Effects of St. Louis on Convective Cloud Heights

Roscoe R. Braham, Jr., and Daniel Wilson

Cloud Physics Laboratory, The University of Chicago, Chicago, Ill. 60637

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ABSTRACT

Heights and locations of the tallest 3 cm radar echoes at each half-hour through the convective parts of 140 summer days were measured during Project METROMEX. Comparison of the area-weighted frequencies of echoes occurring over and downwind of St. Louis, Mo., with those over a large nearby rural area, shows a substantial enhancement in the frequency of tall echoes over the city and near-downwind areas. This enhancement comes mainly during the late morning and early afternoon and possibly again during the evening hours. The data also show a substantially different echo height distribution over urban and rural areas. Whereas the rural height distribution is distinctly bimodal, the urban height distribution shows no such bimodal character. This means that urban clouds are frequently able to penetrate mid-level arresting levels which limit the growth of rural clouds. These observations suggest an important role for urban-enhanced cloud dynamics in causing the St. Louis rainfall anomaly.

1. Introduction

As a part of the University of Chicago participation in METROMEX, a TPS-10 radar was used to study the characteristics of precipitation echoes over and downwind of St. Louis (Braham, 1974). The location of the radar with respect to the city and other geographical features is shown in Fig. 1. This paper is concerned with the locations and heights of the tallest convective cloud echoes occurring within the 10 053 mi^2 radar field which included Metropolitan St. Louis, rural areas frequently downwind of it, and rural areas seldom downwind.

In keeping with the METROMEX emphasis on summer convective clouds, we attempted to operate the radar continuously throughout the midday convection period on all cloudy days during the five summer seasons of METROMEX. The vary large amount of data collected necessitated use of only a sample of it in this analysis. We extracted from the echo data the locations and heights of the single tallest convective radar echo recorded anywhere within the 20–60 statute mile radar range at each half-hour. (Data inside 20 mi were excluded because of the radar's limitation in accurately observing very large echoes at close range.) For purposes of discussion we denote each of these observations as a "hi-cu." From 140 days of data, this procedure gave 1573 hi-cu observations (Table 1) occurring generally between 1000 and 2000 LDT.

The use of one azimuth scan at half-hourly intervals provides unbiased data on the locations of the tallest echoes in the entire radar field, but suffers disadvantages of not always giving absolute maximum echo heights and, more importantly, that the adjacent observations may sometimes involve the same cloud and thus not be independent in a statistical sense. Some analyses have been carried out on the data subset involving only the single tallest echo observed on each day. Although these are regarded as statistically independent, the small sample limits the strengths of conclusions.

2. Analysis methods

We began by defining the city to be a region within a compact polygon encompassing St. Louis and nearby built-up areas in Missouri, and Alton, East St. Louis, Granite City, and nearby suburbs in Illinois (Fig. 1). This area includes substantially all of the major sources of atmospheric pollution in the St. Louis area, as determined by the Environmental Protection Agency emissions inventory. It also rejects as much as possible of the nearby rural area while keeping a simple compact

TABLE 1. Number of days and observations making up the hi-cu sample.

	June		July		August	
Year	Days	Observations	Days	Observations	Days	Observations
1971			3	21	10	67
1972	11	123	16	127	11	139
1973			16	216	13	170
1974	1	2	13	121	13	199
1975	6	72	15	184	12	132

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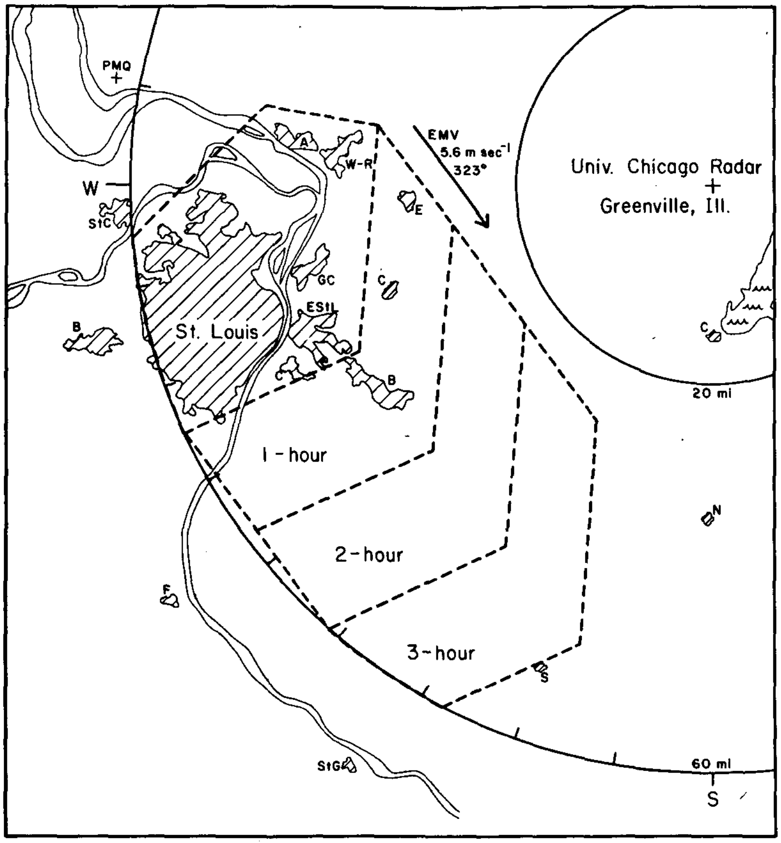

FIG. 1. Map showing the location of The University of Chicago radar, Greenville, Ill., relative to St. Louis, Mo. Only about one-third of the circular radar area, defined by 20 and 60 mi range markers, is shown. Areas outlined by dashed lines are discussed in the text.

shape. The 60 mi outer limit of the radar data imposes a slight, but not too serious problem.

In view of the facts that primary city effects, such as thermal and pollutant plumes, are advected by low-level winds and that up to an hour may elapse between the birth and time of maximum height of a cumulus cloud, it is also necessary to examine an area "downwind" of the city for possible hi-cu differences. We have attempted to do this in the following way. For each day a mean echo movement vector (EMV) was determined by tracking three or more widely separated small echoes. By applying the EMV to the boundary of the city, areas corresponding to the limits of 1, 2 and 3 h of advection, within the 20–60 mi radar range annulus, were constructed and measured for area. The remainder of the 10 053 mi^2 radar field, outside the combined city and three advection areas, we call rural (R). The city area remained the same for all days, 588 mi^2, but the three 1 h advection regions and the rural region may have different areas within each day and differ from day to day depending upon the echo movement vector.

The use of a vector determined from the movement of small echoes represents a compromise between use of the boundary layer winds that would advect surface pollutants and thermal plumes and some mid-tropospheric "steering" wind governing the movement of the large clouds. The uncertainties introduced by use of the EMV, in defining "downwind areas" in which to look for urban effects, is not inconsistent with the uncertainties as to the mechanisms of urban enhancement of convective clouds.

Since the city is along the southwest edge of our radar field, the three advection areas cannot be sampled on days with EMV between about 45° and 135°. On days with EMV between about 000° and 045°, and between 135° and 225°, the 2 and 3 h regions may not be sampled. Out of 140 days in the study, the numbers of days with EMV in these three groups of directions were 5, 3 and 12. On 120 days the EMV was between 225° and 360°. Thus the location of the city on the edge of the radar field does not seem to be too serious from this point of view; a more serious issue is raised in a later section.

An example of the three 1 h, advection areas on a day with an EMV of 323°, 5.6 m s^{-1} is given in Fig. 1.

The first part of our study is to compare hi-cu frequencies over the city and over the three 1 h advection regions with those found in the rural region. Results are presented as area-weighted frequencies computed from

$$\mathrm{RF}=\frac{\Sigma_j\chi_{ij}/\Sigma_jN_jA_{ij}}{\Sigma_i\chi_{Rj}/\Sigma_jN_jA_{Rj}},$$

where χ_{ij} is the number of hi-cu events in region i on day j [subscript i denotes the city (C), rural (R), and three 1 h downwind regions (1, 2, 3)], A_{ij} is the area of region i on day j, and N_j the total number of hi-cu observations on day j (1–140).

3. Location of the tallest echo of each day

Measurements on the single tallest echo of each day form an attractive data set since these observations may be regarded as statistically independent. The frequency distribution of the daily maximum echo height (Fig. 2) is unimodal with a maximum at about 45 000 ft. The average tropopause height for St. Louis on these days was about 50 000 ft (15 km). Thus, almost half of the METROMEX rainy days produced echoes with tops reaching the tropopause. The average daily maximum echo heights for June, July and August were 36 300, 38 800 and 38 700 ft. These values are slightly higher than those reported by Changnon and Morgan (1976), and do not show the same monthly progression. Little significance is attached to this point since the within-month variance is large compared with the between-month differences.

Table 2 gives the area-normalized frequencies with which the daily maximum hi-cu is found over the city and downwind regions. For the entire sample of 140 days we find a value of 1.34 for the city and about 1.7 for the first 2 h downwind. The third-hour advection region gives essentially rural values. On 118 days with EMV$\geqslant$3 m s^{-1} the urban effect is found only downwind of the city in the first two advection areas where it has a value of about 1.6. There were 22 days when EMV was less than 3 m s^{-1}. With such light winds we can ignore any slight downwind drift and take the entire radar field outside of the "city" as representing rural conditions. This gives a value of 2.55 for the relative frequency of daily maximum echo height over the city. For these days we can assume that the areas of both the city and rural areas are unchanged from day to day. This allows us to compute the significance of the 2.55 value for the city effect under the null hypothesis that the location of hi-cu is purely random. This would give the expected relative frequency of hi-cu over the city as simply the ratio of the two areas. Using the binomial test we reject this null hypothesis at a level of 0.136 (1 tail), suggesting a real city effect but not at a very convincing level.

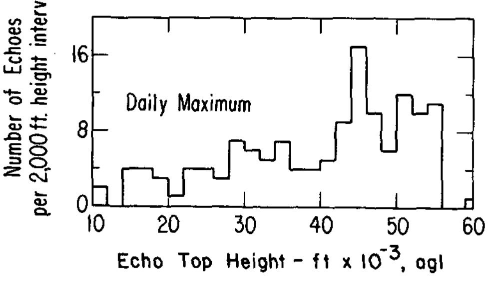

FIG. 2. Top height distribution for the tallest echo on each day of the 140-day data set.

TABLE 2. Area normalized frequency of the daily maximum hi-cu over and downwind of St. Louis.

	Number of days	Relative frequency City	1 h	2 h	3 h	Rural
EMV<3 m s^{-1}	22	2.55				1.00
EMV$\geqslant$3 m s^{-1}	118	1.07	1.57	1.61	0.86	1.00
Total sample	140	1.34	1.67	1.72	0.92	1.00

4. Urban effects upon hi-cu locations

Next we turn to the complete sample of 1573 hi-cu observations. Table 3 gives the relative frequencies for finding the half-hourly hi-cu in various parts of the urban area and for various partitions on EMV. Immediately we note that in all partitions the third hour advection area has values very close to those of the rural region. There is evidence for an urban effect in increasing the probability of finding the tallest echoes over the city and in the first 2 h downwind. This evidence is strengthened when the data are partitioned on wind speed. With EMV <3 m s^{-1} the relative frequency of hi-cu over the city is about twice that of the rural area. In the 3.0$\leqslant$ EMV $\leqslant$7.9 m s^{-1} partition, this effect is reduced and spread over the city and the first hour downwind. With still greater wind speeds, we find the urban effect decreasing in magnitude and shifting to the first two advection areas, while the city has returned to near-rural values.

In assessing the statistical significance of relative frequency values of hi-cu we encounter several problems. The observations cannot be regarded as independent as we did in the subset containing only the daily maximum. The city and three downwind areas are always much

TABLE 3. Area normalized relative frequency of the half-hourly hi-cu in various parts of the urban area.

	Number of days	Relative frequency City	1 h	2 h	3 h	Rural
All data	140	1.19	1.46	1.30	0.96	1.00
Wind partition						
EMV<3 m s^{-1}	22	1.99				1.00
3.0– 7.9 m s^{-1}	42	1.42	1.43	1.09	1.01	1.00
8.0–10.9 m s^{-1}	37	0.98	1.69	1.41	0.92	1.00
11.0–19.9 m s^{-1}	39	0.80	1.38	1.37	1.01	1.00

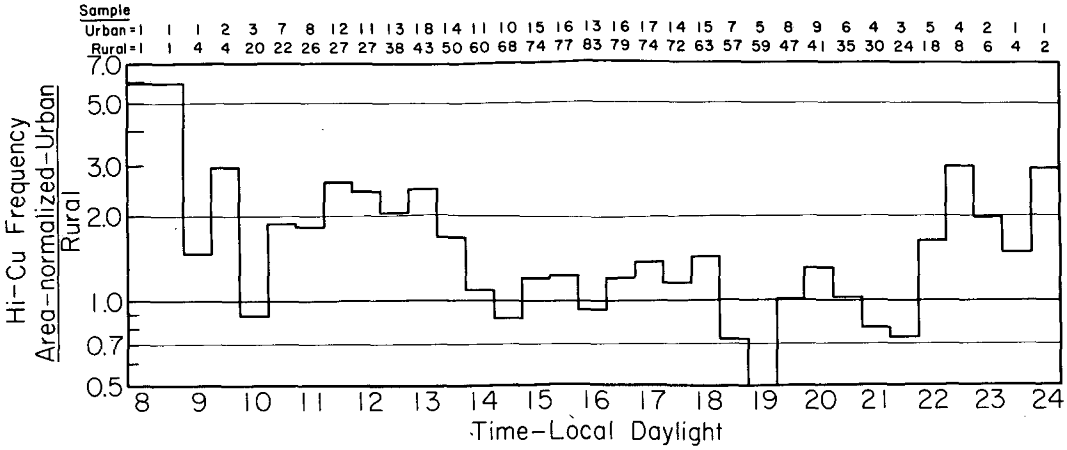

FIG. 3. Frequency of urban hi-cu compared with rural as a function of time of day.

smaller than the rural area. (The examples given in Fig. 1 are somewhat smaller than average.) They vary in size among themselves on any given day and from day to day. On any given day, more often than not, one or more of the areas, other than rural, do not contain a hi-cu event.

In the light wind partition we can assume that the urban effect is restricted to the city area, while the remainder of the radar field remained unaffected. For this case, we can compute the probability that a random distribution of hi-cu over the radar field would give the same, or greater, number of city echoes as was actually observed. Using the Poisson approximation to the binomial expansion we obtain a standardized normal deviate of 3.65. If the data were independent, this would lead to a rejection of the null hypothesis at a significance level of 0.0001 (1-tailed).

Previously we showed that by using only the single maximum hi-cu of each day, where independence was more likely, we could reject the null hypothesis of no urban effect at a level of only 0.136 (1-tailed). Thus, although the city effect was about the same in the two cases (1.99 vs 2.55), the differing sample sizes markedly affect the calculated significance.

5. Urban effect on the times and heights of convective echoes

Tables 2 and 3 indicate that the frequency anomalies associated with the city are limited to the city and the downwind area within 2 h of small echo travel. The area covered by the third hour of advection gave values indistinguishable from the rural area. Therefore, in the following analysis we combine the data for city and the first two advection areas into what we call the "urban" area. The definition of the rural area remains unchanged.

Fig. 3 shows the relative frequency with which the tallest echo in the radar field was found in the urban region, as a function of time of day. For this figure, observed urban frequencies were divided by the observed rural frequencies and multiplied by the ratio of the average daily urban and rural area. This allows for the differing sizes of urban and rural regions and for the differing numbers of observations at different hours. Actual frequencies are given at the top of the figure.

We find that consistently throughout the late morning and early afternoon the frequency with which the tallest echo occurred over the urban region was substantially higher ($\leqslant 2.7\times$) than that expected from a random distribution. From about 1400 to 2130 LDT the relative frequencies are about equal though there may be a tendency for urban excesses until about 1830 and urban deficits from 1400 to 1600 and from 1830 to 2130. There also is a suggestion of an urban enhancement prior to 1000 and after 2130 LDT but the samples are small. Urban deficits of tall echoes during the 1400–1600 period is a little surprising since this is the time of maximum surface temperatures. It may be related to the fact that the urban boundary layer tends to be drier than the rural boundary layer during this period (Dirks, 1974). Urban enhancement of large-echo frequencies after 2130 is compatible with the observations of the Illinois State Water Survey that the St. Louis rainfall anomaly is strongly influenced by evening storms.

Fig. 4 is a plot of the frequency distributions of heights of urban and rural hi-cu. Urban frequencies have been normalized on the average size of the rural area. The rural distribution is distinctly bimodal with peaks at 18 000–20 000 ft and 40 000–42 000 ft AGL. The upper height mode obviously represents storms that have reached the tropopause. The lower height mode may represent the response of rural clouds to some frequently occurring mid-tropospheric arresting level such as a stable layer or the top of the low-level moisture layer. Or it might represent the difference between glaciated and unglaciated clouds.

In contrast, the urban data show little tendency for a bimodal height distribution. These data reach a maximum frequency at about 18 000–22 000 ft AGL, decrease slowly through 42 000 ft and then drop sharply. Urban values are well above rural values for heights below 16 000 ft and above 40 000 ft, and about equal to rural values for heights below 16 000 ft and above 40 000 ft.

Fig. 5 gives joint time-height probabilities for the occurrence of hi-cu echoes. Solid lines delineate zones in the time-height field where urban frequencies exceeded rural values by the indicated factors. Stippled areas indicate zones where the urban values are less than rural.

These figures show clearly that summer convective clouds over St. Louis and its near-downwind area systematically grew to greater heights than clouds in nearby rural areas during late forenoon and early afternoon periods, and possibly also during late evening hours.

It is interesting to speculate as to possible mechanisms which could cause the urban area to have up to a twofold greater probability of being the site of the tallest echoes and cause urban echoes to have a unimodal height distribution in contrast to the bimodal distribution found for rural echoes. It is well understood how surface thermal and surface frictional effects promote convergence of low-level winds over cities. This has been established both observationally and theoretically for St. Louis. Uthe and Russell (1974), using a mobile lidar, showed that the morning deepening of the mixing layer at St. Louis begins earlier and stays ahead of the upwind rural region through the early afternoon. Ackerman (1974a,b) measured disturbed and convergent wind fields over the city using double-theodolite pilot balloon measurements. It has been observed that the city and certain industrial areas are preferential sites for initiation of small cumulus clouds (Auer, 1976; Schickedanz, 1974). Numerical model calculations show the enhancement of urban convection at St. Louis (Ochs, 1975; Spangler and Dirks, 1974).

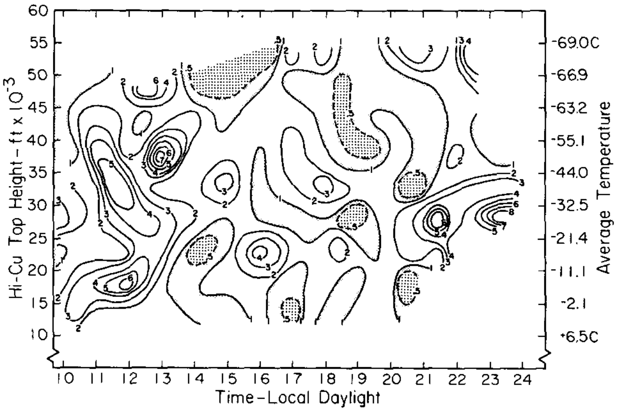

FIG. 4. Area-normalized height distributions of urban and rural hi-cu.

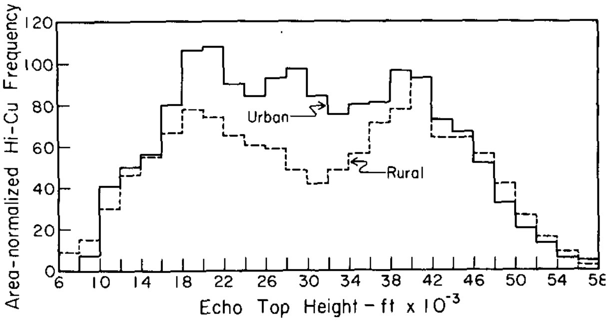

FIG. 5. Joint time-height distribution of urban hi-cu frequencies relative to rural values.

Our observation that urban frequencies of hi-cu exceed rural values during the late morning and early afternoon is consistent with these earlier findings.

Three mechanisms come to mind which could give urban clouds a slight additional impetus and allow them to penetrate the arresting level which brings about the low height mode of rural hi-cu. The first is an enhanced updraft at cloud base as a result of the low-level convergence and thermal forcing over the city. The second postulates a greater frequency of small clouds over the city which may progressively moisten the lower troposphere over the urban area resulting in reduced effects of entrainment in some of the urban clouds.

The third possibility has to do with cloud glaciation. Since the freezing level in summer at St. Louis is usually 14 000–16 000 ft, the clouds in the lower height mode of the rural distribution may not be glaciated. Perhaps the observed differences in heights of urban and rural echoes were caused by seeding of urban clouds by anthropogenic ice nuclei. Although there are a number of scattered measurements in the literature suggesting that urban and industrial areas are sources of ice forming nuclei, systematic measurements using Millipore filters at St. Louis suggest a net urban reduction of ice nuclei, with superposed low grade sources in some of the industrial areas (Braham and Spyers-Duran, 1974; Czys, 1977).

It is interesting to note the analog between these hypotheses and the enhancement of cumulus clouds through "dynamic seeding" (Simpson and Dennis, 1974). Fig. 4 suggests that rural clouds of Illinois in summer may be suitable for rain enhancement through dynamic seeding.

The first and third of these possibilities would apply to convective clouds associated with cold fronts and squall lines as well as to air mass convection. It would be interesting to partition the data to study separately the effect on frontal and air mass days, although as yet this has not been possible.

6. Conclusions

Measurements of radar echoes show that St. Louis exerts a substantial influence on the heights of summer convective clouds. There is roughly a twofold higher probability of finding the tallest echo in the entire region over and downwind of the city during the midday and late evening hours. The height distribution of the tallest echoes over nearby rural areas is distinctly bimodal. In contrast, a unimodal distribution of heights of urban echoes is explained in terms of an urban boundary layer effect giving urban clouds an additional impetus enabling them to penetrate a mid-tropospheric arresting layer which restricts the growth of many rural clouds.

Although a direct cause-and-effect relationship between the urban area and cloud heights has not been proven, this analysis gives strong evidence for such an effect and provides a reasonable explanation for increased frequencies of heavy rains and thunderstorms observed downwind of St. Louis and several other cities. It also suggests the need for similar studies at other cities, since it follows from this argument that urban effects on heavy rainstorms and thunderstorms would be most marked in regions where mid-level arresting layers are a common feature of convective days.

The validity of our conclusions depends on several factors. We assume that our "city" encompasses the source areas responsible for any urban effect upon cloud heights, and that the movement of small echoes can be used to describe the way in which these effects advect or propagate downwind. We also are well aware of the fact that our "city" region is one edge of the radar field. Should it be that there is a natural gradient of echo properties across this area, say as a result of the higher terrain to the southwest, our interpretation of these results as due to St. Louis might be in error. Since neither the urban agents nor advection mechanisms are well understood, and our data do not allow a check of the third concern, we view these results as preliminary and subject to refinement as our knowledge increases.

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