Inadvertent Rain Modification as Indicated by Surface Raincells

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ABSTRACT

Rainfall data from a large dense network are being used to study inadvertent rainfall modification in the St. Louis area. Surface raincells are delineated and then analyzed to determine the character of any urban-induced changes in precipitation. Results for comparisons of 605 potential effect cells and 870 non-effect cells from the summer of 1971–72 provide strong evidence that cell characteristics have been sizeably altered by the local urban-industrial environment. For cells occurring in the urban-industrial zone of St. Louis, the average rainfall volume was 176% greater than for cells in the control sample. For cells occurring in the separate industrial region of Wood River, the average volume was 262% greater than the cells in the control sample. The results show that the primary change in St. Louis cells is total rain area, and this and other results suggest that this relates to dynamic effects induced by the urban heat island. The primary change in Wood River cells is in rain intensity, and this and other results suggest that this relates to microphysical effects from the industrial aerosols and additions of moisture into the atmosphere, particularly in dry summers. Importantly the primary causes of observed rain increases in St. Louis and Wood River appear to differ, and additional data must be collected and analyzed to enlarge on the interesting two-summer results.

1. Introduction

One of many methods being used to evaluate the effect of the urban-industrial complex on precipitation in METROMEX (METROpolitan Meteorological EXperiment) at St. Louis has been the analysis of surface raincells (Schickedanz, 1972, 1973b). The data for surface raincell analysis have been obtained from the METROMEX network (Changnon *et al.*, 1971; Changnon, 1973) of recording raingages which has an area of 2000 mi^2 and a density of 9.4 mi^2 per gage. The resulting raincell analysis is being used to identify the precipitation characteristics that are being altered by the urban-industrial complex. These altered characteristics are determined by isolating individual raincells (patterns of rain usually produced by a single convective entity) and determining their history as to initiation, movement, maximization, duration, size, and total rain production. The chief advantages of this technique include 1) the spatial portrayal of a cell, the smallest definable rain producing entity, and 2) the description of several cell parameters which provide means to infer how physical processes have been changed by the urban area. Objective definitions for cells and analytical procedures for them have been developed in order to minimize subjectivity for cell delineation (Schickedanz, 1972, 1973a, b). In addition, large portions of the analysis have been computerized, thus reducing the effort involved in handling the vast quantity of data.

In this paper, the characteristics of surface raincells are used 1) as a *descriptive tool* for demonstrating the magnitude, structure and characteristics of the urban-industrial influence on rainfall; and 2) as an *investigative tool* for exposing and explaining causes of the altered precipitation. It is the purpose of this paper to present some of the results obtained from the analysis of the first two years of METROMEX data, June–August, 1971–72.

2. The raincell approach to the identification of the character of the urban-induced rainfall

a. Rationale

Under favorable conditions, individual updraft areas within a thunderstorm develop into units of convective circulation. These units can be detected on a radar scope and are defined as regions of localization of convective activity within the thunderstorm (Byers and Braham, 1949). There may be more than one cell during a storm period, each of which may be either independent or dependent of surrounding cells in the storm. During the period of the storm, each cell may be in different stages of development at any one time. The stages of development for a cell are (i) the cumulus stage characterized by updrafts in the cell, (ii) the mature stage characterized by both updrafts and downdrafts in the cell, and (iii) the dissipating stage characterized by weak downdrafts throughout the cell (Byers and Braham).

In the Thunderstorm Project (Byers and Braham) it was found that the surface rainfall pattern under a thunderstorm follows closely the arrangement of cells, and reflect, to a considerable extent, the various stages of development. In METROMEX, small isolated precipitation areas in the surface rainfall patterns (that generally reflect conditions within the cells aloft) which are characterized by closed isohyets are designated as *surface raincells*. Thus, cells investigated were those from rain showers as well as those from thunderstorms. The underlying assumption of the METROMEX raincell analysis is that *changes which occur in the surface raincell parameters in the vicinity of urban-industrial sources are broadly indicative of potential urban-industrial induced changes in the clouds aloft.* Thus, the analysis of surface raincells in the vicinity of urban-industrial complexes can yield insight into the physical processes involved.

b. *Analytical procedure*

A raincell was defined in the following manner: A raincell in a multicellular system is a closed isohyetal entity within the overall enveloping isohyet of the rain-producing system; that is, it defines an isolated area of significantly greater intensity than the system enveloping isohyetal. When raincells develop apart from a multicellular storm system, the system-enveloping isohyet will not be present, and the single cell is uniquely defined by the separation between rain and no rain.

The delineation of these cells requires several steps. First, 5-min rainfall amounts are digitized directly from the raingage charts (weighing bucket gages) and these are entered on punch cards through the use of a Model 3400 X-Y digitizer (Autotrol). The digitized amounts are then processed by the IBM 360 computer so that a 5-min printout of rainfall amounts is obtained. The 5-min amounts and pre-determined contour intervals are then plotted by the computer.

From the 5-min isohyetal maps, a determination of which rainfall entities constitute a raincell must be made. This determination is made using the definition; however, a size restriction on the area, an intensity restriction on the rainfall rate, and a time restriction on the initiation and dissipation of cells are necessary. These restrictions are as follows:

1) A cell cannot envelop more than one-third of the underlying isohyet of the storm.

2) A cell can be delineated by rainfall rate when the difference between its smallest point value and the base isohyetal equals or exceeds a rate of 0.75 inch hr^{-1}.

3) In order for a cell to initiate, it must be present longer than 5 min.

These definitions and procedures provide a semi-objective method of cell delineation. It should be noted that these definitions were developed after much inspection of the rain data, and much trial and error attempts at defining a large volume of different rain types.

Once the raincells were defined on the 5-min maps, various cell parameters were determined for each cell. These parameters include rainfall volume, mean rainfall, area, duration, maximum rain per 5 min, maximum area per 5 min, mean path length, mean path velocity, maximum point rainfall, minimum point rainfall, as well as an isohyetal representation of the total rainfall pattern resulting from each cell. This phase of the analysis was computerized prior to the 1972 cell analysis.

c. *Statistical and design considerations*

The chief problem in evaluating inadvertent rain changes is that the treatment (urban) effect is not assigned at random to the experimental unit. Even if randomization is disregarded, there is the difficulty that the treatment effect is uncontrollable, and the factors which cause the treatment effect are either unknown, or the degree to which they are present is unknown (Changnon and Schickedanz, 1971). This concept eliminates the usual treatment vs non-treatment (seeded vs non-seeded) comparisons that are so useful in planned weather modification where the non-treatment data serve as the control.

Another consideration in evaluating inadvertent modification is that the target area for the precipitation increase or decrease is unknown. In planned weather modification, the location of the treatment is known and thus the target area is better defined. Also, since the seeding is often assigned at random, the most valid and useful comparison is seeded vs non-seeded data and the exact boundary of the target area is not as critical as when the comparison must be based on a target vs non-target comparison. Therefore, assumptions must be made regarding how the urban complex acts as a treatment agent (roughness, increased aerosols, and added heat) in order to delineate apparent target (effect) and control (non-effect) regions.

Since the lack of randomization is unavoidable in inadvertent rain modification evaluation, the approach will be that of "data analysis" (Flueck, 1971). *In this approach, the final proof and acceptance of inadvertent modification of precipitation does not rest entirely upon statistical evidence and results from tests of hypothesis. The test statistic will be treated as an informative summary statistic and is to be clearly distinguished from the concept of the test statistic as a strict accept-reject rule.* Thus, the flexibility of attack and the willingness to study things as they are, rather than as they, hopefully, should be, are stressed.

In applying the concept of data analysis to non-randomized comparisons we are guided by the general

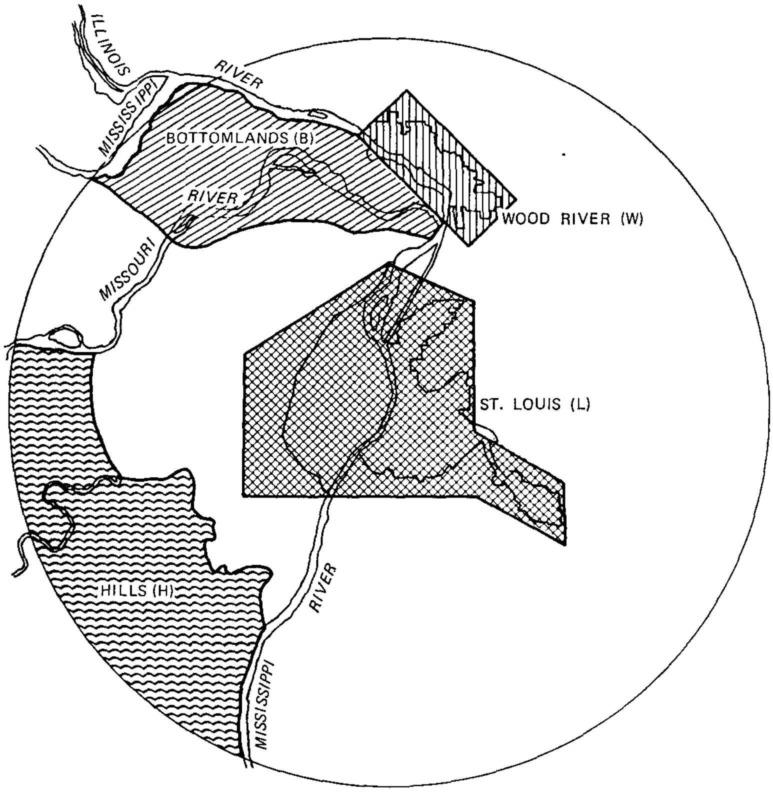

FIG. 1. Hypothesized regions of potential treatment agents.

concept of data analysis as described by Tukey (1962), who indicates that much of data analysis must be a matter of judgment. "Theory," whether statistical or non-statistical, will have to guide, not command. Tukey states: "Data analysis must progress by approximate answers, at best, since its knowledge of what the problem really is will at best be approximate. It would be a mistake not to face up to this fact, for denying it, we would deny ourselves the use of a great body of approximate knowledge . . . ."

Thus, the METROMEX raincell analysis proceeded with the knowledge that the treatment effect was not assigned at random. Therefore, the definition of target (effect) and control (non-effect) areas in the analysis and ensuing text may not be completely rigorous. However, there is a great wealth of "approximate" knowledge available from the analysis of METROMEX raincell data, because of the well-designed field instrumentation program (Changnon *et al.*, 1971). This knowledge yields invaluable information which can be used as a broad basis for establishing the causes and effects of inadvertent precipitation modification.

d. Delineation of effect and non-effect cells

An inherent problem in this study has been how to classify, on any basis, cells as potentially affected by any (or all) urban factors and those not affected by any (or all) urban factors. Any delineation of urban-effect and non-urban-effect cells is complicated by the uncertainty of the source of "treatment agents" and by the manner in which these are transported to and interchanged between cells aloft. Three-dimensional continuous monitoring of all treatment agents is quite difficult if not impossible over a prolonged period of several months. However, detailed three-dimensional monitoring of all possible treatment agents is available for certain "case study" storms and cloud systems of 1971–72. Since this type of information is not available for all rain periods and since the agents are unspecified, some general stratification methods are required which can only approximate the true effect and non-effect cells. However, by defining and then studying a variety of stratifications, speculation can be made concerning the most likely sources, and their potential contributions can be explored.

From a survey performed by Venezia and Ozolins (1966) and from information provided by METROMEX personnel, St. Louis area industries were plotted on a base map. For convenience, a simplified boundary was drawn around the contiguous urban-industrial area of St. Louis, and it was designated as the L area (Fig. 1). This area was considered to be a potential source of heat, nuclei, turbulence, and possibly moisture (treatment agents) to the atmosphere. Certainly,

TABLE 1. Comparison of rainfall volume from effect and non-effect raincells (means value in acre-feet).*

	Areas where cells developed and/or passed				
	St. Louis	Wood River	Hills	Bottom-lands	Contro
			All cells		
1971	215 (113)	409 (305)	191 (89)	107 (6)	101
1972	372 (210)	416 (247)	179 (49)	149 (24)	120
1971–72	315 (176)	413 (262)	184 (61)	131 (15)	114
			Moving cells		
1971	299 (57)	522 (175)	289 (52)	164 (−14)	190
1972	524 (140)	531 (144)	280 (28)	206 (−6)	218
1971–72	447 (114)	527 (152)	284 (36)	188 (−10)	209
			Stationary cells		
1971	72 (132)	38 (23)	31 (0)	20 (−35)	31
1972	36 (16)	113 (265)	35 (13)	53 (71)	31
1971–72	51 (64)	84 (171)	34 (10)	38 (23)	31

* Effect—control differences are expressed as percent of control in parentheses.

there are point sources of treatment agents which are not included within this boundary; however, the maximum concentration was enclosed and it served as a basis for stratifying the raincells into potentially effect and non-effect cells. Aircraft observations of temperature, aerosols, and other atmospheric conditions during 1971–72 (Semonin and Changnon, 1974; Auer and Dirks, 1974; Braham, 1974) support the concepts that a temperature perturbation exists over the highly urbanized area of St. Louis, and the city serves as a source of CCN, but do not support the concept of the city being a moisture source. In addition, airflow measurements during 1971–73 (Ackerman, 1973) have shown that the city disturbs the circulation, often producing convergence over and downwind of the city in the low atmosphere, which would tend to concentrate aerosols and potential CCN and ice nuclei for cloud base ingestion.

Somewhat removed from St. Louis are the contiguous areas of Wood River and Alton which have a dense concentration of heavy industries including petroleum refineries, iron and steel foundries, and coke plants. For convenience, a simplified boundary was drawn around these areas and designated the Wood River (W) area. The W area is a nuclei source (CCN and ice) not unlike St. Louis in its volume (Semonin and Changnon, 1974; Auer and Dirks, 1974; Braham, 1974), but it has a much smaller thermal perturbation than St. Louis. In fact, there is some suggestion that the effluents of the major cooling towers in the W area may result in a localized increase in atmospheric moisture.

In addition, there are two areas which are non-urban related, but which were considered potential sources of vertical perturbations, heat and moisture. These are the major river bottomlands northeast of St. Charles in the northwestern part of the network between the Missouri and Mississippi Rivers, and the foothills of the edge of the Ozark Plateau in the southwestern part of the network. From an inspection of topographical maps, the area between the two rivers and the surrounding marshy land was designated as the Bottomlands (B) and is shown on Fig. 1. Likewise, from the topographical maps, the prominent area of roughness and elevation was designated as the Hills (H) and is also shown on Fig. 1. These areal stratifications were made to help separate some topographical and marine influences from the control sample, and by a deductive process they may be used to more clearly estimate the urban influences.

All cells which occurred (i.e., cells which developed and/or passed) within one of the four source areas (L, W, H, B), but never in any of the other three, were designated as "effect" cells. Cells which never occurred in any of the four areas (L, H, W, B) were considered to be control (C) or "non-effect" cells. In addition, cells which were in both L and H only, and in W and B only, were considered as two more classes of effect cells.

3. The character of the urban-induced rainfall increase as indicated by surface raincells

a. *Evidence for an urban-induced increase in the total rain production of cells*

Results for rain volume of cells are employed in this paper because rain volume is the single most important parameter insofar as the ultimate economic benefit of enhancement or suppression of rainfall is concerned. This parameter represents the total rain production by the cell and is an integrated measure of the other cell parameters and of the various atmospheric conditions which produced the cell. Results of the comparison of 605 effect cells and 870 non-effect cells (control cells) are listed in Table 1.

Since all effect values are compared to the control values, the validity of the control values is important. Thus, a comparison was made of these mean control (natural) values to those obtained in earlier studies of unmodified raincells. In the Thunderstorm Project (Ohio), Braham (1952) obtained a mean value of 1.24×10^8 kg or approximately 100 acre-feet for the total rain volume. Huff and Schickedanz (1970) obtained a median value of 110 acre-feet for raincells on a dense rural network in extreme southern Illinois. When we consider that different techniques were used to delineate the raincells, the agreement of the two-year control value of 114 acre-feet with these previous values is quite good. This agreement lends support to the validity of using the described control values in the various comparisons.

Inspection of the All Cells category in Table 1 indicates that cells occurring in the urban-industrial areas produced the largest percentage differences. The percent differences of cells were 176% for St. Louis (L), 262% for Wood River (W), 61% for the Hills (H), and only 15% for the Bottomlands (B). Although there were increases in hill cells, the cells in the urban-industrial areas were approximately three times greater than those in the hills, while the increase in the bottomlands was relatively small. These urban differences would seem to represent alterations of dramatic proportions. It is of passing interest to compare these percentage increases to those obtained for single cloud seeding in Florida. Simpson *et al.* (1973) state, "The single cloud seeding factor on rainfall is virtually conclusively established as positive, in the vicinity of three." Thus, the increases in the L cell and those in the W cells are very comparable to Simpson's results for single cloud seeding since these increases indicate "seeding" factors in the vicinity of 2–3.

In relation to the seeding factors, there can be a recognizable bias associated with ratio estimates of mean precipitation in target and control areas. This situation can lead to an overestimation of the modification effect when rainfall distributions are highly skewed (Flueck and Holland, 1973). However, the volume data are well fitted by the log-normal distribution, and thus a logarithmic transformation can be employed to approximate normality. Even though the cell data are in reality complete populations, and not samples, the "*t*" test was applied to the L vs C and W vs C comparisons for both transformed and non-transformed volume data. The resulting *t* values were of similar magnitude for the transformed and non-transformed data. In fact, the *t* value for the L vs C comparison was larger for transformed data than for non-transformed data. Thus, although the possibility of bias is recognized, it is certainly inconsequential insofar as the volume data are concerned.

One of the problems inherent with the raincell analysis is that of cells not completely contained in the network. Because of this problem, the analysis was restricted to cells that were completely contained on the network. The analysis of complete cells, only, presents the possibility that the data may be biased toward the effect cells. This bias may occur because St. Louis is located in the center of the research circle, and has the greatest opportunity to sample the heavier, longer-moving raincells. To circumvent this difficulty, the cells were partitioned into 802 moving and 673 stationary[1] cells. Thus, if there is a bias toward sampling more of the longer moving cells in the urban area, the stationary cells provide a method of investigating the urban effect free of this bias. The results of the comparison of effect and non-effect cells partitioned according to moving and stationary cells are also listed in Table 1.

[1] A stationary cell has a core that remains at one location even though its outer boundary may fluctuate due to growth and dissipation along the boundary.

For cells in St. Louis the percentage increase is 114% in moving cells compared to 64% in stationary cells. For cells in Wood River the percentage increase was 152% for moving cells and 171% for stationary cells. Thus, over the two-year period, the percentage increase is larger for the moving cells in St. Louis and larger for the stationary cells in Wood River. For the hills and bottomlands, the percentage increases (or decreases) are relatively small. *The most important point is that the percentage increases occur in both stationary and moving cells.* Thus, if a bias is present in the moving cells, the percentage increases are also present in the stationary cells, which are not biased in this regard. However, it is noted that the moving cells produced a mean volume that is approximately 6–9 times greater than the mean volume for stationary cells.

Test comparisons were made between the cells of various pairs of the areas (L, W, H, B) and C. For each of the comparisons, discriminant analysis (Cooley and Lohnes, 1971) was employed to obtain a function which was a linear combination of all cell parameters except cell volume. (Cell volume was not used since it is the net result of the other parameters.) There were seven parameters in the discriminant function for all cells, ten in the discriminant function for moving cells, and seven in the discriminant function for stationary cells. (Parameters are listed in Table 5.)

Barlett's chi-square approximation (Cooley and Lohnes, 1971) was then employed to obtain χ^2 values for judging the ability of the functions to discriminate between the cells of two different areas. Thus, one summary statistic was obtained for each comparison to determine whether the cells in one area were different from those in another. This approach is superior to the procedure of obtaining a statistic for each parameter for this procedure would tend to overestimate the importance of a single parameter. The χ^2 values are compared to determine which comparison has the greatest difference in relation to sample size, but are not used as a strict accept-reject rule. The chi-square values for the various comparisons are listed in Table 2.

Although the discriminant analysis was performed on total populations of cells, it is of interest to consider what values of chi-square would be required for significance at the 10% level if these were random samples. For the L vs C and W vs C comparisons, the χ^2 values indicate that the cells would be significantly different than the control cells at the 10% level. Thus, the L and W cells appear to have different characteristics than the control cells. These differences are present in both moving cells and stationary cells with the exception of 1972 in the L stationary cells and 1971 in the W stationary cells. For the H vs C comparisons, the χ^2 values indicate that the cells in the hills would be significantly different from the control cells in both stationary and

TABLE 2. Chi-square values for test comparisons of effect and non-effect cells as obtained from discriminant analysis.

	Test comparisons				
	L vs C	W vs C	H vs C	B vs C	L vs W
			All cells		
1971	43.2*	23.0*	16.9*	7.0	15.5*
1972	104.0*	27.5*	6.6	5.7	4.2
1971–72	141.9*	38.2*	18.2*	9.5	9.6
			Moving cells		
1971	21.9*	16.4*	16.1*	6.9	19.6*
1972	72.9*	18.5*	6.0	2.7	9.7
1971–72	87.3*	18.2*	13.7	3.7	14.2
			Stationary cells		
1971	27.5*	4.3	18.9*	14.9*	16.7*
1972	11.8	22.1*	2.1	26.7*	10.2
1971–72	21.1*	14.8*	6.0	25.6*	6.1

* Significant at 10% level, if cells were randomly selected.

moving cells during 1971. For all cells, the H vs C comparison is significant in the 1971–72 period as well as in 1971. For the B vs C comparisons, the χ^2 values indicate that the cells in the bottomlands would be significantly different from the control cells during 1971 and 1972, and 1971–72 for stationary cells. For the L vs W comparisons, the L and W cells would be significantly different from each other for all cells, moving cells, and stationary cells in 1971, but not in 1972. It is emphasized that these are differences in the structure of the cells and not necessarily differences in overall rain production as indicated by volume. That is, one group of cells may have greater mean rainfall, but shorter duration than another group of cells, while the total rain production could be the same.

b. Meteorological and temporal conditions associated with the increase in rain production

The raincells were partitioned according to synoptic types used by Huff and Schlessman (1973). This partitioning reduced the sample to a size such that only squall lines, air mass and cold fronts had sufficient numbers of raincells to make a comparison between effect and non-effect cells. A comparison of cell volume from effect and non-effect cells according to synoptic type for the combined summers of 1971 and 1972 is presented in Table 3. In the control sample, the cold front cells were the heaviest rain producers, and the air mass cells were the lightest rain producers. In the St. Louis (L) and Wood River (W) cells, the rainfall was greater than the control in all three synoptic types. However, squall cells had the largest percentage increase in L, whereas cold front cells had the largest percentage increase in W. The squall cells also had the largest percentage increase in the Hills (H). The percentage differences in the H and B areas are in general smaller than those in L and W. Also, the negative differences are generally smaller than the positive differences, and both negative differences relate to small sample sizes. Thus, the negative differences have little meaning, unless they continue to occur as a larger sample is collected.

These findings are in agreement with Huff and Schlessman (1973) who found that most of the rainfall contributing to 1971–72 summer rainfall maxima east of St. Louis, and relatable to potential urban effects, was associated with frontal or organized non-frontal squall activity. They also indicated that in 1972, the major high in the Edwardsville area (immediately downwind of Wood River) was associated with rain from cold fronts.

The diurnal distribution of cell rainfall for the summers of 1971 and 1972 was investigated by dividing the cells according to occurrence in four periods, 0001–0600, 0601–1200, 1201–1800 and 1801–2400 (Central Daylight). The purpose of this division was to determine if the four areas representing potentially different source agents produced different effects during certain periods of the day. If so, this might provide indirect indications of the contribution of diurnal and urban heat inputs to the urban enhancement of rainfall. The urban heat island is most pronounced during the early morning hours in the city of St. Louis (Jones, 1973). The mean volumes for each area are listed in Table 4.

The control data revealed that the heaviest rainfall occurred during the maximum heating period, 1201–1800 and that the lightest rainfall occurred during the minimum temperature period, 0001–0600. This was also true for cells in the W and B areas. However, this was not true for L and H cells and the percentage differences in the L and H cells reveal some interesting departures from the diurnal trend of the W, B and C cells. For cells in St. Louis the increase for the two-year period is 172% for the period 0001–0600 and is larger than those for the other three areas during the

TABLE 3. Comparison of rainfall volume from effect and non-effect cells according to synoptic type for summer 1971–72.*

	Areas where cells developed and/or passed				
	St. Louis	Wood River	Hills	Bottom-lands	Control
			Mean value (acre-feet)		
Squall	357 (175)	514 (295)	216 (66)	161 (24)	130
Air mass	154 (71)	129 (43)	127 (41)	106 (18)	90
Cold front	315 (96)	836 (436)	100 (−38)	157 (−2)	161
			Sample size		
Squall	148	34	21	64	329
Air mass	73	14	23	33	239
Cold front	54	10	16	17	127

* Effect—control differences are expressed as percent of control in parentheses.

TABLE 4. Comparison of rainfall volume from effect and non-effect cells according to time of day for summer 1971–72 (mean value in acre-feet).*

Time	Areas where cells developed and/or passed St. Louis	Wood River	Hills	Bottom-lands	Control
	Mean value (acre-feet)				
0001–0600	177 (172)	87 (34)	109 (68)	57 (−12)	65
0601–1200	158 (100)	400 (406)	90 (14)	108 (37)	79
1201–1800	560 (187)	968 (396)	329 (69)	191 (−2)	195
1801–2400	276 (179)	159 (61)	165 (67)	148 (49)	99
	Sample size				
0001–0600	72	20	20	29	182
0601–1200	63	16	12	29	198
1201–1800	97	19	21	37	240
1801–2400	96	15	22	37	250

* Effect—control differences are expressed as percent of control in parentheses.

same period. Also, for the L cells, the percentage increase is nearly the same as that for the periods 1201–1800 and 1801–2400. Further analyses reveal that the percentage increase in the L cells during the 0001–0600 period is present in both 1971 and 1972 and is larger than those for the other three areas during the same period. This consistency indicates that the differences are not the result of bias from one year.

It would seem likely that the L percentage increase during the early morning hours may be due to the well-developed urban heat island during these hours. The magnitude of cell rainfall is less during this period, even though the percentage increase is large; this suggests that the increase is occurring with lighter rainfall. Duckworth and Sanberg (1954) indicate that the nighttime urban heating in three California cities has an influence extending to appreciable heights and capable of causing atmospheric instability, at least in a shallow layer over the city. Martin *et al.* (1967) indicate that the nocturnal inversion, which generally is close to the ground, is lifted to some distance above St. Louis. Auer and Dirks (1974) indicate that there is a pronounced doming of surfaces of discontinuous airflow over St. Louis during both day and night and they indicate that this may possibly be explained by thermal mechanisms. Also, Ackerman (1973) indicates that the nocturnal airflow can be perturbed over the St. Louis urban complex in the lower part of the boundary layer, and that this perturbation may extend through much of the boundary layer. This perturbation also results in convergence over the city in the lower 200–300 m. These findings suggest that at times low-level atmospheric instability is greater over the city during nighttime than in the area surrounding the city. The greater instability indicates upward motion and vertical transport of effluents such as heat, moisture, and gaseous and solid pollutants. Whether this upward motion is sufficient to produce convection cells of sufficient intensity to break through nocturnal inversions is uncertain. However, it represents the most likely mechanism for the percentage increase of rain in the 0001–0600 period.

For cells in the Wood River area, the largest percentage increases (Table 4) occur in the daytime period; the smallest percentage difference occurs during the 0001–0600 period. METROMEX temperature data indicate a much weaker heat island in the W area during the early morning hours (Jones, 1973). It is possible that the normal nocturnal inversions are not destroyed or penetrated as frequently over the W area as over the L area because the W area has a weaker surface nocturnal heat island. Thus, the effluents from the W area would not reach cloud base as often as in the L area, and would not contribute as much to a nocturnal rainfall increase.

For cells which occurred in the hills, the diurnal pattern is similar to that of the L cells, but the magnitude of the percentage differences is much smaller. Surface temperature data (Jones, 1973) show some evidence of a southwestward extension of the nocturnal heat island toward the hills.

c. The structure of the rainfall increase as revealed by cell parameters

In order to determine the structure of the rainfall increase, the percentage differences between the cell parameters of the effect cells and those of non-effect cells were determined for the combined summers of 1971 and 1972 (Table 5) and then compared. For

TABLE 5. Percentage differences* between parameters of effect cells and those of non-effect cells for summer 1971–72.

	Areas where cells developed and/or passed St. Louis	Wood River	Hills	Bottom-lands
	Moving cells			
Volume	114	152	35	−10
Mean rain	21	31	29	−8
Total area	68	28	22	2
Duration	38	8	15	−3
Maximum rain	32	29	18	−9
Maximum area	30	6	19	2
Path length	62	39	26	9
Velocity	13	24	7	11
Volume/time	25	56	6	−6
Mean/time	−13	15	−8	−6
Volume/path length	15	3	−8	−30
	Stationary cells			
Volume	63	169	8	23
Mean rain	18	111	19	1
Total area	17	12	11	19
Duration	−12	−5	2	8
Maximum rain	26	84	27	25
Maximum area	15	13	8	9
Volume/time	21	41	26	−18
Mean/time	6	25	33	−27

* Effect—control differences are expressed as percent of control.

TABLE 6. Comparison of the most important cell parameter in selected test comparisons as determined by standardized discriminant coefficients.

	Test comparison		
	L vs C	W vs C	L vs W
		All cells	
1971	total area	mean rain	maximum rain
1972	total area	total area	volume/time
1971–72	total area	total area	volume/time
		Moving cells	
1971	total area	mean rain	mean rain
1972	total area	volume/time	volume/time
1971–72	total area	volume/time	volume/time
		Stationary cells	
1971	total area	maximum rain	maximum rain
1972	maximum rain	maximum area	maximum area
1971–72	maximum rain	mean rain	mean rain

St. Louis (L), the volume parameter has the largest percentage increase in both moving and stationary cell classes. For the moving L cells, the parameter with the second largest percentage increase is total area (68%), followed by path length (62%) and duration (38%). For stationary L cells, the maximum rain, volume intensity (volume/time), mean rain, total area and maximum area all have percentage increases in the range 15–26%. Thus, for stationary cells, several parameters of area and intensity have approximately the same size of percentage increase.

For Wood River (W), the volume parameter also has the largest percentage increase in both moving and stationary cells. For moving W cells, the parameter with the second largest percentage increase is volume intensity (56%) followed by path length (39%), mean rain (31%) and maximum rain (29%). For W stationary cells, the second largest percentage increase occurs with mean rain (111%) followed by maximum rain (84%) and volume intensity (41%).

A comparison of W and L cells reveals that the area parameters dominate in the L cells, whereas the intensity dominates in the W cells. Furthermore, the overall intensity (mean/time) is greater in the W cells than the L cells. In fact, the overall intensity for L cells is slightly less than that for all cells in the control. The tendency for the L cells to be dominated by the area parameter and the W cells to be dominated by the rain intensity was stronger in 1971 than in 1972, and the overall characteristics of the cells in the two areas were more nearly the same in the 1972 data (see the L and W comparison in Table 2). In this regard, it is noted that the 1971 summer rainfall pattern was similar to that of dry summers, whereas the 1972 summer rainfall pattern was similar to that of moderate summers (Huff and Changnon, 1972; Huff and Schlessman, 1973).

The discriminant analysis failed to discriminate between stationary cells in the hills and stationary cells in the control. It also failed to discriminate between moving cells in the bottomlands and hills and moving cells in the control. Therefore, the percentage differences of the individual parameters have little meaning in these cases and are mostly due to sampling variation.

The standarized discriminant coefficients obtained from the discriminant analysis were used to determine the relative importance of the cell parameters in the L and W areas. The number of coefficients were 7, 10 and 7, respectively, for all cells, moving cells and stationary cells. These coefficients were ranked according to magnitude, and the parameter associated with the largest coefficient was judged to be the most important parameter in a given test comparison.

The most important parameter in discriminating between L and C cells was total rain area during 1971, 1972 and 1971–72 for all cells and moving cells (Table 6). For the W vs C comparisons the most important parameter was mean rain during 1971 for all cells and moving cells; total area was the most important parameter for all cells and volume/time the most important parameter for moving cells during 1972 and 1971–72. The most important parameters in discriminating between L and W cells were those related to rainfall intensity. This was also true for stationary cells in the L vs C and W vs C comparisons with the exception of 1971 in the L vs C comparison. These results indicate that two different physical processes were involved in 1971 in St. Louis and in Wood River. However, in 1972, total area was important in both areas for the all cells category and thus the cells appear to be more similar than in 1971. Also, the chi-square values in Table 2 for the L vs W comparisons and the mean volumes in Table 1 indicate that the L and W cells were more similar in 1972 than in 1971. Thus, the physical processes between the cells in St. Louis and Wood River appear to be different, but the differences appear to be much stronger in the 1971 data.

4. Conclusions and discussion

a. Conclusions

Analyses of the two-summer raincell data have provided a substantial amount of information and knowledge useful in identifying an anomaly at St. Louis. The results have also been useful as we begin the difficult task of identifying the precise causes of precipitation modification. The major results and conclusions derived from the various stratification analyses are listed below:

1) For cells that occurred in the urban-industrial region of St. Louis, the average rainfall volume was 176% greater than for cells in the control sample.

The most important parameter in discriminating between cells in the St. Louis area and those in the control area was total areal extent. The increase in volume was present in both moving and stationary cells.

2) For cells that occurred in the industrial region of Wood River, the average rainfall volume was 262% greater than for control cells. The most important parameter in discriminating between cells in Wood River and those in the control area was mean rainfall. The increase in volume was present in both moving and stationary cells.

3) For cells in the hill region southwest of St. Louis, the rainfall volume was 61% greater than for cells in the control sample. Thus, the increase in volume was approximately one-third of the increase in the urban and industrial cells. For cells that occurred in the bottomlands region, the increase in volume was very small, averaging only 15%. If one assumes that topographical and marine influences are present in the "urban cells," and these influences are no greater than the differences found for H and B cells, then these 15–60% influences can be calculated and substracted out of the "urban cells."

4) For cells which occurred in St. Louis, the largest percentage increase occurred with squall cells, and these were also the heaviest rain producers. For cells which occurred in Wood River, the largest percentage increase occurred with cold front cells, and these were also the heaviest rain producers. These results are in agreement with Huff and Schlessman (1973) who found that any substantial contribution from urban effects to the primary highs in the 1971–72 summer rainfall pattern were associated with frontal or organized non-frontal squall activity.

5) In general, the greatest cell rainfall occurred during the maximum heating period, 1201–1800 (Central Daylight), and the lightest during the coolest period, 0001–0600. However, the percentage increase of St. Louis cells over the control cells was 172% for the period 0001–0600. This percentage increase is nearly the same as that for the 1201–1800 period. Conversely, the largest percentage increase occurred for Wood River cells in the 0601–1200 and the 1201–1800 periods, while the least occurred during the 0001–0600 period.

METROMEX data to date establish that both St. Louis (L) and Wood River (W) are major nuclei sources. They differ as moisture sources and by thermal perturbations. The W area is suspected to be a greater moisture source and the L area definitely perturbs the thermal structure to a greater extent than W.

b. Discussion

There is strong statistical evidence that the raincells have been altered by the urban-industrial environment. Some differences between hypothesized effect and non-effect cells are so great, and the sample size so large, as to leave little doubt as to the reality of these differences. These analyses have provided a substantial amount of information useful for substantiation of the anomaly at St. Louis and useful for probing into the precise causes of precipitation modification. However, additional data must be collected to verify the two-summer results, permit additional meaningful stratifications of the data, and increase confidence in the present results from the synoptic and temporal stratifications. Such additional data will also help to identify further the physical causes of the observed differences.

Some raincell results, albeit preliminary, indicate that the causes of the rain changes in St. Louis are related to a dynamic effect induced by the urban heat island. Evidence includes (i) the large percentage changes found in cell rainfall during highly unstable squall conditions, (ii) percentage changes in the city cells during the 0001–0600 period (when the temperatures are lowest, yet the urban heat island is most pronounced), and (iii) the dominant influence of the cell parameters of total areal extent and maximum area per 5-min period. Findings in St. Louis and other cities indicate that atmospheric instability is greater over the city during nighttime than in the area surrounding the city. The greater instability indicates upward motion and vertical transport of vertical effluents such as heat, moisture and gaseous and solid pollutants. Thus, it is conceivable that part of the percentage increase could be due to nighttime urban convection cells caused by increased instability at or near the ground.

It is of interest to speculate on the physical causes for the greater areal extent of the city cells. It is conceivable that the primary effect of the urban heat island may be to produce a dynamic effect on the cloud structure. This would likely increase the areal extent of the downdraft, and since the rainfall begins with the onset of the downdraft at the surface, there should be a corresponding increase in the area of the surface rainfall. This horizontal cloud explosion has been demonstrated by Simpson and Wiggert (1971) in the dynamic seeding of single clouds in Florida. In fact, they demonstrated in the Florida experiment that it was probably the high wind shear in the later part of the 1968 experiments that inhibited seeded rain production by preventing the horizontal expansion of the cloud body.

The major differences found between the St. Louis and the Wood River cells indicate that the primary causes of the observed increases in the two areas may differ. The Wood River cell differences include: 1) the dominant influence of the cell parameters of mean rainfall, maximum rainfall and rainfall intensity; 2) the lack of a percentage increase in the 0001–0600 period (as indicated by the city cells); 3) differences in synoptic conditions most amenable to cell changes; and 4) the tendency for the structure of the raincell parameters in Wood River to be more similar to the cells in St. Louis during 1972, a relatively wetter summer than 1971. Available METROMEX data show that the Wood River area does not produce a thermal perturbation in the atmosphere comparable to that at St. Louis. However, Wood River does produce comparable CCN and ice nuclei quantities and may produce a low-level moisture anomaly in excess of that at St. Louis. Therefore, the characteristics (structure) of the W cells that differ markedly from those at St. Louis may indicate the changes in precipitation that result solely from nuclei and/or moisture additions into the atmosphere, particularly in dry summer conditions.

The above tentative explanations are based strictly on the observations of cell rainfall at the surface, and it is recognized that entirely different interpretations may be forthcoming when the detailed studies of radar, raindrop and aircraft data are completed. These explanations seem to relate to some of the observed characteristics of raincells at the surface, and are presented as working hypotheses for guiding further research of METROMEX.

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