THE INFLUENCE OF THE GROWTH OF THE DALLAS/FORT WORTH (DFW) METROPLEX ON REGIONAL PRECIPITATION PATTERNS

A Thesis

by

ANNA MARIE NORDFELT

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2008

Major Subject: Geography

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Approved by:

Chair of Committee,	Steven Quiring
Committee Members,	Wendy Jepson
	John Nielsen-Gammon
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ABSTRACT

The Influence of the Growth of the Dallas/Fort Worth (DFW) Metroplex on Regional Precipitation Patterns. (August 2008)

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Chair of Advisory Committee: Dr. Steven M. Quiring

Due to the effects urbanization has on land-use and land cover change (LULC), urban areas have a major influence on the environment. The strong coupling between the land and atmosphere can alter the microclimatology of cities and their surrounding regions. Previous research has shown that cities can influence regional precipitation patterns. This is a result of many factors such as: increased heating and lifting caused by the urban heat island effect (UHI), increased pollution and aerosols, alteration of land use/land cover (which includes surface albedo, presence or lack of vegetation, and surface roughness changes), and urban design (which leads to increased friction and convergence). This study analyzes temporal and regional changes in the precipitation patterns of the Dallas/Fort Worth Metroplex as it has grown over the past century, and provides a methodology for testing urban influences on precipitation in other metropolitan areas.

Precipitation from 1930 – 2007 was analyzed for the following three study regions: DFW (urban area), CRA (upwind control region), and CRB (downwind control region). By comparing early (1930 – 1950) and late period (1987 – 2007) precipitation within each region, it was found that there were no statistically significant differences between the two periods. Entire period precipitation (1930 – 2007) at CRB was statistically significantly different from both DFW and CRA although early and late period precipitation was not. While precipitation was similar between the two periods in all regions, comparing precipitation between the regions using the entire period shows potential anthropogenic influences. Land cover change between 1976 and 2001 was analyzed and it was found that water in the DFW Metroplex study region increased by 54.75%, vegetation decreased by 20.34%, and urban land cover increased by 176.14%. This may increase atmospheric moisture, surface temperature, friction and lifting over the urban center, and decrease the amount of heat released from the ground. While natural climate variability is the most important factor influencing precipitation in this region, it is possible that urbanization is also changing local and regional precipitation patterns, it may not be the only factor influencing change.

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CHAPTER I

INTRODUCTION

As urban areas continue to grow at rapid rates, the influence they have on their environment will increase in response. Arnfield (2003) states that as of the year 2000, almost half of the world's population was living in urban areas. The Dallas/Fort Worth Metropolitan region has grown by 58% since 1980 (Texas State Data Center and Office of the State Demographer (TSDCOSD)). With such dramatic growth occurring in cities globally, it is important to know how the impacts of an urban environment extend beyond the city itself into the surrounding regions. As cities continue to grow and exhibit outward sprawl, the relationship between land use/land cover (LULC) and the urban climate will be affected. Because the land and atmosphere are closely coupled, altering the land use and land cover (LULC) influences the local (micro) and regional (meso) climate.

The main purpose of this research is to determine if Dallas and Fort Worth have changed local and regional precipitation patterns as these cities have grown and merged into a single large metropolitan region. This study will improve the understanding of how urbanization influences regional precipitation patterns and provide a methodology for similar studies. Urban climate research will be beneficial as it can be used to project future changes in precipitation patterns in urban areas.

Previous research has demonstrated that urbanization tends to cause precipitation

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This thesis follows the style of Climate Research.

to increase in and around cities (Changnon et al. 1971, Huff & Changnon 1973, Shepherd et al. 2002, Diem & Brown 2003, Burian & Shepherd 2005, Shepherd 2006). Huff and Changnon (1973) have shown that this increased region of precipitation is usually found downwind (generally to the east or northeast in the United States) of the main urban center. Although urban influences have been found during all times of the year (Changnon et al. 1991), warm-season precipitation (June, July, and August) is used in this analysis because it is the season shown to be most influenced by urbanization (Diem & Brown 2003, Burian & Shepherd 2005). Since the mean wind direction during the summer is from the Gulf of Mexico (south), the theorized enhanced downwind precipitation region would be on the north and northeastern boundaries of the metroplex.

This research fills a gap in urban precipitation literature since only a few studies have undertaken a historical analysis of urban influence on precipitation (a time period greater than or equivalent to 50 years) (Diem & Brown 2003, Diem & Mote 2005, Shepherd 2006). Additionally, there has only been one study to analyze precipitation patterns in and around the DFW Metroplex using three years of data (Shepherd et al. 2002). Precipitation in DFW will be compared to the mean rainfall of two nearby less-urbanized control regions, so that any significant differences between DFW and precipitation in the control regions can be attributed to urban influences. The three main objectives of this research are:

(1) To characterize the land cover changes and urban growth in and around the DFW Metroplex

(2) To determine how precipitation in and downwind of the DFW Metroplex has changed since 1930 (a temporal analysis)

(3) To determine how precipitation in the control regions has changed in comparison to the DFW Metroplex (a spatial analysis).

It is hypothesized that downwind precipitation has increased as the metroplex has grown and become more urbanized, in spite of fluctuations caused by natural climatic variations (e.g., ENSO). It is anticipated that the region receiving the largest increase in precipitation is located downwind, and the relationship between the metroplex and the upwind and downwind control regions has changed since 1930.

As anthropogenic influences in climate studies are becoming an increasingly timely and significant issue, it is important to determine the magnitude of these roles. Due to the lack of understanding of the relationship between land cover type and local precipitation, studies such as this one are greatly needed. The DFW Metroplex can benefit from this study as it will provide a better understanding of their urban climate and lead to more efficient urban planning and water management. If the climate in and around DFW is responding to land cover changes, then these changes should be incorporated in future city planning.

CHAPTER II

LITERATURE REVIEW

Research has shown that there is a link between urban areas and increased precipitation because convective activity tends to increase in and around urban areas (Huff & Changnon 1973). There are many possible causes of this increase such as the urban heat island (UHI) effect, increased pollution, and changes in land use/land cover (including surface albedo and effects due to presence or lack of vegetation). After briefly discussing these influences, it will be shown how this research fills a gap in scientific knowledge.

2.1 Urban Heat Island

As urban areas grow, the strength of the urban heat island (UHI) tends to increase in response. As stated by Souch and Grimmond (2006), the element of urban climate most widely studied is the UHI. It is very important to understand the UHI effect when studying urban precipitation, because it has been shown that the temperature gradient between an urban area and its rural surroundings is partly responsible for precipitation initiation (Bornstein & Lin 2000, Dixon & Mote 2003).

An UHI is defined as an urban area where temperatures are warmer than the surrounding (non-urbanized) areas, and the gradient between these regions is strongest on calm, clear nights. Voogt and Oke (2003) found that an UHI moderates air temperature in the lower layers of the atmosphere and influence the energy and moisture balances at the surface (Voogt & Oke 2003). According to Arnfield (2003), the general characteristics of an UHI may vary between different cities due to differences in albedo, anthropogenic heat, emissivity, sky view factor, and thermal inertia. While these factors are important, the resistance of the surface to evaporate water was found to be the most influential factor controlling the UHI (Atkinson 2003). Hawkins et al. (2004) compared hourly temperature data from two sites in Phoenix: a rural farm southeast of the city and from Sky Harbor Airport, located in the center of the city. It was found that the average UHI effects ranged from 9.4°C to 12.9°C, confirming that Phoenix has one of the largest UHI in the world (Hawkins et al. 2004).

2.2 Pollution

The increased amount of air pollution in and around urban areas also affects urban climate. Aerosols released by industries can influence precipitation (Hobbs et al. 1970). For example, large aerosols promote raindrop coalescence more than small aerosols, and so the release of large aerosols may lead to increased precipitation. Hobbs et al. (1970) found that anthropogenically-produced cloud condensation nuclei (CCN) led to an increase in precipitation in western Washington. The effect on precipitation varies with the size of the aerosol. Aerosols larger than 1 μm increase precipitation and those smaller than 0.1 μm inhibit precipitation (Givati & Rosenfeld 2004). Smaller aerosols inhibit precipitation by suppressing the drop-coalescence process. This was also confirmed by Rosenfeld (2000). He found that larger aerosols (>1 μm) lead to an enhancement of precipitation, but that these have mostly been eliminated from emissions, leaving the smaller particles suspended in the atmosphere (Givati & Rosenfeld 2004). Givati and Rosenfeld (2005) state that regions with clouds that have warms tops and short lifetimes experience the greatest precipitation suppression due to pollution. Results of Jirak and Cotton (2006) demonstrate that orographic precipitation west of urban areas along the Front Range of the Rocky Mountains has decreased since 1950. This decrease is attributed to anthropogenically-produced pollution along the Front Range. This trend occurred during a period of industrialization and urbanization and so they imply that air pollution is the cause. Therefore, as urban areas continue to grow, so will the industrial needs of the city, causing the UHI effect to intensify and increase the number of aerosols emitted (Rosenfeld et al. 1995).

2.3 Land Use and Land Cover

Land use and land cover (LULC) has a direct influence on the microclimate of urban regions. The presence or absence of vegetation (and its size and type), alignment and density of buildings downtown (and height), and the color of the surfaces that comprise an urban area (dark for vegetation, light for sidewalks) are a few variables that can influence an urban area's climate (Grimmond et al. 1996, Shashua-Bar & Hoffman 2000, Gomez et al. 2004). Even though these variables will not be analyzed in great detail, they have been shown to alter the local climate and will be discussed for the purpose of understanding the urban microclimate.

2.3.1 Vegetation

Vegetation affects the climate by changing the albedo of the surface, preventing solar radiation from reaching the ground, lowering the surface temperature, and increasing surface humidity through transpiration. It was found that "green zones" lower the surface temperature (Grimmond et al. 1996, Shashua-Bar & Hoffman 2000, Gomez et al. 2004, Hirano et al. 2004). "Green zones" are generally defined as regions within a city consisting of high tree or green vegetative density that cool the air temperature by controlling the heat and moisture fluxes at an urban surface and reducing the amount of solar radiation that reaches the surface (Grimmond et al. 1996, Gomez et al. 2004).

Gomez et al. (2004) claim that green zones may modify microclimatic conditions by regulating temperature changes. In their study of Valencia, Spain, Gomez et al. (2004) were able to develop an index of comfort based upon local meteorological factors and compared them to the environment and availability of green zones. The three variables used to classify the level of comfort were humidity, wind, and radiation. Results showed a positive correlation between human comfort and green zones. The green zone must be at least 10 Ha in size to cool surface temperature by 1ºC. According to Shashua-Bar and Hoffman (2000), vegetation has a lower radiative temperature than a non-living surface of the same color. Shashua-Bar and Hoffman (2000) studied specific characteristics of a green zone that directly affect its microclimatology when compared to the surrounding region. On a large scale, vegetative regions the size of parks can change the thermal properties of a city within 1 – 2 km (Jauregui & Romales 1996). On a small scale (0.5 Ha), the influence these patches have on their surroundings is not as strong but still be important. The purpose of Shashua-Bar and Hoffman (2000) was to uncover which variables (shade coverage, background air temperature, site specific characteristics) within the green zones had the strongest influence on the cooling effect (difference between air temperature at the site and air temperature at a reference point 50 – 100 km away) within the sites. In an urban area, 11 sites were studied and found the average cooling to be 2.8°C. This value ranged from as low as 1°C, in a region of heavy traffic, to 4°C, in a region where the garden was very small (0.15 Ha). This finding contradicts Gomez et al. (2004), who found that 10 Ha of vegetation were needed to cool the air by 1°C. This shows that the influence of green zones is dependent on site characteristics. Shashua-Bar and Hoffman (2000) also found that the intensity of the cooling depended on the background temperature (higher background temperatures caused higher cooling values). They attribute 80% of the cooling to the amount of shading from trees. About 0.5°C from the cooling effect is attributed to the characteristics of the site (e.g., hydrologic cycle, tree characteristics, geometry of site). If traffic was heavy, then more trees would be needed in order to negate the additional heat added by the traffic.

Modeling studies have shown that urban vegetation can have a significant influence on UHI (e.g., 1.5℃ in low-rise residential areas (Hirano et al. 2004)). With most satellite-derived land cover classifications, each land cover class is based upon the majority of cover within a specific area and assigned that type to the entire pixel. This causes small vegetative regions, such as a garden outside of a business, to be classified as commercial, misrepresenting the actual characteristics and land-use of that region. Since these vegetative areas react differently to sunlight and rainfall from commercial land cover (most likely concrete), the modeled response to climatic events is commonly inaccurate and misrepresented. In the study by Hirano et al. (2004) of the Taiwan Metropolitan Area (TWA), a land cover model including these vegetative areas was compared to one without vegetation. Results showed that there was a difference of 1.5°C during the day over a residential area, and compared to observed meteorological data, found that the inclusion of vegetation in the model provided more accurate results. It was also concluded that because vegetative regions have not been addressed in previous studies, modeled UHI intensities can no longer be considered accurate.

In North America, many urban regions have tree cover of 20 – 40%, and so the influence they have on the climate is very important (Grimmond et al. 1996). Grimmond et al. (1996) determined their effect on energy exchanges within local boundary layer due to vegetation from two Los Angeles neighborhoods: a lower tree coverage neighborhood (LTN), 10% tree and shrub coverage, and a higher tree coverage neighborhood (HTN), 30% tree and shrub coverage. By only studying clear-sky days, radiation received is nearly the same at the two sites. They found that the LTN site had a higher albedo, a higher surface area covered in concrete, and larger heat fluxes at night. The HTN region had greater air temperatures during the day (~ 1°C), and cooler temperatures at night (~ 1°C). They concluded that vegetation in neighborhoods as a variable has a stronger influence on local heat and moisture fluxes than surface roughness.

2.3.2 Urban Design

The design of an urban area can also have a great impact on the overall temperature and comfort of a city. The addition of densely urban commercial and business zones will change the microclimate. Adding new buildings will change the wind regime and will add variable shade (shade that changes depending on the time of day) to its surroundings (Capeluto et al. 2003).

Givoni (1994) describes the ideal way to design a city in hot humid or dry regions to allow for maximum cooling. The location of a city in respect to slope, nearby large water bodies, or ability of land to be naturally irrigated are important to take into account. His study describes how the surroundings of an urban area, density of the urbanization, street orientation, surface roughness (due to building height), and location and size of green areas can influence the urban comfort level. The first aspect, an urban area's surroundings, is important because it can affect the ventilation of the city. Givoni (1994) states that it is important to design the layout of the streets so that ventilation can readily occur. A city can use the slope of a valley to its advantage where windward slopes can provide more comfort. This also comes into account near bays or shores, where a sea/land breeze provides additional comfort in hot-humid climates. He states that a city located near a river outlet or coast will experience heavy rains and potentially hurricanes. This allows for a natural irrigation of the land but flooding can also occur due to excess run-off (brought on by impervious land cover). If this is a factor then an increase in natural land surfaces and preservation of naturally occurring drainage features is important. Givoni (1994) claims that street layout also affects ventilation. It is stated that designing streets parallel to the direction of afternoon prevailing winds will allow for cooling, especially during the hottest time of the day. Streets that are perpendicular to the mean wind flow allow for little ventilation. Also, centers with high urban density usually lead to reduced ventilation capacity. He states that in a highly dense area, buildings of different heights should be placed near each other to increase ventilation where buildings of similar height should be placed parallel to the direction of mean wind. Givoni (1994) also describes the effects building size has on human comfort and found that small, detached houses are ideal as they cool down fastest and orientation is not as large a factor. Givoni (1994) also stresses the importance of adding green zones as they provide shade and so cool the surface temperature, have varying heights and so ventilation is encouraged. They also save irrigation costs in hot-humid regions as they increase humidity.

Golany (1996) describes the differences between the climate in the central business district (CBD) and the peripheral portions of the city. He states that the CBD of a city is much warmer, as a result of the continuous movement of people and automobiles. Faster snow melt has been observed in the city center compared to the city surroundings, illustrating the effects the UHI. In peripheral portions of the city, streets can be arranged so that the mean wind easily penetrates the CBD. This can cause the inner city to be cooler. He describes the thermal performance of a city so that urban designers can incorporate these details into future plans. He compares various types of cities (dispersed, compact, and clustered urban form) with varying types of climates (hot-humid, cold-humid, hot-dry, cold-dry, seashore climates, and mountain climates), describing how urban design can improve the comfort (and energy savings) of the city. Compact urban forms where similar land use is consolidated in a small, consolidated location are claimed to have a better response to stressful climates, and are able to devote less energy to heating and cooling, thus the overall cost to the city (operations, time and energy conservation) is reduced. The dispersed urban form (more space between buildings and single family, detached housing units) is more common in developed countries and consumes more financial resources for construction. This style influences the microclimate by requiring more energy for heating and cooling; its response to a stressful climate is not as good as is the response of the compact urban form.

Rosenfeld et al. (1998) presents ideas that can help Los Angeles save energy and money that is directed towards air conditioning and a plan that can be potentially implemented across the U.S. by the year 2015. They claim that a sixth of the electricity used in the United States is directed towards air conditioning and half of all use occurs in urban areas (Rosenfeld et al. 1998). The two methods proposed to implement a "cool community" are: (1) plant shady trees on a wide-scale and (2) change roofing and pavement to lighter colors. Although the implementation of these two methods is costly at first, it saves money in the long run by cooling the surface, and so less energy is required for air conditioning. They created a model that analyzes the implementation of 11 million trees in the city, 5 million houses with lighter-colored roofs, and increase in the urban solar reflectivity by about 25%. Results showed that by implementing these changes, the heat island in Los Angeles would decrease by 3°C. Additionally, the ozone exceedance levels would decrease by 12% and reduce the amount of air-conditioning in a single home by half. When extrapolated to the entire United States, it was predicted that it would reduce energy usage by 10%.

Xie et al. (2006) conducted a study that simulated pollutant dispersion in a street canyon of varying characteristics. He then analyzed which layout of streets (various combinations of leeward building height to street width) would provide the most amount of ventilation, allowing for greater scattering of pollutants. It was found that the scattering is directly dependent on a combination of the canyon flow regime with the air exchange between the canyon and air above the roof level (Xie et al. 2006).

2.3.4 Albedo

Alterations in small-scale, local heat fluxes of an urban region (for example, the addition of a parking lot), can influence the overall surface energy budget. The albedo of a surface is greatly dependent on the color and type of surface, and so heat storage directly depends on the albedo of the land cover. A study conducted by Kjelgren and Montague (1998) analyzed the transpiration of trees over two different surfaces: a mostly paved area, such as a parking lot, and a turf area that was not irrigated. They found that the trees placed over the asphalt received more long-wave radiation than the trees over the turf because the surface temperature of the asphalt was higher (Kjelgren & Montague 1998).

Prado and Ferreira (2005) studied various colors and compositions of roofing tiles in Brazil to determine the effect different materials had on surface temperature. It was determined that red and white ceramics were the only type to lead to a surface temperature lower than the air temperature. Materials with lower emitting properties (metallics) and similar albedo values had higher surface temperatures (Prado & Ferreira 2005).

2.3.5 Surface Heat Fluxes

Asaeda et al. (1996) studied the influence of pavement during the summer on the local climate on the lower atmosphere. They compared the heat storage of different materials and their corresponding near-surface heat fluxes. Results showed that asphalt, one of the primary surfaces in an urban area, has the highest capacity for absorbing and releasing heat. It is thought that this occurs due to the low albedo and high conductivity (Asaeda et al. 1996). The results of this study show that the daily minimum temperatures within urban areas have increased, as radiation from these surfaces is emitted more slowly than from a natural landscape.

2.4 Urban Precipitation

When increases in the urban heat island effect, pollution, vegetation, urban design, albedo, and surface heat fluxes occur over an urban area, it can change the frequency, intensity, and amount of precipitation received. This anthropogenic alteration is strongest in warm-season precipitation, when rain events are mainly convective. Project METROMEX, a field study intended to analyze the effects of weather modification by urbanized areas and the basis for most urban precipitation studies, was one of the first examinations of the effect of urban areas on precipitation. It was determined that not only did afternoon rainfall increase, but also clouds over urban areas were more likely to merge with developing storm systems resulting in stronger storm units (Changnon et al. 1971). The "Eight Cities Study" was a more in-depth analysis of urban precipitation inspired by METROMEX. It analyzed the precipitation climatology of eight individual cities (St. Louis, Chicago, Cleveland, Washington, Indianapolis, Tulsa, Houston, and New Orleans). Evidence of daily and seasonal precipitation increases were found in St. Louis, Chicago, Cleveland (strongest June through August for these three cities), and Washington (strongest September through November), while Houston and New Orleans only experienced more rainfall May through September (and October respectively). There was no significant evidence to show that Indianapolis and Tulsa experienced changes in precipitation. Also, it was discovered that not only does the UHI destabilize the atmosphere, but industries also add CCNs, leading to greater amounts of condensation (Huff & Changnon 1973). Dettwiller and Changnon (1976) analyzed seasonal maximum daily rainfall (1871–1970) at three cities (Paris, St. Louis, and Chicago) to determine the strength of urban influences. A time series analysis was conducted and results fitted to a normal distribution for each city. The Kolmogorov-Smirnov (K–S) test was performed to determine the probability of differences between the data and normal distribution occurring by chance. It was found that, with the exception of the warm season precipitation in Paris, data from the remaining cities were normally distributed. For the case where the precipitation during the warm season in Paris could not be fitted by a normal distribution, the Mann-Kendall rank statistic test was used. The trend was found to be significant. This paper concluded that because the results were similar in the three cities (and two different continents), it is possible that either that changes were caused by urban influences or global climate change (Dettwiller & Changnon 1976). Huff and Vogel (1978) analyzed 5 years (1971-1975) of rainfall data over 17 regions within a portion of the METROMEX study region. The total rainfall volume was normalized by dividing by the area of each region. This allowed for a direct comparison of precipitation between 16 of the potentially urban influenced areas and a defined upwind control area. They found precipitation increased by 30 – 35% northeast of the city (downwind), but urban effects were most pronounced in storms where greater than 25 mm of precipitation fell (Huff & Vogel 1978).

As stated by Souch and Grimmond (2006), research in urban precipitation slowed down up until the last few years when new technology, such as data from the Tropical Rainfall Measuring Mission (TRMM) and radar precipitation data have become available. Changnon et al. (1991) studied precipitation during the fall, winter, and spring, although it has been shown larger urban-influenced increases in precipitation occur during the summer. A total of 116 stations were separated into quadrants of St. Louis, to determine the upwind/downwind regions of influence. They found that fall precipitation increased by 17% downwind of the urban area. Winter precipitation downwind changed very little, while spring precipitation increased by 4% (Changnon et al. 1991). A study of Mexico City by Jauregui and Romales (1996) found that increases in convective precipitation were evident, occurring most often during the afternoon and evening. They suggest that this trend of intensification of wet-season precipitation is due to the 2-3°C increase in urban temperatures (Jauregui & Romales 1996). Bornstein and Lin (2000) studied the effects of the Atlanta urban area on the initiation of six convective storms within a nine-day period during the summer. They found that the presence of a UHI convergence zone led to initiation of storm convergence or affect storm movement for days with calm wind flows. Days with stronger flows led to a bifurcation of storms, causing storms to move around the city (Bornstein & Lin 2000).

Shepherd (2002) studied seven cities (Atlanta, Montgomery, Nashville, San Antonio, Waco, Austin, and Dallas) using TRMM (Tropical Rainfall Measuring Mission) satellite data to validate station precipitation data, quantify urban area influences on rainfall, and determine if urban area influences could be found at numerous cities. In order to exclude any topographic land – water boundary effects, these seven cities were chosen to minimize these effects. Warm-season precipitation (May through September) for 1998 – 2000 was studied using the urban rainfall ratio (URR) to compare changes at the different study regions. The ratio is URR = R_i / R_{BG}, where R_i is the mean rainfall rate for the given grid point and R_{BG} is the mean background value calculated by taking the average of all the stations in the study area. By performing t-tests on the mean of each study region, it was found that the area downwind of the urban area had significantly more rainfall than the upwind control area. All four Texas cities studied (San Antonio, Waco, Austin, and Dallas) had higher rainfall rates 30 – 100 kilometers east and northeast of the cities. Minimum rainfall rates were found directly to the west of these cities. It was also concluded that TRMM rainfall data are appropriate for such analyses (Shepherd et al. 2002).

Diem and Brown (2003) studied the effects of irrigation in Phoenix on summer precipitation. Their objectives were to determine whether changes in urban and agricultural land use influenced rainfall and also which regions were most affected. Regions which are highly irrigated can increase water vapor emittance by seven times compared to the nearby arid desert. June, July, and August precipitation data for the period 1950 – 2000 in the downwind region were compared to the urban area. They found that precipitation increased and proposed three mechanisms possible for this increase: (1) the addition of available water vapor, (2) the increase of convergence due to the urban landscape, and (3) the increase of CCNs (Diem & Brown 2003).

Dixon and Mote (2003) discuss that a possible diurnal wind direction change occurs between urban and rural areas, much like a sea-breeze. This occurs on calm nights where the horizontal surface temperature gradients are strongest, and a low pressure occurs over the urban area. They reported that in their 5-year study (1996-2000) of Atlanta, Georgia, a total of 37 precipitation events were caused by the UHI effect. They hypothesized that these events occur on days when the UHI effect is particularly strong. It was found that in addition to an above average UHI, increased low-level moisture content may play an important role in enhancing precipitation. Diem and Mote (2005) also conducted a 50-year study of Atlanta, Georgia and found stations upwind of the city were receiving less precipitation. The central/west-central stations received the most precipitation where there was also a significant increase in urbanization. There was also an increase in dewpoint at the same locations where increases in precipitation were observed.

In their study of Houston, Texas, Burian and Shepherd (2005) compared the precipitation in a pre-urban setting (1940 – 1958) to that of a post-urban setting (1984 – 1999). They found that distribution of rainfall had changed such that there was a 25% increase in precipitation in the urban area compared to an 8% decrease in precipitation in the upwind control region (where urban influences were not a factor). When comparing the defined Houston urban area to its surrounding regions in the post-urban setting, the urban area had 80% more warm-season rainfall episodes (Burian & Shepherd 2005).

Shepherd (2006) studied two arid regions, Phoenix, Arizona and Riyadh, Saudi Arabia, for a 108-year precipitation record to find potential urban-influenced precipitation increases. Because arid regions are growing so rapidly, it is important to determine how this growth has changed precipitation patterns. The analysis compared data from a “pre-urban” time (1895 – 1949) to a “post-urban” time (1950 – 2000). The precipitation data for Phoenix comes from a very high-quality and topographically sensitive record available from the Spatial Climate Analysis Service (SCAS), the parameter-regression independent slopes model (PRISM) which takes topography into account, and TRMM satellite records. Riyadh rainfall data comes from the global climate observing system (GCOS) network which incorporates atmospheric, oceanic, hydrologic, cryospheric and terrestrial processes. Additionally, an algorithm from TRMM is used to produce data for this region. Results show that mean rainfall increased by 12% – 14% in the post-urban period in Phoenix. Gauge data in the Riyadh study did not show any trends, but potentially urban-linked trends were found downwind using satellite data (Shepherd 2006).

Diem (2006) studied central Arizona, including the Phoenix metropolitan region, to see if urbanization changed the amount of rainfall occurring during the summer monsoon season. To represent the atmospheric instability associated with the monsoon, cloud-to-ground lightning data was used to test for anomalies downwind of the city. It was found that the relationship between monsoonal rainfall and lightning flashes are highly correlated in the study region. These results were found to be consistent with

Diem and Brown (2003), where precipitation anomalies were greatest in the northeastern portion of the urban area.

Gero et al. (2006) ran a numerical model (RAMS) for Syndey Basin, Australia to test which types of land cover will affect storms. It was found that synoptically forced storms were not influenced by land cover changes while convective storms were. The differences in convective storm enhancement are linked to the interaction between the sea breeze, atmospheric moisture, and buoyancy caused by surface heating. It was found that and increase in urban land cover led to an increase in the instability of the atmosphere, affecting the triggering mechanisms behind the convective systems (Gero et al. 2006).

Mote et al. (2007) used NEXRAD radar data to determine how Atlanta influenced June, July, August precipitation. It was found that the downwind region of the city (eastern metropolitan area) received 30% more daily average rainfall than the upwind region (western metropolitan area). The anomalous region extended up to 80 km east of the city, the largest anomalies 40 km east, which is consistent with results from Shepherd (2005).

Bäumer and Vogel (2007) analyzed 12 meteorological stations in Germany for weekly periodicities in the data. The variables tested were temperature, sunshine duration and cloud amount, precipitation, relative humidity, air pressure, average wind speed and daily maximum wind speed. It was found that seven-day periodicities existed in many of these variables, and patterns were not exclusively found at stations in urban settings. This provides evidence of anthropogenic influence on the microclimatology of this region (Baumer & Vogel 2007).

Bell et al. (2008) studied aerosol data across the southern U.S., and found that concentrations increase in the middle of the week. TRMM rainfall data for the summer months were then studied to determine if weekly cycles in precipitation were present. Compared to rain gauge data, weekly cycles that were seen in TRMM data were not as easily detectable by the gauge data. It was found that maximum rainfall amounts fell during the middle of the week, with a decrease Sunday, mirroring patterns seen in CCN concentrations. Even though CCN concentrations and increased amounts of rainfall were found to be highly correlated, it may not possible to imply that these aerosols are the sole cause for rainfall patterns. It was concluded that various other human activity, such as driving cars and irrigation, may play a role but were thought to be too small to influence the circulation of the atmosphere on a larger scale (Bell et al. 2008).

Based on the previous research, it is expected that there will be increased amounts of precipitation downwind of the DFW Metroplex (north, northeast of the city). It is likely that this anthropogenic-induced signal has become stronger in recent years as the rate of urbanization has increased.

CHAPTER III

DATA AND METHODS

3.1 Study Area

The study area is the DFW metroplex (DFW) which is located in Dallas and Tarrant Counties and also includes portions of nine surrounding counties (Collin, Denton, Ellis, Hunt, Johnson, Kaufman, Parker, Rockwall, and Wise Counties (Figure 3.1). The surrounding counties have been considered because it is hypothesized that the environmental effects of urban areas are not completely localized.

Because there is an existing west-to-east zonal gradient in precipitation, it is necessary to attempt to control for this by using two control regions. Control Region A (CRA) is located south of DFW, while Control Region B (CRB) is located north of DFW (Figure 3.2). The size of these two control regions will be identical to DFW, so that they can be directly compared. Using control regions will provide a method to isolate urban-induced changes in precipitation because even if precipitation in Texas has changed over time, it is assumed that these changes should be consistent in all three regions (DFW, CRA, CRB). Wind data from the National Resources Conservation Service (NRCS) show that CRA is upwind and CRB is downwind of DFW since June, July, and August (JJA) are dominated by southerly wind (Figure 3.3). For most of the year, the mean wind direction is from the south, but it does vary by season. From November through February, an equal amount of wind, on average, is received from both the north and the south. From September through November, the mean direction is from the south, southeast, or east. For the purpose of this study, CRA and CRB will be referred to as “control” regions, although due to their location relative to DFW, they are thought to act like upwind (CRA) and downwind (CRB) regions.

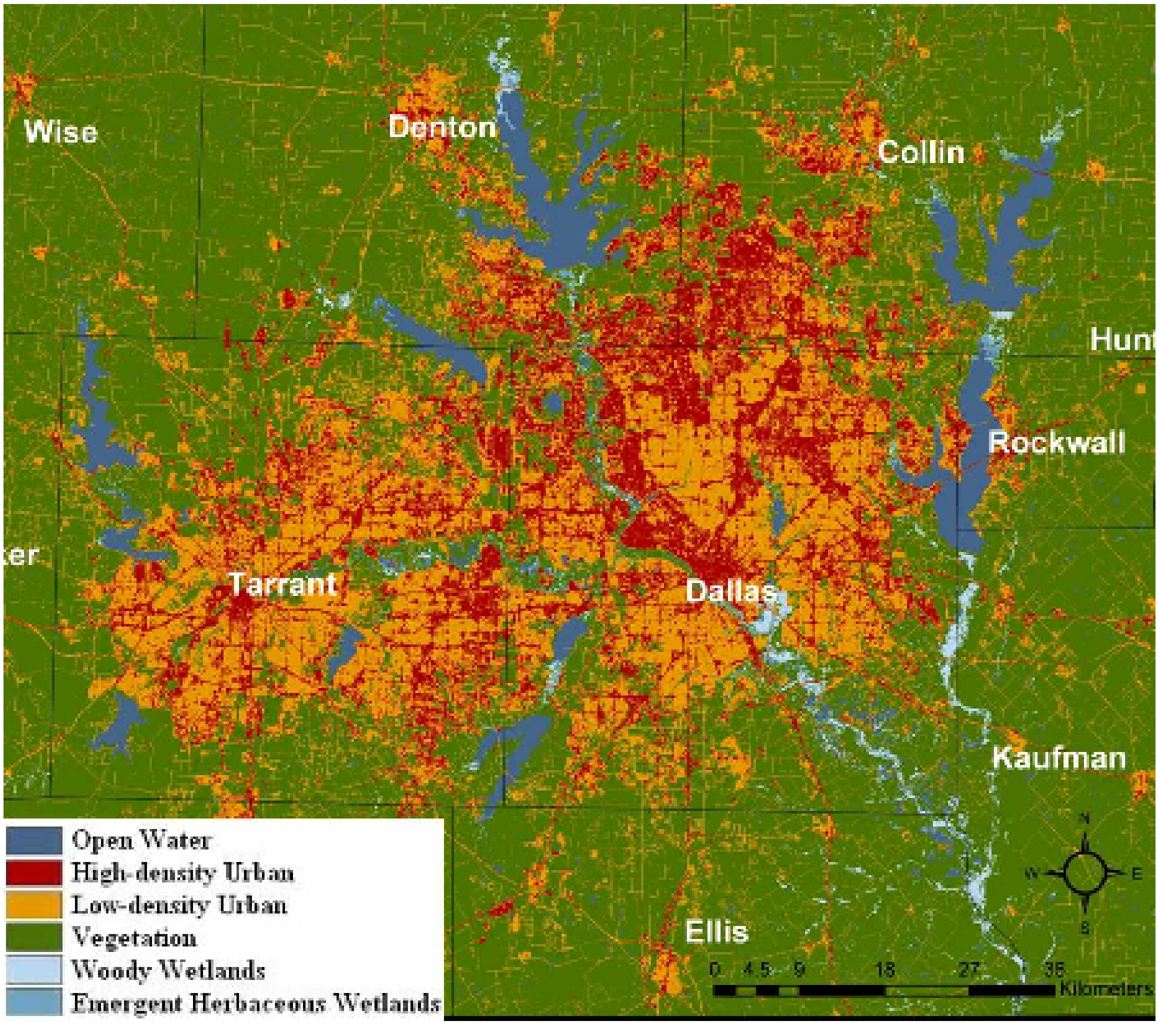

Figure 3.1. The Dallas/Fort Worth (DFW) Metroplex. The land cover shown here is from 2001 and classified according to the simplified classifications (National Land Cover Dataset 2001 (NLCD 2001), Price et al. 2007).

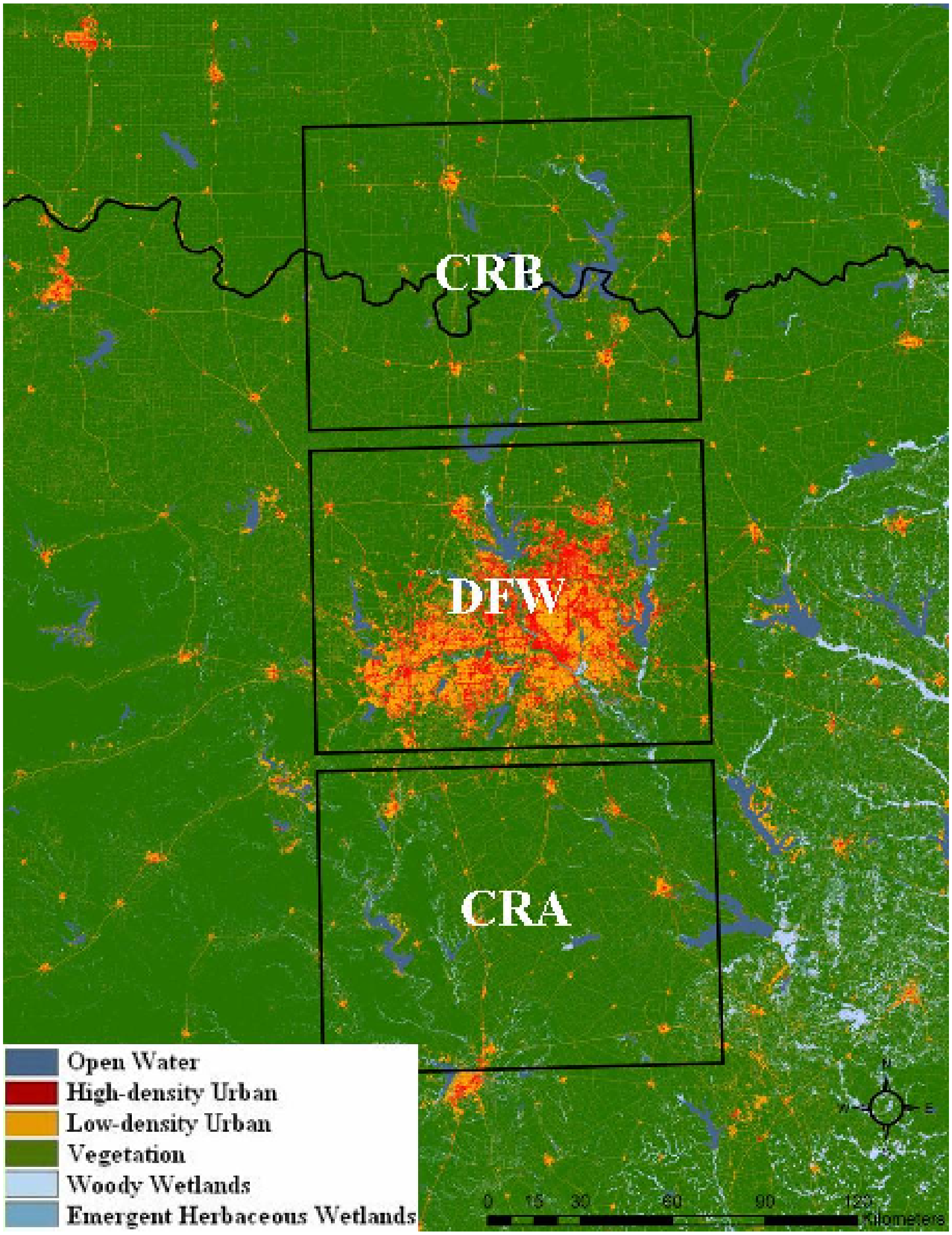

Figure 3.2. Locations of the three precipitation control regions: Control Region A (CRA) on the bottom, Dallas/Fort Worth (DFW) in the middle, and Control Region B (CRB) on the top.

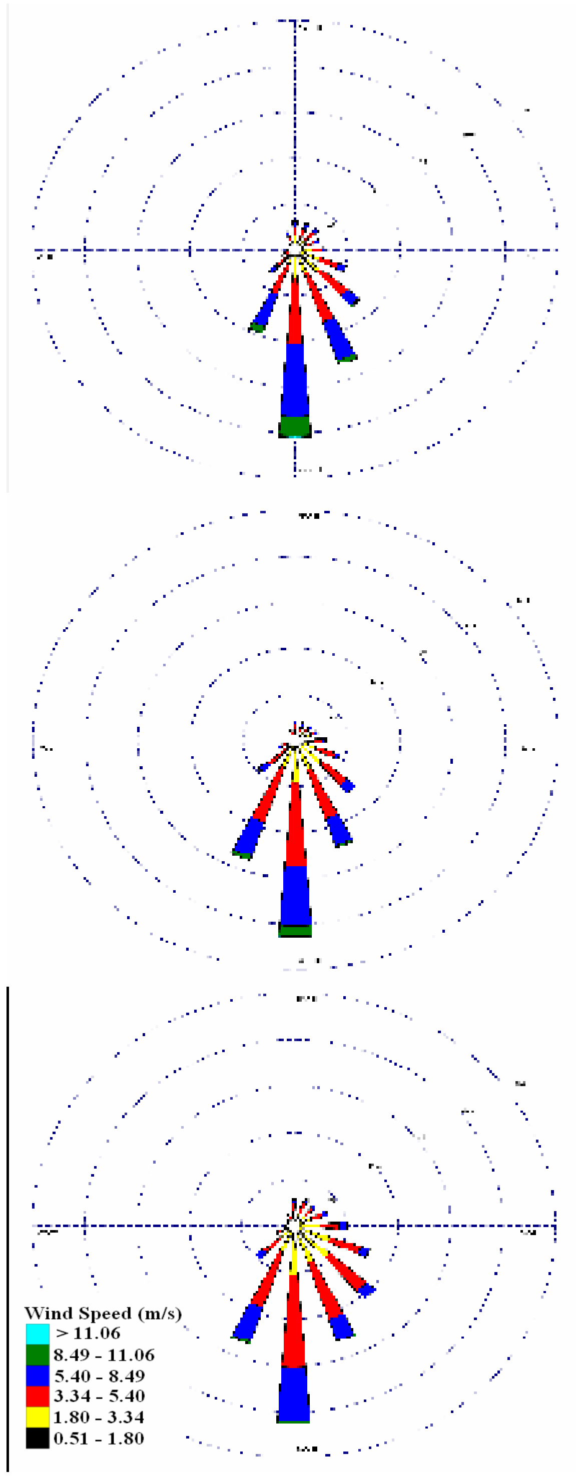

Figure 3.3. Wind rose diagrams for Fort Worth, Texas for June (top), July (middle), and August (bottom).

Normal climate values are based on data from the years 1971 – 2000 using data available from the Dallas/Fort Worth National Weather Service Regional Forecast Office. Table 3.1 shows the normal monthly minimum, maximum, and mean temperature, and precipitation values. The mean temperature ranges from 6.72°C in January to 29.44ºC in July. The mean of minimum temperatures was 1.11°C in January while the mean of maximum temperatures was 35.22°C in July. The maximum amount of rainfall is received in May (mean = 130.81 millimeters) while the minimum was in January (mean = 48.26 millimeters).

Table 3.1. Normal monthly mean temperature (Tmean inºC), minimum temperature (Tmin inºC), maximum temperature (Tmax inºC), and mean precipitation (Pmean in mm) for the Dallas/Fort Worth region (1971 – 2000) measured at the Dallas/Fort Worth International Airport.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{mean}	6.72	9.67	14.11	18.33	22.83	27.17	29.44	29.11	25.28	19.56	12.83	8.17
T_{min}	1.11	3.72	8.00	12.22	17.22	21.5	23.67	23.33	19.56	13.56	7.28	2.67
T_{max}	12.28	15.61	20.17	24.39	28.44	33.28	35.22	34.89	30.94	25.50	18.39	13.61
P_{mean}	48.26	60.20	77.72	81.28	130.81	82.04	53.85	51.56	61.47	104.39	65.28	65.28

3.2 Data

3.2.1 Precipitation Data

Monthly, warm-season precipitation data (June, July, August) are used as most rainfall during the summer is convective and is more likely to be influenced by urbanization. These data were obtained from a network of stations within and surrounding the metroplex available from the National Climatic Data Center (NCDC). Only stations that have a long record (greater than 70 years) and that are spatially representative (evenly distributed across each study region) were selected. These data have undergone a quality control and interpolation process as outlined in McRoberts (2008). This was done based on the Inverse Weighting of Square Distance (IWSD) scheme of Sun and Peterson (2005). For each month in the study period, out of the closest twenty USHCN stations, the four stations with the highest weights were used to develop an interpolated value (McRoberts 2008). This process develops a homogenous data record using surrounding United States Historical Climate Network (USHCN) stations. Each USHCN station is given a particular bias which is dependent on how closely it follows neighboring stations for a particular month. Values greater than “1” indicate that the USHCN station is experiencing a wet bias comparing to the target COOP station for that month. In this research, raw station data is used when available, but missing months were replaced with interpolated data from McRoberts (2008).

These gauge data may still contain errors or biases resulting from poor choice of station locations (under a tree, over a parking lot), human error in reading and recording measurements, and changes in station location. Despite the problems that missing or inaccurate data present, there are many advantages to using gauge data. Because rain gauges are point sources, they tend to be more accurate at a particular location than radar or satellite-derived data. Also, the length of record for gauge data is much longer than that for radar or satellite data. There are 683 stations within the two climate divisions that encompass the three study regions, but only 325 of these have data for greater than 70 years. Of those existing longer than 70 years, only 33 are located within the three study regions. Stations that were missing more than 30% of raw data were excluded from the study. The stations used in this study are shown in Table 3.2 and Figure 3.4, where they are divided into categories by control region, showing which stations are used for the three different-sized areas that will be tested (as further described in section 3.3). The original area size was drawn for DFW to completely cover the extent of the urbanized land cover. The same size boxes were drawn for CRA and CRB, keeping longitude and distance from DFW consistent. The large area is 25% greater than the original area, while the small area is 25% less than the original area. In Table 3.3, the station name, latitude (lat), longitude (lon), elevation (elev), year of station establishment (first year), last year of data available (last year), and percent of data missing are listed for the period 1930 – 2007. Percent of data missing was calculated by determining how many summer months (June, July, and August) did not have values from 1930 to 2007. Some stations do have greater than 10% missing due to their later year of establishment (after 1930). These stations were kept in this study because, not only do they spatially represent the study regions, but because the relationship between raw data available for that station and the interpolated data was very close. Figure 3.5 shows the three different areas for each region that will be studied.

Table 3.2. Stations from the Cooperative observing network (COOP) used in this study. The numbers represent their COOP station ID.

Area Size (see Table 3.3)	CRA	DFW	CRB
Original	411800, 412019, 414182, 415869, 419419, 419522, 419715	410691, 412404, 413691, 417028, 417659, 417707, 419125	340292, 342678, 344001, 345463, 345568, 348884, 413247, 416130, 418274
Large	411800, 412019, 413485, 414182, 415611, 415757, 415869, 417388, 419419, 419715	410691, 412404, 413247, 413691, 414705, 417028, 417659, 417707, 417773, 418929, 419522, 419532	340292, 342678, 344001, 345468, 345563, 348884, 410923, 416130, 418274
Small	411800, 412019, 414182, 419715	410691, 412404, 413691, 417659, 417707	340292, 344001, 345468, 345563, 348884, 416130, 418274

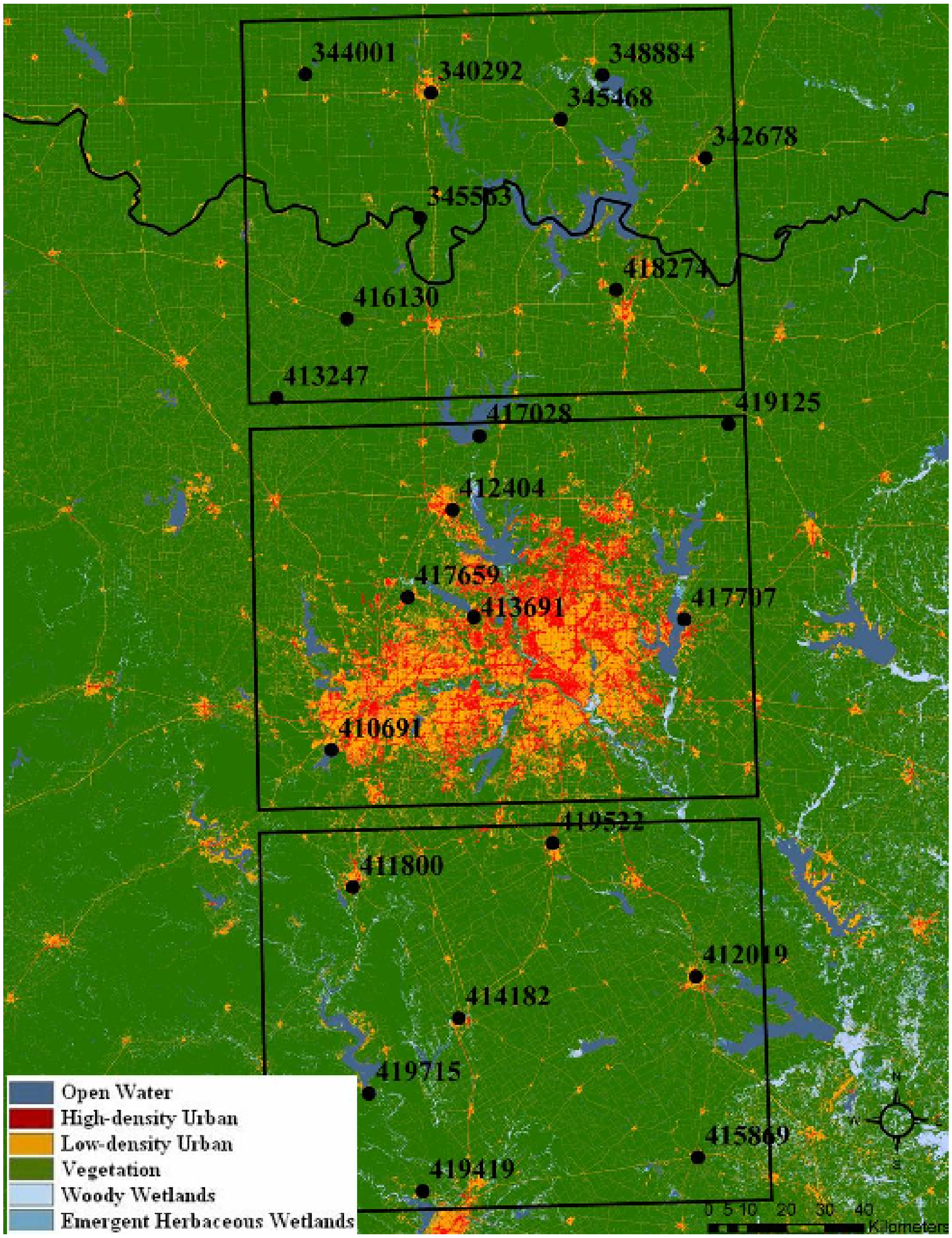

Figure 3.4. The stations used in this study.

Table 3.3. Metadata for the stations used in this study. Those denoted with "*" are used in more than one location.

Study Region	Station ID	Name	Lat	Lon	Elev	First year	Last year	Percent missing
CRA	411800	Cleburne	32.31	-97.41	783	1931	2007	1.7
	412019	Corsicana	32.11	-96.47	413	1893	2007	0.4
	414182	Hillsboro	32.02	-97.11	550	1931	2007	3.8
	415611	Marlin 3 NE	31.33	-96.86	388	1933	2007	6.4
	415757	McGregor	31.44	-97.40	723	1931	2007	2.1
	415869	Mexia	31.70	-96.51	530	1905	2003	7.3
	417388	Rainbow	32.26	-97.71	648	1935	2007	7.3
	419419	Waco Regional Airport	31.62	-97.23	500	1947	2007	22.2
	419522*	Waxahachie	32.43	-96.84	630	1931	2007	3.4
	419715	Whitney Dam	31.86	-97.38	574	1950	2007	25.6
DFW	410691	Benbrook Dam	32.65	-97.44	790	1950	2007	24.8
	412404	Denton 2 SE	33.20	-97.11	630	1931	2007	3.8
	413247*	Forestburg 5 S	33.47	-97.58	1110	1940	2007	17.1
	413691	Grapevine Dam	32.95	-97.06	585	1950	2007	26.9
	414705	Kaufman	32.56	-96.27	420	1931	2007	3.0
	417028	Pilot Point Isl Du Boi	33.37	-97.01	690	1941	2003	24.8
	417659	Roanoke	33.01	-97.22	623	1942	2007	16.2
	417707	Rockwall	32.93	-96.47	543	1942	2007	17.1
	417773	Rosser	32.46	-96.45	364	1942	2007	20.1
	419125	Trenton	33.43	-96.34	760	1947	2007	24.4
	419522*	Waxahachie	32.43	-96.84	630	1931	2007	3.4
	419532	Weatherford	32.75	-97.77	955	1897	2007	0.4
CRA	340292	Ardmore	34.17	-97.13	880	1904	2007	3.4
	342678	Durant	34.00	-96.37	600	1902	2007	5.6
	344001	Healdton	34.22	-97.48	734	1914	2007	19.7
	345468	Madill	34.09	-96.77	770	1937	2007	11.5
	345563	Marietta 5sw	33.88	-97.16	802	1938	2007	12.4
	348884	Tishomingo National Wr	34.19	-96.64	642	1925	2007	0.0
	410923	Bonham 3nne	33.64	-96.17	600	1931	2007	4.7
	413247*	Forestburg 5 S	33.47	-97.58	1110	1940	2007	17.1
	416130	Muenster	33.65	-97.38	1005	1941	2007	14.1
	418274	Herman	33.7	-96.64	760	1931	2007	1.7

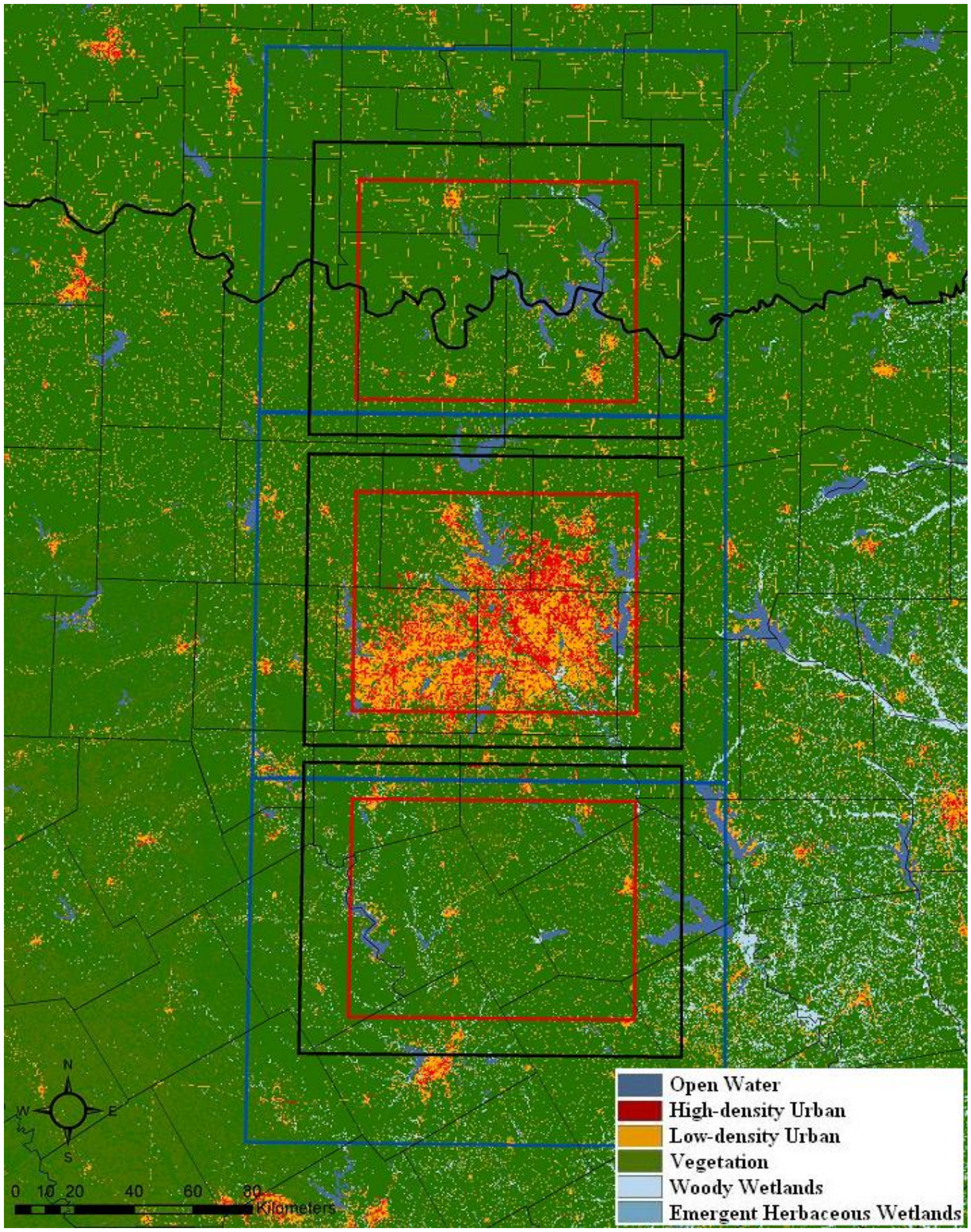

Figure 3.5. The three areas to be analyzed for each study region. The black boxes are the original area (Test 1). The blue boxes are 25% greater than the original area (Test 2). The red boxes are 25% smaller than the original area (Test 3).

3.2.2 Population Data

The population data used in the analysis consists of two datasets: the historical population data (1900 – 1990) and the current and projected data (2000 – 2040). The historical data is available from the United States Census Bureau by county. The projected data is available from the Texas State Data Center and Office of the State Demographer. It is also available by county where four various growth scenarios are used to determine the growth over time. These scenarios are based upon net migration for the DFW Metroplex. The Zero Migration (0.0) Scenario takes into account the growth of the county as if there were no in- or out-migration. The population change in each county is due to the natural increase from births or deaths. The One-Half 1990-2000 Migration (0.5) Scenario is an average of the Zero Migration and the 1990 – 2000 Scenario, where migration in and out of the city is half of the 1990 – 2000 rate. The 1990-2000 Migration (1.0) Scenario uses the migration rates that were occurring during the 1990s. Because the rates during this period were larger than any other decade, it is highly unlikely that the rates will continue (Texas State Data Center and Office of the State Demographer (TSDCOSD)). Lastly, the 2000-2004 Migration Scenario uses migration rates that were occurring in the years following 2000.

For the purpose of Census 2000, two metropolitan statistical areas make up the DFW Metroplex: the Dallas Metropolitan Area (consisting of Collin, Dallas, Denton, Ellis, Hunt, Kaufman, Rockwall, and Henderson counties) and the Fort Worth-Arlington Metropolitan Area, (consisting of Hood, Johnson, Parker, and Tarrant counties). Once the census data analysis was complete, the Census Bureau redesigned United States metropolitan areas, and so the DFW Metropolitan area was defined using eight counties for Dallas (Collin, Dallas, Delta, Denton, Ellis, Hunt, Kaufman, and Rockwall) and four counties for Fort Worth-Arlington (Johnson, Parker, Tarrant, and Wise). According to the North Central Texas Council of Governments, the DFW urbanized area is contained within the following nine counties: Collin, Dallas, Denton, Ellis, Johnson, Kaufman, Parker, Rockwall, and Tarrant.

Population data for the DFW Metroplex were collected for the period 1900 to 2000. Population projections were also available from the Texas State Data Center and Office of the State Demographer (SDCODC). Using the population data for each county, growth rates were determined. Population projection data was also available from the SDCODC, and consisted of five-year population estimates for the DFW Metroplex based on several migration scenarios (further discussed in Section 6.1). The projections are available for the years 2010 to 2040.

3.2.3 Land Cover Data

There are two data sets used in the LULC analysis: the Enhanced Historical Land-Use and Land-Cover Data Sets of the U.S. Geological Survey and the National Land Cover Dataset 2001 (NLCD 2001) data set (Table 3.4). The historical data set was developed by the U.S. Geological Survey (USGS) to aid in the USGS National Water-Quality Assessment (NAWQA) Program. Photographs used to create the dataset were collected from 1970 to 1985 and presented at a scale of 1:250,000. The NLCD 2001 was developed in order to expand the NLCD 1992 using Landsat 5 and 7 imagery, as a 30-meter resolution.

Table 3.4. The 1976 and 2001 land cover datasets were simplified into six classifications for this research (water, vegetation, high-density urban, low-density urban, woody wetlands, and emergent herbaceous wetlands).

	1976		2001	
New classification	**Code**	**Classification**	**Code**	**Classification**
Water	51	Streams and Canals	11	Open Water
	52	Lakes		
	53	Reservoirs		
	54	Bays and Estuaries		
Vegetation	21	Cropland and Pasture	41	Deciduous Forest
	22	Orchards, Groves, Vineyards, Nurseries	42	Evergreen Forest Land
	23	Confined Feeding Operations	43	Mixed Forest Land
	24	Other Agricultural Land	52	Shrub/Scrub
	31	Herbaceous Rangeland	71	Grassland/Herbaceous
	32	Shrub and Brush Rangeland	81	Hay/Pasture
	33	Mixed Rangeland	82	Cultivated Crops
	41	Deciduous Forest Land		
	42	Evergreen Forest Land		
	43	Mixed Forest Land		
	72	Beaches		
	73	Sandy areas not beaches		
High-density urban	12	Commercial Services	23	Developed, Medium Intensity
	13	Industrial	24	Developed, High Intensity
	14	Transportation, Communications		
	15	Industrial and Commercial		
Low-density urban	11	Residential	31	Barren Land
	16	Mixed Urban or Built-Up Land	21	Developed, Open Space
	17	Other Urban or Built-Up Land	22	Developed, Low Intensity
	75	Strip mines, quarries, gravel pits		
	76	Transitional areas		
Woody wetlands	61	Forested Wetlands	90	Woody wetlands
Emergent herbaceous wetlands	62	Nonforested Wetlands	95	Emergent herbaceous wetlands

3.3 Methods

This study examines long-term changes in precipitation (temporal comparison), and regional changes in precipitation in DFW and the control regions (regional comparison). Then in order to connect precipitation trends to urbanization, a land cover analysis was performed. In order to determine if urbanization is having an influence, consistent with previous research, it is expected that the mean precipitation in DFW is significantly greater than the mean of the earlier decades in downwind regions. As stated in Chapter I, the objectives of this study are:

(1) To characterize the land cover changes and urban growth in and around the DFW Metroplex

(2) To determine how precipitation in and downwind of the DFW Metroplex has changed since 1930 (a temporal analysis)

(3) To determine how precipitation in the control regions has changed in comparison to the DFW Metroplex (a spatial analysis).

If precipitation changes are similar in all three regions, it would imply that a larger-scale influence is causing these changes and that they are not necessarily due to urbanization and human activities. In order to examine how sensitive the results are to increasing (decreasing) the number of stations used and the area of the control regions, there are six sensitivity tests carried out for each analysis (Table 3.5). Test 1 is for the areas shown by the black boxes in Figure 3.4 (Area 1), include all available stations for each region. Test 2 is for the areas shown by the blue boxes, which is 25% greater than Area 1. Test 3 is shown by the red boxes, which is 25% smaller than Area 1. Tests 4, 5, and 6 use Area 1 but include only 2, 3, and 4 stations respectively for each study region.

Table 3.5. The six sensitivity tests that will be altered in each temporal and regional analysis. Test 1 is using all available stations for an area of the size that completely incorporates the DFW Metroplex. Test 2 uses all available stations for an area 25% greater than in Test 1. Test 3 uses all available stations for an area 25% smaller than in Test 1. Tests 4, 5, and 6 use two, three, and four stations (respectively) for the area defined in Test 1.

Test	Variables altered
1	Area 1 (A1, initial size, same for all other analyses unless specified)
2	Area 2 (A2, Area is 25% greater than A1)
3	Area 3 (A3, Area is 25% less than A1)
4	2 stations/ region (stations: 412019, 419715, 416130, 418274, 417707, 417659)
5	3 stations/ region (stations: 412019, 419715, 419522, 416130, 418274, 340202, 417707, 417659, 417028)
6	4 stations/ region (stations: 411800, 412019, 419715, 419522, 416130, 418274, 340202, 348884, 417707, 417659, 417028, 419125)

Additionally, for each spatial/temporal analysis, JJA precipitation totals for each region were derived using two different methods: (1) the arithmetic average method and (2) the Thiessen-weighted polygon method because the averaging method may not be the best method for handling precipitation data where the spatial characteristics must included. The arithmetic average method is determined by taking the sum of precipitation at all stations and then dividing that number by the total number of stations considered. The Thiessen-weighted polygon method weights each stations based on the area that it represents by comparing nearby precipitation stations. The calculated area, an irregularly-shaped polygon, is then multiplied by the station's precipitation to find how much land is represented by the amount of rainfall measured at that particular gauge (Dingman 2002).

3.3.1 Land Cover Analysis

The first objective is to determine how the LULC changes in the metroplex relate to changes in precipitation patterns. This was performed using ArcGIS and land cover data for the study regions from two different time periods: a historical dataset (1976) and a current dataset (2001). Also, population data is used (available from the US census) to show periods of high growth and overall growth since 1930. A simplified LC classification system is used where there will be six land cover classifications: water, vegetation, low-density urban, high-density urban, woody wetlands, and emergent herbaceous wetlands (Table 3.4). Because there were two different land cover classification systems used in the data sets, the codes used in the two sets were not consistent. In order to compare land cover change between the two time periods, each classification was individually converted to the simplified system. Once the maps are classified, the percent of each land type that has changed between the two periods was determined (if vegetation increased or decreased over time). Then stations were categorized for each study region into station type based on the six LC classifications to determine which LC types influence local precipitation at a single station (urban and non-urban). This was using the same three statistical tests (t-test, Mann-Whitney U-test, K-S test) as done in the temporal and regional analyses. The early period data was compared to the late period data in order to determine if local precipitation has changed at each station. It is expected that stations that have changed from non-urban to urban have experienced a difference in mean precipitation between the two periods.

The results of this analysis will show how these specific LC changes could contribute to precipitation on a broader, city-wide scale. As Dallas and Fort Worth have grown since 1900, numerous smaller surrounding cities were established and continued to grow in number and size until they have merged into what is now the DFW Metroplex.

3.3.2 Station and Population Trend Comparisons

The first method for analyzing precipitation between study regions was comparing trends in precipitation. The first trend was calculated by taking the slope of the best-fit line for the entire period (1930 – 2007). Then, decades were subtracted one at a time and a new trend was calculated (e.g., 1940 – 2007, 1950 – 2007, etc.). If slopes are larger in DFW and CRB, this will allow us to conclude that urbanization is affecting the regional precipitation. Because there was significantly less land being converted to low- and high-density urban in the earlier part of the record, the effects the DFW Metroplex has on the rate of increase (decrease) should not be as considerable when compared to trends in the later part of the record. The same method was applied when determining the trends in population growth. Decades were subtracted from the entire period as each new trend was calculated.

3.3.3 Temporal Comparison

The second objective is to analyze the temporal changes in precipitation from 1930 to 2007. It is expected that precipitation will naturally fluctuate as a result of many factors, and so it may be difficult to determine if these changes are caused by urbanization. Data from an "early" time period will be compared to that of a "late" period. The years chosen for this analysis are 1930–1950 ("early") and 1987–2007 ("late"), because these decades had near-normal rainfall (McRoberts 2008). These comparisons occurred within each study region. For example, the early period in CRA was compared to the late period in CRA, and not any other region. These comparisons are done six times in each region using the six sensitivity tests described in Table 3.3.

There are three statistical tests employed in this comparison: the Two Independent Samples t-test, the Mann Whitney U-test, and the Kolmogorov-Smirnov (K-S) test. The t-test tests the null hypothesis that the means of two sets of data sets are equal. It requires normality (although it is tolerant of some skewness) and similar variance between the two data sets. It was used in Shepherd (2006) and Baumer and Vogel (2007) and will be used in this study to compare mean precipitation in each region from the late period to the mean from the early period. The Mann Whitney U-test compares data sets where the data can be ranked. It does not require normality of the data and can be used on data sets with small sample sizes. The null hypothesis for the U-test is that there is no difference between the mean ranks for each group. The U-statistic measures the segregation and distribution of the data, where greater segregation leads to a lower U-statistic. This test was used in Diem and Mote (2005) and, similar to the t-test, will be used to test how the mean varies between the early and late periods. Lastly, the Kolmogorov-Smirnov (K-S) test is used to compare the probability distribution functions (PDF) of the early period with the late period. It requires that the two samples be independent. This approach was used in Detwiller and Changnon (1967). If it is found that the late period PDF (1930 – 1950) does not match the early period PDF (1987 – 2007), then this will also show overall precipitation change at these regions (Shaw & Wheeler 1994).

The F-test is used to determine if there are any statistically significant differences in standard deviation between the early and late periods. If standard deviation increased (decreased) between the two periods, then the variability of precipitation received at each region has increased (decreased). If it is found that the precipitation in DFW and CRB is becoming more variable, then anthropogenic influences may be the cause.

3.3.4 Regional Comparison

The final objective of this study is to define regional precipitation patterns. This is done by comparing the early and late period values between the three study regions. Consistent with the temporal comparison, the sensitivity tests shown in Table 3.3 will also be applied in this analysis. The same three statistical tests used in the temporal analysis are also used here. First, the early period means are compared between each region (CRA vs. DFW, CRB vs. DFW, CRA vs. CRB). Then, the late period means are compared between each region. The K-S test is used to determine how different the PDF of early and late period rainfall is between the regions. If it is found that DFW or CRB are not similar to CRA, then this confirms that precipitation in the upwind region is significantly different than the urban area or downwind regions.

CHAPTER IV

LAND COVER RESULTS

The purpose of the analyses in this chapter is to determine how the growth and changes in the DFW Metroplex have influenced temporal and regional changes seen in precipitation. Section 4.1 discusses the population growth seen in the metroplex since 1930, and how it is projected to grow over the next 32 years. Section 4.2 compares this population growth with trends in precipitation. Section 4.3 summarizes the changes seen in land cover throughout the three regions since 1976 and Section 4.4 presents individual stations analyses, where the early period was compared to the late period to determine if local influences exist.

4.1 Population

Population data is important in this research as it acts as a proxy for urbanization of the DFW Metroplex. The growth in population is directly related to the growth and extent of the urban area, and so by showing how quickly the metroplex has grown, it may be possible to connect these trends with those seen in precipitation. It was found that population in Dallas County grew the most between 1970 – 2000, followed by Tarrant County, and Collin County. Delta County was growing the slowest but still considered part of the DFW Metroplex. Dallas and Tarrant Counties are the most populated in the metroplex. Table 4.1 shows the total population for each country from 1900 – 2000. Table 4.2 shows the various projections as calculated by the SDCOSD. These projections are useful in that each scenario shows a continuous increase in metroplex population. This allows for the conclusion that if previous urbanization has affected regional precipitation, then these anthropogenic influences are likely to continue in the future as the DFW Metroplex continues to grow and expand. The Zero Migration (0.0) Scenario takes into account the growth of the county as if there were no in- or out-migration. The One-Half 1990-2000 Migration (0.5) Scenario is an average of the Zero Migration and the 1990 – 2000 Scenario. The 1990-2000 Migration (1.0) Scenario uses the migration rates that were occurring during the 1990s. Lastly, the 2000-2004 Migration Scenario uses migration rates that were occurring in the years following 2000. Figure 4.1 shows the growth of each county by decade, allowing for direct comparison between the different scenarios.

Table 4.1. Population of the Dallas/Fort Worth Metroplex by county (in thousands). The total is the sum of population for each county. Projections used here are for the One-half (0.5) scenario as recommended by the Texas State Data Center and Office of the State Demographer (SDCODC) available from their online database.

Year	Collin	Dallas	Delta	Denton	Ellis	Hunt	Johnson	Kaufman	Parker	Rockwall	Tarrant	Wise	Total
1900	50	83	15	28	50	47	34	33	26	9	52	27	**455**
1910	49	136	15	31	54	48	34	35	26	8	109	26	**572**
1920	50	211	16	35	56	50	37	41	23	9	153	23	**704**
1930	46	326	13	33	54	49	33	41	19	8	198	19	**838**
1940	47	399	13	34	48	49	30	38	20	7	226	19	**930**
1950	42	615	9	41	46	43	31	31	22	6	361	16	**1,263**
1960	41	952	6	47	43	39	35	30	23	6	538	17	**1,778**
1970	67	1,327	5	76	47	48	46	32	34	7	716	20	**2,424**
1980	145	1,556	5	143	60	55	68	39	45	15	861	27	**3,017**
1990	264	1,853	5	274	85	64	97	52	65	26	1,170	35	**3,989**
2000	492	2,219	5	433	111	77	127	71	88	43	1,446	49	**5,162**
2010	669	2,563	5	607	136	92	152	90	105	56	1,663	59	**6,197**
2020	863	2,941	5	800	166	108	182	112	123	71	1,896	71	**7,340**
2030	1,097	3,396	5	1,011	197	125	214	138	140	89	2,153	83	**8,649**
2040	1,349	3,919	5	1,243	230	142	250	169	156	110	2,438	95	**10,107**

Table 4.2. Population projections according to the various net migration scenarios and total population for the DFW Metroplex (in thousands) from the Texas State Data Center and Office of the State Demographer (SDCODC) online database.

year	Zero (0.0)	One-half (0.5)	1990 - 2000 (1.0)	2000 - 2004
1900	455	455	455	455
1910	572	572	572	572
1920	704	704	704	704
1930	838	838	838	838
1940	930	930	930	930
1950	1,263	1,263	1,263	1,263
1960	1,778	1,778	1,778	1,778
1970	2,424	2,424	2,424	2,424
1980	3,017	3,017	3,017	3,017
1990	3,989	3,989	3,989	3,989
2000	5,162	5,162	5,162	5,162
2010	5,683	6,197	6,807	6,571
2020	6,052	7,340	9,160	8,567
2030	6,308	8,649	12,522	11,398
2040	6,399	10,107	17,250	15,312

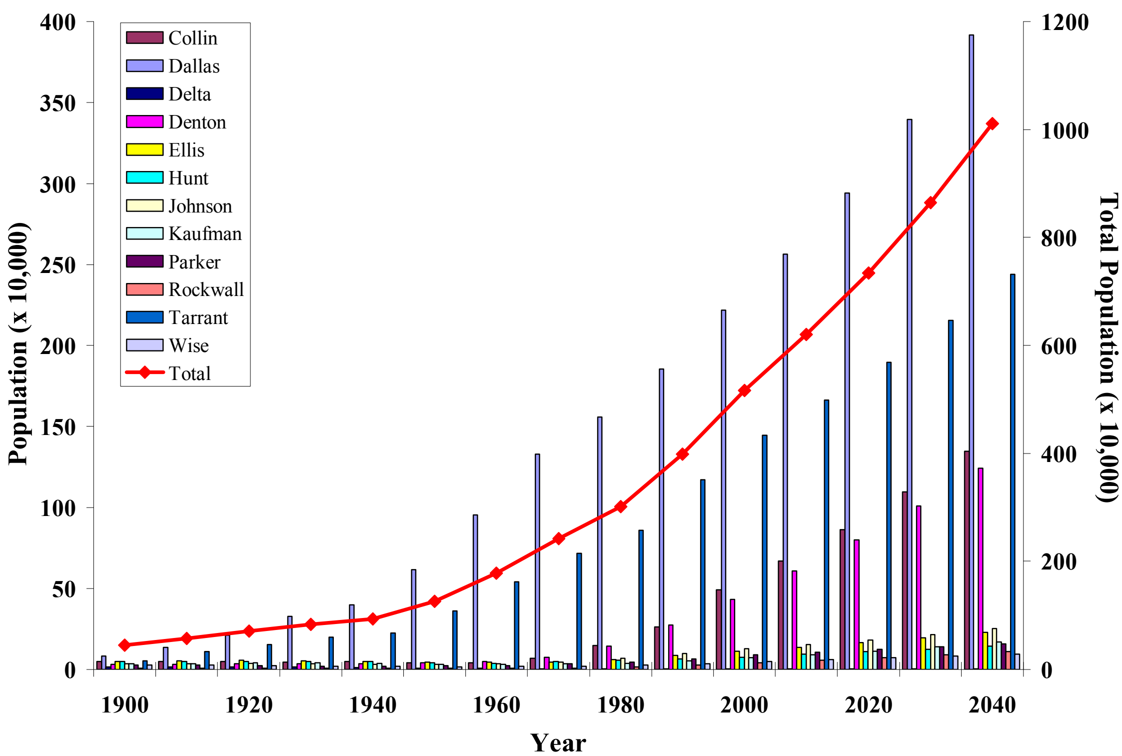

Figure 4.1. The population of each county by decade.

It is projected that by the year 2040, the DFW Metroplex could have approximately 17,250,034 people (using the 1.0 scenario). This is the maximum possible projected growth, where the lowest, using the 0.0 scenario, estimates the metroplex population at 6,398,674 people. With the recommended 0.5 scenario, the metroplex population is estimated to be 10,106,814 people. Figure 4.2 shows the projected growth in population comparing the various scenarios.

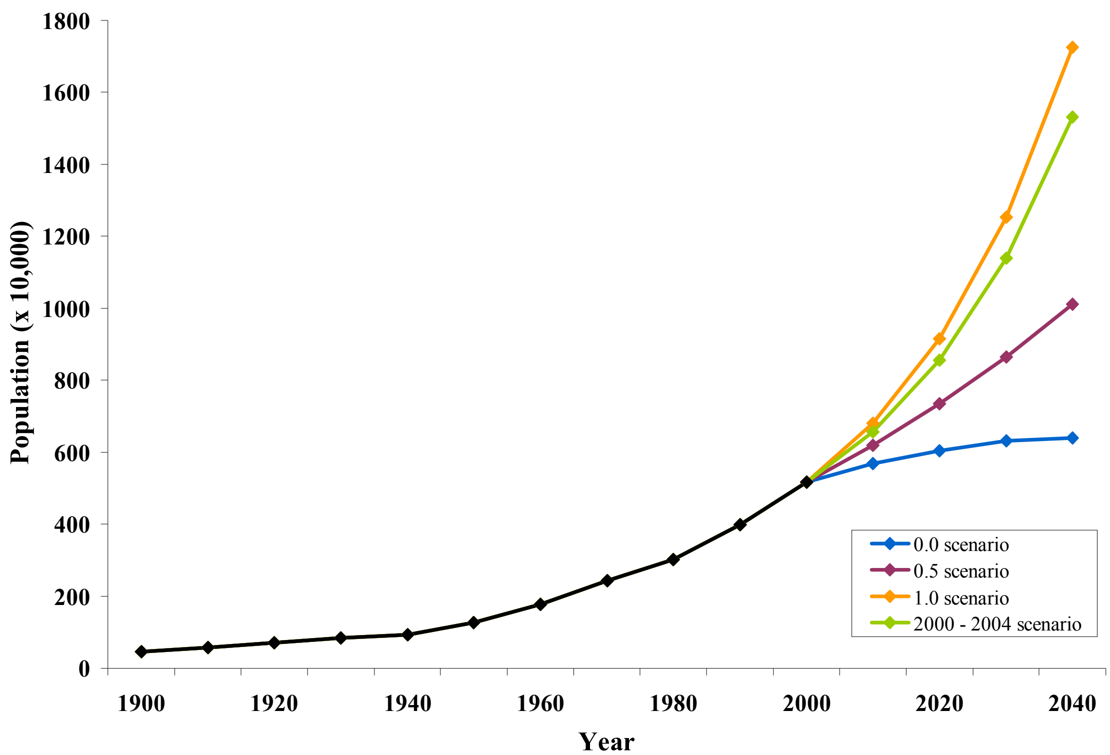

Figure 4.2. The projected growth of the DFW Metroplex to the year 2040 according to the different migration scenarios.

4.2 Comparing Population and Precipitation Trends

A trend analysis was performed to compare the trends in population growth in the DFW Metroplex with precipitation in the three study regions. There have been no studies to compare precipitation directly to population growth although there have been some that found that growing urban regions increase water demand, putting stress on water management during multiyear dry spells (Diaz et al. 1985, Diaz & Anderson 1995). The trends were created by determining the slope of the best-fit line for the data in each period. A total of seven trends were calculated. Decades from the beginning of the period were removed until there are seven trends for each test. Figure 4.3 shows the trends using precipitation data in DFW for Test 1, where a linear trend line is fitted to the population data (using Scenario 0.5). The slopes of the trends for the remaining regions and tests are shown in Table 4.3 for the arithmetic average method. These trends were calculated using the arithmetic average method. The largest slopes for every region were found for the years 2000 – 2007. The slope for CRB increased with each decade, implying that precipitation and the rate of precipitation increase are both is increasing over time. Although, the slopes are also dependent on sample size, the largest slope for each region occurred when the number of stations was small. This further shows how influential individual stations can be when a small number are used to determine a regional value. Slopes for the best fit lines using data from Thiessen-weighted polygons are in Table 4.4. As with the arithmetic average method, slopes increased with each decade, and the largest slopes in the years 2000 – 2007. DFW had the largest slopes, where CRA had the smallest. The time period with the smallest slopes was from 1940 – 2007.

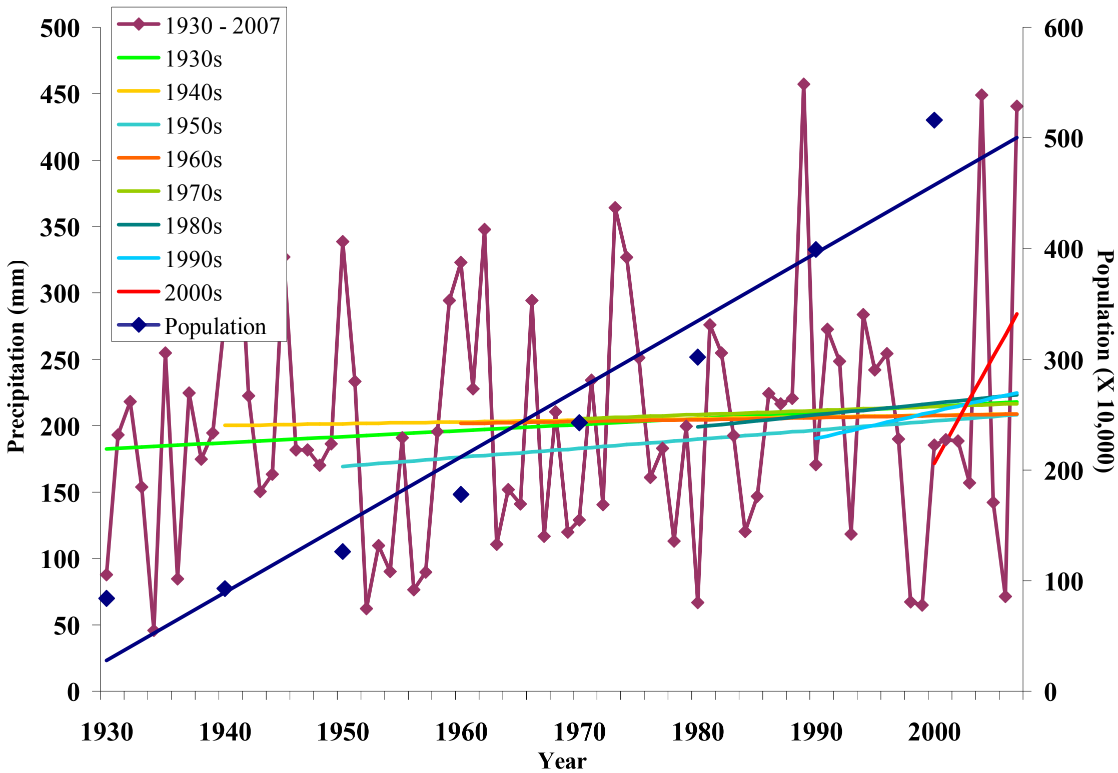

Figure 4.3. The precipitation trends for DFW by decade (shown in legend). The dark blue is the population of the DFW Metroplex while the dark purple is regional precipitation of DFW. The precipitation values are for June, July, and August.

Table 4.3. Slope of the trend line for each corresponding decade to 2007 for the arithmetic average method.

CRA								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.71	0.33	1.18	0.88	0.66	1.32	4.17	9.46
2 (large area)	0.78	0.54	1.25	0.79	0.95	1.92	4.62	14.59
3 (small area)	0.71	0.36	1.14	0.79	0.52	0.93	4.88	10.83
4 (2 stations)	0.68	0.28	1.15	0.68	0.40	0.28	4.88	16.28
5 (3 stations)	0.83	0.41	1.27	1.15	1.24	1.49	4.39	12.51
6 (4 stations)	0.90	0.48	1.33	1.33	1.40	2.04	4.55	10.29
DFW								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.53	0.20	0.70	0.27	0.34	1.01	1.21	19.59
2 (large area)	0.60	0.24	0.85	0.59	0.78	1.26	1.88	21.48
3 (small area)	0.55	0.26	0.78	0.27	0.67	1.20	2.07	18.68
4 (2 stations)	0.41	0.20	0.80	0.29	0.44	0.42	1.97	32.66
5 (3 stations)	0.45	0.20	0.72	0.27	-0.03	0.52	1.55	25.28
6 (4 stations)	0.44	0.12	0.66	0.27	-0.03	0.48	0.51	20.39
CRB								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.60	0.15	0.57	1.06	1.36	1.59	0.50	16.69
2 (large area)	0.64	0.21	0.58	1.13	1.55	1.80	0.98	13.48
3 (small area)	0.52	0.06	0.51	1.04	1.38	1.95	1.41	15.92
4 (2 stations)	0.44	-0.02	0.56	1.46	2.44	4.15	5.98	16.59
5 (3 stations)	0.34	-0.20	0.47	1.35	1.82	3.01	4.07	19.26
6 (4 stations)	0.44	-0.05	0.53	1.13	1.43	1.96	2.22	17.60

Table 4.4. Slope of the trend line for each corresponding decade to 2007 for the Thiessen-weighted polygon method.

CRA								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.71	0.32	1.16	0.86	0.60	1.11	4.19	10.19
2 (large area)	0.72	0.41	1.18	0.72	0.64	1.21	4.27	14.37
3 (small area)	0.59	0.23	1.01	0.51	0.12	0.36	4.50	10.98
4 (2 stations)	0.69	0.29	1.15	0.68	0.40	0.26	4.99	16.35
5 (3 stations)	0.78	0.38	1.23	0.96	0.92	0.99	4.75	14.10
6 (4 stations)	0.82	0.40	1.26	1.10	1.03	1.42	4.61	12.38
DFW								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.59	0.15	0.59	1.18	1.64	2.16	1.30	21.81
2 (large area)	0.62	0.19	0.58	1.14	1.51	1.81	1.20	21.58
3 (small area)	0.54	0.07	0.53	1.08	1.55	2.26	1.25	18.57
4 (2 stations)	0.45	-0.01	0.57	1.46	2.41	4.05	5.70	32.22
5 (3 stations)	0.35	-0.18	0.49	1.34	1.78	2.82	3.51	24.50
6 (4 stations)	0.42	-0.07	0.52	1.18	1.52	2.19	2.60	21.54
CRB								
Test	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**
1 (original area)	0.46	0.13	0.68	0.15	0.31	0.88	2.03	16.07
2 (large area)	0.64	0.29	0.87	0.63	0.83	1.15	1.26	13.60
3 (small area)	0.45	0.14	0.71	0.18	0.58	1.00	2.36	16.42
4 (2 stations)	0.50	0.36	0.92	0.50	0.81	0.61	1.62	18.10
5 (3 stations)	0.66	0.60	1.04	0.79	1.08	0.96	0.85	21.87
6 (4 stations)	0.52	0.33	0.86	0.48	0.57	0.65	1.13	18.90

4.3 Regional Land Cover Change between 1976 and 2001

Land cover data for the years 1976 (Figure 4.4) and 2001 (Figure 4.5) were compared in order to determine how different the study regions were. Each dataset was reclassified into the six simple classifications described in Section 3.3.1 (water, vegetation, low-density urban, high-density urban, woody wetlands, and emergent herbaceous wetlands). The percent change of each land cover class for each region was determined in order to find out how much non-urban land cover was converted into low- or high-density urban.

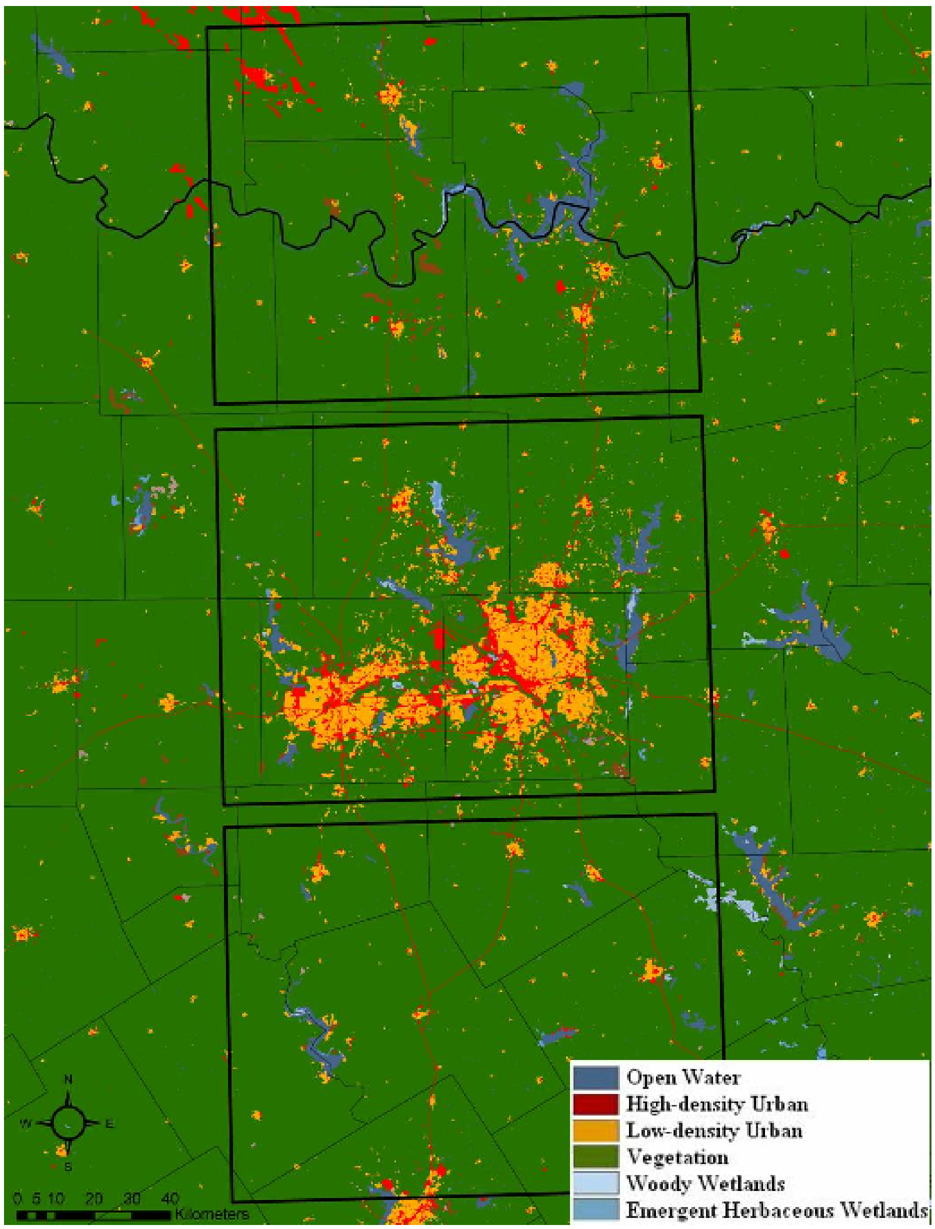

Figure 4.4. 1976 land cover for the three study regions.

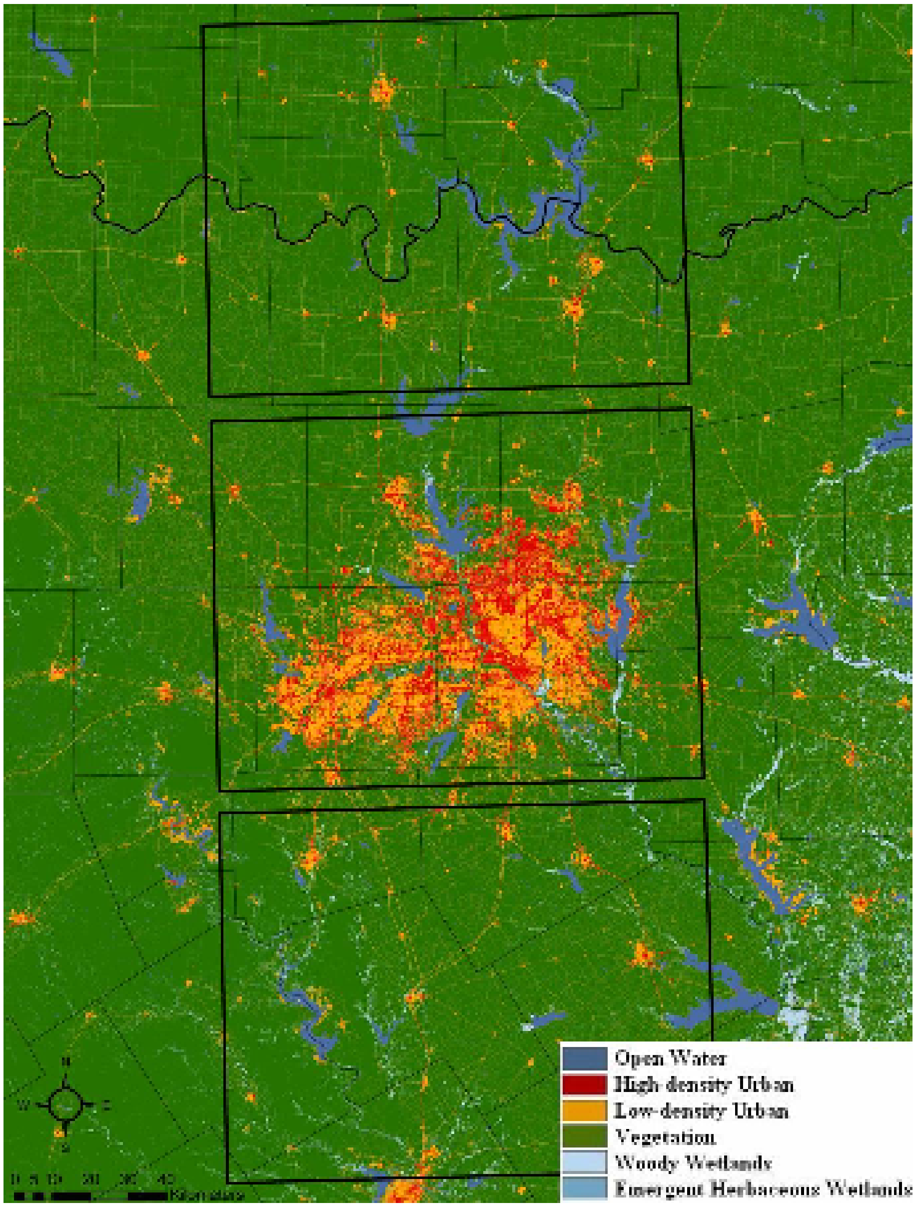

Figure 4.5. 2001 land cover for the three study regions.

The results in Table 4.5 show that vegetation is the dominant land cover in all three regions. DFW had the highest percentages of low- and high-density urban land cover between the two periods. Table 4.6 shows the percentage of land cover in each region that changed between the two periods. Positive values indicate that the classification has increased in land cover while negative values indicate a decrease in land cover. Each region increased their land cover in water, woody wetlands, and emergent herbaceous wetlands. The change in land cover dedicated to water increased at each region (CRA by 75.71%, DFW by 54.75%, and CRB by 26.51%). Vegetation decreased at all regions but it decreased the most (20.34%) in DFW. The amount of low-density urban land cover increased in all areas, with CRA (272.48%) and CRB (136.36%) having the largest percentages. The area dedicated to high-density urban increased only at DFW (113.88%), while it decreased in both CRA (39.02%) and CRB (66.92%). It is not possible to determine why this is occurring without further investigation, but it is hypothesized that industries located in the small towns have been displaced, or the towns are becoming more agricultural-based (thus the increase in low-density land cover as residential land uses are increased). The largest percent change was seen in the increase in woody wetlands at each region. CRA increased the most at 856%, followed by DFW at 203.45%, and CRB by 120%. Figure 4.6 graphically shows the percentage of land cover that has changed at each study region between 1976 and 2001. In order to determine where the three regions have experienced increases in urban land cover, each region was reclassified into urban and non-urban classes (binary system) (Figure 4.7). Then, the dataset for 1976 was subtracted from the 2001 dataset to determine which regions have changed. Areas shown in red were converted to urban and those shown in blue were converted to non-urban between the two periods. It is confirmed that DFW experienced the largest increase in urban land cover while largely decreasing the non-urban land cover. While urban land cover has increased in all directions surrounding the Metroplex, the growth of the metroplex mostly expanded northward and between the cities of Fort Worth and Dallas. CRA and CRB experienced less increases in urban land cover while more increases in non-urban land cover.

Table 4.5. Land cover distribution by region (%).

	1976			2001		
Land cover class	**CRA**	**DFW**	**CRB**	**CRA**	**DFW**	**CRB**
Water	1.40	3.05	3.32	2.46	4.72	4.20
Vegetation	95.97	78.82	92.71	88.99	62.79	89.33
Low-density urban	1.49	12.77	2.42	5.55	20.72	5.72
High-density urban	0.82	4.90	1.33	0.50	10.48	0.44
Woody wetlands	0.25	0.29	0.10	2.39	0.88	0.22
Emergent herbaceous wetlands	0.07	0.17	0.11	0.11	0.41	0.09
Total	**100**	**100**	**100**	**100**	**100**	**100**

Table 4.6. Land cover change by region (changes in class (%)). Positive values indicate an increase in land cover while negative values indicate a decrease in land cover.

Land cover class	**CRA**	**DFW**	**CRB**
Water	75.71	54.75	26.51
Vegetation	-7.27	-20.34	-3.65
Low-density urban	272.48	62.26	136.36
High-density urban	-39.02	113.88	-66.92
Woody wetlands	856.00	203.45	120.00
Emergent herbaceous wetlands	57.14	141.18	-18.18

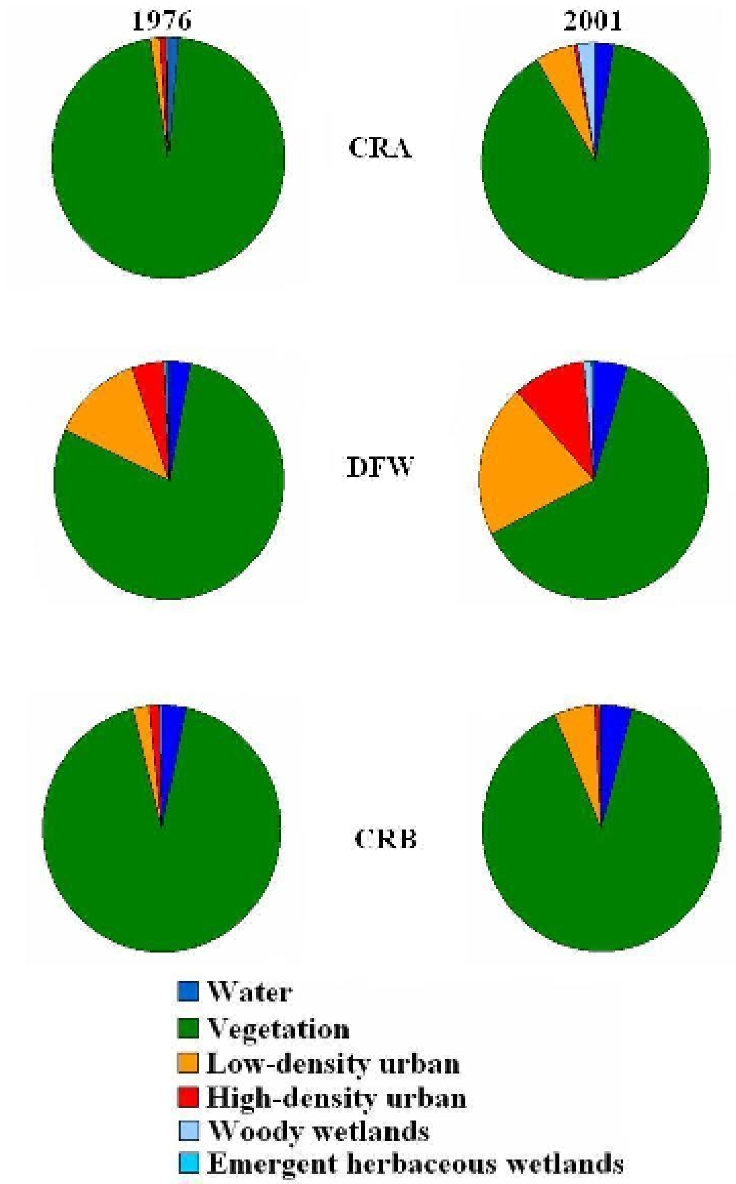

Figure 4.6. Land cover change in each study region between 1976 and 2001.

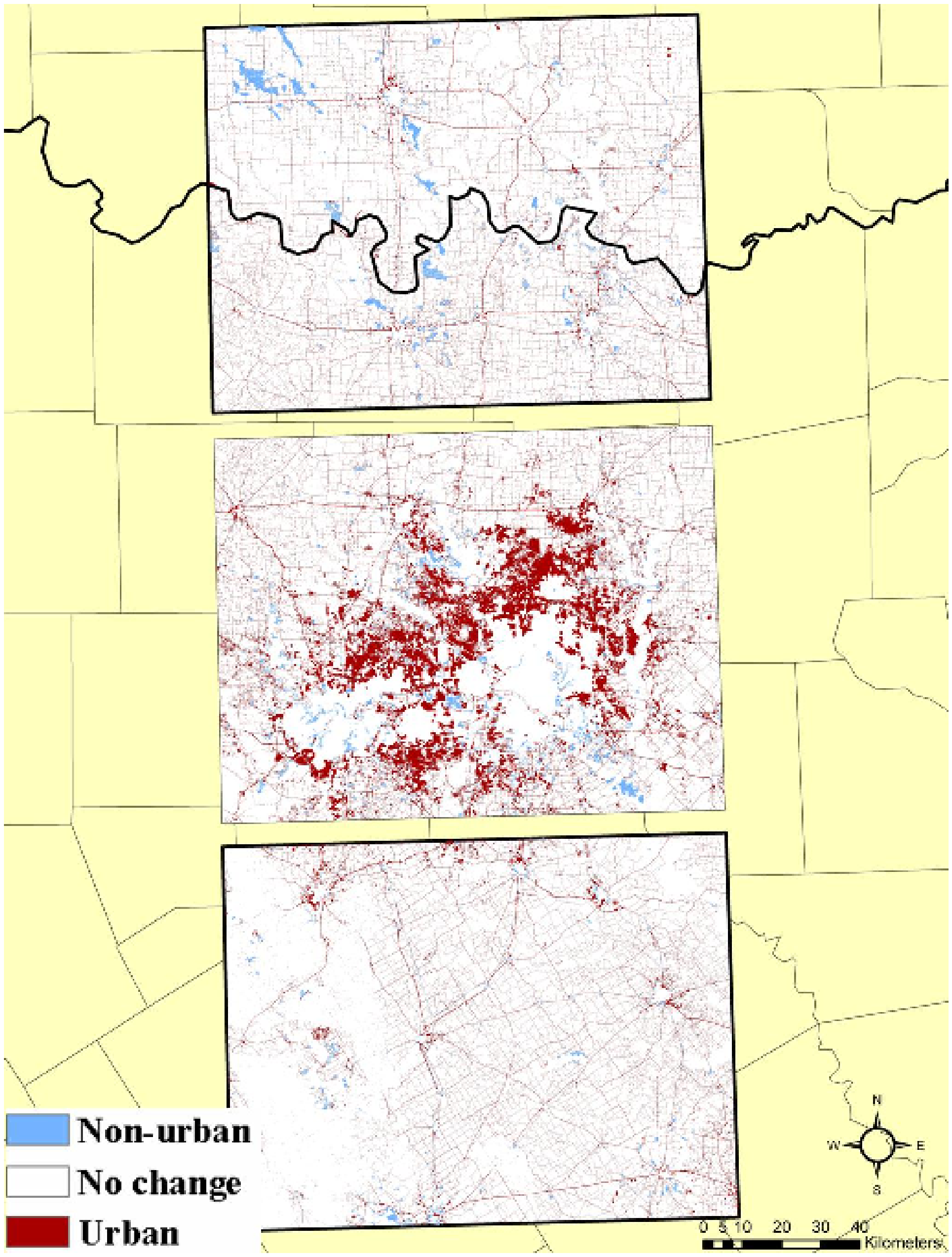

Figure 4.7. Changes in land cover for all three study regions. Areas in blue were converted to non-urban, areas in red were converted to urban, while areas that remain white have not changed between 1976 and 2001.

For all three regions, the main land cover changes are: increases in water, decreases in vegetation, increases in low- and high-density urban, and increases in woody and emergent herbaceous wetlands. Each land cover change will have a direct influence on the local climate. By increasing the amount of water, and local wetlands, there is more available moisture for evaporation. During the summer when temperature increases rapidly throughout the day, or even if the UHI were to strengthen, the additional water will increase atmospheric moisture (which can also decrease the UHI effect in response). This moisture will then increase the local or downwind rainfall. By decreasing the amount of vegetation in the region, the albedo and surface composition are changed. This will lead to an increase in temperatures as radiation is not released from the ground as easily, strengthening the UHI effect. Also, evapotranspiration will decrease, lessening the amount of atmospheric moisture that contributes to local precipitation. By increasing the amount of low- and high-density urban land cover, similar to the situation with vegetation, the albedo and surface characteristics are changed, leading to higher temperatures. As various types of surfaces are established (especially impervious surfaces), surface runoff is increased as water available for evaporation is transported downstream. Lastly, the wind pattern is altered as buildings are constructed, which may increase friction, convergence, and lifting over the city.

4.4 Station Comparison

A total of 23 stations from the three study regions were chosen for further analysis of the precipitation by LC type: fourteen stations located in an urban LC setting and nine stations located in a vegetative or non-urban setting (Figure 4.8, Table 4.7). If the station was surrounded by urban land cover, it was considered urban (if the station was not then it was considered non-urban). The three statistical tests that will be used in Chapters V and VI were run to compare precipitation from the early and late periods in each station individually to determine if any statistically significant changes have occurred over time. If it is found that precipitation is statistically significantly different between the two periods for stations classified as urban in 2001, then nearby urbanization may be an influence. It is possible that by changing nearby land cover, local precipitation can be influenced. The addition of reservoirs can increase the amount of available atmospheric moisture. Changing vegetation to urban land cover will increase the surface temperatures and decrease available moisture. Because the scale of urban influence on precipitation is up to 75 km downwind (Shepherd et al. 2002), stations that do experience a change in precipitation over time may be affected by more than local land cover, where further investigation is necessary to approximate the source of main influence. The results of the t-test in Table 4.8 show that only one station received a statistically significant different mean precipitation between the early and late periods. In CRA, station 419522 had a t-statistic of 2.190 and a p-value of 0.034. One station in CRB, 342678, was close with a p-value of 0.069. The results of the Mann-Whitney U-test show that two stations are receiving statistically significant different amounts of precipitation between the early and late periods, station 419522 (p-value = 0.038) and station 342678 (p-value = 0.044) (Table 4.9). The results of the K-S test found that none of the urban stations received statistically significant different precipitation between the early and late periods (Table 4.10), although two stations were close (419522, p-value = 0.095; 342678, p-value = 0.095).

Table 4.7. Each station classified as "urban" or "non-urban".

Region	COOPID	1976 classification	2001 classification	Final classification
CRA	412019	urban	urban	urban
	419419	urban	urban	urban
	411800	urban	urban	urban
	419522	urban	urban	urban
	415869	urban	non-urban	transition
	419715	non-urban	non-urban	non-urban
	414182	non-urban	non-urban	non-urban
DFW	413691	urban	urban	urban
	412404	urban	urban	urban
	417707	urban	urban	urban
	410691	urban	urban	urban
	419125	non-urban	non-urban	non-urban
	417028	non-urban	non-urban	non-urban
	417659	non-urban	urban	transition
CRB	340292	urban	urban	urban
	342678	urban	urban	urban
	418274	urban	urban	urban
	345468	non-urban	urban	transition
	344001	non-urban	urban	transition
	413247	non-urban	non-urban	non-urban
	416130	non-urban	non-urban	non-urban
	345563	non-urban	non-urban	non-urban
	348884	non-urban	non-urban	non-urban

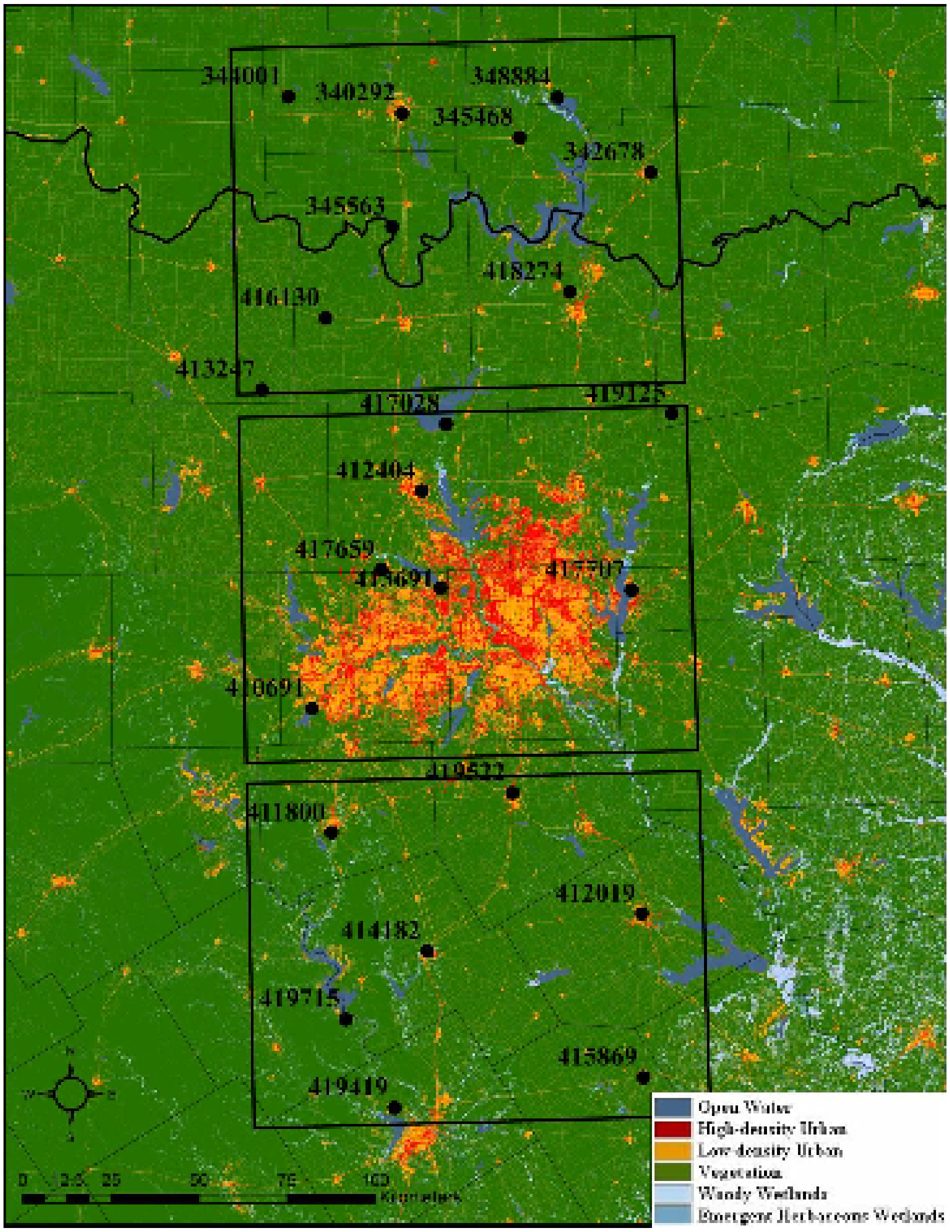

Figure 4.8. The urban and non-urban stations used in the station comparison.

Table 4.8. P-values and t-statistic values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for urban stations.

Study region	Station ID	t-statistic	p-value
CRA	415869	0.710	0.482
	419419	0.046	0.964
	419522	2.190	0.034*
	411800	1.570	0.124
	412019	0.391	0.698
DFW	410691	0.877	0.386
	412404	1.033	0.308
	413691	0.765	0.449
	417707	0.665	0.510
	417659	1.665	0.104
CRB	340292	0.083	0.934
	418274	0.247	0.806
	344001	0.734	0.467
	342678	1.866	0.069

Table 4.9. P-values and U-statistic values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for urban stations.

Study region	Station ID	U-statistic	p-value
CRA	415869	187.5	0.406
	419419	219.0	0.970
	419522	138.0	0.038*
	411800	178.5	0.291
	412019	201.0	0.624
DFW	410691	188.0	0.414
	412404	198.0	0.571
	413691	204.5	0.687
	417707	177.5	0.279
	417659	177.0	0.274
CRB	340292	214.0	0.870
	418274	214.0	0.870
	344001	200.0	0.606
	342678	140.5	0.044*

Table 4.10. P-values and Z-values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for urban stations.

Study region	Station ID	Z-value	p-value
CRA	410691	0.772	0.591
	412404	0.617	0.841
	413691	0.772	0.591
	417707	0.926	0.358
	417659	0.772	0.591
DFW	415869	0.617	0.841
	419419	0.617	0.841
	419522	1.234	0.095
	411800	0.772	0.591
	412019	0.617	0.841
CRB	340292	0.463	0.983
	418274	0.772	0.591
	344001	0.617	0.841
	342678	1.234	0.095

The results of the t-test in Table 4.11 show that none of the non-urban stations received a statistically significant different mean precipitation between the early and late periods. In CRB, station 342678 was close with a p-value of 0.069. Results of the Mann-Whitney U-test did find statistically significant differences between early and late precipitation at station 342678 (p-value = 0.044) (Table 4.12). There were no statistically significant results from the K-S test but the same station, 342678, was close with a p-value of 0.095 (Table 4.13).

Table 4.11. P-values and t-statistic values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for non-urban stations.

Study region	Station ID	t-statistic	p-value
CRA	419715	0.973	0.337
	414182	0.164	0.870
DFW	419125	0.393	0.696
	417028	0.656	0.516
CRB	345468	0.626	0.535
	345563	0.411	0.684
	348884	0.626	0.535
	413247	0.270	0.789
	416130	0.574	0.569

Table 4.12. P-values and U-statistic values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for non-urban stations.

Study region	Station ID	U-statistic	p-value
CRA	419715	193.0	0.489
	414182	208.0	0.753
DFW	419125	216.0	0.910
	417028	191.0	0.458
CRB	345468	201.0	0.624
	345563	211.0	0.811
	348884	216.5	0.920
	413247	213.0	0.850
	416130	211.5	0.821

Table 4.13. P-values and Z-values (arithmetic mean method) for comparing the early (1930 – 1950) and late (1987 – 2007) periods for non-urban stations.

Study region	Station ID	Z-value	p-value
CRA	419715	0.772	0.591
	414182	0.463	0.983
DFW	419125	0.617	0.841
	417028	0.617	0.841
CRB	345468	0.617	0.841
	345563	0.463	0.983
	348884	0.617	0.841
	413247	0.772	0.591
	416130	0.617	0.841

In order to see how much change has occurred between the early and late period, at these stations, a difference map was created using both urban and non-urban stations (Figure 4.9). There are a few stations that have received higher amounts of precipitation in the late period (342678, 417659, 419522, and 411800), while only a couple are experiencing decreases between the early and late periods (340292 and 417707). This figure shows that precipitation has increased in the northern half of CRA, western half of DFW, and northeastern half of CRB. This is different from the findings of Shepherd et al. (2002) who found increased amounts of precipitation to the east and northeast of the DFW Metroplex.

4.5 Summary

The purpose of this chapter was to investigate the relationship between land cover change and changes in regional precipitation patterns in and around the DFW Metroplex. The population data showed that the fastest growing counties in the DFW Metroplex were Dallas, Tarrant, and Denton Counties. By the year 2000, there were a total of 5,162,000 people living in the twelve counties that makeup the metropolitan region.

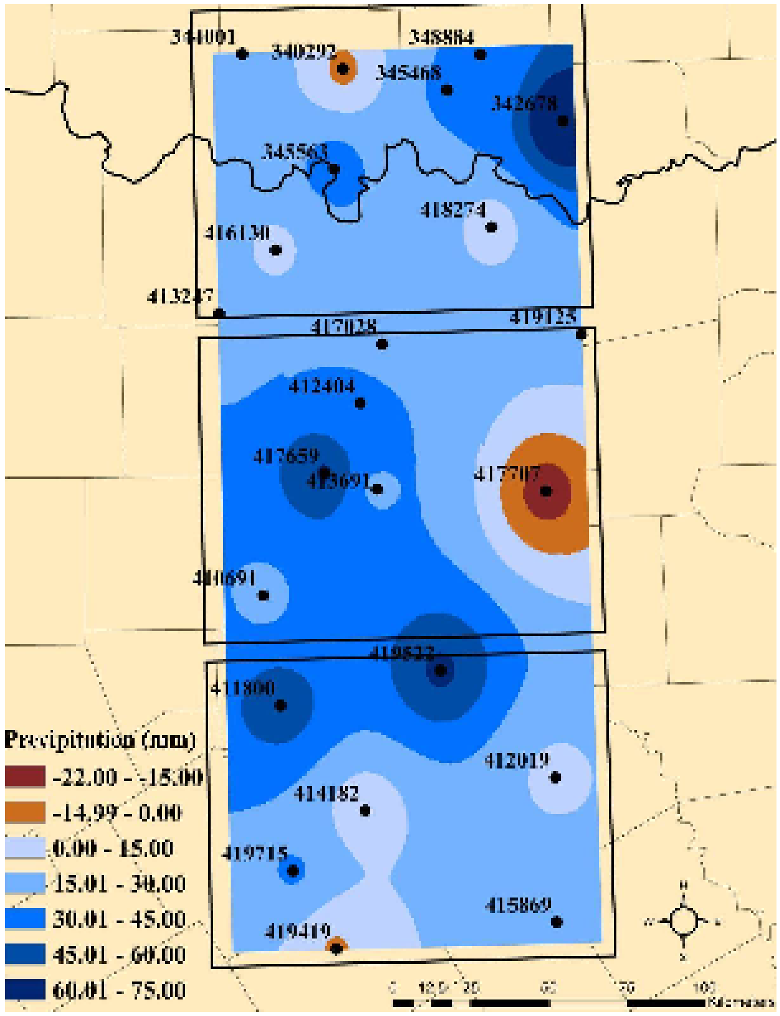

Figure 4.9. Late period precipitation (mm) minus early period precipitation (mm) for stations used in the urban and non-urban station comparison.

With analyzing the trends in precipitation occurring at each station over the entire time period, it was found that the period with the largest slopes was for the years 2000 – 2007. The period with the smallest slopes was for the years 1940 – 2007. The region with the largest slopes was DFW, followed by CRB. Data derived from the arithmetic average method tends to produce slopes larger than those of the Thiessen-weighted polygon method for any time period, growing larger in the later decades. The periods that seemed to have the greatest difference between arithmetic average-derived precipitation and Thiessen-weighted polygon-derived precipitation were from 1960- to 1980 – 2007. Lastly, Tests 3, 4, and 5 seemed to have the highest slopes in the later decades as the values are dependent on only a small number of stations.

The results of the land cover change analysis showed that low-density urban and woody wetlands had the largest percent changes in each region between 1976 and 2001. CRA also experienced decreased high-density urban land cover and increased low-density urban land cover. In 1976, 95% of the land cover was vegetative but decreased to 88% in 2001. DFW experienced a large decrease in vegetative cover from 78% in 1976 to 63% in 2001. The low-density urban cover increased by almost 8% while the high-density urban cover increased by about 5.5% between the two periods. CRB experienced a slight decrease in vegetation from 93% in 1976 to 89% in 2001. Low-density urban land cover increased by 3.3%. Even though woody wetlands had the highest percent changes between the two periods, it still only encompasses 2.39% at CRA, 0.88% at DFW, and 0.22% at CRB.

All urban and non-urban stations in each study region for Test 1 were compared to each other using the three statistical tests from Chapters V and VI in order to determine if there was a statistically significant difference in the precipitation received between the early and late periods. For the urban stations, only one station (419522) had statistically significant differences in mean precipitation between the early and late decades for both the t-test and Mann-Whitney U-test, while being close to significant for the K-S test. The cause for this may be the increase in urban land cover surrounding the station. The same influences may be occurring at station 342678 in CRB, which was statistically significant in the Mann-Whitney U-test, and close for the t-test and K-S tests. Because there were no stations for the rural analysis found to be statistically significant, or even close to significant, it is possible that these stations are not as sensitive to local changes in land cover as the urban ones.

To revisit what was stated in the literature review (Chapter II), there are many aspects of land use and land cover change within an urban environment that can influence the micro-climate and precipitation measured at a station. If there are nearby factories or industrial areas, emitted aerosols will either inhibit or enhance (depending on size) local and downwind precipitation. If a station is located within a green zone, then the local temperatures would be lower (compared to a station located over concrete) and the relative humidity would be higher. The location of a station relative to nearby buildings can influence the wind field around the rain gauge, affecting how much precipitation is measured. Additionally, increasing the number and density of buildings will lead to increased friction and convergence. Changes in available surface water (e.g., addition of reservoirs, expansion of rivers, etc.) will affect the amount of atmospheric moisture available for evaporation. Even though land use and land cover surrounding each station was not studied at a scale that would allow for specific conclusions based upon these influences, it is important to state that they all play a role in the amount of precipitation measured at each station.

With the evidence provided by the population growth, precipitation trend results, and urban station analyses, it is possible that the urbanization of the DFW Metroplex is influencing regional precipitation patterns. The rapid population growth in the metropolitan region mirrors the trends seen in the rainfall over the last few decades. The urban station analysis shows that local land cover may have an influence in some cases, but if there is an influence throughout DFW, it is not large enough to detect using these methods. Although it cannot be stated that urbanization is the sole cause of these changes, it seems to be a contributing factor.

CHAPTER V

TEMPORAL COMPARISON RESULTS

The following temporal analyses were performed by comparing the early period (1930 – 1950) to the late period (1987 – 2007) for each region in order to detect statistically significant differences in rainfall in those decades that were chosen to represent low- and high-urban periods of development. The three statistical tests described in Chapter III are employed here (Two Independent Samples t-test, Mann-Whitney U-test, Kolmogorov-Smirnov test) for both the arithmetic average method and Thiessen-weighted polygon method. Lastly, the F-test is used to test whether there has been a statistically significant change in the standard deviation between the early and late periods. Section 5.1 describes the results based on the arithmetic average method, Section 5.2 describes the results based on the Thiessen-weighted polygon method, and Section 5.3 summarizes the results of the temporal comparison.

5.1 Arithmetic Average Method

In the arithmetic average method, the regional precipitation value is determined by taking the sum of all the stations in the region, and then dividing by the total number of stations (as described in section 3.3). For each test performed, if there was a significant change in values that occurred between the early and late periods, it may be possible to infer that urbanization or anthropogenic processes may be influencing precipitation.

5.1.1 Two Independent Samples t-test

The six sensitivity tests described in Section 3.1 (Table 5.1) were performed using the two independent samples t-test. The early period (1930 – 1950) was compared to the late period (1987 – 2007) for each region individually (Figures 5.1 and 5.2). The difference in means (Tables 5.2 and 5.3) shows that precipitation has increased in all three regions but by similar amounts (CRA increased the most). Test 1 consisted of all stations that were available for the study period (1930 – 2007) and that met the selection criteria described in section 3.2.1. By analyzing CRA, CRB, and DFW individually, it was found that none of the difference of means for the early and late period are statistically significant (at 0.05 level) (Table 5.4). In studying the standard deviation between the two periods, it was found that CRA and DFW have become increasingly variable (Figures 5.3 and 5.4). DFW experienced the largest change in standard deviation while it decreased at CRB (Table 5.5 and Figure 5.5). In order to determine if the difference in standard deviation between the early and late periods is statistically significant, an F-test was performed. Table 5.6 shows the F-statistic values and p-values for all tests using precipitation from the arithmetic average method but no values were found to be statistically significant.

Table 5.1. The six sensitivity tests that will be altered in each temporal and regional analysis as previously described in Section 3.3.

Test	Variables altered
1	Area 1 (A1, initial size, same for all other analyses unless specified)
2	Area 2 (A2, Area is 25% greater than A1)
3	Area 3 (A3, Area is 25% less than A1)
4	2 stations/ region (stations: 412019, 419715, 416130, 418274, 417707, 417659)
5	3 stations/ region (stations: 412019, 419715, 419522, 416130, 418274, 340202, 417707, 417659, 417028)
6	4 stations/ region (stations: 411800, 412019, 419715, 419522, 416130, 418274, 340202, 348884, 417707, 417659, 417028, 419125)

Table 5.2. Mean precipitation (mm) for the early and late periods.

	Early period (1930 – 1950)			Late period (1987 – 2007)		
Test	**CRA**	**DFW**	**CRB**	**CRA**	**DFW**	**CRB**
1 (original area)	185.17	203.81	225.17	211.49	227.82	252.46
2 (large area)	180.96	198.01	231.01	215.42	223.82	260.64
3 (small area)	185.51	192.01	231.23	211.13	217.79	251.31
4 (2 stations)	183.50	203.27	227.29	205.21	223.13	237.90
5 (3 stations)	182.37	212.03	235.23	217.70	233.25	241.26
6 (4 stations)	182.86	218.28	236.35	222.75	238.00	248.85
Mean	**183.40**	**204.57**	**231.05**	**214.00**	**227.30**	**248.74**

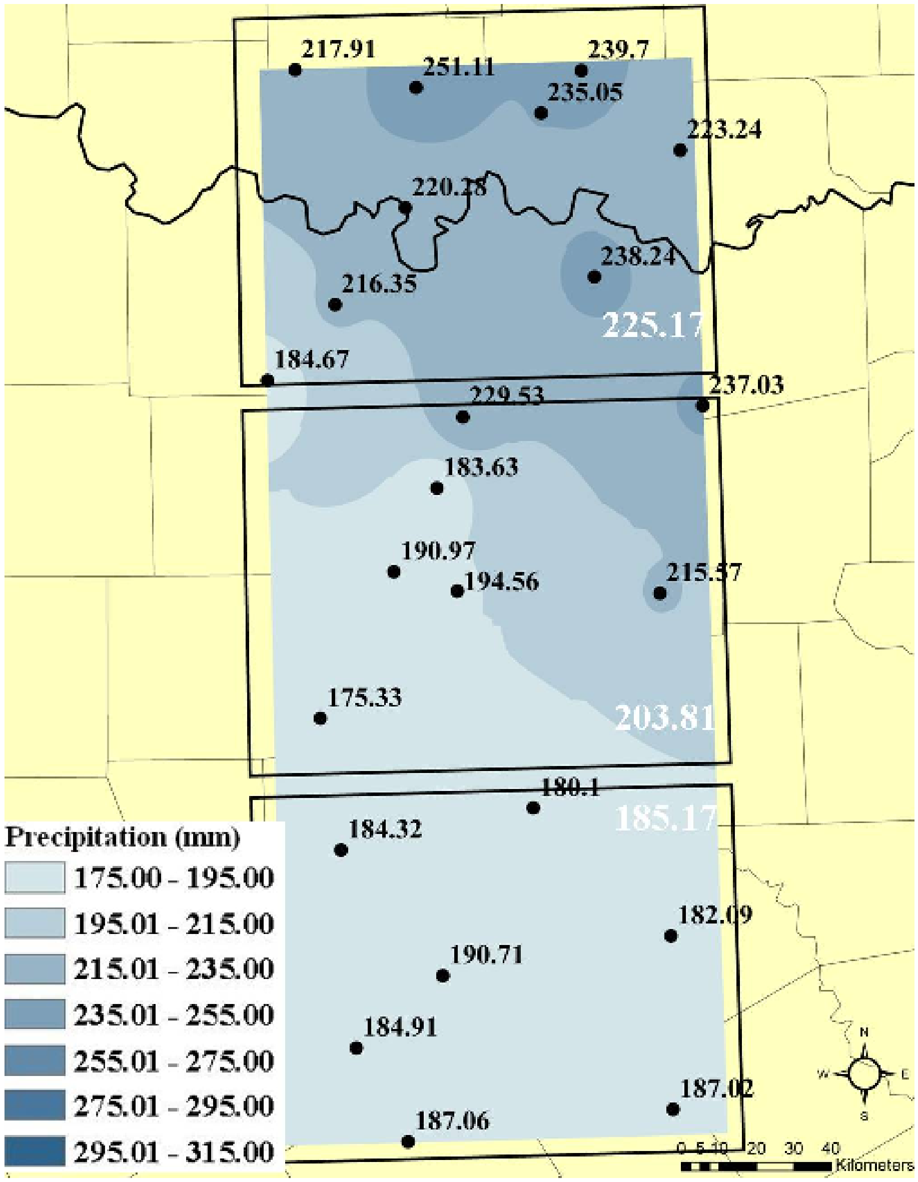

Figure 5.1. Early period precipitation (mm) (1930 - 1950) for the regions CRA, DFW, and CRB with regional mean precipitation (arithmetic average method) labeled in white.

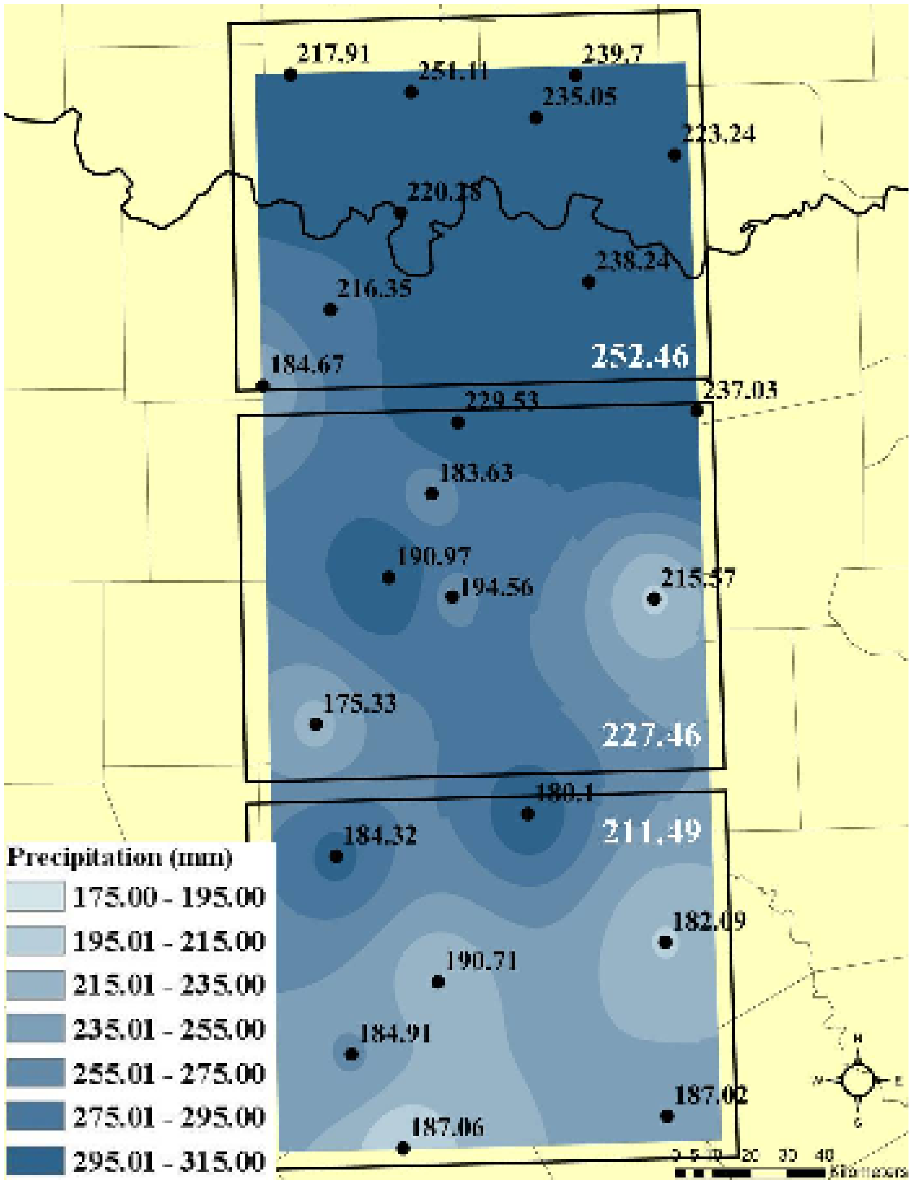

Figure 5.2. Late period precipitation (mm) (1987 - 2007) for regions CRA, DFW, and CRB with regional mean precipitation (arithmetic average method) labeled in white.

Table 5.3. Difference in means (mm) between the early and late periods (Late period – early period).

	Difference in Means (Late period – early period)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	26.32	24.01	27.29
2 (large area)	34.46	25.81	29.63
3 (small area)	25.63	25.78	20.08
4 (2 stations)	21.71	19.85	10.61
5 (3 stations)	35.33	21.22	6.02
6 (4 stations)	39.89	19.72	12.50
Mean	**30.56**	**22.73**	**17.69**

Table 5.4. Difference of means for early and late period (two independent samples t-test) for the arithmetic mean method.

	t-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	0.982 (0.332)	0.766 (0.449)	0.247 (0.806)
2 (large area)	1.361 (0.181)	0.879 (0.385)	0.907 (0.370)
3 (small area)	0.892 (0.378)	0.842 (0.406)	0.598 (0.553)
4 (2 stations)	0.744 (0.461)	0.618 (0.540)	0.287 (0.776)
5 (3 stations)	1.270 (0.210)	0.660 (0.513)	0.169 (0.867)
6 (4 stations)	1.438 (0.158)	0.601(0.551)	0.353(0.726)

Table 5.5. Standard deviation (mm) for mean precipitation (arithmetic mean method) for the early and late period.

	CRA		DFW		CRB	
Test	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
1 (original area)	83.48	90.16	87.92	113.73	111.82	102.50
2 (large area)	76.32	87.33	84.82	99.14	113.95	104.58
3 (small area)	89.25	96.91	80.77	114.89	116.58	100.68
4 (2 stations)	94.97	94.07	78.26	124.94	124.66	114.80
5 (3 stations)	88.31	94.42	87.76	118.13	83.43	90.16
6 (4 stations)	87.73	95.64	91.53	119.23	124.30	104.38
Mean	**86.68**	**93.09**	**85.17**	**115.01**	**112.46**	**102.85**

Table 5.6. F and p-values for the F-test determined using the arithmetic average method.

	F-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	0.857 (0.367)	0.598 (0.129)	1.190 (0.350)
2 (large area)	0.764 (0.276)	0.732 (0.246)	1.187 (0.352)
3 (small area)	0.848 (0.358)	0.494 (0.062)	1.340 (0.259)
4 (2 stations)	1.020 (0.483)	0.392 (0.021)*	1.179 (0.358)
5 (3 stations)	0.933 (0.439)	0.552 (0.096)	1.395 (0.232)
6 (4 stations)	0.766 (0.289)	0.591(0.471)	1.418 (0.221)

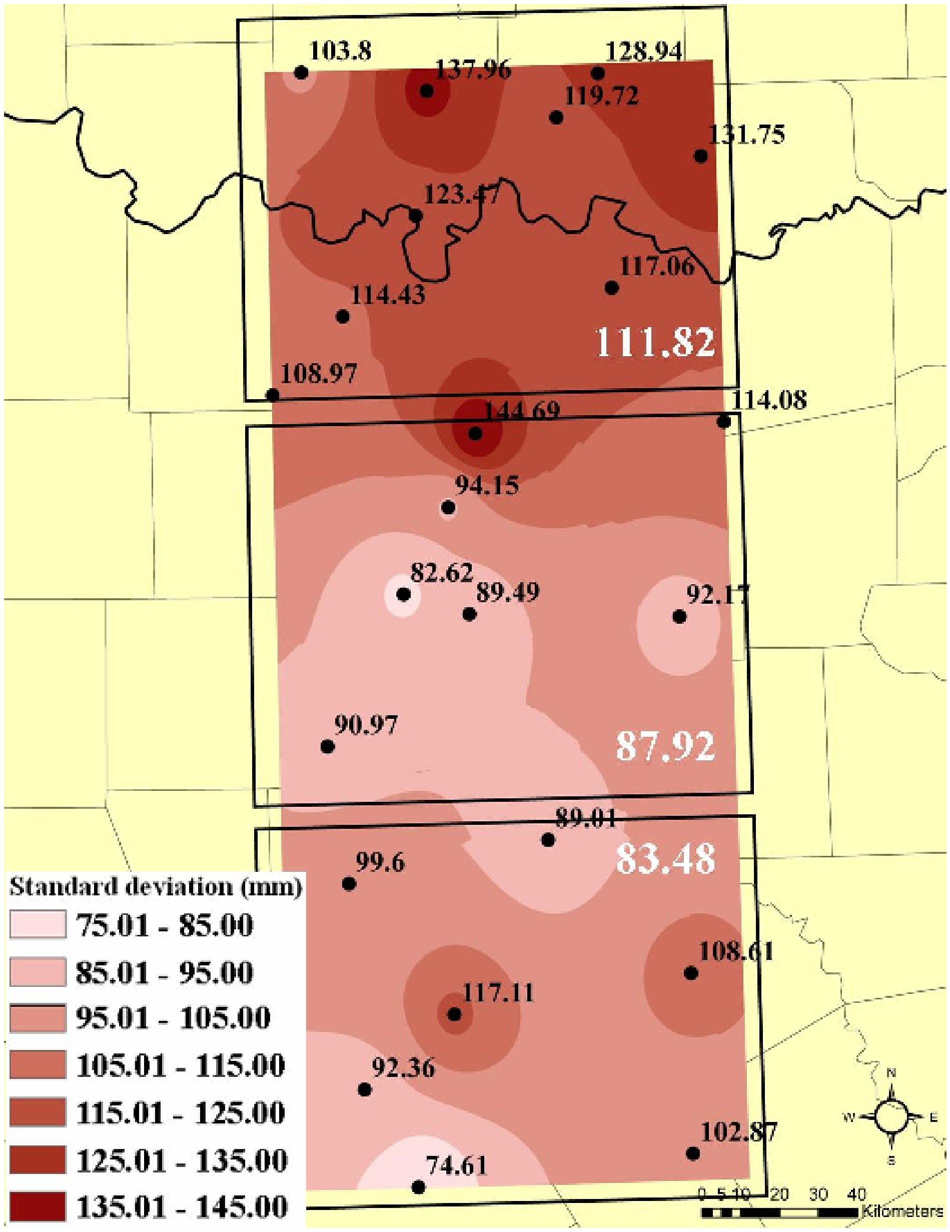

Figure 5.3. Early period (1930 - 1950) standard deviation (mm) for CRA, DFW, and CRB with regional mean standard deviation (arithmetic average method) labeled in white.

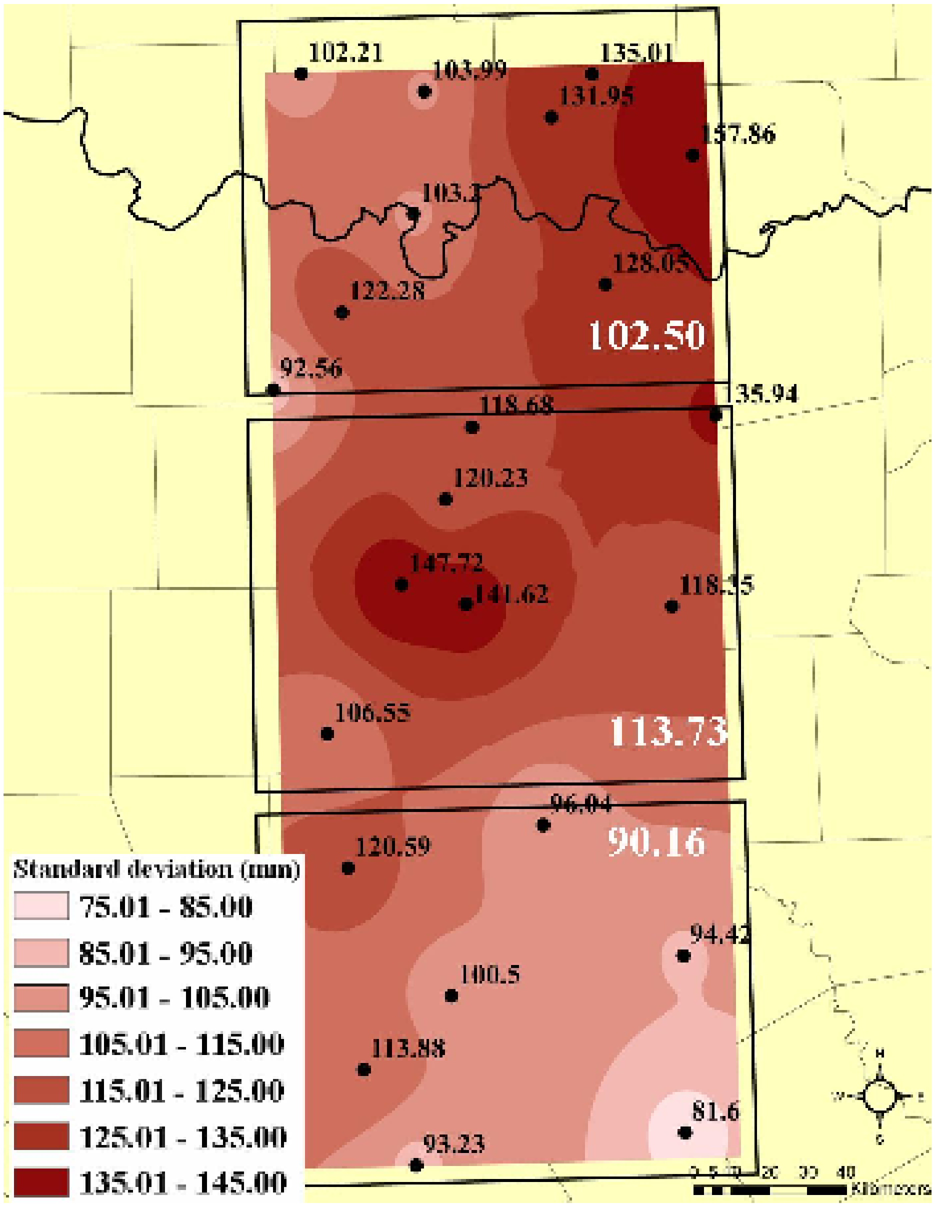

Figure 5.4. Late period (1987 - 2007) standard deviation (mm) for CRA, DFW, and CRB with regional mean standard deviation (arithmetic average method) labeled in white.

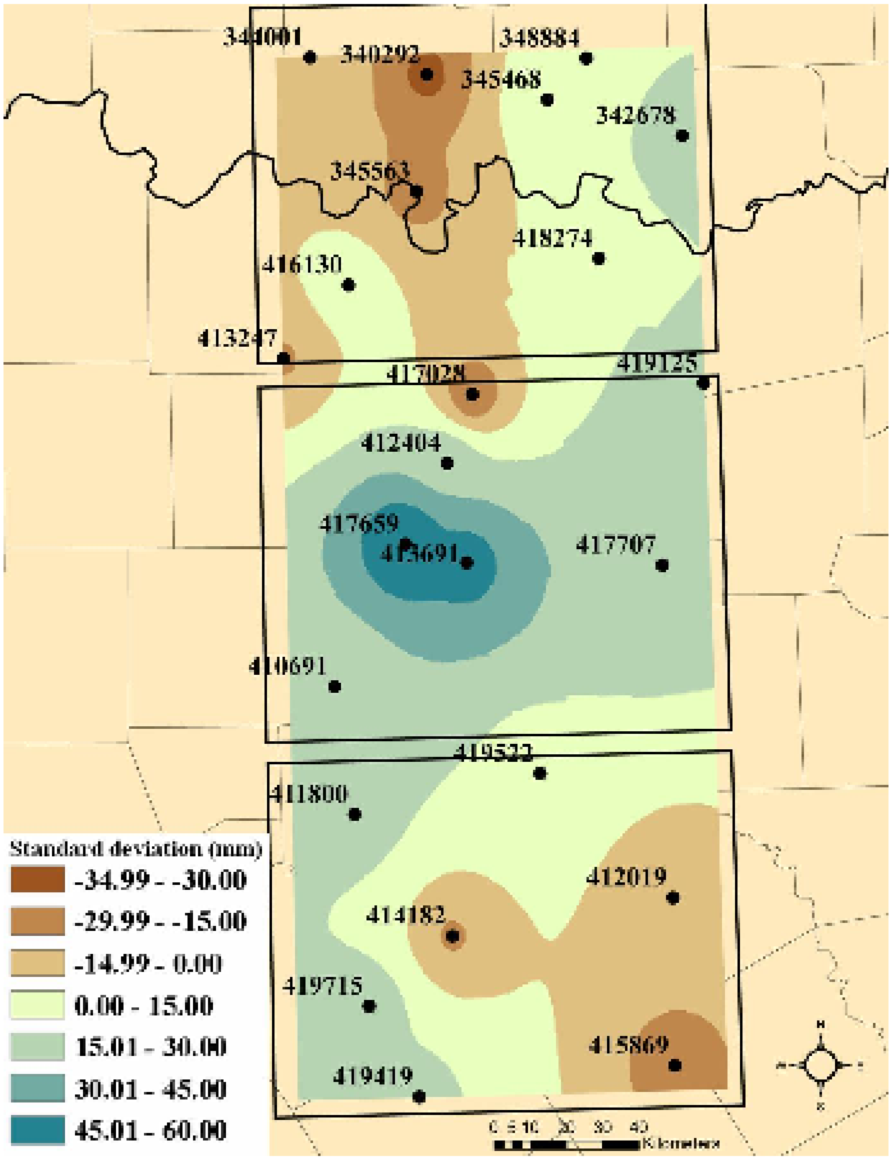

Figure 5.5. Difference in standard deviation (mm) between the early (1930 - 1950) and late (1987 - 2007) periods.

As the study area for each region was increased by 25%, Test 2 consisted of adding additional stations to the same stations in Test 1. As seen in the first test, there were no statistically significant values although the CRA was the closest (p-value = 0.181). The change in standard deviation was not found to be statistically significant (Table 5.6).

In Test 3, the size of the original study areas was decreased by 25%, and so a smaller number of stations were used. There were no statistically significant results, but the difference in means shows that precipitation increased in all regions. Since this test is for the smallest area, stations in the DFW region should be mainly urban. The standard deviation has increased at both CRA and DFW, meaning they have become more variable but decreased at CRB. Only DFW was close to significant for comparing standard deviation between the early and late periods (p-value = 0.062). Also, the difference in means for CRA and DFW were very similar.

Since Test 4 only uses two stations for each region, it is not surprising to see that results are similar to those of Test 3 where the area was small. The stations were chosen to spatially represent the study regions and have similar longitudes to those from the other regions in order to prevent influences caused by the west-to-east precipitation gradient. There were no statistically significant values but precipitation did increase in all regions (although the difference between means is much smaller for CRA). The standard deviation slightly decreased at CRA and CRB, but increased by a larger amount at DFW, which was the only region found to have a statistically significant difference between the early and late periods (p-value = 0.021).

Test 5 uses the same two stations from Test 4 but adds an additional one. None of the values were found to be statistically significant. Test 4 and 5 had the least significant values across all regions compared to the other tests. Standard deviation increased slightly at CRA, decreased at CRB, and increased at DFW but was not statistically significant at any of the regions.

Similar to fifth test, Test 6 found that CRA is the closest to significant (p-value = 0.158) but DFW (p-value = 0.551) and CRB (p-value = 0.726) were not statistically significant. Since this test includes a total of four stations, these results may be heavily dependent on the particular stations chosen for analysis. CRB and DFW were not found to be statistically significant. The standard deviation was similar to that of Test 5 where CRA and DFW increased but CRB decreased. The difference between early and late periods was not statistically significant at any of the regions.

5.1.2 Mann-Whitney U-test

Tests 1 through 6 were also conducted with the Mann-Whitney U-test. Because this test works well for smaller data samples, it was thought to be appropriate for the temporal analyses (n = 21). Similar to the t-test, none of the differences in means were statistically significant. The smallest p-value was in Test 5, when comparing the early and late periods for CRA (p = 0.285). Also, a comparable value was found in Test 6 for the same region (p = 0.263). Table 5.7 shows the results of these analyses. Tests 1 and 4 have the least significant values compared to those from the other tests.

Table 5.7. U-statistic and p-values for the Mann-Whitney U-test for the arithmetic mean method.

	U-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	194.0 (0.505)	199.0 (0.589)	182.0 (0.333)
2 (large area)	173.0 (0.232)	180.5 (0.314)	184.5 (0.365)
3 (small area)	191.0 (0.458)	191.0 (0.538)	196.0 (0.458)
4 (2 stations)	196.0 (0.538)	214.0 (0.870)	205.0 (0.697)
5 (3 stations)	178.0 (0.285)	201.0 (0.624)	204.5 (0.687)
6 (4 stations)	176.0 (0.263)	203.0 (0.660)	197.0 (0.554)

5.1.3 Kolmogorov-Smirnov

The Kolmogorov-Smirnov (K-S Test) is used to compare the probability density function (PDF) of the early period to the late period in order to determine if there is a statistically significant different distribution of precipitation between the two time periods. If the results were significant, then it would imply that one of the two time periods is either receiving more rain or experiencing more extreme events (changing the shape of the PDF). Results show that none of the tests were statistically significant. The values are quite similar between each test and region and are shown in Table 5.8. The smallest p-value (0.591) was found for all tests at CRA, Tests 1 and 4 at CRB, and Tests 1 and 2 at DFW.

Table 5.8. Z and p-values for the Kolmogorov-Smirnov test using the arithmetic average method.

	Z (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	-0.772 (0.591)	-0.772 (0.591)	-0.772 (0.591)
2 (large area)	-0.772 (0.591)	-0.772 (0.591)	-0.617 (0.841)
3 (small area)	-0.772 (0.591)	-0.617 (0.841)	-0.617 (0.841)
4 (2 stations)	-0.772 (0.591)	-0.463 (0.983)	-0.772 (0.591)
5 (3 stations)	-0.772 (0.591)	-0.463 (0.983)	-0.617 (0.841)
6 (4 stations)	-0.772 (0.591)	-0.617 (0.841)	-0.617 (0.841)

5.2 Thiessen-Weighted Polygon Method

The same analyses from section 5.1 were performed using the Thiessen-weighted polygon method to determine if the results were sensitive to the averaging method. As this method incorporates amount of rainfall received at the station into the area of its assigned polygon, it is thought that the results of the analyses will better represent what is occurring throughout the study regions.

5.2.1 Two Independent Samples t-test

The difference in means (Tables 5.9 and 5.10) showed that precipitation did increase in all regions but it increased the most in CRA. By analyzing CRA, CRB, and DFW individually, it was found that none of the analyses proved statistically significant in Test 1 (Table 5.11). The p-values between the regions were quite different, but increased from south to north, as was seen also in Test 2. The standard deviation increased at all regions except CRB, meaning that the data has become more variable in later years (Table 5.12). By performing an F-test, it was possible to determine if any of the regions experienced statistically significantly different standard deviation values between the early and late periods. Only DFW was close for Test 1 with a p-value of 0.082 (Table 5.13).

Table 5.9. Mean precipitation (mm) for the early and late periods.

	Early period (1930 – 1950)			Late period (1987 – 2007)		
Test	**CRA**	**DFW**	**CRB**	**CRA**	**DFW**	**CRB**
1 (original area)	185.19	201.02	228.19	210.77	220.47	253.51
2 (large area)	182.38	198.76	229.50	210.37	227.92	257.82
3 (small area)	186.30	196.60	231.08	203.02	217.00	251.84
4 (2 stations)	183.58	201.14	228.08	205.78	228.20	238.60
5 (3 stations)	182.93	202.95	236.72	213.73	241.52	242.63
6 (4 stations)	183.06	207.19	236.13	216.08	234.34	247.28

Table 5.10. The difference in means (mm) between the early and late periods (Late period – early period).

	Difference in Means (Late period – early period)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	25.58	19.45	25.32
2 (large area)	27.99	29.16	28.32
3 (small area)	16.72	20.40	20.76
4 (2 stations)	22.21	27.06	10.52
5 (3 stations)	30.80	38.57	5.91
6 (4 stations)	33.01	27.15	11.15
Mean	**26.05**	**26.97**	**17.00**

Table 5.11. P-values and t-statistic values for the Thiessen-weighted polygon method.

	t-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	0.942 (0.352)	0.629 (0.533)	0.753 (0.456)
2 (large area)	1.075 (0.289)	1.006 (0.320)	0.841 (0.405)
3 (small area)	0.573 (0.570)	0.657 (0.515)	0.615 (0.542)
4 (2 stations)	0.761 (0.451)	0.829 (0.413)	0.285 (0.777)
5 (3 stations)	1.092 (0.281)	1.151 (0.258)	0.166 (0.869)
6 (4 stations)	1.183 (0.244)	0.835 (0.410)	0.315 (0.755)

Table 5.12. Standard deviation values for the Thiessen-weighted polygon method.

	CRA		DFW		CRB	
Test	**Early**	**Late**	**Early**	**Late**	**Early**	**Late**
1 (original area)	85.73	90.16	83.39	114.62	113.95	103.77
2 (large area)	82.65	86.20	86.33	100.76	113.87	103.91
3 (small area)	96.02	92.90	79.63	117.98	116.87	101.47
4 (2 stations)	94.53	94.67	77.63	127.88	123.65	115.21
5 (3 stations)	89.65	93.10	83.43	128.98	123.06	106.79
6 (4 stations)	86.79	94.11	82.83	123.96	124.00	104.37
Mean	**89.23**	**91.86**	**82.21**	**119.03**	**119.23**	**105.92**

As the area of the study region is expanded in Test 2, results were similar to those in the first test. No values were statistically significant and the difference of means showed a precipitation increase at a similar amount for all three regions. The standard deviation was similar to the first test where it increased at CRA and DFW and decreased at CRB, although no values were found to be statistically different between the two periods.

By decreasing the size of the original study region, the t-statistic in Test 3 showed that precipitation increased at all regions but not as much as in the first two tests. This implies that the stations on the outskirts of the original DFW study region (similar for CRA and CRB) are responsible for the large increases in rainfall. Also, the results were not found to be statistically significant as the p-values were very similar at each region. As in Tests 1 and 2, standard deviation increased at DFW and decreased at both CRA and CRB. This may be due to the smaller number of stations used, as each station is more heavily weighted in Test 3. Only DFW was found to have a statistically significant difference between the early and late periods (p-value = 0.043).

Since only two stations are used in Test 4, the results will be more heavily weighted on the stations chosen. There were no statistically significant values but precipitation did increase slightly at all regions. As in Test 3, the standard deviation decreased at CRA, CRB, but increased by a much larger amount for DFW (p-value = 0.015). The largest difference in means occurred during this test at DFW (2.065).

By adding a single station to those used in the third test, the t-statistics in Test 5 did not change dramatically. DFW did have the lowest p-value (0.258), but was still not significant. No other p-values were near to a statistically significant level but the standard deviation did increase slightly at CRA (p-value = 0.434), largely at DFW (p-value = 0.029), and decrease slightly at CRB (p-value = 0.266).

The final test (Test 6) showed that no region had statistically significant changes between the early and late periods. The t-statistic did change between regions compared to the previous test further proving how influential using a small number of stations can be. The standard deviation for CRA (p-value = 0.360) and CRB (p-value = 0.224) decreased slightly while the increase at DFW was not as large as in previous tests (p-value = 0.471).

Table 5.13. F and p-values for the F-test determined using the Thiessen-weighted polygon method.

	F-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	0.904 (0.412)	0.529 (0.082)	1.206 (0.340)
2 (large area)	0.919 (0.426)	0.734 (0.248)	1.200 (0.344)
3 (small area)	1.068 (0.442)	0.456 (0.043)*	1.327 (0.267)
4 (2 stations)	0.997 (0.497)	0.368 (0.015)*	1.152 (0.377)
5 (3 stations)	0.927 (0.434)	0.418 (0.029)*	1.328 (0.266)
6 (4 stations)	0.850 (0.360)	0.446 (0.471)	1.411 (0.224)

5.2.2 Mann-Whitney U-test

Using the Thiessen-weighted polygons, the results of the Mann-Whitney U-test using the arithmetic average method and were not found to be statistically significant. As shown in Table 5.14, the p-values were quite large and so it is not possible to conclude that the early and late periods are statistically different in any of the regions.

Table 5.14. U-statistic and p-values for the Mann-Whitney U-test determined using the Thiessen-weighted polygon method.

	U-statistic (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	195.0 (0.521)	204.0 (0.678)	187.0 (0.399)
2 (large area)	188.0 (0.414)	174.5 (0.247)	184.0 (0.359)
3 (small area)	200.0 (0.606)	200.0 (0.697)	192.0 (0.473)
4 (2 stations)	195.0 (0.521)	203.0 (0.660)	209.0 (0.772)
5 (3 stations)	183.0 (0.346)	181.0 (0.320)	210.0 (0.792)
6 (4 stations)	184.0 (0.359)	196.0 (0.538)	196.0 (0.538)

5.2.3 Kolmogorov-Smirnov

Using the Kolmogorov-Smirnov (K-S Test) to compare the early and late periods using the Thiessen-weighted polygon method was not found to be very different from results determined using the arithmetic average method. Results show that none of the differences are statistically significant. The values are quite similar between each test and region and are shown in Table 5.15.

Table 5.15. Z and p-values for the Kolmogorov-Smirnov test determine using the Thiessen-weighted polygon method.

	Z (p-value)		
Test	**CRA**	**DFW**	**CRB**
1 (original area)	-0.772 (0.591)	-0.463 (0.983)	-0.617 (0.841)
2 (large area)	-0.617 (0.841)	-0.772 (0.591)	-0.617 (0.841)
3 (small area)	-0.617 (0.841)	-0.617 (0.841)	-0.617 (0.841)
4 (2 stations)	-0.772 (0.591)	-0.463 (0.983)	-0.772 (0.591)
5 (3 stations)	-0.772 (0.591)	-0.617 (0.841)	-0.617 (0.841)
6 (4 stations)	-0.772 (0.591)	-0.463 (0.983)	-0.617 (0.841)

5.3 Summary

When comparing the early period (1930 – 1950) and late period (1987 – 2007) precipitation for each region, it was found that none of the difference of means tests were statistically significant although precipitation increased at all regions (CRA ~+28 mm, DFW ~+24 mm, and CRB ~+17 mm), based on both the arithmetic average and Thiessen-weighted polygon methods. These increases were not large enough to be statistically significant. Therefore, it is not possible to conclude that urbanization has had a statistically significant (e.g., detectable) influence on precipitation around DFW based on these results.

Standard deviation changes between the periods did seem to reflect potential anthropogenic influences. Standard deviation at DFW increased dramatically between the early and late periods in each test. This implies that the rainfall patterns at DFW are becoming increasingly variable over time. The standard deviation for CRB decreased, by a moderate amount, between the two periods in every test. CRA experienced an increase in standard deviation between the two periods, but it was not a very large amount and seemed quite variable. It is possible that the urbanization of DFW is altering the standard deviation, but because CRA is also experiencing increases, urbanization may not be the only factor that is responsible for these changes. Also, as CRB is downwind of the urban area, the long-term growth of the Metroplex may be keeping the downwind rainfall patterns more stable.

One of the limitations of these tests is the sensitivity to sample size (n). In order for a comparison to be statistically significant, the difference between the two periods must be large. The t-test works best with large data sets, and so in comparing the early and late periods, even though precipitation increased by about 23 mm across the three regions, these changes were not statistically significant. The K-S test also works best with a large data set, so the issues faced in using the t-test are similar here. So even though precipitation in each region increased by a significant amount, the increases were not large enough to be statistically significant, which is a factor of the sample size.

There are numerous other factors that may affect the applicability of these tests in this analysis. First, the years chosen for the early and late periods may not adequately represent the long-term precipitation patterns in each region. As is with any temporal analysis, it is difficult to compare two time periods due to the influence of natural climatic variation. Because this variation is not accounted for then it would be extremely difficult to pinpoint any anthropogenic effects. Secondly, the stations chosen have a larger role in the lack of significant results. As stated in Chapter III, rain gauge data has many strengths and weakness. Measured values can be highly sensitive to nearby land usage as they are located near various types of land cover. Anthropogenic influences may affect only a few of the stations and would be difficult to account for. Data within each study region had to be interpolated to a larger scale in order to get a regional value. Finally, it is possible that there is not an anthropogenic signal in these regions, or if it exists, it is too small to be detected through the overall increase in precipitation seen across all three regions. If this is the case, then changes seen in the patterns would be noticed in each region.

While variability may be increasing over the period, the changes were not found to be statistically significant. This may be a factor of the small dataset and relatively short record, as both the t-test and K-S test respond better with a large sample size. As a result, it is not possible to conclude that the changes are anthropogenically-caused. The results of the F-test imply that the urbanization in DFW may be causing the increased variability (standard deviation) in summer precipitation based on comparing the early and late periods. This agrees with Huff and Vogel (1978) who found that urbanization tended to have more influence on larger storms (> 25 mm precipitation). Even though standard deviation increased in each region, the only statistically significant increases were found at DFW, and mainly when there were a small number of stations used.

CHAPTER VI

REGIONAL COMPARISON RESULTS

The regional analyses consisted of comparing the regions to determine if there are any statistically significant differences in rainfall. This was done using the arithmetic average and Thiessen-polygon methods. For each test values from each region were analyzed for the entire time period (1930 – 2007) to determine if there was a difference in the mean rainfall received in each region. Then the early period was compared between regions (1930 – 1950) to determine how different the regions were during a time of less urbanization. Lastly, the late period rainfall (1987 – 2007) was studied at each region. If there was a significant change in values that occurred between the early and late periods, it may be possible to infer that urbanization or anthropogenic processes may be influencing the results. Section 6.1 discusses the results of the t-test (Section 6.1.1), Mann-Whitney U-test (Section 6.1.2), and Kolmogorov-Smirnov (Section 6.1.3) test using data from the arithmetic mean method. Section 6.2 discusses results for the same tests (t-test in Section 6.2.1, Mann-Whitney U-test in 6.2.2, and Kolmogorov-Smirnov test in 6.2.3) using data from the Thiessen-polygon method.

6.1 Arithmetic Average Method

As in Chapter V, the arithmetic average method is determined by taking the sum of all the stations in the region, and then dividing by the total number of stations (as described in section 3.3). For each test performed, if there was a significant change in values when comparing DFW to CRB or CRB to CRA, it may be possible to infer that urbanization or anthropogenic processes may be influencing precipitation.

6.1.1 Two Independent Samples t-test

In Test 1, mean precipitation in CRB was higher than CRA (Table 6.1). Statistically significant differences between study regions were found between CRA and CRB (p-value = 0.015) (Table 6.2). Additionally, the standard deviation at CRB and DFW shows they are slightly more variable than CRA (Table 6.3). When studying the early and late periods, none of the comparisons were statistically significant (Table 6.4 and 6.5).

Table 6.1. Mean precipitation for the arithmetic average for the entire period (1930 – 2007).

Test	CRA	DFW	CRB
1 (original area)	190.62	205.16	226.46
2 (large area)	189.94	200.80	233.11
3 (small area)	192.60	194.17	227.98
4 (2 stations)	189.58	200.00	216.68
5 (3 stations)	191.51	211.57	206.78
6 (4 stations)	193.32	216.31	227.07
Mean	**191.26**	**204.67**	**223.01**

Table 6.2. P-values and t-statistic values for the arithmetic mean method for the entire period (1930 – 2007).

	t-statistic (p-value)		
Test	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.996 (0.321)	1.424 (0.156)	2.455 (0.015*)
2 (large area)	-0.775 (0.440)	2.207 (0.029*)	2.949 (0.004*)
3 (small area)	-0.106 (0.916)	2.261 (0.025*)	2.339 (0.021*)
4 (2 stations)	-0.679 (0.498)	1.048 (0.296)	1.725 (0.087)
5 (3 stations)	-1.335 (0.184)	-0.301 (0.764)	0.999 (0.319)
6 (4 stations)	-1.529 (0.128)	0.684 (0.495)	2.238 (0.027)*

Table 6.3. Standard deviation for mean precipitation (arithmetic mean method) for the entire period (1930 – 2007).

Test	CRA	DFW	CRB
1 (original area)	88.80	93.34	93.50
2 (large area)	87.55	87.59	95.14
3 (small area)	94.12	91.89	94.83
4 (2 stations)	94.56	97.17	101.69
5 (3 stations)	89.52	97.91	101.07
6 (4 stations)	89.54	97.99	98.55
Mean	**90.68**	**94.31**	**97.46**

Table 6.4. P-values and t-statistic values (arithmetic mean method) for the early period (1930 – 1950).

	t-statistic (p-value)		
Test	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.704 (0.485)	0.688 (0.495)	1.314 (0.197)
2 (large area)	-0.685 (0.498)	1.065 (0.294)	1.672 (0.103)
3 (small area)	-0.248 (0.806)	1.267 (0.213)	1.427 (0.162)
4 (2 stations)	-0.736 (0.466)	0.748 (0.460)	1.280 (0.208)
5 (3 stations)	-1.092 (0.282)	-0.343 (0.733)	0.776 (0.442)
6 (4 stations)	-1.308 (0.198)	0.537 (0.595)	-0.458 (0.650)

Table 6.5. P-values and t-statistic values (arithmetic mean method) for the late period (1987 – 2007).

	t-statistic (p-value)		
Test	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.515 (0.609)	0.738 (0.465)	1.375 (0.177)
2 (large area)	-0.291 (0.772)	1.171 (0.249)	1.521 (0.136)
3 (small area)	-0.203 (0.840)	1.006 (0.321)	1.318 (0.195)
4 (2 stations)	-0.525 (0.603)	0.399 (0.692)	1.009 (0.319)
5 (3 stations)	-0.477 (0.636)	-0.671 (0.506)	-0.222 (0.826)
6 (4 stations)	0.314 (0.755)	0.845 (0.403)	-1.007 (0.315)

In Test 2, more stations were added to each region as the study area was expanded by 25%. For the entire period, mean precipitation in CRB was different from both DFW (p-value = 0.029) and CRA (p-value = 0.004), although the standard deviation was similar between all regions. In comparing mean precipitation for the early and late periods, there were no statistically significant values (similar to results from Test 1).

In shrinking the study area by 25% of its original size, the results for Test 3 were similar to those of Test 2 for the entire period. Mean precipitation in CRB was found to be different from both DFW (p-value = 0.025) and CRA (p-value = 0.021). Standard deviation was similar between all regions. There were no significant differences between the regions for both the early and late periods.

For Test 4, all regions were similar to each other for the entire period, early period, and the late periods. Because there are only 2 stations in this test, the number and specific stations chosen may play a role.

In Test 5, none of the comparisons were statistically significant (including entire period, early and late periods). This test only adds a single station to those used in Test 4.

In Test 6, CRA was statistically significantly different from CRB (p-value = 0.027). Again, no comparisons were significant for either the early or late periods.

6.1.2 Mann-Whitney U-test

The Mann Whitney U-test was another way to determine if there were statistically significant differences between the three study regions. As stated in Chapter III, this test works well for smaller data samples, so the data sets used in Tests 1 through 6 for the regional analysis may show significant results with this method (n = 21). In Test 1, there were no statistically significant values although when comparing CRA against CRB for the entire region, the p-value was close to significant (0.099) (Table 6.6). In Test 2, comparing CRB against DFW and CRA for the entire period proved to be significant (p-value = 0.027 and p-value = 0.005). As the area is increased for this test, the addition of stations has increased the overall difference in precipitation between the three regions.

The same comparisons were also significant in Test 3, where the area is smaller than in Tests 1 and 2. The p-value was 0.021 for comparing CRB with DFW and 0.022 for comparing CRB with CRA. No values were found to be significant for any of the time periods in Tests 4 and 5. The comparison of CRA with CRB for the entire period was significant in Test 6 (0.039).

Table 6.6. P-values for the Mann Whitney U-test (arithmetic mean method) for all three periods (Entire period, 1930 – 2007; Early period, 1930 – 1950; Late period, 1987 – 2007).

Test	Period	U-statistic (p-value)		
		CRA vs. DFW	**CRB vs. DFW**	**CRA vs. CRB**
1 (original area)	Entire	2803.5 (0.397)	2594.0 (0.136)	2412.5 (0.099)
	Early	197.0 (0.554)	171.5 (0.678)	154.0 (0.252)
	Late	209.0 (0.772)	211.0 (0.443)	186.0 (0.163)
2 (large area)	Entire	3025.5 (0.433)	2389.0 (0.027*)	2389.0 (0.005*)
	Early	215.0 (0.458)	178.5 (0.359)	178.0 (0.122)
	Late	219.0 (0.850)	178.0 (0.320)	166.0 (0.204)
3 (small area)	Entire	3025.5 (0.952)	2389.0 (0.021*)	2396.5 (0.022*)
	Early	215.0 (0.890)	178.5 (0.285)	178.0 (0.285)
	Late	219.0 (0.970)	178.0 (0.285)	166.0 (0.170)
4 (2 stations)	Entire	2864.5 (0.530)	2605.0 (0.251)	2719.0 (0.121)
	Early	184.0 (0.359)	177.5 (0.697)	205.0 (0.279)
	Late	213.0 (0.850)	191.0 (0.458)	207.0 (0.734)
5 (3 stations)	Entire	2745.0 (0.295)	2864.0 (0.637)	2560.0 (0.519)
	Early	180.0 (0.308)	204.5 (0.642)	168.0 (0.443)
	Late	208.0 (0.753)	211.5 (0.624)	194.5 (0.772)
6 (4 stations)	Entire	2687.0 (0.208)	2814.5 (0.417)	2459.0 (0.039*)
	Early	168.5 (0.195)	204.5 (0.678)	168.0 (0.187)
	Late	209.0 (0.772)	203.5 (0.669)	187.0 (0.399)

6.1.3 Kolmogorov-Smirnov

The Kolmogorov-Smirnov (K-S Test) was used in the regional analysis to directly compare the probability density function (PDF) of each region. These comparisons were done for the entire period, the early period, and the late period in order to determine if there is a statistically significant different precipitation distribution between the three regions. In Test 1, CRA compared to CRB was found to be statistically significant for the entire time period (p-value = 0.031) (Table 6.7). In the early period, CRB was found to be different from both DFW (p-value = 0.095) and CRA (p-value = 0.042), but this was not the case in the late period. In Test 2, CRB was also different from DFW (p-value = 0.075) and CRA (p-value = 0.012) for the entire time period, but this was the only statistically significant result. The same comparisons were significant for Test 3 (p-value = 0.075, p-value = 0.031), but no other time periods were. None of the remaining tests were found to be significant using this method.

Table 6.7. P-values for the Kolmogorov-Smirnov test (arithmetic mean method) for all three periods (Entire period, 1930 – 2007; Early period, 1930 – 1950; Late period, 1987 – 2007).

		Z (p-value)		
Test	**Period**	**CRA vs. DFW**	**CRB vs. DFW**	**CRA vs. CRB**
1 (original area)	Entire	0.721 (0.677)	1.121 (0.162)	1.440 (0.031*)
	Early	0.772 (0.591)	1.234 (0.095)	1.389 (0.042*)
	Late	0.463 (0.983)	0.463 (0.983)	0.617 (0.841)
2 (large area)	Entire	0.881 (0.420)	1.281 (0.075)	1.601 (0.012*)
	Early	0.772 (0.591)	0.772 (0.591)	0.926 (0.358)
	Late	0.463 (0.983)	0.926 (0.358)	0.772 (0.591)
3 (small area)	Entire	0.560 (0.912)	1.281 (0.075)	1.441 (0.031*)
	Early	0.309 (1.000)	0.772 (0.591)	0.772 (0.591)
	Late	0.617 (0.841)	0.772 (0.591)	0.926 (0.358)
4 (2 stations)	Entire	0.641 (0.807)	0.881 (0.420)	1.201 (0.112)
	Early	0.772 (0.591)	0.463 (0.983)	1.080 (0.358)
	Late	0.617 (0.841)	0.463 (0.983)	1.080 (0.194)
5 (3 stations)	Entire	0.961 (0.314)	0.721 (0.677)	0.721 (0.677)
	Early	0.926 (0.358)	0.772 (0.591)	0.617 (0.841)
	Late	0.463 (0.983)	0.772 (0.591)	0.463 (0.983)
6 (4 stations)	Entire	0.801 (0.543)	0.721 (0.677)	1.201 (0.112)
	Early	0.772 (0.591)	0.617 (0.591)	0.926 (0.358)
	Late	0.463 (0.983)	0.463 (0.983)	0.617 (0.841)

6.2 Thiessen-Weighted Polygon Method

The same statistical tests in Section 6.1 were performed using the Thiessen-weighted polygon method to determine how sensitive results were to the averaging method. As described in Section 3.3, this method incorporates amount of rainfall received at the station into the area of its assigned polygon, and it is thought that the results of the analyses will better represent what is occurring throughout the study regions.

6.2.1 Two Independent Samples t-test

The following tests consisted of comparing precipitation between regions to detect statistically significant differences at each location. The regional average rainfall for these analyses was determined using the Thiessen-weighted polygon method. As in section 6.1, values from each region were analyzed for the entire time period (1930 – 2007), and then the early period (1930 – 1950) and the late period (1987 – 2007) was studied for each region.

In Test 1, statistically significant differences between study regions were found when comparing CRA with CRB (p-value = 0.015), although CRB and DFW were close to significant (p-value = 0.071) (Table 6.8). This means that CRB receives more rainfall on average than CRA or DFW (Table 6.9). The standard deviation also shows that CRB is slightly more variable than the other two regions (Table 6.10). As with the arithmetic average method, no significant values were found when comparing the early and late periods between regions (Table 6.11, Table 6.12).

Table 6.8. Mean precipitation for the Thiessen-weighted polygon method for the entire period (1930 – 2007).

Test	CRA	DFW	CRB
1 (original area)	191.11	200.25	227.52
2 (large area)	182.38	164.63	210.90
3 (small area)	190.99	195.27	227.65
4 (2 stations)	189.90	200.08	217.52
5 (3 stations)	191.11	206.78	223.02
6 (4 stations)	191.86	207.02	225.92
Mean	**189.56**	**195.67**	**222.09**

Table 6.9. P-values and t-statistic values for the t-test (Thiessen-weighted polygon method) for the entire period (1930 – 2007).

	t-statistic (p-value)		
Test	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.626 (0.532)	1.821 (0.071)	2.470 (0.015*)
2 (large area)	0.659 (0.514)	1.692 (0.098)	1.099 (0.278)
3 (small area)	-0.283 (0.778)	2.146 (0.033*)	2.388 (0.018*)
4 (2 stations)	-0.665 (0.507)	1.091 (0.277)	1.766 (0.079)
5 (3 stations)	-1.017 (0.311)	1.015 (0.312)	2.098 (0.038*)
6 (4 stations)	-1.017 (0.315)	1.205 (0.230)	2.255 (0.026*)

Table 6.10. Standard deviation for mean precipitation (Thiessen-weighted polygon method) for the entire period (1930 – 2007).

Test	CRA	DFW	CRB
1 (original area)	89.70	92.72	94.32
2 (large area)	82.65	91.60	85.49
3 (small area)	96.17	92.92	95.54
4 (2 stations)	94.72	98.30	101.29
5 (3 stations)	91.17	101.07	98.70
6 (4 stations)	90.19	97.68	98.30
Mean	**90.77**	**95.72**	**95.60**

Table 6.11. P-values and t-statistic values for the Thiessen-weighted polygon method for the early period (1930 – 1950).

Test	t-statistic (p-value)		
	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.606 (0.548)	0.384 (0.882)	1.382 (0.175)
2 (large area)	-0.628 (0.533)	0.986 (0.331)	1.535 (0.133)
3 (small area)	-0.378 (0.707)	1.117 (0.271)	1.357 (0.183)
4 (2 stations)	-0.658 (0.514)	0.846 (0.404)	1.310 (0.198)
5 (3 stations)	-0.749 (0.458)	1.041 (0.305)	1.619 (0.114)
6 (4 stations)	0.922 (0.362)	0.889 (0.380)	1.607 (0.117)

Table 6.12. P-values and t-statistic values for the Thiessen-weighted polygon method for the late period (1987 – 2007).

Test	t-statistic (p-value)		
	CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	-0.305 (0.762)	0.979 (0.333)	1.425 (0.162)
2 (large area)	-0.607 (0.548)	0.946 (0.350)	1.610 (0.115)
3 (small area)	-0.427 (0.672)	1.026 (0.311)	1.626 (0.112)
4 (2 stations)	-0.658 (0.514)	0.846 (0.404)	1.310 (0.198)
5 (3 stations)	-0.749 (0.458)	1.041 (0.305)	1.619 (0.114)
6 (4 stations)	0.922 (0.362)	0.889 (0.380)	1.607 (0.117)

In Test 2, the area of each study region was expanded by 25%, which resulted in no significant difference in mean precipitation for the entire period, although CRB and DFW were close to being significantly different (p-value = 0.098). There were no significant values for mean precipitation for the early and late periods. The standard deviation was similar at all regions but largest at DFW.

The study area in Test 3 was 25% smaller than its original size, and so mean precipitation at CRB was found to be different from both DFW (p-value = 0.033) and CRA (p-value = 0.018). Standard deviation was also similar between all regions. When comparing the early and late periods, no regions had significantly different mean precipitation.

For Test 4, no regions were significantly different from each other for the entire period, contrary to the first three tests. Because this test is only using two stations, results may be a heavily dependent on the stations chosen. The comparison between regions of the early and late periods showed no statistically significant results.

In Test 5, a total of three stations were used. For the analysis of the overall period, comparing CRB with CRA was the only statistically significant result (p-value = 0.038). There were no significant values for the early and late periods, meaning that all the regions had similar precipitation. The standard deviation increased in all regions except CRB.

Similar to the previous two tests, in Test 6, CRA was different from CRB for the overall (p-value = 0.026). Again, the mean precipitation for the early and late period was not found to be statistically significantly different between the regions.

6.2.2 Mann-Whitney U-test

As done for the arithmetic average method, the Mann Whitney U-test was performed using the Thiessen-weighted polygons as another method for determining significant differences between the three study regions. Also quite similar to the results received from using the arithmetic average method, the only significant values occurred when comparing the entire time period between regions (Table 6.13). In Test 1, there both DFW and CRA were found to be significantly different from CRB (p-value = 0.048, p-value = 0.021). In Test 2, comparing CRB against DFW and CRA also proved to be significant (p-value = 0.056 and p-value = 0.006). In Test 3, the same pairs were found to be significant (p-value = 0.021 and p-value = 0.019). No values were found to be significant in Tests 4 and 5 although CRA compared to CRB was close (p-value = 0.099, p-value = 0.065). Lastly, comparing CRA with CRB for the entire period was significant in Test 6 (p-value = 0.043).

Table 6.13. P-values for the Mann Whitney U-test (Thiessen-weighted polygon method) for all three periods (Entire period, 1930 – 2007; Early period, 1930 – 1950; Late period, 1987 – 2007).

		U-statistic (p-value)		
Test	**Period**	**CRA vs. DFW**	**CRB vs. DFW**	**CRA vs. CRB**
1 (original area)	Entire	2902.0 (0.620)	2484.0 (0.048*)	2391.0 (0.021*)
	Early	200.0 (0.606)	187.0 (0.399)	176.0 (0.263)
	Late	217.0 (0.930)	175.0 (0.252)	166.0 (0.170)
2 (large area)	Entire	2821.0 (0.417)	2419.0 (0.056)	2244.0 (0.006*)
	Early	191.0 (0.489)	184.0 (0.385)	159.0 (0.134)
	Late	213.0 (0.734)	181.0 (0.414)	170.0 (0.122)
3 (small area)	Entire	2813.0 (0.710)	2502.0 (0.021*)	2269.0 (0.019*)
	Early	193.0 (0.505)	186.0 (0.297)	161.0 (0.213)
	Late	207.0 (0.850)	288.0 (0.232)	159.0 (0.122)
4 (2 stations)	Entire	2883.0 (0.573)	2692.0 (0.215)	2577.0 (0.099)
	Early	184.0 (0.359)	201.0 (0.624)	176.0 (0.263)
	Late	212.0 (0.831)	211.0 (0.811)	189.0 (0.428)
5 (3 stations)	Entire	2846.0 (0.487)	2701.0 (0.227)	2522.0 (0.065)
	Early	194.0 (0.505)	186.0 (0.385)	166.0 (0.170)
	Late	203.0 (0.660)	214.0 (0.870)	190.0 (0.443)
6 (4 stations)	Entire	2836.0 (0.465)	2680.0 (0.199)	2472.0 (0.043*)
	Early	183.0 (0.346)	193.0 (0.489)	169.0 (0.195)
	Late	209.0 (0.772)	196.0 (0.538)	182.0 (0.333)

6.2.3 Kolmogorov-Smirnov

Using Thiessen-weighted polygons, the Kolmogorov-Smirnov (K-S Test) was again performed to compare the probability density function (PDF) of each region. There were very few statistically significant values in this analysis, all of them being for the entire time period comparisons (Table 6.14). In Test 1, CRB was found to be statistically significant from DFW (p-value = 0.075) and CRA (p-value = 0.031). In Test 2, CRB was different from only CRA (p-value = 0.020). Test 3 showed that CRB was different from both DFW (p-value = 0.0205) and CRA (p-value = 0.007). Test 5 showed significant results only for CRB being different from CRA (p-value = 0.075). Tests 4 and 6 had no statistically significant values.

Table 6.14. P-values for the Kolmogorov-Smirnov test (Thiessen-weighted polygon method) for all three periods (Entire period, 1930 – 2007; Early period, 1930 – 1950; Late period, 1987 – 2007).

Test	Period	p-value		
		CRA vs. DFW	CRB vs. DFW	CRA vs. CRB
1 (original area)	Entire	0.641 (0.807)	1.281 (0.075)	1.441 (0.031*)
	Early	0.772 (0.591)	0.617 (0.841)	0.772 (0.591)
	Late	0.617 (0.841)	0.772 (0.591)	0.772 (0.591)
2 (large area)	Entire	0.881 (0.420)	1.121 (0.162)	1.521 (0.020*)
	Early	0.772 (0.591)	0.772 (0.591)	0.926 (0.358)
	Late	0.617 (0.841)	0.772 (0.591)	0.926 (0.358)
3 (small area)	Entire	0.881 (0.420)	1.521 (0.020*)	1.681 (0.007*)
	Early	0.926 (0.358)	0.772 (0.591)	0.926 (0.358)
	Late	0.617 (0.841)	0.772 (0.591)	0.926 (0.358)
4 (2 stations)	Entire	0.641 (0.807)	1.121 (0.162)	1.121 (0.162)
	Early	0.772 (0.591)	0.617 (0.841)	0.926 (0.358)
	Late	0.617 (0.841)	0.463 (0.983)	1.080 (0.194)
5 (3 stations)	Entire	0.641 (0.807)	0.881 (0.420)	1.281 (0.075)
	Early	0.617 (0.841)	0.617 (0.841)	0.926 (0.358)
	Late	0.617 (0.841)	0.463 (0.983)	0.617 (0.841)
6 (4 stations)	Entire	0.721 (0.677)	0.961 (0.314)	1.121 (0.162)
	Early	0.617 (0.841)	0.617 (0.841)	0.926 (0.358)
	Late	0.463 (0.983)	0.617 (0.841)	0.617 (0.841)

6.3 Summary

The results of the t-tests demonstrate that CRB was found to be significantly different from CRA and DFW in both Tests 2 and 3 for the entire time period (arithmetic average method) (Table 6.3). CRA and CRB were also significantly different from each other for Test 1 for the entire time period. The use of Thiessen-weighted polygons led to different results in that CRA and CRB were significantly different from each other for the entire time period for Tests 1, 3, 5, and 6, and were close to significant for Test 4 (Table 6.7). CRB was also significantly different from DFW in Test 3, although close to significant in Tests 1 and 2. There were no statistically significant results for the early or late periods (Table 6.9 and 6.10). The p-values for Test 5 in for the t-test (also Mann-Whitney U-test and K-S test) were very different when comparing CRB to DFW or CRA. Even though the values were not found to be statistically significant, this test was based on only three stations, and so the mean precipitation at each station may have a larger influence on the regional mean.

The Mann Whitney U-test showed that CRB and DFW were significantly different for Tests 2 and 3 for the entire time period when using the arithmetic average method. CRA and CRB were significantly different from each other in Tests 2, 3, 6 for the same period (Table 6.5). With the Thiessen-weighted polygon method, CRB and DFW were different for Tests 1, 2, 3, while CRA and CRB were different for Tests 1, 2, 3, and 6 for the entire period (Table 6.11). There were also no statistically significant results for the early or late periods.

The results of the Kolmogorov-Smirnov analyses were different from the previous two in that when using the arithmetic average method, CRB was found to be significantly different from DFW and CRA during the early period in Test 1 (Table 6.6). Because none of the late periods were found to be significant, it can be concluded that the three regions are becoming more similar over time. CRB and DFW were also different in Tests 2 and 3, while CRB was different from CRA in the same tests. The Thiessen-weighted polygon method did not find any statistically significant results in the early or late periods at any region. It was found that CRB was different from DFW in Tests 1 and 3, while different from CRA in Tests 1, 2, 3, and 5 for the entire period (Table 6.12). While these tests do provide more statistically significant results than in the temporal analyses, the issues faced in those analyses may still be a factor. As stated previously, the t-test works best with large data sets, as does the K-S test, and so the sample size may not be large enough to produce statistically significant results. As was an issue in the temporal analyses, the years chosen for the early and late periods may not adequately represent the long-term precipitation patterns in each region. The stations that were used will also influence results as conditions vary between stations. Even though the hypothesis (significant differences in mean precipitation during the late period at DFW and CRB imply anthropogenic influence) was rejected, there is evidence that points to possible urban effects. For example, because the p-values between the three statistical tests were similar for the early and late periods, it can be concluded that mean precipitation was relatively similar. Also, since the entire period was the only time found to be statistically significant, any existing differences between the regions are long-term and are seen throughout the entire period. Even though there may be an anthropogenic signal caused by the DFW Metroplex, it is possible that overall increase in precipitation seen across all three regions due to climatic variability is overshadowing any anthropogenic signal.

CHAPTER VII

CONCLUSION

The main purpose of this research was to determine if the DFW Metroplex has changed the local and regional precipitation patterns as it has grown and evolved over time. This question was answered by the following objectives: (1) how has urbanization and land cover changed in and around the DFW Metroplex, (2) how has precipitation in and downwind of the metroplex changed since 1930 (a temporal analysis), and (3) how has precipitation in the control regions changed in comparison to the metroplex (a spatial analysis)? In previous urban precipitation studies, it was found that precipitation downwind of the main urban area experienced increased amounts of rainfall (Shepherd et al. 2002, Diem & Brown 2003, Dixon & Mote 2003). Shepherd (2002) studied the DFW region and found that increases in precipitation occurred to the east and northeast of the metroplex. Even though Shepherd (2002) found highest amounts of precipitation to the east, north east of the DFW Metroplex (the region he defined as downwind), results of this study were similar in that the highest amounts of precipitation were found to the north to the northeast of the city (the region defined in this research as downwind).

7.1 Conclusions

The DFW Metroplex has a total population of 5,162,000 people as of the year 2000, and is projected to have a total population of 10,107,000 people by the year 2040 (Texas State Data Center and Office of the State Demographer (TSDCOSD)). Precipitation data was compared to this growth it was found that: as population grows in the DFW Metroplex, the regional precipitation also increases. Trends in precipitation for each decade were determined and it was found that the DFW region has the highest rate of increase, especially in most recent decades. This may be a result of the rapid growth in urban land cover seen in most recent decades. Even though portions of CRA and CRB are urbanized, they are relatively small and did not grow at the rate of DFW. Because the trends for CRB fall between those of CRA and DFW, CRB may be experiencing downwind effects caused by the metroplex.

Land cover (LC) data for 1976 and 2001 were studied to determine the percent of land converted to an urban classification between the two periods. It was found that for DFW low-density urban increased by 62.26%, high-density urban increased by 113.88%, while vegetation decreased by 20.34%. Stations from around the DFW region were then classified into urban or non-urban stations and studied to determine if the local land cover had any influence on the long-term increases in precipitation. It was found that only two stations, 419522 in CRA and 342678 in CRB, had statistically significant differences in the mean precipitation between the early and late periods. Station 419522 was statistically significant for both the t-test (p-value = 0.034) and the Mann-Whitney U-test (p-value = 0.038), while station 342678 was only statistically significant for the Mann-Whitney U-test (p-value = 0.044). The low- and high-density land cover surrounding these two stations has increased. It is concluded that these stations may have been influenced by local land cover conditions, where the urban land cover has grown rapidly so the record may be long enough to detect this influence. It is possible that this is not seen at stations in other regions either because there is not enough urban land cover to have an influence, or because the record of the station has not existed long enough to detect any influence using these tests.

This study differs from previous ones in that it compares three statistical tests used in previous urban studies (Independent two-sample t-test, Mann-Whitney U-test, Kolmogorov-Smirnov Test). It also compares the urban area rainfall to an upwind and downwind control region. It was hypothesized that an increased amount of precipitation in the downwind region (CRB), and the relationship between the metroplex and the control regions has changed since 1930, implying an anthropogenic influence.

The temporal analysis consisted of comparing precipitation from an early period (1930 – 1950) in each region to a late period (1987 – 2007) of that same location in order to detect long-term changes in the amount of rainfall received. The tests were performed using data derived from both the arithmetic average method and Thiessen-weighted polygons. Between the early and late periods, precipitation in CRA increased by 28 mm, in DFW by 24 mm, and in CRB by 17 mm. However, based on the t-test, Mann-Whitney U-test, and Kolmogorov-Smirnov test, these changes are not statistically significant

Using the same three tests from the temporal analysis, the precipitation at each region was compared to the precipitation in the other study regions for the entire period (1930 – 2007), early period (1930 – 1950), and late period (1987-2007). It was hypothesized that increases in mean precipitation between early and late periods in the urban area and downwind region would occur due to urbanization. Using data from the arithmetic average method, the t-test and Mann-Whitney U-test showed that CRB was different from CRA and DFW for the entire period (1930 – 2007). The K-S test found that CRB was different only from CRA in Test 1 for the entire and early periods and in Tests 2 and 3 for the entire period. When comparing the early and late periods between regions, no values were found to be statistically significant which means that precipitation was similar at each region during these two periods. When using precipitation values derived from the Thiessen-weighted polygon method, the three statistical tests found that CRB was statistically significantly different from CRA and DFW. Because these changes were detected for only the entire period (1930 – 2007), and not in the early or late periods, it can be concluded that potential urban influences are not detected at such a short time scale, but may be a factor in the changes seen in the downwind (CRB) long-term precipitation. It is possible that when comparing the early and late periods, the three regions had similar precipitation patterns because the signal is not strong enough to detect given the small sample size and that precipitation is naturally highly variable from year to year. When the length of record increases and the remaining decades are included in the analyses, the changes seen at the downwind region are more easily distinguished. It cannot be concluded that urbanization in the DFW Metroplex has contributed to the long-term increase seen in regional precipitation.

7.2 Implications

If the precipitation variability in the metropolitan region continues to experience similar increases, then this will complicate water resource and urban planning, agriculture, and numerous other climate-sensitive sectors. If land cover in DFW continues to change in the future as much as it has between 1976 and 2001 (water increased by 54.75%, vegetation decreased by 20.34%, low- and high-density urban increased by 176.14%), it can be projected that water and low- and high-density urban land cover will continue to increase as vegetation decreases. This will alter the heat and moisture fluxes, leading to further influence on precipitation patterns. As previous research has shown and is confirmed by this study, urban areas can have an impact on their environment. This study has shown that as variability in precipitation has increased in DFW (Section 5.1.1), and regional climate forecasting may become more difficult.

7.3 Future Research

Future research on the impact of urbanization on precipitation patterns is needed to further support the main hypothesis. Micro-scale analyses are important in determining how the local land cover surrounding each station directly affects its recorded rainfall. It is not possible to conclude why individual stations in Section 4.4 were experiencing different precipitation patterns without a more in-depth study of individual site characteristics. It is also necessary to continue to investigating the long-term trends in each region and at each station individually. The years used to represent the early and late periods were chosen so that no extreme events would influence precipitation patterns. Another approach for analyzing trends would be to use varying time scales, including the strength and frequency of such events. Because there are numerous climatic influences occurring throughout the study period, adjusting the precipitation record for these may strengthen the anthropogenic signal. Also, in order to fully understand the dynamics of the DFW Metroplex, a climate model that varied the local land cover would provide insight into the dynamics of an urban climate and the mechanisms responsible for precipitation changes. As discussed in Chapter IV, the increases (decreases) in water, vegetation, low- and high-density urban, woody wetlands, and emergent herbaceous wetlands could potentially have a large impact on the region's microclimate. By determining the strength of the relationship between the precipitation patterns in the metroplex and land cover, it might be possible to predict how local climate will change as the area continues to grow and expand.

Based on previous research, it was expected that increased amounts of precipitation would be found downwind of the DFW Metroplex (CRB). Consistent with these studies, this research found that there are increased amounts of precipitation in the northern study region, which may be a result of the upwind urbanization. If urbanization has had an influence in the downwind precipitation, then it is likely to continue to have an influence as the rate of urbanization increases. It is also likely that an anthropogenic-induced signal could become stronger in future years as the DFW Metroplex is projected to develop and expand over time.

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