

A COMPARATIVE ANALYSIS OF WARM SEASON
PRECIPITATION DISTRIBUTION AND LAND COVER IN
THE GREATER TUSCALOOSA AREA

by

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A THESIS

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ABSTRACT

On an annual basis Tuscaloosa and surrounding areas are exposed to a variety of weather hazards associated with thunderstorms. The synoptically benign conditions during the warm season over this region create a more favorable environment for the development of air mass type thunderstorms. These storms are often chaotic in nature developing in random locations. This study attempts to find patterns in this development by comparing warm season precipitation data with types of land cover.

Correlations between land cover and precipitation totals were investigated by using 24-hour estimated precipitation totals provided by the National Weather Service River Forecast Centers and comparing these data with a land use/land cover classification dataset. Non-parametric statistical analysis was then used to determine if positive correlations exist. Spatial Synoptic Classification was also used to isolate days more conducive to thunderstorm formation based on air mass type.

Results indicate that over a five year study period, more daily precipitation accumulated in the eastern portions of Tuscaloosa County. On days more conducive to convective precipitation development, heavier precipitation occurred in the area with the greatest urban land cover concentration and areas directly east and northeast of the urban center. Further research is needed to validate these findings, mainly because of a positively skewed precipitation dataset obtained over the five year study period.

DEDICATION

This thesis is dedicated to everyone that supported me and helped me over the past two years while working to complete this study. In particular, the faculty and staff in the University of Alabama's Department of Geography, my wonderful wife Nicole, and the Wyatt and Schilleci families.

LIST OF ABBREVIATIONS AND SYMBOLS

α	Asymptotic significance
p	Probability value of a statistical hypothesis test
n	Number of observations
Z	Reflectivity factor
UTC	Zulu Time or Universal Time
A	Adjustment coefficient
B	Adjustment coefficient
R	Rate of precipitation
km^2	Kilometers squared
ft	feet
m^2	Meters squared
mm	Millimeters
$^{\circ}$	Degrees latitude and longitude
H_0	Null hypothesis
H_a	Alternative hypothesis
$<$	Less than
\leq	Less than or equal to
$>$	Greater than

= Equal to

KW Kruskal-Wallis

MWW Mann-Whitney-Wilcoxon test

MCS Mesoscale Convective System

BH Bermuda High

UHI Urban Heat Island

AHPS Advanced Hydrologic Prediction Service

HRAP Hydrologic Rainfall Analysis Project

DPA Digital Precipitation Array

RPG Radar Product Generator

MT Maritime Tropical Air Mass

ETM+ Enhanced Thematic Mapper Plus

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CHAPTER 1

INTRODUCTION

Understanding the processes that govern the development of warm season precipitation in the United States is of great concern in the study of weather and climate. Previous heavy precipitation events highlight this fact. For example, heavy precipitation in the Upper Mississippi River Basin during the summer of 1993 resulted in the “Great Flood” that ranks as one of the most significant natural disasters in U.S. history (Kunkel et al. 1994). Storm total precipitation above 16 inches was reported in many locations within the Midwest. Heavy precipitation coupled with already saturated soils resulted in flooding that impacted 400,000 square miles, impacting nine states. Fifty flood-related deaths were reported along with damage costs that were estimated in the billions of dollars. Flood durations for some communities lasted for nearly 200 days (Larson 1996). All modes of transportation were halted due to flooded railways, airports, roads, and failed bridge infrastructures (Larson 1993). The multiple atmospheric processes associated with this flood occurred at varying spatial and temporal scales. One of the key factors that led to The 1993 Great Flood was the wet conditions that occurred over the upper Mississippi River Drainage basin during the previous fall season of 1992. This was followed by heavy snowfall during the winter season and the associated snowmelt during the spring season. The flooding initially impacted the Redwood River in Minnesota during May and then the Black River in Wisconsin during June. This was followed by the record flooding along the Missouri, Mississippi, and Kansas Rivers (Lott 1993). Persistent fronts that occupied the region for at-least 40 days in June and July, along with possible Mesoscale Convective Systems in August, were

reportedly responsible for the heavy precipitation that fell on the saturated soils (Kunkel et al. 1994). Trenberth and Guillemot (1996) noted the large scale impacts of El Nino in the process of influencing an active upper air pattern over the flood region. They also noted the small scale processes such as local evaporation as a possible contributor in enhancing local precipitation.

Tropical Storm Allison was another significant warm season event that struck the United States in June of 2001. Allison made two landfalls in the states of Louisiana and Texas and was one of the most costly tropical storms to ever impact the United States (Evans et al. 2001; FEMA 2006). Allison was responsible for 33 fatalities between southeast Texas and northern Florida, 22 of which occurred in the Houston area, and over \$5 billion in damage. Storm total precipitation peaked at 939.55 mm at Port Houston, TX and at 758.44 mm in Thibadoux, LA (Evans et al. 2001). The heavy rainfall associated with this historical event is also attributed to multiple atmospheric processes that govern warm season precipitation. For example, synoptic scale influences of the semi-permanent Bermuda High, east of Florida, was responsible for steering Allison towards Galveston, Texas where the first landfall occurred on 5 June 2001. As the system moved inland, intense precipitation resulted in over six inches of rain in less than five hours for cities like Beaumont, Texas where roads and homes were flooded. On 8 June 2001 the low level center of Allison drifted southward and the combination of moisture and strong daytime temperature fluctuations resulted in local scale forcing that triggered thunderstorm development in the Houston area. This set the stage for heavy rain during the night of June 8th that led to significant flash flooding (Evans et al. 2001). The greater precipitation intensity associated with these storms created widespread flash flooding that was linked to most fatalities and loss of property (Evans et al. 2001). Allison drifted offshore on 10 June 2001 however dry air in the mid and upper levels of the atmosphere, coupled with strong westerly upper level wind shear,

prevented re-strengthening of the tropical systems low level center (Stewart 2002). Allison began to re-organize as a subtropical storm with frequent thunderstorm development located east of the low level center. A new low level circulation materialized due to these storms on June 11th and this newly organized subtropical storm drifted east-northeast impacting neighboring Southeastern States (Stewart 2002).

A third highlighted event took place on 19 August 2007 when remnant circulation associated with Tropical Storm Erin re-intensified over western Oklahoma (Arndt et al. 2009). The combination of the remnant tropical circulation, light winds, moist atmosphere, and ascent from a mid-level short wave, all contributed to this re-strengthening (Arndt et al. 2009). These complex interactions resulted in significant flooding, severe winds, and tornadoes that caused extensive property damage and loss of life (Arndt et al. 2009). High resolution satellite imagery captured by the Moderate Resolution Imaging Spectrometer on board the Terra Satellite highlights the extreme river flooding caused by this event (Figure 1) (Przyborski and Remer 2007). The analysis of Tropical Storm Erin was significant because of the dense network of surface observations in the region that provided the high spatial and temporal resolution needed to characterize the subtle processes underlying the tropical systems re-strengthening (Arndt et al. 2009).

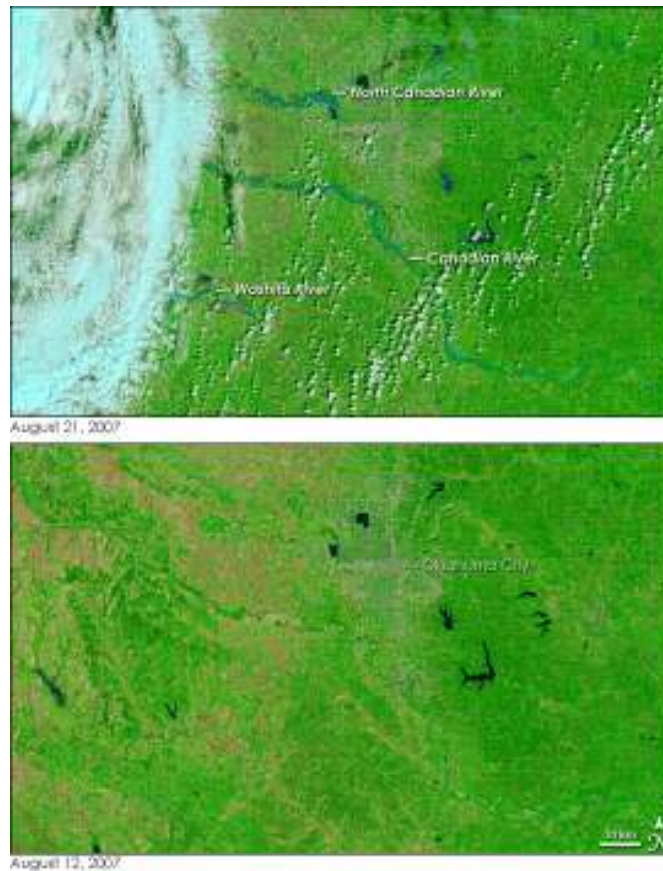


Figure 1. Image captured by the Terra Satellite (MODIS) on 12 August 2007. The bottom image displays the impact area prior to Tropical Storm Erin and the top image displays the significant river flooding caused by Tropical Storm Erin (Przyborski and Remer 2007).

By providing a higher number of weather observations on a frequent basis, a dense weather observing network or mesonet would allow for greater success in the detection of small scale atmospheric phenomena that can contribute warm season precipitation development. These observations might otherwise be unnoticed using the broader network of surface observations provided by the National Weather Service. A high resolution surface observing network would be very beneficial to locations within the southeastern United States, where convective precipitation events are quite frequent during the warm season when strong diurnal temperature fluctuations

promote air mass thunderstorm development. These storms are a result of a number of processes occurring across different temporal and spatial scales, making forecasting difficult. While these storms are often isolated or scattered in nature, they can sometimes become clustered and sometimes re-develop over similar locations. On 11 June 2008, Tuscaloosa, Alabama experienced a flash flood event in the downtown area because of a slow-moving air mass



Figure 2. City of Tuscaloosa flash flood event 11 June 2008.

thunderstorm (Figure 2). Due to intense, localized convective precipitation, numerous streets and intersections in the downtown area were closed because of standing water, while a short distance away, no rain was reported. Differences such as these highlight the importance of understanding not only the larger-scale processes that promote precipitation development, but also factors that influence convective type precipitation at the local scale.

There are several reasons why localized convective precipitation events over the southeast should be investigated. Precipitation associated with thunderstorms during the warm season can often be intense. In addition, storms often move slowly and sometimes re-occur over similar locations, increasing the chance of a life-threatening flash flood. Thunderstorms also bring the threat of deadly lightning and high winds. Considering the increase in outdoor activities during the warm season, a successful forecast would greatly benefit planners, organizers, and others with recreational interest. Although not life-threatening, understanding where heavy rainfall may or may not occur would benefit those with agricultural interests. The behavior of these storms is also of great interest with regard to utility providers and transportation (Fritsch et al. 1998). Therefore, examining the timing and occurrence of local scale convective precipitation would greatly assist forecasters and planners. Additionally, a better understanding of local precipitation anomalies would assist governmental agencies and local leaders with decisions involving drainage systems or the ability to adequately control precipitation run-off. The importance of these links between weather and society should be of great concern over the southeastern United States because of an increasing population and higher risk of population exposure.

Several studies have provided insight on the localized behavior of warm season convective precipitation by examining relationships between convective atmospheric processes and underlying land cover (i.e. Pielke and Zeng 1989; Rabin et al. 1990; Seagal and Arritt 1992; Brown and Arnold 1998). Such studies suggest that changes in land cover can create variability in surfaces fluxes of sensible and latent heat. For example, variations in soil and changes in vegetation can create differing fluxes of temperature and moisture.

These discontinuities can generate boundaries that trigger convective precipitation development during the warmer months.

Additional studies have investigated the impacts of anthropogenic changes on this delicate land-atmosphere balance. This is most noted in studies regarding the impacts of urbanized locations on precipitation development. For example, Changnon (1980) suggested convection enhancement as a result of the large urbanized area of Chicago. Additionally, Dixon and Mote (2003) examined the role of Atlanta with regard to inducing precipitation development. Considering warm season precipitation enhancement by smaller cities, little research has been conducted. However, some small scale urbanized zones have been evaluated with respect to their ability to generate an urban heat island similar to large metropolitan areas. For example, Kopec (1970), observed the urban heat island effects in the city of Chapel Hill, North Carolina. Also, Norwine (1973) evaluated the heat island properties of a shopping center located in the west suburbs of Chicago. While these studies are not directly concerned with precipitation relationships, they determined that small urban areas can create heat islands similar to those of much larger metropolitan areas.

a. Statement of Problem

I hypothesize that land cover influences the distribution of precipitation in the greater Tuscaloosa area located within West Central Alabama. With respect to climate and weather-related investigations, this corridor should be considered of great interest for several reasons. During the warm season the region is susceptible to both severe droughts and extreme rain events. Significant rain events are sometimes associated with larger weather systems, such as mesoscale convective systems, and tropical storms, or as a result of smaller-scale phenomena that drive intense, localized convection.

The objective of this thesis is to determine the spatial characteristics of warm season precipitation in the Tuscaloosa, Alabama area, and if warm season convection is influenced by land cover types in the region. Furthermore, because of urban land cover associated with highly populated zones, an increased understanding of warm season rainfall can assist in regional planning with respect to heavy rain events. Dyer (2008) describes the southeast as a unique region varying in land cover, land use, and climatic variables, which potentially effect local precipitation patterns. It is believed that such variables may exist in west-central Alabama and that these variables influence warm season precipitation.

This thesis is structured as follows: Chapter Two, the background literature describing in greater detail the atmospheric process associated with warm season precipitation over the southeast. These processes will be evaluated with respect to their occurrence at various geographic scales. The literature review will also provide a foundation for the processes linked to the development of small-scale convective events and how changes in land cover may influence such occurrences. Chapter Three will provide a description of the study area and address the data and methods used to evaluate the relationships between precipitation amounts, the synoptic classification, and the land cover types. This Chapter will also provide a description of the data acquisition and calibration, as well as temporal characteristics of the data. Chapter Four will provide the results of the statistical and land cover analysis. This chapter will also provide a detailed discussion about the results of each analysis technique. Chapter Five provides a summary and conclusion as well as the avenues of future research. The goal of this thesis is to determine links between areas that receive more or less precipitation and land cover types within the greater Tuscaloosa area.

CHAPTER 2

BACKGROUND LITERATURE

The ability to accurately predict precipitation is a fundamental component of weather forecasting (Fritsch et al. 1998) and is especially important when forecasting heavy precipitation. In fact, Heideman and Fritsch (1988) suggest that over 80% of the heavy precipitation in the United States is a product of thunderstorms. While storms can occur throughout the year over various portions of the United States, convectively-induced precipitation is most prevalent during the warm season (Wallace 1975). The chance of predicting convective precipitation is more difficult resulting in a lower forecast accuracy during the warmer months (Fawcett 1977; Charba and Klein 1980; Heideman and Fritsch 1988; Olson et al. 1995; Carbone and Tuttle 2008), which is especially true in the humid subtropical climate of the southeastern United States where precipitation is often dominated by convective processes that occur at varying spatial and temporal scales (Diem 2006).

Part of the goal of this thesis is to determine if unique distribution patterns associated with warm season precipitation exist within the Tuscaloosa metropolitan area. Heavy precipitation can have a significant impact on life and property (e.g. Henry 1913; Lautzenheiser and Fay 1966; Lapenta et al. 1995; Ashley and Ashley 2008) and it is important to understand the mechanisms responsible for convective precipitation at the synoptic scale, the mesoscale, and the storm scale (Orlanski 1975, Glickman 2000). This chapter will provide background literature reviewing the larger scale processes linked with controlling warm season precipitation over the southeast, the importance of the mesoscale and storm scale atmospheric processes during the

warm season, the influences of varying land cover in the development of land-atmosphere interactions, recent trends in precipitation behavior, and the importance of heavy precipitation with respect to society and human well-being.

a. Synoptic Scale Controls

Prediction of when and where precipitation will occur is easier to resolve when forecasting events at the synoptic scale (Charba and Klein 1980). Atmospheric phenomena that occur at this scale exist within a spatial domain at or above 1000 km (Glickman 2000). One of the primary controllers of precipitation at this scale is the extratropical cyclone and due to their larger expanse over space and time, these systems are better analyzed thanks to improvements in atmospheric sampling via soundings and numerical modeling (Charba and Klein 1980; Heideman and Fritsch 1988; Olson et al. 1995). These systems are most influential during the cooler months and are commonly associated with stratiform precipitation (Heideman and Fritsch 1988). In fact, the heaviest precipitation associated with these synoptic scale systems is often caused by imbedded thunderstorms (Wallace 1975; Schumacher and Johnson 2006). When compared to the warm season, extratropical cyclone-induced thunderstorms are forecasted with greater accuracy due to their association with a large scale system (Charba and Klein 1980). Previous research has addressed connections between synoptic scale systems during the warm season and anomalous precipitation occurrences (Gamble and Meentemeyer 1997; Diem 2006). For example, Diem (2006) suggested troughs in the mid-troposphere significantly increase the potential for anomalous warm season precipitation over the Southeast. Given the oppressive and often stagnant environmental conditions associated with mid to late summer over the Southeast, the presence of such synoptic scale phenomena might not seem quite as obvious. However, statistical correlations between the frequency of troughs and wetter periods across the southeast

are documented and associated with upper-level troughs and stronger lower tropospheric flow over the interior southeast (Diem 2006). Cold fronts associated with this type of upper air pattern are also noted to trigger some of the most intense precipitation events over the southeast, sometimes associated with warm season floods (Konrad 1997; Gamble and Meentemeyer 1997).

Although synoptic scale processes are linked with multi-day, dry and wet warm season precipitation anomalies over the southeast, forcing mechanisms at this scale tend to be more subtle than those observed in cooler months (Weisman 1990; Diem 2006). Synoptic scale forcing mechanisms are less frequent during the warm season over the interior southeast (Dyer 2009). A key variable in this synoptically benign environment is the establishment of the Bermuda High (BH). This ridge of high pressure usually becomes better established over the southeastern United States as the warm season progresses, with the orientation of the more favorable synoptic-scale forcing shifting northward and westward (Heideman and Fritsch 1988; Medline and Croft 1998).

For example, in 2007 the expansion of the BH over states like Alabama and Georgia limited precipitation development and forced organized areas of heavy precipitation to occur in the south-central United States (Leslie 2007). As a result, vegetation was severely stressed and water restrictions were implemented for several communities (Heim 2007). These outcomes exemplify the importance of the BH as a controlling variable on warm season precipitation distribution over the southern United States. In fact, the BH is considered one of the most influential synoptic scale phenomena during the warm season over the southeastern United States (Katz et al. 2003).

The presence of broad anticyclones, such as the BH, is rather common in humid subtropical locations like the southeastern United States (Medline and Croft 1998; Diem 2006).

During the cooler months, this anticyclone becomes anchored over the eastern Atlantic where it is appropriately termed the Azores High (Glickman 2000). During the warm season this high migrates westward and becomes centered near the island of Bermuda, hence the label BH (Glickman 2000). A measure to which this east-west expanse occurs is known as the Bermuda High Index (BHI) and it varies during the spring and warm season (Stahle and Cleaveland 1992). For example, when evaluating the impacts of urban areas on precipitation development, Diem and Mote (2005) linked a negative BHI, which is a westward expanding and strengthening BH, to a decrease in warm season precipitation at sample locations south of Atlanta. In addition, Keim (1997) attributes a strengthening BH with a decrease in precipitation and thunderstorms due to the increase in atmospheric stability and subsidence associated with the high pressure ridge.

In some instances however, thunderstorms may develop as a result of atmospheric processes within the confines of the BH's influence. By allowing for a build-up of heat and moisture, the BH augments the energy fluxes and potential buoyancy necessary to initiate convective thunderstorm development over the southeastern United States. Temporally, this development exhibits a marked diurnal pattern during the warm season (i.e. Shands 1947; Easterling and Robinson 1985). However, the strength of the BH can be a determining factor in the number of thunderstorms. For example, an intense BH may prevent widespread convective thunderstorm development and in some instances, act to inhibit storm development all together.

When the BH becomes an influential feature over the southeastern United States, and synoptic scale forcing weakens, the frequency of precipitation development at the mesoscale increases (Heideman and Fritsch 1988). The importance of these mesoscale controls will be discussed in greater detail in the following section.

This section will also provide information regarding storm scale atmospheric processes that can influence the development of warm season precipitation over the southeastern United States.

b. Mesoscale and Storm Scale Controls

During the warm season approximately half of the precipitation in the United States is associated with synoptic scale weather systems. The other half of precipitation is associated with forcing mechanisms occurring at the mesoscale (Heideman and Fritsch 1988). Processes that occur at this scale exist within a spatial domain of 2 to 200 km (Orlanski 1975). Over the southeastern United States, two of the main atmospheric phenomena responsible for organized warm season precipitation at this scale include mesoscale convective systems (MCS) and tropical systems (Schumacher and Johnson 2006).

The MCS is broadly defined as an organized system of precipitation and clouds that includes at-least one thunderstorm cell during its lifetime, and storm scale events (2-20 km) (Orlanski 1975) that interact over the dimension of space and time (Zisper 1982; Geerts 1998). A preliminary study by Geerts (1998) indicated that the MCS was more frequent during the summer over the Southeastern United States and were also smaller and short-lived. The development of an MCS in the southeast often involves a two-staged evolution in which unorganized thunderstorms merge to form an organized system that later transitions into a decaying and stratiform MCS phase (Knupp and Cotton 1987; Geerts 1998). This highlights an importance of storm scale convection on the evolution of the larger, more organized, MCS.

Tropical systems are another mesoscale feature responsible for some of the heaviest precipitation in the southeast United States during the warm season (Konrad 2001). Although these systems can occur during the warmer months, the number of tropical systems and landfall

locations can vary annually. For example, Schumacher and Johnson (2006) found that over a three year study period, tropical systems accounted for a small percentage of extreme precipitation events over the eastern third of the United States, excluding Florida. However, the few tropical systems mentioned in their study were associated with some of the most severe precipitation and flooding. Tropical Storm Allison was one noted system that was responsible for the loss of life and property over southeast Texas in 2001. Interactions with the land surface aided in convective thunderstorm development that increased the severity of flooding associated with Allison. These localized storms developed away from the low level center of circulation as a result of daytime heating and the presence of a very moist air mass (Evans et al. 2001).

Additional studies have examined atmospheric processes over the southeastern United States that may enhance the severity of convective precipitation at the mesoscale (i.e. Konrad 1997). According to Doswell et al. (1996), factors such as identifying a storm systems movement, a storms systems scale, and variations in rainfall intensity that occur within the parent storm system, can determine the possibility of flooding. Therefore, an understanding of storm scale precipitation patterns and behavior may provide additional insight into precipitation characteristics associated with parent storm systems such as a tropical system or MCS.

While the mesoscale type systems noted in this section produce precipitation that is convective in nature and more organized, it is important to note thunderstorms during the warm season often occur in absence of these features (Garrett 1982; Bauman et al. 1997). This is especially true within the synoptically benign atmosphere in the southeastern United States during the warm months. Over the southeastern United States there is a high variability in summer precipitation distribution due to the development of air mass thunderstorms (Baigorria et al. 2007) in random geographic locations as a result of diurnal temperature variability.

Air mass thunderstorms are also labeled as convective thunderstorms due to the convective updrafts resulting from air mass instability (Byers and Braham 1949), and this label will be applied to this storm type throughout the remainder of this manuscript. Strong daytime temperature fluctuations produce the instability necessary for afternoon convective thunderstorm development (Wallace 1975), even when larger scale atmospheric forcing mechanisms are absent or weak (Garrett 1982). These seemingly chaotic storms are very difficult to predict because of their small spatial coverage and temporal scale. Although these storms may sometimes randomly develop, their initiation is also linked to mass converge associated with boundaries of varying spatial scales (Wallace 1975). The next section will highlight the importance of land cover in generating the instability necessary for convective thunderstorm development. Furthermore, this section will highlight the importance of varying land cover in generating boundaries which can initiate convective thunderstorm formation.

C. Land Cover and Convective Storms

During the warm season there is a certain degree of short term predictability associated with convective thunderstorms based on the development of atmospheric boundaries which create preferred locations for convection. By using remote sensing tools such as radar and satellite imagery, these boundaries can be more readily detected, allowing for improved short-term forecasts (Purdom 1976). For example, cool outflow from thunderstorms can generate gust fronts (Glickman 2000) that act as triggering mechanisms for convective precipitation. This cool outflow is the result of the rain-cooled air from the downdraft of previous storms and can be identified on satellite as either arc clouds or cloud rings (Purdom 1976; Lima and Wilson 2008). These gust fronts can act as lifting mechanisms by creating mass convergence in the lower levels of the atmosphere.

Other types of boundaries may form because of differences in thermal and moisture properties associated with land cover. For example, the synoptically benign environment established by the BH over the southeast United States can create the optimal atmospheric conditions necessary for the development of land and sea breeze circulations (Medline and Croft 1998). The sea breeze is a frequent contributor to warm season precipitation over coastal areas of the southeast and can often influence precipitation development well inland (Medlin and Croft 1998; Carbone and Tuttle 2008; Kursinski and Mullen 2008). Such breezes are a function of temperature discontinuities over land and water that effect changes in air pressure (Haurwitz 1947; Defant 1951; Seagal and Arritt 1992). At a much smaller scale, similar sea-breeze type circulations have been documented along lakes (i.e. Lyons 1966) and rivers (i.e. Dubinskii 1956).

Some convective precipitation can develop freely, when the mass convergence associated with fronts or elevated surfaces are not available (Bauman et al. 1997). This can occur when energy interactions between the land cover and the atmosphere produce the necessary forcing to initiate convective currents (i.e. Malkus and Stern 1953; Lettau 1956; Carson and Moses 1963; Mahfouf et al. 1987; Diem and Mote 2005). Within synoptically benign environments the energy fluxes associated with land cover type modifies the lowest level of the atmosphere, known as the planetary boundary layer (Garrett 1982; Pielke 2001). According to Garrett (1982), convective thunderstorms are more likely to form when the boundary layer is deep and moist, and the atmosphere is unstable with respect to saturated air (Haurwitz 1947). The depth of the planetary boundary layer is a function of the sensible and latent heat fluxes as determined by the type of surface cover in the lowest level of the atmosphere (Garrett 1982). For example, healthy vegetation can transpire more freely resulting in a potential for larger latent energy fluxes; however, the opposite reaction can occur when vegetation is stressed and stomata close resulting

in large fluxes of sensible heat (McPherson 2007). Therefore, different types of vegetation can create fluxes of sensible and latent energy (Segal and Arritt 1992; Brown and Arnold 1998) that influence the depth of the planetary boundary layer and possibly the development of convective thunderstorms.

It is important to note that the same energy interactions highlighted above are responsible for generating non-classical mesoscale circulations (NCMSs) (Brown and Arnold 1998). The differential heating responsible for atmospheric circulations generated between land and water can generate inland circulations between differing vegetation and soil types (Pielke and Segal 1986). In fact, much research has examined the role of temperature and moisture discontinuities with respect to inland circulations similar to that of the sea breeze (i.e. Mahfouf et al. 1987; Segal and Arritt 1992; Brown and Arnold 1998). For example, heterogeneous land cover type, such as terrain containing urban, forest, and agricultural areas, can vary in the amount of transmitted sensible or latent energy (Mahfouf et al. 1987; McPherson 2007). The discontinuities related to soil-order type, soil moisture, vegetation type/coverage, evapotranspiration rates, surface albedo, cloud cover solar irradiance absorption/reflection, and concentrations of atmospheric aerosols are all linked to the development of NCMCs (Garrett 1982; Ookouchi et al. 1984; Pielke and Zeng 1989; Segal and Arritt 1992; Brown and Arnold 1998). Like the land-sea breeze, these circulations can create areas of mass convergence necessary for the development or enhancement of warm season convective precipitation (Brown and Arnold 1998).

By comparing convective cloud initiation using Geostationary Operational Environmental Satellite (GOES) imagery to moist and/or dry vegetative surfaces, Brown and Arnold (1998) determined convective showers often developed along crop order boundaries

rather than elsewhere in the region. The initial convection was found to occur often along the moister side of the land cover boundary on synoptically benign days. This finding was similar to that of Pielke and Zeng (1989) and Rabin et al. (1990) in which initial cumulus development occurred over moister surfaces. In addition, Mahfouf et al. (1987) found that the transition zones between bare soil and vegetation appeared to be the most favorable areas for convective development. Pielke (2001) provided evidence of such land-atmosphere interactions by linking the spatial structure of surface heating that is influenced by landscape patterning with focal regions for deep cumulonimbus convection. Hypothetically, this information supports the possibility of land cover influences on precipitation distribution during the warm season over the southeastern United States. However, Dyer (2009) determined that few synoptically benign days were associated with the development of convective boundaries over a portion of western Mississippi during the warm season. The boundaries that did form had a short life span and were generally disorganized.

Brown and Arnold (1998) examined major mesoscale vegetation and land use boundaries within Illinois mainly because of the rather uniform elevation. The role of orographical influences is of great importance with respect to precipitation development (i.e. Garrett 1982; Lapenta et al. 1995; Konrad 1997; Carbone and Tuttle 2008). Elevated terrain can promote the formation of upslope flow and lee side troughs which can impact the distribution of precipitation (Hoxit et al. 1978; Lapenta et al. 1995). Lima and Wilson (2008) linked convective thunderstorm initiation with higher elevations over the moist southwest Amazon region. When examining the delta region of western Mississippi, Dyer (2009) found that some of the strongest convective boundaries were associated with the higher-elevation areas along the eastern boundary of the delta region, known as the bluff line. The strong variations in land cover type along the bluff line

posed the question as to which surface characteristic was most influential in the convective precipitation development. Dyer (2009) noted that perhaps the combination of energy fluxes due to varying land cover creates unstable air masses that are forced to ascend because of the eastern bluff line, therefore initiating convective precipitation development.

This section highlights the linkages between convective precipitation development and differing types of land cover. However, it is important to note that specific land cover is also exposed to change over time as a result of anthropogenic factors. Several studies have examined the influence of anthropogenic factors on the development of precipitation and climate in general. For example, Senkbeil (2007) reviewed the impacts of increased irrigation (3 million acres in 1950 to greater than 20 million in 2002) over the Great Plains. It was hypothesized that clouds would more likely form over irrigated areas first because of the less dense-moisture laden air and that the boundary delineating this agricultural cool island might trigger or enhance convective thunderstorms. The findings of this study suggested irrigation was a minor contributor to warm season precipitation, although it might influence instability within certain synoptic conditions.

Other anthropogenic influences on climate include modified land surfaces as a result of growing metropolitan areas. Several studies have examined the influence of urban sprawl on precipitation development (i.e. Metropolitan Meteorological Experiment, Berry and Beadle 1974; Changnon 1981). In fact, urban land use change has been noted as one of the biggest anthropogenic impacts on the natural environment (Kaufman et al. 2007). The following section will provide a detailed overview of literature describing the important role of urban land cover in the development of warm season precipitation.

d. Urban Land Cover

As population continues to increase over the southeastern United States, there will also be changes in land cover. Some studies have suggested modifying natural landscapes in an effort to modify local climate. For example, Black and Tarmy (1963) suggested the use of asphalt coatings to increase precipitation in arid regions. In population dense areas such as cities however, enhanced precipitation due to urban land surface modifications could have a more profound impact on life and property.

According to Huff and Changnon (1973) changes in precipitation behavior can occur as a result of urban land cover in an unstable atmosphere which is created by an established urban heat island (UHI). It has been documented for some time that urbanized areas generate warm ambient environments (Howard 1833) as incoming solar radiation is absorbed by artificial structures, such as roads and buildings. At night the absorbed radiation creates a slower rate of cooling as compared to rural areas (Clarke and Peterson 1973). After observing 28 U.S. cities, Gallo and Owen (1999) determined that temperature differences between urban and rural areas were greatest during the months of July and August. However, the study of urbanized areas and climate is not only limited to cities of a predetermined size. The UHI effect has been evaluated in locations ranging from small shopping centers (Norwine 1973) to large metropolitan areas (Huff and Changnon 1973) and the effect is most noticeable when the atmosphere is synoptically benign, as is the case during the warm season over the southeastern United States (Findlay and Hirt 1969).

The thermal and moisture gradients between the center of urban areas and rural locations can also generate NCMCs (Brown and Arnold 1998). As noted in the previous section thermal and moisture gradients are a function of land cover properties such as albedo and transpiration

rates. The NCMCs that are generated not only act to initiate convective precipitation but also act to enhance the vertical growth of convective clouds (Brown and Arnold 1998). Many studies have highlighted the ability of urban landscapes to enhance precipitation development (i.e. Metropolitan Meteorological Experiment, Berry and Beadle 1974; Changnon 1981)

Changnon (1976) suggest precipitation enhancements associated with urban land cover are a function of the mentioned UHI effect, surface roughness, and increases in aerosols that can affect cloud condensation nuclei. It is easy to visualize the presence of increased aerosols in heavily industrialized locations but the influence on precipitation is rather complex. For example, increased aerosols or nuclei from industries over and downwind of urban areas may serve to suppress rainfall or reduce rain droplet size (Huff and Changnon 1973; Hand and Shepherd 2009). According to Rosenfeld (2000), increased aerosols promote the development of smaller raindrops and prevent the formation of larger drops, therefore impacting precipitation intensity. Although such industrial emissions may not enhance precipitation, the impact of aerosols cannot be ignored as a variable that impacts the distribution of precipitation in and around urban locations.

The precipitation enhancements associated with surface roughness, as noted by Changnon (1976), are a function of the complex terrain associated with urban areas. The land cover associated with such urbanized locations varies in the number of natural landscapes and buildings, which also varies in size and geometry (Huff and Changnon 1973; Dixon and Mote 2003). These characteristics highlight the fact that different cities are unique. Furthermore, different cities are exposed to different atmospheric phenomena based on geographical positioning. Shepherd et al. (2002) determined the influence of urbanized areas can be quite challenging when faced with the presence of other local scale influences, such as a sea-breeze.

Changnon (1980) discovered such a localized influence when investigating the urban influences of the Chicago metropolitan area. Although precipitation enhancements were detected within the city, downwind precipitation enhancements were suppressed by atmospheric influences related to Lake Michigan.

One of the most-cited investigations regarding precipitation enhancement is the Metropolitan Meteorological Experiment (METROMEX) (Berry and Beadle 1974; Changnon 1981). This was an intense five year study conducted in the St. Louis area that primarily analyzed urban influences during the warm season. It was determined that thermal enhancements and surface roughness within the St. Louis metropolitan area enhanced precipitation development by modifying the planetary boundary layer (Diem and Mote 2005). Evidence of this enhancement was realized when a marked increase in precipitation was measured downwind of the city as opposed to upwind of the city. In related studies, Huff and Changnon (1973) found evidence of urban enhanced precipitation in seven cities within the United States including: St. Louis, Missouri, Cleveland, Ohio, Washington D.C., Baltimore, Maryland, Houston, Texas, New Orleans, LA, and Chicago, Illinois. These enhancements ranged from directly above the city center to a range of 80 km downwind of the city center (Huff and Changnon 1973).

While UHI effects may be strongest during the warmer months (Gallo and Owen 1999), Changnon (1980) suggests that enhanced precipitation created by urban environments are generally more prevalent when an organized heavy rain event is occurring (i.e. squall line). However, when investigating urban precipitation effects of Atlanta, Diem and Mote (2005) noted precipitation increases at a reporting station northeast of the central metropolitan area. This enhancement was discovered by evaluating precipitation patterns during the warm season over the southeast United States.

In a similar study, Hand and Shepherd (2009) noted that the north-northeast sections of the Oklahoma City metropolitan area were statistically wetter than other regions.

As opposed to urban precipitation enhancements, Dixon and Mote (2003) investigated urban-induced precipitation in the Atlanta area. It was determined that in the presence of weak synoptic flow regimes and marginal instability, the anomalous heat of the Atlanta metropolitan area may act as a triggering mechanism for convective precipitation development. One interesting part of this study was that most of the UHI events took place before sunrise. It was also determined that low level moisture was a significant ingredient for UHI induced precipitation development. These findings agree with the statements by Garrett (1982), which suggest convective thunderstorms are more likely to form when the boundary layer is deep-moist and the atmosphere is unstable with respect to saturated air. When the atmosphere is too stable, represented by a strong Bermuda High, convective precipitation development may be limited or if the atmosphere is too unstable widespread convective precipitation development will take place regardless of urban influences (Medline and Croft 1998; Dixon and Mote 2003).

While a number of the presented cases involve different regions of the United States, this thesis is concerned with the southeast United States. The background literature in this section suggests urban areas are unique and that urban areas of varying size and structure may act to influence climate. As population continues to increase over regions such as the southeastern United States, more insight into local scale influences on precipitation development and enhancement is necessary, especially in the population dense locations.

While urban areas may act to influence precipitation (i.e. Changnon 1976) or suppress precipitation (i.e. Rosenfeld 2000), recent studies have noted changes in precipitation characteristics associated with thunderstorms in general and the next section in this chapter will highlight in the importance of these findings.

e. Precipitation Characteristics

According to the National Climatic Data Center (1994), the average annual precipitation over the 20th century displayed a 10% increase, primarily reflected as increases due to extreme and heavy precipitation episodes (Karl and Knight 1998). When comparing trends of the ten wettest days of the year with overall precipitation, Michaels et al. (2004) found that in the southeast United States there is evidence that increases in precipitation on the wettest days exceeds that of the total precipitation increases. The Intergovernmental Panel on Climate Change states that the frequency of such heavy precipitation events has increased over most land areas in conjunction with warming and observed increases of atmospheric water vapor (IPCC 2007). Brommer et al. (2007) also notes that a progressively small number of long-duration storms are becoming wetter.

These noted changes in precipitation behavior are of great interest in the study of global climate change. These findings are also of great importance in weather and climate related investigations similar to this study. For example, if urban land cover or forest land cover boundaries serve as the most favorable locations for warm season precipitation, then these areas may be exposed to heavier precipitation in the future. Changes in the temporal behavior of precipitation are beyond the scope of this study; however, the characteristics of the precipitation data (i.e. heavy versus light precipitation) will be used to analyze spatial precipitation patterns in the Tuscaloosa area.

f. Summary

This chapter has highlighted the various controls of warm season precipitation over the southeastern United States. During the warm season, the atmosphere is often synoptically benign, an environment that promotes the development of less organized convective precipitation. The strength and the positioning of the Bermuda High dictate the amount of stability that can sometimes prevent convective precipitation development or allow for widespread precipitation development. These conditions are of great importance to this thesis, which will investigate the possibility of land cover influences on local precipitation distribution patterns in and around the city of Tuscaloosa, Alabama.

It is hypothesized that smaller-scale forcing mechanisms may develop within the greater Tuscaloosa area because of heterogeneous land cover, which in theory should be most apparent within the ambient warm season environment over the Southeast. Such forcing mechanisms may be the direct result of underlying land cover or boundaries generated by land cover variations. By choosing the warm season, an underlying goal of this study is to seek subtle precipitation triggers that may go unnoticed in the presence of organized precipitation which is common during other seasons. In addition, when examining the synoptic and mesoscale controls in this chapter it is apparent that thunderstorms serve as internal component to larger-more organized systems (i.e. MCS, tropical cyclones). Therefore, smaller scale forcing that can influence convective precipitation may further increase the severity of larger scale systems. In some instances unorganized convective thunderstorms can develop into organized convective systems (Knupp and Cotton 1987). In several instances, organized areas of thunderstorms have been observed to split or move north-south of the main population center of Tuscaloosa.

While the size of Tuscaloosa is much smaller with respect to most urban studies noted in this chapter, this thesis should provide additional insight into the influences of a medium sized urban environment on convective precipitation development. Since convective thunderstorms occur frequently over the chosen study area during the warmer season an understanding of when and where they may occur can provide several benefits. For example, storms in general can create the intense convective precipitation necessary for the development of flash floods (Schumacher and Johnson 2006). In the United States, flooding is regarded as the number one weather related killer (Lapenta et al. 1995). Flash floods are the result of heavy precipitation associated with slow moving thunderstorms (Doswell et al. 1996). The onset of a flood can be further influenced by the presence of impervious land cover, small drainage basins, and large amounts of antecedent precipitation (Doswell et al. 1996). By understanding favorable locations for convective precipitation, local leaders and planners can prepare for and implement effective drainage networks capable of sustaining increased amounts of water runoff.

Those with agricultural interest would also benefit from findings in this type of study. When examining the American Midwest, Brown and Arnold (1998) noted that economical impacts related to unexpected convective precipitation costs the agricultural industry millions of dollars. Given the significance of the agricultural industry over the southeastern United States, a better understanding of convective precipitation development would allow farmers to make the necessary preparations such as relocating livestock or planting and harvesting.

Finally, there are other weather related hazards posed by isolated and organized areas of convective precipitation. For example, convective precipitation is often accompanied by lightning. As noted in the introduction, the warm season is a popular time for outdoor recreation. This means that more people are exposed to the dangers of lightning.

Even though the spatial characteristics of lightning as compared to precipitation patterns vary greatly, areas more susceptible to warm season precipitation may also have a higher exposure to this particular weather hazard.

Due to a small study area, this investigation does not evaluate large-uniformly defined land cover boundaries, as noted earlier in this chapter (i.e. Dyer 2009). However, despite the lack of significant disparity, this thesis applies methods to land cover unique to the Tuscaloosa area and the climate unique to the southeastern United States. By comparing precipitation data to land cover types, this thesis will seek to provide preliminary evidence of land-atmosphere interactions within the greater Tuscaloosa area. The next chapter in this thesis will provide a detailed overview of the data and methods utilized to test this hypothesis.

CHAPTER 3

DATA AND METHODS

The study of land surface-climate interactions has become a popular subject in contemporary climatology, reinforcing the geographical tradition of climate analysis across varying scales (Carlton 1999). Important questions addressed in such studies involve spatial and temporal variations of soil moisture, surface cover type, the energy budget, temperature, humidity, wind speed, and precipitation/convective cloud development. Addressing questions associated with land surface-climate interactions can assist in resolving issues related to precipitation or cloud development with respect to underlying surfaces. This thesis will take the contemporary climatological approach of comparing precipitation distribution patterns and comparing this data with underlying land cover. Through the use of remote sensing, climate data can be gathered and spatially analyzed with the aid of a geographic information system (GIS) (Chapman and Thornes 2003).

This thesis will investigate the greater Tuscaloosa area located in West Central Alabama. The study area is chosen based on regional climatology, population, land cover, and industry. A unique aspect of this region is that it lies within the Dixie Alley Corridor, an area highlighted by dual annual peaks in the frequency of severe weather, one in the fall and spring (Gerard et al. 2005). In addition to the threat of flooding as noted in Chapter Two, the other risks and hazards associated with thunderstorms make this a desired location for meteorological and climatological investigations. Furthermore, this region is exposed to the synoptically benign warm season environment that is supportive of frequent convective precipitation development. This warm

season environment can create the conditions necessary for discovering subtle influences land cover may have on the development and behavior of convective precipitation. The first section in this chapter will provide a detailed description of the study area and the time period for this investigation. Additionally, this chapter will highlight how precipitation and land cover data were gathered and the methods chosen to evaluate these data. By applying these methods, findings should help in evaluating the role of heterogeneous land cover in the Tuscaloosa area and the influence of this variability on the behavior of warm season precipitation patterns.

a. Study Period and Study Area

The chosen time period for this investigation consisted of the warm season months of June, July, and August. This time period was selected because of the lower frequency of synoptically-induced precipitation events. Precipitation during this time period is often convective in nature (Easterling and Robinson 1985), sometimes caused by smaller scale forcing mechanisms that can be the result of differing land cover types. For example, Brown and Arnold (1998) chose this synoptically-benign study period when investigating the influence of heterogeneous land cover on the development of convective precipitation over Illinois. In addition, some of the strongest climatic variations between differing surface cover can exist during the warm season. Gallo and Owen (1999) suggest that the largest difference in maximum, minimum, and average temperature between urban and rural areas exist during the months of July and August. Diem and Mote (2005) examined the influences of the Atlanta UHI during the months of June, July, and August due to the ambient atmospheric conditions present over the Southeast United States. Since the warm season climate in the Atlanta area is similar to that of west Alabama, the time period of June, July, and August was chosen for this investigation.

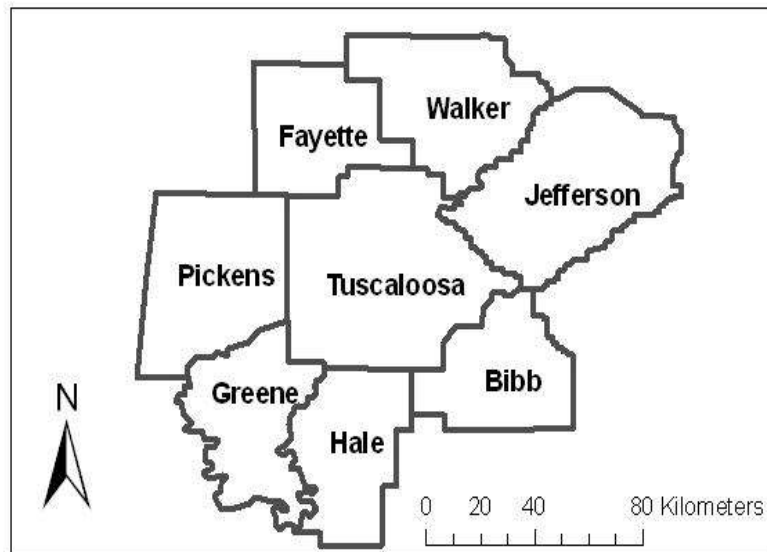
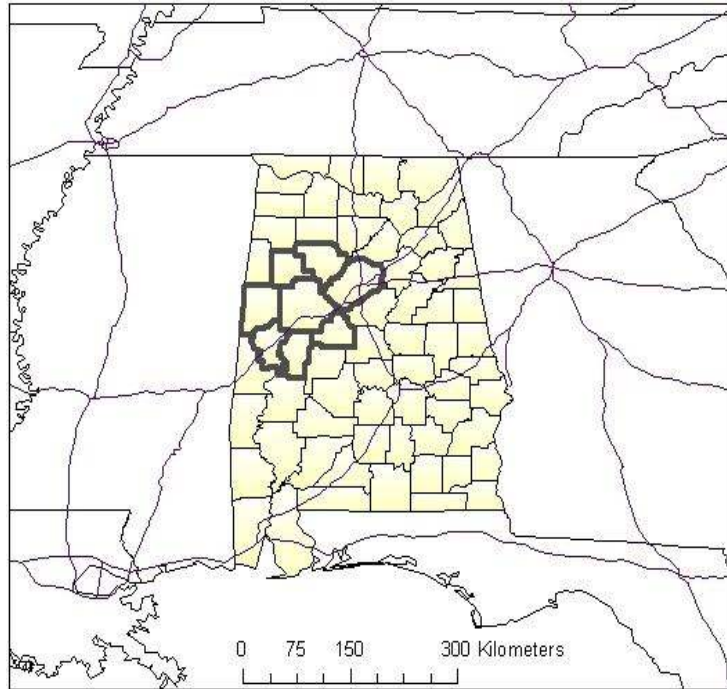


Figure 3. The study area includes Tuscaloosa County and a small portion of some neighboring counties located in west central Alabama.

Studies similar to this investigation evaluate locations that vary in shape and size. For example, Dixon and Mote (2005) examined urban influences of the Atlanta metropolitan area. However, Kopec (1970) examined the urban effects of a smaller city, Chapel Hill, North Carolina. The study area in this investigation includes Tuscaloosa county and a small portion of

some neighboring counties (Figure 3). Most of the study area however, lies within the confines of Tuscaloosa County. The county occupies approximately 2,157 km² with the major urban center of Tuscaloosa occupying approximately 80 km². Bordering counties include Hale, Bibb, and Greene to the south; Jefferson to the east; Pickens to the west; and Fayette and Walker counties to the north. The largest city in Alabama, Birmingham, is located in Jefferson County just 58 miles northeast of the city of Tuscaloosa.

According to the United States Census, the population of Tuscaloosa County in 2009 was approximately 184,035 people. Since 2000, the population in Tuscaloosa County increased by approximately 19,160 (U.S. Census 2010). The increase in population over the Southeastern United States has been at the heart of many climate related studies (i.e. Dixon and Mote 2003; Diem and Mote 2005) and given the growing population within Tuscaloosa County, an understanding of precipitation distribution patterns is of great interest with respect to life and property.

Land cover outside of the urban center within Tuscaloosa County include forests, agricultural land, lakes, and rivers. The Oakmulgee District of the Talladega National Forest, a predominately pine forest, is located in the southeastern part of the study area (USDA Forest Service). Land dedicated to agriculture includes approximately 3,486 acres of cotton, approximately 12,437 acres of hay, 3,648 acres of corn, and 1,167 acres of soybeans (USDA 2010). Additional land is dedicated to raising livestock further signifying the importance of agriculture within the chosen area of study. The Black Warrior River is a major transportation network located within the heart of the study area. Heavy precipitation can trigger flooding along this waterway over southern sections of the study area, which can also impact bordering lands dedicated to agriculture. The Sipse River is a smaller waterway located in the western part of

Tuscaloosa County associated with a north-south oriented Alluvial Plain. The elevation over western sections (≤ 250 ft) of the study area is generally lower than eastern sections (250 ft - 750 ft) (University of Alabama Cartographic Research Lab 2010). The single largest body of water within the study area is Lake Tuscaloosa, a large 5,885 acre water reservoir located approximately five miles northeast of the city of Tuscaloosa (DCNR 2008). It is hypothesized that variations in land cover may provide the delineations necessary to influence precipitation patterns, which make the Tuscaloosa area an acceptable location for this investigation. The next section will describe how land cover data is acquired and the method of performing a land use/land cover classification.

b. Land Use/Land Cover Mapping

Since the underlying goal of this thesis was to find evidence of possible land-atmosphere interactions, a land use/land cover classification was necessary. This classification was performed by using a digital satellite image of West Alabama acquired by Landsat 7 on 25 June 2001. Landsat 7 is part of a series of earth-observing satellites managed by NASA (National Aeronautics and Space Administration) and the USGS (United States Geological Survey) (NASA 2010). The sensor onboard the Landsat 7 satellite is the Enhanced Thematic Mapper Plus (ETM+), which is an eight-band multispectral scanning radiometer. This instrument provides an Instantaneous Field of View (IFOV) of 30 meters in bands 1 through 5, and 7. There is also an IFOV of 60 meters in the thermal band (6) and an IFOV of 15 meters in the panchromatic band (8). This high-spatial resolution was sufficient in providing the necessary detail in land cover characteristics within the greater Tuscaloosa area. In May 2003, there was a failure of the Scan Line Corrector onboard Landsat 7 and since the digital image used in this thesis was conceived prior to the hardware malfunction, there was no evidence of systematic distortions (NASA 2010).

The first step in performing the land use/land cover classification involved inputting the digital image from 25 June 2001 into the remote sensing application ERDAS Imagine. A hybrid classification was performed in which an unsupervised classification was first used to determine the spectrally separable classes associated with the false-color composite representation of the digital imagery (Lillesand et al. 2004). These separated classes were displayed in the ERDAS Imagine signature editor and by comparing ground reference data, these signature classes were grouped into four land cover types that included rangeland, water, forest, and urban. The modified signatures were then used in a supervised classification in which the maximum likelihood classifier was selected to create a final land use/land cover classification map.

The four class categories (water, rangeland, urban, and forest) selected in the classification were based on the USGS Land Use/Land Cover Classification System (Lillesand et al. 2004) (Figure 4 and Figure 5). The urban land cover represented the highly populated portions of the area in which land area was occupied by features such as buildings and transportation networks, the forest land cover representing the most densely forested areas, and water cover representing rivers, lakes, and streams. Rangeland was selected to represent the transitional zones such as grasses and shrubs. Due to a high variation in spectral properties associated with the agricultural areas, land used for planting and grazing was incorporated into the rangeland class.

Cloud cover was observed in the digital imagery however, cloud contamination was not a major factor within the study area. A random precipitation sample selection was performed in the study area and this selection process avoided the few clouds that were observed in the greater Tuscaloosa area. This enabled better spectral response in the process of classification underlying

surface cover associated with precipitation sample locations. The method of acquiring and selection precipitation data will be discussed in greater detail later in this chapter.

After performing the land use/land cover classification, the final classified image was inputted into the GIS interface ArcMap. The classified image had to be re-projected in order for proper alignment of the raster data and overlying vector data themes. This procedure involved re-projecting the classified image using a custom polar stereographic projection associated with the precipitation data displayed in the Hydrologic Rainfall Analysis Project (HRAP) Grid system. Ground control points (GCP) were also used to further align the county theme data with the underlying classified land use/land cover image. Using approximately 20 GCP, a third order polynomial transformation was used properly align the county vector data with the underlying raster data (Figure 4). Unlike a first order polynomial transformation which results in a more affined transformation, the third-order polynomial caused a slight bending of the classified image. However, the newly transformed image had a Root Mean Square Error less than 20 meters.

Once the land cover imagery was classified, a precipitation dataset was acquired and calibrated for analysis. The primary automated surface observation station representing the study area is located at the Tuscaloosa Regional Airport, latitude 33.13° North and 87.37° West. This station was activated on 1 January 1933 as a Weather Bureau Airport Station. Through the mid 1900s, the station became a cooperative station maintained by the Civil Aeronautics Administration, and later the Federal Aviation Administration. The climatological records from this station indicate an average annual rainfall of 1,453.09 mm. In the warm season, June averages 106.68 mm, July 145.03 mm, and August 93.98 mm (AOSC 2010). March is typically the wettest month, with October the driest.

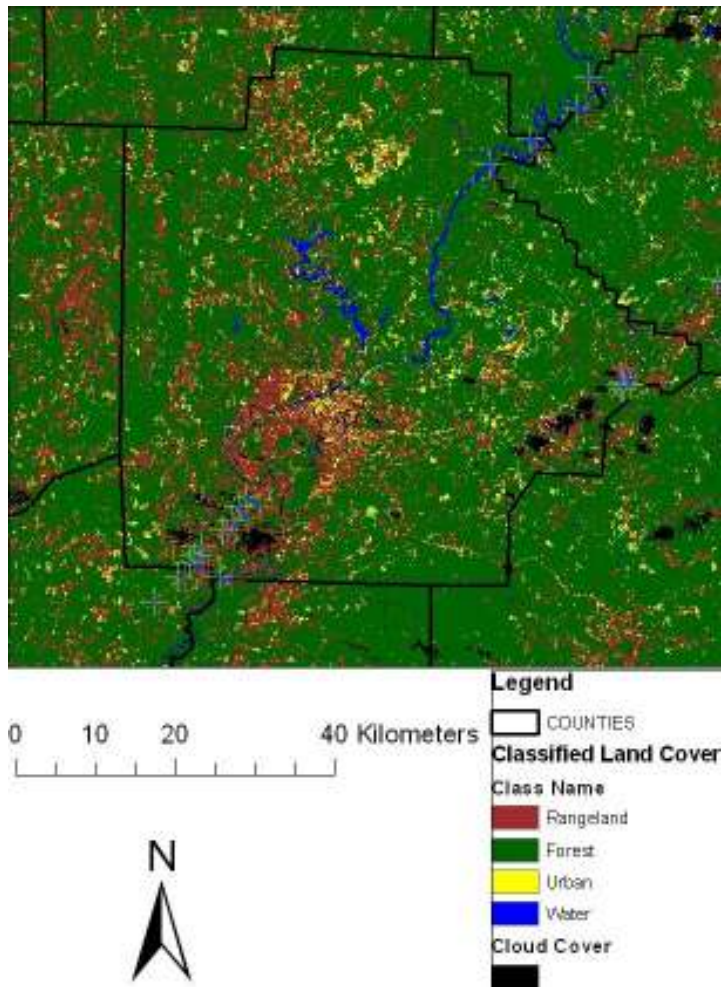


Figure 4. County vector data properly aligned with underlying raster data.

While these data provide useful information, this is the only first order station representing a large north to south expanse in West Central Alabama, which leaves much to be desired when examining precipitation patterns in a region with diverse weather activity. The following section will highlight how estimated precipitation data is used to account for this lack of ground reference information.

c. Multi-Sensor Precipitation Data

One of the problems with conducting a precipitation distribution study over the Tuscaloosa area is the lack of ground reference locations. However, to compensate for the lack of

ground reference points this thesis chose estimated precipitation data made available by the Advanced Hydrologic Prediction Service (AHPS). Precipitation data are quantified by examining rain reporting gauges and estimates from radars and satellites. The AHPS maintains an archive of these data in a compressed format.

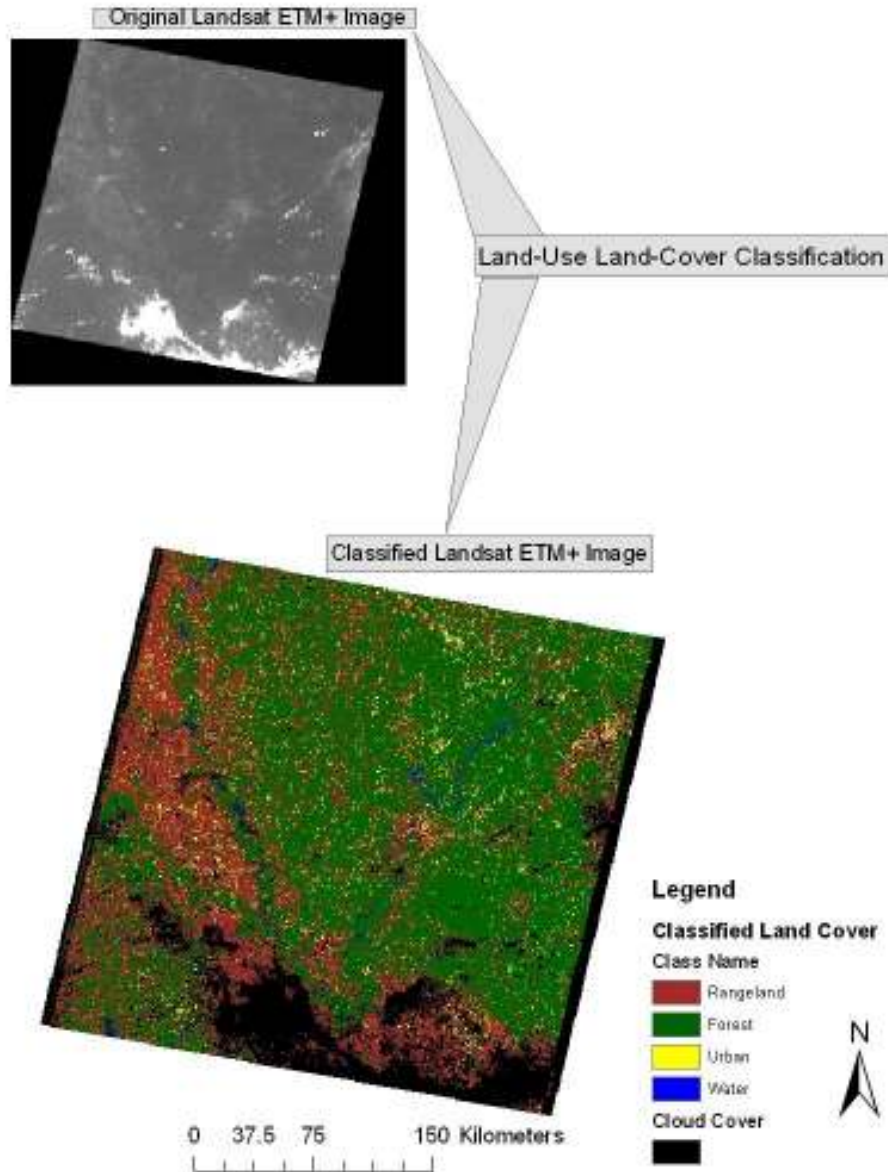


Figure 5. Original Landsat 7 (ETM+) data from 25 June 2001 is used to perform a land use/land cover classification. Land cover classes include rangeland, forest, urban, and water.

These data are collected by 12 River Forecast Centers (RFCs) and when extracted, estimates are displayed in a gridded format with bins containing a spatial resolution of 4 km² (NWS 2010).

The RFCs collect precipitation data using an application known as the Multi-Sensor Precipitation Estimator (MPE) algorithm. The MPE application utilizes data derived by Weather Surveillance Doppler Radar (WSR-88D). This remote sensing tool provides spatial detail that is unmatched by simple observational gage methods (Lawrence et al. 2003). The WSR-88D contains a Radar Product Generator (RPG) that applies a Z-R relationship (Table 1) to a raw radar reflectivity field (Lawrence et al. 2003). The reflectivity is a measure of the efficiency of a radar target in intercepting and returning radio energy, dependent upon the size, shape, aspect, and dielectric properties of the target (Glickman 2000).

Z-R Relationship Equation	
Z = Reflectivity	$Z = AR^B$
R = Rate of precipitation	
A and B = Adjustment coefficients based on type of precipitation event and time of year.	

Table 1. The Z-R relationship equation: the rate of precipitation as a function of radar reflectivity (Lawrence et al. 2003)

RPG data are distributed in a DPA (Digital Precipitation Array) product, a 131 x 131 array of grid boxes that utilize the Hydrologic Rainfall Analysis Project (HRAP) grid, which contains an array of 4x4 km² recti-linear grid bins based on the polar stereographic projection (Lawrence et al. 2003). Because of the changing season and the type of precipitation, as

indicated by the A and B coefficients, observations from rain gages are used as ground reference data (Lawrence et al. 2003). These data are used to compute a correction factor which is applied to the radar data, resulting in a multi-sensor field (Seo et al. 1999). The MPE data are monitored hourly for quality control and in some instances radar data may be replaced by Satellite Precipitation Estimates (SPE), in the event no radar coverage is available (NWS 2010).

According to Breidenbach and Bradberry (2001), the MPE produces the most accurate and highest resolution gridded estimates of rainfall. Also, when compared to raw radar mosaics and bias-corrected radar mosaics, MPE data had the smallest root mean square error and highest correlation with precipitation gauges. For example, precipitation estimates from Hurricane Floyd, obtained from the Mid-Atlantic RFC, revealed a 0.77 correlation coefficient using raw radar estimates when using the MPE this correlation was increased to 0.91 (Breidenbach and Bradberry 2001). However, there are weaknesses associated with the chosen data. First, the precipitation data are based on radar estimations. Correction factors are applied in an effort to resolve radar errors such as beam blockage, hail contamination, anomalous propagation, non-precipitation echoes, bright banding, range degradation, algorithm errors, and improper Z-R relationships (Murphy and Pavelle 2010). Secondly, ground reference data used for HRAP quality control may sometimes be inaccurate as a result of faulty surface instrumentation (Murphy and Pavelle 2010), although cooperative observer reports are included to compensate for erroneous data related to instrumentation. When considering the study area, HRAP provides an excellent spatial sampling across an otherwise instrument-void study region. The following section will highlight the methods involved with downloading, extracting, and inputting this HRAP data for analysis.

d. HRAP Data Analysis

The HRAP grid data was obtained at the Advanced Hydrologic Prediction Service (AHPS) website (AHPS 2010). The HRAP gridded rainfall data can be download in a compressed format by querying associated fields in a web based form (Figure 6). Grid data were downloaded into organized folders by date and once downloaded, each file was uncompressed twice to reveal the shapefile compatible with ArcMap.

The screenshot shows the AHPS website interface for downloading gridded rainfall data. The page title is "Downloading Gridded Rainfall Data" and it shows a last update of "02/18/2010 19:26 GMT". The interface includes a navigation menu with options like "Home & Forecasts", "Graphical Forecasts", "National Maps", "Radar", "Water", "Air Quality", "Satellite", "Climate", "River Observations", "River Forecasts", "Precipitation", "River Download", and "Other Information". Below the navigation menu, there are tabs for "Images", "Download", "About NWS Precip Analysis", "Other Useful Information", "Survey & Feedback", and "Regional / RFC Precip Data".

The main content area is a form for downloading data. It has four numbered steps: (1) Choose Format, (2) Select Download, (3) Select Date, and (4) Press the "Download" Button. Under (1), there are radio buttons for "Shapefile" (selected) and "netCDF". Under (2), there is a dropdown menu for "Continental U.S. & Puerto Rico Legend File". Under (3), there are dropdown menus for "Feb", "18", and "2010". Under (4), there is a "Download" button.

Below the form, there is a table showing the files included in the download:

File Name	Files Included	Size
nws_precip_20100218.tar.gz	nws_precip_20100218.shp nws_precip_20100218.shx nws_precip_20100218.dbf	Approx. 0.5 to 7.0 MB

The data source is listed as <http://water.weather.gov/download.php>.

Below the screenshot, there are two callouts: "Unique Grid Point ID Value" pointing to the 'id' column in the table below, and "Globvalue=24-Hour Precipitation" pointing to the 'Globvalue' column.

The table below shows the attributes of a specific grid point (id=1572):

ID	Shape	id	Hraps	Hrpy	Lat	Lon	Globvalue
0	Point	1572	535	11	24.8422	-100.18	0
1	Point	1573	536	11	24.8395	-100.12	0.07
2	Point	1574	537	11	24.8367	-100.05	0.05
3	Point	1575	538	11	24.8339	-100.05	0.21
4	Point	1576	538	11	24.8311	-100.02	0.25
5	Point	1577	540	11	24.8282	-99.984	0.31
6	Point	2524	538	12	24.872	-100.12	0.04
7	Point	2525	537	12	24.8692	-100.08	0.04
8	Point	2526	538	12	24.8664	-100.05	0.09
9	Point	2527	538	12	24.8635	-100.01	0.15
10	Point	2528	540	12	24.8607	-99.981	0.16
11	Point	2529	541	12	24.8578	-99.945	0.04
12	Point	3575	536	13	24.9044	-100.12	0.03
13	Point	3576	537	13	24.9017	-100.08	0.04
14	Point	3577	538	13	24.8989	-100.04	0.05
15	Point	3578	538	13	24.896	-100.01	0.07
16	Point	3579	540	13	24.8932	-99.978	0.06
17	Point	3580	541	13	24.8903	-99.942	0.02
18	Point	3581	542	13	24.8874	-99.906	0
19	Point	4726	536	14	24.9389	-100.11	0.01
20	Point	4727	537	14	24.9342	-100.06	0.01

Figure 6. Precipitation data collection and attributes associated with grid points.

Five years worth of data were downloaded covering the warm season months of June, July, and August.

Once downloaded and extracted, each shapefile contains an attribute table (Figure 6) that reveals an identifying value for each grid bin (*id*), a north-south column number associated with the HRAP grid cell (*hrapx*), an east-west row number associated with the HRAP grid (*hrapy*), latitude of the HRAP grid point (*latitude*), and longitude of the HRAP grid point (*longitude*). The attribute data also contains a 24-hour precipitation value in inches that represents a 12 UTC to 12 UTC hydrologic day (*globvalue*). The Zulu Time (UTC) scale correlates to a morning end time for the 24 hour rain record within the study area. This 24-hour system is a standard method in river modeling known as the hydrologic day (Murphy and Pavelle 2010; NWS 2010). It is important to note however, that the rainfall days examined in this study represent 24-hour totals that range from 7 a.m. to 7 a.m. CDT. As an example, a bulk of the precipitation estimated for Tuesday should contain precipitation measured on the preceding Monday afternoon. The time variable is not an issue with regard to statistical comparisons based on groupings. This is an issue when evaluating select days and adjustments to account only for specific 24-hour hydrologic days are performed as needed.

Within ArcMap, the theme directory was pointed to the structure associated with daily precipitation shapefiles. Once opened, each shapefile or theme revealed a dense network of grid points covering the entire United States (Figure 7). Each shapefile theme is displayed in a HRAP polar stereographic projection using a spherical earth datum centered at 60° North and 105° West, which is unrecognized by ArcMap (Dyer 2009; NWS 2010; Murphy and Pavelle 2010). Earth is accurately represented as an oblate spheroid as opposed to uniform sphere therefore, if samples are obtained with regard to a spherical representation, significant distortions can be

expected when examining small study areas (Reed and Maidment 1999). According to the NWS (2002), a projection correction can be applied but is almost negligible at 33° North (~0.4 meters). Since Tuscaloosa is located at 33.13° North the sample points collected in the default polar stereographic projection are accepted.

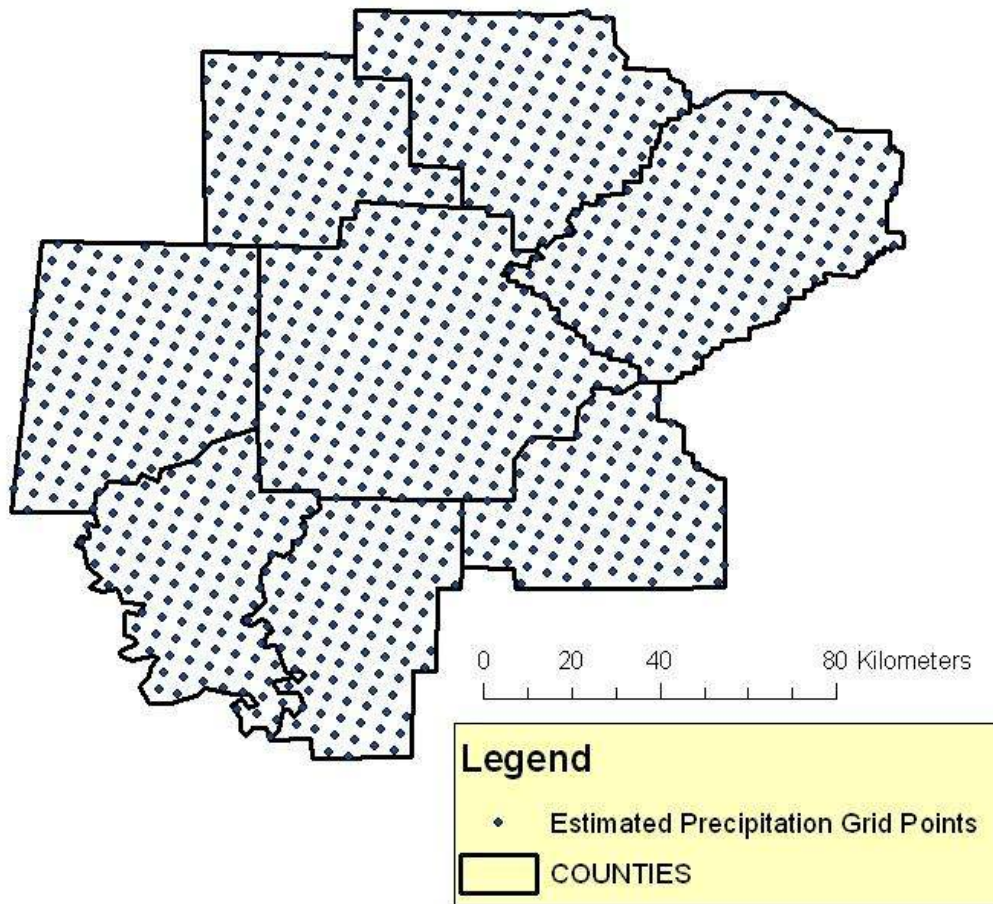


Figure 7. Example 24-hour estimated precipitation shapefile from the Hydrologic Rainfall Analysis Project (HRAP).

The method of selecting the sample locations involved the creation of a sample key theme. By using the ArcMap select by location functions on state and county themes included in the ESRI software package, a layer with the selected the study area was created. This new study area theme was referenced to the projection of the HRAP data. When precipitation is estimated in a location on a given date a grid point is made available within the HRAP data. Therefore, this

allows for GIS software to quickly determine whether precipitation did or did not occur on a particular date at a particular location. Therefore, a random HRAP theme, representing a 24-hour hydrologic day, was opened and clipped to the confines of the new study area theme. This drastically reduced the number of grid points displayed. A total of 13 grid points within the study area were selected as samples for testing. Once these sample points were identified, the unique id value for each sample was used to extract the 13 sample locations, thus creating a sample key theme (Figure 8).

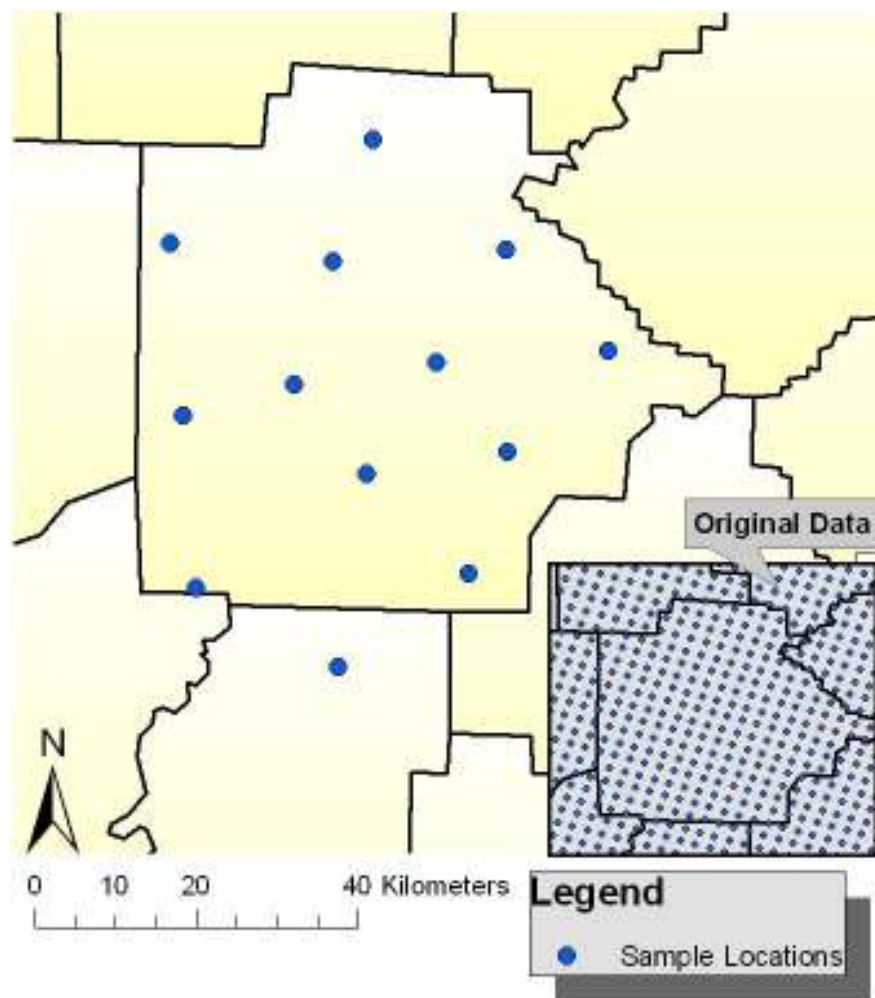


Figure 8. Random grid points are selected from the original HRAP dataset to represent sample locations. Grid point attribute data includes estimated 24-hour precipitation amounts.

The method of extracting rainfall values for each grid point per day, month, and year, was conducted by comparing daily precipitation estimate grids (shapefiles) with the sample key theme (Figure 9). The entire daily theme files were opened by month and by using the select by location function, a query was targeted to select all features identical to features in the sample key theme. This procedure successfully extracts all grid points in the daily themes in which precipitation was measured. Although 13 points are associated with the sample key, the newly created daily themes vary in the number of samples. This is the result of absent grid points on days in which no precipitation was present. A final process of grouping attribute data was performed by joining tables associated with the new themes, based off of the sample key theme, and exporting the data to an excel spreadsheet. This was repeated for all months included in the five year study period.

This section provides an overview of the methods chosen to derive a sample set of estimated precipitation data for the study area. After the precipitation data was extracted, further organization was necessary to prepare the precipitation data for statistical analysis. This involved organizing the precipitation data in spreadsheets by using the excel program and inputting the data into the statistical analysis program (SPSS). The following section will further detail the statistical tests chosen for comparative analysis.

e. Precipitation Data Statistical Procedures

Various nonparametric statistical tests were conducted on the organized precipitation data. Using the statistical analysis program SPSS, a two part test was conducted to compare monthly precipitation totals by site and daily precipitation totals by site. Another statistical test was conducted to compare precipitation totals based on categorizing the precipitation data.

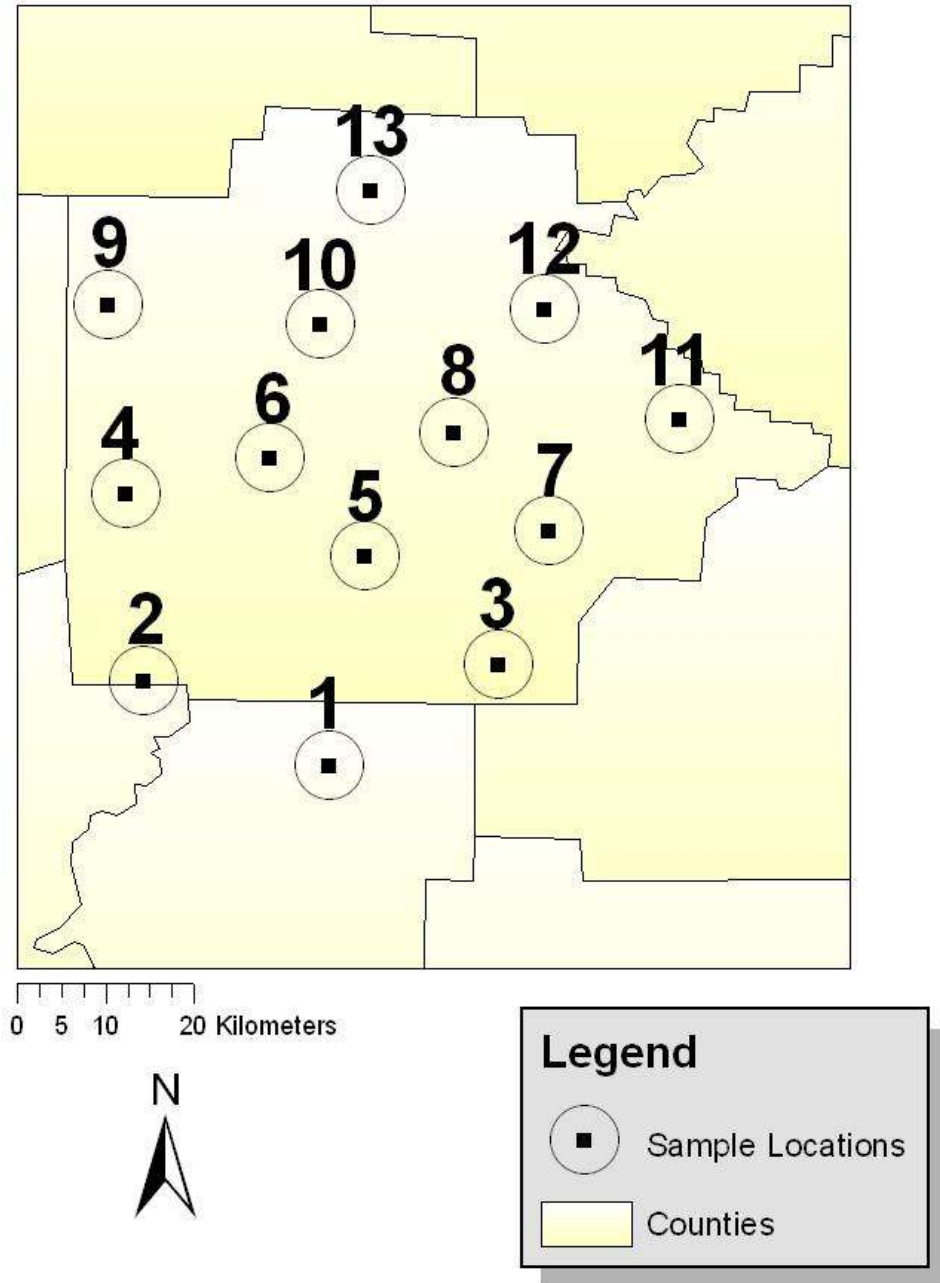


Figure 9. Random HRAP grid points are selected as sample locations, identified by a numerical value.

The reasoning for this chosen method was based on the distribution of the dataset which exhibited a positively skewed distribution because of light precipitation amounts. Since actual dates were not included in the final output of merged tables, it was chosen to categorize the data to determine possible sites that may receive light precipitation amounts as opposed to heavy precipitation amounts.

A third method involved the process of reorganizing the data and choosing maximum precipitation days. Only the top 20 maximum values for each sample site were used in performing this test. The goal of this method was to test locations that may or may not receive the heaviest daily precipitation.

In an effort to further evaluate spatial relationships within the study area (i.e. sites in central and west Tuscaloosa) precipitation data was reorganized into six groups containing three sites per grouping determined by location within the study area. A fourth nonparametric statistical analysis was chosen to examine the spatial relationships of these groups throughout the study area. The goal of this method was to uncover upstream or downstream precipitation minimums and maximums that could potentially be the result of land cover influences.

After performing statistical analysis between precipitation amounts at each sample location, these data were then compared with underlying land cover occupying the 4 km² grid bins. Estimates of the percentage of land cover occupying these sample locations were conducted by creating buffer zones which are discussed in the next section.

e. Sample Site Buffers

The process of integrating the classified image for analysis involved an approach similar to that of Kaufmann et al. (2007) in which buffers were used to determine the fraction of land cover within a predetermined distance from a central location. Because of the spatial resolution

of the precipitation data, buffers were considered when associating land cover and precipitation sample locations. The precipitation data are displayed in a gridded format, with a spatial resolution of 4 km². Although the grid bin in the HRAP data represent a rectangular area, the buffer tool in ArcMap made it possible to create 13 buffer zones with a radius of 4 km for each sample location. For quality control, the center of these buffer points were further compared to the underlying classified image by examining latitude and longitudinal positioning. The masking tool was used in ArcMap to extract the buffer zone from the classified land cover image for each precipitation sample point. This step made it possible to determine the percent of classified land cover occupying each buffer zone. These percent values were calculated using the count values located in the attribute tables associated with the buffer masks (Figure 10). The buffers associated with this classified image made it possible to determine the dominant land cover associated with the sample locations.

While this chapter has highlighted the various methods involved with acquiring, disseminating, and comparing precipitation and land cover data, additional steps were taken to further isolate days more conducive to convective precipitation development. The following section will provide an overview of spatial synoptic classification and how this was utilized in determining days more conducive to convective precipitation.

f. Spatial Synoptic Classification (SSC)

The convective thunderstorms that often occur during the summer are also termed air mass thunderstorms based on characteristics of the air mass they occupy. As noted in the previous chapter, these storms can create a high variability in warm season precipitation over Alabama. The air mass in which these convective storms evolve is termed Maritime Tropical (MT) identified by large amounts of moisture and noted by warmer temperatures.

Kalkstein et al. (1996) derived a method for classifying air mass types based on historical meteorological data. This classification method is known as Spatial Synoptic Classification (SSC). To establish the SSC, seed days were selected for locations during various times of the year. These days were selected based on ranges in afternoon surface temperature, dew point, dew point depression, wind speed, wind direction, cloud cover, and diurnal temperature range.

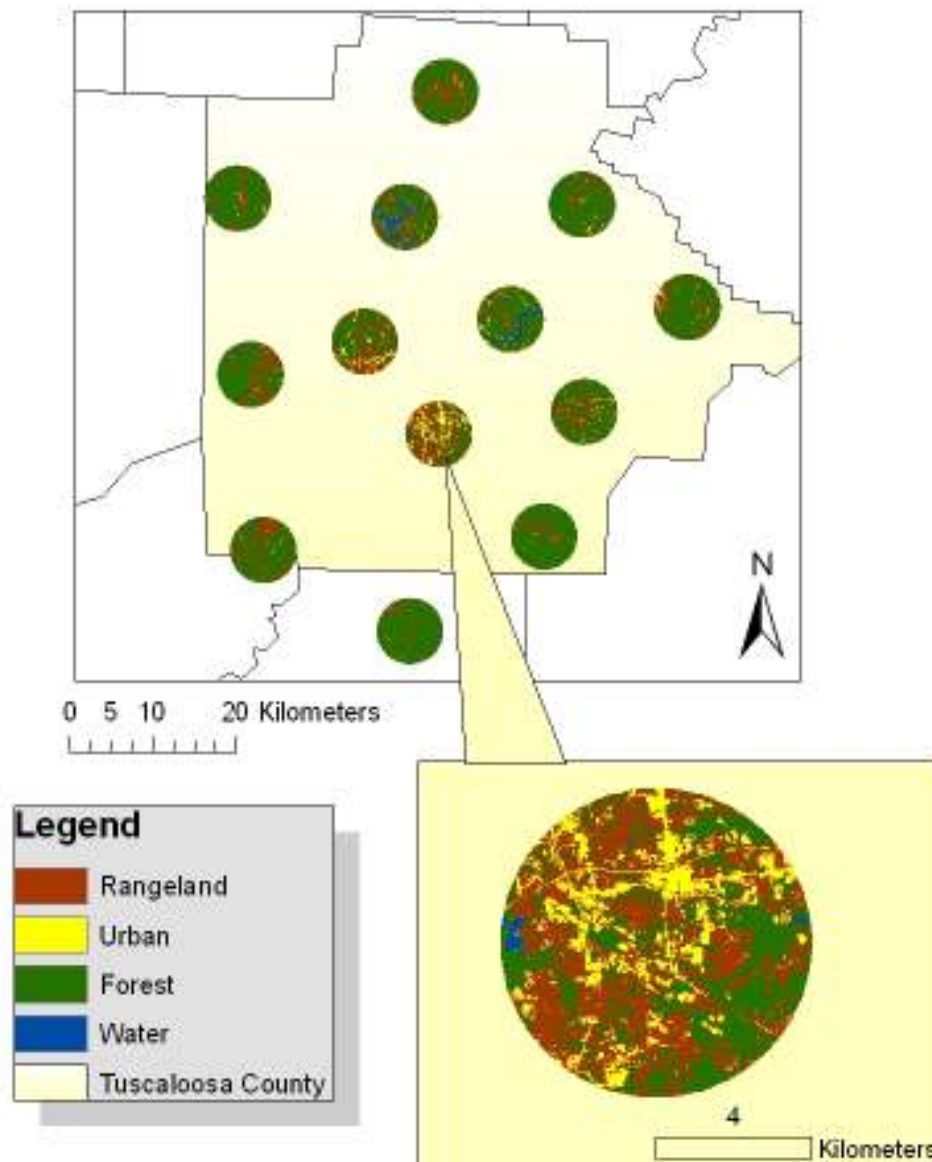


Figure 10. 4 km buffer zones are extracted from the land use/land cover classification image using ArcMap.

Additional selection criteria involved a six hour evaluation of dew point change in an effort to choose seed days not susceptible to impacts of a passing storm system. A discriminant function analysis was used to evaluate all days to determine the seed grouping of greatest resemblance (Kalkstein et al. 1996). Once this process is complete, each day is classified into a designated category. The weather types used in the SSC include DR (dry polar), DM (dry moderate), DT (Dry Tropical), MP (Moist Polar), MM (Moist Moderate), MT (Moist Tropical), MT+ 9 (Moist tropical Plus), TR (Transitional).

The SSC was updated to include all days of the year and classifications were expanded to include a broader coverage area and this redevelopment is known as SSC2 (Sheridan 2002). Sheridan (2002) notes that SSC is properly labeled as Synoptic Weather Typing and the primary weather type of interest in this thesis is that of MT and MT+. Because the MT air mass often exists in the warm subtropics, an MT+ air mass category was devised to account for lack of air mass variability (Sheridan 2002). The final method of using the SSC2 was chosen in an effort to test precipitation variability on days most susceptible to convective precipitation. This method involved classifying the air mass type of each day in the study period and organizing the precipitation data to match each weather type day. This method also considered the fact that the precipitation data was based on a 24-hour hydrologic day, which meant that precipitation totals for a particular date must be ranked with the precipitation total reported on the following date.

The final section in this chapter will highlight a final normalization technique that was applied to the precipitation dataset. Due to the small spatial scale of the study area, the result from Dyer (2009) were used to further normalize the data in an effort to provide additional evidence of anomalous precipitation distribution patterns associated with the selected precipitation sample locations.

g. Normalization

A final method of normalizing the precipitation data was chosen in which precipitation values were categorized based on a reference dataset. The motivation behind this method was the availability of a detailed map of average daily precipitation created in a former study by Dyer (2009). The average 24-hour precipitation amounts defined by Dyer (2009) were used as reference in categorizing precipitation data used in this study. It was a goal to determine if certain sample sites were favorable areas for higher than average precipitation or lower than average precipitation as defined by Dyer (2009).

This method compared the 24-hour precipitation totals for each sample site with the findings of Dyer (2009) in which land surface influences on precipitation development were investigated over the lower Mississippi Alluvial Plain. This region referred to as the Mississippi Delta was found to exhibit lower precipitation amounts during the warm season, with higher precipitation amounts in neighboring locations to the east. Dyer (2009) produced a large scale map that details mean daily precipitation estimates over Mississippi and Alabama using MPE precipitation data. According to the map, daily precipitation averages over the greater Tuscaloosa included three mean precipitation contours (0.9 mm - 1.4 mm, 1.5 mm - 1.9 mm, and 2.0 - 2.4) and these three ranges were combined into a single range. These findings are results of calculations conducted over a 13-year, 5-month study period.

Data within this investigation were reorganized so that 24-hour precipitation amounts that fell below the average were identified by (1), within the average range (2), and above the average range (3). Earlier methods proposed in this chapter include categorizing precipitation amounts for each sample location by month and by day. In a similar approach, this normalization technique categorizes the precipitation data for each sample location based on reference data

obtained from Dyers study. The results achieved in this approach may support initial findings by uncovering trends in how precipitation is distributed based on an average daily precipitation reference source. The results may also differ because the lighter precipitation amounts that force a positively skewed distribution in the data will be grouped together, becoming further isolated from the heavier precipitation amounts.

In summary, this chapter provides an overview of the procedures and steps taken to gather and calibrate precipitation data. The statistical tests noted in this chapter will be applied to the precipitation data associated with each sample location randomly selected from the HRAP grid. Furthermore, the precipitation data will be compared with the land cover buffer zone associated with each precipitation sample location. It must be noted that land cover may not directly trigger anomalous precipitation at select sample locations but may serve to enhance precipitation amounts (i.e. Diem and Mote 2005). The following chapter will provide a detailed overview of the results of the tests and procedures associated with this methodology. Furthermore, this chapter will note whether the results of the chosen methods support or reject the proposed hypothesis.

CHAPTER 4

RESULTS AND DISCUSSION

One of the goals of this thesis is to evaluate a possible influence of varying land cover on the distribution of warm season precipitation in the greater Tuscaloosa area. The previous chapter discussed the methodology used to test whether anomalies exist within the study area. This chapter will provide a detailed overview of the results of several tests that were conducted by comparing estimated precipitation data for 13 sample locations. Furthermore, this chapter will provide an overview of how these data compared to buffers containing classified land cover within the study area. Several tests conducted involved statistical applications using the Statistical Package for the Social Sciences (SPSS) program. This chapter will provide the results of the various statistical tests that compared daily and monthly precipitation totals for the five year study period. The first section will provide the results of the buffering technique applied to extract percentages of land cover associated with each sample location.

a. Land Use/Land Cover Analysis

Before the precipitation totals were analyzed, the proportion of land cover type occupying the areas represented by the precipitation data was determined. Using an approach similar to Kaufmann et al. (2007), buffers were used to calculate the percent of land cover within the 4 km² areas being represented by each HRAP grid point (Figure 10). Although this proximity-based approach computed land cover percentages based on a circular area as opposed to a square grid bin, this method made it possible to provide a more discrete representation of land cover proportions (i.e. urban versus forest) for precipitation values representing each sample

location (Figure 12). The estimated precipitation data representing each sample location will be further discussed in the following sections. The results presented in this section include the relationships between land cover type and the select sample locations.

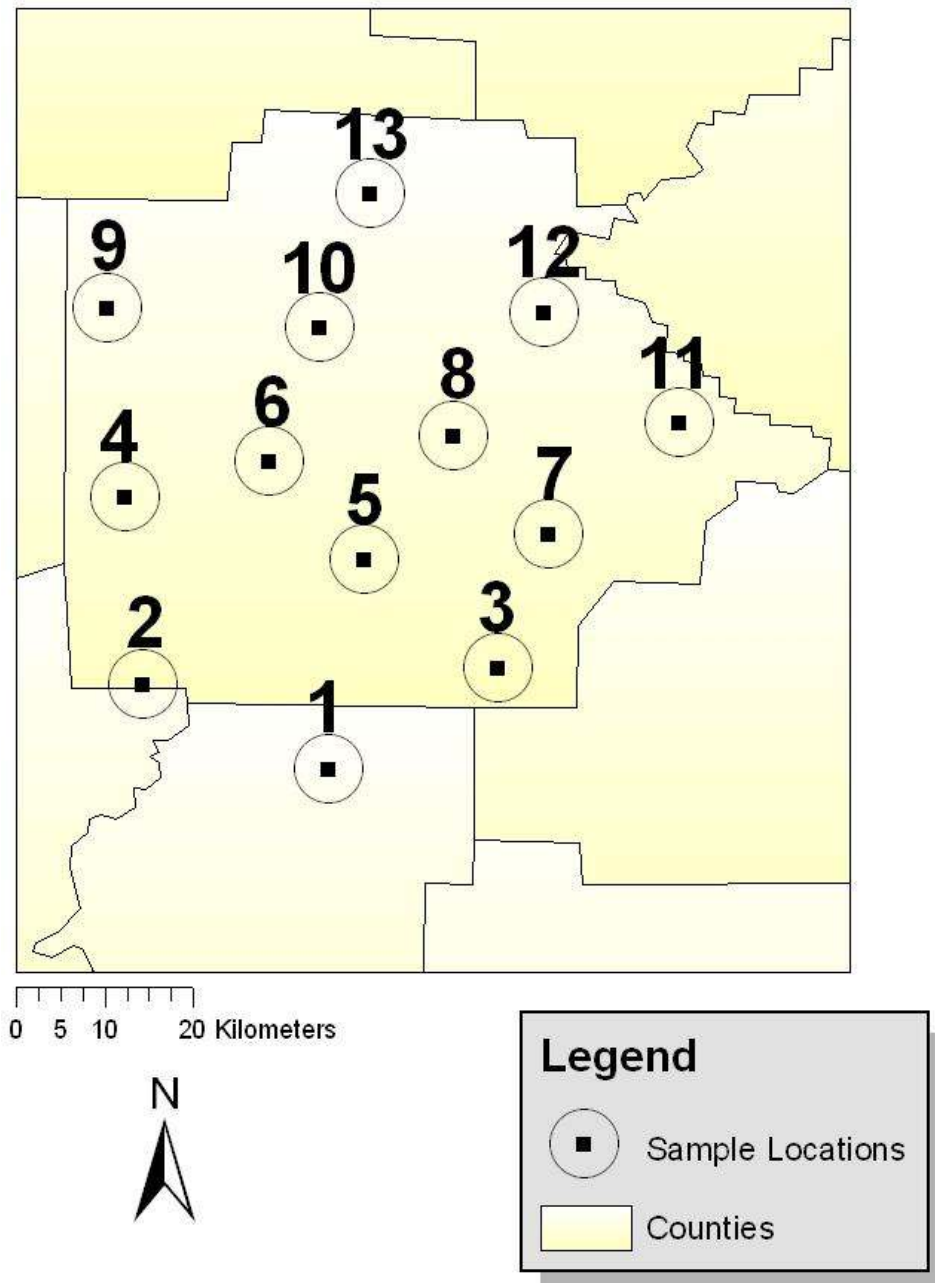


Figure 11. Sample locations and numerical identification values.

Using the buffering technique outlined above, forest cover was noted as the dominate land cover type (Figure 12). The higher percentage of forest cover (over 50% for 12 of the 13 sample buffers) was due in part to the chosen study area, level of classification (only four categories), chosen sample locations, and the imagery from the Landsat Enhanced Thematic Mapper Plus (ETM+). Outlying portions of the study area are heavily forested with a higher percentage of rangeland (35% to 50%) and urban cover (7% to 18%) in and around the city of Tuscaloosa. By choosing only four class categories, there is a chance that some pixels may have been assigned to the wrong class. For example, pixels associated with the rangeland classification may have been included in the forest grouping. While the buffering method used in the initial analysis could be considered course, the classification scheme successfully distinguished sites with proximity-based land cover proportions notably different from the others. For example, the percentage of forest cover is much lower for sample locations 5 (33.79%) and 6 (55.10%) located in the center portion of the study area (Figure 12).

Table 2 shows the sample sites associated with the top four percentages of each land cover class. The highest percentage of urban and rangeland land cover between all sample sites was located within the buffer of sample site 5 (rangeland 47.49% and urban 17.92%). Rangeland was selected in the initial classification because it includes the various land cover comprising the transitional zones, including grasses and various agricultural areas, which includes urban-recreational grasses and pasture lands. Of all sample locations, the buffer zone for site 6 contains the second highest percentage of the rangeland (36.55%) and urban (7.59%) land cover. Therefore, samples 5 and 6 are of great interest because of the noteworthy differences in land cover occupancy as compared to all other sample sites.

These two sites contain the complex urban terrain noted by Changnon (1976) that could theoretically enhance or suppress precipitation development.

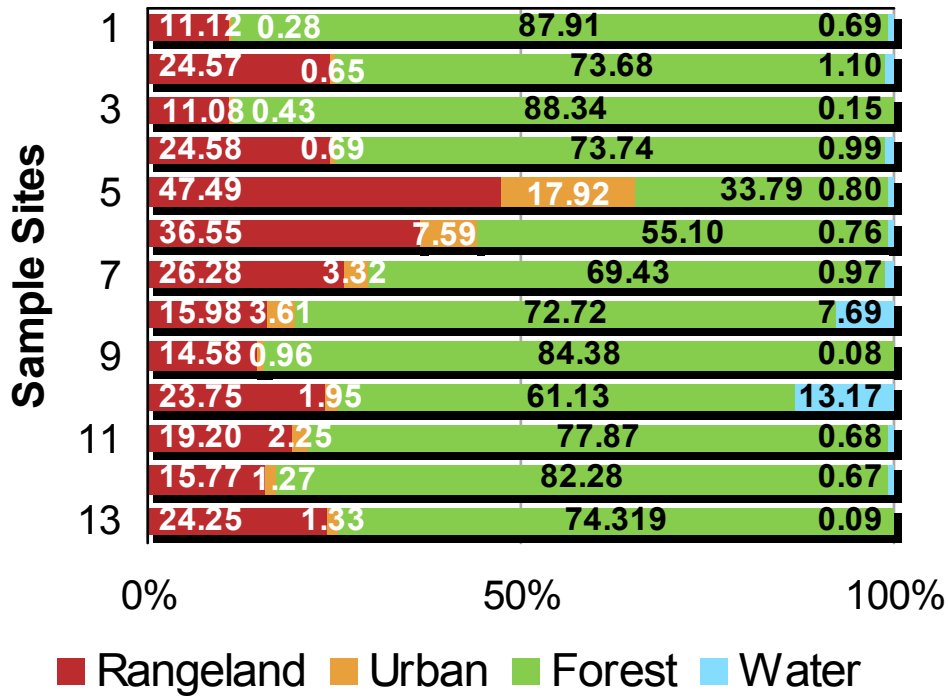


Figure 12. Percent land cover within 4 km² buffers for sites 1 through 13.

The coarse classification in this section is similar to the one chosen by Brown and Arnold (1998) in which only three land cover classification categories were created to represent agricultural, urban, and forest. Their classification approach was used for a much larger study area to evaluate land surface-atmosphere interactions in Illinois. Doran (1992) analyzed large surface areas in which energy fluxes were evaluated based on a distinct land cover type occupying 10 km or

greater. However, on a much smaller scale, Dixon and Mote (2003) used a subset of the Atlanta area to create four classes of land cover type: high-density, low-density, non-urban, and water cover. It is important to note that Dixon and Mote (2003) analyzed sub-classes of urban land cover type while Brown and Arnold (1998) further analyzed sub-classes of agricultural land cover type. Because the landscape within the chosen study area does not include a major metropolitan area or large agricultural plain, the method of using buffers made it possible to create uniform land cover proportions for comparative analysis. While the interior sample sites 5 and 6 revealed the highest percentages of the urban and rangeland class (Figure 12), due to the buffering technique the land cover associated with these zones are evaluated based on occupancy as opposed to uniformity. A comparison of precipitation values between the interior and outlying site locations should help determine if there is enough land cover complexity to possibly influence precipitation distribution. The next section in this chapter will highlight the results of the first statistical test performed by comparing monthly precipitation amounts and the 24-hour precipitation amounts during the five year study period.

Land Cover	Rank I	Rank II	Rank III	Rank IV
Forest	Site 3 (88.34%)	Site 1 (87.91%)	Site 9 (84.38%)	Site 12 (82.28%)
Water	Site 10 (13.17%)	Site 8 (7.69%)	Site 2 (1.10%)	Site 4 (0.99%)
Rangeland	Site 5 (47.49%)	Site 6 (36.55%)	Site 7 (26.28%)	Site 4 (24.58%)
Urban	Site 5 (17.92%)	Site 6 (7.59%)	Site 8 (3.61%)	Site 7 (3.32%)

Table 2. Top four land cover type percent concentrations and associated sample sites.

b. Monthly and Daily Precipitation Totals Test

The first two statistical tests conducted in this thesis compared precipitation totals that were extracted from the Hydrologic Rainfall Analysis Project (HRAP) grid data. Although these precipitation totals represent an estimated value for a 4 km² grid bin, Mearns et al. (1995) suggests such values can be viewed as discrete precipitation observations. The attribute tables for each of the 13 sample sites across the entire study period were grouped into one table and data were reorganized into two spread sheets. The first spreadsheet was organized to include the month, year, site number, and monthly precipitation total. The combined dataset was highly dominated by lighter precipitation values resulting in a positive skewed or gamma distribution. Therefore, non-parametric tests, similar to methods applied by Senkbeil (2007), were applied based on the highly skewed distribution associated with the entire precipitation dataset.

These data were evaluated using the non-parametric Kruskal-Wallis test (KW-test), because the test involved more than two populations (Burt and Barber 1996). Additionally, the KW-test was ideal for the non-normal distribution presented in this dataset. The null hypothesis (H_0) presented in this section was that the rank sums of the monthly precipitation totals at each site do not significantly differ. The alternative hypothesis (H_a) was that the rank sums of the monthly precipitation totals at each site do significantly differ. The KW-test did not reveal a level of significance ($p \leq 0.05$) in precipitation data considering monthly groupings. The lack of statistical significance was likely attributed to a smaller sample set and resulting lack of variation. Therefore, based on monthly precipitation totals there was not a statistically significant difference in precipitation totals between the 13 sample locations.

Given the availability of data, the HRAP grid contained five years of data. Therefore, to provide a more substantial sample size for testing, 24-hour precipitation amounts for each site

were tested. By increasing the sample size, there is also a lower probability of obtaining relationships by chance. The attribute data from the merged tables associated with each site were reorganized into a spreadsheet including the month, year, day, site number, and precipitation value per 24-hour hydrologic day. A second KW-test was conducted to observe significant trends between all sites (Table 4). The null hypothesis (H_0) presented in this test was that rank sums of the 24-hour precipitation totals for each sample site do not significantly differ. The alternative hypothesis (H_a) was that the rank sums of the 24-hour precipitation totals for each sample site so significantly differ. Assuming a level of significance ($\alpha = 0.05$), H_0 was accepted since the KW-test revealed $p = 0.355$ (Table 3).

While the KW-test did not reveal a statistically significant difference in 24-hour precipitation amounts among all sample sites, a lowest rank sum is noted at sample site 5, which contains the greatest percentage urban and rangeland land cover (Table 2). The sites with the two highest rank sums are 2 and 11, sites southwest and east of site 5, respectively (Figure 9). Because the KW-test calculations present interesting disparities in rank sums, a second non-parametric test was selected to independently evaluate the 24-hour precipitation totals at sample site 5 and neighboring sample sites. The Mann-Whitney-Wilcoxon test (MWW-test) was selected for pairwise comparisons because it evaluates two sample populations (Burt and Barber 1996). The H_0 in this test was that the 24-hour precipitation rank sums are the same for two sample locations; the H_a in this test is that the 24-hour precipitation rank sums significantly differ between sample sites locations.

Sample Sites	N	Rank Sums
1	147	1078.93
2	144	1121.39
3	160	1038.94
4	161	1073.10
5	181	969.03
6	166	1070.82
7	170	1065.58
8	176	1060.91
9	147	1023.99
10	175	1104.14
11	166	1167.74
12	172	1107.75
13	173	1030.98

	Day Total
Chi-Square	13.199
Degrees of Freedom	12
Asymptotic Significance	0.355

Table 3. KW-test results for 24-hour precipitation values for each site.

Multiple MWW-tests were conducted in which 24-hour precipitation totals at sample site 5 were compared with 24-hour precipitation totals at 11 of 13 neighboring sample sites. In order to account for possible Type I Error, a Bonferroni Adjustment (Anisimova and Yang 2007) was applied in which (α) was adjusted to (α/n). Therefore, the adjustment reassigned the level of

significance to ($\alpha/n = 0.05/11 = 0.004$). The H_a in this case is still accepted for the relationships between site 5 and 11 ($p = 0.003$).

Sample Sites	Mann-Whitney-Wilcoxon Test Results
5 and 2	$p = 0.028$
5 and 12	$p = 0.035$
5 and 11	$p = 0.003$

Table 4. Significant Mann-Whitney test results from comparing 24-hour precipitation amounts at site 5 and surrounding sample locations.

Based on a MWW-test, there is a statistically significant difference in the rank sums of the 24-hour precipitation amounts at sites 5 and 11. Without correcting for possible Type I Error, Table 3 reveals the MWW-test results with ($p \leq 0.05$) for sites 5 vs. 12 and 5 vs. 2. Since the strongest statistical significance ($p = 0.003$) from the MWW-test was found between sites 5 and 11, a Kolmogorov-Smirnov non-parametric test, examining frequency distribution as opposed to rank sum, was conducted. This test (5 versus 11) also yielded a statistically significant value ($p = 0.002$). This non-parametric test was conducted to further support the results of the MWW-test.

The MWW-test only revealed a significant difference in rank sums between sites 5 and 11 and it is important to note that there was no statistical significance between sites 5 and 8 ($p = 0.169$) and 5 and 7 ($p = 0.163$). A test that may have yielded a statistical significance between the interior sites (i.e. 5 and 7, 5 and 8) would be of great interest regarding the immediate downwind proximity to the greatest urban cover (Figure 11). However, it is interesting to note the low rank sum at site 5 as compared to the respective upstream and downstream sample locations 2, 11, and 12.

The next section in this chapter will highlight why a ranking of the 24-hour precipitation amounts was applied and this section will also highlight the results of the statistical tests used to compare these data.

c. Precipitation Category Test

The next test in this study evaluated categorized 24-hour precipitation data for each sample location to determine if more intense or lighter 24-hour precipitation amounts are favored at certain sample locations. The 24-hour precipitation test in the previous section evaluated the dataset as a whole; however, the goal of this test is to determine if lighter 24-hour precipitation totals are associated with select sample locations or if heavier 24-hour precipitation totals are associated with select sample locations.

Variations in land cover type between urban and rural environments have been linked to precipitation increases and decreases over space-time (Changnon 1976; Huff and Changnon 1973). It is possible that the higher rank sums, as noted in the previous section, may be a result of more light to moderate 24-hour amounts as opposed to a small number of extreme 24-hour precipitation amounts. Since total 24-hour precipitation amounts evaluated in the previous section rank higher for sites upwind and downwind of sample site 5 (Figure 11), this test based on categories will determine if heavier 24-hour precipitation totals exists upwind or downwind of site 5. In addition, this categorical test will determine if heavy or lighter 24-hour precipitation amounts favor other sample locations. Schumacher and Johnson (2006) note that fixed thresholds, like the ones applied to categories in this analysis, can reveal the frequency of an amount of precipitation from one location to the next. Furthermore, high precipitation totals can equal lighter precipitation accumulated over multiple days (Okabe 1995). By applying categories, high and low 24-hour precipitation amounts can be further distinguished for

comparisons between each sample site. The thresholds used to categorize the precipitation data are provided in Table 5. These categories were chosen based on a range of QPF categories used by forecasters at the National Weather Service and similar to the one used by Sisson and Gyakum (2004).

The merged attribute tables associated with each precipitation layer were organized to include sample location, the daily precipitation category, year, and month. Because of the uneven distribution associated with this test, another non-parametric KW-test was performed. The H_0 presented in this test was that the monthly precipitation categories rank sums do not significantly differ between all sample locations. The H_a was that the precipitation category rank sums for all sample locations differ. The asymptotic significance with this test was lower when compared to the test of the 24-hour precipitation amounts ($p = 0.088$). While there is a greater significance in the results of this test as compared to the test examining actual 24-hour precipitation estimates, the result ($p > 0.05$) allowed the H_0 to be accepted (Table 6).

No statistically significant difference between 24-hour categorized precipitation amounts can be reported, although there are noted differences in rank sums. For example, according to table 6 the lowest rank sum values are noted at sample sites 1, 3, and 9. The highest rank sums are noted at sites 10, 11, and 12. Sites 1 and 3 are located in the southeast portion of the study area (Figure 11) and site 9 is located in the far northwest corner of the study area. These three sites contain the greatest percentage of forest land cover (Table 2). Sites 11 and 12, with the highest rank sums, also contain a high percentage of forest cover (Figure 12). The sites with the highest rank sums however, contain greater percentages of urban, rangeland, and water land cover as opposed to the sites with lowest rank sums dominated by forest land cover type (Figure 12).

Precipitation Amount Category	Precipitation Category Amount (mm/in)
1	Equal To or Less Than 6.35 mm (0.25 in.)
2	6.60 mm (0.26 in.) - 12.70 mm (0.50 in.)
3	12.95 mm (0.51 in.) - 19.05 mm (0.75 in.)
4	19.30 mm (0.76 in.) - 25.40 mm (1.00 in.)
5	Greater Than 25.40 mm (1.00 in.)

Table 5. Assigned precipitation categories and precipitation amounts included in each category.

It is believed that the highly skewed categorical data were a factor in the categorical KW-test results. A MWW-test was conducted to determine if a statistically significant difference exists between the sites with the lowest and highest rank sums (1 vs. 11). The H_0 for this test is that the rank sums of the precipitation categories are not significantly different between sites 1 and 11. The H_a is that there is a statistically significant difference in the rank sums of the precipitation categories between sites 1 and 11. To account for a potential Type I Error a Bonferonni Adjustment (Anisimova and Yang 2007) was applied considering all 13 sample locations ($n = 13$). Therefore, the level of significance was adjusted ($\alpha = 0.004$). The outcome of this test found that H_0 is accepted and that a significant difference in precipitation category rank sums does not exist between sites 1 and 11 ($p = 0.005$). The test result was nearly significant, suggesting the possibility of differences in the character of precipitation (light versus heavy) at sites 1 and 11.

Figure 13 contains graphs representing each category and the number of categorical days for each sample site. For example, there are 11 category 5 days (>25.40 mm) at sample site 5.

This descriptive technique reveals that sample site 1 contains the greatest amount of days with lighter precipitation as opposed to site 11 which has the highest number of days with heavier precipitation (Figure 13).

Sample Sites	N	Rank Sums
1	279	1745.63
2	279	1782.95
3	279	1746.56
4	279	1820.60
5	279	1779.57
6	279	1813.11
7	279	1803.10
8	279	1847.36
9	279	1749.96
10	279	1900.19
11	279	1929.29
12	279	1853.87
13	279	1809.80

	Day Total
Chi-Square	19.039
Degrees of Freedom	12
Asymptotic Significance	0.088

Table 6. Results for KW-test comparing precipitation categories for each sample site.

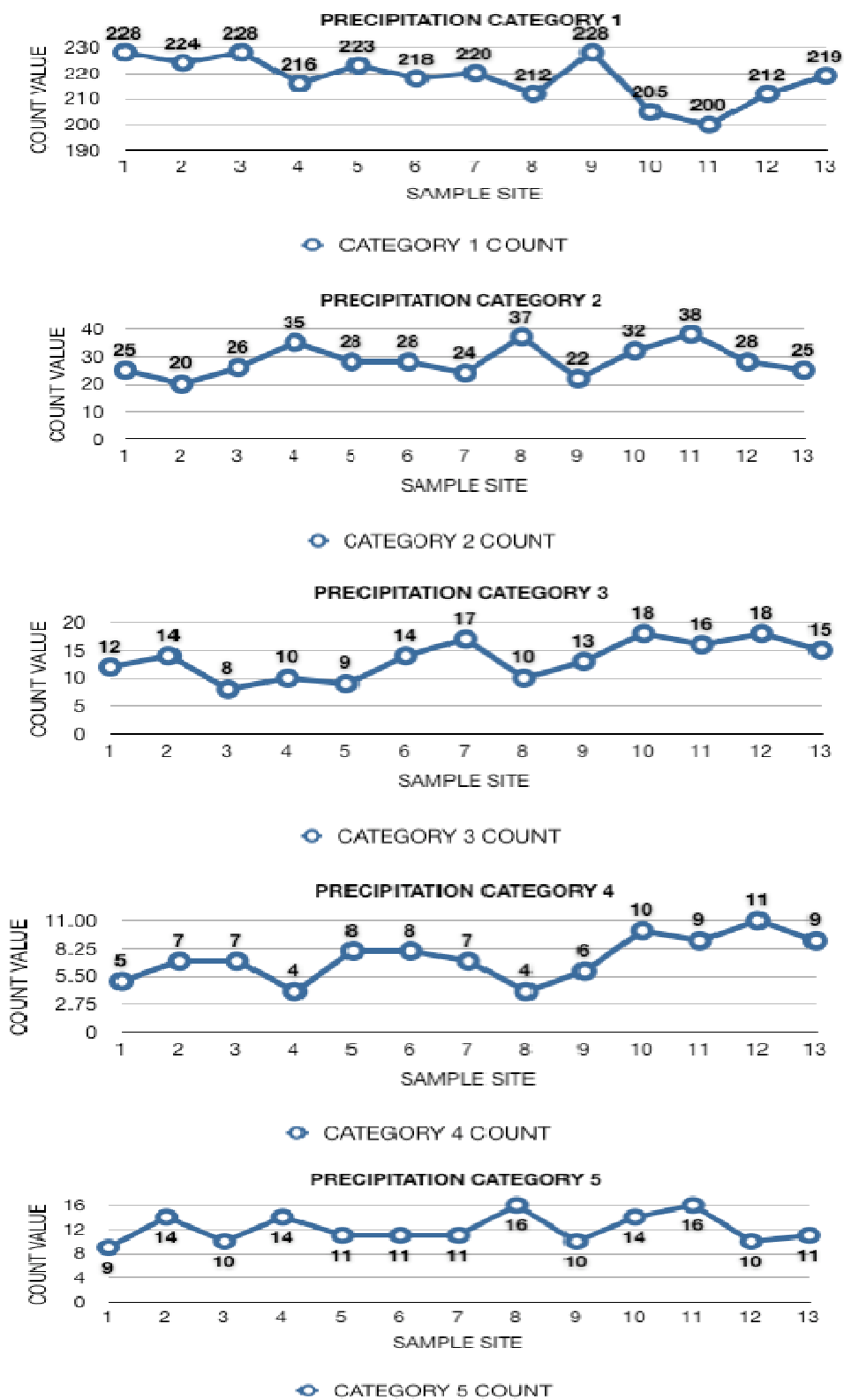


Figure 13. Number of precipitation category days for each sample site.

It is interesting to note the land cover differences between site 1 (forest 87.91%, urban 0.28%, rangeland 11.12%) and 11 (forest 77.87%, urban 2.25%, rangeland 19.2%). Site 11 contains a greater percentage of urban and rangeland when compared to site 1 (Figure 12), the location with more forest land cover. Also, sample site 1 was associated with more light precipitation days. Another interesting comparison involves other sample sites with high percentages of forest cover between site 3 (88.34%) and 9 (84.38%). These highly forested locations also have high numbers of light precipitation days (Figure 12, Figure 13). Sample sites 8, 10, 11, and 12 are similar in which there is a lower percentage of forest cover and more days with heavier precipitation. The relationship between land cover and precipitation category however, cannot be proven as statistically significant. Secondly, if such a relationship was significant, it is assumed that sample site 5 with the lowest percentage of forest cover would have few light precipitation days. Perhaps the categorical precipitation trends east of Tuscaloosa (sites 8 and 12) reveal that the site with greatest percentage of urban land cover (site 5) influences precipitation development.

It is interesting to note the increase in the number of days between precipitation categories 4 and 5 for sample sites 4 and 8. Based on precipitation categories during the five year study period, there were only 4 days in which precipitation ranged between 19.30 mm and 25.40 mm at sample sites 4 and 8. The number of days classified in category 5, representing greater than 25.40 mm, increased at site 4 (14 days) and site 8 (16 days) (Figure 13). These sample sites are located west and east of the more urbanized sample areas (sites 5 and 6). The categorical comparisons in Figure 14 suggest that higher 24-hour precipitation amounts occur west and east of the more urbanized areas of sites 5 and 6 (Figure 12). This observation is very preliminary and the next section in this chapter will provide additional insight by comparing the extreme

precipitation values between each sample site. This section will highlight the statistical procedures used to compare extreme precipitation amounts and whether significant results between all sample locations can be found.

d. Extreme Precipitation Days Test

Several methods have been applied to evaluate the temporal aspects of extreme precipitation. For example, Kunkel et al. (1994) compared extreme precipitation calculated over five year periods to determine if heavy precipitation events are more frequent; Junker et al. (1999) used extreme precipitation amounts to link areal precipitation coverage with the cause of the precipitation; and Brommer et al. (2007) evaluated the relationship between heavy precipitation and storm duration. The approach chosen in this section will evaluate the top 20 precipitation days for each sample site to determine if a statistical significance exist between the extreme totals at all sample locations. These results will then be compared to the land cover results to determine if links can be made between associated land cover and heavy precipitation characteristics. The statistical techniques used in this comparison will follow similar non-parametric statistical methods applied by Senkbeil (2007). An additional reason for examining these higher precipitation totals is that these amounts can equal lighter precipitation accumulated over multiple days (Okabe 1995). Therefore, by only focusing on extreme amounts, the test can provide a conclusion of whether the heaviest precipitation occurs upwind, downwind, or within the confines of a chosen sample location.

A KW-test evaluating the top 20 precipitation amounts for each site during the five year study period was conducted. This non-parametric test was chosen based on descriptive statistics that revealed a positive kurtosis (3.86) and positively skewed distribution (1.902). The top 20 precipitation days (greatest to least) for each sample site during the study period were inputted

into SPSS and the KW-test was conducted. The H_0 in this test was that there is not a statistically significant difference in the top 20-extreme precipitation rank sums between all sample locations. The H_a in this test is that a statistically significant difference in top 20-extreme precipitation rank sums exists between sample locations. The KW-test did not reveal a statistically significant difference ($p = 0.581$) and H_0 was accepted (Table 7).

Although H_0 is accepted, the highest rank sum is associated with site 8 immediately east of the greatest urban cover (Figure 11). This is an interesting observation because higher rank sums are also noted in the categorical test at sample sites 10, 11, and 12. By focusing strictly on the heaviest 24-hour precipitation days, the rank sum is greatest at site 8, just east of the greatest urban cover. It is important to note that the KW-test is providing a rank sum as opposed to actual precipitation mean values. While most of the results in this chapter have so far accepted H_0 , the statistical tests hint that a greater variation in rank sums occurs in areas east-northeast of the greatest urban cover. The next section in this chapter will provide the results of a test conducted for all sample locations based on spatial groupings. In addition, the section will highlight how spatial groupings were organized and test results examining the relationship between select quadrants of the study area.

e. Sample Site Groupings Test

This section will provide the results of a test between groups of sample sites based on location within the study area. Sample locations were arbitrarily chosen using a proximity-based approach and they were organized into groups of three. For example, in the eastern section of the study area, sites 2, 4, and 9 were grouped together and assigned a value (Table 8). Landin and Bosart (1985) used a grouping method to create a probability of precipitation forecast for the northeastern United States. Their groups were assigned by examining factors such as annual

precipitation, geography, and topography. This test will assign groups based on location within the study area. Each three-group sample was then compared using the 24-hour precipitation amounts over the five year study period.

Sample Sites	Rank Sums
1	107.52
2	148.60
3	115.85
4	130.50
5	122.35
6	125.72
7	119.62
8	156.45
9	111.60
10	146.48
11	149.88
12	130.75
13	131.18

	Day Total
Chi-Square	10.397
Degrees of Freedom	12
Asymptotic Significance	0.581

Table 7. KW-test for the top 20 heaviest 24-hour precipitation amounts.

Spatial Groups	Sample Sites	Location
1	2-4-9	West
2	5-6-10	Central
3	7-8-12	East
4	1-2-3	South
5	7-11-12	Far East
6	9-12-13	North

Table 8. Sample site groupings based on location within the study area.

Due to the non-parametric distribution, another KW-test was performed on the sample groupings within the study area. The H_0 for this test was that the 24-hour precipitation rank sums between groups did not significantly vary. The H_a for this test was that the 24-hour precipitation rank sums between groups did significantly differ. No statistically significant relationship was noted in this test, allowing for the H_0 to be accepted (Table 9).

An interesting observation from these results is that the lowest rank sum occurred in the central group containing the greatest percentages of urban cover (Figure 12), while the highest rank sum was evident in the far eastern portion of the study area. Higher rank sums were also associated with sites 11 and 12 in the categorical test. Over the years there has been several observation of precipitation decreasing in coverage closer to the City of Tuscaloosa. The lower rank sum associated with the central group 2 (Table 9) might suggest a change in precipitation behavior as a result of the land cover with the highest percentage of urban, rangeland, and water cover (Table 2) and lowest percentage of forest cover (Figure 12). While these assumptions can be made they cannot be statistically validated in this section.

Spatial Groups	Rank Sums
1 (West)	1468.51
2 (Central)	1433.12
3 (East)	1476.02
4 (South)	1476.99
5 (Far East)	1524.70
6 (North)	1447.15

	Day Total
Chi-Square	3.508
Degrees of Freedom	5
Asymptotic Significance	0.622

Table 9. KW-test results for the grouping test involving three sample locations per group.

A MWW-test was conducted to determine if a statistically significant difference could be found between the central group (2), with the lowest rank sum, and the far eastern group (5), with the highest rank sum. The H_0 for this test was that the 24-hour precipitation data rank sums do not significantly differ between groups 2 and 5. The H_a for this test is that a significant difference between 24-hour precipitation rank sums exists between groups 2 and 5. This test did not yield a statistically significant difference and H_0 was accepted ($p = 0.089$). Considering possible Type I Error, the statistical significance of this test is further reduced.

The statistical procedures so far have evaluated the entire precipitation dataset and examined these data categorically and by original estimated values. Due to the varying nature of precipitation intensity, extreme values were tested to determine if heavier precipitation occurred more often over certain locations. Furthermore, regions within the study area were tested in this

section for the possibility of finding locations with more frequent precipitation occurrences. According to the statistics analyses presented here, very few significant correlations can be made with the tests conducted. The temporal aspect of the precipitation will be taken into consideration in the next section which will examine days most conducive to convective precipitation development. This section will also provide the results of a statistical test comparing 24-hour precipitation amounts between each sample location on days conducive to convective precipitation development.

f. Spatial Synoptic Classification Test

The study period in this thesis was chosen because of the synoptically benign environment most favorable for random convective precipitation events. These convective events are considered because they can be triggered by small scale atmospheric processes influenced by heterogeneous land cover (i.e. Garrett 1982; Brown and Arnold 1998). The goal of this test is to examine the air mass type present on each day during the study period since these days contain the proper air mass environments favorable for convective precipitation development. It is important to note that other atmospheric parameters govern atmospheric stability such as the strength and positioning of the Bermuda High (i.e. Katz et al. 2003, Keim 1997). Garrett (1982) stated that convective storms form when the lowest level of the atmosphere is moist. In addition, Dixon and Mote (2003) determined that Urban Heat Island-induced precipitation occurred more frequently in the presence of a moist air mass. Therefore, moisture availability is an important variable in convective precipitation formation. This test utilizes spatial synoptic classification (SSC) data to determine the air mass type present on each day for the five year study period.

The air mass types considered in this test included moist tropical (MT), moist tropical plus (MT+), and moist tropical double plus (MT++). There are three tropical type air masses

because a moist air mass is often in place over the Southeast United States during the warm season. This is one reason why the southeastern United States is often termed a humid region during the warm season. The various levels of tropical air mass types are applied to isolate days with higher amounts of tropical moisture in the lower atmosphere. The original SSC (Kalkstein et al. 1996) was expanded to the SSC2 (Sheridan 2002), the SSC2 was used as the reference for determining days with an MT air mass.

The data were organized to only include 24-hour precipitation amounts for days associated with the three tropical air mass types. A non-parametric KW-test was chosen following the statistical method applied by Senkbeil (2007). The H_0 for this test was that a statistically significant difference in 24-hour precipitation rank sums for each site does not exist between the sample locations on tropically moist days. The H_a in this test was that a statistically significant difference in 24-hour precipitation amount rank sums for each site does exist on tropically moist days. By choosing only days with tropically moist air mass, the number of 24-hour precipitation samples was reduced. Otherwise, the chosen statistical method in this section is similar to the 24-hour precipitation test performed in section b.

The KW-test results yielded no statistically significant difference between all sample locations on days in which a tropically moist air mass was in place (Table 10). Therefore, H_0 is accepted. The result of this test does not suggest convective precipitation does not occur on moist tropical days but that a difference in the estimated 24-hour precipitation amounts between sample locations cannot be statistically verified given the data used in this study. There are some noteworthy trends in the rank sums between this test and the initial test that included all 24-hour precipitation amounts for each sample (section b). For example, when rank sums are organized from greatest to least for the two tests using 24-hour precipitation amounts and compared, there

is a noteworthy shift in the rankings of sample sites (Table 11). The sites with the top five rank sums (Table 11) in the SSC test are located east and northeast of the sites with the greatest urban cover (Figure 12). Figure 11 reveals that sample sites 7, 8, 10, 11, and 12 with the greatest rank sums in the SSC test are located in a part of Tuscaloosa containing higher elevations. These trends may provide some evidence of possible elevation influences. When considering all precipitation days, the rank sums for sites 1 and 2 are much greater (Table 11). Perhaps the shift in rank sums suggests a change in precipitation behavior on tropically moist days conducive to convective precipitation development. Although this test did not produce a statistically significant result, perhaps more data would yield a different result. The following section in this chapter will highlight the steps taken to normalize the precipitation data and present the results of a test comparing 24-hour precipitation amounts at each sample location based on a denser network of HRAP grid bins.

g. Normalization Test

Although addressed earlier in this chapter, the precipitation data evaluated in this study are highly skewed. The positively skewed distribution presented by the light precipitation amounts are a noted factor in several past precipitation investigations (i.e. Sisson and Gyakum 2004, Seinkbel 2007, Gutowski et al. 2007). In this section, a technique was chosen to evaluate the 24-hour precipitation amounts based on a known 24-hour precipitation average. Dyer (2009) created an image depicting an average 24-hour precipitation range for locations in Mississippi and Alabama. Although his study was focused on the Delta Region of Mississippi, the data were made readily available and served as a useful reference source for this investigation.

Sample Sites	Rank Sums
1	1342.85
2	1336.79
3	1395.46
4	1396.80
5	1413.95
6	1395.14
7	1443.00
8	1449.23
9	1323.48
10	1465.85
11	1464.75
12	1476.28
13	1420.14

	Day Total
Chi-Square	12.33
Degrees of Freedom	12
Asymptotic Significance	0.419

Table 10. Spatial Synoptic Classification KW-test results.

The 24-hour precipitation data were assigned a categorical value based on a mean daily precipitation reference source. According to Dyer (2009), 0.9 mm to 2.4 mm of precipitation occur over various portions of the study area, on average. The 24-hour precipitation amounts used in this study were then assigned a value of 1 if they were below the average, a value of 2 if they were located within the average, and a value of 3 if they were located above the average. By assigning a value to each 24-hour precipitation amount, this provided a categorical reference for comparing precipitation totals between all 13 sample locations.

Spatial Synoptic Classification Test		Test Including All Precipitation Days	
Sample Sites	Rank Sums	Sample Sites	Rank Sums
12	1476.28	11	1167.74
10	1465.85	2	1121.39
11	1464.75	12	1107.75
8	1449.23	10	1104.14
7	1443.00	1	1078.93
13	1420.14	4	1073.10
5	1413.95	6	1070.82
4	1396.80	7	1065.58
3	1395.46	8	1060.91
6	1395.14	3	1038.94
1	1342.85	13	1030.98
2	1336.79	9	1023.99
9	1323.48	5	969.03

Table 11. Top five KW-test rank sums and associated sample sites for select SSC days and all precipitation days.

A non-parametric KW-test was used to determine if the rank sums of the categorical precipitation values were significantly different between the 13 sample locations (H_a). The H_o in this test is that no statistically significant difference in rank sums of the categorical precipitation values can be found between sample locations. To help clarify this procedure, the results should determine whether some sample sites contain more precipitation amounts that fall above or below the average mean defined by Dyer (2009) also uncovering possible anomalies associated with the numerous light precipitation totals. The KW-test did not reveal a statistical significance

and H_0 was accepted ($p = 0.445$) (Table 12). The lowest rank sum in this test was associated with site 5, which suggests the site with the greatest urban concentration has the largest disparity based on an average daily precipitation total defined by Dyer (2009) (Table 12). The rank sums associated with the test in this section are also very similar to the rank sums associated with first precipitation comparison test in this chapter. Therefore, this test suggests that if a longer term dataset was used in this study there is a possibility of finding similar results.

In summary, the rank sums associated with the non-parametric statistical procedures in this chapter reveal some interesting trends. The results in this chapter are dependent on the method of using estimated precipitation data in a small study area. This data was chosen because of the lack of standard observations available in the chosen study area. The following chapter will provide a summary and conclusion, further linking the background literature, methodology, and results presented thus far.

Sample Sites	Rank Sums
1	1128.07
2	1091.17
3	1068.47
4	1078.67
5	984.90
6	1070.41
7	1078.92
8	1051.69
9	1022.48
10	1083.69
11	1141.49
12	1090.17
13	1026.58

	Day Total
Chi-Square	12.004
Degrees of Freedom	12
Asymptotic Significance	0.445

Table 12. Results for the normalization KW-test based on a pre-defined average 24-hour precipitation range.

CHAPTER 5

SUMMARY AND CONCLUSION

Within the southeastern United States, west-central Alabama is uniquely positioned to experience a variety of atmospheric phenomena throughout the year. The area is susceptible to land-falling tropical systems, severe thunderstorms, and a variety of winter weather conditions that provide a unique environment to investigate weather and climate occurrences. During the warm summer months, synoptically benign atmospheric conditions create an environment more conducive to short-lived convective thunderstorms that seem to develop in random locations. While these storms may have a short life cycle, they bring the threat of flash flooding, cloud to ground lighting, and damaging straight-line winds. When embedded in larger scale storm systems, convective thunderstorms have the potential to increase the severity of precipitation.

The atmospheric processes that govern when and where convective precipitation occurs are easier to resolve at large spatial scales. For example, the strength and positioning of the Bermuda High can often dictate if convective precipitation may or may not occur (i.e. Medline and Croft 1998), while on a much smaller scale, the degree of forecast skill becomes increasingly difficult (i.e. Charba and Klein 1980) as complex mechanisms such as differing land cover types can act to influence or initiate the development of convective precipitation (i.e. Malkus and Stern 1953; Lettau 1956; Carson and Moses 1963; Mahfouf et al. 1987; Diem and Mote 2005). Land cover can either directly influence convective thunderstorm development or indirectly influence development by way of boundaries resulting from differing sensible and latent energy fluxes (i.e. Segal and Arritt 1992; Bauman et al. 1997; Brown and Arnold 1998). Studies involving land-

atmosphere relationships have been conducted for a variety of locations including agricultural and urbanized areas (i.e. Brown and Arnold 1998; Dixon and Mote 2003). While many past studies examine larger spatial domains, this thesis examined a small to medium sized urban zone and outlying-rural locations.

One of the pitfalls of studying precipitation patterns and trends for small study areas is the lack of ground reference data. This thesis attempted to overcome this weakness by using a readily available estimated precipitation dataset constructed by the Advanced Hydrologic Prediction Service. Randomly selected grid points with attribute data containing discrete 24-hour precipitation amounts were compared through a variety of tests based on categorizations, locational distributions, and seasonality. The data format was compatible with the remote sensing and geographical information system (GIS) tools necessary to extract precipitation estimates across the study area.

The precipitation data used in this study was recorded over a three-month, five-year study period. Although intense precipitation is often associated with convective storms, the precipitation data didn't provide a large number of heavy precipitation events. In fact, light precipitation amounts outweighed the heavier precipitation amounts resulting in a positively skewed precipitation dataset. This type of distribution is not unusual however, as several studies have reported similar distribution characteristics (i.e. Sisson and Gyakum 2004; Senkbeil 2007). This study chose 13 randomly selected grid points from a dense network of grid points containing estimated 24-hour precipitation amounts over the five year study period. A buffer was created around each of these randomly selected grid points to capture specific land cover characteristics associated with each site.

Based on the three-month, five-year study period, methods, and data used in this thesis the following conclusions regarding precipitation distribution are noted:

- During the warm season, precipitation develops more often in the far eastern part of Tuscaloosa County as opposed to the city of Tuscaloosa. Otherwise, 24-hour precipitation distributions are rather uniform in areas north, south, and west of the city of Tuscaloosa.
- During the warm season, there were more days in which precipitation totals exceeded 25.40 mm west and east of the city of Tuscaloosa. However, the most extreme precipitation during the warm season was rather uniform across Tuscaloosa County. Trends in non-parametric statistical rank sums suggest some of the heaviest 24-hour precipitation over the five year study period occurred directly northeast of the City of Tuscaloosa.
- Trends in non-parametric statistical rank sums suggest areas with the greatest percentage of urban, water, and rangeland land cover in the central portion of Tuscaloosa collectively receives less precipitation than surrounding locations.
- There are no statistically significant differences in the amount of precipitation occurring at locations within the study area on tropically moist days. However, trends in the non-parametric statistical rank sums suggest the possibility of more precipitation occurring within and directly east and northeast of the city of Tuscaloosa on tropically moist days.

While the test results provide limited statistical verification, there are interesting trends in the non-parametric statistical analysis regarding the development of precipitation in and around the location with the greatest percentage of urban and rangeland land cover, the city of Tuscaloosa. In the categorical test, a greater number of days with precipitation totals exceeding 25.40 mm were reported west of the city. These higher precipitation amounts could be linked to an easterly flow pattern associated with the positioning of the Bermuda High. This east to west flow pattern, commonly observed during the second half of the warm season, could create an ideal setup for urban precipitation enhancements downwind. Respectively, the increased precipitation east of the city of the Tuscaloosa might be associated with urban enhancements associated with a west or southwesterly flow. A future study comparing the ideal conditions for the east to west flow pattern and the development of precipitation in west and central Alabama may provide additional insight into possible land-atmosphere interactions.

It is interesting to note that sample sites directly south and southwest of the city contain noticeably lower KW-test rank sums on precipitation days associated with a tropically moist air mass. When considering precipitation amounts for all days during the study period, the rank sums for sites directly south and southwest of the city are noticeably higher. These trends, based on air mass type and study period, suggest there is a possibility of less convective precipitation directly south and southwest of the city. An opposite trend was noted in which the KW-test rank sums were much higher on tropically moist days within the city of Tuscaloosa and areas directly east and northeast of the city, suggesting the possibility of more convective precipitation within and directly east and northeast of the city. When considering all days during the study period however, the lowest KW-test rank sum was in the city of Tuscaloosa. Therefore, when a tropically moist air mass is in place, it is possible that short-lived convective precipitation may

develop over the city and travel eastward or northeastward before dissipating. Future research should examine the role of elevation over different portions of the study area. Higher elevated areas are located in the east and northeast portions of the area and it is interesting to note that the top five KW-test rank sums on tropically moist days included all sample sites east and northeast of the city of Tuscaloosa.

In Chapter Four the possibility of a “weather hole” (Parker and Knieval 2005), in which precipitation was observed to develop around the city of Tuscaloosa, was addressed. When considering all days in the study period, more precipitation was observed over the far eastern portion of the study area. Since radar measurements play a major role in how the precipitation data were acquired, perhaps the higher totals over the far eastern portions of the study area correlate with the closer proximity to the National Weather Service Doppler Radar located in Central Alabama. There is a good chance that the distribution of precipitation in this study is simply random with no distinct correlations with land cover. However, after comparing land cover and precipitation data on days most favorable for convective storms, there are increases in the amount of precipitation in the city of Tuscaloosa (greatest urban and rangeland cover) and eastern locations (low percentage of urban and rangeland cover).

Parker and Knieval (2005) reported on weather holes in which weather observers often reported that thunderstorms avoided their cities. Perhaps the preliminary results in this study suggest that instead of a “weather hole,” land cover associated with the city of Tuscaloosa enhances warm season diurnal convective precipitation. A good example of such possible enhancement was presented in Chapter One, in which an afternoon thunderstorm on 11 June 2007 created significant flash flooding in downtown Tuscaloosa. While the possibility of urban enhancement cannot be proven statistically, the results in this study reveal that changes in

precipitation behavior on days more conducive to convective possibly occur. Although the results in this test are very preliminary, this study has provided a foundation for future climate and weather related investigations specific to Tuscaloosa and surrounding areas.

A recent observation of thunderstorms exhibiting a location bias was noted on 30 May 2010. Figure 14 contains composite radar imagery acquired from the Weather Surveillance Radar 88-D. On the afternoon of 30 May 2010 short-lived thunderstorms first formed in the eastern part of Tuscaloosa County, followed by development directly south, west, and north of the city. As the core of each of these storms reached a mature level, each were classified as severe by the National Weather Service Office in Birmingham. While the storm development may simply be random or triggered by an outflow boundary, it is interesting to note that the city of Tuscaloosa initially received little to no rain. The storms weakened over time and developed into a stratiform precipitation shield over the city, similar to the two stage MCS evolution described by Knupp and Cotton (1987). Future research should consider the use of radar or satellite imagery to focus only on thunderstorm initiation or cumulus cloud formation. This could provide addition detail regarding possible urban enhancement within and east of the city. This would also provide much more detail regarding stages of precipitation development that cannot be found in a simple 24-hour precipitation total.

This thesis re-affirms that warm season convective thunderstorm behavior over West Alabama is very complex. When determining if subtle changes in the behavior of these storms exists, future research should consider only choosing moist tropical days and days with marginal instability, possibly by examining the Bermuda High Index. According to Breidenbach and Bradberry (2001), the multi-sensor precipitation data produces the most accurate and highest resolution gridded estimates of rainfall. Instead of choosing random grids within the estimated

precipitation dataset, future research should consider using all grid points available in the study area. By using more data and increasing the specific criteria for convective thunderstorm days, other precipitation distribution patterns and anomalies may be discovered. Furthermore, heavy precipitation amounts should only be considered in an effort to filter out the high number of light precipitation days.

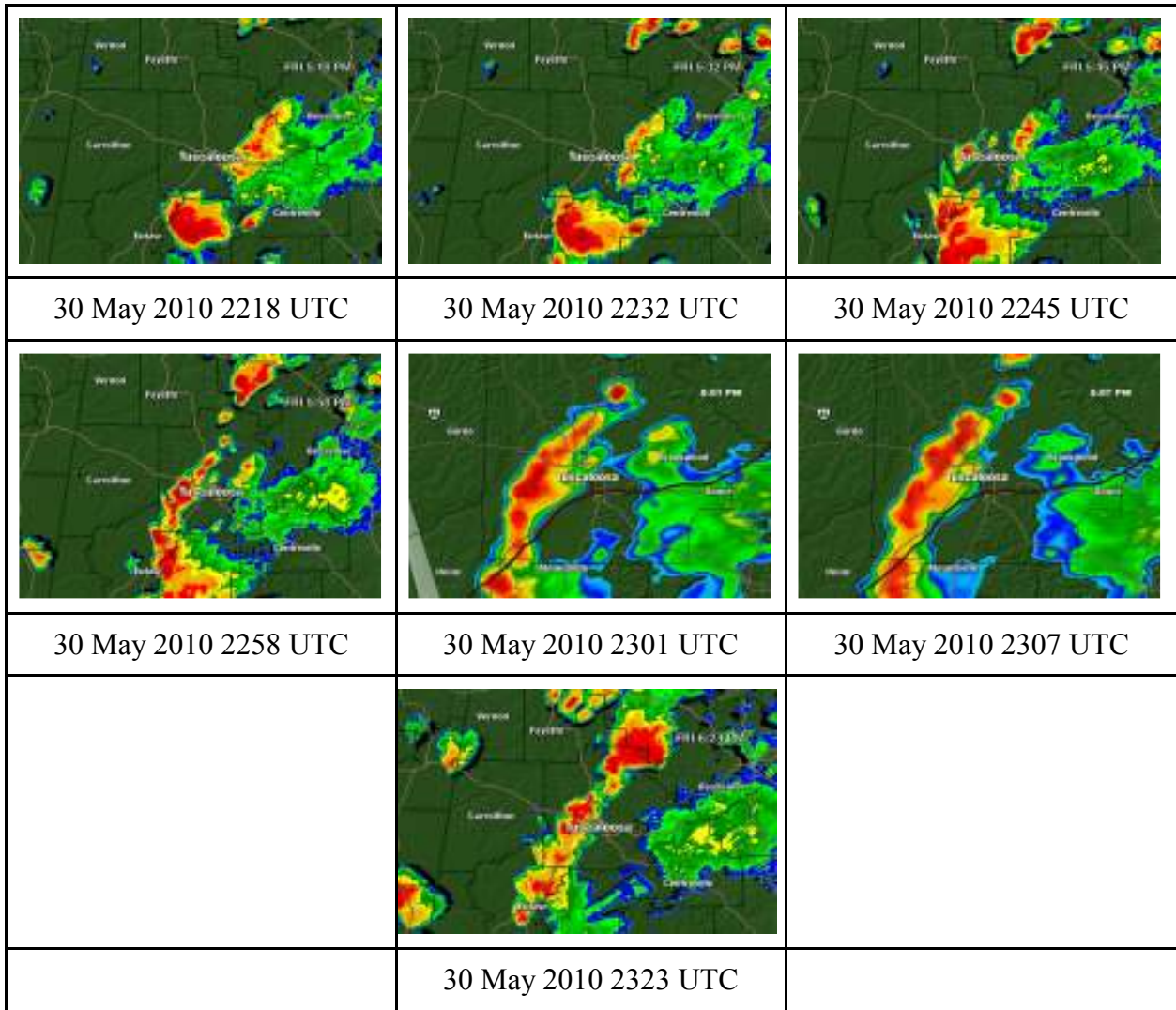


Figure 14. Images captured using Weather Centrals ESP-Live Graphics System at WVUA Television in Tuscaloosa. Data in this image was acquired by the Weather Surveillance Radar at the National Weather Service Office in Birmingham, Alabama. Images reveal storm development in areas east, south, west, and north of the city of Tuscaloosa.

This study mainly focused on the central and rural portions of Tuscaloosa County and future studies should also consider a larger study area to include more data in neighboring counties. This would allow for more precipitation and land cover comparisons to be made around the sample sites in rural portions of Tuscaloosa County.

Future studies should also consider the possibility of determining the atmospheric conditions necessary for an east to west flow pattern. Based on the positioning of the Bermuda High, convective storms during the later portion of the warm season sometimes travel from east to west. By including neighboring counties in a study, it may be possible to determine if the large metropolitan area of Birmingham is responsible for the higher precipitation totals reported in the far eastern part of Tuscaloosa County. It would also be interesting to examine weakening tropical systems after landfall which may be in the proper position to create an east to west flow over the Tuscaloosa area.

Additionally, future studies should address the potential for localized convective precipitation enhancement that occur in conjunction with land falling tropical systems. Depending on where a tropical cyclone makes landfall, these systems can vary in strength and intensity. For example, Hurricane Katrina's strength, speed, and trajectory, allowed strong tropical storm force winds to penetrate well inland causing wide-spread wind damage across the Tuscaloosa area. Hurricane Rita however, made a landfall well southwest of Alabama near Houston, Texas. On 25 September 2005 the remnants of Rita tracked north of Tuscaloosa. Increased instability due to daytime heating, tropical moisture, and strong winds above the surface, combined to produce 21 confirmed tornadoes in West Alabama, with 10 of the tornadoes occurring in Tuscaloosa County.

Considering the variety of atmospheric phenomena that occur in West Alabama, more climate and weather related investigations should be conducted. The benign setup during the warm season creates an opportunity to determine if there are subtle processes that increases the chance of thunderstorm development and the attendant heavy precipitation. The quality of future research would be greatly improved with the availability of a dense network of weather observation stations or Mesonet. Until such a dense network is made available however, future studies should resort to GIS compatible data. These resources will allow for additional weather and climate related investigations in small study areas similar to Tuscaloosa containing very few weather reporting stations.

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