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Synoptic Analysis of Heavy Rainstorms over Urban Areas in the Southern United States*

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미국 남부지방 도시호우의 종관적 분석*

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Abstract : The purpose of this paper is to determine the atmospheric conditions in which urban areas affect the precipitation processes and to evaluate whether certain weather types show more apparent urban effect on precipitation modification over five cities in the southern United States. Each heavy rainstorm is classified into one of three synoptic weather types (frontal storm, airmass storm or tropical disturbance storm). Heavy rainstorm day is defined as a day producing rainfall totals that equal or exceed 2 inches (50.08 mm). Houston, Dallas and San Antonio show possible urban effects on rainfall totals and frequencies of heavy rainstorms by airmass storm type while New Orleans and Memphis do not reveal any distinct precipitation enhancements through the synoptic analysis. The results of TSA (Trend Surface Analysis) show that frontal and tropical disturbance storm types have stronger climatic gradients than airmass types and the patterns of rainfall totals have stronger trends than those of rainfall frequencies for the five cities. The results suggest that airmass type events may well reveal possible precipitation enhancements due to urban effects since they are less influenced by a strong climate gradient and they provide favorable conditions for development of urban heat islands. Residual analysis confirms that rainfall totals and frequencies of heavy rainstorms by airmass storm type have positive residuals over the city or the major effect area.

Key Words : synoptic analysis, heavy rainstorm, urban effect, trend surface analysis (TSA), residual analysis

요약 : 미국남부지방의 5개 도시를 연구지역으로 도시의 영향에 의한 강수특성변화를 파악하고 종관기상유형에 따른 특성을 규명하기 위하여 2 인치 (50.08 mm) 이상의 일강수량을 가지는 강수일을 선택하여 3가지 강수유형 (기단성 강수, 전선성 강수, 열대저기압성 강수)으로 구분하여 분석하였다. Houston, Dallas, 그리고 San Antonio 에서는 기단성 강수가 발생할 때, 도시지역과 풍하측에 호우로 인한 강수량과 강수빈도의 증가가 나타나고 있으나 New Orleans와 Memphis에서는 종관적 분석을 통해서 볼 때 현저한 증가현상을 보이지 않는다. 경향면 분석결과는 전선성 강수와 열대저기압성강수 발생시 기단성 강수로 인한 호우보다 강한 경향성을 가지는 것을 보여주고, 호우로 인한 총강수량은 강수일수빈도보다 강한 경향성을 가진다. 잔차도 분석결과는 기단성 호우 발생시 도시지역과 풍하지역에 양의 잔차가 나타나는 것을 보여준다. 미국 남부의 5개도시에서 강수특성변화에 미치는 도시화의 영향에 대한 연구는 도시기후는 종관적으로 유사한 조건하일지라도 도시의 규모, 공간구조, 수체의 유무, 산업구조 등 다양한 특성에 따라 상이하게 반응함을 알 수 있었다.

주요어 : 호우, 종관적 분석, 도시의 영향, 경향면분석, 잔차분석

1. Introduction

Classified as meso-scale or even micro-scale, urban effects on climate have been well recognized during this century, associated with the sharply accelerated urbanization trend. In general, the temperature of urban areas is higher than that of rural areas and cloud cover, total precipitation amounts, and thunderstorms in urban areas are more than those in rural areas (Chandler, 1970;

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Oke, 1974; Landsberg, 1981; Lee, 1984). However, of many weather conditions influenced by urban area, precipitation is the most controversial in characterizing the urban climate. General conclusions for precipitation modification due to the urban area might be summarized as follows: 1) whereas all intensities of daily rainfall appear to be increased by inadvertent weather modification in the vicinity of large cities, the most pronounced effect appears to be on those days with moderate to heavy rainfall; 2) the inadvertent modification is most pronounced in the warmer seasons; 3) both thermal and aerosol inputs can lead to increase precipitation from existing storm systems; 4) when cloud treatment is uncontrolled, increases in surface precipitation are very likely to be accompanied by increase in the frequencies of severe weather events; and 5) precipitation enhancements are likely to occur more downwind of the city than within the city (Huff and Changnon, 1973; Dettwiller and Changnon, 1976; Sanderson and Gorki, 1978; Changnon, 1980; Faiers, 1994). Also, it was suggested that if the urban environment affects precipitation significantly downwind of urban areas this would be reflected in the precipitation patterns when the data for each rainstorm is stratified by synoptic weather types (Vogel and Huff, 1978).

The purpose of this paper is to determine the atmospheric conditions in which urban areas affect the precipitation processes and to evaluate whether certain weather types show more apparent effects on precipitation modification over five major cities in the southern United States. To archive this goal, the synoptic or meso-scale weather features that produce heavy rainstorms have been classified by a manual process. Heavy rainstorm day is defined as a day producing rainfall totals that equal or exceed 2 inches (50.08 mm), and is classified into synoptic weather types on a daily basis without considering how many rainstorms happened in a day.

2. Study Areas

Six states (Texas, Oklahoma, Arkansas, Louisiana, Tennessee and Mississippi) are included in the study area of Southern Regional Climate Center (SRCC) which is one of the six regional climate centers in the United States. The five largest cities are selected for the study of precipitation modification due to urban area: Houston, Dallas, San Antonio, New Orleans, and Memphis. The general geography of study areas was discussed in Choi and Henderson (1995).

Overall, all five cities are included in the subtropical climate region where there is abundant rainfall with no distinct dry months. They are dominated by the maritime tropical air which flows inland from the anticyclonic circulation of subtropical high cells during summer. The climate is very hot and humid because the air from subtropical highs flows onto the land from the lower latitudes with a path over warm water of the Gulf of Mexico (Critchfield, 1966). Summer precipitation is primarily from airmass thunderstorms. Hurricanes occasionally visit the coast in the late summer and autumn and increase the monthly rainfall totals during those seasons. As the polar front moves into the region, thunderstorms of the frontal type are common in the converging poleward flow of air drawn into the warm sectors of cyclones. In winter, these areas are influenced primarily by the belt of mid-latitude cyclones, with two main airmass types being continental polar and maritime tropical. Winter precipitation is mostly related to fronts (Trewartha, 1981).

3. Data and Methodology

1) Data

The primary source of data for this study is daily precipitation data published by the National Climate Data Center (NCDC) of National Oceanic and Atmospheric Administration (NOAA) for Texas, Louisiana, Mississippi, Arkansas and Tennessee during the period of 1961-1990. The first-order and cooperative stations which are located within 62 miles (100 km) of each city and have less than 10% missing data, are used for the study (24 stations for Houston; 34 stations for Dallas; 26 stations for San Antonio; 21 stations for New Orleans; and 23 stations for Memphis). Daily weather maps (1961-1990) published by the National Weather Service (NWS) are used to identify the basic synoptic storm type associated with each heavy precipitation day over urban areas.

2) Methodology

A major problem in studying urban effects on precipitation is defining the area of potential effects (Huff and Changnon, 1972). For this study, the same method which was used for the St. Louis area was applied. Each urban area is divided into the following 5 regions: 1)urban areas; 2)the major effect area; 3)the minor effect area; 4)the upwind control area; and 5)the downwind control area. Various techniques have been employed in an attempt to establish the existence of urban effects on rainfall totals and frequencies of heavy rainstorms. First, spatial patterns of rainfall totals and frequencies of heavy rainstorms by each synoptic type are mapped and analyzed to examine the existence of urban effects on enhancement of precipitation over downwind and five cities. Second, Trend Surface Analysis (TSA) is applied to examine the existence and magnitude of climate gradients. The southern United States has a strong climatic gradient (trend) on the precipitation distribution which increases from W to E because the moisture content of the atmosphere decreases with the distance from the Gulf of Mexico (Lydolph, 1985). If there is a strong climate gradient from E to W over study areas with a maximum over a city and the city has higher mean value of rainfall totals and frequencies than E of the city, it might be confirmed that there is precipitation enhancement due to urban effects over the city. Third, statistical methods such as t-test and Wilcoxon-Mann-Whitney test are used to evaluate the statistical validity of precipitation modification. Fourth, residual maps are drawn after eliminating a natural gradient for the patterns of rainfall totals and frequencies which have statistically significant %RSS (percentage reduction in sum of squares achieved) values. Finally, temporal changes are examined through time series analysis (moving average and simple linear regression methods). Mathematical and analytical details about Trend Surface Analysis and residual analysis were discussed in Choi and Henderson (1995).

Table 1 shows one method for defining synoptic weather types applied for the study of urban effects on precipitation modifications in the St. Louis and the Chicago area. Daily synoptic weather maps depicting surface atmospheric pressure patterns, locations of frontal boundaries and storm centers are used to identify synoptic weather types. Because only one or two surface weather maps and upper air charts are available for each day, the weather typing under these circumstances could not be as detailed as the types listed in Table 1. Therefore, only three types (airmass storm, frontal storm and tropical disturbance storm) are identified for this study using guidelines provided by Muller (1977). First, frontal storm types are identified as situations just before, during, or just after the passage of a frontal boundary. Tropical disturbance storm types are those generated by weak easterly waves, unnamed tropical depressions, tropical storms and hurricanes. Finally, airmass storm types include local convection, or upper-air-induced storms that showed no apparent surface manifestation of frontal or tropical disturbance mechanisms. According to Keim (1996) this system was applied successfully to analyze heavy rainfall events in New Orleans and across Louisiana. The

Table 1. Definition of synoptic weather types used in identifying discrete rain periods for Chicago and St. Louis.

Squall Line	A nonfrontal group of thunderstorms accompanied by a trigger mechanism, usually a short wave trough. The convective activity associated with the storm systems was intense, well-organized and often was arrayed in a narrow band or line of active thunderstorms.
Squall Zone Storms	A mesoscale system of thunderstorms organized into an area or cluster and independent of a frontal zone. These storms, like squall lines, tended to move across large regions of the Midwest, and an upper-air impulse was usually discernible.
Frontal Storms	Precipitation formed within 75 miles (120 km) of a surface front (cold static, or warm). There was no synoptic evidence that this precipitation was associated with a squall line or squall zone which, on occasion, moved 25 miles (40km) or more ahead of the fronts.
Pre-Frontal and Post-Frontal Storms	Precipitation associated with a frontal structure but a distance of 75 to 150 miles (120 to 240 km) ahead or behind of front (cold, static or warm).
Air Mass Storms	A shower or thunderstorm generated within an unstable air mass. No large scale or mesoscale synoptic causes were evident. The resulting convective activity was usually widely scattered and weak.
Low Pressure Storms	A cyclonic storm situated so close to the study area that it was not possible to associate the precipitation with a frontal or mesoscale weather structure. These systems were rare during the summer months.

(after Changnon, 1984)

Muller system categorizes the weather patterns of Louisiana and the Central Gulf of Coast based on atmospheric pressure patterns at the surface using a manual method. Although this system was primarily developed to classify weather patterns in Louisiana, it can provide the foundation for the method to categorize heavy rainfall events throughout the entire Southeast regions with some regional modifications.

Since this research uses a manual method, daily weather maps are examined and interpreted for each day producing rainfall totals of 2 inches or higher. The derived synoptic weather catalogs for the five cities are used in a number of ways. They are used first to analyze the pattern of rainfall totals from heavy rainstorms for all synoptic weather types combined, frontal storm types, airmass storm types and tropical disturbance storm types to examine whether there are precipitation enhancements over the city or its downwind area. The same steps are applied for the number (frequencies) of heavy rainstorms by each synoptic type. Spatial patterns of rainfall totals and frequencies are obtained by combining all heavy rainstorms associated three weather types and are also determined by each synoptic type and season.

4. Characteristics of Each Synoptic Type

Frontal systems, mostly cold fronts, are the dominant mechanism that induces heavy rainstorms across the study area, but tropical disturbances and air mass storms also contribute at the more coastal locations (Keim, 1996). Frontal type storms represent the most organized weather systems observed to cause precipitation within the research area. These rainstorms are characterized by intense, well organized lines of convection and are normally accompanied by strong, upper air troughs (Vogel and Huff, 1978).

Tropical disturbances influence the southern United States along the Gulf coast during summer, fall and even late spring. These tropical weather events range from relatively weak easterly waves to hurricanes. Tropical disturbances are characterized by great instability through a deep moist layer of the atmosphere (Muller, 1983). These storms rarely show signs of distinct precipitation modification due to urban effects because they are too dynamic and fast to be influenced by the city area. Airmass types of rainstorms usually occur within warm, moist air masses which dominate the general weather conditions during summer. Airmass storms are characterized by widely scattered showers and thunderstorms which develop in an apparent random manner with no organized movement. Huff and Changnon (1973) found that there was a 10% increase of summer rainfall to N of New Orleans and 17% increase of summer rainfall within the Houston city center by non-frontal storms

Table 2 shows the contribution of each synoptic weather type to annual rainfall totals and frequencies of heavy rainstorms. Frontal weather types make up the majority of events with values greater than 60% (even 90% in Memphis). Because of their inland locations, frontal types in Dallas and Memphis contribute more highly (80-90%) to rainfall totals and frequencies than in Houston and New Orleans. Houston and San Antonio show a higher contribution from airmass storms than other cities because of their nearness to the coast.

5. Discussion and Results

Results at Houston are discussed in greater detail because it has the most distinct precipitation enhancements both on rainfall totals and on frequencies of heavy rainstorms by synoptic analysis. Airmass type storms show more apparent enhancements than two other storm types during summer. Residual analysis also supports theory that there are positive precipitation anomalies in the pattern of heavy rainstorm frequencies by airmass storm types in summer.

1) Houston

(1) Rainfall totals of heavy rainstorms by synoptic types

Annual rainfall totals of heavy rainstorms

The spatial patterns of annual rainfall totals of heavy rainstorms by each synoptic type and all types combined are mapped and analyzed for Houston through this section. The basic assumption of this study is that spatial analysis can detect and locate the existence of precipitation modification due to urban effects with localized (closed) maxima over the city or its downwind. Figure 1 displays the spatial pattern of mean annual rainfall totals of heavy rainstorms by all synoptic weather types combined at Houston and its surrounding areas during the period of 1961-1990. This pattern clearly shows the E-W/S-N decline in rainfall totals, with a maximum S of the study area where more than 20 inches of annual totals result from heavy rainstorms. A minimum is found NW of the city with about 9 inches. The high rainfall totals might result from the effects of

Table 2. Contribution of each synoptic weather type to annual rainfall totals and frequencies of heavy rainstorms by percentages at five cities.

(unit : %)

Weather Type	Houston		Dallas		San Antonio		New Orleans		Memphis	
	Totals	Freq.	Totals	Freq.	Totals	Freq.	Totals	Freq.	Totals	Freq.
Frontal Storm	61	62	86	85	73	72	74	72	92	92
Airmass Storm	25	27	10	12	25	24	16	17	5	5
Tropical Disturbance Storm	14	11	4	3	2	4	10	11	3	3

Freq.: Frequency.

proximity to the Gulf, warm waters and intense afternoon warming of the surface at Houston and its surrounding areas (Keim, 1996). The pattern of rainfall totals from all weather types combined do not reveal any localized maximum over the city area or its downwind because of a strong climatic gradient on precipitation which increase from W to E.

TSA is applied to detect and to evaluate the magnitude of the climatic gradient from E-S to W-N in the pattern of rainfall totals of heavy rainstorms. Table 3 lists TSA equations and %RSS values of annual rainfall totals by all synoptic weather types combined and each synoptic weather type. Since values of %RSS range from 40% for airmass storm types to 73% for tropical types, it may be concluded that airmass types are more randomly distributed and less influenced by the regional effect in Houston and its surrounding areas than tropical and frontal storm types. The %RSS value of tropical disturbance types indicates that there was a very highly marked climatic gradient E-W and S-N. It is not surprising that the pattern of tropical storms has the highest %RSS value because these type storms weaken abruptly after landfall and with distance from the coast.

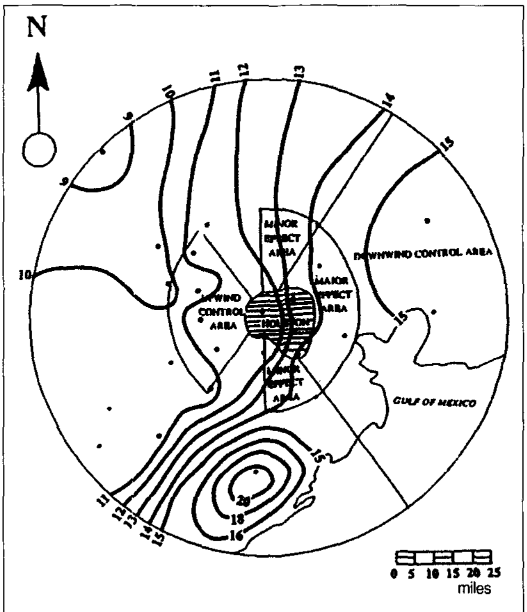

Figure 1. Pattern of mean annual rainfall totals of heavy rainstorms by all weather types combined at houston and its surrounding areas(unit : inch).

If mean rainfall totals over the city area are higher than E of the city, it would confirm the existence of precipitation enhancement due to urban effects over the city, even considering the climatic gradient from E-W/S-N. Table 4 calculated areal mean values of rainfall totals for all synoptic weather types combined and each individual weather type. Areal means of rainfall totals for all weather types combined showed an E-W decline as the major effect area (14.54 inches) has a higher value than other areas (11.61 inches) and the mean totals over the city area are not higher than the minor effect area. With these results for rainfall totals of all types combined, it is very difficult to detect and confirm any distinct urban effects on the existence of enhancement of precipitation over the city area and its surroundings, especially downwind due to the strong climatic gradient.

Table 3. TSA results for mean annual rainfall totals of heavy rainstorms by each weather type and all types combined at houston and its surrounding areas.

Weather Type	Trend Surface Equation	%RSS	F-Value	Prob > F
Frontal Storm	$Y=357.10-0.55X_1+3.48X_2$	50	10.23	0.001**
Airmass Storm	$Y=116.42-1.37X_1+0.76X_2$	40	6.92	0.005**
Tropical Disturbance Storm	$Y=174.37-1.28X_1+1.40X_2$	73	28.17	0.001**
All Storms Combined	$Y=647.90-3.20X_1+5.66X_2$	62	16.85	0.001**

Y: Precipitation Totals, X_1: Latitude, X_2: Longitude, %RSS: Percentage reduction in sume of squared achived,
**: significant at 99% level.

Table 4. Areal comparisons of mean annual rainfall totals and frequencies of heavy rainstorms by each weather type and all types combined at houston and its surrounding areas.

(unit : inch)

Weather Type	Area	Totals	Frequency	Number of Stations
Frontal Storm	Major	**9.29**	**3.05**	2
	City	8.16	2.68	3
	Minor	8.34	2.66	3
	Upwind	7.11	2.42	5
	Total	7.89	2.57	24
Airmass Storm	Major	**3.07**	**1.08**	2
	City	2.95	1.05	3
	Minor	2.53	0.86	3
	Upwind	2.54	0.85	5
	Total	2.69	0.92	24
Tropical Disturbance Storm	Major	2.17	0.46	2
	City	1.77	0.47	3
	Minor	**2.31**	**0.51**	3
	Upwind	1.50	0.40	5
	Total	1.68	0.42	24
All Storm Combined	Major	**14.54**	**4.60**	2
	City	12.88	4.21	3
	Minor	13.19	4.04	3
	Upwind	11.61	3.68	5
	Total	12.27	3.92	24

Boldfaces are the greatest values among the areas.
Major : major effect area, Minor : minor effect area,
Upwind : upwind control area.

However, it is interesting to note that the difference between the major effect area and the city is 12% in frontal weather types (in this type, the city has lower totals than the minor effect area), but is 1.3% in airmass storm types.

The geographical pattern of annual rainfall totals of heavy rainstorms by frontal weather types shows maxima NE and S of the city producing more than 10 inches of rainfall per year whereas minima located SW and NW of the city produced less than 7 inches. Since the mean annual rainfall totals in the major effect area are the highest and the city has lower totals than the minor effect area, there is no possible precipitation enhancement when the frontal type storms are considered. Residual analysis did not reveal any positive residuals over the city or the major effect area.

Airmass storms showed the most favorable conditions for precipitation enhancements due to urban effects in the humid climate region (Huff and Changnon, 1973). Airmass storms show a strong coastal orientation in the study area so that it might be hypothesized that ingredients needed to produce an abundance of precipitation during airmass storms are proximity to the coast, warm waters, and intense heating of the surface. The spatial pattern of rainfall totals by airmass weather types shows the existence of possible precipitation enhancement due to urban effects displaying a closed maximum over the city area (Fig. 2). This pattern has more scattered and less organized pattern than two other types, with a lower %RSS value (40%, moderate-substantial trend). Residual analysis supports the result of the simple spatial analysis with positive residual values over the city (Fig. 3). The results of METROMEX which is a

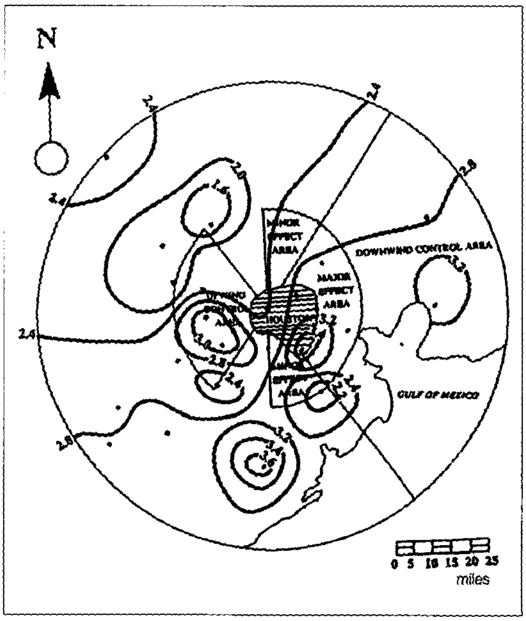

Figure 2. Pattern of mean annual rainfall totals of heavy rainstorms by airmass weather type at houston and its surrounding areas (unit : inch).

comprehensive study of precipitation modification due to urban effects in the St. Louis area, revealed that most of the rain which fell over the network during summer was caused by organized meso-scale or synoptic scale convective systems (Ackerman *et al.*, 1978). Therefore, results from Houston are different from St. Louis.

The spatial pattern of annual rainfall totals from tropical type heavy rainstorms shows a strong E-W/S-N decline because the intensity of tropical disturbances weakens quickly as they move inland. The contribution of tropical disturbances to annual rainfall totals of heavy rainstorms is greatest S of the city, near coast. Maxima are located along the coast and minima located far inland. This finding is readily explained by distance from the coast. The farther inland a site is located, the less likely it is to receive a storm induced by tropical disturbances because of the rapid breakdown of tropical disturbances after landfall and distance from a moisture source (Keim, 1996). In fact, Cry (1967) suggested that moisture produced from tropical cyclones is negligible beyond about 150-200 miles inland. Mean rainfall totals from tropical disturbances decrease abruptly inland and reach minimum values NW of the city area. TSA results confirm that the pattern shows an E-W/S-N gradient with higher %RSS values (73%). There are no distinct urban effects on precipitation enhancements on tropical disturbance type heavy rainstorms since there is no maximum over the city or the major effect area. These storms might be too dynamic to be influenced by the city area as mentioned earlier.

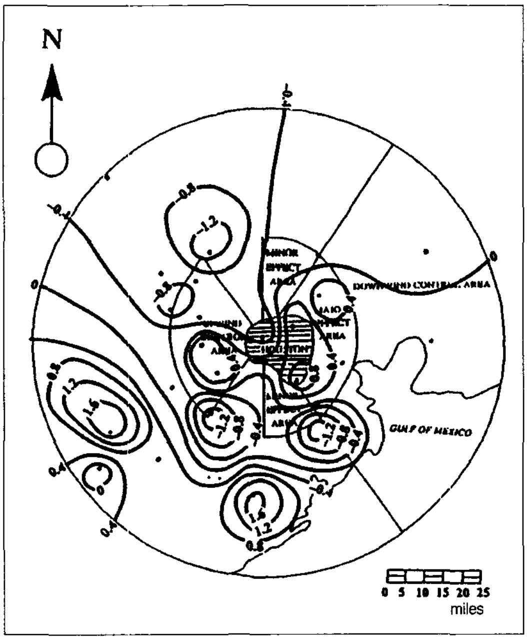

Figure 3. Residual map of mean annual rainfall totals of heavy rainstorms by airmass weather type at houston and its surrounding areas.

Because the pattern of airmass storms shows stronger evidence for the existence of precipitation enhancement over the city area seasonal patterns of airmass storms are analyzed and discussed in the next section in detail. The examination of seasonal airmass storms reveals how the existence of precipitation enhancement differs by season. The same steps, simple spatial analysis, TSA, residual analysis and comparison of areal mean are applied for seasonal rainfall totals of airmass type storms.

Seasonal Patterns of Rainfall Totals by Airmass Storms

More apparent precipitation enhancement due to urban effects might be apparent on a seasonal basis rather than an annual basis (Landsberg, 1981). The patterns of seasonal rainfall totals of heavy rainstorms by airmass type are found to be persistent and the pattern in summer is illustrated in Figure 4. The pattern shows a localized maximum over the city area. These features include a maximum over the city and a minimum NW of the city except for the fall pattern. Winter and spring patterns also show a small maximum over the city. The areal mean summer rainfall totals by airmass storms show the greatest values in the major effect areas (E of the city) and the second highest in the city (Tab. 5). In winter and spring the city area has the greatest totals with 10-76% higher totals than the upwind control area. Summer needs to be analyzed with more caution because of a natural climatic gradient.

TSA results show that the patterns of mean seasonal rainfall totals from airmass storms are more random in winter and spring than in summer and fall (Tab. 6). Because %RSS values of these two season were lower than 20%, residual maps for these seasons are not meaningful. The fall pattern had a higher marked gradient from E-W/S-N and spring and winter patterns had definite but small gradients. The residual map in summer clearly shows positive residual values over the city indicating that the maximum over the city is a

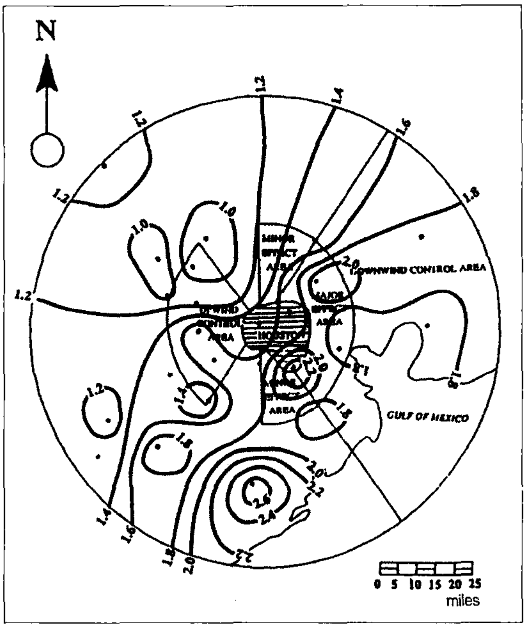

Figure 4. Pattern of mean summer rainfall totals of heavy rainstorms by airmass weather type at houston and its surrounding areas(unit : inch).

Table 5. Areal comparisons of mean seasonal rainfall totals and frequencies of heavy rainstorms by airmass weather type at houston and its surrounding areas.

(unit : inch)

Season	Area	Totals	Frequency	Number of Stations
Winter	Major	0.08	0.03	2
	City	**0.17**	**0.08**	3
	Minor	0.02	0.01	3
	Upwind	0.04	0.01	5
	Total	0.09	0.04	24
Spring	Major	0.28	0.11	2
	City	**0.37**	**0.14**	3
	Minor	0.28	0.10	3
	Upwind	0.33	0.13	5
	Total	0.31	0.12	24
Summer	Major	**1.92**	**0.66**	2
	City	1.84	0.62	3
	Minor	1.61	0.52	3
	Upwind	1.39	0.46	5
	Total	1.54	0.52	24
Fall	Major	**0.77**	**0.27**	2
	City	0.57	0.21	3
	Minor	0.61	0.23	3
	Upwind	0.76	0.23	5
	Total	0.75	0.25	24

Boldfaces are the greatest values among the areas.
Major : major effect area, Minor : minor effect area,
Upwind : upwind control area.

Table 6. TSA results for mean seasonal rainfall totals of heavy rainstorms by airmass weather type at houston and its surrounding areas.

Season	Trend Surface Equation	%RSS	F-Value	Prob > F
Winter	$Y=6.59+0.007X_1+0.07X_2$	7	0.81	0.46
Spring	$Y=20.69-0.14X_1+0.17X_2$	15	1.92	0.17
Summer	$Y=92.24-0.73X_1+0.72X_2$	41	7.20	0.004**
Fall	$Y=-3.10-0.50X_1-0.20X_2$	51	10.83	0.001**

Y=Precipitation Total, X_1=Latitude, X_2=Longitude, %RSS=Percentage reduction in sum of squared achieved,
** significant at 99% level, * significant at 95% level.

result of localized effects (Fig. 5). This summer effect produced the maximum over the city area in the pattern of annual totals from airmass storms (Fig. 2). Summer rainfall totals contribute 62% of rainfall totals by airmass storms because of intense afternoon warming and atmospheric instability. T-test results substantiate the validity of the maximum over the city area during winter but the maximum during spring was statistically insignificant.

(2) Frequencies of heavy rainstorms by synoptic types

Annual Rainfall Frequencies of Heavy Rainstorms

If urban area intensify or moderate naturally occurring heavy rainstorms, the frequency and magnitude of flooding-producing storms will differ from those experienced in the surrounding areas. Of heavy rainstorms, 62% were classified as frontal, 27% resulted from airmass storms and 11% were induced by tropical storms. Figure 6 illustrates the pattern of mean annual frequencies of heavy rainstorms by all synoptic weather types combined in Houston and its surrounding areas. The pattern clearly shows that frequencies of heavy rainstorms experience an E-W/S-N decline with a maximum value S of the city and a minimum NW of the city. This pattern is very similar to the one for rainfall totals (Fig. 1). Although the mean of 3 stations over the city is higher than areal mean of the other 24 stations, the pattern does not show any distinct evidence of urban effects on enhancement of precipitation as there is not a localized maximum over the city area or the major effect area.

TSA results show that the pattern of mean annual frequencies of heavy rainstorms has a similar gradient to rainfall totals with slightly lower %RSS values. The annual frequencies of heavy rainstorms had a 58% RSS value indicating a high marked gradient over the pattern. Tropical storms have the highest %RSS with 68% RSS value while airmass storms have a 37% value (Tab. 7). Residual analysis does not locate positive residual areas over

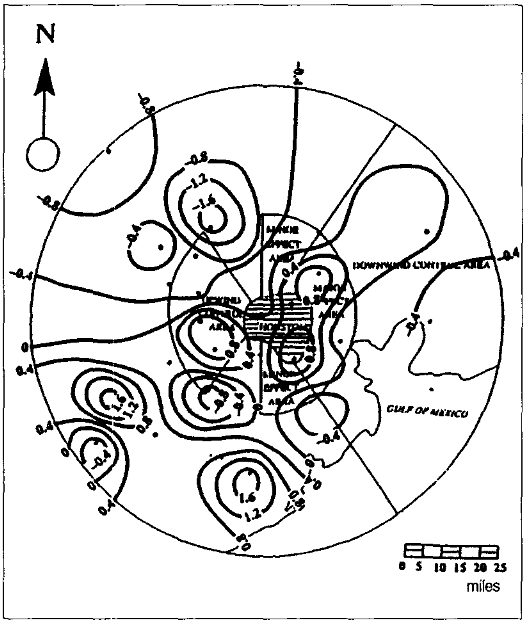

Figure 5. Residual map of mean summer rainfall totals of heavy rainstorms by airmass weather type at houston and its surrounding areas.

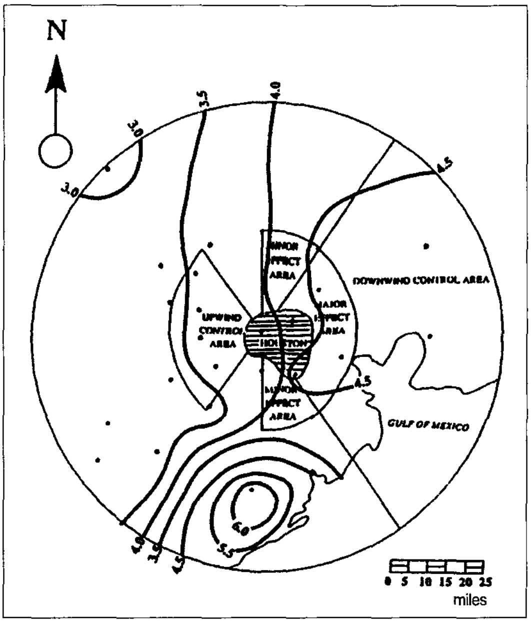

Figure 6. Pattern of mean annual frequencies of heavy rainstorms by all weather types combined at houston and its surrounding areas.

Table 7. TSA results for mean annual frequencies of heavy rainstorms by each weather type and all types combined at houston and its surrounding areas.

Weather Type	Trend Surface Equation	%RSS	F-Value	Prob > F
Airmass Storm	$Y=39.45-0.44X_1+0.27X_2$	37	6.16	0.008**
Frontal Storm	$Y=92.51-0.09X_1+0.97X_2$	53	11.60	0.001**
Tropical Disturbance Storm	$Y=33.55-0.26X_1+0.26X_2$	68	22.36	0.001**
All Storms Combined	$Y=165.51-0.61X_1+1.5X_2$	58	14.50	0.001**

Y=Precipitation Total, X_1=Latitude, X_2=Longitude, %RSS=Percentage reduction in sum of squared achieved,
** significant at 99% level, * significant at 95% level.

the city or downwind although areal comparisons show the highest frequencies in the major effect area and the second highest value over the city.

Frontal type heavy rainstorms contribute 60-75% of frequencies of heavy rainstorms and the pattern of mean annual frequencies of heavy rainstorms by frontal type is little different from that of all synoptic weather types combined. Maxima are found NE and S of the city with 3 storms per year while minima are located NW and SW of the city with 2 storms per year. This pattern also does not reveal any precipitation enhancements due to urban effects. The areal comparison of frequencies by frontal storms shows the highest value in the major effect area and the second highest in the city (Tab. 4). However, residual analysis did not show positive but negative residual values over the city. The frequency pattern of tropical storms also displays strong E-W/S-N gradients (68%) and does not reveal any urban effects on precipitation.

Airmass type heavy rainstorms producing more than 2-inch rainfall totals take place one time per year at Houston. Figure 7 illustrates maxima S of the city and over the city itself and minima NW of the city. The areal comparison of frequencies by airmass storms have the highest frequencies in the major effect area and the second highest value in the city. The residual map also supports this enhancement over the city with positive residual values. Therefore, frequencies of airmass storms are analyzed by season in the next section. The

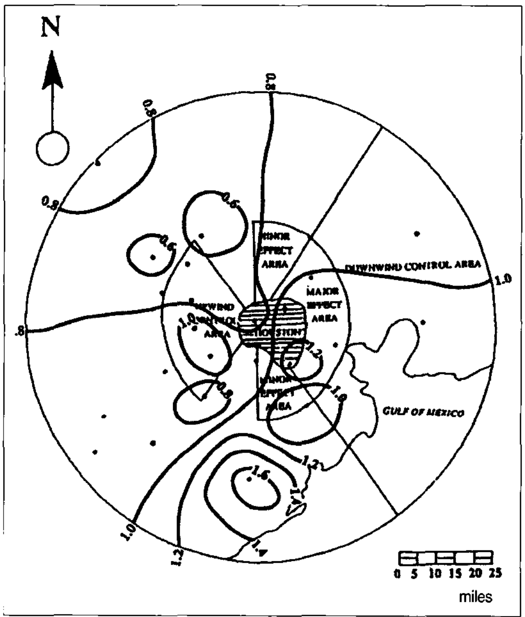

Figure 7. Pattern of mean annual frequencies of heavy rainstorms by airmass weather type at houston and its surrounding areas.

difference between the city and the upwind control area is 21.3%.

Seasonal Patterns of Rainfall Frequencies by Airmass Storms

The spring pattern reveals a possible precipitation enhancement due to urban effects with a localized maximum over the city. The winter and summer patterns also show a maximum over the city area. The results of TSA support the possible existence of precipitation enhancements with a lower %RSS value (11%) in spring. Table 5 lists mean seasonal rainfall frequencies by airmass types and bold numbers highlight the greatest values. Winter and spring have the greatest mean values over the Houston city areas. However, a Wilcoxon-Mann-Whittney test shows that these maxima are not statistically significant. In summer, the major effect area includes all areas E of the city while the upwind control area includes all areas W of the city. The areal frequencies of storms by airmass storms in summer are the highest E of the city and the second highest over the city. The residual map also shows positive residual values over the city.

(3) Temporal Analyses

In this section, annual and seasonal rainfall totals and frequencies of heavy rainstorms by each synoptic weather type and all types combined are examined to determine whether they increased or decreased through time over the Houston city area. Time-series analyses did not reveal any increasing or decreasing trends to be statistically significant. The high variability of precipitation and the sampling problem make the time-series analysis difficult. This result differs considerably from the good results in determining urban effects on temperature (Landsberg, 1981).

2) Other cities

The same procedures(spatial analysis, TSA and areal mean comparisons) are applied to other cities, Dallas, San Antonio, Memphis and New Orleans. Dallas and San Antonio reveal possible precipitation enhancements due to urban effects for rainfall totals and frequencies through synoptic analysis in spring and fall while New Orleans and Memphis do not. Significant findings from these cities are discussed in this section.

(1) Rainfall Totals of Heavy Rainstorms by Synoptic Types

The pattern of rainfall totals of heavy rainstorms by synoptic types at Dallas shows less climatic E-W gradients than that of Houston as %RSS values are more or less 20% for all three types of rainfall totals. Also the patterns of rainfall totals did no show any localized maximum over the city or downwind area for all types combined or each synoptic type. Although mean rainfall totals from tropical storms have the greatest value over the city, it is very hard to conclude that this is the result of precipitation enhancement because the number of samples is too small.

Although San Antonio did not show any distinct precipitation enhancement due to urban effects except for the pattern of spring rainfall totals from airmass types. Under these conditions the greatest mean value is located over the city area producing a localized maximum in spring(Fig. 8). The areal difference between the city and the upwind control area is 64%(Tab.8). The examination of New Orleans and Memphis areas did not reveal any evidence of precipitation enhancement due to urban effects for rainfall pattern by synoptic weather types. The presence of complex land cover in New Orleans such as Lake Pontchartrain N of

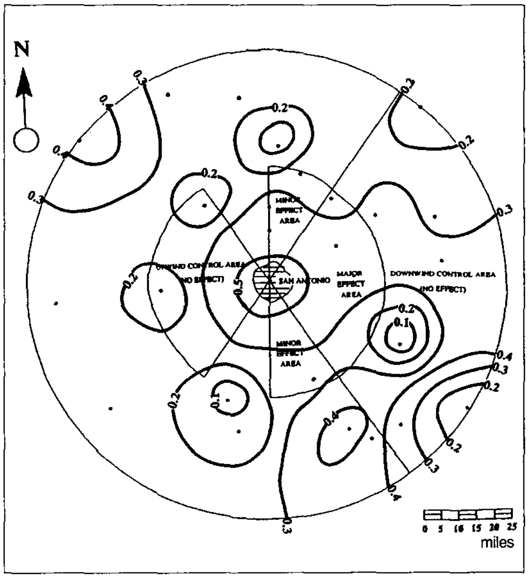

Figure 8. Pattern of mean spring rainfall totals of heavy rainstorms by airmass weather type at san antonio and its surrounding areas(unit : inch).

the city and the Mississippi River S of the city makes it difficult to detect possible precipitation modifications due to urban effects.

(2) Frequencies of Heavy Rainstorms by Synoptic Types

The mean frequency of heavy rainstorm events by each synoptic type over the Dallas and its surrounding areas shows the highest frequency over the major effect area for airmass types, tropical types and all types combined. This high value of airmass events resulted primarily from summer frequencies. Since summer shows the greatest number of events over the major effect area and the second highest over the city, it suggests a possible urban effect over the city in Dallas. Fall airmass storm frequencies also show the greatest frequency over the city. The areal difference between the city and the upwind control area is 64.7% in fall(Tab.9). Both the summer and fall pattern of frequencies also display localized maxima over the Dallas city and its major effect area.

For the San Antonio area, only spring frequencies of the airmass storm show the greatest number over the city with a maximum over the urban areas. The difference between the city and the upwind control area is 56.2%(Tab. 10). Examination of the Memphis and New Orleans areas do not reveal any evidence of urban effects on precipitation enhancement as the frequencies of heavy rainstorms by synoptic types are analyzed.

6. Summary

To examine the existence of precipitation modification due to urban effects, each heavy rainstorm is classified into one of three storm

Table 8. Comparisons of mean seasonal rainfall totals of heavy rainstorms by airmass weather type at san antonio and its surrounding areas.

(unit : inch)

Area	Season			Number of Stations
	Spring	Summer	Fall	
Major Effect Area	0.37	1.02	0.27	2
City	**0.50**	1.05	0.33	1
Minor Effect Area	0.29	1.08	0.22	4
Upwind Control Area	0.18	**1.17**	**0.43**	2
Total	0.30	1.12	0.37	26

Boldfaces are the greatest values among the areas.

Table 9. Areal comparisons of mean seasonal frequencies of heavy rainstorms by airmass weather type at dallas and its surrounding areas.

Area	Season			Number of Stations
	Spring	Summer	Fall	
Major Effect Area	0.06	**0.17**	0.15	2
City	0.03	0.13	**0.17**	1
Minor Effect Area	**0.08**	0.11	0.14	4
Upwind Control Area	**0.08**	0.08	0.06	2
Total	0.1	0.13	0.11	26

Boldfaces are the greatest values among the areas.

Table 10. Areal comparison of mean seasonal frequencies of heavy rainstorms by airmass storm type at san antonio and its surrounding areas.

Area	Season			Number of Stations
	Spring	Summer	Fall	
Major Effect Area	0.1	0.4	0.1	2
City	**0.16**	0.36	0.1	1
Minor Effect Area	0.11	0.34	0.08	4
Upwind Control Area	0.07	**0.43**	**0.17**	2
Total	0.11	0.36	0.12	26

Boldfaces are the greatest values among the areas.

synoptic weather types (frontal storm, airmass storm or tropical disturbance storm). Houston, Dallas and San Antonio showed possible urban effects on rainfall totals and frequencies of heavy rainstorms by airmass storm while New Orleans and Memphis did not reveal any distinct precipitation enhancements through the synoptic analysis. The results of TSA showed that frontal and tropical disturbances have stronger climatic gradients than airmass types and the patterns of rainfall totals have stronger trends than those of rainfall frequencies for the five cities. This result suggests that airmass type events clearly reveal possible precipitation enhancements due to urban effects since they are less influenced by a strong climate gradient. Residual analysis was only performed on the patterns which have statistically significant %RSS values. Residual analysis confirms that annual rainfall totals and frequencies of heavy rainstorms by airmass type in summer have positive residuals over the city or the major effect area in Houston. In the seasonal airmass analysis, Houston has some evidence of enhancement in all seasons except for fall while Dallas had summer and fall effects and San Antonio had an impact in spring for both rainfall totals and frequencies. With the highest value over the major effect area and the second highest over the city, Dallas showed that possible urban effects on precipitation extend downwind while for San Antonio urban effects are limited over the city itself. The three Texas cities reveal more distinct urban effects on heavy rainstorms through synoptic analyses than New Orleans and Memphis. The complex land cover of New Orleans makes it very difficult to reveal any possible precipitation enhancement and Memphis may not be large enough to influence on precipitation processes.

The most distinct effect on precipitation totals and frequencies by airmass type storms during summer at Houston results from a combination of favorable conditions which trigger or intensify storms. It is believed that the precipitation enhancement due to urban effects can occur when all conditions are just right. Houston has the right conditions in summer and airmass synoptic conditions are not overwhelmed by larger scale dynamic features. With the supply of abundant moisture and intensive heating the Houston city area can help to intensify or moderate naturally induced heavy rainstorms.

Reference

Ackerman, B., Changnon, S. A. Jr., Dzurisin, G. Gatz, D. L. Groch, R. C. Hilberg, S. D. Huff, F. A. Mansell, J. W. Ochs III, H. T. Peden, M.

E. Schickedanze, P. T. Semonin, R. G. and Vogel, J. L. 1978, *Summary of METROMEX, Vol. 2: Causes of Precipitation Anomalies, Bulletin*, 63, Illinois State Survey, Urbana.

Chandler, T. J., 1970, *Urban Climate: Inventory and Prospect*, Urban Climate WMO Tech. Note, 108.

Changnon, Jr. S. A., 1980, Evidence of urban and lake influences on precipitation in the Chicago area, *Journal of Applied Meteorology*, 19, 1137-1159.

Changnon, Jr. S. A., 1984, Urban and the lake effects on summer rainfall in the Chicago area, *Physical Geography*, 4, 1-23.

Choi, Y. and Henderson, K. G. 1995, Application of trend surface analysis(TSA) to a precipitation modification study over urban areas in the southern United States, *Journal of the Korean Geographical Society*, 30, 4, 333-351.

Critchfield, H., 1966, *General Climatology*, Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Cry, G.W., 1967, *Effects of Tropical Cyclone Rainfall on Distribution of Precipitation over the Eastern and Southern United States*, Environmental Science Services Administration, Professional Paper No.1.

Dettwiller, J. and Changnon, S.A. Jr., 1976, Possible urban effects on maximum daily rainfall at Paris, St. Louis, and Chicago, *Journal of Applied Meteorology*, 15, 517-519.

Faiers, G.F., 1994, An evaluation of urban-enhanced extreme 24-hour rainfall in the New Orleans Area, *National Weather Digest*, 19, 25-30.

Huff, F.A., and Changnon, S.A. Jr., 1972, Climatological assessment of urban effects on precipitation at St. Louis, *Journal of Applied Meteorology*, 11, 823-842.

Huff, F. A., and Changnon, S. A. Jr., 1973, Precipitation modification by major urban areas, *Bulletin American Meteorological Society*, 54, 1220-1232.

Keim, B. D., 1996, Spatial, synoptic and seasonal pattern of heavy rainfall in the southeastern United States, *Physical Geography*, 17, 313-328.

Landsberg, H. E., 1981, *The Urban Climate*, International Geographical Series V28, Academic Press, New York.

Lee, D. O., 1984, Urban Climate, *Process in Physical Geography*, 8, 1-31.

Lydolph, L. B., 1985, *The Climate of the Earth*, Roman & Littlefield Publishers Inc.

Muller, R. A., 1977, A synoptic climatology for environmental baseline analysis: New Orleans, *Journal of Applied Meteorology*, 16, 20-33.

Muller, R. A. and Willis, J. E. 1983, *New Orleans Weather 1961-1980: A Climatology by Means of Synoptic Weather Types*, Miscellaneous Publication 83-1, School of Geoscience, Louisiana State University.

Oke, T. R., 1974, *Review of Urban Climatology 1968-73.*, World Meteorological Organization Technical Note 169, Geneva.

Sanderson, M. and Gorski, R., 1978, The Effect of Metropolitan Detroit-Windsor on Precipitation, *Journal of Applied Meteorology*, 17, 423-427.

Trewartha, G.T., 1981, *The Earth's Problem Climate, University* of Wisconsin Press, Madison, Wisconsin.

United States of Department of Commerce, 1961-1990, *Daily Synoptic Series*, Asheville, North Carolina.

Vogel, J. L. and Huff, F. A. 1978, Relation between the St. Louis urban precipitation anomaly and synoptic weather factors, *Journal of Applied Meteorology*, 17, 1141-1152.