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A Model of Precipitation Rates in Kentucky, 1965-1996

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A MODEL OF PRECIPITATION RATES IN KENTUCKY, 1965 - 1996

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A MODEL OF PRECIPITATION RATES IN KENTUCKY, 1965 - 1996

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Hourly precipitation data from thirty cooperative stations in Kentucky from 1965 to 1996 were used to determine the diurnal distribution of precipitation rates. Descriptive summaries for the diurnal distribution for each climate division in Kentucky and for Kentucky as a whole were calculated. In each case, the trends were similar. Precipitation rates increased into the afternoon and then decreased until sunrise.

A stochastic model was developed to estimate mean seasonal precipitation rates in Kentucky by using regional and localized parameters. More than half of the variation (r^2 = 0.57) in precipitation rates can be explained by the following variables: 1) Distance away from the moisture source, the Gulf of Mexico; 2) Roughness of topography; 3) Degree of urbanization.

Precipitation rates decrease in a northeasterly direction across Kentucky as air moves farther away from the Gulf of Mexico along its path of migration. The maritime tropical air mass migrating out of the Gulf of Mexico loses its water vapor over its path of migration. As a result, less water vapor is available for precipitation processes in areas farther away. As a precipitation event moves over rougher terrain and more urbanized areas, precipitation rates decrease as well. A rougher terrain absorbs more solar radiation because it has more

surface area. An urbanized area absorbs more solar radiation because of the urban structures (e.g., buildings, asphalt, roofs). As a result, both will radiate more heat causing the air to be buoyant at the surface to either enhance convection or increase vertical air motions. Increased vertical air motions will cause an increase in air resistance acting upon precipitation falling, thereby, causing a decrease in the amount falling to the surface per hour.

CHAPTER I

INTRODUCTION

A particular climate is usually characterized by its temperature and precipitation. The focus of this research is precipitation. Precipitation can be averaged over any given time period and mapped as part of a precipitation climatology. As stated by Oki and Musiake (1994, p. 1445), "The spatial and temporal distribution of precipitation is an important index reflecting climatic state and climatic change." Descriptively, precipitation is climatically summarized over an area by annual, seasonal and monthly amounts over any given time period. The knowledge of the causal processes influencing the spatial and temporal patterns of precipitation is helpful to further our understanding.

A new avenue of exploration in precipitation research involves precipitation rates. Research concerning precipitation rates is used in General Circulation Models (GCMs), short-term weather forecasting and modeling land-surface hydrology in Kentucky. GCMs are complex models and predict climate conditions for a grid square (2.5^0 of latitude by 2.5^0 of longitude) (Creating, 1999). However, Gao and Sorooshian (1994, p. 238) stated that "it is commonly assumed that the precipitation processes are homogenous over a GCM grid square and that the precipitation intensity is uniformly distributed." A previous study concerning precipitation rates in the western climatological division of Kentucky by Kevin Cary (1998) contradicts the assumption that precipitation intensities are homogenous over a GCM grid square.

Knowledge of the seasonal and diurnal distribution of precipitation rates in Kentucky would improve the understanding of short-term weather forecasting. Questions of concern addressed in this research are which season and time of day are heavy precipitation events likely to occur?. An example of short-term weather forecasting would include flash floods.

Urban planners could benefit from this research in planning flood channels and storm sewage systems. This research could lead to improvements of methods for channeling flood water to maximize the public safety to the residence. Furthermore, this research could contribute to minimizing the damage caused by flood water.

Precipitation is an important element used in hydrological models. Examples of hydrological models are land-surface models that include infiltration, residence time of rainfall in streams and predicting stream flow. These models do require the input of precipitation rates since absorption rates of the soil are already incorporated into the model. Chen, Zeng, Dickinson (1998, p. 876) concurred that "Without such realistic precipitation input, it may be impossible to simulate realistic land-surface hydrological processes." Furthermore, Chen, Yen, Hsieh and Arritt (1995, p. 2234) stated that ". . .the diurnal variation of rainfall might be regarded as a comprehensive indicator of the diurnal variation of the hydrological system."

A preliminary analysis of precipitation rates revealed some distinctive spatial and temporal patterns. The purpose of this study is to determine factors that influence precipitation rates in Kentucky; it will be focused on the diurnal distribution of precipitation rates in Kentucky, and it will determine the basic processes that underline precipitation rates in Kentucky.

CHAPTER II

REVIEW OF LITERATURE

Precipitation Patterns. According to Köppen's climate classification system, the southeastern United States is humid subtropical (cf). Kentucky's climate contains no dry season and is characterized by a hot summer followed by a mild winter. The general precipitation pattern in annual amounts for the area east of the Mississippi River decreases northward from the Gulf of Mexico to the Great Lakes (Prism, 2000). Hill (1976) determined this same pattern to exist in Kentucky. In southern Kentucky, the precipitation amounts are 13" greater per year than in the north (Conner, 1991). Conversely, for the western region of Kentucky the average is 2-4" per year greater than that of the eastern region. In general, the mean annual precipitation distribution for Kentucky decreases in a northeasterly direction as shown in Figure 2.1 (Conner, 1979).

It is important to identify the major influences such as the moisture source and prevailing winds to explain the processes influencing this northeasterly pattern in mean annual precipitation. Kentucky's primary moisture source is the Gulf of Mexico. Areas closer to the moisture source generally receive more precipitation because the warm-air mass from the Gulf of Mexico will lose its moisture during its migration. For Kentucky, the westerlies are the prevailing winds that push the precipitation events to the east and influence the west to east pattern (Conner, 1991). These two factors influence Kentucky's spatial pattern in annual precipitation.

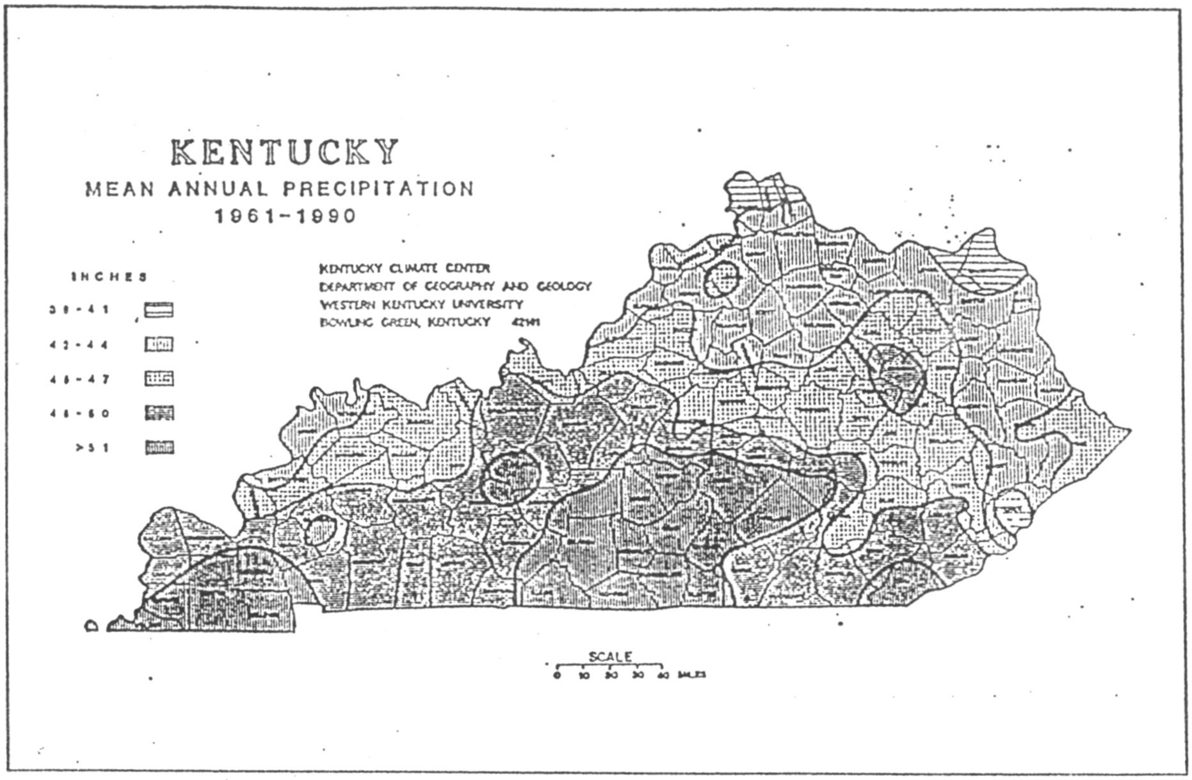


Figure 2.1 Kentucky's Mean Annual Precipitation

Kentucky Precipitation Rates. In 1981, Conner published a study about the seasonal diurnal distribution of hourly precipitation rates for the time period of 1949 to 1973. He discovered that the most intense rainfall in Kentucky occurred in the afternoon hours for all seasons. Furthermore, the summer season contained the highest mean precipitation rate for all hours with the winter season at the lowest. He also discovered that the western half of Kentucky contained higher precipitation rates than the east, and the southern half contained higher precipitation rates than the north. However, no explanation was given for the influence of this pattern. His methodology of the data had the middle month of each meteorological season to be representative of its respectable season, leaving eight months of data unused (Conner, 1981). In 1998, I expanded on the study for the Western Kentucky climatological division to determine if the diurnal distribution of precipitation rates were similar to Conner's study with all months present. Hourly precipitation amounts for the years 1965 to 1996 from six cooperative stations were averaged for all the hours in each meteorological season. Similarly, the summer season contained the highest mean hourly precipitation rate with the winter showing the lowest. In each season, the hours containing the most intense rainfall for Western Kentucky occurred in the afternoon (Cary, 1998).

Illinois and Louisiana Precipitation Rates. There were other studies in Illinois and Louisiana with similar results pertaining to precipitation rates. Huff (1971) investigated the geographic and diurnal distribution of precipitation rates in Illinois. In each season, a maxima in the diurnal distribution occurred in the afternoon. However, two maxima exist in the summer with a primary maxima in the morning. Mingxuan Chen confirmed that temperature is indicative of monthly precipitation rates over the continental United States (Chen, 1998). The spatial distribution of annual and seasonal hourly precipitation rates in Illinois decreased northward (Huff, 1971). This pattern coincides with the spatial pattern of annual and seasonal precipitation amounts in Illinois as well (Huff, 1979). In Louisiana, 24-hour rainfall frequency maps were created to estimate runoff in hydrologic studies for ungauged sites. Most of Louisiana's intense rainfall frequently occurred in the southern areas (Naghavi, 1993).

Japan and Taiwan Precipitation Rates. Studies pertaining to diurnal distribution of precipitation rates have also been done in Japan and Taiwan. Musiake and Oki (1994) catagorize three groups of precipitation rates in Japan on the basis of their diurnal cycles.

They used hourly precipitation data over a ten-year period and used a cluster analysis to categorize the diurnal variations of stations in Japan. Stations in the first cluster are located along the coasts with a maxima occurring in the morning. Stations in the second cluster are located inland with a maxima occurring in the morning and in the evening. Stations in the third cluster are located further inland with a maxima occurring only in the evening. They concluded that the diurnal distribution of precipitation rates in the first cluster is representative of a maritime climate, the second cluster experienced severe convective showers as identified by a secondary peak in the afternoon, and the third cluster's "...precipitation is brought mainly by thunderstorms in the summer evenings" (Oki, 1994, p. 1449). In Taiwan, the maxima in the diurnal distribution of precipitation rates occurred in the evening. It was concluded that this time period was the one in which the atmosphere contained the most water vapor (Oki, 1994).

Flash Flood Events. There are studies using precipitation rates to further the understanding of heavy precipitation events. "In general, heavy precipitation can be considered a rain event of such magnitude and intensity as to disrupt human activities and/or cause flash flooding" as defined by Winkler (1992, p. 127). Flash floods are a direct result of a heavy rainfall event occurring over a short period of time in a small area. Most flash floods are predicted in short-term weather forecasting. However, Guttman and Ezell (1980, p. 70) concurred that ". . .there is no general consensus on what rainfall intensity/thresholds define a flash flood." Therefore, understanding the diurnal distribution of heavy rainfall events are inevitable for predicting flash flood events. Giordana (1983) put an emphasis on researching precipitation rates to determine probabilities of flash flood events. In the mid-Atlantic states, the diurnal distribution of heavy rainfall events reveals a maxima in the evening with a minima in the morning (Giordana, 1983). The afternoon and early evening hours are the most frequent times of occurrence for heavy precipitation events causing flash floods (Crysler, 1982). Furthermore, the summer season of the eastern and central United States most frequently has flash floods in the afternoon (Winkler, 1987). On the contrary, the seasonal distribution in the frequency of heavy precipitation events in the southern plain states of the United States was the highest in the spring and fall (Bradley, 1994).

Heavy precipitation events are associated with thunderstorms. The summer contains the highest mean number of thunderstorms in a season for the contiguous United States (Changery, 1981). The spatial variability in the time of occurrence in heavy precipitation events across the United States is identified by Winkler. "Generally, spatial variability in the time of occurrence of heavy precipitation is small in summer and large during the transitions seasons of spring and autumn and in winter" (1992, p. 143).

Mesoscale Convective Complexes. Occasionally, a number of individual convective thunderstorms will grow in size and merge together creating a large convective weather system, called Mesoscale Convective Complexes (MCCs). There is a high frequency of occurrence in the United States for MCCs in the warm months of March through September in the mid-west of the United States. Typically they occur most often in the areas of Missouri and Kansas (Augustine, 1991). Intense rainfall from MCCs sometimes can be identified in the nocturnal portion of the day. Maddox (1980, p. 1383) stated that ". . .it seems likely that MCCs are, in large part, responsible for the nocturnal maxima in thunderstorm and precipitation frequencies over the central United States" (Maddox, 1980).

Urban Induced Precipitation. Urban areas have been known to induce precipitation. An increase in precipitation amounts downwind of Chicago, Illinois, was discovered soon after a rain gage was installed at a sewage plant in La Porte, Indiana, in 1962 (Holzman, 1970). The possible causes of urban induced precipitation are the pollutants released from factories and vehicles in the city. The pollutants can serve as condensation nuclei that are essential to precipitation processes. An increase in pollutants increases the likelihood of water vapor condensing in larger numbers into cloud droplets. As a result, more precipitation will be produced downwind (Miller, 1999). Furthermore, urban environments absorb more heat than do rural areas resulting in an increase in vertical air motions of rising parcels of air (Changnon, 1969). Observation alone has revealed that an urban area can enhance convection. During the 1996 Summer Olympics, four convective thunderstorms were seen developing over the city of Atlanta (Helmuth, 1999).

Topographic Effects. Gao, and Sorooshian (1994, p. 239) concluded that "topography and land surface properties strongly impact the distribution of precipitation at the mesoscale." The roughness of the topography would also enhance convection. There is more surface area in rougher terrain than on a flat surface thus resulting in more heat being absorbed. The addition in absorption would cause an increase in the vertical air motions entering a precipitation event (Changnon, 1971).

Orographic Uplift. Elevation is another factor that could have an influence on precipitation rates in Kentucky. One of the major mechanisms of uplifts necessary for condensation is orographic uplift on the windward side of a mountain. It is known that annual precipitation amounts are higher at higher elevations on the windward side versus the leeward side (Taylor, 1980). In Kentucky, the westerlies carry the air over land in a gradual increase of elevation. Western and eastern Kentucky differ in land elevation since the Mississippi basin is located to the west and the Appalachian Mountains are in the east.

Statistical Usages. Identifying factors influencing precipitation amounts is essential for input in General Circulation Models (GCMs). GCMs are complex models that are used to predict climate conditions (Creating, 1999). Statistics, such as a regression analysis, are being used as an objective approach to identify influences on a climate patterns. Altitude, latitude, and distance away from the moisture source were the independent variables in a statistical study that explained most of the spatial variation in a study on mean annual precipitation in California (Taylor, 1980). However, Stewart (1989, p. 53) noted that "statistics is a method for panning precious order from the sand of complexity." However, Bailey and Gatrell's (1996, p. 37) advise is that ". . .humility is indeed wise for the spatial analyst."

CHAPTER III

METHODOLOGY

The analysis of precipitation rates was carried out in two sections. First, descriptive summaries of diurnal data on precipitation rates were generated. Second, a stochastic model of the spatial and seasonal distribution of precipitation rates was developed. This chapter details the methods used in each step.

Descriptive summaries document the diurnal distribution of precipitation rates and facilitate the comparison of distributions across seasons and climatic divisions. This analysis involved calculating descriptive statistics and producing graphs. Statistics measuring central tendency (mean) and dispersion (range) were calculated for the following:

i) all hours in each climate division for each season

ii) all hours in Kentucky for each season

Furthermore, maxima and minima were identified in the scatterplots produced. The scatterplots displayed the diurnal distribution of rainfall intensities for each hour in each climate division for each season and then again for Kentucky (climate divisions combined) for each season.

A stochastic model of the average hourly precipitation rate was developed using linear regression techniques. Determinants of precipitation rate are theorized to consist of "regional" and "local" spatial effects. The model can be generalized as follows.

Average hourly precipitation rate = f(regional effects, local effects) + noise.

The noise term is assumed to consist of independent and identically distributed random normal variates. Based on this assumption, ordinary least squares regression was used to estimate the model. The residuals were then analyzed to determine if the assumed properties of the noise term were reasonable. A histogram was used to visually check the normality assumption. Scatterplots were utilized to evaluate evidence of heteroskedasticity and the linearity of the model. Moran's I statistic was calculated to test for spatial autocorrelation. If one or more of the assumptions concerning the noise term proved unreasonable, then corrective actions were taken. These included some combination of variable transformations and use of a generalized least squares model.

CHAPTER IV

DATA

A summary about primary and secondary data on hourly precipitation amounts will be discussed to provide a background overview on the origination of the data used in this study. The criteria for the stations selected in this study are given before the data is partitioned into meteorological seasons and climate divisions. The dependent variable and independent variables were identified along with their rationale in this study, and the method of collecting data for the independent variables is discussed.

Measuring Precipitation. Precipitation has traditionally been measured using a weighing rain gauge. The gauge collects precipitation in a bucket that sits upon a weight scale. Precipitation amounts are recorded automatically. A pen attached to an arm that is sensitive to the weight of the bucket records the precipitation over time onto a graph. Now, most weather stations are equipped with a tipping bucket rain gauge that records precipitation amounts on an hourly basis. Inside the gauge are two funnel-shaped collectors that can hold up to 0.01" of precipitation. These collectors are positioned side by side at an angle. When one collector is filled, gravity pulls it down and causes it to empty. As one collector is emptied, the other moves into place to collect precipitation. Each cup that is emptied is then recorded into a data logger at an automated weather station as an additional 0.01 inch for that recording hour.

After precipitation data are recorded by the National Weather Service (NWS), they are stored in a database at the National Climatic Data Center (NCDC) in Asheville, North

Carolina. EarthInfo, a private company in Boulder, Colorado, processes hourly precipitation data and makes them available on compact disk.

Hourly precipitation data are available for numerous weather stations across Kentucky. However, many stations have short periods of record. Thirty weather stations with sufficient precipitation records form March 1, 1965 through February 28, 1996 were identified and used for this research (Figure 4.1).

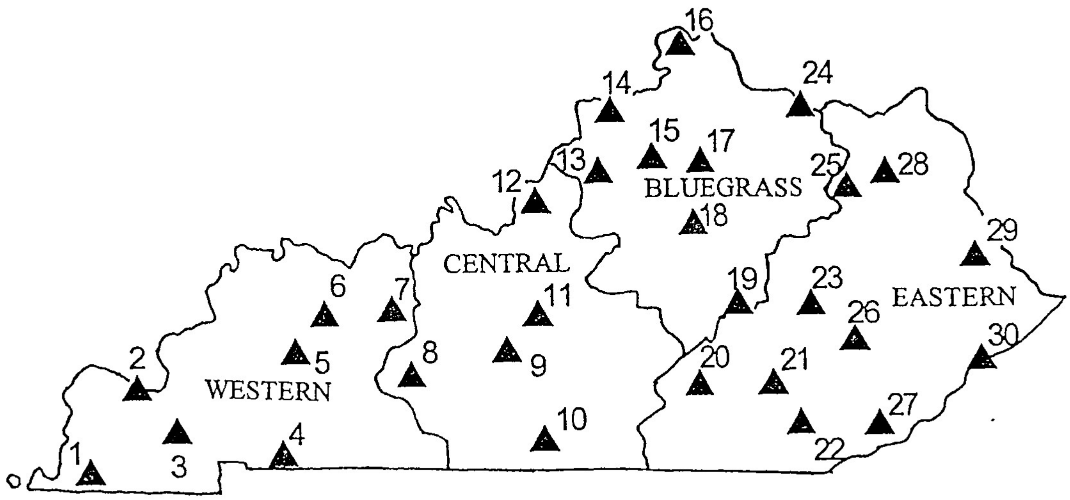
Calculating Precipitation Rates. Each station's data were partitioned into the following meteorological seasons: 1 March to 31 May (Spring), 1 June to 31 August (Summer), 1 September to 30 November (Autumn), and 1 December to 28 February (Winter). The stations were also partitioned into the climate divisions of Kentucky. The data were then summarized in the following order of explanation for analysis:

i) each hour in each climate division for each season.

ii) each hour in Kentucky for each season

iii) for all hours in each climate division for each season.

The following was used to calculate mean seasonal precipitation rates for each ending hour in a climate division: the sum of the precipitation amounts from all stations in their respective climate division and season for a given ending hour divided by the number of precipitation events from all stations in their respective climate division and season. A precipitation event for an ending hour is defined as an ending hour recording precipitation. Calculating mean seasonal precipitation rates for each ending hour for Kentucky (climate divisions combined) was done in a similar manner by combining all thirty stations' data.



Numerical Order

1 Clinton	7 Dundee	13 Smithfield	19 Berea College	25 Morehead
2 Paducah	8 Woodbury	14 Carrollton	20 Somerset	26 Buckhorn Lake
3 Benton	9 Munfordville	15 Gest Lock	21 London	27 Baxter
4 Herndon	10 Tompkinsville	16 Covington	22 Barbourville	28 Olive Hill
5 Madisonville	11 Hodgenville	17 Sadieville	23 Heidelberg	29 Davella
6 Calhoun	12 Louisville	18 Lexington	24 Maysville	30 Burdine

Alphabetical Order

Barbourville 22	Calhoun 6	Gest Lock 15	Louisville 12	Paducah 2
Baxter 27	Carrollton 14	Heidelberg 23	Madisonville 5	Sadieville 17
Benton 3	Clinton 1	Herndon 4	Maysville 24	Smithfield 13
Berea College 19	Covington 16	Hodgenville 11	Morehead 25	Somerset 20
Buckhorn Lake 26	Davella 29	Lexington 18	Munfordville 9	Tompkinsville 10
Burdine 30	Dundee 7	London 21	Olive Hill 28	Woodbury 8

Figure 4.1 Stations Utilized in Study with Climate Divisions in Kentucky

Mean seasonal precipitation rates for each climate division in Kentucky were calculated to provide a coarse evaluation of spatial variation. All the stations' hourly data were combined in their respective climate division and season in determining the mean seasonal precipitation rates for each climate division. Mean seasonal precipitation rate for a climate division is defined as follows: the total precipitation amounts from all the stations in the selected climate division in the indicated season for all the hour divided by the total number of precipitation events that occurred in all the stations in their respectable climate division and season.

A data set comprised of a dependent variable and independent variables was used for the regression analysis. The dependent variable in modeling precipitation rates in Kentucky is the station's mean seasonal precipitation rate from 1965 to 1996. It is defined as the sum of the precipitation amounts for a station in the indicated season divided by the total number of precipitation events in the indicated season. Mean seasonal precipitation rates for each station may be influenced by the following independent variables as stated in the previous chapter: meteorological season, distance away from the moisture source, the degree of roughness in the topography, and the degree of urbanization. The rationale behind the selection of variables, along with method of collecting their data, is provided below.

The seasons in the data set to be created are represented as indicator variables. These variables will indicate the season represented by the value of the mean seasonal precipitation rate in the data set. Spring, summer and autumn are the indicator variables used in the data set for this study. Winter is the default season.

Measuring Regional Parameters. Spatial variation in precipitation rates is modeled as a function of regional and localized effects. Regional effects influencing precipitation in Kentucky include proximity to the primary moisture source, which is the Gulf of Mexico (Conner,1979), and elevation (Taylor, 1980), which broadly trends higher from east to west. Proximity to the primary moisture source is reflected in the latitude and longitude of the weather stations used in the study. The locations of weather stations were obtained from the Kentucky Climate Center (KCC). These locations were recorded in degrees and minutes of latitude and longitude. More precise locations were determined by using directions to weather stations listed in the cooperative station reports available in the KCC. For each station, a 7.5 minute topographic quadrangle map from the U.S. Geological Survey (USGS) was downloaded as a digital raster graphic file into ESRI's ArcView GIS, version 3.0, and ArcView's measure tool was used to follow the directions to the station's location. Finally, the locational coordinates were converted from the spherical grid system of latitude and longitude into a plane grid system using Universal Transverse Mercator (UTM) coordinates for zone 16. In addition, elevation for stations are included in the cooperative station reports available through the KCC.

Measuring Local Parameters. Local effects on precipitation rates include smaller scale influences that might vary significantly form station to station. Gao and Sorooshian concluded (1994, p. 238) that "topography and land surface properties strongly impact the distribution of precipitation." That conclusion implies the importance of the effects of the roughness of topography and degree of urbanization on precipitation. Therefore, the roughness of topography and degree of urbanization are included in the model to capture these effects. Rougher topography has more surface area than flat land. As a result, a greater absorption of solar radiation of heat from the sun enhances the upward air motions in the atmosphere. The enhancement would cause an increase in the air resistance acting upon precipitation. The precipitation rate is speculated to decrease.

In urban areas, synthetic surfaces cover the ground (e.g., asphalt, concrete), and buildings fill the skyline. Each of these urban features absorbs a significant amount of heat from the sun in contrast to a rural environment. Changnon, Floyd, and Semonin (1971, p. 962) concluded that the addition of absorption of heat brought on by urban environments ". . .would. . .lead to upward motions of the air to initiate or enhance convection." As a precipitation event moves over an area with an influx of vertical air motions brought on by a warmer surface, the precipitation rate will decrease. A decrease in the precipitation rate would be caused by an increase in air resistance on falling precipitation. The effect of an urban environment on a precipitation rate is similar to that of a rougher terrain.

A measure of roughness was calculated for each station using ArcView GIS. First, digital elevation models (DEMs) for the vicinity of the station were downloaded from the Kentucky Office of Geographic Information Web Site. The DEMs are in raster format, where each pixel has a resolution of 30 meters. The ArcView Spatial Analyst was then used to calculate the slope for each pixel. A semicircular buffer with a 5-mile radius was created next around the station (Figure 4.2). This buffer was used to select the pixels lying on the western side of the station. (The western orientation was based on an average direction from which precipitation approaches sites in Kentucky.) A histogram of nine classes of slope values was created (Figure 4.3). The histogram was then used to calculate the mean slope,

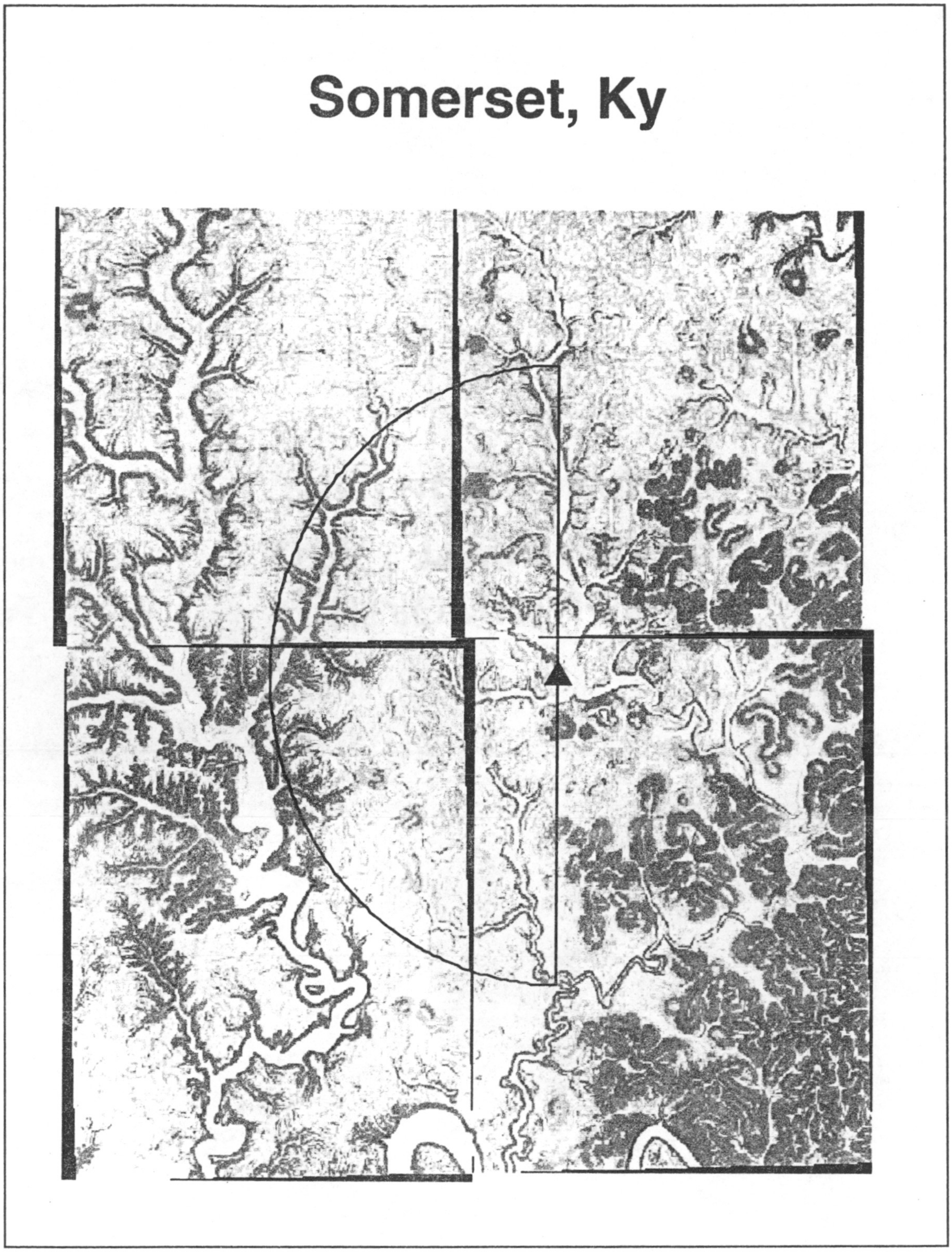


Figure 4.2 Buffer around Cooperative Station to Measure Roughness of Topography

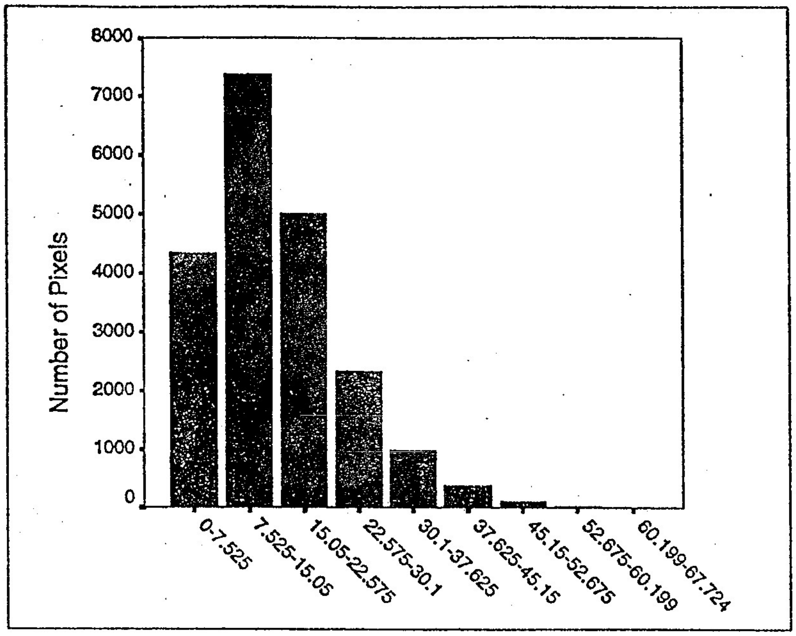


Figure 4.3 Histogram of Slope Classes in Degrees

using the midpoints of the class intervals and the frequency of pixels occurring in each interval. The resulting value was taken as the measure of roughness.

The degree of urbanization is reflected by population density in the vicinity of a weather station. While the precipitation data were compiled over a long period, population density was calculated based on the 1990 Census of Population and Housing. Population data are available at many geographic scales. U.S. Census Bureau block groups were used in this research. Block groups are smaller than census tracts and tend to have a population near 1000 people. Hence, in densely settled areas, block groups are smaller in area. Again, a semicircular buffer with a 5-mile radius was placed around each station, and all block groups intersected by the buffer on the western side of a station were selected (Figure 4.4). The population density was calculated based on the total population and area of the selected block groups. This value was taken to represent urbanization.

Figure 4.4 Buffer around Cooperative Station to Measure Population Density

CHAPTER V

RESULTS AND DISCUSSION

Results from the analysis of precipitation rates are presented in two sections. First, a descriptive summary of the diurnal variation of precipitation rates by season for each of Kentucky's climate divisions and Kentucky as a whole is shown. Second, the results from the stochastic model of the spatial and temporal distribution of average hourly precipitation rates are given.

Section 5.1 Kentucky's Variations in Hourly Precipitation Rates

This section shows comparisons of diurnal precipitation intensities among climate divisions in Kentucky (Figure 4.1) by season. Figures 5.1 through 5.4 show divisional summaries.

Divisional Variations in Spring. The highest mean precipitation rate occurred in the Western Division with a mean of 0.14 inches per hour. The lowest occurred in the Bluegrass Division with a mean of 0.08 inches per hour (Figure 5.1). The Central and Eastern divisions contained means of 0.11 and 0.09 inches per hour, respectively. A maximum occurred in the afternoon hours for all divisions. A secondary maximum of equal intensity occurred in the evening hours for the Western, Eastern, and Bluegrass Divisions. The Western and Eastern Divisions shared a minimum at noon. Furthermore, the Western Division contained another minimum of equal intensity in the pre-noon hours. The highest value in precipitation intensities, 0.17inches per hour, was discovered in the Western and

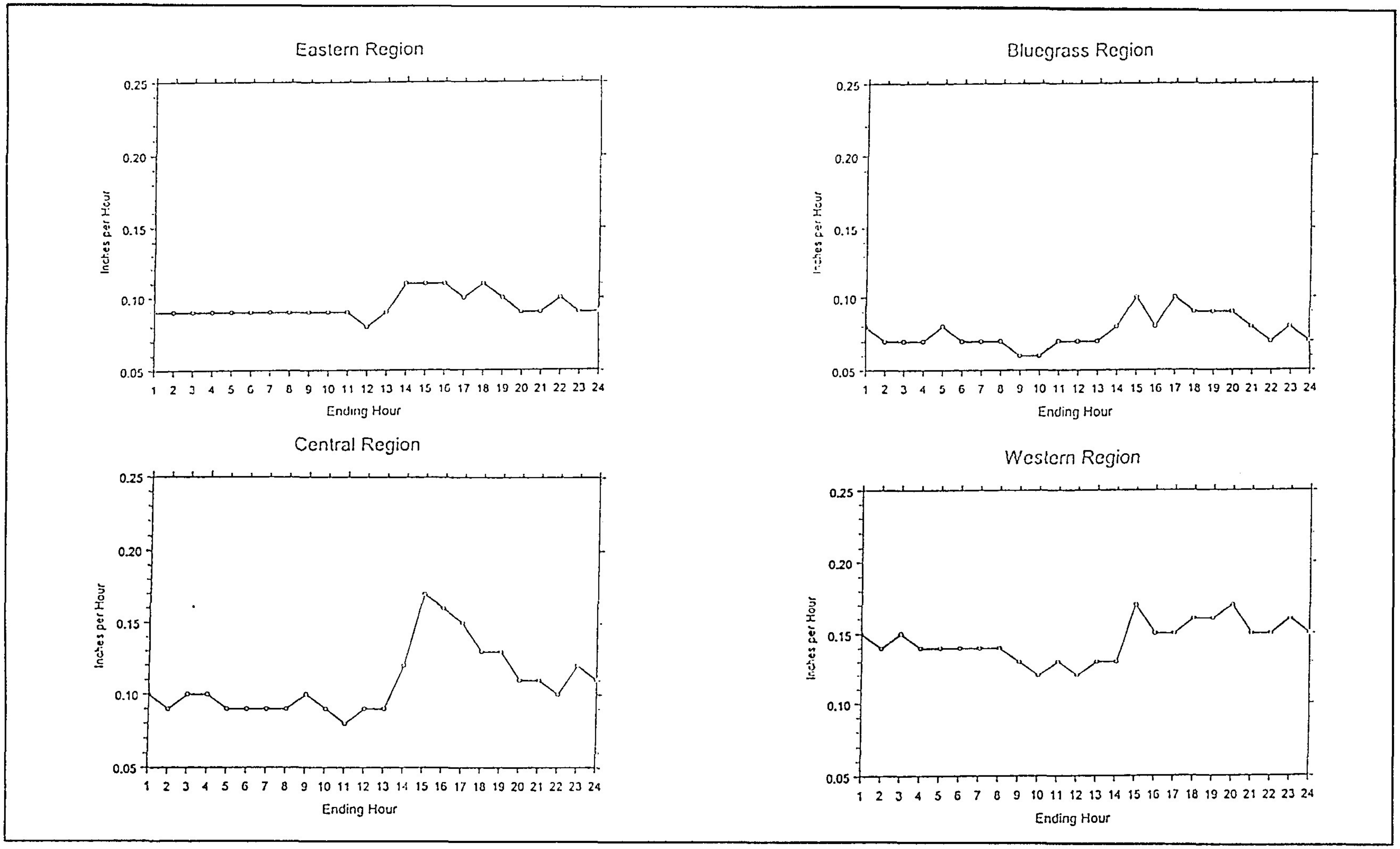


Figure 5.1 Divisional Variations in Spring

Central Division. The lowest value, 0.06 inches per hour, was found in the Bluegrass Division.

The range of the hourly precipitation rates varied among divisions. The greatest variation in the hourly precipitation rates occurred in the Central Division. Each division shared a similar pattern of rainfall intensities increasing into the afternoon hours and then decreasing till late morning. This pattern is associated with the diurnal pattern of temperature. In general, temperature increases from sunrise into the afternoon and decreases from the afternoon to sunrise.

Divisional Variations in Summer. Precipitation intensities are highest in the summer (Figure 5.2). The Western Division contained the highest mean precipitation rate of 0.20 inches per hour. The Bluegrass Division contained the lowest of 0.15 inches per hour. A maximum occurred in the afternoon hours for all divisions. However, the minimum was not as consistent throughout climate divisions. Minima for the Western, Central, Bluegrass, and Eastern Divisions occurred shortly after sunrise, in the evening, and after midnight, respectively. The highest hourly precipitation intensity was discovered in the Central Division with a rate of 0.25 inches per hour. The lowest value occurred in the Central and Bluegrass divisions with a rate of 0.10 inches per hour in the afternoon and after midnight, respectively. The Central Division contained the largest range of 0.15 inches per hour.

The summer season in Kentucky contained the largest range in precipitation intensities. In each division, precipitation intensities increased into the afternoon and decreased into the morning, once again following the diurnal pattern of temperature.

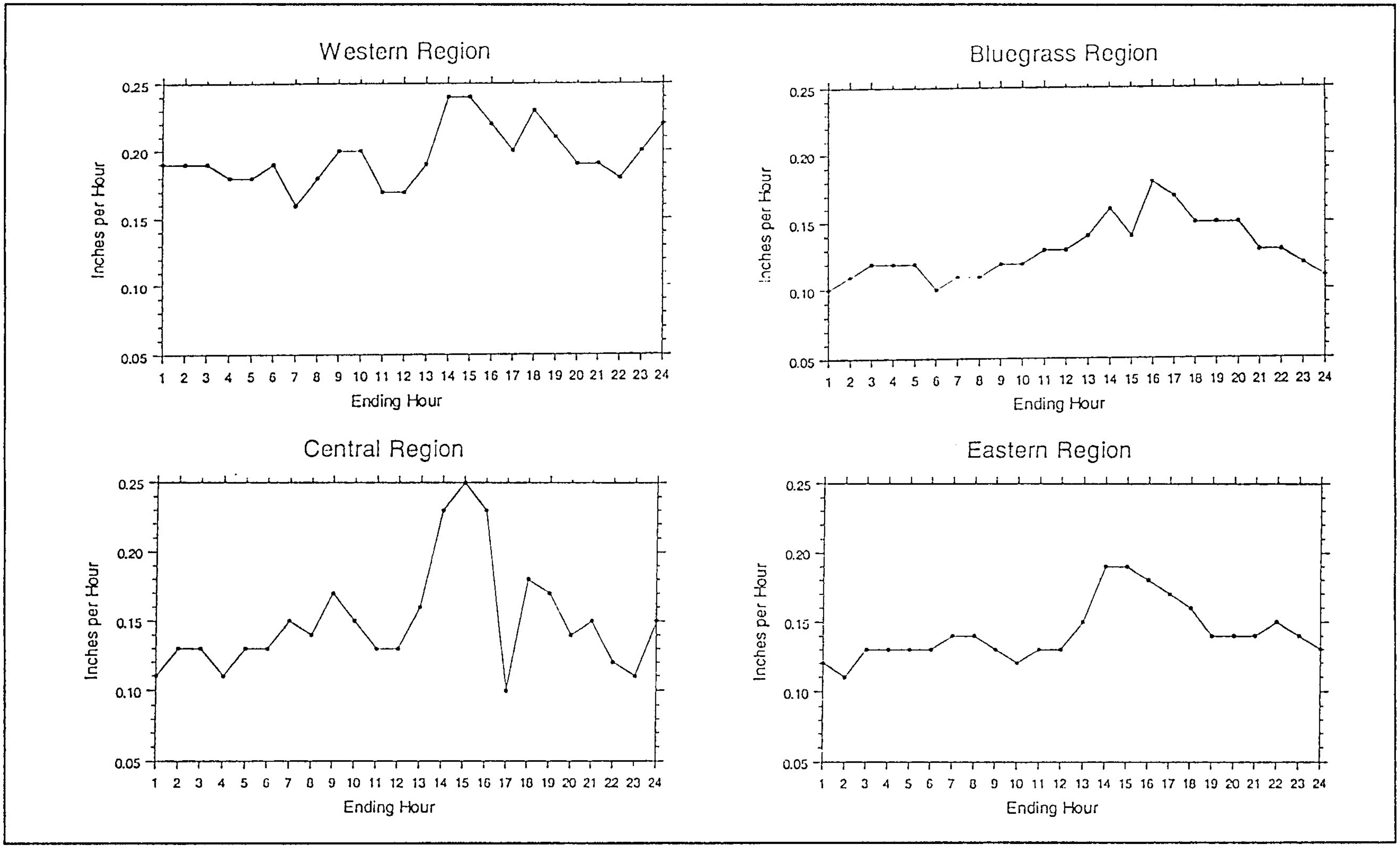


Figure 5.2 Divisional Variations in Summer

Divisional Variations in the Autumn. The highest mean precipitation rate occurred in both the Western and Central Divisions with a rate of 0.12 inches per hour (Figure 5.3). Meanwhile, the lowest rate occurred in both the Bluegrass and Eastern Divisions with a rate of 0.09 inches per hour. A maximum occurred in the early evening hours for the Western, Central, and Eastern Divisions. In the Bluegrass Division, a maximum occurred in the late evening. The Western and Central Divisions contained a minimum before noon and after sunrise, respectively. A minimum for the Eastern Division occurred after midnight. However, there was no pronounced minimum for the Bluegrass Division. The highest hourly value of precipitation intensity was discovered in the Central Division. The lowest value was discovered in the Bluegrass and Eastern Divisions.

The Central Division contained the largest range in precipitation intensities. In each division, precipitation intensities increased into the afternoon and decreased into the morning. That variation is associated with the diurnal pattern of temperature.

Divisional Variations in the Winter. The highest mean hourly precipitation rate occurred in the Western Division of 0.11 inches per hour (Figure 5.4). The lowest occurred in the Bluegrass Division of 0.06 inches per hour. A maximum occurred at or around sunset for the Western and Central Divisions; however, there was no pronounced maximum for the Bluegrass and Eastern Divisions. A minimum occurred in the Western Division after midnight, however; there was no pronounced minimum for the remaining climate divisions. The highest hourly value of precipitation intensity was discovered in the Western and Central Divisions.

The Western Division contained the largest range of precipitation intensities. The

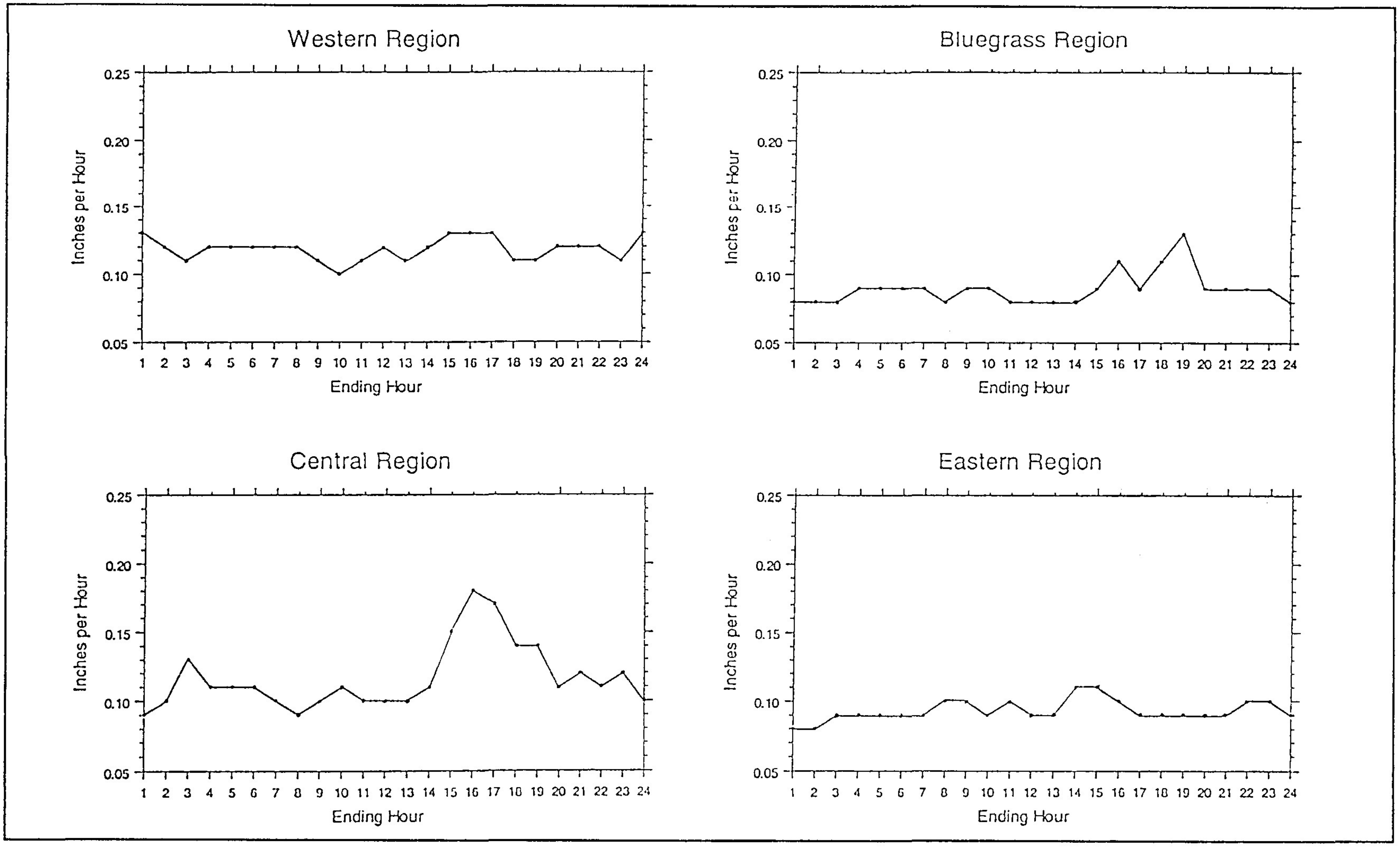


Figure 5.3 Divisional Variations in Autumn

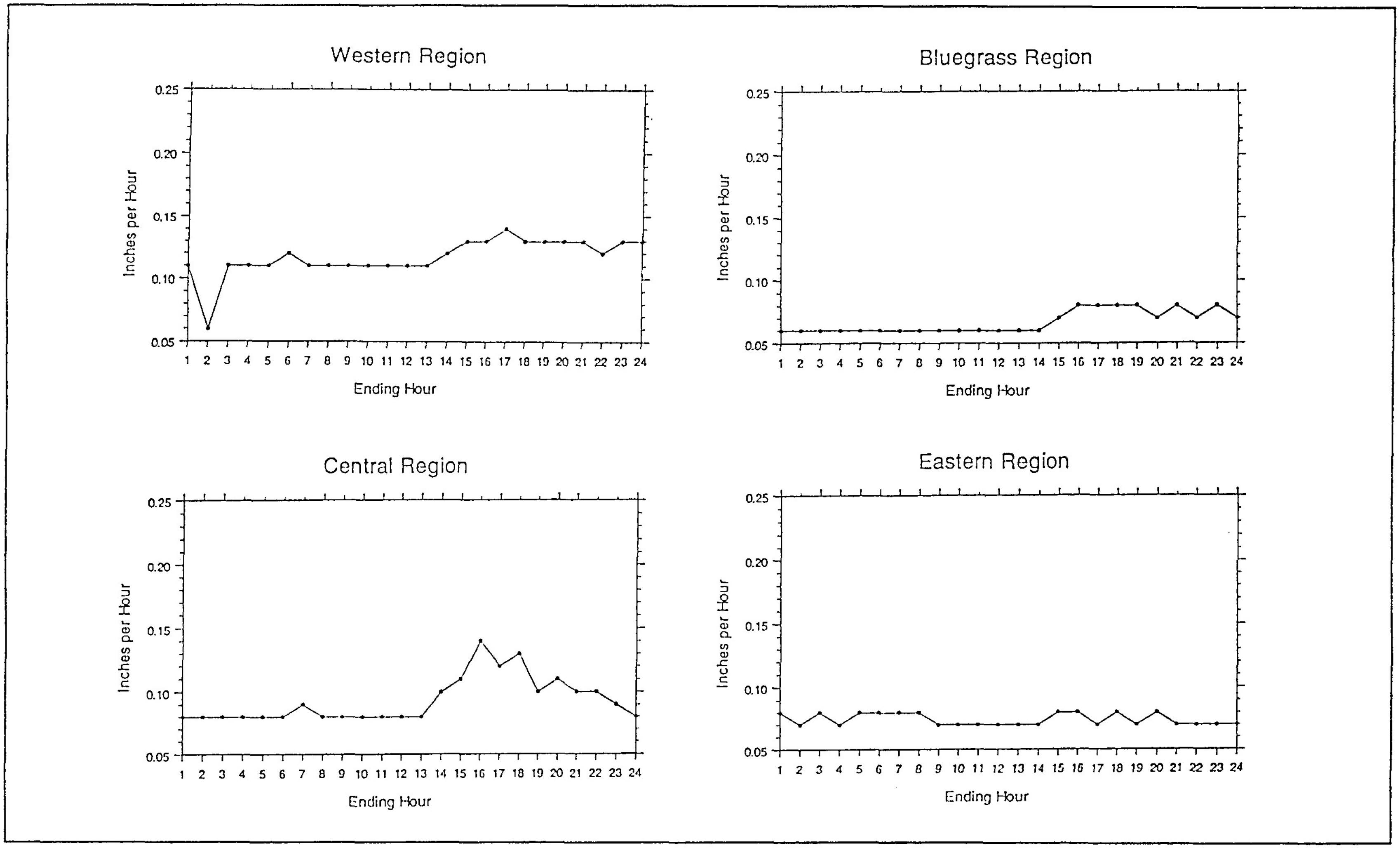
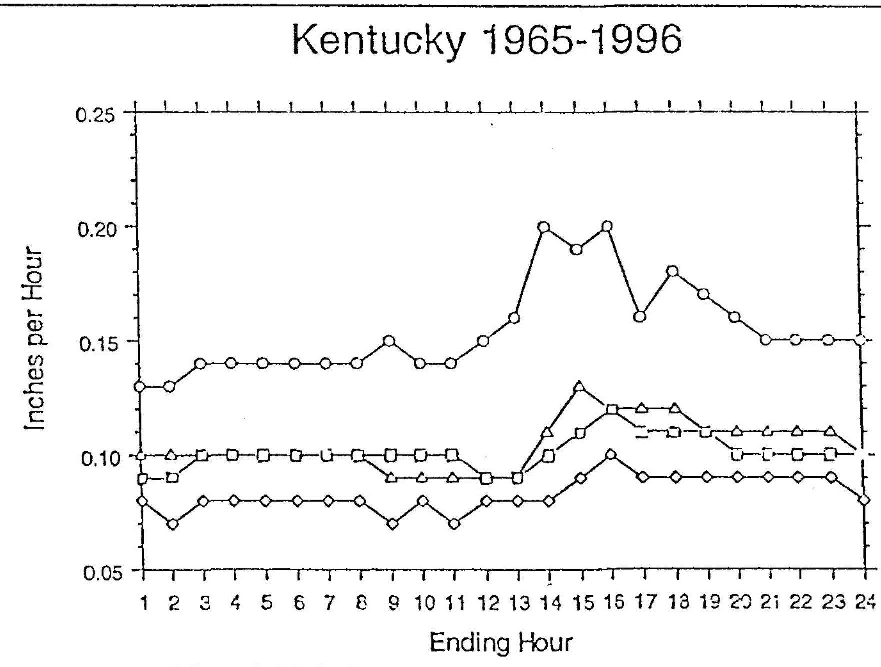


Figure 5.4 Divisional Variations in Winter

winter season contained the smallest range in hourly precipitation rates. Precipitation intensities increased into the afternoon and decreased into the morning. However, the Eastern Division does not conform to this general pattern.

Kentucky Seasonal Variations. The diurnal pattern of precipitation intensities averaged over the entire state by season are shown in Figure 5.5. The highest hourly precipitation intensities are in the summer, and the summer season has the greatest range of hourly values. Two maxima occurred in the afternoon hours of the summer. A minimum developed after midnight. The lowest mean precipitation rate among the seasons is in the winter, and the winter season also has the smallest range of hourly values. A winter maximum fell in the afternoon hours.



Diurnal Variation in Precipitation Rates in Kentucky. Spring's data is plotted with a "△", Summer's data is plotted with a "○", Autumn's data is plotted with a "□", and Winter's data is plotted with a "◇".

Figure 5.5 Diurnal Variations in Kentucky

Section 5.2 Mean Seasonal Precipitation Intensities.

Having taken a broad look at diurnal variations in precipitation intensities for Kentucky and its climate divisions, the focus now shifts to analyzing precipitation rates for individual cooperative stations across Kentucky. Mean seasonal precipitation intensities for 30 stations in Figure 5.6 show evidence of regional variation. Precipitation intensities are generally higher in the south than in the north. Furthermore, the precipitation intensities are generally higher in the west than in the east. These patterns are also suggested in Figure 5.7, which shows mean seasonal precipitation intensities averaged over climate divisions. Looking back at Figure 5.6, precipitation rates appear to be persistently high or low from season to season for individual stations, suggesting the possible significance of localized influences on precipitation rates. Table 5.1 identifies stations with maximum and minimum precipitation rates in each season (Map locations of stations can be identified from Figure 4.1)

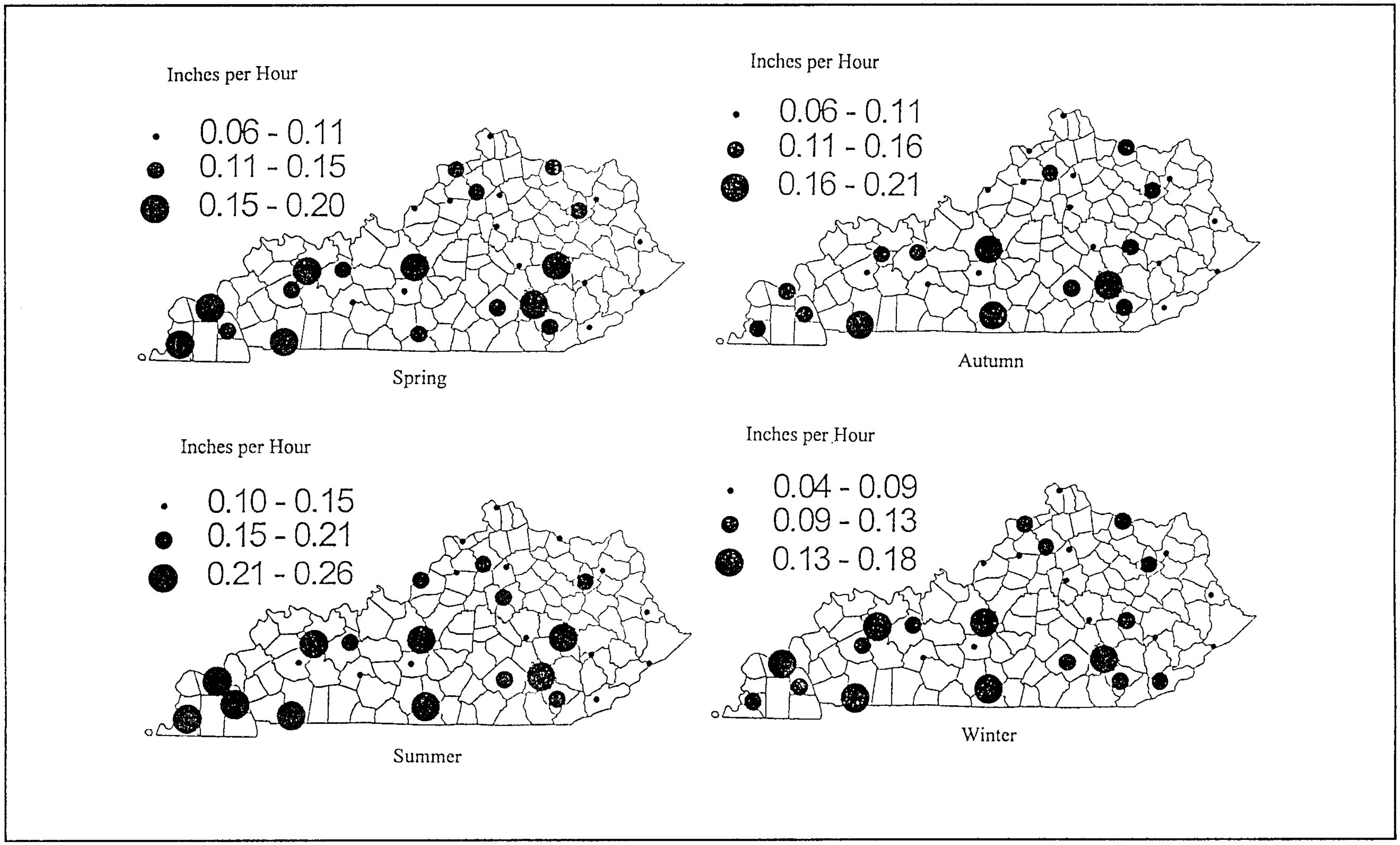


Figure 5.6 Stations' Mean Seasonal Precipitation Intensities

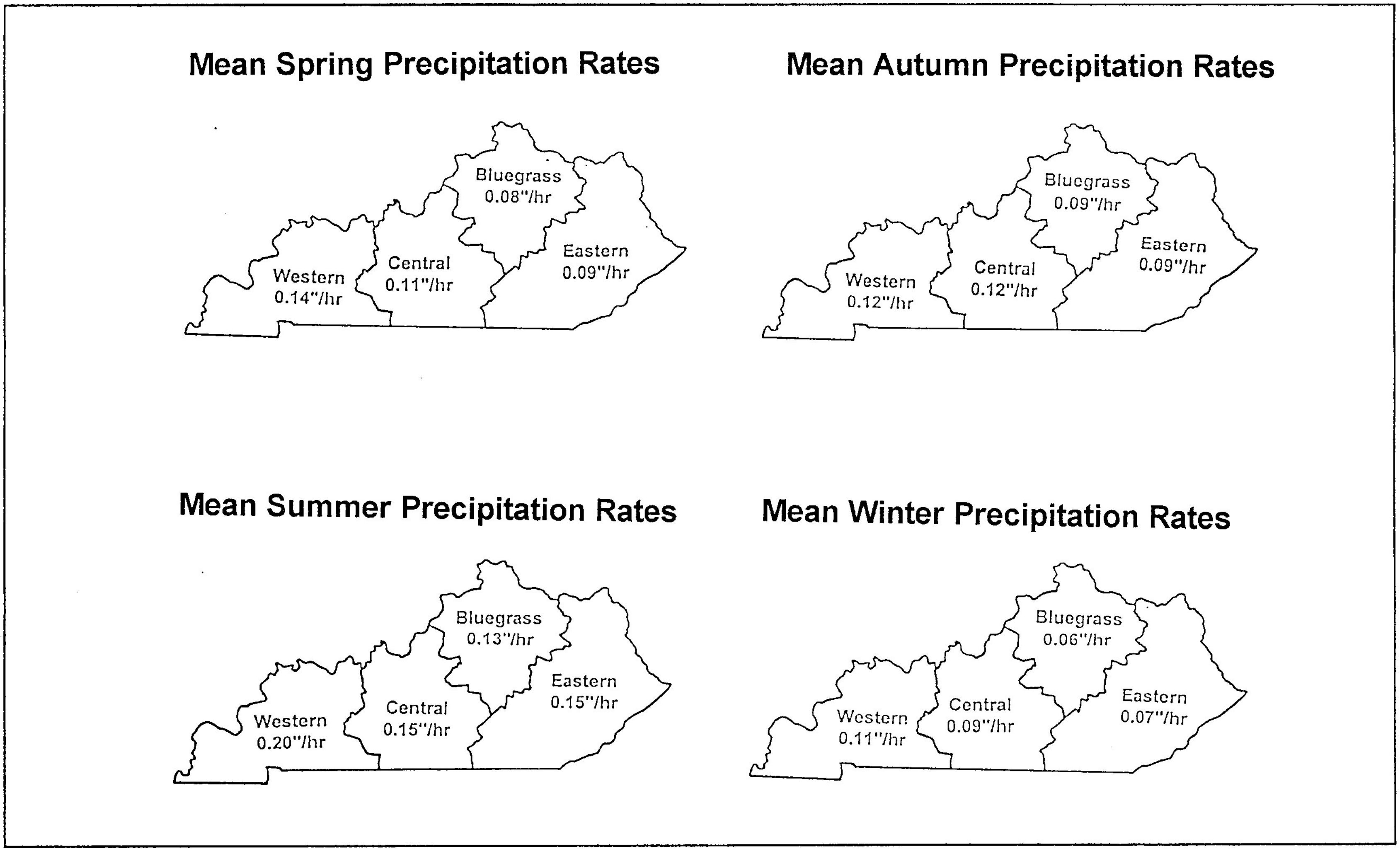


Figure 5.7 Divisional Mean Seasonal Precipitation Intensities

	SPRING	SUMMER	AUTUMN	WINTER
1 (STATION MAX)	Hodgenville	Hodgenville	Hodgenville	Hodgenville
2	London	Tompkinsville	Herndon	London
3	Herndon	Herndon	London	Herndon
4	Paducah	London	Tompkinsville	Calhoun
5	Heidelberg	Heidelberg	Benton	Paducah
6	Clinton	Paducah	Calhoun	Tompkinsville
7	Calhoun	Clinton	Clinton	Benton
8	Tompkinsville	Benton	Heidelberg	Clinton
9	Benton	Calhoun	Paducah	Heidelberg
10	Somerset	Gest Lock	Somerset	Somerset
11	Gest Lock	Somerset	Dundee	Dundee
12	Morehead	Morehead	Gest Lock	Gest Lock
13	Barbourville	Barbourville	Barbourville	Maysville
14	Dundee	Lexington	Maysville	Barbourville
15	Maysville	Dundee	Morehead	Baxter
16	Carrollton	Louisville	Carrollton	Carrollton
17	Madisonville	Burndine	Louisville	Madisonville
18	Burndine	Maysville	Baxter	Morehead
19	Baxter	Carrollton	Burndine	Burndine
20	Smithfield	Madisonville	Lexington	Lexington
21	Lexington	Baxter	Madisonville	Smithfield
22	Louisville	Smithfield	Smilthfield	Woodbury
23	Woodbury	Woodbury	Woodbury	Louisville
24	Munfordville	Munfordville	Munfordville	Munfordville
25	Berea College	Olive Hill	Berea College	Berea College
26	Sadieville	Davella	Olive Hill	Buckhorn Lake
27	Olive Hill	Sadieville	Sadieville	Davella
28	Davella	Covington	Buckhorn Lake	Olive Hill
29	Buckhorn Lake	Berea College	Covington	Sadieville
30 (STATION MIN)	Covington	Buckhorn	Davella	Covington

Table 5.1 Stations Seasonal Rank of Mean Seasonal Precipitation Rate

Section 5.2.1 The Model

A stochastic model of average hourly precipitation rates based on data from 30 cooperative stations is developed below. The model specification is

$$PR_i = b_0 + b_1XUTM_i + b_2YUTM_i + b_3ELEV_i + b_4RGH_i + b_5URB_i + b_6SPR_i + b_7SUM_i + b_8AUT_i + e_i$$

where:

i is the ith Station used in the study
PR_i is the estimated mean seasonal precipitation rate for the *i*th station
$XUTM_i$ is the UTM 16 longitudinal coordinate for the *i*th station multiplied by 10^{-6}
$YUTM_i$ is the UTM 16 latitudinal coordinate for the *i*th station multiplied by 10^{-6}
$ELEV_i$ is elevation above mean sea level for the *i*th station multiplied by 10^{-1}
RGH_i is the degree of roughness for the *i*th station multiplied by 10^{-4}
URB_i is the natural log (ln) of the degree of urbanization for the *i*th station multiplied by 10^{-4}
SPR_i is an indicator variable for the spring season for the *i*th observation
SUM_i is an indicator variable for the summer season for the *i*th observation
AUT_i is an indicator variable for the autumn season for the *i*th observation
$b_0, \ldots, b_8$ are parameters
e_i is the error term for the *i*th observation and is assumed to be independent and identically distributed according to a $N(0,\sigma)$.

Regional effects are represented by latitudinal and longitudinal planar coordinates and elevation. Local effects are captured by the degree of roughness and the degree of urbanization. Seasonal effects are represented by using indicator variables.

The model was estimated using ordinary least squares. Results, with p-values under the associated parameters, are shown below:

$$PR_i = \underset{(.000)}{0.95} - \underset{(.230)}{0.05}XUTM_i - \underset{(.000)}{0.18}YUTM_i + \underset{(.877)}{0.89}ELEV_i - \underset{(.012)}{0.11}RGH_i - \underset{(.026)}{0.65}URB_i +$$

$$\underset{(.020)}{0.02}SPR_i + \underset{(..000)}{0.07}SUM_i + \underset{(.012)}{0.02}AUT_i + e_i$$

The independent variables that are not statistically signicant in predicting mean seasonal precipitation rates are XUTM and ELEV. These variables are highly correlated (r=.70) since elevation in Kentucky increases eastward. Therefore, elevation was taken out of the model. Results of the new model are shown here:

$$PR_i = \underset{(.000)}{0.93} - \underset{(.048)}{0.05}\, XUTM_i - \underset{(.000)}{0.18}\, YUTM_i - \underset{(.012)}{0.11}RGH_i - \underset{(.020)}{0.66}URB_i +$$

$$\underset{(.020)}{0.02}SPR_i + \underset{(.000)}{0.07}SUM_i + \underset{(.012)}{0.02}\, AUT_i + e_i$$

F-Statistic = 21.13 on 7 and 112 degrees of freedom with p-value = 0.000

Standard Error for the Model = 0.03 on 112 degrees of freedom

$r^2 = 0.57$

Note that the F-statistic is significant (p-value = 0.000), and the model accounts for slightly more than half of the variation in precipitation rates ($r^2 = 0.57$). The standard error for the estimating equation is 0.03 inches per hour. According to the model, the mean seasonal precipitation rate declines as one moves to the north and east. It is also lower in areas of rougher terrain and higher urbanization. Modeled precipitation rates are highest in the summer and lowest in the winter.

The model results are conditional upon the validity of assumptions made about error term. The first step in evaluating these assumptions is to examine a histogram of the residuals. The histogram in Figure 5.8 suggests that the assumption of normality is reasonable. Next, the residuals were plotted against the predicted values of the dependent variable. Figure 5.9 shows a random dispersion of residuals around the predicted values, hence no evidence of heteroskedasticity. This result suggests that the assumption that the error terms are identically distributed is reasonable. Also, scatterplots showing the residuals plotted against the predicted precipitation rate (Figure 5.9) and independent variables (Figures 5.10) are well behaved.

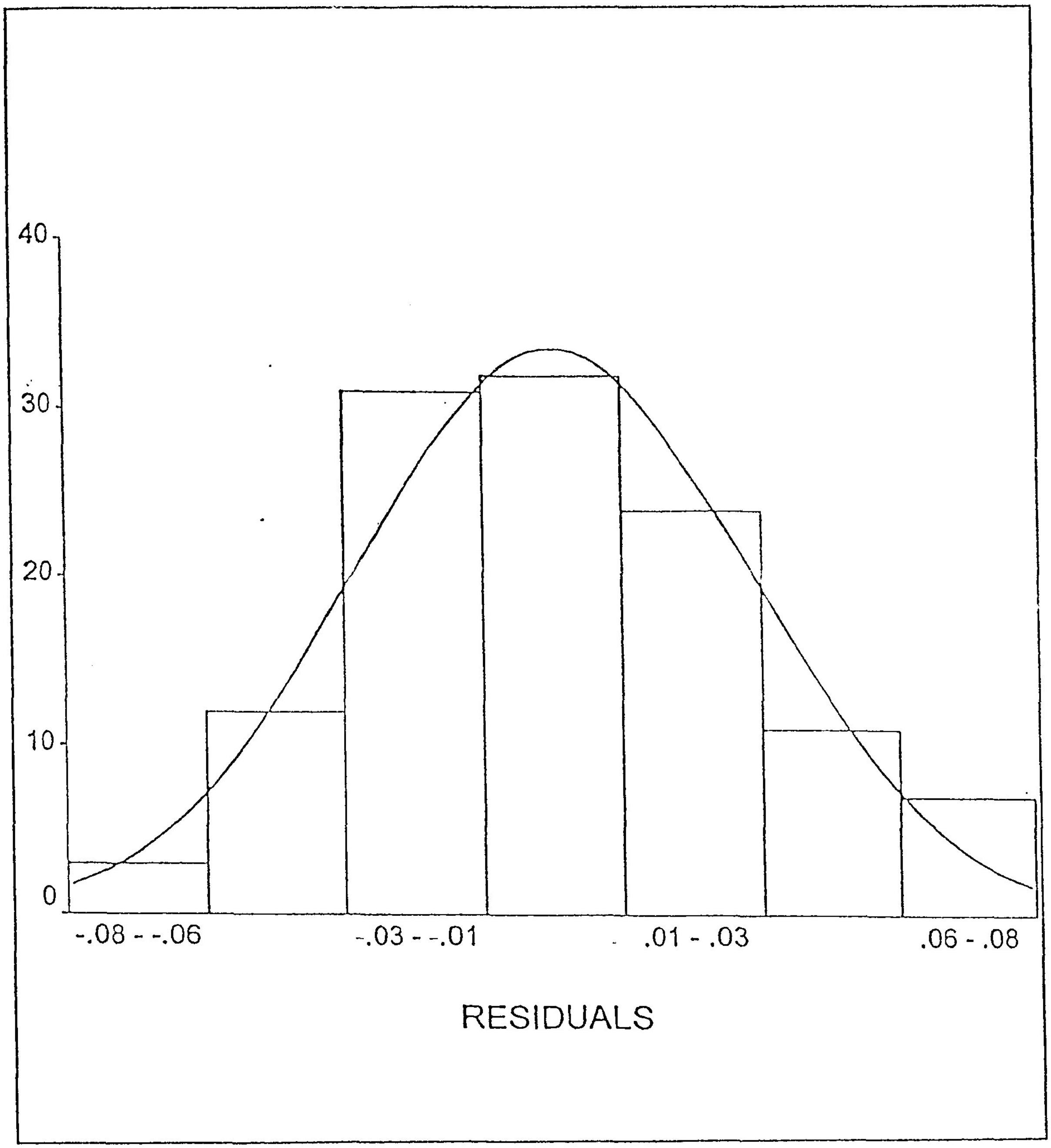


Figure 5.8 Histogram of the Residuals

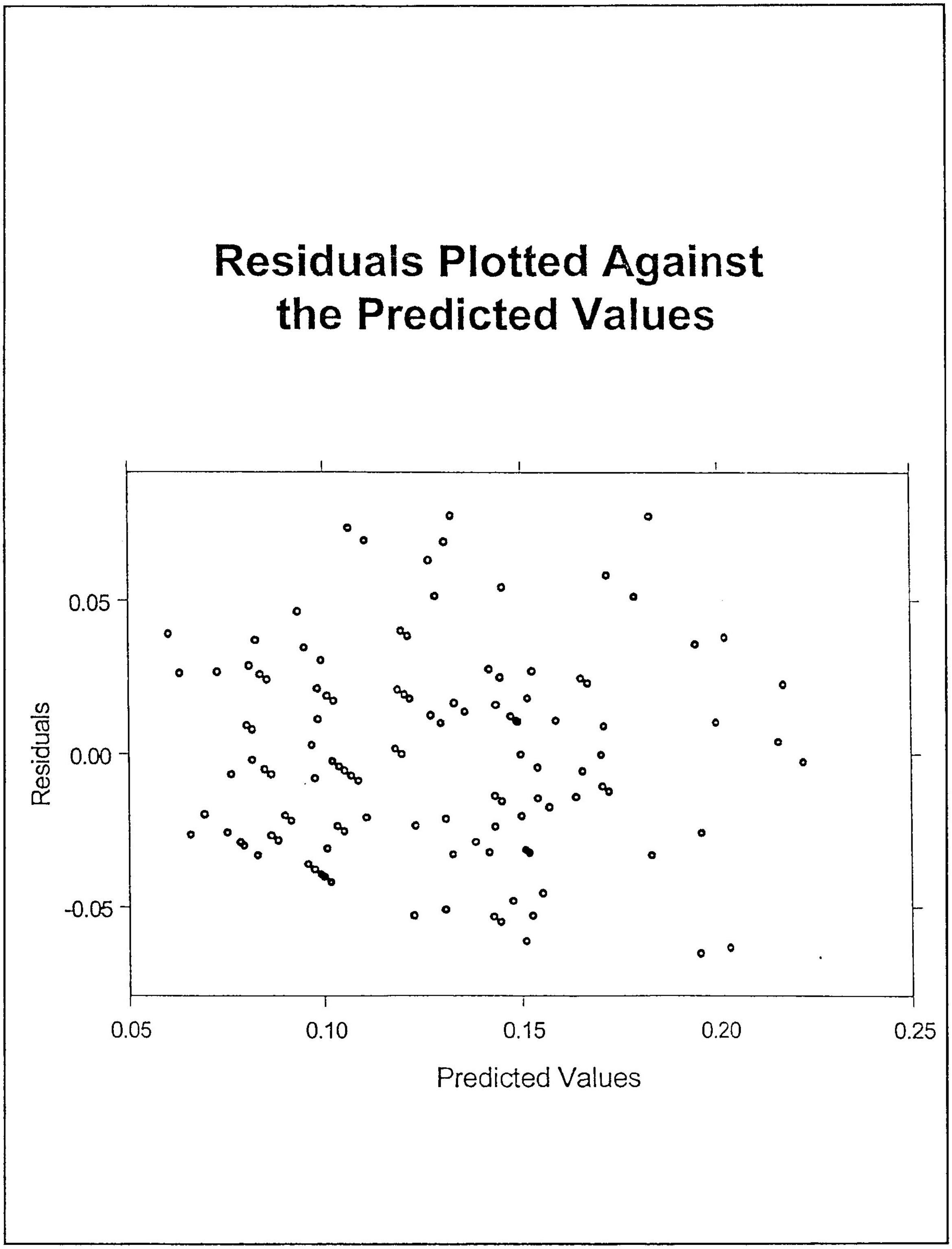


Figure 5.9 Scatterplot of Residuals against the Predicted Values

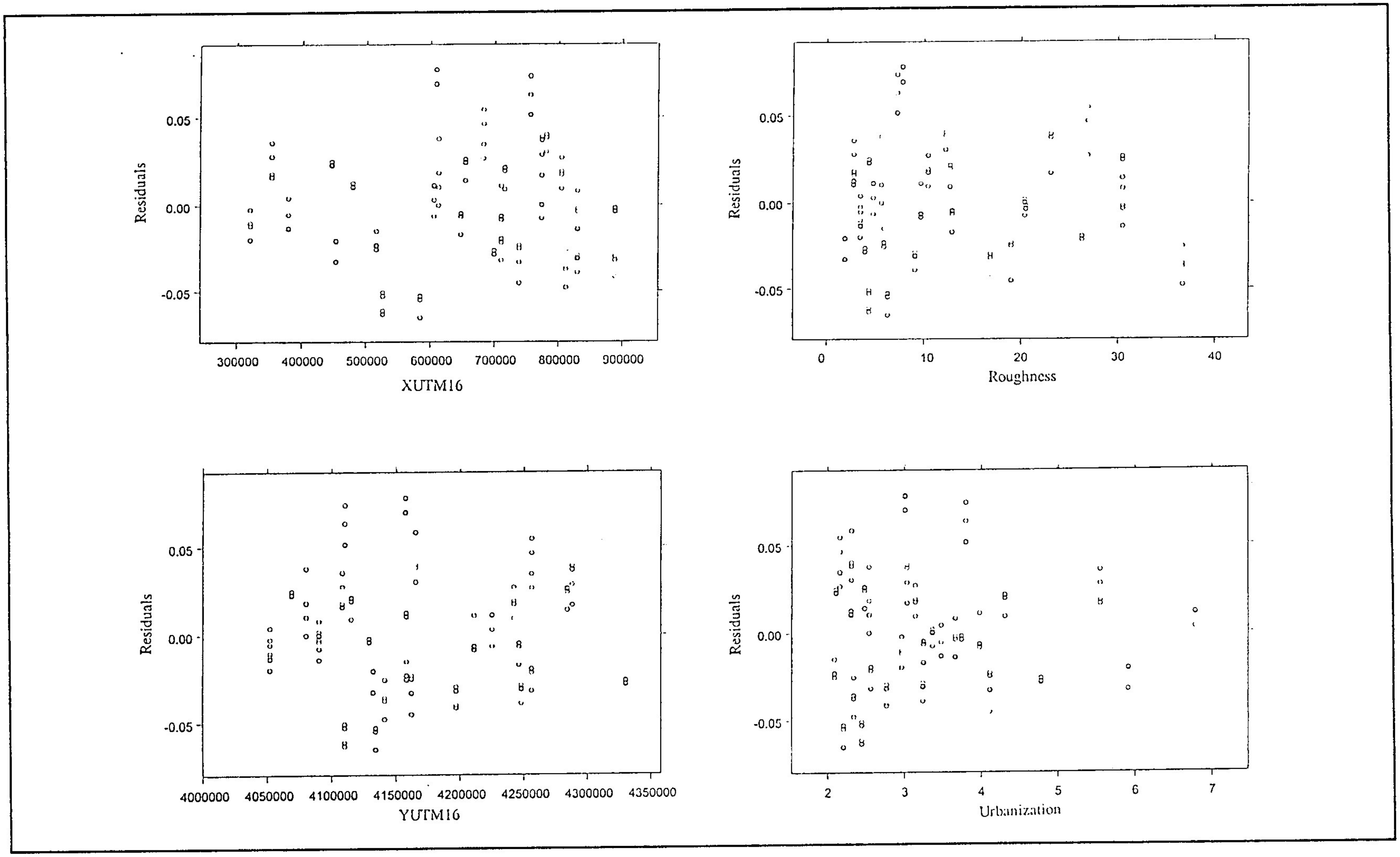


Figure 5.10 Scatterplots of Residuals Plotted against Independent Variables

The assumption of independence was evaluated by using a spatial autocorrelation analysis. The major concern here was that the residuals would show evidence of spatial persistence which would be reflected by significant positive spatial autocorrelation. Moran's I-statistic for spatial autocorrelation was calculated and a t test was performed to evaluate its significance. The evaluation was done for the residuals associated with each of the four seasons. Results are shown in Table 5.1. The coefficient for summer was marginally significant, but none of the other seasons produced values that approached a significant level. Overall, there is insufficient evidence to reject the assumption that the residuals are independent from a spatial perspective.

Season	Correlation Coefficient	P-Value
Spring	-0.07	0.40
Summer	-0.12	0.05
Autumn	-0.09	0.23
Winter	-0.07	0.39

Table 5.2, Spatial Autocorrelation of Residuals

Another angle on independence of residuals involves the interseasonal correlations among residuals. Ideally, residuals would not be correlated from season to season. The results of correlating the residuals between seasons are shown in Table 5.3.

	Spring	Summer	Autumn	Winter
Spring	1.00	.96	.98	.98
Summer	.96	1.00	.97	.94
Autumn	.99	.97	1.00	.98
Winter	.98	.94	.98	1.00

Table 5.3, Correlation Matrix of Seasonal Comparison of Residuals

Interestingly, the correlation coefficients show evidence of strong seasonal persistence among the residuals.

Section 5.2.2 Discussion

This section details the inferences behind the model's relationship and a discussion of the residuals. First, the regional effects will be discussed, followed by the localized variables.

The variables, XUTM and YUTM, representing regional effects both have significant negative coefficients, inferring that precipitation intensities decrease away from the moisture source, the Gulf of Mexico. A maritime tropical air mass from the Gulf of Mexico brings in the moisture that is readily available for any precipitation event. As the air mass migrates northward, and is pushed to the east by the Westerlies, moisture is lost. Therefore, less moisture is available in the northern and eastern areas of Kentucky. As a result, less precipitation per hour will occur in areas farther away from the moisture source. In the model, YUTM is more significant than XUTM. The level of significance in the regional effects corresponds to the dominate migration path of the air mass in Kentucky from the Gulf of Mexico, which is more of a south to north direction than east to west. Furthermore, the Local Climatological Data Annual Summaries by the National Oceanic and Atmospheric Administration conclude that the prevailing surface winds in Kentucky are out of the southwest.

The localization effects are represented by roughness, RGH, and urbanization, URB. These variables both have significant negative coefficients. These results are consistent with expectations. As a precipitation event moves over a rougher terrain and/or a higher degree of urbanization, the precipitation intensity decreases. Rougher terrain and more heavily urbanized areas absorb more heat, thus, causing an influx in vertical air motions that produce an increase in air resistance upon precipitation. The ultimate result should be a lower rate of precipitation.

The indicator variables, SPR, SUM, and AUT, all have significant positive coefficients as expected. The winter season contains the lowest precipitation rates for Kentucky. The summer season has the largest precipitation intensities and the largest coefficient.

Although 57% of the variation in precipitation rates can be explained by regional effects and localized parameters, the persistence of residuals for cooperative stations from season to season could not be eliminated (Figure 5.11). Since the residuals are persistantly positive or negative over seasons for each station, it is speculated that there may be a possibility of more localized influences near the station. However, these influences remain unknown. Note, there remains 43% of the variation in precipitation rates left unexplained.

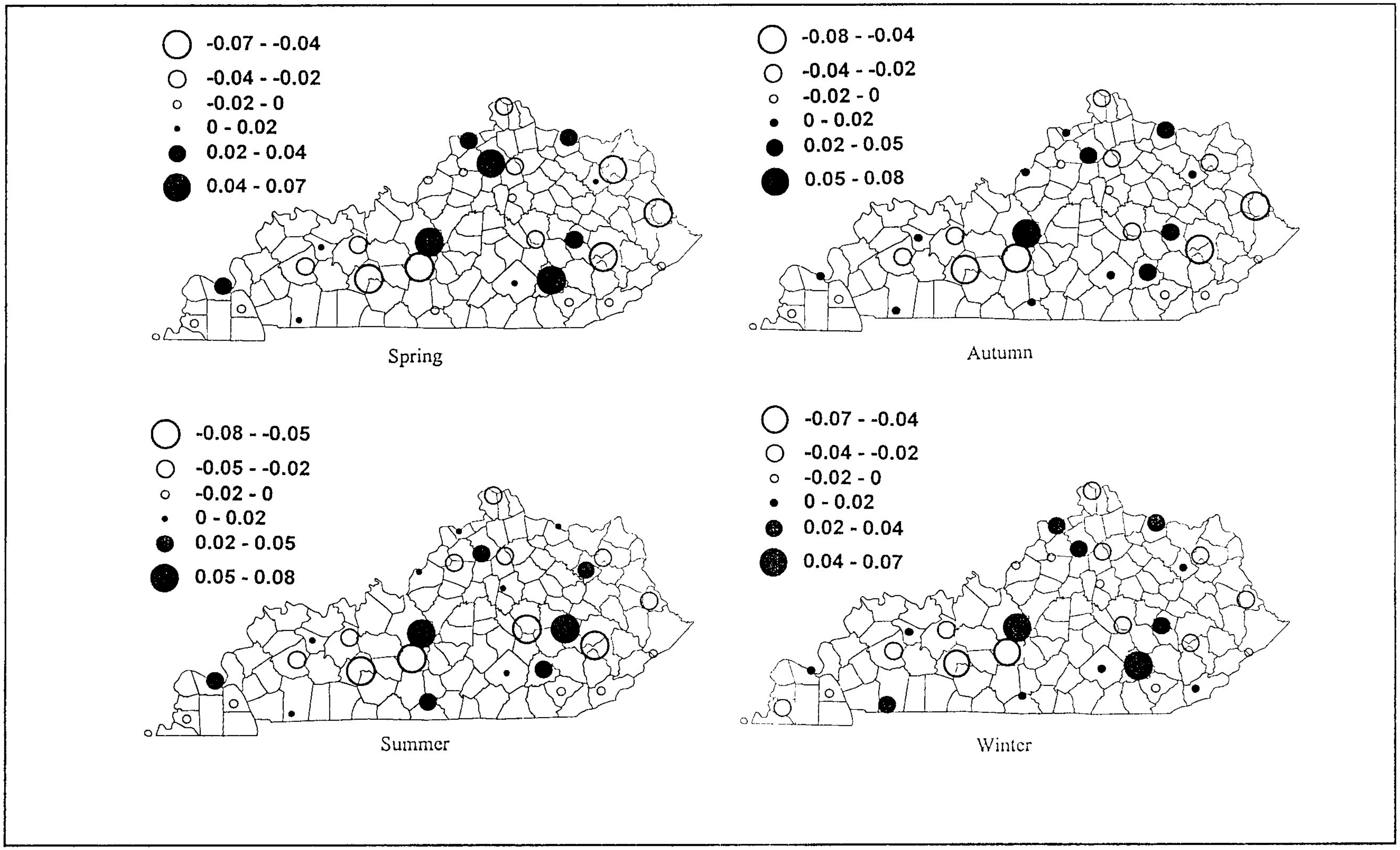


Figure 5.11 Residuals of Stations per Season

CHAPTER VI

CONCLUSIONS

This section details the conclusions drawn from the results generated. The first section of the results describes the diurnal distribution of hourly precipitation rates. A summary of the overall trend and its applications will be discussed. The results generated from the modeling section infer different relationships among regional and local effects. However, it is worth noting some effects that may lead to irregularities in the results.

The diurnal distribution of the hourly precipitation rates reveal the time of day a high and low precipitation rate event are most likely to occur. As seen in the seasons, climate divisions, and for the whole state of Kentucky, the highest precipitation rates occur in warmer temperatures and the lowest precipitation rates occur in the coolest temperatures. A trend for precipitation rates can be identified to increase into the afternoon and decrease into the late morning hours. These results can be used in probability measures in the likelihood of a heavy precipitation event occurring in Kentucky for short-term weather forecasting and forensic climatology.

The assumptions made about the data generating the results from the modeling section could be warranted in some cases. In particular, the local effects are of concern. The inference drawn from the degree of roughness state that as a precipitation event moves over a rougher terrain, the precipitation rates will decrease. A point of worthy mention is that there may be a threshold to the degree of roughness acting upon precipitation intensities. The average slope was used to indicated the degree of roughness. If the average slope is very high, then there may be a portion of the area that is blocked from the sun thereby absorbing little to no sunlight. As a result, less radiation is absorb causing some kind of effect on the vertical air movements. Given such conditions, speculation is that where the degree of roughness is so high it may cause an effect opposite from the inferences drawn in this study.

The degree of urbanization was represented by population density. It is known that pollutants do have an effect on precipitation processes as well. However, they were exempted from this study due to the lack of data needed in the study's time period. Pollutants can be emitted into the air from an industry that is upwind from a cooperative station. They serve as condensation nuclei for precipitation processes. An increase in condensation nuclei would result into more raindrops being produced.

There remains less than half of the variation in precipitation rates unexplained. The regional effects are explained by the distance away from the moisture source. In analyzing the residuals, there is a high degree of association between the residuals among seasons indicating the possibility of additional localized effects. The localized effects needs to be further researched.

The results in this study can be applied to areas needing to identify frequent times during a day and year for occurrences of heavy precipitation events, forecasting models using precipitation rates, and selecting areas most likely to have an increase in precipitation rate due to local characteristics. Short-term weather forecasters predict flash flood events that are greatly associated with heavy precipitation events. General Circulation Models (GCMs) assume that precipitation intensities are the same over a 28,900mi^2 of land. Land-surface models require input of precipitation rates since infiltration of water through the subsurface is incorporated into the model. Engineers planning routes to channel flood or storm water assume precipitation intensities are homogeneous over different characteristics of urban and rural landscapes.

REFERENCES

Augustine, John A. and Kenneth W. Howard (1991). Mesoscale Convective Complexes over the United States during 1986 and 1987. Monthly Weather Review, 119, 1575-1589.

Bailey, Trevor C. and Anthony C. Gatrell (1995). Interactive Spatial Data Analysis. England: Addison Wesley Longman Limited.

Bradley, A. Allen and James A. Smith (1994). The Hydrometeorological Environment of Extreme Rainstorms in the Southern Plains of the United States. Journal of Applied Meteorology, 33(12), 1418-1431.

Cary, Kevin B. (1998). Western Kentucky's Seasonal Variations of Hourly Precipitation. Paper presented at the meeting of Sigma Xi, The Scientific Research Society, Bowling Green, KY.

Changnon, Jr., Stanley A., Floyd A. Huff and Richard G. Semonin (1971). METROMEX: an Investigation of Inadvertent Weather Modification. Bulletin of American Meteorological Society, 52(1), 958-967.

___ (1969). Urban-Produced Thunderstorms at St. Louis and Chicago. Preprints of 6th Conference of Severe Local Storms, Chicago, 95-99.

Chen, Mingxuan, Xubin Zeng, and Robert E. Dickinson (1998). Adjustment of GCM Precipitation Intensity over the United States. Journal of Applied Climate, 37, 876-887.

Chen, Tsing-Chang, Ming-Cheng Yen, Jung-Chieh Hsieh, and Raymond W. Arritt (1999). Dirurnal and Seasonal Variations of the Rainfall Measured by the Automatic Rainfall and Meteorolgy Telemetry System of Taiwan. Bulletin of the American Meteorological Society, 80(11), 2299-2312.

Conner, Glen. (1979). *Climatological Summary, Barren River Area Development District.* Bowling Green, KY: Western Kentucky University.

___ (1981). Hourly Precipitation Distribution in Kentucky 1949-1973, Kentucky Climate Center (No. 24). Bowling Green, KY: Western Kentucky University.

___ (1991). Climate of Kentucky, Climatology of Kentucky Series. Bowling Green, KY: Western Kentucky University.

Creating a Climate for Change (1999). Validation of General Circulation Models. http://www.nrcan.gc.ca/es/ep/ed/engish/validations.html

Crysler, Kenneth A., Robert A. Maddox, L. Ray Hoxit, and Bradley M. Muller (1982). Diurnal Distribution of Very Heavy Precipitation over the Central and Eastern United States, National Weather Digest 7(1), 33-37.

Fraser, Alistair B. (2000). Bad Clouds. http://www.ems.psu.edu/~fraser/bad/badclouds.html

Gao, Xiaogang and Soroosh Sorooshian (1994). A Stochastic Precipitation Disaggregation Scheme for GCM Applications. Journal of Climate 7, 238-247.

Giordano, Louis A. and J. Michael Fritsch (1983, October). The A-Typical Mid-Level Flow for Flash Floods in the Mid-Atlantic States. 5th Conference on Hydrometeorology in Tulsa, Oklahoma, 142-148.

Guttman, Nathaniel B. and Devoyd S. Ezell (1980, March). Flash Flood Climatology for Applachia. 2nd Conference on Flash Floods of the American Meteorological Society in Atlanta, Georgia, 18-20.

Helmuth, L. (1999). Rainy Night in Georgia. Science News 155, 198.

Hill, Jerry D (1976). Climate of Kentucky. Lexington, KY: University of Kentucky.

Holzman, B. G., and H. C. S. Thom (1970). The La Porte Precipitation Anomoly. Bulletin of American Meteorological Society 51, 335-337.

Huff, Floyd A. (1971). Distribution of Hourly Precipitation in Illinois (Circular 105). Urbana, IL: Illinois State Water Survey.

___ (1979). Spatial and Temporal Correlation of Precipitation in Illinois (Circular 141). Urbana, IL: Illinois State Water Survey.

Maddox, Robert A. (1980). Mesoscale Convective Complexes. Bulletin of the American Meteorological Society 61(11), 1374-1387.

Miller, Christopher. (1999, January). Why Weekend Weather is Worse. Popular Mechanics, 30.

Naghavi, Babak, Vijay P. Singh and Fang Xin Yu (1993). Development of 24-Hour Rainfall Frequency Maps for Louisiana. Journal of Irrigation and Drainage Engineering, 119(6), 1066-1080.

Oki, Taikan, and Katumi Musiake (1994). Seasonal Change of the Diurnal Cycle of Precipitation over Japan and Malaysia. Journal of Applied Meteorology, 33(12), 1445-1463.

Prism, United States Department of Agriculture. (1999). http://www.ftw.nrcs.usda.gov/prism/prism.html

Stewart, Ian. (1989). Does God Play Dice? The Mathematics of Chaos. Cambridge, Massachusetts: Basil Blackwell Inc.

Taylor, P. J. (1980). A Pedagogic Application of Multiple Regression Analysis: Precipitation in California. Geography, 65, 203-212.

Winkler, Julie A. (1987). Diurnal Variations of Summertime Very Heavy Precipitation in the Eastern United States. Physical Geography, 8(3), 210-224.

___ (1992). Regional Patterns of the Diurnal Properties of Heavy Hourly Precipitation. Professional Geographer, 44(2), 127-146.