	27	51	13	9	0	0
Maximum height	152	18	23	44	12	3	0
Maximum 5 min growth	150	23	27	28	13	9	0

TABLE 8. Characteristics of urban merged echoes and urban non-merged echoes.

	Average lifetime (min)	Average duration over urban area (min)	Number that initiated over urban area, as percent of total	Occurrences over urban area in each stage, expressed as percent of total: Stage 1	Stage 2	Stage 3	Stage 4	Average height (100 m): Pre-urban	10 min into urban	Maximum urban value	Exit from urban	Percent of total dissipated over urban area
Merged echoes (ME)	100	35	26	36	63	43	23	90	123	135	125	10
Non-merged echoes (NME)	44	23	53	68	80	84	57	63	75	93	66	34
Difference (ME−NME))	66	12	−27	−32	−17	−41	−34	27	48	42	59	−24

of downwind plumes which had once been considered in the urban classification. Echoes initiated in 56 instances (41% of the urban total) over the two urban areas (Table 10) and 32 dissipated (23%) over the urban areas.

The urban echoes with $\geqslant$300 m of vertical growth totaled 115 (84% of total), and 103 urban echoes (75%) had durations $\geqslant$30 min. Of the 565 non-urban echoes, only 53%, as compared with 84% of the urban echoes, had vertical growth. Only 40% of the non-urban echoes had durations $\geqslant$30 min compared to 75% of the urban total. Clearly, the urban echoes exhibited growth in size and longevity much more often than the natural (rural) echoes.

Sixty-one of the 137 urban echoes (44%) fell into the merger category, representing 32% of the merged echoes. Rural echoes which merged represented 23% of the 565 rural total, considerably less than the urban 44%.

a. *Urban merged vs non-merged echoes*

Some characteristics of the 61 urban echoes which merged over or beyond (generally east) the cities and those of the 76 urban echoes that did not merge are listed in Table 8. The urban merged echoes averaged 35 min over the cities, about 50% longer than did the non-merged urban echoes. However, the fact that there were fewer merged echo occurrences in each stage (over the urban area) results either because these merger echoes were faster moving or because of the generally shorter lifetime of many non-merger urban echoes (44 min vs 110 min for urban merger echoes). A shorter lifetime allowed many of the non-merged urban echoes (48 of the 76) to have three or four of their stages over the urban area. Importantly, only 26% of the merged echoes initiated over the city, whereas 53% of the non-merged echoes initiated over the urban area.

The differences in heights at different times (Fig. 4) are dramatic. The merger echoes not only were much larger prior to urban entry, but also grew more rapidly in the 10 min after their urban entry. The average increase of urban merger echo height 10 min after urban entry was 3300 m (37% of pre-urban height), whereas that of the non-merged echoes was 1200 m or 19% of their pre-urban values. Importantly, the merged echoes at time of exit from urban area were quite high (12 500 m) as compared to 6600 m for the decreasing non-merger echoes. The greater growth and continued strength of the merger echoes is also reflected in the dissipation results which show that only 10% of the merged echoes dissipated over the city compared to 34% of the non-merged ones. The infrequency of dissipation of urban merger echoes, when coupled with the longer duration and the high frequency of these echoes over the city in their stage 2 (Table 8), points to the fact that the urban echoes that merged (over or beyond the cities) typically existed for 30–70 min beyond their exit from the cities and in the area to the east where rainfall increases are greatest (Huff and Changnon, 1972).

b. *Urban merged vs rural merged echoes*

These differences suggest important urban effects on echoes that merged and on the merging process. To

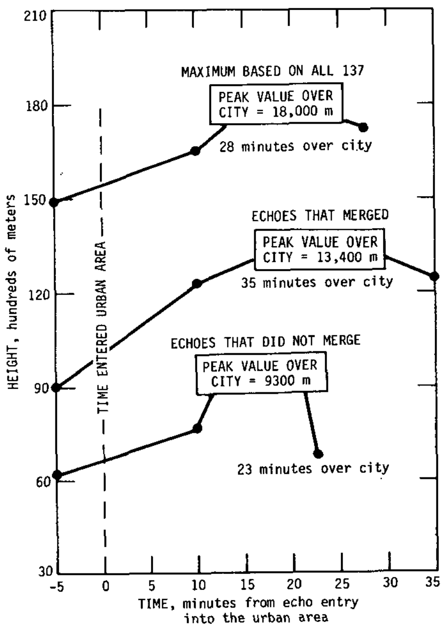

FIG. 4. Average and maximum echo tops for echoes crossing the urban area.

TABLE 9. Characteristics of urban and rural merged echoes.

	Urban	Rural	Difference urban-rural	Difference as percent of rural value
Distribution of mergers by stages, expressed as percent of total				
Stage 1	47	46	+1	2
Stage 2	35	30	+5	17
Stage 3	15	20	−5	25
Stage 4	3	4	−1	25
Duration average (min)	110	73	+37	51
Average height change 10 min after merger (m)	+1800	+1500	+300	20
Average height change 20 min after merger (m)	+2100	+900	+1200	133
Average heights (100 m)				
Initiation	69	66	+3	5
Stage 1	93	72	+21	29
Stage 2	111	84	+27	32
Stage 3	111	84	+27	32
Stage 4	99	69	+30	43
Dissipation	72	63	+9	14
Maximum in life	141	102	+39	38
Average maximum 5-min growth (100 m)	48	24	+24	100

test this suggestion further, the characteristics of the 61 merged echoes over the urban area were compared with those of the 129 echoes that merged over the non-urban area (Table 9).

The temporal distribution of merger occurrences shows relatively more urban ones in stage 2 and relatively less in stage 3, but the temporal differences are not great. However, startling differences appear in all other echo characteristics. The difference in their durations, 51%, is great as are the growth-related differences. The average height change 20 min after merger for the urban echoes was 133% greater than that of rural echoes, and the average maximum 5 min growth of urban echoes was double that of the rural echoes. This results in sizeably greater average urban height values in all stages, as shown, but the lack of difference at the echo initiation (5%) reveals both classes of echoes began much the same.

The differences in the averages for duration (and stages) coupled with the average height values were used to prepare Fig. 5. Clearly, the urban merged echoes were much more vigorous, longer lived, and larger than the non-merged urban echoes, and the merged rural echoes. Notice (Fig. 5) also that the average characteristics of the urban echoes that did not merge are not too different than the rural non-merger echoes. Thus, it appears that urban effects are present and affect echo behavior but basically through those that merge. This could occur because the urban area causes more mergers because of a greater number of urban-induced echoes (Huff and Schlessman, 1974a), and/or because the urban area promotes greater growth in certain cells that have passed over the urban areas and this increases the likelihood of a merger there or somewhere beyond (east) the urban area.

c. All urban echoes

Certain analyses were performed for the entire sample of 137 urban echoes. Included was a counting for the stages of echo duration when an echo was over the urban areas. The frequency values appear in Table 10 and reveal that the greatest numbers were in the two mature stages, 2 and 3. The lower value for stage 4 indicates that many urban echoes had moved beyond the urban area by their later phases. This is supported by the fact that 56 echoes initiated over the urban areas,

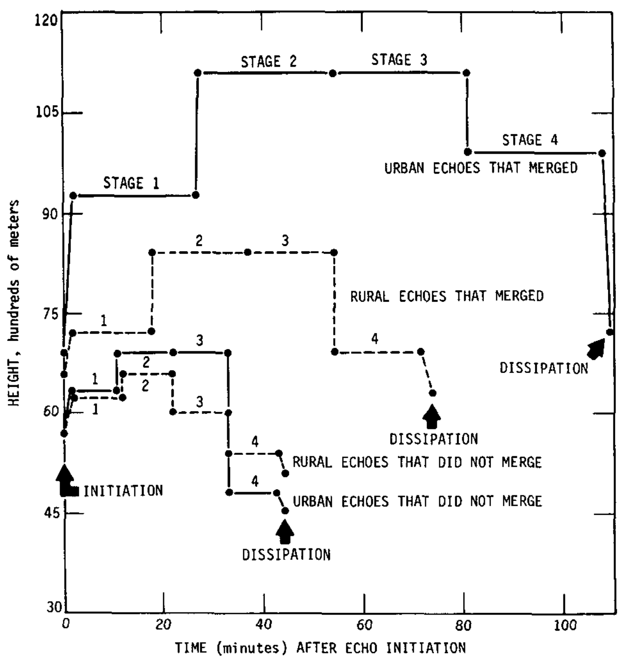

FIG. 5. Time-height profiles for urban and rural echoes.

TABLE 10. Frequency and top heights of 137 urban echoes at various phases.

	Initiation	Stage 1	Stage 2	Stage 3	Stage 4	Dissipation
Number of times echo over urban area	56	74	99	90	58	32
Average height (100 m)	63	75	87	87	69	57
Maximum height (100 m)	111	135	159	180	132	111

but only 32 urban echoes dissipated over the urban area.

Other temporal results for the urban echoes appear in Tables 2 and 3. The Table 2 results on urban echo initiation show a distribution comparable to other classes (excepting the merger class) with a maximum in the 1500–1800 CDT period. Average duration of urban echoes (Table 3) was 78 min, in close agreement with the vigorous (⩾30 min) class. The temporal results indicate the urban echoes were, on the average, much above the total echo averages and definitely in the vigorous category.

The duration of each urban echo over the urban area(s) was computed, and the average of these periods was 28 min with a one-echo maximum of 125 min. The 28 min average is 36% of the average urban echo lifetime, and typically the "over-urban" period occurred in portions of any two stages of an echo duration.

Standard echo height analyses were performed and are summarized for all urban echoes in Table 10. The distributions of the maximum height values in each urban echo stage are shown in Table 4. Interestingly, the urban echo class is the only class that is bi-modal in all four stages. The higher urban mode is in the 9000–12 000 m layer in all stages, and in general, and is as high or higher than the high mode of the other four echo classes. The considerable growth of urban echoes is further reflected in Table 5. The average growth was 3000 m, in excess of all other echo types. In fact, 54% of the urban echoes grew more than 3000 m, as compared with 40% of the merged, 36% of the ⩾30 min class, 31% of the vertical growth class, and 18% of all echoes. These results on growth and heights of echoes further indicate that the urban echoes were *the most vigorous convective storms.*

d. Inter-daily variations

Urban echoes occurred on 17 echo periods, and the daily differences between the characteristics of each urban echo and the daily mean of the non-urban echoes on the same day was determined. The values of the urban echoes on a given day were expressed as a percentage of the non-urban means on that day, and these percentages were then combined to evolve average daily percentage differences (Table 11). In general, the average values are slightly less than those obtained for the difference between merger and non-merger echoes (Table 7), but the average of the maximum 5 min growth value, 161%, is greater than that found for differences in merger and non-merger echoes (150%). The duration differences are quite great with an average of 219%, and 69% of the urban echoes lasted longer than the daily average of the non-urban echoes.

The frequency of echoes sorted by various urban vs non-urban percentages (Table 11) reveals further important differences. At initiation and dissipation, the heights of urban echoes were nearly equivalent to those of non-urban echoes, but about 70% of the urban echoes were taller than the non-urban echoes in the last three stages and in the maximum height attained.

5. Summary

Echo-top histories for 702 echoes from 19 rain periods in the 1973 summer in the St. Louis area were analyzed to perceive whether urban-related echoes and merged

TABLE 11. Comparison of urban echoes and non-urban echoes based on data from 17 periods with both types.

Echo characteristic	Average percentage, urban ÷ non-urban values	Number of urban echoes in each urban ÷ non-urban percentage class, expressed as percent of total (137) urban echoes					
		50–100%	100–150%	150–200%	200–250%	250–350%	>350%
Duration	219	31	17	19	3	10	19
Height							
Initiation	103	54	38	8	0	0	0
Stage 1	118	37	39	21	3	0	0
Stage 2	124	31	42	25	1	1	0
Stage 3	130	30	31	37	1	1	0
Stage 4	124	35	28	36	1	0	0
Dissipation	108	44	43	10	3	0	0
Maximum height	138	25	39	33	3	0	0
Maximum 5 min growth	161	16	36	28	18	2	0

echoes behaved differently than non-urban echoes or non-merged echoes. Although the sample is limited to one summer, the sample was taken during near-normal conditions and it produced results in agreement with rainfall results based on longer periods of data. Attenuation of the 3 cm radar signal meant careful analysis and resulted in the elimination of many echoes from the study because their entire lifetimes could not be followed with certainty.

The 190 echoes that merged during their lifetime represented 27% of the total. Merging occurred most often in the first and second stages (growth periods) of echo lifetimes. All merged echoes grew vertically and 93% had durations exceeding 30 min. Conversely, only 60% of all 702 echoes grew vertically and 47% lasted 30 min or more. The merger echoes were most prevalent in the 1800–2100 CDT period, 3 h later than the maximum for the other echo classes, and they lasted longer (94 min) than all of the other echoes (43 min).

The average height of merged echoes in all four stages was from 1500–2700 m higher than all other echo classes, except the urban echoes which were the highest. The average maximum 5 min growth of merged echoes (2700 m) was higher than those of all echo classes except the urban. Hence the typical urban echo had a faster growth rate and achieved higher tops than the typical merged echo, but the merged echo lasted longer than the urban echo and was bigger than all other classes of non-urban echoes.

Echo growth after merger was sizeable. The change 10 min after the mergers was an average increase of 1500 m and 74% of the merged echoes had grown. Twenty minutes after merger, the average echo height was 1200 m higher than that at merger.

Comparison of the merger echoes with the average of non-merger echoes on any given day shows that only 9% of the merger echoes had shorter durations. Heights of formation were not different, but at any given time the heights of the merged echoes were greater than that of the non-merged echoes.

The 137 echoes that developed or passed over the two urban areas were classed as potentially urban affected. Analyses of their characteristics revealed that the 61 merged echoes in the urban class were truly major echoes in duration (110 min), heights (typically 50% higher than the non-merger urban echoes), and growth rates (110% higher). The characteristics of the 61 urban merger echoes were compared with those of the 76 urban non-merged echoes, and their durations differed greatly, 110 min for the merger vs 44 min for the non-merger group. The merged echo was over the urban area 50% longer, and only 10% of those that merged dissipated over the urban area as compared to the dissipation of 34% of the non-merged echoes. Heights of these two sub-classes of urban echoes differed greatly with the merger class averaging 4800 m

TABLE 12. Summary of urban and non-urban echo differences.

	Urban class	Non-urban echo class
Percent of class total with		
Vertical growth	84	53
⩾30 min durations	75	40
Mergers	44	23
Selected merger echo characteristics		
Duration (min)	110	73
Average height change 20 min after merger (m)	2 100	900
Average maximum height in lifetime (m)	14 100	10 200
Average of maximum 5 min growth (m)	4 800	2 400

higher at 10 min after entering the urban area and 5900 m higher when they exited the urban area.

Comparisons of urban echoes with rural echoes on any given day revealed that 65–75% of the urban echoes were taller at all stages of life, and 84% had maximum 5 min growth rates that exceeded those of the rural echoes. The average duration of the urban echoes was 219% greater than the average of the non-urban echoes.

Table 12 summarizes some other key differences between urban and non-urban storms. Clearly, the urban echoes were much more often vigorous storms (in growth and longevity) than those in the non-urban sample. Almost twice as many urban echoes merged, a condition to be expected since 1) the typical urban echo was taller (larger) and longer lasting, and 2) prior METROMEX echo studies had shown that urban areas cause a greater frequency of echo initiation than occurs in any comparable sized area in the surrounding rural area.

Table 12 also presents the most significant differences between selected characteristics of the urban echoes that merged and non-urban merged echoes. The urban merged echoes were 40–130% greater in the four characteristics indicating urban inducement of more vigorous convection. The heights of the 137 urban echoes (mergers and non-mergers) had a bi-modal (high and low) distribution in all stages, and since all other echo classes had only a single height mode, this suggests that the effects of the urban area resulted in two classes of convection. Furthermore, the urban non-merged echoes were not different from rural non-merged echoes (Fig. 4). Thus, *the key finding of this study relating to the influence of urban conditions on convective rain processes is the considerable urban enhancement of the vertical growth, height (dimensions) and longevity of echoes that passed over the cities and merged over or beyond (generally east) the urban areas.* Merging of precipitation cells has long been noted to enhance convective activity (Simpson *et al.*, 1971), to result in heavier rain rates (Huff, 1967), and on occasion to produce other forms of severe weather. It appears that the urban conditions affected about 45% (61) of the echoes leading to sufficient growth and duration to result in merging. Mechanisms and processes whereby the urban factors are able to influence the frequency and strength of the cells (echoes) that merged remain to be explained in the on-going METROMEX research. However, in-depth investigations of ten precipitation periods at St. Louis revealed that urban-produced convergence zones in seven cases were places where convective activity initiated and/or intensified through storm mergers (Changnon and Semonin, 1975). This finding about sizeable urban effects on convective processes of merged storms has been useful in focusing 1975 field operations and analyses on the study of the thermodynamic processes and their effects on storms (echoes) in and around St. Louis.

Acknowledgments. This research has been performed under the general direction of William C. Ackermann, Chief of the Illinois State Water Survey. The research was sponsored by NSF Grant AEN 73-07796, as part of the research on METROMEX from the Weather Modification Program, Research Applications Directorate, National Science Foundation. Special credit is due Art Sims and Phyllis Stone who carefully and laboriously analyzed the radar film data, and to Edna Anderson for processing the resulting data.

REFERENCES

Braham, R. R., 1974: Cloud physics of urban weather modification—A preliminary report. *Bull. Amer. Meteor. Soc.*, **55**, 100–106.

——, M. Dungey, T. R. Morris, S. A. Changnon and F. A. Huff, 1975: A summary of Project METROMEX radar findings. *Preprints 16th Conf. Radar Meteorology*, Houston, Amer. Meteor. Soc., 404–409.

Byers, H. R., and R. R. Braham, 1949: *The Thunderstorm.* U. S. Dept. of Commerce, Weather Bureau, Washington, D. C., 287 pp.

Changnon, S. A., 1972: Illinois radar research for hail suppression applications, 1967–1969. Report of Investigation 71, Illinois State Water Survey, Urbana, 23 pp.

——, 1974: RHI first-echo study. Interim report of METROMEX studies: 1971–1973. Illinois State Water Survey, Urbana, 71–76.

——, and R. G. Semonin, 1975: Studies of selected precipitation cases from METROMEX. Report of Investigation 81, Illinois State Water Survey, Urbana, 318 pp.

——, F. A. Huff and R. G. Semonin, 1971: METROMEX: An investigation of inadvertent weather modification. *Bull. Amer. Meteor. Soc.*, **52**, 958–967.

Dungey, M., T. R. Morris and R. R. Braham, 1974: Radar data analyses in METROMEX, 1971–72–73. *Preprints 4th Conf. Weather Modification*, Ft. Lauderdale, Amer. Meteor. Soc., 358–361.

Huff, F. A., 1967: Mesoscale structure of severe rainstorms. *Preprints 5th Conf. Severe Local Storms*, St. Louis, Amer. Meteor. Soc., 211–218.

——, and S. A. Changnon, 1972: Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor.*, **11**, 823–842.

——, and E. Schlessman, 1974a: Analyses of PPI radar echo distributions. Interim Report of METROMEX Studies: 1971–1973, Illinois State Water Survey, Urbana, 53–70.

——, and ——, 1974b: 1973 Analyses of monthly, seasonal, and storm rainfall with summary of 1971–1973 findings. Interim Report of METROMEX Studies: 1971–1973, Illinois State Water Survey, Urbana, 17–29.

Schickedanz, P. T., 1973: Use of surface raincells in evaluating inadvertent weather modification. Summary Report of METROMEX Studies, 1971–1972, Report of Investigation 74, Illinois State Water Survey, Urbana, 57–83.

Simpson, J., W. L. Woodley and A. H. Miller, 1971: Precipitation results of two randomized pyrotechnic cumulus seeding experiments. *J. Appl. Meteor.*, **10**, 526–544.

Vogel, J. L., 1974: Synoptic analyses. Interim Report of METROMEX Studies: 1971–1973, Illinois State Water Survey, Urbana, 6–16.