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Application of Trend Surface Analysis (TSA) to a Precipitation Modification Study over Urban Areas in the Southern United States of America

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Trend surface analysis (TSA) was selected to estimate a natural trend in precipitation and to examine urban influences on precipitation over five urban areas (Houston, Dallas, and San Antonio, TX; New Orleans, LA; and Memphis, TN) in the southern United States. TSA was applied to monthly, seasonal and annual normal precipitation data for the period of 1961-1990. Winter and spring have more trends than summer and fall and the period of November through March have more marked trends than the period of April through October in all study areas except the Houston area. Residual maps for Houston, Dallas and San Antonio have positive residuals in the city and downwind during summer indicating that urban effects on precipitation enhancement in these areas do exist during these seasons after eliminating the natural precipitation variations. Summer residual maps for New Orleans and Memphis have no distinct precipitation increases due to urban effects. The June residual map in New Orleans and the July residual map in Memphis have positive values in the city, but the magnitude of values is smaller than other cities.

Key Words: trend surface analysis, precipitation enhancements, urban effects, residuals

1. Introduction

Many climatologists and meteorologists have been interested in possible weather modification caused by the growth of urban areas. Of the many weather conditions influenced by urban areas, precipitation is one of the most controversial and important elements in characterizing the urban climate. According to Huff and Changnon (1973), urban-caused changes in precipitation may result from four potential factors: 1)atmospheric destabilization due to the existence of a well-developed urban heat island; 2)modification of microphysical and dynamic processes by the addition of condensation and/or ice nuclei from industrial discharge; 3)increases in low-level mechanical turbulence due to urban obstructions to air flow; and 4)modification of the low-level atmospheric moisture content by changes in the natural evaporation process within the city resulting from the larger percentage of impervious surfaces in central urban areas.

Various techniques have been employed in an attempt to establish the existence of urban effects and to estimate their locations, timings, and intensities. Time-trend analyses such as 2- and 5-year moving averages of monthly and seasonal

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**Assistant professor, Department of Geography & Anthropology, Louisiana State University precipitation are often used to smooth out some of the year-to-year natural variability in the data, in order to evaluate any long-term trends (Changnon, 1978; and Changnon et al., 1981). The comparison of precipitation ratios between urban areas and non-urban areas has also been frequently used to examine precipitation variation in an urban industrial region (Khemani and Murty, 1973; and Lowry, 1977). Isopleth maps are widely used as a general research device for the spatial analyses of not only precipitation, but also other climatic elements (Schikendanz, 1973).

The southern United States of America which was selected for this study has a strong climatic gradient in precipitation which decreases from E to W because the moisture content of the atmosphere decreases with distance from the Gulf of Mexico. In many urban precipitation studies performed in the mid-latitudes, the E of the city is usually defined as a major urban effect area. It is assumed that there is an enhancement of precipitation whereas the W of the city is defined as a control area where it is assumed that there is no urban effect on precipitation. The St. Louis study showed the major area of rain increase from 1 to 10km E–NE of St. Louis and the Chicago study showed an abnormal increase in summer rainfall in La Porte, 40km from E of Chicago (Changnon, 1968; and Changnon, 1980a). Although there is an increasing trend in precipitation over the southern United States, it is very difficult to define precipitation increases caused by the urban effects because of the natural decreasing trend in the precipitation pattern from E to W. Goldreich (1987) used multiple regression analysis to examine urban effects on the spatial distribution of rainfall over Israel's coastal plain using variables such as the latitude and distance from the sea. Goldreish and Gadoth (1989) also applied the DISCORMAT technique, a relatively new form of spatial analysis, to estimate the influence of urbanization on rainfall distribution in the same area. They concluded that these techniques clearly showed the displacement of rainfall centers caused by urban effects.

Among the many spatial pattern analysis methods, trend surface analysis (TSA) was selected to estimate the natural trend in precipitation and to examine urban influences on precipitation in the southern United States. TSA was chosen because it can abstract the most simple large-scale patterns from irregular local and random variations and was applied to monthly, seasonal and annual normal precipitation data over five urban areas in the southern United States for the period of 1961-1990. This paper summarizes the results of TSA application to normal precipitation data with emphasis on summer when the urban effect appears to be most pronounced (Changnon, 1978).

2. Study Areas

Six states (Texas (TX), Oklahoma (OK), Arkansas (AR), Louisiana (LA), Tennessee (TN) and Mississippi (MS)) are included in the study area of the Southern Regional Climate Center (SRCC) which is one of the six regional climate centers in the Unites States. The five largest cities were selected for the study of precipitation modification due to urban areas: Houston (29. 52°N, 95.25°W), TX; Dallas (32.51°N, 96.51° W), TX; San Antonio (29.32°N, 98.28°W), TX; New Orleans (29.55°N, 90.08°W), LA; and Memphis (35.03°N, 90.00°W), TN (Figure 1). These cities have populations of more than one million in their metropolitan areas and are located in relatively flat areas except the San Antonio area which has the Edward Plateau in the NW of the region.

1) The geography of study areas

Houston is the largest city in the South and ranks as the fourth largest city in the United States. Houston, which lies in southeast Texas, about 50 miles (80km) from the Gulf of Mexico, is a major industrial city in the United States. The city covers 598 mi^2 (1,548km^2) with 1,630, 533 population and the metropolitan area of Houston covers 5,921 mi^2 (14,079km^2) with 3,731,131 population. Average temperature is 55°F(13°C) in January and 80°F (28°C) in July with an average annual precipitation of 45 in. (114cm).

Dallas, the second largest city in the South, is

Figure 1. Locations of Cities Selected for the Study

located in the heart of one of the fastest growing metropolitan areas in the Unites States. Dallas covers 378 mi^2 (979km^2) with 1,006,877 population. Its metropolitan area is 6,491 mi^2 (16,812km^2) with 4,037,282 population. The average temperature is 43°F (6°C) in January and 85°F (30°C) in July. Average annual rainfall is 33. 7 in.(85.6cm).

San Antonio, the third largest city in the South, ranks as one of the South's leading cultural and trade centers. The city covers about 328 mi^2 (850km^2) with 935,933 population and its metropolitan area covers 3,354 mi^2 (8,687 km^2) with 1,324,749 population. The average altitude is 701 feet (214m) above sea level. Average temperature in January is 52°F(11°C) and 84°F (29°C) in July. Average annual precipitation amount is 28 in. (71cm).

New Orleans, the fourth largest city in the South, is a leading business, cultural and industrial center of the southern United States. New Orleans lies along the Mississippi River about 100 mi.(160km) north of where the river flows into the Gulf of Mexico. New Orleans covers 364 mi^2 (943km^2) with 496,938 population and the metropolitan area of New Orleans covers 3,400 mi^2 (8,806km^2) with 1,285,270 population. The main part of the city lies between the river on the south and Lake Pontchartrain on the north. Much of New Orleans is below sea level and lacks natural drainage. The average temperature is 54°F (12°C) in January and 82°F (28°C) in July and the average annual precipitation is 54 in. (137cm).

Memphis, which is the fifth largest city in the South, lies on a bluff on the east bank of the Mississippi River. The city covers 288 mi^2 (746 km^2) with 610,337 population and its metropolitan area covers 3,092 mi^2 (8,008km^2) with 1,007,306 population. The Mississippi River flows to the west of Memphis and the Tennessee-Mississippi state line forms the southern boundary of the city. The altitude of the city is 331 feet (101m) above sea level. The average temperature in January is 40°F (4°C) and July is 82°F (28°C). The average annual precipitation is 52 in. (132cm).

3. Data and Methodology

1) Data

Monthly station normals of precipitation (1961-1990) published by the National Climatic Data Center (NCDC) were used to examine the urban effects on monthly, seasonal and annual precipitation distributions. Standard seasonal definitions were used (i.e. winter= December, January, and February). Data from 24 stations for the Houston area, 37 stations for the Dallas area, 28 stations for the San Antonio area, 21 stations for the New Orleans area and 23 stations for the Memphis area were used for the study. All stations were located within 60 mi. (100km) of each city.

2) Trend surface analysis (TSA)

Trend surface analysis can be used not only to describe a spatial series or to separate a spatial trend into regional and local components, but also to remove the local fluctuation from the more general pattern of variation (Clark and Hosking, 1986). There are some advantages associated with the use of trend surface analysis for determining the contribution of weather modification activities, of urban–industrial complexes, or of orographic–marine features to the existence and magnitude of isolated rainfall maxima and minima. TSA can provide significance factors for maxima and minima in the rainfall pattern with residuals, showing the critical values that are required for statistical hypotheses testing of pattern features (Schickdanze, 1973).

Trend surface analysis is derived from the best-fitting polynomial equation involving more terms as complexity increases from the linear to quadratic and possibly cubic forms. Trend surface analysis from 2-dimensional regression surfaces, the simplest form, was used for this study. Trend surface analysis can be used for differentiating each observation of a spatially distributed variable into a component associated with any regional trends present in the data, and a component associated with purely local effects (Unwin, 1973). This separation into two components is accomplished by fitting a best-fit surface to variables using standard regression techniques.

The linear multiple regression equation of the form can be expressed as;

$$R_{ti} = A + B_{1xiyi} + B_{2xiyi} \tag{1}$$

where, xi = the east-west axis increasing to the east with origin at the western edge of the map (the longitude of each station)

yi = the north-south axis increasing to the north with the origin at the southern edge of the map (here, it is the latitude of each station)

R_{ti}= the estimate of the mapped rainfall variables at the xi and yi location

A = the intercept

B_1, B_2 = the slope parameters of the linear plane

The standard output from regression analyses, such as multiple correlation, standard error of estimate, and standard errors of the slope parameters would yield a measure of the amount of variance explained and how well the surface actually describes the trend. However, in the analysis of the maxima and minima, it is the unexplained portion, the residuals from regression, that is of interest because these represent the difference between actual observed precipitation and the estimated precipitation through the trend or the model. The values predicted by this trend-surface are assigned to the regional effects whereas residuals are assigned to the local effects.

The basic equation of any trend analysis becomes

$$R_{obsi} = f(x_i, y_i) + u_i \tag{2}$$

where, R_{obsi} = the observed rainfall of the surface at the ith station

x_i = the co-ordinate on the x-axis (the longitude) of the ith station

y_i = the co-ordinate on the y-axis (the latitude) of the ith station

u_i = the residual at the ith station

$f(x_i, y_i)$ = the trend surface or function = R_{ti}

The main concern of this paper is the residual, the difference between the observed surface height (R_{obsi}) and the estimated trend component (R_{ti}) at each station. Since the analysis of residuals represents the effects of particular local factors, the technique can be used as an analytical tool as well as a means of objective description (Barry and Perry, 1973).

$$u_i = R_{obsi} - R_{ti} \tag{3}$$

A positive residual (above zero) indicates that the trend surface lies below the observed surface, whereas a negative residual lies below the predicted trend surface. The standard residual provides the necessary significance factor. Values of this residual assume a range from −3.00 to 3.00 regardless of the average magnitude and range character of the data.

A goodness of fit statistic suitable for use in trend surface analysis is the percentage reduction in sum of squares achieved, or %RSS. This is simply the ratio, expressed as a percentage, of the corrected sum of squares of the computed trend values (R_{ti}) to the corrected sum of squares of the of the observations (R_{obsi}), or

$$\%\text{RSS} = \frac{\text{corrected sum of squares of computed trend}}{\text{corrected sum of squares of observed values}} \times 100\%$$

where, the corrected sum of squares of the computed values is

$= \Sigma R_{ti}^2 - (\Sigma R_{ti})^2/N$

and that for the observed values is

$= \Sigma R_{obsi}^2 - (\Sigma R_{obsi})^2/N$

If the trend surface fits perfectly without leaving any residual, the %RSS will be 100, whereas lesser fits will give values between 0 and 100. The %RSS statistic used in trend surface analysis is analogous to the coefficient of

Table 1. Suggested Terms for Describing the Strength of a Trend Based on its %RSS

%RSS	Equivalent Coefficient of Correlation	Adjectival Description
0-4%	< 0.2	Slight; almost negligible trend
5-15%	0.2-0.4	Low; definite but small trend
16-49%	0.4-0.7	Moderate-substatial trend
50-80%	0.7-0.9	High; marked trend
81-100%	0.9-1.0	Very high; marked trend

Unwin, 1973

multiple correlation so that %RSS value can be transformed into equivalent correlation coefficients and that the relative strengths of trends might be described using the adjectives listed in Table 1.

3) Application of trend surface analysis (TSA) to precipitation data over a city area

Studies of synoptic patterns which produce the heavy rainfall in the southern United States have indicated that most rainstorms moved from SW or W to E or NE (Maddox et al., 1979; and Belville and Stewart, 1983). Thus, the E, SE, and NE can be assumed to be downwind of the city area. Therefore, the definition of areas in a major effect area, a minor effect area, upwind control area, and downwind control area followed the method which was used for the St. Louis area (Changnon, 1978). The terms "upwind" and "downwind" in this paper are used in a climatological sense only. Downwind refers to potential effect areas (urban or topographic barriers), whereas upwind refers to areas that are infrequently in the path of storm movement across an urban or topographic area. The built-up urban zone, including its industrial complex, was selected as the region having potential effects on all passing precipitation systems. Each urban area was defined to include 5 regions: 1) the urban area; 2) the major effect area–the area within 26 mi.(40km) of the eastern edge and within 110° sector; 3) the minor effect area–the urban complex and those areas to the N, NNE, SSE, and S that are downwind of infrequent storm motions; 4) the upwind control area–chosen to match the general size and shape of the major effect area; and 5) the downwind control area–a fan shape extending from the major effect area. However, this definition of areas is more difficult to apply during summer because of the southerly position of the study areas (Trewartha, 1981). During summer, frontal passages become less frequent and afternoon convective storms become more important in the production of heavy rain in the study areas. Also, the activity of the westerlies diminishes rapidly and the upper trough shifts westward into the Gulf of Mexico during summer. Therefore, the wind aloft changes from NW to SW or SE. As a result of these conditions, the downwind effect areas will be located not E of the city but N of the city area during summer. As mentioned earlier, it is presumed that there will be positive residuals over the city area and downwind of the city if there is an anomalous precipitation increase due to urban effects.

4. Results and Discussion

1) Houston

(1) Annual and seasonal precipitation distribution

Annual and seasonal precipitation patterns are analyzed before TSA is applied to these patterns. In general, seasonal and annual precipitation patterns in Houston show that the SE of the city has higher precipitation than the NW of the city. Figure 2 shows the summer precipitation pattern in Houston for the period of 1961-1990. Because summer is the season which shows the most profound urban precipitation effect in many cities (Changnon, 1980b; Dettwiller and Changnon, 1976; and Harnack and Landsberg, 1975), the summer precipitation pattern is highlighted here. During summer, the zonal westerly flow in the upper troposphere is much weaker, and the tropical air stream which originates in the western end of the subtropical high in the Atlantic crosses the Gulf Coast. Therefore, the Houston area is dominated by maritime tropical air and southerly air flow including southwesterly and southeasterly (Trewartha, 1981). The maritime tropical air is prevailingly from the Gulf of Mexico to the heated land, so that the air experiences surface warming and increased instability. However, the Gulf moisture supply gradually decreases westward and this contributes to the strong natural climatic gradient of precipitation decreasing from SE to NW in the Houston area during summer. Since the most distinct features are localized maxima E and S of the city area and localized minima W and NW of the city during this season, it is very difficult to distinguish precipitation enhancements due to urban effects in the Houston area. The maxima S and E of the Houston area might be caused by the natural climate precipitation gradient due to the proximity of the Gulf of Mexico rather than the urban effect. Sea breeze effects can also influence these maxima S and E of the city. Sea breeze occurs along the coast in all seasons and rarely has a depth of more than 10 miles. The most strongly affected regions are the coastal areas in summer when its maximum strength can extend inland about 30 miles (Critchfield, 1966). The magnitude of the maximum over the S of the city area in each season is different, but it is located in all seasonal precipitation patterns. The maximum to the E of the city is only present in the summer precipitation pattern. Although there is a localized anomaly in the Houston precipitation patterns, it is very difficult to identify or to determine whether this anomaly has resulted from urban-industrial effects, topographic effects or a combination of these two factors.

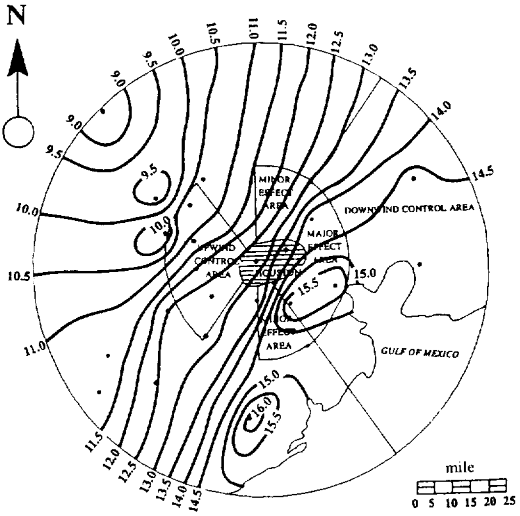


Figure 2. Summer Precipitation Pattern in the Houston Area (1961-1990, unit: inch)

TSA was used in an effort to separate the components of the large-scale regional patterns from local and random variations. Table 2 shows the results of the TSA applied to seasonal and annual normal precipitation data in Houston for the period of 1961–1990. The primary concern of this paper is that the residual map of TSA can show maxima and minima in the city and/or downwind of the city after eliminating the natural climatic variation occurring in the southern United States. Since convective shower type storms become more prevalent during summer, summer patterns might have a weaker trend than other seasons. However, the value of %RSS during summer shows a very high marked

Table 2. TSA Results for Annual and Seasonal Precipitation Patterns in the Houston Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > F
Spring	$Y=108.74+1.07X_1+0.36X_2$	59	15.05	0.01**
Summer	$Y=565.22-3.65X_1+4.62X_2$	84	56.01	0.01**
Fall	$Y=251.82-1.57X_1+2.01X_2$	63	18.17	0.01**
Winter	$Y=194.51+0.44X_1+2.07X_2$	60	15.99	0.01**
Annual	$Y=1117.29-3.72X_1+10.05X_2$	78	37.53	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

trend and suggests that 84% of precipitation variation can be explained by the regional effect, the natural climatic variation indicating that maritime tropical air from the Gulf of Mexico is very dominant in Houston, but it loses moisture as it moves west. Since the value of %RSS in the annual pattern is 78%, a high marked trend exists. The values of %RSS in other seasons also range from 59% to 63% indicating that there is a high marked trend in these seasonal precipitation patterns.

The summer residual map shows positive residuals NW of the city and in the city itself indicating precipitation enhancements due to urban effects. It suggests that there is an urban precipitation enhancement over the city area and that extends downwind (Figure 3). According to results of residual analyses, there are no distinct urban effects on precipitation increases during spring, fall and winter.

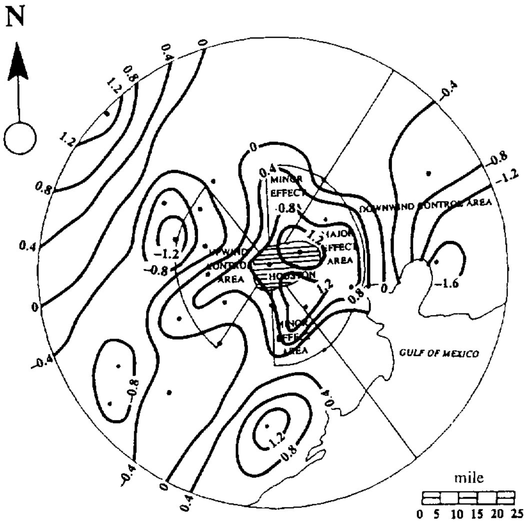


Figure 3. Summer Residual Map for the Houston Area (unit: inch)

(2) Monthly precipitation distribution

TSA was applied to monthly normal precipitation data for the period of 1961-1990 in an effort to delineate urban effects on precipitation further. As Table 3 shows, the highest %RSS values occurred in July indicating that there is a very high marked trend in precipitation distribution in Houston. Three summer months–June (79%), July (82%), and August (64%)–have higher %RSS than other months in Houston. Cooler months (December-April) have 34-70% of %RSS indicating from moderate-substantial to high marked trends. October and May have the smallest %RSSs representing definite–small to moderate–substantial trends. Even though it is believed that the summer months have more precipitation from localized convective activities, their precipitation patterns vary with a marked trend in Houston. July and August residual maps show

Table 3. TSA Results for Monthly Precipitation Patterns in the Houston Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > F
January	$Y=89.91-0.22X_1+0.84X_2$	62	17.24	0.01**
February	$Y=21.57+0.37X_1+0.31X_2$	34	5.43	0.01**
March	$Y=39.74+0.34X_1+0.49X_2$	51	11.04	0.01**
April	$Y=40.39+0.44X_1+0.53X_2$	66	20.33	0.01**
May	$Y=28.60-0.29X_1+0.34X_2$	25	3.43	0.05**
June	$Y=207.25-0.88X_1+1.84X_2$	79	38.93	0.01**
July	$Y=215.57-1.54X_1+1.74X_2$	82	48.45	0.01**
August	$Y=139.87-1.23X_1+1.04X_2$	64	18.79	0.01**
September	$Y=132.87-0.86X_1-1.41X_2$	63	18.21	0.01**
October	$Y=26.14-0.23X_1+0.16X_2$	8	0.889	0.43
Nobemver	$Y=92.82-0.16X_1+0.98X_2$	70	24.28	0.01**
December	$Y=83.04-0.29X_1+0.92X_2$	65	19.32	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

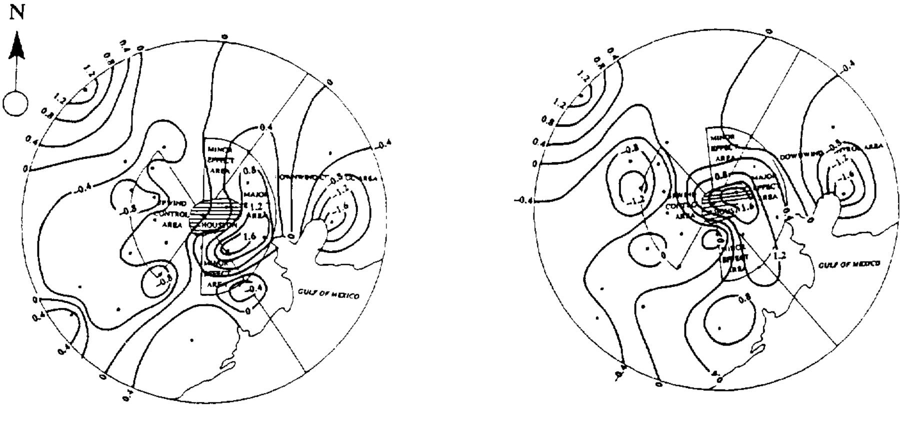
positive residual values in the city area indicating precipitation enhancements (Figure 4). Cooler months exhibit negative residual values in the city area.

In the seasonal analyses, the application of TSA to summer precipitation data and residual analyses clearly show precipitation enhancements due to urban effects. In monthly analyses, the application to June, July and August precipitation data have also well-demonstrated the urban effects on precipitation enhancements in the city.

2) Dallas

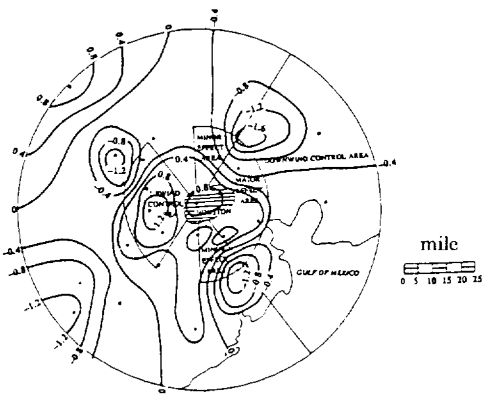
(1) Annual and seasonal precipitation distribution

Annual and seasonal precipitation patterns were examined before TSA was applied. General precipitation maxima are located E, NE and SE of the city area, while general minima are found W, SW and NW for the annual, fall and winter precipitation distributions. A broad localized maximum is located N of the city, while the localized minima are located S and SW of the city during spring and summer indicating precipitation enhancements downwind of the



(a) June

(b) July



(C) August

Figure 4. June, July and August Precipitation Residual Maps for the Houston Area (1961-1990, unit: inch)

city (Figure 5). Spring is the wettest season in the Dallas area. This feature results from increasing convective activities in addition to numerous frontal disturbance during spring. Although surface heating is at maximum and the inflow of surface maritime air from the Gulf of Mexico is strong during summer, it is drier than spring because of the presence of a large anticyclonic ridge over the southern Great Plains. The summer precipitation pattern is more localized and spotty than other seasonal patterns since it is mainly associated with air mass thunderstorms (Lydolph, 1985.) TSA was applied to seasonal and annual normal precipitation data for 1961-1990 (Table 4). Annual, spring, fall, and winter precipitation patterns show high or very high marked trends while summer has a moderate-substantial trend. It is not surprising that there is lower %RSS during summer since precipitation in this season is mainly caused by the localized shower types. The spring residual map shows positive residuals N and SW of the city indicating precipitation enhancements after eliminating large regional

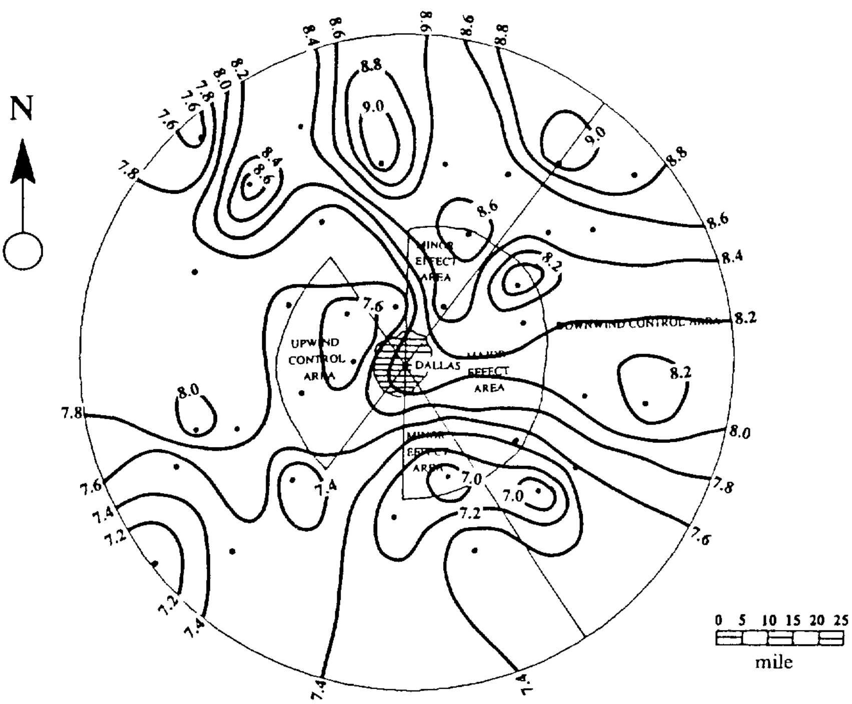


Figure 5. Summer Normal Precipitation Pattern in the Dallas Area (1961-1990, unit: inch)

Table 4. TSA Results for Annual and Seasonal Precipitation Patterns in the Dallas Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > F
Spring	$Y=1443.88+0.96X_1+1.68X_2$	71	37.97	0.01**
Summer	$Y=14.80+0.79X_1+0.34X_2$	29	18.83	0.01**
Fall	$Y=141.12+0.23X_1+1.77X_2$	80	70.01	0.01**
Winter	$Y=210.11-0.27X_1+2.01X_2$	87	132.09	0.01**
Annual	$Y=509.90+2.71X_1+5.80X_2$	83	87.31	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

effects. The summer residual map shows positive values N and SW of the city indicating the urban area has more precipitation than the estimated precipitation after considering the climatic gradient (Figure 6).

(2) Monthly precipitation distribution

Table 5 shows TSA results applied to monthly precipitation data in Dallas. June and August show a moderate-substantial trend, while July and May have high marked trends. September (60%), October (54%) and January (74%) show high marked trends and February (84%),

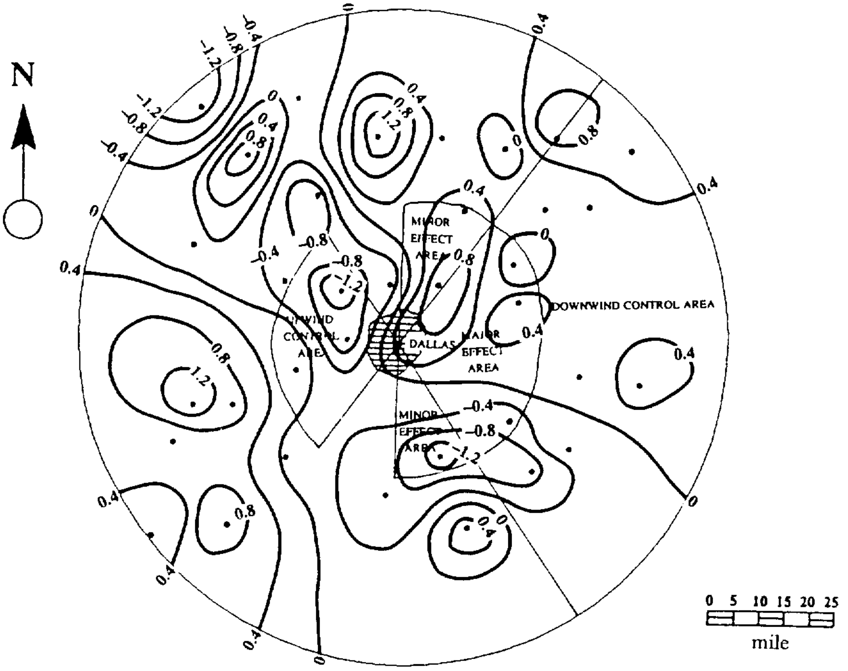


Figure 6. Residual Map of the Summer Precipitation Pattern in the Dallas Area (1961-1990, unit: inch)

Table 5. TSA Results for Monthly Precipitation Patterns in the Dallas Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > F
January	$Y=50.91-0.18X_1+0.44X_2$	74	47.41	0.01**
February	$Y=73.19+0.02X_1+0.74X_2$	84	90.09	0.01**
March	$Y=52.05+0.29X_1+0.60X_2$	73	48.10	0.01**
April	$Y=45.44+0.20X_1+0.50X_2$	56	21.02	0.01**
May	$Y=46.39+0.46X_1+0.58X_2$	52	17.71	0.01**
June	$Y=18.00+0.25X_1+0.24X_2$	27	6.33	0.01**
July	$Y=21.91-0.26X_1+0.29X_2$	53	18.80	0.01**
August	$Y=-25.11+0.27X_1-0.19X_2$	43	12.68	0.01**
September	$Y=13.69+0.39X_1+0.84X_2$	74	48.07	0.01**
October	$Y=40.45+0.26X_1+0.47X_2$	50	16.04	0.01**
November	$Y=86.98+0.13X_1+0.91X_2$	89	134.67	0.01**
December	$Y=86.00-1.11X_1+0.83X_2$	89	136.46	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

November (89%) and December (88%) have very high marked trends. Cooler months have higher values of %RSS than warmer months because the precipitation distribution of these months are influenced by mid-latitude cyclones. There are positive residuals E of, and in the city, in April and May indicating possible urban effects on precipitation during these months. The August residual map shows positive residuals in the city and downwind indicating precipitation enhancements in the city and extending downwind during these months (Figure 7).

3) San Antonio

(1) Annual and seasonal precipitation distribution

In general, annual and seasonal precipitation patterns show that maxima are located NE of the city area while general minima are located SW of the city, except during summer. Because the San Antonio area has a natural climatic gradient due to the proximity of the Gulf of Mexico and the Edward Plateau, it is very difficult to differentiate the precipitation increases caused by urban effects from these topographic effects. Unlike other study areas, there is a high altitude area located NW of the city. Figure 8 shows the summer precipitation pattern in the San Antonio area for the period of 1961-1990. The summer pattern has a distinct localized precipitation enhancement NE of the city.

TSA was applied to normal annual and seasonal precipitation data for the period of 1961-1990. The summer precipitation pattern has a moderate-substantial trend while spring, fall, and winter patterns have high marked trends (Table 6). The smaller %RSS in summer may be a result of the summer precipitation being controlled by smaller scale precipitation systems such as air mass thunderstorms. Annual, and all seasonal residual maps except winter, indicate that there are not only positive residual values in the city, but also downwind indicating precipitation increases. The summer residual map has higher positive values in the central urban area compared to other seasonal and the annual residual maps (Figure 9). Therefore, summer shows the most profound urban effects

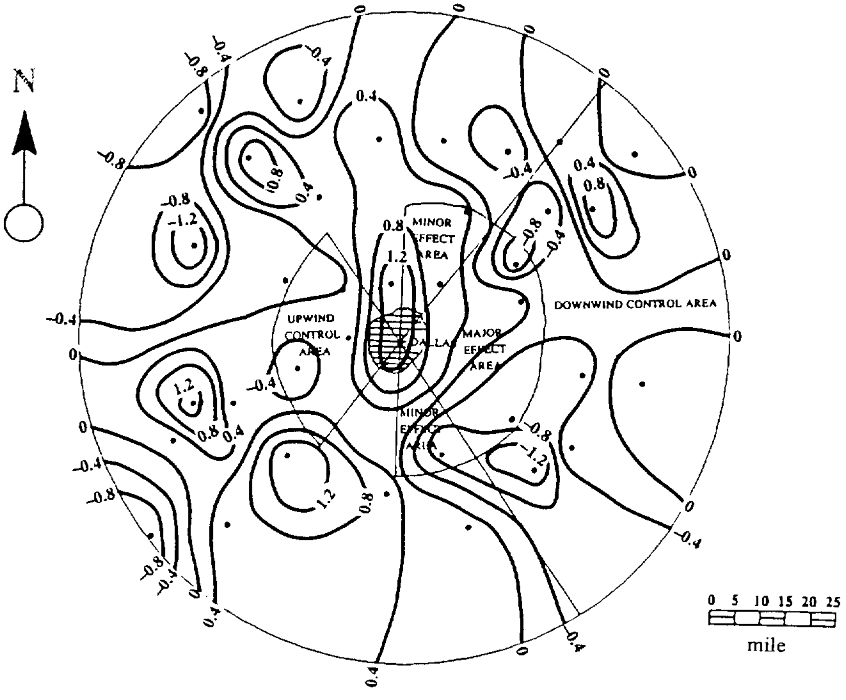


Figure 7. June and August Residual Maps in the Dallas Area (1961-1990, unit: inch)

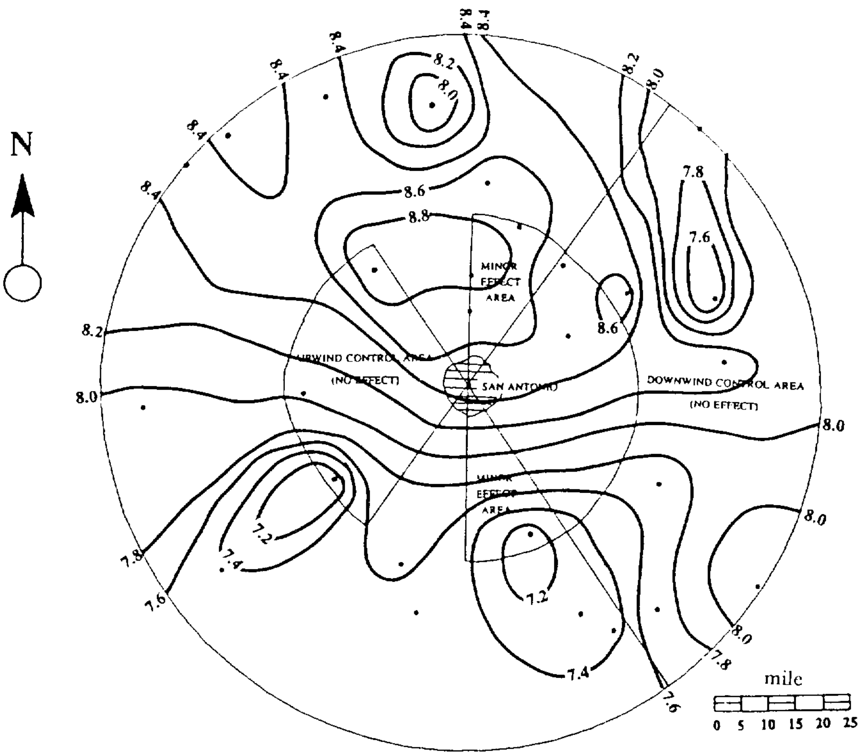


Figure 8. Summer Precipitation Pattern in the San Antonio Area (1961-1990, unit: inch)

Table 6. TSA Results for Annual and Seasonal Precipitation Patterns in the San Antonio Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > F
Spring	$Y=68.19+1.44X_1+1.04X_2$	72	33.48	0.01**
Summer	$Y=-15.94+0.75X_1-.018X_2$	41	8.69	0.01**
Fall	$Y=124.93+0.90X_1+1.45X_2$	61	19.83	0.01**
Winter	$Y=117.58+0.65X_1+1.34X_2$	76	38.08	0.01**
Annual	$Y=294.76+3.74X_1+3.80X_2$	67	25.53	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

on precipitation increase in San Antonio.

(2) Monthly precipitation distribution

TSA was applied to monthly normal precipitation data for the period of 1961-1990 to estimate the regional precipitation variation in San Antonio. TSA model results for each month are shown in Table 7. Cooler months (November-April) have higher %RSS than warmer months (March-October). April, June and July show moderate-substantial trends, while the rest of the months show high, marked trends in precipitation patterns. January, May, June, July, August, and November residual maps show positive values in the city and downwind indicating precipitation increases in these areas. June and July residual maps show higher positive residuals in the city and downwind so that warmer months appear to have the distinct possible precipitation enhancements due to urban influences in the San Antonio area (Figure 10).

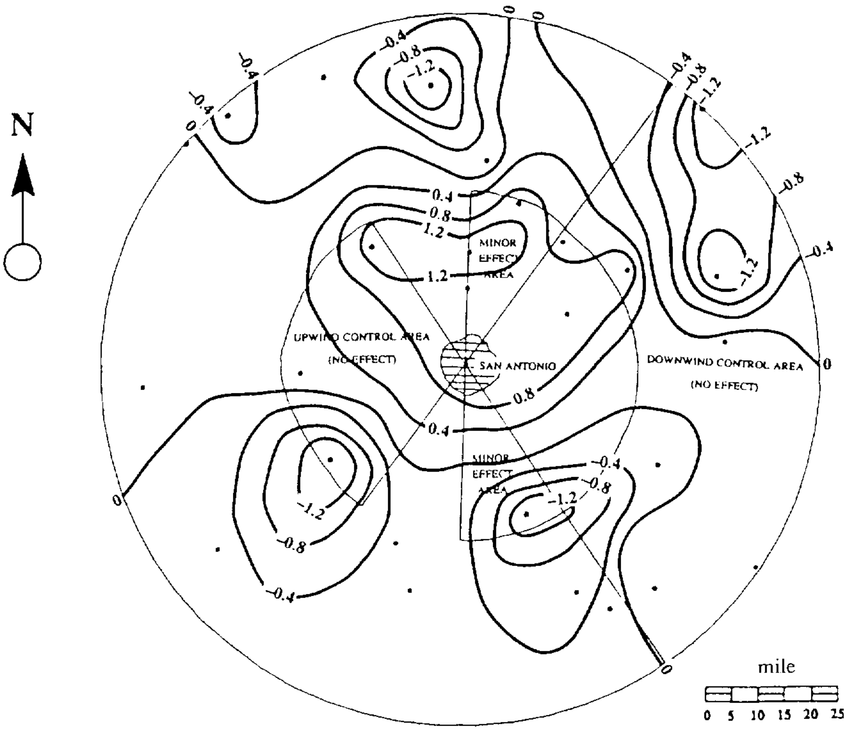


Figure 9. Summer Residual Map for San Antonio (1961-1990, unit: inch)

Table 7. TSA Results for Monthly Precipitation Patterns in the San Antonio Area (1961-1990)

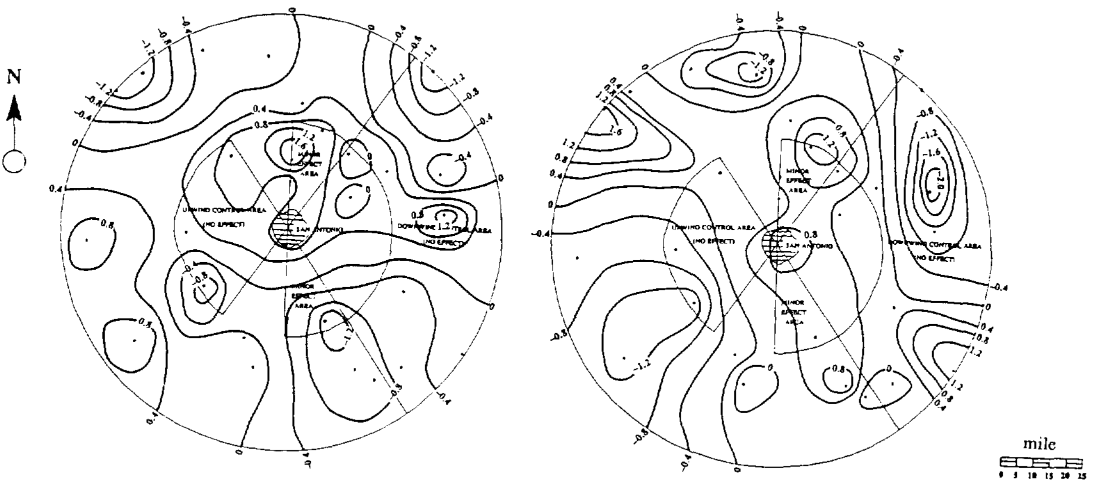
Month	Trend Surface Equation	%RSS	F-value	Prob > f
January	$Y=54.87+0.06X_1+0.56X_2$	76	40.60	0.01**
February	$Y=26.86+0.32X_1+0.35X_2$	74	35.65	0.01**
March	$Y=8.63+0.58X_1+0.25X_2$	70	28.50	0.01**
April	$Y=26.19+0.20X_1+0.30X_2$	46	10.71	0.01**
May	$Y=33.29+0.65X_1+0.49X_2$	65	23.40	0.01**
June	$Y=39.93+0.43X_1+0.50X_2$	47	10.92	0.01**
July	$Y=-18.47+0.31X_1-0.12X_2$	43	9.46	0.01**
August	$Y=-37.39+0.01X_1-0.40X_2$	61	18.58	0.01**
September	$Y=76.72+0.70X_1-0.14X_2$	51	13.44	0.01**
October	$Y=-4.87+0.55X_1+0.08X_2$	62	20.70	0.01**
November	$Y=53.07+0.49X_1+0.66X_2$	67	25.62	0.01**
December	$Y=35.84+0.27X_1+0.43X_2$	67	25.62	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

4) New Orleans

(1) Annual and seasonal precipitation distribution

The New Orleans area has a denser network of urban precipitation stations than the other cities examined for this study. However, the lack of stations in downwind areas and the minor effect area, and the existence of Lake Pontchartrain,



(a) June

(b) July

Figure 10. June and July Residual Maps for the San Antonio Area (1961-1990, unit: inch)

north of the city area make examination of urban effects on precipitation in the New Orleans area very difficult. Keim and Muller (1992) examined the annual maximum storm series from 1978 to 1991 in New Orleans and found that storm magnitude during the more recent 14 years (1978-1991) differed significantly from the rest of the series although there was no long-term trend. Faiers (1994) found that the New Orleans urban area enhances extreme 24-hour rainfall in all seasons except winter and the enhancements are located E and NE of the city in the spring, in the city through summer, and NE and E of the city during fall. However, seasonal and annual precipitation patterns show that there are no distinct precipitation increases downwind of the city. There is a localized maximum in the city area, but there is no distinct increase downwind of the city. It is possible that the precipitation might be influenced by the relatively cooler water of Lake Pontchartrain during summer. Although Lake Pontchartrain is not as big as Lake Michigan, it might influence the precipitation pattern just inland and along the shore of the lake. According to Changnon (1984), the stabilizing influence of Lake Michigan on convective rainfall is considerable, with fewer raincells and lower rain rates than over adjacent rural areas. The lake effect is realized largely in less well-organized and weaker convective conditions, whereas squall lines do not exhibit any great diminishment in rainfall production over the lake.

TSA results applied to annual and seasonal precipitation data show that there are moderate-substantial trends during the warmer seasons, while there are high-marked trends during cooler seasons in the New Orleans area (Table 8). The summer residual map shows positive values in the city and negative values downwind of the city. Since the spring, fall, winter and annual residual maps have negative values in the city and major effect areas, there are no distinct local precipitation enhancements during these seasons in the New Orleans area. These results differ from those of extreme rainfall studies (Faiers, 1994).

(2) Monthly precipitation distribution

TSA was applied to monthly normal precipitation data and results are shown in Table 9. Trends range from moderate-substantial to high marked trends in the warmer months while there are moderate-substantial to very high marked trends in the cooler months. June and August residual maps show positive residuals in the city. April and May residual maps have positive values in the city and downwind of the city showing an indication of downwind effects on precipitation increases. However, the

Table 8. TSA Results for Annual and Seasonal Precipitation Patterns in the New Orleans Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > f
Spring	$Y=-213.53+3.80.X_1-1.26X_2$	79	38.63	0.01**
Summer	$Y=-43.25-1.14X_1-1.09X_2$	28	3.97	0.03*
Fall	$Y=-74.67+0.12X_1-0.93X_2$	26	3.52	0.05*
Winter	$Y=-173.74-3.07X_1-1.08X_2$	76	30.31	0.01**
Annual	$Y=-505.19+5.85X_1-4.34X_2$	42	7.19	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

Table 9. TSA Results for Monthly Precipitation Patterns in the New Orleans Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > f
January	$Y=-47.70+0.74X_1-0.27X_2$	50	10.17	0.01**
February	$Y=-49.06+0.99X_1-0.28X_2$	66	19.04	0.01**
March	$Y=56.58+1.75X_1-0.10X_2$	84	50.60	0.01**
April	$Y=-104.1+1.41X_1-0.74X_2$	71	23.43	0.01**
May	$Y=-52.85+0.64X_1-0.43X_2$	38	6.18	0.01**
June	$Y=8.84+-0.64X_1-0.17X_2$	33	4.93	0.02*
July	$Y=-48.90-0.07X_1-0.64X_2$	22	2.81	0.08
August	$Y=-3.18-0.42X_1-0.24X_2$	21	2.67	0.08
September	$Y=15.59-0.20X_1-0.95X_2$	45	8.09	0.01**
October	$Y=-37.64+0.27X_1-0.36X_2$	25	3.36	0.06
November	$Y=-52.98+0.79X_1-0.37X_2$	63	16.99	0.01**
December	$Y=-82.99+1.34X_1-0.54X_2$	82	44.77	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

magnitude of values is smaller than the three cities in Texas.

5) Memphis

(1) Annual and seasonal precipitation distribution

Unusual characteristics of the Memphis seasonal precipitation distributions include a maximum rainfall in the cooler seasons (spring and winter) and a minimum rainfall in the warmer seasons (summer and fall). Since there is weak convergence or positive divergence throughout the air column in the Memphis area during the warmer seasons, especially summer, the suppression of precipitation occurs. According to Trewartha (1981), such a vertical structure does not represent as favorable a condition for convective overturning as that over the Florida coast where there exists stronger convergence at all levels up to about 1,000ft (300m). Seasonal and annual precipitation patterns show that general maxima are located E and SE of the city area and general minima are located N and NW of the study area except during fall. There are no distinct precipitation enhancements due to urban effects except during the summer which shows the presence of a localized minor maximum in the city area. Like other cities examined for this study, the Memphis city area has a natural climatic gradient so that precipitation increases from NW to SE due to the proximity of the Gulf of Mexico.

TSA was applied to annual and seasonal precipitation data for the period of 1961-1990 (Table 10). Annual precipitation has a high marked trend. The summer and fall precipitation patterns have a definite, but small to a high marked trend, and the winter and spring patterns

Table 10. TSA Results for Annual and Seasonal Precipitation Patterns in the Memphis Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > f
Spring	$Y=95.02-1.02.X_1+0.50X_2$	39	36.63	0.01**
Summer	$Y=141.22-1.47X_1+0.88X_2$	59	14.48	0.01**
Fall	$Y=54.18-0.26X_1+0.37X_2$	13	1.43	0.2
Winter	$Y=174.37-1.49X_1+1.20X_2$	73	26.98	0.01**
Annual	$Y=464.78-4.25X_1+2.93X_2$	64	18.01	0.01**

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

Table 11. TSA Results for Monthly Precipitation Patterns in the Memphis Area (1961-1990)

Month	Trend Surface Equation	%RSS	F-value	Prob > f
January	$Y=85.63-0.81X_1+0.59X_2$	81	44.26	0.01**
February	$Y=64.15-0.57X_1+0.44X_2$	68	21.22	0.01**
March	$Y=60.80+-0.58X_1+0.39X_2$	56	12.68	0.01**
April	$Y=11.20+0.09X_1+0.10X_2$	7	0.76	0.48
May	$Y=22.96-0.53X_1-0.01X_2$	29	4.03	0.03*
June	$Y=39.71-0.74X_1-0.11X_2$	48	9.3	0.01**
July	$Y=78.90-0.46X_1+0.66X_2$	52	10.92	0.01**
August	$Y=-22.60-0.27X_1+0.11X_2$	9	1.03	0.37
September	$Y=-1.22+0.18X_1+0.60X_2$	35	5.46	0.01**
October	$Y=9.45-0.90X_1-0.08X_2$	39	6.34	0.01**
November	$Y=45.95-0.47X_1+0.27X_2$	51	10.45	0.01**
December	$Y=24.59-0.11X_1+0.17X_2$	24	3.90	0.07

Y=precipitation, X_1=latitude, X_2=longitude, %RSS=the percentage reduction in sum of squared achieved. * significant at 95% level, ** significant at 99% level.

range from a moderate-substantial to a high marked trend. The higher %RSS in summer may be caused by strong maritime tropical air effects from the Gulf of Mexico to this area. There are positive values over the city in the summer residual map, but the magnitude of the value is not as high as that of other study areas. Residual maps for the other seasons and annual pattern have no positive values in the city and downwind. Therefore, there are no distinct urban effects on precipitation increases in the Memphis area.

(2) Monthly precipitation distribution

TSA was applied to monthly normal precipitation data to examine urban effects on precipitation enhancements in the Memphis area (Table 11). All summer and fall months have moderate-substantial to high marked trends except during August which shows a definite but small trend. Cooler months have a definite but small trend in April, a moderate-substantial trend in December, and high marked trends in February and March. January, July, August, October, November and December residual maps have positive values over the city, but the magnitude of values is smaller than other cities.

5. Conclusions and Summary

Using monthly station normals of precipitation (1961-1990), precipitation enhancements over the five largest cities in the southern United States of America were examined. A trend surface analysis was applied to precipitation data to eliminate the natural precipitation variation. Winter and spring have more trends than summer and fall and the period of November through March has more marked trends than the period of April through October in all study areas except the Houston area. More marked trends in cooler seasons and months are a result of the concentration of jet stream positions in the study area at that time of year and consequent passage of cyclonic storms along cold or stationary fronts which move toward E. The average position of the jet stream moves southward from the Great Lake area into the southern United States between October and November bringing some frontal disturbances to the study area. The jet is located at its most southerly position near 30° N during January and moves back northward to the Great Lakes area by June (Lydolph, 1985) when precipitation from the frontal passages in the South is infrequent.

Residual maps for Houston, Dallas and San Antonio have positive residuals in the city and downwind during summer and spring, indicating that urban effects on precipitation enhancement in these areas do exist during these seasons after eliminating the natural precipitation variation. Also June, July, and August residual maps in Houston, Dallas, and San Antonio show some precipitation enhancements due to urban effects with positive values in the city and downwind of the city. Summer residual maps for New Orleans and Memphis have no distinct precipitation increases due to urban effects. The June residual map for the New Orleans area and the July residual map for Memphis show positive residuals in the city, but the magnitude of values is smaller than other cities.

Future study must focus on increasing the %RSS of some seasons using quadratic or cubic terms in TSA. Some seasons have definite, but small to moderate-substantial trends, which are not enough to eliminate regional effects. For instance, there were positive residuals in the Dallas urban area and downwind of the city after eliminating 29%RSS of regional effects. It is necessary to discern whether these positive residuals will be located in the city area and downwind of the city after using higher terms and better trend surfaces to confirm urban effects on precipitation increase.

If the urban area affects precipitation significantly downwind of urban-industrial regions, this would be reflected in the precipitation patterns when the data for each rainstorm are stratified by synoptic weather types (Vogel and Huff, 1978). Further synoptic study for five cities will be examined using the daily weather maps.

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미국 남부지역의 도시화로 인한 강수변화 연구에 대한 경향면 분석의 적용

최 영 은* · Keith G. Henderson**

미국 남서부 지역의 5개 도시 즉, 텍사스주의 Houston, Dallas 및 San Antonio, 루이지애나주의 New Orleans 그리고 테네시주의 Memphis에서 강수의 자연적 경향과 강수에 미치는 도시의 영향을 파악하기 위하여 경향면 분석(Trend surface analysis, TSA)을 시도하였다. 분석기간은 1961년부터 1990년까지 30년간이다. 사용한 자료는 월강수량, 계절강수량 그리고 연강수량이다. Houston을 제외한 4개 도시에서는 겨울철과 봄철에 비하여 여름철과 가을철에 보다 큰 경향값을 보였다. 월별 분석에서는 11월부터 3월까지 기간에 4월부터 10월까지 기간에 보다 현저한 경향을 나타냈다. 자연적 강수의 변동을 제거한 후의 잔차도를 보면, Houston, Dallas, San Antonio 등지에서는 여름철에 도시와 풍하지역에서 양의 잔차값을 보이고 있는데 이러한 현상은 다른 계절에 비하여 여름철에 도시의 영향으로 인한 강수가 더 많아지고 있음을 의미하는 것이다.

Memphis와 New Orleans의 여름철 잔차도에서는 도시의 영향에 기인하는 강수의 현저한 증가를 발견할 수 없었다. New Orleans의 6월과 Memphis의 7월 잔차도에서는 도시에서는 양의 값을 보였으나 다른 도시에 비해 그 규모가 크지 않았다.

주요 용어: 경향면분석, 강수 강화, 도시의 영향, 잔차

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