Precipitation Changes in Fall, Winter, and Spring Caused by St. Louis

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ABSTRACT

Analysis of precipitation events in the St. Louis area, based on pre-event low-level wind flow, was pursued to ascertain the presence of urban effects on fall, winter, and spring precipitation. Data from a circular, dense, raingage network were used to define quadrant (NW, NE, SE, SW) average precipitation. Winds before each event (443 events in 1971–75) were used to define the urban plume and identify which quadrant was "downwind" of the city. Results for fall revealed a 17% increase in precipitation downwind of St. Louis and a 13% increase in events with their peak rainfall occurring downwind; both outcomes were statistically significant at the 1% level. The downwind enhancement was greatest when pre-event winds were from the SE, and when average precipitation in the quadrant with the maximum value was either light (<5.1 mm) or quite heavy (>17.9 mm). The fall results agree well with earlier findings for summer rainfall that revealed a 25% increase due to enhancement in isolated airmass showers and during heavier, well-organized convective systems. Winter precipitation indicated little precipitation change downwind of St. Louis. However, when SW pre-event winds existed (a flow often associated with convection), there was a statistically significant downwind increase in winter precipitation; but when pre-event winds were from SE or NW (flows frequently associated with stratiform precipitation), downwind decreases occurred. The number of spring precipitation conditions that maximized downwind of St. Louis was significantly greater than expected by chance particularly in light (<5.1 mm) events, but the total spring rainfall downwind increased only 4%. There was no suggestion of decreased precipitation in spring or fall. The urban influences to enhance precipitation appeared to be related to precipitation conditions with convective processes, and urban influences in more stratiform precipitation situations were negligible.

1. Introduction

Climatological studies of the past 25 years have indicated that major urban areas influence clouds and precipitation. In general, these have shown that urban effects lead to increased precipitation during summer months (June–August), with values in and downwind of the city reflecting increases of 5%–25% over background values (Landsberg 1970; Changnon 1968; Huff and Changnon 1973; Sanderson and Gorski 1978). Meteorological field studies of conditions at St. Louis and Chicago established that atmospheric effects resulted from urban increases in heating, mechanically induced convergence in the lower atmosphere, and urban-added aerosols (Changnon et al. 1981). Urban-enhanced rainfall occurred largely during existing rain situations and rainfall was often intensified during moderately heavy convective conditions (Changnon 1978). These results were further verified in a statistical analysis of the St. Louis summer precipitation data (Changnon 1979).

Climatological studies of urban precipitation effects during the colder seasons of fall, winter, and spring, have been more limited (Changnon 1983). Climatological analyses of cold season conditions have largely found lesser precipitation increases than in summer, but there have been no in-depth meteorological studies. Huff and Changnon (1986) analyzed historical data (1941–80) at St. Louis to examine for possible cold-season precipitation effects in St. Louis. Results indicated average precipitation increases in and beyond St. Louis of 14% in spring, 5% in winter, and 7% in fall.

It is difficult to evaluate inadvertent urban modification of precipitation because there can be no randomization between precipitation events as in purposeful weather modification, and thus, a "data analysis" approach that combines physical insight and statistical testing appears well suited (Tukey et al. 1978). A major 5-yr meteorological field project (METROMEX) was launched at St. Louis in June 1971 with a focus on study of summer conditions, and was terminated in September 1975 (Changnon et al. 1981). That effort included operation of a network of densely spaced recording raingages, and data collection was maintained during fall, winter, and spring seasons of this period.

This study utilizes the St. Louis raingage network data plus local wind data to examine possible urban effects on fall, winter, and spring precipitation relative to the low-level prestorm wind direction. The physical/

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statistical approach used herein was previously employed to analyze summer rainfall at St. Louis to discern possible urban-related precipitation changes (Changnon 1979). The precipitation analysis focused on two conditions: where each precipitation event maximized (relative to the pre-event wind direction), and on the magnitude of the maximum value. The basic hypothesis is that low-level winds moving across the urban area define a plume or atmospheric zone of urban-altered conditions (aerosols, heat, convergence, and/or moisture) that can affect precipitation conditions over and beyond or downwind of the city, as demonstrated by Shea and Auer (1978). Since 80% of all precipitation elements in the St. Louis area move from westerly directions, one would expect the greatest influence to be exerted somewhere east of the city (Changnon et al. 1976; Braham and Dungey 1978).

If urban influences on the atmosphere are real, a precipitation change downwind (based on the low-level wind, or plume direction, and not on the precipitation motion) of the city should potentially occur under any low-level wind direction. Hence, a change should be located northwest of St. Louis when low-level winds are from the southeast or north of the city with southerly winds, etc. For this reason, precipitation values downwind of the city were compared with those upwind and on each side of St. Louis, under different wind directions before each precipitation event began. Prior climatic research using limited historical data has indicated that urban influences on the atmosphere led to small precipitation increases in fall, winter, and spring, but this investigation examined for changes, either up or down, in the downwind areas.

2. Data and analysis

Precipitation data were collected at 116 recording raingages evenly distributed within a circle 80 km in diameter centered on St. Louis (Fig. 1). Studies of the precipitation data, analyzed in concert with synoptic weather conditions producing precipitation, revealed that 443 individual precipitation events occurred in the fall, winter, and spring seasons of four years, 1971–72 through 1974–75. Specifically, 154 occurred in fall (September–November), 110 in winter (December–

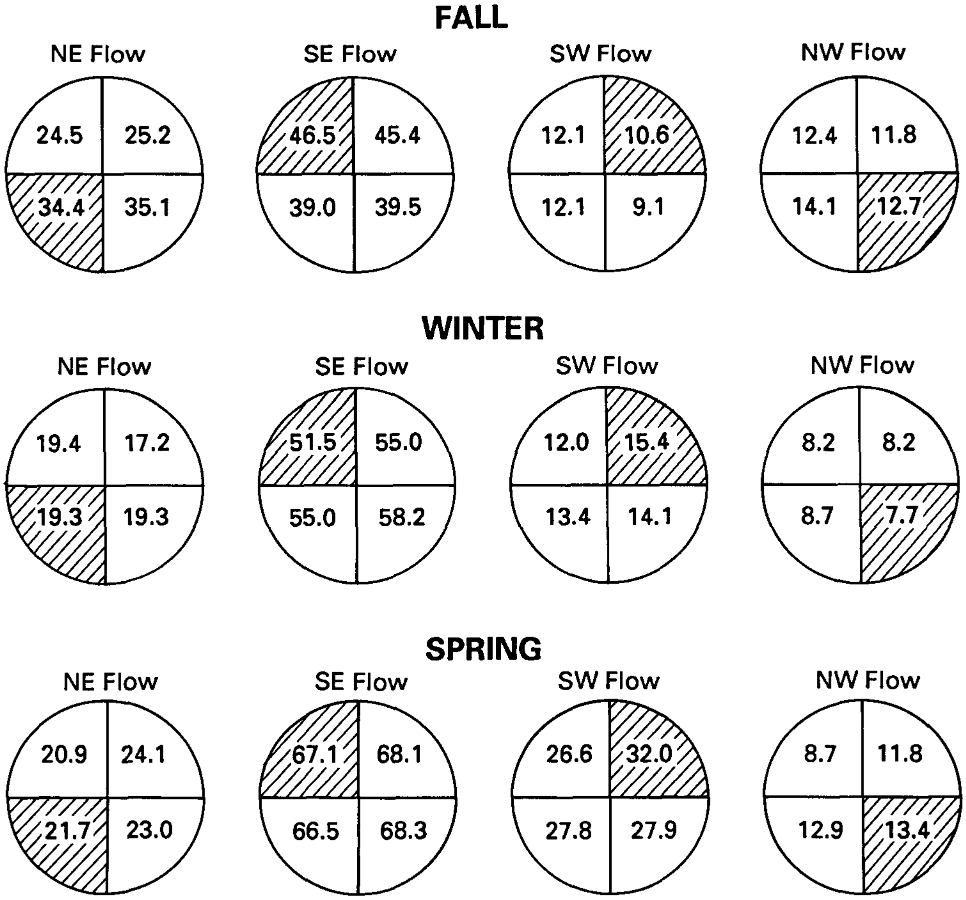

FIG. 1. Total seasonal precipitation (cm) for each pre-event flow direction, 1971–75 (downwind quadrant shaded).

February), and 179 in spring (March–May). A precipitation event was defined as a period of precipitation over two or more raingages in the network area, separated in time from another period of precipitation by six hours or more, and having a definable synoptic weather condition associated with it.

For each precipitation event, the low-level wind direction during the three hours prior to the precipitation was determined as in one of 16 directions from the available wind data at five area stations, coupled with an analysis of the synoptic weather conditions causing the events. The prevailing winds before the rain were used to provide a general estimate of the pre-precipitation placement of the urban plume, and hence defined the area of influence. Whether the urban influence on any given day is related to temperature, moisture, altered convergence, aerosols or all of these factors is unimportant here; the urban plume serves only as a means of defining the "downwind" area of potential urban influence on the atmosphere, and the "upwind" area of no influence.

The circular network of raingages was divided into four equally sized quadrants (Fig. 1), each containing 29 recording raingages. The pre-precipitation event, wind directions were sorted into four basic directions of motion: NW, NE, SE and SW. Then, for each direction, the precipitation for each rain event was calculated for each quadrant by averaging the 29 values. Monthly and seasonal values were then calculated from the inidividual events, as sorted for preevent wind direction.

Four statistical tests were employed to determine if the quadrant downwind of St. Louis tended to receive a significantly different amount of precipitation. The tests were chosen to answer two basic questions: 1) is the proportion of rain events where the maximum rainfall occurred downwind significantly greater than that obtained by chance, namely 25%, and 2) does the difference between the measured rainfall in the downwind and the upwind quadrant tend to be significantly greater than zero?

Two tests were used to assess the first question. First, if there is no effect from the urban area on downwind precipitation, the number of events where the maximum rainfall occurred downwind would be a binomial variable with a success rate of 25%. The binomial test was consequently used to test the hypothesis that this success rate was different than 25%. The second test used each rain event's quadrant ranks: the wind-relative quadrants (downwind quadrant, etc.) were ranked by decreasing magnitude of rainfall. That is, the quadrant in each event with the highest rainfall was assigned a rank of 1, and the one with the lowest was assigned a rank of 4. If there is an effect on downwind rainfall due to the urban influence, the average rank of the downwind quadrants would be significantly less than the chance average rank of 2.5 $[(1 + 2 + 3 + 4)/4]$. A test of downwind quadrant ranks, similar to that used in Changnon (1979), was used to statistically examine this condition.

The two remaining tests, the Wilcoxon signed-rank test and the sign test (see Bickel and Doksum 1977) assessed the second question. The Wilcoxon test was used to detect whether a positive difference existed in the measured rainfall between the downwind and upwind quadrants. The null hypothesis, that the statistical distribution of this difference is symmetric about zero, would indicate that there is no effect on precipitation due to the influence of St. Louis. The one-sided alternative that the difference between downwind and upwind rainfall is positive was examined by this test. The sign test also was used to detect a positive difference between downwind and upwind rainfall, but only the signs of the differences of the individual rain events, not the magnitudes, were considered (the Wilcoxon test also considers the magnitudes). If the proportion of precipitation events with positive (downwind–upwind) differences is significantly greater than 50%, then this is evidence that the downwind rainfall is significantly greater than upwind rainfall.

The Wilcoxon and sign tests were used in tandem to address the significance of (downwind–upwind) rainfall differences because one test exhibits better power to detect these differences in some situations, whereas the other exhibits better power in others. Thus, both were used to assure adequate power in a wide variety of testing circumstances. For example, if only light precipitation events (e.g., <5.1 mm) were considered, the Wilcoxon test is more powerful than the sign test in the detection of greater downwind rainfall. However, if a wide variety of precipitation events (e.g., those between >2.5 mm and <17.8 mm) are being considered, the Wilcoxon test can lose power by integrating data with widely varying but opposite differences. Hence, the sign test is essential. In general, the Wilcoxon test is used when a restricted-by-magnitude group of rain events is tested; and the sign test is appropriate when a larger, less restrictive group is considered for assessment. In addition to the four tests discussed above, a multinomial test was used in certain instances to test for the difference of percentages of events in two quadrants.

3. Climatological analysis

a. *Precipitation amounts: seasonal*

Figure 1 presents the total precipitation found in each quadrant for the three seasons, classified according to the four preevent wind directions. The NE flow map for fall shows an upwind area value of 25.2 cm compared with a downwind value of 34.4 cm. This latter value ranks the downwind area as the third highest value of the four in fall with NE pre-event winds. Spring downwind values rank as the highest when SW and NW flows occurred. However, little apparent urban effect in amounts is seen in spring with the NE and SE pre-event wind conditions.

In the fall season, a notable outcome is with SE flow, the conditions that produce approximately half of the total fall precipitation. Under these conditions (SE winds), a marked increase occurs in the downwind area. The downwind quadrant values with NE and NW flows in fall rank as the second highest.

Results for winter precipitation amounts are markedly different from the other two seasons. The downwind quadrant value is the highest of the four quadrants with SW flow (downwind value 15.4 cm versus upwind of 13.4 cm), but in SE flow (as in all seasons, the heaviest seasonal precipitation situation) and NW flow, the downwind quadrant values are the lowest of all four quadrants. This suggests urban effects under certain conditions may also act to decrease winter precipitation downwind of St. Louis.

One can examine the rank values achieved by the values of the downwind quadrants based on the 12 possible seasonal outcomes found on Fig. 1. The downwind values achieve rank 1 (highest possible value) in four instances, which is one more than would be expected by chance, with three outcomes achieving rank 2. There is no strong indication of urban effects when the three seasons are considered together. However, analysis of the seasonal amounts according to preevent winds suggests that urban enhancement might be present in precipitation conditions preceded 1) by SW flow (with a downwind maximum in two of the three seasons), and 2) by NE flow (with downwind increases that were at or near maxima in the fall and winter seasons).

In order to investigate increased downwind precipitation due to urban enhancement regardless of pre-event wind direction, all quadrants for each rain event were classified as "downwind," "upwind," "left" (relative to upwind direction) and "right" (also relative to upwind direction). The total precipitation for each season was subsequently calculated for the downwind, upwind, left, and right quadrants, separately. The resulting values, those adjusted regardless of wind direction, for the three seasons appear in Fig. 2. The fall map shows an upwind value of 89.2 cm and a downwind value of 104.6 cm, indicating a 15.4 cm increase over the upwind value (17%). The winter pattern shows a different outcome, with the downwind quadrant total of 94 cm being 3 cm less than the upwind, a 2% decrease. Spring precipitation totals show a 4% downwind increase with the value being 5.2 cm more than the upwind. These values compare very favorably with the climatological findings of Huff and Changnon (1986) based on historical (1941–80) data from fewer stations and using regional precipitation pattern analyses. In general, these results suggest that an urban effect leading to increased precipitation amounts exists in the fall, but is negligible in spring and not present in winter. The fall increase is largely due to the increase under SE and NE flows, the wetter of the four wind directions (Fig. 1).

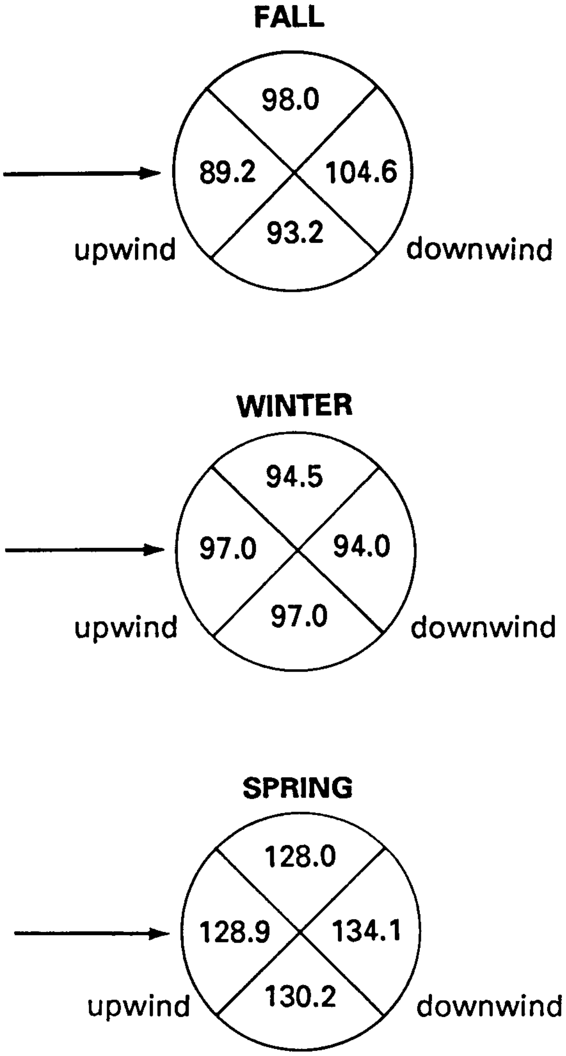

FIG. 2. Quadrant precipitation values (cm) for each season based on combining quadrant values in all events based on pre-event wind flow direction (shown as arrows).

b. Precipitation events

Individual precipitation events were analyzed to examine the relative frequencies of maxima in each of the four quadrants, relative to the preevent wind direction. Table 1 presents the percent of all events maximizing in each quadrant. The percentage expected with no urban-related precipitation effects in each quadrant would be 25%. The downwind quadrant values of 38% in fall and 36% in spring are strongly suggestive of urban-related increases. They are both significantly greater than 25% at the 0.1% level, using the binomial test. No apparent effect exists in winter in any quadrant although the 17% value in the left

TABLE 1. Percent of maximum quadrant precipitation values, per precipitation event, occurring in each quadrant.

	Upwind[2]	Left[1]	Right[1]	Downwind[2]
Fall	23	21	21	38
Winter	28	17	28	27
Spring	23	21	20	36

[1] Left with respect to flow from upwind; right with respect to flow from upwind.

[2] Upwind of St. Louis and downwind of St. Louis.

quadrant could be considered indicative of a decrease due to urban effects; this value is significantly less than 25% at the 5% level.

Figure 3 presents the monthly percentages of all storms that maximized in the downwind and upwind quadrants for each month. Their differences are potentially indicative of the presence and magnitude of urban effects acting to maximize event rainfall downwind of the city. One notes clear differences (potential increases) in September, October, and November. Then, little difference between upwind and downwind frequencies of maximum precipitation in events occurs in December, January, and February. The downwind frequency of increased precipitation events reappears in March, April, and May, realtive to the upwind frequency. The slight reversals in percentages during December and February may also reflect periods of minor decreases due to urban influences. However, the percentage differences in both December and February were not significantly negative at the 5% level, using a multinomial test.

The frequency of precipitation events achieving a maximum precipitation value in the downwind quadrant was analyzed according to preevent wind directions in each season. Examination of the fall percentages shown in Table 2 indicates possible downwind enhancement (values >25%) with respect to all four wind directions, with the largest enhancement effect coming with NW preevent flow. Spring values also show well above 25% in all four wind classes, but in the winter, only the SW flow value shows much above expectation, in agreement with total winter precipitation amount for SW flow, as shown in Fig. 1. It was found using the binomial test that the downwind rainfall was significantly enhanced (at the 5% level) in fall when pre-event flow was from the SE, NE, and NW; then in winter when there was SW flow; and in spring when there was SW or NW flow.

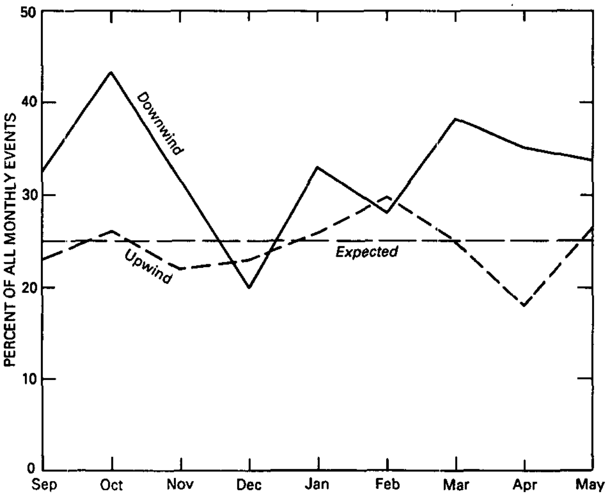

FIG. 3. Percent of all precipitation events in each month that maximized in the quadrant upwind and in the quadrant downwind of St. Louis,

Consideration of the wind direction results in Table 2 reveals: 1) slightly higher than chance (>25%) percentages downwind of St. Louis with SE flow in all seasons; 2) consistently relatively high downwind values with pre-event SW flow in all seasons; and 3) higher than chance values in all seasons with NE flow. The NW pre-event wind values are of interest, being significantly high percentages in fall and spring (more than 40%, a 2% level of significance), but quite low in winter, at only 13% (significantly lower than 25% at the 10% level). This small winter value with NW flow strongly suggests that a decrease due to urban effects on winter precipitation conditions occurs with precipitation events preceded by NW flow. This outcome is supported by the amount of winter precipitation with NW winds (Fig. 1). These were typically postfrontal precipitation conditions associated with a secondary cold front or with the passage of an Alberta low.

The potential effect of urban influences on different classes of even precipitation, light to very heavy, was examined. The amount of precipitation in the quadrant with the maximum amount was used, and the values were scaled to seven levels, as shown in Table 3. The frequency of total events maximizing in the downwind quadrant was expressed as a percentage of all events; these are also shown in Table 3 and Fig. 4 to help illustrate seasonal differences. In essence, results for all three seasons suggest an urban influence to enhance precipitation in the very light events with percentages much greater than 25%, with events having 0.3 (lowest

TABLE 2. Number of precipitation events achieving a maximum precipitation value in the downwind quadrant, with the number expressed as percent of all events occurring with a given pre-event wind direction.[1]

	SE	SW	NE	NW
Fall	33	31	38	45
Winter	27	46	30	13
Spring	32	37	36	42

[1] A value of 25% is expected by chance.

TABLE 3. The number of times the maximum event precipitation, based on quadrant values, occurred in the downwind quadrant, expressed as a percent of total events in selected class intervals.

Class intervals of maximum precipitation in any quadrant, mm	Fall		Winter		Spring	
	Total events	Percent in downwind	Total events	Percent in downwind	Total events	Percent in downwind
0.3–2.5	48	40^2	42	31	51	33
2.6–5.0	16	44^1	14	21	25	52^2
5.1–7.6	12	25	9	22	16	25
7.7–10.2	10	30	6	33	16	44^1
10.3–12.7	7	43	6	$50^{1,3}$	8	25
12.8–17.8	12	25	8	25	22	27
>17.9	20	45^2	16	13	29	31
Total	125	38^2	101	27	167	35^2

[1] Significantly greater than 25% at the 5% level of significance, using the binomial test.
[2] Significantly greater than 25% at the 1% level of significance, using the binomial test.
[3] Caution should be taken in interpreting this value's significance since there were few events.

measurable level) to 2.5 mm as the peak precipitation value. These include 40% in the fall in the downwind quadrant, 31% in the winter, and 33% in spring. The fall percentage of 40% is significantly greater than 25% at the 1% level, according to the binomial test, and at the 7% level with the Wilcoxon test. The spring percentage of 33% is significantly greater than 25% at the 10% level using the binomial test and at the 1% level using the Wilcoxon test.

Enhancement in the downwind quadrant is further reflected in the next to lowest class interval, 2.6–5.0 mm, in the spring and fall seasons; in fact, this enhancement is significant in both seasons at the 1% level. No evidence of downwind enhancement of precipitation in any season occurs with events in the 5.1–7.6 mm class, but in the 7.7–10.2 and 10.3–12.7 mm classes there is weak evidence of downwind enhancement. The winter precipitation events with peak values of 10.3–12.7 mm show significantly high percentages, as does the fall value for heavy rains, those of 17.9 mm or higher. The season with the most marked urban-enhanced precipitation, fall, is due to enhancement in the light and heaviest precipitation events. The winter results (Fig. 4) exhibit potential urban enhancement in moderate precipitation with a suggestion of a decrease downwind in the heavier events.

The percent of precipitation events with a maximum in the downwind quadrant for the precipitation classes showing the greatest enhancement appear in Table 4. The values have been stratified by wind directions prior to the precipitation events. Examination of the directional percentage values for the fall season (and the three class intervals shown) reveals an enhancement in the downwind quadrant with all wind directions when there was more than one precipitation event in wind–rain-level class. When pre-event winds were from the NW, 43% of all events peaked downwind in the 0.3–2.5 mm level, 100% (all events) in the next level (2.5–5.6 mm), and 60% of all events producing more than 17.9 mm peaked in the downwind quadrant.

The spring directional analysis for the class intervals with significant downwind increases (Table 4) shows that most directional values are above 25%. Percentages for all directions suggest marked increases, except in two cases, indicating wind direction in spring was not important to the development of urban effects.

The winter results for the light interval with enhancement (0.3–2.5 mm) indicate sizable percentages (downwind increases) under conditions of southerly

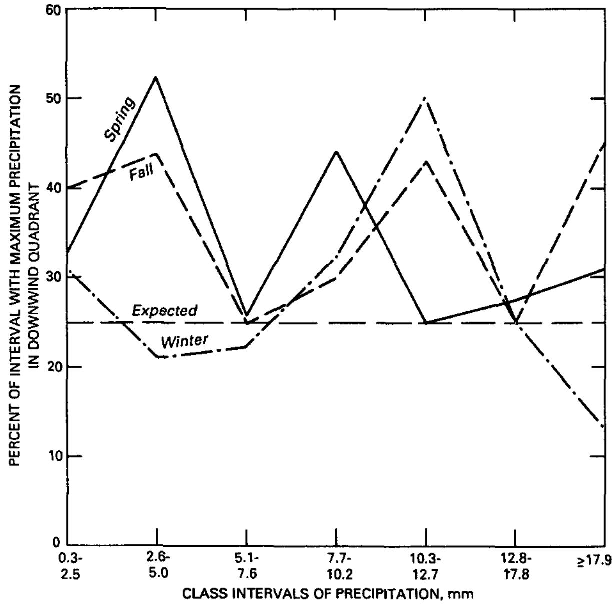

FIG. 4. Percent of all seasonal precipitation events maximizing in the quadrant downwind of St. Louis, based on average quadrant precipitation events.

TABLE 4. Percent of events with pronounced seasonal maximum in downwind quadrant (for precipitation classes exhibiting greatest urban enhancement, as based on values in Table 3).[1]

		Wind direction			
		Fall			
Class interval, (mm)	All events (%)	NW (%) (events)	SW (%) (events)	SE (%) (events)	NE (%) (events)
0.3–2.5	40	43 (14)**	50 (8)**	29 (17)	44 (9)**
2.6–5.0	44	100 (2)**	50 (4)	44 (9)	0 (1)*
≥17.9	45	60 (5)	33 (3)	66 (9)**	33 (3)
		Spring			
0.3–2.5	33	25 (12)	29 (14)	37 (19)	59 (6)**
2.6–5.0	52	100 (4)**	63 (8)**	43 (12)**	0 (1)*
7.7–10.2	44	50 (4)	66 (3)	43 (7)	0 (2)
		Winter			
0.3–2.5	31	15 (13)	33 (6)	47 (17)	17 (6)
10.3–12.7	50	0 (1)*	66 (3)**	0 (1)*	100 (1)*

* One storm only in these classes.

** Significantly greater than 25% at the 5% level.

[1] Numbers in parentheses signify number of events.

flow (SW or SE) prior to the precipitation. Conversely, the NE and NW values suggest a downwind decrease. The enhancement in the 10.3–12.7 mm category (Table 3) was due to downwind increases with SW and NE winds.

4. Analysis of seasonal results

a. Fall

The fall season results suggested a measurable urban effect on precipitation, primarily an enhancement of 17% in the amounts in the downwind area; with 38% of all fall precipitation events achieving their maximum value in the downwind quadrant, versus the 25% expected there by chance. Most of the increased precipitation occurred with the preevent winds from the NE or SE (the two conditions of heaviest fall precipitation, Fig. 1, and greatest likelihood that it will be convective). When precipitation winds were from the SE, heavy and widespread convective storms occurred, associated with a short wave aloft, surface cold fronts, and differential heating along a cloud area. The fall months of greatest enhancement were September and October, and the results collectively indicated that the urban enhancement of rainfall in fall was related to atmospheric effects during convective storms. This agrees with earlier results on urban rain enhancement during summer months (Changnon et al. 1981).

The frequency of precipitation events that peaked in the downwind quadrants was above expectation in all three fall months, September through November. The frequency of enhanced events downwind of St. Louis was found under all four wind directions but was greatest under NE (38%) and NW flows (45%).

Since summertime precipitation is enhanced by urban influences (Changnon et al. 1981) generated, in part, from a greater surface heat capacity (and thereby, increased surface temperatures) of the city versus the rural areas surrounding it, it is logical to assume that this process would continue, at least into the early fall (September–October). Therefore, the relatively intense heat island of summer would tend to be maintained during the many clear, dry and still warm days of early fall. This, in turn, would provide added support for enhanced vertical air motions over the city, destabilization of the local environmental air mass, and increased potential for enhanced precipitation over and downwind of the city. This process should act to increase rainfall, regardless of the prestorm wind direction. However, it remains true that the ambient conditions are different with different plume winds, and the level of enhancement is reflected in those directions whose advecting air masses have the greatest potential instability.

b. Winter

The winter findings were quite dissimilar to those of fall and spring. When all winter precipitation amounts were summed according to wind direction, the downwind area had slightly less precipitation (2%) than the upwind value. Under SW and NE flows, the downwind quadrant showed enhancement of total precipitation. These results may be expected because SW prestorm flow in winter was typically related to cold frontal passages, and these conditions provide for the best convective conditions during winter. The strongest interaction between the subtropical/tropical air mass to the south and the approaching arctic/polar air mass was found along the cold front south of the surface cyclone, often leading to convective activity in the St. Louis area. The dynamics of the air to the south was usually weak and SW flow developed. Northeasterly prerain flow in winter was also found to be weakly convective due to deep cyclone passages to the SE. The direct overrunning of warm, moist air to the south (aloft of the colder surface air) frequently caused convective bands of precipitation under these conditions.

Under NW pre-event winds, the winter downwind values show a decrease. Northwest pre-event flows commonly occurred in postfrontal conditions with strong winds aloft, low moisture content, shallow cloud depths, and light precipitation. The winter analysis indicates that the urban area acts either to increase or to decrease the amount of downwind precipitation, depending on wind directions prior to precipitation and the prevailing types of weather conditions producing the precipitation.

c. Spring

Several spring results were similar to those in fall, and this likely reflects the fact that urban effects that act to enhance precipitation are most evident during convective preicpitation conditions, and these typically begin in the St. Louis region during late March or April and continue well into October (but are infrequent in the winter). Precipitation quantities in spring with all amounts stratified according to wind direction, indicated a weak increase (4%) downwind of the city. Amounts downwind were enhanced during SW and NW pre-event flow conditions, but with no apparent effect when SE and NE preevent winds existed. The frequency of maximization of spring precipitation events showed greater evidence of urban enhancement than did precipitation amounts with 36% of all spring precipitation events attaining their maximum in downwind quadrants. Most event enhancement was found with light (<5.1 mm) rain events. Spring precipitation-event frequency exceeded chance expectations in all months and under four preevent wind directions. Southeast pre-event winds occurred commonly with frontal conditions and some form of convection.

5. Conclusions

This study used low-level winds before precipitation events to indicate the area downwind of St. Louis and where urban-induced changes in precipitation would be expected in the fall, winter, and spring seasons. The results for the fall season revealed a marked increase of precipitation downwind of St. Louis. The downwind enhancement was most pronounced during September and October, but still present in November precipitation amounts. The beyond-city (downwind) maximization in fall occurred in both the quantity of precipitation (+17%) and in the frequency of precipitation events that maximized beyond St. Louis (+13% above expected frequency). Both changes were found to be highly statistically significant at the 1% level and apparent in all four statistical tests used (binomial, Wilcoxon signed-rank, sign test, and test of downwind quadrant ranks). Winter precipitation conditions indicated little change in precipitation quantity downwind of St. Louis.

In spring, the amount of downwind precipitation change, by averaging all wind directions, was small, only 4%, and this change was not statistically significant. However, the frequency of precipitation events achieving maximum precipitation in the quadrants beyond St. Louis was 36%, much above chance (25%) and statistically significant in the binomial test.

The results have implications relating to the conditions under which St. Louis acts to influence the atmosphere sufficiently to alter precipitation conditions. In general, the results reveal an enhancement of rain occurred when conditions conducive to convection existed. Enhancement of precipitation downwind of St. Louis during the two transition seasons, fall and spring, was similar. The enhancement came 1) either when rainfall was light or moderate to heavy, 2) when large-scale convective activity was present, and 3) under any prerain wind direction. This agrees with summer season findings (Changnon et al. 1981), and with prior season research (Huff and Changnon 1986).

Little evidence of increases was found when winter stratiform precipitation conditions existed, and downwind decreases in winter came with postfrontal stratiform precipitation. The results, in general, indicate that when the atmospheric dynamics are strongest, as in late fall, winter, and early spring, urban influences sufficient to alter precipitation are negligible. The lack of precipitation increases in winter when the urban area (as compared to rural areas) is relatively warmer and more moist than it is in early spring, summer, and fall, suggests these urban factors are not the critical ones for altering the precipitation-forming environment.

The winter results suggest urban heating and moisture changes are not critical factors; the transition seasons results suggest that urban-produced aerosols (cloud condensation nuclei and/or ice forming nuclei), and/or urban-induced strengthening of the boundary layer convergence (and resulting upward air motions), were the most critical atmospheric factors leading to precipitation increases. Inadvertent cloud modification may be occurring to initiate more often the rain process in convective clouds, as noted in summer clouds (Ochs and Johnson 1979). The fall and spring downwind rain enhancement, when light quadrant rainfall occurred, existed on days when very few isolated small rain showers developed. This finding is similar to those for summer conditions with localized enhancement of first echo activity in cumulus congestus clouds (Braham 1981). Urban-induced convergence leading to earlier and more clouds, to more rain-producing clouds (Braham and Dungey 1978), and to more mergers of convective storms (Changnon et al. 1976) also seems highly likely in fall and spring, as noted in summer (Braham 1981). The summer findings for St. Louis established that urban influences were most prevalent in moderate to heavy convective activity (Changnon et al. 1981).

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