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The Urban Heat Island and Its Influence on Precipitation in Denver, Colorado

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The Urban Heat Island and its Influence on Precipitation in Denver, Colorado

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A Thesis

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Master of Arts

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by

Diana R. Thunen

June 2013

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Abstract

Anthropogenic modification of the climate is an unintended yet serious effect of urbanization and it is happening in every city across the globe in the form of the urban heat island. The purpose of this study was to see if Denver, Colorado exhibits evidence of an urban heat island using meteorological data and if there has been a change in precipitation amounts since the urbanization of the city. It was concluded that Denver, Colorado does have an urban heat island that varies seasonally throughout the year with an average magnitude of 3.57°C during the day and 3.82°C at night. The summer season exhibits the most prominent urban heat island of 4.22°C during the night. Overall, there has been a significant decrease in precipitation for the study area that can possibly be attributed to the urbanization of Denver. A non-significant but still noteworthy increase in precipitation in a small area downwind of southern Denver could be due to the urban heat island around the city.

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1.0 Introduction

There is no doubt the topic of global warming or climate change has become a hot-button issue over the past few years. While scientists have discussed and researched this subject for decades, it is only since the turn of the 21st century that the topic has become a caustic political and social issue. As newspapers are reporting on how the warming global environment is causing the loss of critical habitat for the iconic image of climate change, the polar bear, many are failing to realize that in every city across the globe there is a far more alarming anthropogenic-induced local climate change: the urban heat island.

Anthropogenic modification of the local environment was first documented by Luke Howard in early 19th century London, England. Howard compared temperatures from within the urbanized area of London to temperatures from the rural countryside. Howard saw a large difference between the two and recognized this difference to be the result of anthropogenic interference (Howard 1833). Howard explained this artificial warmth was caused by the city's structure, population, and the burning of fires (Mills 2008). Howard found the urbanized center of London to be 3.7°F (2.04°C) warmer than the countryside and the difference to be greatest at night (Howard 1833). This phenomenon was later coined the Urban Heat Island (UHI) in the 1940s by Gordon Manley (Landsberg 1981).

After nearly two hundred years of research on this phenomenon, it has been found that these heat islands can manifest themselves in many different ways including diurnal and seasonal variations. The most common documented effects in northern hemisphere cities include an increase in average air temperature of around 2°C, decrease in solar radiation by 12%, increase in clouds by 8%, and an increase in rainfall by 14% and snowfall by 10%. It was also found that thunderstorms have increased by 15% and there are ten times as many air pollutants in cities as compared to non-urban areas (Taha 1997a; Changnon 1976, 1981).

Heat islands can form at many different scales: around a single building, a vegetative canopy, or a whole city (Thurow 1983; Taha *et al.* 1989; Taha 1997b; Taha *et al.* 1991). In most cities where the urban heat island (UHI) has been studied the largest increase in temperatures is found on calm and clear nights with a maximum occurring in the late evening after the sun has set or early morning hours before the sun has risen (Oke 1987; Kim and Baik 2002). These urban heat islands (UHI) are caused by numerous factors: increase in thermally different materials, decrease in the latent heat flux, decrease in surface albedo, increase in anthropogenic heating, decrease in wind speed, and reduced sky-view factor (Taha 1997b; Dixon and Mote 2003; Shepherd 2005b).

As naturally vegetated environments are replaced with artificial manmade surfaces such as buildings, roads, and paved areas, it is changing the natural thermal balance of the environment. These new surfaces have different thermal behaviors than natural ones: primarily being they absorb solar radiation and reemit it as sensible heat. As the sensible heat is transferred from surfaces to the air, it can increase the air temperature by 2-10°C (Shepherd 2005a).

As urban areas expand so do impervious surfaces. A study done in 2004 by Elvidge *et al.* calculated the density of impervious surfaces for the contiguous United States to be 112,610 km^2. In other words, these surfaces could completely cover the state of Ohio if combined. These impervious surface areas (ISA) are replacing vegetation that would normally help to cool an area through evapotranspiration and shading. Vegetated areas can produce a daytime oasis effect of 6°C in favorable conditions according to Taha (1988). On the other hand, vegetation canopies can create a nighttime heat island by trapping warm air below the canopy. This vegetative heat island can raise air temperatures by as much as 2°C in heavily forested areas (Taha *et al.* 1989, 1991).

Impervious surfaces generally have more runoff than rural areas because the water is not able to infiltrate into the ground. Water quickly leaves urban areas which results in less surface water available for evapotranspiration. This leads to a decrease in the latent heat flux and an increase in sensible heat. According to Taha (1997), the lower evapotranspiration rates are a major factor in increasing daytime temperatures in urban areas. In arid cities where human presence has increased the amount of surface water in the form of irrigated lands such as Phoenix, Arizona a heat sink around the city can be found due to the increase in energy being converted to latent heat rather than sensible heat (Diem and Brown 2003).

These ISAs also have a lower albedo or reflectance than natural surfaces which results in the increased absorption of solar radiation. Taha *et al.* (1992) found that a surface with a high reflectance value or albedo of 0.72 (on a scale of 0-1) was 45°C cooler than surfaces with an albedo of 0.08. In a similar study done by Taha in 1988 it was found that if the urbanized areas of Los Angeles, California increased the surface albedo by 0.13, a reduction in surface temperatures of between 2-4°C could be achieved.

Anthropogenic heating can also cause surface temperatures to increase, amplifying the urban heat island. This type of warming is caused by the heat released when energy is consumed by humans and their activities. Whether it is from driving cars, manufacturing, power generation, or heating and cooling buildings, all of these activities release waste heat that can raise air temperatures in cities (Shahmohamadi *et al.* 2011). The largest influence from anthropogenic heating is typically found in colder environments due to the excessive heating load from warming buildings. Anthropogenic heating values can vary from 20-40 Wm^{-2} during the summer and 70-210 Wm^{-2} during the winter for city centers (Taha 1997b). According to a different study by Taha *et al.* (1992), anthropogenic heating can create a heat island of 2-3°C during both day and night in urban centers.

The magnitude of the urban heat island is defined as the largest difference between urban temperatures (T_u) and rural temperatures (T_r) (Chow *et al.* 2012). The urban-rural heat difference is most pronounced during summer nights based on studies in over 28 different U.S. cities (Huff and Changnon 1972; Gallo and Owen 1999), but can vary seasonal in other cities (Myrup 1969). Due to the reduced sky-view factor, radiative heat loss is reduced in large cities. Less surface area of buildings is exposed to the cooler open air resulting in more heat being retained during the night. Oke (1987) found the UHI to grow very quickly once the sun set reaching a maximum 3-5 hours after sunset.

The urban heat island can be measured in a multitude of ways. The most common way is by creating spatial interpolations from weather station data. Automobile traverses using mounted sensors on the vehicle and driving through the city are also common. More recently remote sensing has become popular now that data are widely available. Unfortunately, remotely sensed data only became available during the 1970s; therefore, it is impossible to get a historical perspective using this method. Other methods include time-trend analysis, energy balance calculations, and urban-rural site difference calculations based on in-situ meteorological measurements (Hawkins *et al.* 2004).

Generally, the UHI is perceived to have a negative impact through the increase in demand on air conditioning and energy use during the summer. There are also health consequences including the increase in heat stress and heat related mortality to consider. On the other hand, the UHI has some positive benefits. During cooler seasons or in cooler areas, the UHI can reduce the cost and energy load for heating buildings. Warmer road surfaces lead to fewer driving hazards such as ice or snow packed roads. Lastly, longer favorable growing conditions for plants and animals can be produced from the urban heat island (Stewart and Oke 2012).

With 80.7% of Americans (U.S. Census Bureau 2010) and over 50% of the world’s population (UNDESA 2012) living in urban areas as of 2010, this local climate change is making a considerable impression. Urban populations are expected to at least double by the year 2050 to 7.4 billion inhabitants or 67% of the world’s population

(UNDESA 2012). Billions of people are already affected and billions more will soon be by this human-made phenomenon. Due to the sizable impact of the UHI, it is imperative proper studies be conducted so that appropriate mitigation or adaptation strategies can be put in place.

1.1 Purpose of Study

Of the urban heat island effects on climatic variables besides temperature, the influence on precipitation rates has the most impact on inhabitants, particularly in areas that receive little amounts of precipitation in the first place. Researcher R.E. Horton first noticed an increased tendency for thunderstorms to form over large cities rather than nearby rural areas in the 1920s (Shepherd 2005b). Since this pioneering work the majority of research has agreed there is a noticeable increase in precipitation at locations downwind of urban centers (e.g., Landsberg 1956; Changnon 1968; Huff and Changnon 1972; Balling and Brazel 1987; Lowry 1998; Bornstein and Lin 2000; Diem and Brown 2003; Dixon and Mote 2003; Burian and Shepherd 2005b; Shepherd 2006).

Unfortunately, changes in precipitation due to urban areas can be much harder to measure than changes in temperature due to high variability spatially and temporally. This is why little research has been done in cities that do not receive a lot of precipitation (Dixon and Mote 2003). To date most of the research on urban-induced rainfall has been conducted in cities that receive large amounts of rain such as the humid cities in the eastern United States (Landsberg 1956; Changnon 1968; Changnon *et al.* 1976; Huff and Changnon 1973; Harnack and Landsberg 1975; Sanderson and Gorski 1978; Rosenberger and Suckling 1989). Little research on urban-induced precipitation has been done in arid or semi-arid cities of the western United States (Diem and Brown 2003). While it has been confirmed that anthropogenic activities are having an effect on arid or semi-arid cities just as they are in more humid cities (El-Sharif 1985; Larson 1986; Shaqour 1994; Modaihsh 1997; Raufer 1997; El Arabi 1999; Sohrabour *et al.*1999; Ellis *et al.*2000, Akber *et al.* 2001; Karamouz *et al.* 2001). The semi-arid region of the southwestern United States provides a unique place to study the UHI because many of the large cities in this area have undergone huge population increases in the past 50 or so years. This allows researchers to study the area from a pre-urban and post-urban standpoint. In addition, these arid regions rely more heavily on artificially irrigated lands. This expansion of surface water could have an enhancement effect on precipitation rates (Diem and Brown 2003; Shepherd 2006).

1.2 Research Questions

The purpose of this study is to examine how the urban heat island behaves in the semi-arid region of the western United States, specifically in Denver, Colorado. This study is driven by the following questions:

1. Does Denver, Colorado exhibit evidence of an urban heat island and during which season is it the most evident?
2. Has there been a change in the amount of precipitation since the urbanization of Denver, Colorado?

1.3 Study Area

1.3.1 Geography and Climate

Denver, nicknamed the Mile High City, received its moniker for precisely that reason. At an elevation of around 5,280 feet, Denver is exactly one mile above sea level. The Rocky Mountains are situated to the west of the city extending from the northern border of the state down to the southern border. The Front Range is considered the strip of land just to the east of the Rockies that is home to Fort Collins in the north, Denver in the middle, and Colorado Springs to the south. The land flattens out very quickly to the east of the Rockies with the Great Plains covering all of eastern Colorado.

The climate is semi-arid receiving only around 430 millimeters (17 inches) of precipitation annually (McKee *et al.* 2000). The majority of this precipitation comes from just a few big storms each year. Over half of the annual precipitation comes from only 20% of precipitation days. The wettest time of the year also varies spatially around the region. Denver experiences its maximum precipitation during the spring. The mountains on the other hand receive most of their precipitation during the winter. The main sources of water vapor over Denver are the Pacific Ocean, the Gulf of Mexico, and the Gulf of California (McKee *et al.* 2000). Low humidity and a high frequency of sunny days foster a dry environment. The average temperature is around 10°C (50°F) with an average high of 22°C (71.5°F) in August and an average low of -1°C (30°F) in January (Cities of the United States 2006).

Figure 1. Picture looking at Denver from the southwest at a rainstorm building as it moves over the city and travels east. Denver is located just to the right of the center of the image. Photograph by author. March 30, 2013

1.3.2 History

Denver is not only the capital of the state of Colorado, but it is also considered the capital of the Rocky Mountain Region. In 1858, Denver started out as a supply city for the mining towns when gold was discovered at Pikes Peak. When the 35,000 residents of Denver received the first telephone service in 1879, it cemented Denver’s place as the leading city of the Rocky Mountain Region. Today Denver is a commercial, financial, transportation, and federal government hub for the whole region. The Denver metropolitan is also host to numerous energy companies and is a major center for energy research including home to the National Renewable Energy Laboratory. The “Wall Street of the Rockies” located in Denver, has plenty of national and international banking institutions such as Janus Capital Group, JD Edwards, Charles Schwab, and many others. Additionally numerous federal headquarters are located in the Denver metropolitan area employing thousands of workers.

Located just a few hundred miles from the geographic center of the United States, Denver is in a prime transportation location. The Denver International Airport is one of the largest in the world and the fifth busiest in the United States transporting millions of people into and out of the state each year. Currently, Denver is experiencing a boom in high-technology arenas as more people move to the southwestern U.S. (Cities of the United States 2006).

1.3.3 Current Issues

As populations are expected to rise in the western arid and semi-arid regions of the U.S., from California to Colorado and further south, Denver is central to this major expansion. The city has spent millions of dollars improving downtown amenities and has plans for future expansion (Cities of the United States 2006). As of the 2010 census, the Denver-Aurora-Boulder combined statistical area (CSA) which is comprised of 12 counties has seen its population more than triple in the past 50 years to over 3 million inhabitants (U.S. Census Bureau 2010). Home to over 60% of the state's population, many of the counties in the Denver-Aurora-Boulder CSA are even included in the top 100 fastest growing counties in the nation. By the year 2035, the population of the Denver metropolitan area is projected to grow by over one million people (US Census Bureau 2010). Also by 2035 the Denver Regional Council of Governments (DRCOG), which includes governments of nine Denver-Aurora-Boulder CSA counties, estimates an additional 253 square miles of urban area will be added to the metro area (DRCOG 2011).

A study on the historical land use change by Parton *et al.* (2003) for the Front Range indicates urban areas have experienced a large influx in population since the 1950s. This expansion of urban areas has caused a 35% decrease in irrigated lands along the Front Range. In the counties surrounding the metro area including Weld, Elbert, and Adams there has been a 16% decrease in irrigated lands from 1990-2000. There has also been a reduction in rural populations as more people move to the city. All of this indicates the urban areas of the Denver metro have greatly expanded in spatial extent and population since the middle of the 20th century. Rural areas farther away from Denver on the other hand have experienced a 76% increase in irrigated lands since 1950 (Parton *et al.* 2003) indicating that agricultural and artificial surface water areas have expanded in eastern Colorado.

The Denver Regional Council of Governments' (DRCOG) plan for Denver is to make it a model for multimodal communities around the world. It plans to do this by increasing urban density by at least 10% (DRCOG 2011). While this may reduce the geographical expansion of urban areas and consequently the UHI, it may intensify the magnitude of the UHI due to the increase in concentration of anthropogenic surfaces while decreasing vegetation (Mills 2008). A successful multimodal community will create a desirable place to live for the young and aging populations alike, thus increasing migration to the metro area. Evidence of this comes from a Harris poll that showed Colorado as the fourth state most preferred to live in (Summit Economics and The Adams Group 2009). Pulwarty *et al.* (2005) describes Colorado and the other southwestern states as having one of the highest population growths in the whole country.

As the population of aging inhabitants of Denver increases at an exceptional rate, the UHI can pose a health risk to this group. Laaidi *et al.* (2012) noted an increase in elderly mortality due to urban heat exposure. Golden *et al.* (2008) found there were more heat related dispatch calls when the urban heat island was at a maximum. In a nighttime urban heat island, the human body is unable to recover from the daytime heat exposure so more stress is placed on the body (Laaidi *et al.* 2012). Peng *et al.* (2011) estimates an increase in heat related mortality will occur in large cities as summer time warming trends continue. A report by the Natural Resources Defense Council predicts that warming cities will be the cause of death for 150,000 people in the United States by 2100 with over 3,500 of those deaths in Denver alone. This same report declares that extreme heat event days will increase by 777% in Denver by mid-century just from climate change; this does not even take into account the increase due to the UHI (Altman *et al.* 2012). According to Quattrochi and Luvall (2006), mortality rates during a heat wave increase exponentially with the maximum temperatures, which the UHI amplifies. With over one million people above the age of 60 predicted to be residing in the metro area by 2035 (DRCOG 2011), the UHI can have serious life or death consequences for these inhabitants. Consequently, the urban heat island in Denver must be studied and analyzed so that the health of the city's residents is preserved.

With these large surges in population in the southwest comes a higher demand on already scarce water resources (Pulwarty *et al.* 2005). Denver, Colorado is a perfect example of this. With the projected population increase city planners are trying to figure out how they are going to supply this growing populace with water in an area where there is little to go around. Colorado gets its water supplies from only two sources: precipitation and groundwater. There are no rivers that flow into the state. Therefore, any change in precipitation can have far-reaching effects on the long-term supply of water for the Denver metropolitan area (McKee *et al.* 2000). Additionally, droughts can place significant stress on already low water systems. The most recent drought in the southwestern U.S. (1999-2004) was the seventh worst in the past 500 years (Piechota *et al.* 2004). If populations grow as expected, the demand on water will more than double from less than 1.5 million acre-feet in 2000 to 3 million acre-feet by the year 2050. If no new water source is found, Denver will be in an 1.5 million acre-foot deficit (Summit Economics and The Adams Group 2009).

Research shows that as the intensity of the UHI increases so does residential water use and demand (Balling and Gober 2007; Guhathakurta and Gober 2007, 2010; Lukas 2012). An investigation done by Denver Water showed that a 1.1°C (2°F) increase in air temperature would increase water demand by 6% (Denver Water 2013). In Phoenix, Arizona where water is just as rare, Aggarwal *et al.* (2012) found that with each degree Fahrenheit (0.55°C) rise in nighttime temperatures water consumption increases by 3.8%. Milly *et al.* (2005) calculated runoff in the Colorado basin area could decrease by 30% during the current century if temperatures continue to rise as projected. Even more dire results show that within 20 years the discharge of the Colorado River will be insufficient to meet current water needs (Pulwarty *et al.* 2005).

According to the Intergovernmental Panel on Climate Change, the projected water deficits will result in drought impacts that have never before been experienced in this area and will exacerbate conflicts among water users (IPCC 2008). If air temperatures continue to rise due to the urban heat island or climate change, any future drought will be more severe and last longer compared to today’s standard (Lukas 2012). Higher temperatures in an already dry area will intensify drought conditions according to Lukas (2012), a senior research associate with the Western Water Assessment. As shown by previous droughts in the area, when any economic sector that is dependent on water is impacted, the entire economy of the state is affected (McKee *et al.* 2000). Using tree rings as a historical perspective, experts are predicting worse droughts in the future than we have experienced over the past 100 years (Lukas 2012). Even though droughts are likely controlled by large-scale weather patterns (Hidalgo 2004), anthropogenic-induced changes can amplify extreme conditions.

The number one use of water in the state of Colorado is for agriculture. Farmers use water storage or groundwater reserves when precipitation rates are unable to sustain their crops. If there were an increase in precipitation then farmers would draw less on these water stores. If there were less precipitation, more demand would be placed on the reservoirs depleting the little water there is left (McKee *et al.* 2000). These agricultural sites in Colorado are mainly located to the east or downwind of Denver where previous studies have shown changes in precipitation to occur. Therefore, it is imperative that research be done to see if precipitation amounts are changing due to the urbanization of land.

Any change in the amount of water to the area can have huge implications for millions of people. Water is in short supply in Colorado and will become even scarcer as both temperature and populations rise. Water could very well be the limiting factor in the growth of Colorado’s economy and demographics (Summit Economics and The Adams Group 2009). To date there has not been any research conducted looking into urban-induced precipitation around the Denver area. This is why this study is so important. A more accurate projection of new water supplies that takes into account urbanization can help with water allocation strategies for the future.

Additionally there is not a lot of public awareness of the urban heat island or its detrimental effects in Denver. Through personal communication with Sarah Davis, a member of the National Urban and Community Advisory Council to the U.S. Department of Agriculture, the local government of Denver is currently working on a document that will address the UHI, but up until now there has not been any governmental recognition of this problem. The only governmental action that could be considered as potentially addressing the UHI issue was in 2006 when the mayor of Denver set a goal of planting one million trees across the Denver metropolitan area by the year 2025. The goal of the Mile High Million project, as it was called, is to purify the air, beautify neighborhoods, and to motivate citizens to become stewards of the environment. There is a small section on the website of the Mile High Million (www.milehighmillion.org) that describes how the urban forest can help to cool buildings and streets, but there is no mention of an urban heat island or the effects of one. Hence, it is important that research be done on the UHI and urban-induced precipitation in Denver so that the public and government become more aware of the issue and take proper steps to mitigate the negative consequences.

2.0 Theoretical Context

While it has been clearly and continuously shown that heat islands cause an increase in air temperature the effects on other climatic variables such as precipitation have not been as thoroughly documented or conclusive. Changes in precipitation around urban areas can be caused by a combination of the following factors; formation of an urban heat island (Changnon 1968); enhanced convergence due to increased surface roughness at the urban canopy layer (Changnon 1981; Cotton and Pielke 1995; Bornstien and Lin 2000; Thielen *et al.* 2000; Diem and Brown 2003; Shepherd 2005b); destabilization of the boundary layer and downwind circulation and cloud generation caused by the UHI (Hjelmfelt 1982; Shepherd *et al.* 2002; Shepherd and Burian 2003; Diem and Brown 2003); increase in aerosols for cloud condensation nuclei (Changnon 1968; Hudson and Frisbie 1991; Diem and Brown 2003; Molders and Olson 2004); diversion of precipitation systems due to the urban canopy (Bornstein and Lin 2000; Loose and Bornstein 1977); increase in irrigated lands that supply moisture particularly in arid and semi-arid regions (Diem and Brown 2003); and urban areas serving as a moisture convergence zone needed for convective development (Dixon and Mote 2003). Despite the current research on urban-induced precipitation there is no conclusive answer to which mechanism in the urban environment is causing these changes (Shepherd 2005a). This section highlights some of the major research done on urban-induced precipitation.

It should first be noted the effects of the UHI such as urban-induced precipitation are dependent on the size or magnitude of the UHI. The magnitude of the UHI is an effect of how large the city is in space and in inhabitants. Oke (1973) found a direct relationship between the population of a city and the size of its urban heat island. By using automobile traverses through ten cities with populations ranging from 1,000 to 2 million Oke discovered that heat island intensity is related to the logarithm of the population. Karl *et al.* (1988) found by looking at over 1,000 stations across the United States from 1901-1984 that urban effects on temperature can be first detected starting at populations of 10,000. Cities with populations of 10,000 had on average 0.1°C warmer air temperatures than surrounding rural stations or cities with less than 2,000 inhabitants. This study also showed that as populations continue to increase up to the ten million mark, so does the magnitude of the UHI (Karl *et al.* 1988). Brazel *et al.* (2000) found the relationship between minimum temperatures and urban areas to be distinct and nonlinear using temperature and population data in Baltimore, Maryland and Phoenix, Arizona. Temperatures in these cities would be stable until a large population surge that would cause the minimum temperatures to increase drastically (Brazel *et al.* 2000). Landsberg (1956) and Brazel *et al.* (2000) both found the magnitude of the nighttime UHI to increase as function of population and city size.

Moving on to studies about urban-induced precipitation it is clear the city of Atlanta, Georgia has been the recipient of many such research topics. Bornstein and Lin (2000) looked at six precipitation events over Atlanta, Georgia during the summer of 1996 to explore the interactions between the city's UHI, convergence zone, and convective thunderstorms. The authors used data from Project ATLANTA (ATlanta Land use Analysis: Temperature and Air quality) and the National Weather Service to investigate this issue. Bornstein and Lin (2000) concluded three of the six events studied were initiated by the UHI. Their results showed a positive connection between the maximum UHI, convergence zone, and precipitation values for these three storms.

Dixon and Mote (2003) used land use maps, radar reflectivity, surface meteorological data, upper-air soundings, and air mass classification types to determine when, where, and why precipitation is initiated in Atlanta. The authors found conclusive evidence of a significant spatial and temporal pattern in precipitation events using five years of climatological data. Their results indicated that UHI intensity is not the main driver behind precipitation events, but rather a component that could trigger a precipitation event under the right conditions. For a precipitation event to occur, an air mass with high levels of moisture must interact with the UHI. The authors also note in their article that moist air is likely to converge over urban areas due to the UHI and the vertical profile of the city. Another outcome of their research showed that precipitation events occurred on days that had some atmospheric instability. It was not unstable enough to cause a storm naturally, but just enough to help the UHI induce an event.

In the first study of its kind Rose *et al.* (2008) used eight years of lightning flash data from the National Lightning Detection Network and precipitation data from the North American Regional Reanalysis model to see if there was an increase of either around the Atlanta metropolitan area. Their analysis confirmed an increase in both lightning flashes and precipitation at multiple meteorological stations downwind of Atlanta in the past eight years. They also noted both factors were influenced heavily by wind direction.

To better assess if the precipitation events were indeed initiated by the UHI, longer datasets should have been used in all of the discussed studies in Atlanta. Bornstein and Lin (2000) only used precipitation data from one summer. Multiple years' worth of precipitation events would provide more evidence of a positive connection between the UHI and precipitation events. Even the eight years used by Rose *et al.* (2008) may not be long to enough to determine if the increase in precipitation is a long-term trend. This study will use over 40 years' worth of data to determine if there has been a change in precipitation amounts.

St. Louis, Missouri has also been a hub for various studies indicating a change in precipitation due to the expansion of the urban environment. The Metropolitan Meteorological Experiment (METROMEX) was a government supported multi-institutional research project in St. Louis during the 1970s with a goal of studying the effects of large urban areas on the frequency, formation, intensity, amount, and duration of precipitation processes. The major outcomes of this project include finding a 10-30% increase in precipitation east of the city, enhanced rain and thunderstorm intensities, increase in convergence over and downwind of the city, and increase in Aitken and cloud condensation nuclei (Principal Investigators of Project METROMEX 1976).

Rozoff *et al.* (2003) simulated the atmosphere over St. Louis, Missouri to investigate the UHI's role in atmospheric convection and precipitation events. The study's results indicate the UHI plays a significant role in initiating moist convection downwind of the city. Convergence, due to drag from the vertical profile of the city, combined with the UHI caused air convergence on the leeward side of the city resulting in more precipitation events downwind of the city. Their study also acknowledged the topography of the area can affect storm development.

Hjemfelt (1982) used a numerical model to simulate the UHI of St. Louis to examine what was happening in the atmosphere downwind of the city. He used a number of different variables in his models including urban and rural land uses. When only rural land use was considered for all of St. Louis, the models showed weaker vertical motion in the atmosphere downwind of the city. He found positive vertical velocities downwind when using urban variables. Hjemfelt (1982) proposed that this resulted from the vertical profile of the urban area combined with the UHI. He noted this atmospheric profile caused by urban land use is conducive to storm generation and could be the cause of downwind events. This study was unique in that it was able to look at the meteorological variables as if the city was not there. This is a concern when looking at how urban areas affect the climate because it is not possible to see how the exact storm would behave if the city was not physically present. By using computer models, the researcher was able to mitigate this concern.

In 2003 Changnon looked at 55 years of freezing rain events from a national database in not only St Louis, but in Chicago, Illinois; New York City, New York; and Washington, District of Columbia. He found that freezing rain events in all four of these cities are decreasing due to the UHI. Changnon determined the increase in urban temperatures is preventing the precipitation from freezing and sticking to surfaces. In New York City and Chicago, Changnon found the freezing rain season has decreased by 1–2 months compared to rural areas. St Louis and Washington D.C. did not have a decrease in their freezing rain season as found by Changnon's study (2003).

A similar study done over the mountains of Colorado indicate a warmer climate will increase the melting height of snow and ice thus decreasing the amount of hail to reach the surface (Mahoney *et al.* 2012). This could be comparative to the increase in temperature due to the UHI over the city. Less hail and snow will reach the ground and will instead melt into rain or possibly evaporate before it hits the surface.

Studies conducted in Houston, Texas had similar results. Burian and Shepherd (2005) used a rain gauge network to see if there has been a change in precipitation in the Houston area during two different time periods. They classified pre-urban time as 1940–1958 while the post-urban period was 1984–1999. Their research showed more precipitation events in post-urban times than pre-urban. They also compared upwind areas to downwind areas around Houston. According to this study, downwind locations experienced significantly higher amounts of rainfall than the upwind sites.

Bouvette *et al.* (1982) examined data from four Houston meteorological stations during the 1960s and 1970s. The researchers found rainfall increased by 15% in suburban areas while downtown Houston experienced a decrease in rainfall over the same time period. In the article, the authors hypothesize the increase in urban surface area as the root cause of this.

Similar to the study done in Atlanta that compared lightning flashes with precipitation amounts, Orville *et al.* (2001) surveyed 12 years' worth of lightning data for the Houston area. The authors came to the conclusion there were more lightning flashes over and downwind of the urban center. The authors predicted that there is a higher density of flashes over Houston because of the UHI, convergence zone, and possibly due to enhanced aerosols in the atmosphere.

The only arid city to warrant much research in this anthropogenic phenomenon is Phoenix, Arizona. The research to come out of Phoenix is unusual compared to the other cities studied. The limited precipitation received by the city generally occurs during a specific monsoon season and not at other times of the year. This can often result in a weak UHI or even a heat sink due to the prevalence of human irrigated lands (Diem and Brown 2003). Diem and Brown (2003) found precipitation increased downwind of the city by 11%-14%. The researchers hypothesized this increase could be due to any one or a combination of the following factors: the prevalence of irrigated lands, the UHI, a convergence zone caused by the vertical profile of the city, or an increase of aerosols in the atmosphere.

Shepherd (2006) used 108 years of meteorological data to conclude Phoenix has experienced a 12–14% increase in rainfall in post urban time periods due to the UHI. Shepherd split the meteorological data into two time periods: pre-urban and post-urban.

The pre-urban time period was 1895-1949 while the post-urban period was 1950-2003. His study also noted an anomaly in an area of Phoenix that did not experience an increase in precipitation. Shepherd attributes this to the large amount of irrigated land and the topography of the area. In this same study, Shepherd also looked at the precipitation rates of the arid city of Riyadh, Saudi Arabia. Shepherd noted an increase in precipitation rates over the 1990-2003 timeframe that corresponds with increased urbanization.

Balling and Brazel (1987) noted more storms in Phoenix due to the population growth since the 1950s. These authors did not come to the conclusion that total precipitation amounts have increased like the other studies discussed here did. The authors did notice that the diurnal pattern has changed between 1954 and 1985. Late afternoon storms have become more common and produce larger drop sizes than before the city began to expand.

Using numerical models Thielen *et al.* (2000) determined why there is an increase in precipitation downwind of the urban core. Variations that influence rainfall development are most effective farther away from the central heat source, in this case the urban core according to the study. Rozoff *et al.* (2003) found that the convergence on the leeward side of the city is the reason for the downwind increase.

There are also studies indicating there is no relation between the urban heat island and precipitation rates. Using data from four large cities in Turkey, Tayanç *et al.* (1997) found no effects of urbanization on precipitation rates. In Cairo, Egypt, Raobaa (2003) found an inverse relationship between the degree of urbanization and rainfall rates. Ramanathan *et al.* (2001) declared urban areas reduce rainfall not increase it due to cloud microphysics. Rosenfeld (1999, 2000) also found that urban and industrial aerosols suppress precipitation by increasing the amount of small cloud droplets that do not coalesce to form rain. Clouds must grow higher and have colder cloud-top temperatures for precipitation to form (Rosenfeld 1999, 2000). Borys *et al.* (2000, 2003) found a decrease in winter precipitation because of these same processes.

In light of all the research studying UHI impacted precipitation it becomes clear there is a limited amount of research done in the western United States where precipitation events are scarce. This project aims to examine the UHI and its impacts on a rapidly expanding city in the Western U.S. that has not previously been studied: Denver, Colorado.

3.0 Methods

3.1 Current Urban Heat Island

The first step in this process was to obtain meteorological data for the Denver metropolitan area. The data were obtained from the Global Historical Climatology Network (GHCN) maintained and updated by the National Oceanic and Atmospheric Administration (NOAA). This program records the daily climate summaries from land surface stations across the globe and contains the most comprehensive and complete dataset of daily climate summaries available (Menne *et al.* 2011). There are over 46,000 current or historical GHCN-D stations in the United States. In Colorado alone there are over 3,000 current or historical stations (Menne *et al.* 2011). The climate variables recorded at these stations used in this analysis include total daily precipitation, daily maximum temperature (T_{max}), and daily minimum temperature (T_{min}). The GHCN-D data are available through NOAA's website at ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/.

The GHCN provides some of the earliest climate records in the United States dating back to the early 19th century. In Colorado, the earliest recorded measurement is 1893. The GHCN data are quality checked extensively (Peterson and Vose 1997; Peterson *et al.* 1998; Durre *et al.* 2010). The incoming meteorological data are quality checked using at least 19 tests that look for erroneous data such as duplicate values, exceedence of climatological limits, gaps, and inconsistencies within a station and with neighboring stations (Durre *et al.* 2010). While real-time data are available, archival data are released 45-60 days after the data are collected (Durre *et al.* 2010). This is why data only through the end of 2009 were used for this analysis. This ensures that the data have been thoroughly quality checked and is archival ready. The data have not been adjusted for biases involving station movement, environmental changes, observing practices or instrumentation (Peterson and Vose 1997; Peterson *et al.* 1998; Durre *et al.* 2010).

To answer the first proposed question of whether or not Denver has an urban heat island, daily maximum (T_{max}) and minimum (T_{min}) temperature will be analyzed. In this study the phrase maximum temperature (T_{max}) is used interchangeably with daytime temperature and the phrase minimum temperature (T_{min}) is used interchangeably with nighttime temperatures. A decade of temperature data from 2000-2009 was collected from GHCN-D stations within a 150 kilometer radius around central Denver. A radius of 150 km was chosen for this study because previous studies indicated a precipitation surplus occurring directly over the city and up to 80 km downwind from the urban center (Dixon and Mote 2003; Shepherd 2005a). I chose to expand this to ensure the precipitation signal would be found if there is one around the urban area of Denver. To be included in this study each GHCN-D station had to have at least 90% of the daily minimum and maximum temperatures recorded over the ten-year period of 2000-2009. This resulted in the requirement of each station having a minimum of 3,287 days of recorded temperatures. The actual minimum amount of recorded days used in this study was 3,291 while the maximum was the full ten years at 3,652 days. A total of 58 GHCN-D stations fit these two spatial and temporal conditions (Table 1 and Figure 2).

Table 1. Stations used in the 2000-2009 UHI Analysis including respective GHCN-D identification, location (decimal degrees), elevation (meters), and urban or rural classification using the 2010 U.S. Census Bureau's designations

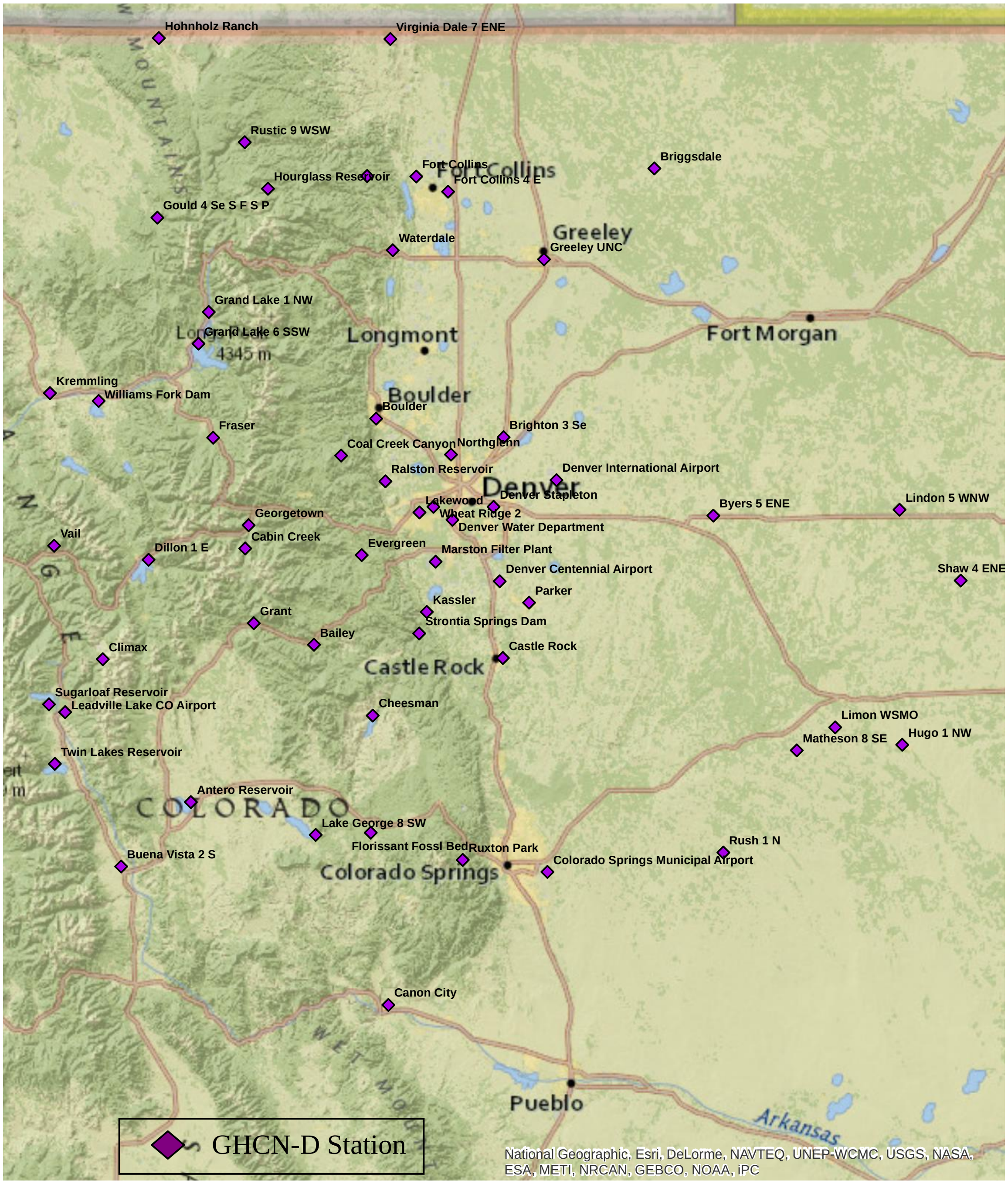
Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Elevation Meters	Urban or Rural
Antero Reservoir	USC00050263	38.99	-105.89	2718.8	Rural
Bailey	USC00050454	39.41	-105.48	2356.1	Rural
Boulder	USC00050848	39.99	-105.27	1671.5	Urban
Briggsdale	USC00050945	40.64	-104.33	1473.4	Rural
Brighton 3 Se	USC00050950	39.94	-104.84	1528.9	Urban
Buckhorn Mountain 1 E	USC00051060	40.62	-105.30	2255.5	Rural
Buena Vista 2 S	USC00051071	38.83	-106.13	2421.9	Urban
Byers 5 ENE	USC00051179	39.74	-104.13	1554.5	Rural
Cabin Creek	USC00051186	39.66	-105.71	3054.1	Rural
Canon City	USC00051294	38.46	-105.23	1624.6	Urban
Castle Rock	USC00051401	39.37	-104.84	1936.1	Urban
Cheesman	USC00051528	39.22	-105.28	2097	Rural
Climax	USC00051660	39.37	-106.19	3450.3	Rural
Coal Creek Canyon	USC00051681	39.90	-105.38	2728	Rural
Colorado Springs Municipal Airport	USW00093037	38.81	-104.69	1871.5	Urban
Denver Centennial Airport	USW00093067	39.57	-104.85	1793.1	Urban
Denver International Airport	USW00003017	39.83	-104.66	1650.2	Rural
Denver Stapleton	USW00023062	39.76	-104.87	1611.2	Urban
Denver Water Department	USC00052223	39.73	-105.01	1593.5	Urban

Table 1. Continued Stations used in the 2000-2009 UHI Analysis including respective GHCN-D identification, location (decimal degrees), elevation (meters), and urban or rural classification using the 2010 U.S. Census Bureau's designations

Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Elevation Meters	Urban or Rural
Dillon 1 E	USC00052281	39.63	-106.04	2763	Rural
Evergreen	USC00052790	39.64	-105.31	2133.6	Urban
Florissant Fossl Bed	USC00052965	38.91	-105.29	2572.5	Rural
Fort Collins 4 E	USC00053006	40.58	-105.02	1499.6	Urban
Fort Collins	USC00053005	40.62	-105.13	1525.2	Urban
Fraser	USC00053116	39.94	-105.82	2609.1	Rural
Georgetown	USC00053261	39.72	-105.70	2596.9	Rural
Gould 4 Se S F S P	USC00053446	40.51	-106.01	2743.2	Rural
Grand Lake 1 NW	USC00053496	40.27	-105.83	2657.9	Rural
Grand Lake 6 SSW	USC00053500	40.19	-105.87	2526.2	Rural
Grant	USC00053530	39.46	-105.68	2644.1	Rural
Greeley UNC	USC00053553	40.40	-104.70	1437.1	Urban
Hohnholz Ranch	USC00054054	40.97	-106.00	2365.2	Rural
Hourglass Reservoir	USC00054135	40.58	-105.63	2901.7	Rural
Hugo 1 NW	USC00054172	39.14	-103.49	1531.6	Rural
Kassler	USC00054452	39.49	-105.10	1676.7	Rural
Kremmling	USC00054664	40.06	-106.37	2252.5	Rural
Lake George 8 SW	USC00054742	38.91	-105.47	2596.9	Rural
Lakewood	USC00054762	39.75	-105.12	1719.1	Urban
Leadville Lake CO Airport	USW00093009	39.23	-106.32	3029.1	Rural
Limon WSMO	USW00093010	39.19	-103.72	1634.9	Rural
Lindon 5 WNW	USC00055025	39.76	-103.50	1490.5	Rural
Marston Filter Plant	USC00055402	39.62	-105.07	1685.2	Urban
Matheson 8 SE	USC00055427	39.13	-103.85	1777	Rural
Northglenn	USC00055984	39.90	-105.01	1635.6	Urban
Parker	USC00056323	39.51	-104.75	1947.7	Urban
Ralston Reservoir	USC00056816	39.83	-105.24	1798.3	Rural

Table 1. Continued Stations used in the 2000-2009 UHI Analysis including respective GHCN-D identification, location (decimal degrees), elevation (meters), and urban or rural classification using the 2010 U.S. Census Bureau's designations

Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Elevation Meters	Urban or Rural
Rush 1 N	USC00057287	38.86	-104.09	1831.8	Rural
Rustic 9 WSW	USC00057296	40.70	-105.71	2347	Rural
Ruxton Park	USC00057309	38.84	-104.97	2758.4	Rural
Shaw 4 ENE	USC00057560	39.57	-103.29	1524	Rural
Strontia Springs Dam	USC00058022	39.43	-105.12	1780	Rural
Sugarloaf Reservoir	USC00058064	39.25	-106.37	2968.1	Rural
Twin Lakes Reservoir	USC00058501	39.09	-106.35	2802.6	Rural
Vail	USC00058575	39.66	-106.35	2520.7	Rural
Virginia Dale 7 ENE	USC00058690	40.97	-105.22	2138.2	Rural
Waterdale	USC00058839	40.43	-105.21	1594.1	Rural
Wheat Ridge 2	USC00058995	39.76	-105.07	1666	Urban
Williams Fork Dam	USC00059096	40.04	-106.20	2322	Rural



National Geographic, Esri, DeLorme, NAVTEQ, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC

Figure 2. Location of the GHCN-D stations used in the Current UHI Analysis

Due to the widely varying topography of the Front Range the temperature data were normalized down to sea level so they could be easily compared. This is a common practice when comparing temperatures or creating interpolated surfaces with meteorological data collected at different elevations (Willmott and Matsuura 1995). The elevations of the GHCN-D stations range from 1437 meters up to 3450 meters. It is known that temperature decreases with elevation due to the decreasing atmospheric pressure; this is otherwise known as the lapse rate. Therefore I cannot directly compare temperatures taken at different elevations; they must be brought to the same elevation. The most common environmental lapse rate (ELR) used when calculating potential temperatures is a decrease in air temperatures of 6.4°C for every one kilometer above sea level. Using the ELR of 6.4°C/km, every recorded temperature used in this analysis was calibrated to sea level. While these new potential temperatures do not reflect the actual temperatures of the area the magnitudes for comparing will still be the same.

The next step in this process was to calculate the seasonal maximum and minimum average temperatures for each station to determine if there is variation in the UHI throughout the year. Spring was calculated as the average of March, April, and May; Summer as June, July, and August; Fall as September, October, and November; Winter as December, January, and February. These months were chosen for the respective seasons because they correlate with the hottest, coldest, and transitional months of the year (Trenberth *et al.* 2000). These are also the designations that are commonly used in the climate modeling community.

Each station was then classified as urban or rural using the United States Census Bureau's urban-rural designations from the 2010 census. The Census Bureau classifies an area as urban if there at least 2,500 people residing there. Rural areas are all regions that have less than 2,500 inhabitants (US Census Bureau 2010). The U.S. Census Bureau provides a shapefile with designated urban areas to be used in GIS software from its TIGER database (2010 TIGER/Line Shapefiles 2012). After importing both the urban area shapefile and the GHCN-D stations into ArcGIS, I was able to determine which stations should be classified as urban or rural. If a station fell within the U.S. Census Bureau's classified urban area then it was considered urban. If the station was not located in a designated urban area then it was considered rural.

The temperatures for all of the classified urban stations were then averaged together over the ten-year period for each season to create an average urban temperature (T_u). The same was done for the rural stations to create an overall average rural temperature (T_r). The difference between the urban and rural average (T_u-T_r) annually and for each season was calculated for both T_{max} and T_{min}. This shows the magnitude of the UHI.

To assess the temperatures visually, maps using ArcGIS 10.1 and an interpolation technique were made. The interpolation technique used in this study for this analysis was Empirical Bayesian Kriging (EBK). This technique was used because it requires minimal interactive modeling, has lower standard errors of prediction, and is more accurate with moderately nonstationary and small datasets (Esri 2012). The data used in this analysis were normally distributed, had slight nonstationarity to it, and no trends. These conditions led to EBK being the interpolation tool of choice. I did a comparison with my data between Simple Kriging, Inverse Distance Weighted, and EBK to see which one would provide the best results. EBK was the easiest to use and resulted in the least error (Table 2). The EBK interpolation method produces a raster containing the predicted temperatures for the specified area. The 2010 Census Bureau urban area shapefile is overlaid on the raster to see if there is a visual correlation between temperature and land use. When looking at the produced maps and interpolated rasters it is possible to see where there are areas of warmer temperatures and cooler temperatures.

Table 2. Difference between IDW, Kriging, and Empirical Bayesian Kriging Standards of Error for one season of data.

Method	Mean	Root-Mean-Square	Mean Standardized	Root-Mean-Square Standardized	Average Standard Error
IDW	0.115783	1.33865	-	-	-
Kriging	0.120086	1.57353	0.06338371	0.9698725	1.626886
EBK	0.10197	1.60533	0.05655105	1.017671	1.593915

The last step in the temperature analysis for the 2000-2009 time period was to run statistical tests on the data to determine if there is a significant difference between the classified urban and rural areas. The program used for the statistical tests was SPSS version 20. Using this program and grouping the data into rural or urban categories, independent t-tests were run on the potential temperature measurements. Independent t-tests were run comparing the annual temperature of each group and by each season as well. This gives results at the 95% confidence level of whether or not the differences between urban and rural areas are statistically significant.

3.2 Urban Heat Island 1920s-1990s

The next question that needs to be addressed is whether or not these warm and cool areas have always been this way or if this is a recent development potentially due to the expansion of the urban center. To do this, decadal temperatures dating back to 1920 were examined in the same process as described above. Seasonal averages were calculated for the following time periods; 1920-1929, 1930-1939, 1940-1949, 1950-1959, 1960-1969, 1970-1979, 1980-1989, and 1990-1999. Unfortunately all of the same stations used in the 2000-2009 did not have records dating back to 1920; therefore I used stations that were within the 150 km radius of Denver and had at least 90% of the temperature data for the decade being calculated. This led to 22 stations for the 1920s, 25 stations for the 1930s, 28 stations for the 1940s, 38 stations for the 1950s, 38 stations for the 1960s, 39 stations for the 1970s, 40 stations for the 1980s, and 50 stations for the 1990s to be used in the comparison (Table 3). ArcGIS and EBK were used in the same manner as described in the previous section to make interpolated temperature surface maps for each decade. After the maps were created for each season of every decade, the scale on each map was changed to match all the other maps of the same decade so that the seasons of every decade could be accurately compared. For example the scale of all the spring maximum temperature maps were made the same so I could accurately see which areas have changed and which have stayed the same over the decades. This was done for every season so they could be visually compared more accurately. The 2010

U.S. Census Bureau’s urban areas were overlaid in every interpolated image so to provide reference between the different decadal images.

Table 3. List of GHCN-D Stations used in each Urban Heat Island decadal analysis from 1920-1990

Station	GHCN-D	Latitude	Longitude	Used in Which Decadal Analysis?							
	Identification	Decimal Degrees	Decimal Degrees	1920	1930	1940	1950	1960	1970	1980	1990
Allenspark 2 NNW	USC00050183	40.200	-105.533				✓	✓	✓		
Antero Reservoir	USC00050263	39.000	-105.883						✓	✓	✓
Arriba	USC00050348	39.317	-103.217		✓	✓					
Bailey	USC00050454	39.400	-105.483			✓	✓	✓	✓	✓	✓
Berthoud Pass	USC00050674	39.800	-105.783						✓		
Bond	USC00050810	39.883	-106.683					✓			
Boulder	USC00050848	40.017	-105.267	✓	✓	✓	✓	✓	✓	✓	✓
Briggsdale	USC00050945	40.633	-104.317							✓	✓
Brighton 3 SE	USC00050950	40.000	-104.800							✓	✓
Buckhorn Mountain 1 E	USC00051060	40.617	-105.283								✓
Buena Vista 2 S	USC00051071	38.817	-106.117		✓		✓	✓		✓	✓
Byers 5 ENE	USC00051179	39.700	-104.217		✓	✓	✓	✓	✓	✓	✓
Cabin Creek	USC00051186	39.650	-105.700						✓	✓	✓
Canon City	USC00051294	38.433	-105.267	✓	✓	✓	✓	✓	✓	✓	
Castle Rock	USC00051401	39.367	-104.867						✓		✓
Cheesman	USC00051528	39.217	-105.283	✓	✓	✓	✓	✓	✓	✓	✓
Cherry Creek Dam	USC00051547	39.650	-104.850					✓	✓		✓
Climax	USC00051660	39.383	-106.200					✓	✓	✓	✓
Colorado Springs Municipal Airport	USW00093037	38.817	-104.700				✓	✓	✓	✓	✓
Cripple Creek	USC00051973	38.750	-105.167			✓					
Denver Lowry AFB	USW00023012	39.717	-104.900				✓				
Denver Stapleton	USW00023062	39.767	-104.883				✓	✓	✓	✓	✓
Denver Weather Service Office City	USW00093002	39.750	-105.000	✓	✓	✓	✓	✓			
Dillon 1 E	USC00052281	39.583	-106.050	✓	✓	✓	✓	✓	✓	✓	✓
Edgewater	USC00052557	39.767	-105.050	✓	✓	✓	✓				
Elbert	USC00052593	39.217	-104.550						✓	✓	
Elk Creek 1	USC00052635	39.500	-105.417	✓							

Table 3. List of GHCN-D Stations used in each Urban Heat Island decadal analysis from 1920-1990

Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Used in Which Decadal Analysis? 1920	1930	1940	1950	1960	1970	1980	1990
Estes Park	USC00052759	40.400	-105.583	✓	✓	✓	✓		✓	✓	
Evergreen	USC00052790	39.633	-105.317						✓	✓	✓
Florissant Fossl Bed	USC00052965	38.883	-105.283								✓
Fort Collins	USC00053005	40.583	-105.083	✓	✓	✓	✓	✓	✓	✓	✓
Fort Lupton 2 SE	USC00053027	40.133	-104.883	✓	✓	✓	✓	✓			
Fort Morgan	USC00053038	40.250	-103.800	✓	✓	✓	✓	✓	✓	✓	✓
Fraser	USC00053116	39.950	-105.817	✓	✓	✓	✓	✓			✓
Georgetown	USC00053261	39.700	-105.700				✓				
Grand Lake 1 NW	USC00053496	40.267	-105.833				✓	✓	✓	✓	✓
Grand Lake 6 SSW	USC00053500	40.250	-105.850				✓	✓	✓	✓	✓
Grant	USC00053530	39.467	-105.683						✓	✓	✓
Greeley	USC00053546	40.433	-104.700	✓	✓	✓	✓				
Greeley UNC	USC00053553	40.417	-104.700						✓	✓	✓
Green Mountain Dam	USC00053592	39.883	-106.333			✓	✓	✓	✓	✓	✓
Grover 10 W	USC00053643	40.900	-104.367	✓	✓	✓	✓	✓			
Hohnholz Ranch	USC00054054	40.967	-106.000								✓
Hot Sulphur Springs 2 SW	USC00054129	40.050	-106.150					✓			
Hourglass Reservoir	USC00054135	40.633	-105.600								✓
Idaho Springs	USC00054234	39.750	-105.550	✓	✓	✓	✓	✓			
Kassler	USC00054452	39.500	-105.100	✓	✓	✓	✓	✓	✓	✓	✓
Kauffman 4 SSE	USC00054460	40.850	-103.900			✓	✓	✓	✓		
Kremmling	USC00054664	40.050	-106.367								✓
Lake George 8 SW	USC00054742	38.917	-105.483					✓	✓	✓	✓
Lake Moraine	USC00054750	38.817	-105.017	✓	✓	✓	✓				
Lakewood	USC00054762	39.750	-105.133						✓	✓	✓
Leadville Lake CO Airport	USW00093009	39.250	-106.300				✓	✓			✓
Limon 10 SSW	USC00055015	39.183	-103.717		✓	✓	✓	✓			
Limon WSMO	USW00093010	39.267	-103.683				✓	✓	✓	✓	

Table 3. List of GHCN-D Stations used in each Urban Heat Island decadal analysis from 1920-1990

Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Used in Which Decadal Analysis? 1920	1930	1940	1950	1960	1970	1980	1990
Lindon 5 WNW	USC00055025	39.683	-103.417								✓
Littleton	USC00055056	39.617	-105.017							✓	
Longmont 2 ESE	USC00055116	40.167	-105.067	✓	✓	✓	✓	✓	✓	✓	✓
Loveland 2 N	USC00055236	40.400	-105.117								✓
Monument 2 WSW	USC00055730	39.083	-104.933	✓	✓	✓	✓				
Monument	USC00055734	39.100	-104.867								✓
Mount Evans Research Station	USC00055797	39.650	-105.600								✓
Nederland 2 NNE	USC00055878	39.983	-105.500						✓		
New Raymer 21 N	USC00055934	40.933	-103.767								✓
New Raymer	USC00055922	40.600	-103.850						✓	✓	✓
Northglenn	USC00055984	39.900	-105.017								✓
Nunn	USC00056023	40.700	-104.783							✓	
Parker 6 E	USC00056326	39.517	-104.750		✓	✓	✓	✓	✓	✓	
Red Feather Lakes 2 SE	USC00056925	40.800	-105.583				✓			✓	
Rush 1 N	USC00057287	38.867	-104.083					✓		✓	
Ruxton Park	USC00057309	38.850	-104.983					✓	✓	✓	✓
Spicer	USC00057848	40.483	-106.417	✓	✓			✓	✓	✓	✓
Strontia Springs Dam	USC00058022	39.433	-105.117								✓
Sugarloaf Reservoir	USC00058064	39.250	-106.367				✓			✓	✓
Twin Lakes Reservoir	USC00058501	39.083	-106.317						✓		
Vail	USC00058575	39.633	-106.367								✓
Victor	USC00058649	38.700	-105.133	✓							
Walden	USC00058756	40.733	-106.267			✓	✓	✓	✓	✓	✓
Waterdale	USC00058839	40.417	-105.200	✓	✓	✓	✓	✓	✓	✓	✓
Wheat Ridge 2	USC00058995	39.750	-105.083								✓
Wiggins 7 SW	USC00059025	40.150	-104.183					✓			
Williams Fork Dam	USC00059096	40.033	-106.217								✓

3.3 Change in Temperature and Precipitation

To accurately assess if temperatures in the Denver area are caused by UHI-forcing, meteorological data from before the city began to build up extensively was obtained. For this study the assumption that the city and suburbs of Denver began their expansion in the 1950s will be used. This cutoff point is used because this is the decade when the population of Denver began to spike. The population of the Denver metropolitan area increased by 45% during the 1950s, one of the largest increases in population for this area not counting the most current surge in the 2000s (US Census Bureau 2010). This was also the decade the population of the metro area hit the one million mark which in previous studies is significant to the formation of the UHI (Karl *et al.* 1988). Therefore this study requires data that extend back beyond this point in time so a baseline of what temperatures were before people interfered can be established.

The meteorological data were again obtained from the Global Historical Climate Network-Daily program. Once acquired, the meteorological data were split into two different time periods, pre-urban and urban. The data were split into two groups so they could be compared to see if there has been a significant change in climate variables, specifically precipitation and temperature, which can be attributed to the urban heat island. The earliest climate record for Colorado in the GHCN-daily network extends back to 1893. Consequently this means the pre-urban time period will range from 1893–1950. The urban time period will range from 1951–2011. Ideally this will give me a total of 119 years of data for each station: 58 years pre-urban and 61 years urban.

When selecting the meteorological stations to use in this study a radius of 150 kilometers around Denver was used just like in the previous analyses. Unfortunately very few stations have continuous or complete meteorological records over the time period from 1893-2011. Many stations were dismantled, moved, or not put up until after the city grew substantially. Therefore stations that had at least 20 years of data during each time period were selected. The data did not have to be continuous, but 90% of the 20 years of data for each season must be available during each time period for it to be used in the study. Each station had to have at least 6,570 recorded data points during spring, summer, fall, and winter for both the pre-urban and urban time frames. A total of 19 GHCN-D meteorological stations were identified that met these criteria. All had more than the 40 years of required data, the minimum amount of years included is 54 and the maximum is 119 (Table 4 and Figure 3).

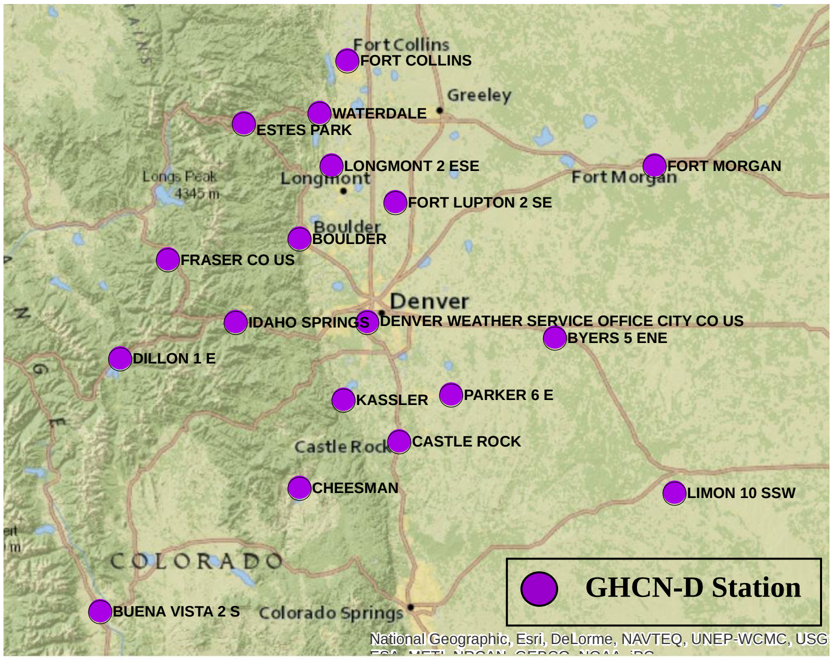


Figure 3. Location of GHCN-D Stations used in the Pre-Urban and Urban Change in Precipitation and Temperature Analysis

Table 4. List of GHCN-D stations used in the Pre-urban and Urban change in Precipitation and Temperature Analysis

Station	GHCN-D Identification	Latitude Decimal Degrees	Longitude Decimal Degrees	Elevation Meters	Total Number of Years of Data
Boulder	USC00050848	40.017	-105.283	1644	118
Buena Vista 2 S	USC00051071	38.817	-106.117	2425	113
Byers 5 ENE	USC00051179	39.700	-104.217	1586	90
Canon City	USC00051294	38.433	-105.267	1629	119
Castle Rock	USC00051401	39.367	-104.867	1891	90
Cheesman	USC00051528	39.217	-105.283	2100	110
Denver Weather Service Office City	USW00093002	39.750	-105.00	1611	54
Dillon 1 E	USC00052281	39.633	-106.033	2766	104
Estes Park	USC00052759	40.383	-105.517	2288	94
Fort Collins	USC00053005	40.583	-105.083	1519	119
Fort Lupton 2 SE	USC00053027	40.133	-104.883	1524	67
Fort Morgan	USC00053038	40.250	-103.800	1317	119
Fraser	USC00053116	39.950	-105.833	2612	94
Idaho Springs	USC00054234	39.750	-105.550	2307	72
Kassler	USC00054452	39.500	-105.100	1677	94
Limon 10 SSW	USC00055015	39.200	-103.717	1634	64
Longmont 2 ESE	USC00055116	40.250	-105.150	1510	101
Parker 6 E	USC00056326	39.517	-104.650	1922	73
Waterdale	USC00058839	40.417	-105.200	1586	110

After the data were collected, the average maximum temperature, minimum temperature, and daily precipitation amounts were calculated for each season, station, and time period. The percent change between the two time periods was calculated for every season at each station for precipitation similar to what Shepherd did in his analysis in

Phoenix, Arizona (2006). The percent change was calculated because each station cannot be directly compared with another station due to the high variability in station elevations. It is widely known that precipitation increases with altitude just as temperature inversely decreases (Basist 1994). The precipitation data were not normalized down to a standard elevation or sea level due to the fact there is no standard or accepted way to do this. Therefore, a station's precipitation amounts can only be compared to itself and no other station. For this reason, the calculated percent change will show if there has been an increase, decrease or no change at each station relative to other stations. The percent change was calculated for temperatures and also the exact difference. When making the interpolated temperature maps the range of percentages was too large for detailed mapping. Therefore the exact change in temperature was used to make the maps and not the percent change.

The interpolated maps made for this part of the analysis were created using ArcMap 10.1. The interpolation tool used was Simple Kriging. Empirical Bayesian Kriging (EBK) was not used because Simple Kriging had lower standards of error than EBK for this specific dataset. The percent change was used in this analysis to create a raster of interpolated percent changes in precipitation. The exact change in temperature in degrees Celsius was used for the temperature maps for the reasons mentioned above. These maps allow the areas where precipitation and temperature has decreased, increased, or stayed the same to be spatially visible. The graphic showing the change in precipitation can be compared visually with the graphic showing the change in temperature to see if there is a spatial correlation between the two. The 2010 U.S. Census

Bureau's urban areas were overlaid in every interpolated image so to provide reference between the different images.

The last step in the precipitation analysis was to see if the changes in temperature and precipitation between the pre-urban and the urban time periods are statistically significant. Independent t-tests were performed on each season for temperature and precipitation. The results give at the 95% confidence level whether or not the changes are significant.

3.4 Limitations

3.4.1 Current Urban Heat Island

The limiting factor in this analysis is the classification of the urban and rural sites. The designation made by the U.S. Census Bureau is based solely on population rather than the actual landcover of the site. This can introduce error because a station may be classified as urban but is located in an open field or surrounded by the natural environment and not manmade structures. This could potentially lower the urban temperature average overall. Another downside of using this designation for this project is it does not take into account urbanized areas that do have people who live there. For example the Denver International Airport (DIA) is a large expanse of developed and paved land yet it is not classified as urban according to the census because no one lives there. This could raise the rural average temperatures.

3.4.2 Urban Heat Island 1920s-1990s

A potential source of error in the historical urban heat island analysis is that the same stations were not used when creating the interpolated surfaces for each decade. As already discussed it was impossible to get a sufficient amount of stations that date back to the early 20th century. Therefore for each decade I used any station available that fit my criteria even if it was not used for every decade. This introduces some error and inconsistencies that should be taken into consideration when interpreting the results.

Errors within the data measurements need to be accounted for as well. In the 1980s there was a widespread shift from glass thermometers to electronic thermometers. This resulted in a cold bias of roughly 0.25°C (Ray *et al.* 2008). Another larger cold bias can happen when the observing time is changed from the afternoon to the morning, which has become more common in more recent years according to Pielke *et al.* (2002). Unfortunately, these changes are not always documented and can result in not knowing if a temperature change is due to measurement or environmental changes (Pielke *et al.* 2007).

3.4.3 Change in Temperature and Precipitation

The main limiting factor in this analysis was the lack of continuous data and stations with the full 119 years of recorded data. Precipitation is highly variable over time and it is extremely rare to find continuous years with similar precipitation patterns (McKee *et al.* 2000). Therefore, it is imperative to use a long-term average to account for this yearly variability. As mentioned earlier in the methods section, not all stations had the full 119 years of records that was my window of data collection for the precipitation analysis. Therefore I had to set parameters of each station having at least 20 years of data during both the pre-urban (1893-1950) and urban (1951-2011) time periods. The data are often not continuous within those 20 years either, but there is at least 20 years for each season available. A work around to the discontinuous data is done by calculating an average for each time period. This will smooth out any years that had significantly high or low temperatures or precipitation.

The other major limiting factor for this analysis is the fact that nearly all of the 19 meteorological stations used in the precipitation analysis moved at least once during their history or had unknown location points for some period during the data collection. Precipitation is highly variable spatially. This is especially true in Colorado where storms are highly episodic with some areas receiving ample amounts and others very little (McKee *et al.* 2000). Therefore station movements can introduce error into precipitation records.

4.0 Results

4.1 Current Urban Heat Island

The first question addressed in this study is whether or not Denver, Colorado exhibits evidence of an urban heat island. To do this the average seasonal maximum and minimum temperatures were calculated at each GHCN-D station for the 2000-2009 decade (Table 5).

Table 5. Average Daytime and Nighttime Seasonal Temperatures in Degrees Celsius for the 2000-2009 Urban Heat Island Analysis

	Spring		Summer		Fall		Winter	
Station	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Antero Reservoir	10.27	28.52	20.73	41.12	10.36	30.74	-1.52	18.66
Bailey	11.00	28.22	20.90	40.14	11.06	28.80	2.66	18.29
Boulder	13.18	28.66	23.66	40.57	14.13	29.46	5.37	18.96
Briggsdale	9.27	27.43	21.33	40.17	9.39	27.86	-1.47	15.51
Brighton 3 SE	11.05	28.17	22.44	40.97	11.50	29.05	0.92	17.29
Buckhorn Mountain 1 E	14.23	26.55	26.16	39.48	16.45	28.98	7.37	19.39
Buena Vista 2 S	13.43	30.30	23.81	42.78	14.00	31.89	4.36	20.45
Byers 5 ENE	10.58	27.49	22.74	40.82	11.32	28.82	0.39	16.72

Table 5. Continued Average Daytime and Nighttime Seasonal Temperatures in Degrees Celsius for the 2000-2009 Urban Heat Island Analysis

Station	Spring		Summer		Fall		Winter	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Cabin Creek	15.00	27.28	25.54	39.45	17.23	29.70	8.35	19.52
Canon City	12.44	29.73	24.36	41.44	13.66	30.92	3.75	20.06
Castle Rock	12.63	28.35	23.68	40.60	13.57	30.15	3.98	19.76
Cheesman	11.19	28.17	22.57	40.58	12.39	30.56	2.46	20.01
Climax	13.60	26.91	25.23	39.51	16.04	29.24	5.65	18.35
Coal Creek Canyon	14.11	26.99	24.70	39.52	16.00	28.88	7.87	18.72
Colorado Springs Municipal Airport	13.36	28.67	24.80	40.36	14.24	29.52	4.32	18.63
Denver Centennial Airport	12.86	27.92	24.59	40.62	13.93	29.18	4.33	18.50
Denver International Airport	12.22	27.74	24.34	40.94	13.26	28.77	3.01	17.36
Denver Stapleton	11.93	27.30	24.04	40.32	12.61	28.82	2.61	17.85
Denver Water Department	13.07	28.74	25.05	41.78	13.53	29.78	3.62	18.76
Dillon 1 E	10.59	27.34	20.33	40.44	11.88	29.59	1.86	17.33
Evergreen	11.01	28.30	21.32	40.36	11.54	30.23	2.46	20.75
Florissant Fossl Bed	10.90	29.83	20.61	41.02	11.44	31.03	1.58	20.21
Fort Collins 4 E	11.08	26.80	22.51	39.24	11.13	27.15	1.03	15.89
Fort Collins	12.13	27.63	23.19	39.31	12.26	27.70	2.54	17.12
Fraser	9.13	27.86	18.57	40.25	9.95	29.22	-1.31	16.48
Georgetown	13.87	28.02	24.01	40.50	15.17	29.95	7.01	19.02

Table 5. Continued Average Daytime and Nighttime Seasonal Temperatures in Degrees Celsius for the 2000-2009 Urban Heat Island Analysis

Station	Spring		Summer		Fall		Winter	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Gould 4 SE S F S P	9.84	25.67	19.76	38.49	11.24	27.55	1.24	16.45
Grand Lake 1 NW	11.35	28.82	20.57	41.17	12.38	30.05	2.79	17.83
Grand Lake 6 SSSW	9.94	27.36	20.47	40.44	12.13	29.07	-0.05	14.74
Grant	12.61	28.25	22.46	40.35	13.77	29.66	4.90	18.98
Greeley UNC	11.45	29.12	22.81	41.54	11.64	28.82	1.47	16.05
Hohnholz Ranch	9.72	27.09	19.27	40.49	9.96	28.91	1.67	16.78
Hourglass Reservoir	13.16	26.50	24.01	39.88	15.86	28.72	7.20	17.68
Hugo 1 NW	9.15	28.11	21.76	40.04	10.48	29.39	-0.63	17.59
Kassler	12.80	28.19	25.11	40.41	14.15	29.96	3.44	19.67
Kremmling	10.41	26.79	20.51	40.73	10.36	28.48	-2.32	12.59
Lake George 8 SW	11.90	28.19	23.46	40.43	13.36	30.24	0.19	18.14
Lakewood	12.56	27.90	24.22	40.75	13.27	29.59	3.80	18.89
Leadville Lake Co Airport	12.90	28.65	22.13	41.09	14.24	30.28	4.65	19.38
Limon WSMO	8.93	27.68	21.25	40.18	9.44	28.64	-1.24	17.12
Lindon 5 WNW	9.62	27.21	22.39	40.30	10.37	28.21	-0.77	15.89
Marston Filter Plant	13.15	27.67	24.86	40.13	14.08	29.53	4.09	18.69
Matheson 8 SE	11.57	28.24	23.25	40.23	12.90	29.36	2.26	17.51
Northglenn	12.78	29.73	24.09	42.49	13.40	30.76	3.75	19.87
Parker	11.69	29.77	23.14	41.18	11.91	30.43	2.06	19.85
Ralston Reservoir	14.22	27.69	25.92	40.28	15.54	28.65	6.25	18.64
Rush 1 N	12.28	28.12	23.97	40.32	13.17	29.16	3.37	18.08

Table 5. Continued Average Daytime and Nighttime Seasonal Temperatures in Degrees Celsius for the 2000-2009 Urban Heat Island Analysis

Station	Spring		Summer		Fall		Winter	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
Rustic 9 WSW	12.11	25.83	22.68	39.46	14.00	28.33	5.86	17.14
Ruxton Park	13.05	28.55	22.49	39.18	14.21	29.81	5.74	21.15
Shaw 4 ENE	10.20	26.99	22.53	39.81	11.24	28.16	0.04	15.69
Strontia Springs Dam	9.05	27.90	21.83	39.84	11.18	29.07	0.41	18.43
Sugarloaf Reservoir	12.20	27.70	22.53	40.50	14.33	29.21	4.44	19.00
Twin Lakes Reservoir	12.54	27.58	22.98	40.42	14.92	29.80	4.12	19.22
Virginia Dale 7 ENE	11.60	25.97	22.47	39.50	12.83	27.43	4.40	16.58
Vail	11.82	26.86	20.50	39.98	12.50	27.85	2.95	14.72
Waterdale	11.01	27.41	22.36	39.94	11.85	28.28	1.39	17.57
Wheat Ridge 2	11.87	28.66	22.81	40.73	11.89	29.82	2.97	19.59
Williams Fork Dam	9.59	26.63	20.02	39.85	10.39	27.95	-2.24	12.18

To calculate the magnitude of the UHI, the overall average rural temperature was subtracted from the overall average urban temperature for each season and for the whole year. For the 2000-2009 decade the magnitude of the urban heat island was 3.57°C during the day and 3.82°C during the night. Seasonally the largest UHI was found on summer nights with an average difference between rural and urban sites of 4.22°C. The smallest UHI magnitude occurs during fall days at 3.29°C. The results from all seasons are listed in Table 6.

Table 6. Seasonal Magnitude of UHI 2000-2009

		Urban T_u (°C)	Rural T_r (°C)	Magnitude T_u-T_r (°C)
Annual	Daytime	17.83	14.26	3.57
	Nighttime	1.60	-2.22	3.82
Spring	Daytime	16.81	13.21	3.60
	Nighttime	0.84	-3.03	3.87
Summer	Daytime	29.18	25.75	3.43
	Nighttime	12.06	7.85	4.22
Fall	Daytime	17.96	14.68	3.29
	Nighttime	1.47	-1.87	3.34
Winter	Daytime	7.14	3.19	3.95
	Nighttime	-8.16	-12.00	3.85

The next step was to run an independent t-test on the rural versus urban stations to see if there is a significant difference between the two for either maximum or minimum temperatures. Using the program SPSS the results of this show there is a statistical difference between the minimum and maximum temperatures of urban and rural meteorological stations for all seasons and annual (Table 7).

Table 7. Current Urban Heat Island Independent T-Test Results

Season	Variable	t-value	Degrees of Freedom	P-Value	Rural/Urban	N^a	Mean	Standard Deviation
Annual	T_{max}	12.463	211282	**.000***	Rural	150140	28.76	10.47
					Urban	61144	29.39	10.57
	T_{min}	12.463	211282	**.000***	Rural	149841	12.28	9.13
					Urban	61096	13.16	8.97
Spring	T_{max}	9.187	27600	**.000***	Rural	37862	27.70	7.47
					Urban	15390	28.38	7.76
	T_{min}	17.069	30050	**.000***	Rural	37779	11.46	5.99
					Urban	15360	12.40	5.65
Summer	T_{max}	11.039	26620	**.000***	Rural	37808	40.26	4.42
					Urban	15382	40.75	4.79
	T_{min}	39.547	32164	**.000***	Rural	37722	22.35	3.70
					Urban	15368	23.63	3.25
Fall	T_{max}	4.212	27528	**.000***	Rural	37339	29.19	8.21
					Urban	15297	29.53	8.52
	T_{min}	6.275	52573	**.000***	Rural	37281	12.64	6.60
					Urban	15294	13.04	6.44
Winter	T_{max}	15.086	26101	**.000***	Rural	37131	17.70	6.36
					Urban	15075	18.68	6.87
	T_{min}	15.221	32003	**.000***	Rural	37059	2.51	6.59
					Urban	15074	3.39	5.71

N^a is the number of meteorological records between 1893-2011 used in each analysis

* Significant at the .001 level

The map of interpolated temperature surfaces showing the average minimum and maximum temperatures for the area during each season are shown in Figures 5 and 6. The census urbanized area overlay shows three distinct urbanized centers. The northern most area will be referred to as Fort Collins, the largest urban area in the center will here forth be called Denver, and the southernmost area will be referred to as Colorado Springs (Fig. 4)

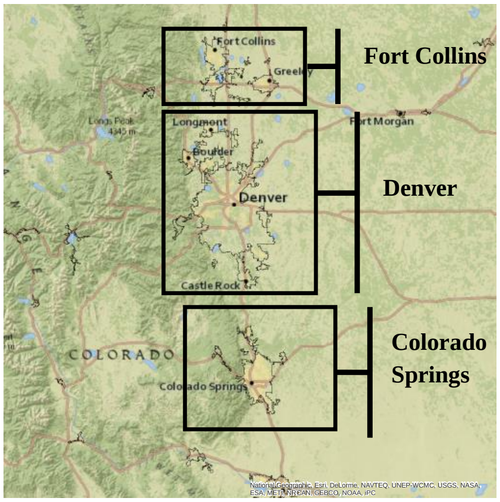


Figure 4. Location of Urban Areas using the 2010 U.S. Census Designations

Spring daytime temperatures (Fig. 5.) are warmest in the southwestern area and are progressively cooler to the north. Spring nighttime temperatures (Fig. 6) show a warm band to the west of all urbanized areas, over Denver, and over Colorado Springs. Summer daytime temperatures (Fig. 5.) show two isolated areas of higher temperatures: one over the northern portion of Denver and one in the southwestern corner of the study area. The coolest temperatures are north and northwest of the Denver Urban Area. Summer nighttime temperatures (Fig. 6) show a band of warmer air covering eastern Colorado Springs travelling northwest to just west of Fort Collins. The warm air covers all of Denver. The coolest area is in the northwest corner. The daytime fall temperatures (Fig. 5.) show a decrease in temperatures from south to north. The warmest temperatures are in the southwestern corner of the study area. The coolest temperatures are in the central northern area. Fall nighttime temperatures (Fig. 6) show a band of warmer temperatures along the eastern base of the Rocky Mountains. There is a cool spot southwest of the urbanized area and in the northeastern portion of the study area. Winter daytime temperatures (Fig. 5.) are warmest in the southern portion of the area. It gets progressively cooler to the north. Winter nighttime temperatures (Fig. 6) show a band of warmer temperatures at the base of the Rocky Mountains, to the west of urbanized areas. There are isolated spots of cooler temperatures located to the southwest, west, and east of the city.

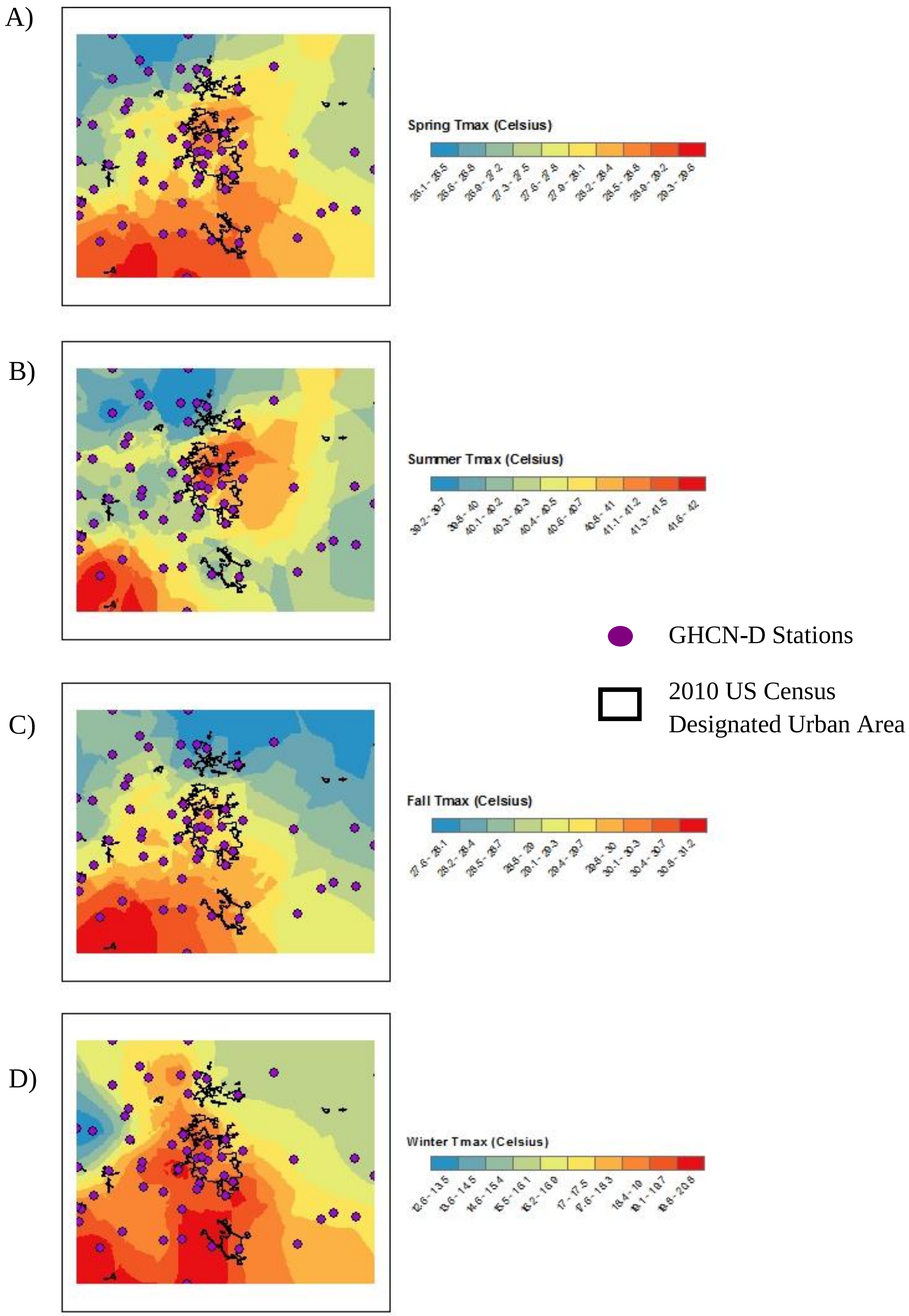


Figure 5. Interpolated Maximum Temperature Surface Maps for the 2000-2009 time period for spring (A), summer (B), fall (C), and winter (D)

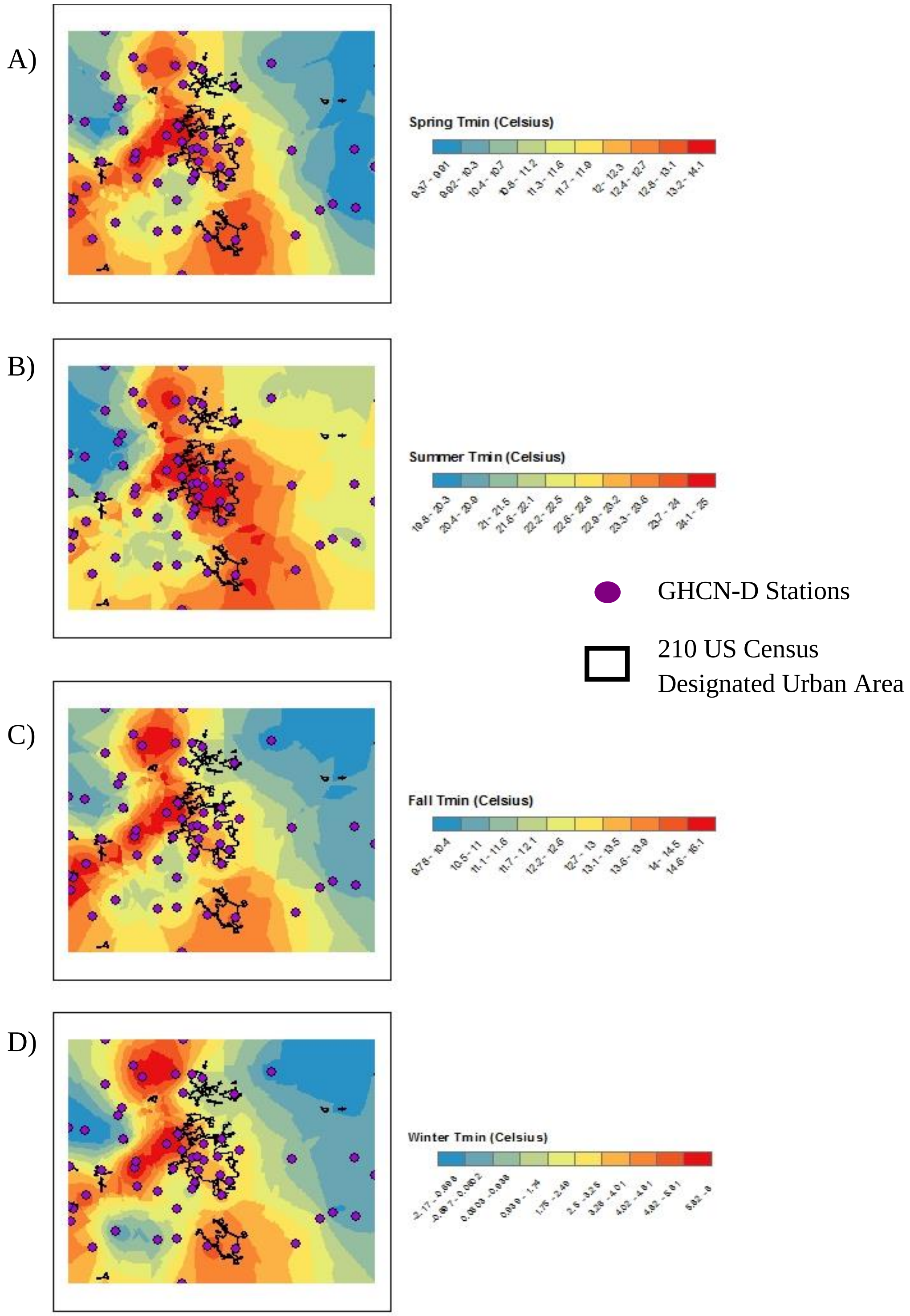


Figure 6. Interpolated Minimum Temperature Surface Maps for the 2000-2009 time period for spring (A), summer (B), fall (C), and winter (D)

4.2 Urban Heat Island 1920s-1990s

The next step was to create interpolated temperature surface maps for each decade extending back to the 1920s. The average minimum and maximum temperatures were calculated for each station used in each decade (Tables 8 and 9). The interpolated surfaces for each decade and each season are shown in Figures 7-14.

The interpolated maps of spring daytime temperatures (Fig. 7) show a strong southern area of warm temperatures during the periods of 1930-1960 and the 1990s. In the 1960s the warm area encompasses the largest spatial area traveling as far north to cover all of Denver. In the 1990s the warm area is more localized over Denver and to the south. In the 1920s there is a small area of warm temperatures to the very south, but the image is more dominated by cool areas to the west, east and northeast of Denver. In the 1980s there is a large cool spot to the east of Denver and Colorado Springs.

Springtime night temperatures (Fig. 8) again show a region of warm air located south of Colorado Springs during the decades of 1920-1960. By the 1970s this region is not as dominate and there are warm areas over Denver, north of Fort Collins, and west of both Denver and Colorado Springs that continue through the 1990s. Cool areas are most obvious in the 1920s in which it encompasses large regions west and east of Denver. This cool region continues through the 1970s. For the 1980s and 1990s the cool region is a small isolated spot on the western edge. The eastern plains also have cooler temperatures throughout the eight decades.

Summer maximum temperatures (Fig. 9) are less continuous through the decades. The 1920s are dominated by cooler temperatures that encompass the whole area except for a small area over Denver and one over Colorado Springs. The 1930s has a large region of warm air that extends from the southern edge into Denver and east into the plains. The 1940s show a semi-warm region over Denver extending southwest into the mountains. Cool pockets exist north and northeast of Fort Collins. The 1950s are similar to the 1930s in that there is a warm region that extends from the southern border to Denver, although it does not quite cover the urban area. The 1960s temperatures are coolest in the north central region and warmest in the southwest and central areas. The 1970s are very similar to the 1960s except the cold pocket around Fort Collins has split into two isolated areas one west of Denver the other west of Fort Collins. The 1980s have a large warm area to the east of Denver and Fort Collins. There is also a warm region in the southwest corner. The 1990s have a cool region encompassing Fort Collins and extending east to the border of the study region. There is also a cooler spot located just west of Denver. A warm area over Denver is present and in the southwest corner.

Summer nighttime temperatures (Fig. 10) show a warm area that covers the southern portion of the study area and extends north to cover the Denver region with some slight variations through the decades. Starting in 1990 there is a warm region over Fort Collins as well. The coolest area is located in the west and northwest corner for all decades as well.

The fall daytime temperatures (Fig. 11) are the warmest in all decades from 1920-1990 in the southwestern corner of the study area. Through the 1960s the warm area extends north closer to the Denver urban area with each decade. Starting in 1970 and continuing through the 1990s the warmest area is smaller and not as pronounced in the southwest corner. The coolest area in all decades is the north and northeastern region of the study area. Through all decades the temperatures decline from south to north.

The fall nighttime images (Fig. 12) show that from 1920s-1960s the highest temperatures were located in the south over the Colorado Springs urban area. Between the 1930s and 1950s the warm temperatures extended far enough north to cover the Denver urban area. In the 1960s the warmest areas in the south began to cool a little and a band of warm temperatures formed along the western edge of the Denver urban area. In the 1990s this warm band extended all the way from west of Fort Collins down to the southwest corner of the region. The coolest temperatures in all decades are located in the northern, northwestern, and northeastern portions of the study area.

Winter daytime temperatures (Fig. 13) again show the warmest temperatures in the south. From the 1920s-1950s the warm area gradually travels north over the Denver urban area and almost to Fort Collins. Starting in the 1960s the temperatures reduce a bit but they are warmest in the south and southwest extending north through Denver. The lowest temperatures are located in the northeastern and northwestern corners.

Winter nighttime temperatures (Fig. 14) again show the south to be the warmest region from the 1920s-1960s. Cool regions from the 1920s-1960s exist along the western edge of the study area, to the east, and the northeast. Starting in the 1970s the south is not quite as warm as it was the previous decades. A warm spot has developed just west of Denver that continues through the 1990s. In the 1990s a warm spot has also developed west of Fort Collins. Cool regions in the later decades are also localized to the eastern portion, the western edge, and a spot west of Colorado Springs.

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Allenspark 2 NNW	--	--	--	25.89	25.81	26.74	--	--	--	--	--	39.44	38.68	39.47	--	--
Antero Reservoir	--	--	--	--	--	26.92	26.64	27.74	--	--	--	--	--	40.18	40.13	40.24
Arriba	--	25.90	26.15	--	--	--	--	--	--	40.66	39.47	--	--	--	--	--
Bailey	--	--	28.17	28.47	29.20	28.11	26.54	27.63	--	--	40.23	41.49	40.80	40.40	38.86	39.31
Berthoud Pass	--	--	--	--	--	24.67	--	--	--	--	--	--	--	37.07	--	--
Bond	--	--	--	--	28.64	--	--	--	--	--	--	--	41.46	--	--	--
Boulder	26.23	27.24	25.83	27.04	27.90	27.20	28.01	27.89	38.67	39.98	38.73	40.86	39.73	40.02	40.15	39.11
Briggsdale	--	--	--	--	--	--	26.60	26.66	--	--	--	--	--	--	40.16	38.92
Brighton 3 SE	--	--	--	--	--	--	27.39	26.67	--	--	--	--	--	--	40.07	39.18
Buckhorn Mountain 1 E	--	--	--	--	--	--	--	26.75	--	--	--	--	--	--	--	39.17
Buena Vista 2 S	--	29.45	--	29.17	29.84	--	28.69	28.63	--	41.25	--	41.89	41.74	--	41.35	40.91
Byers 5 ENE	--	27.02	26.43	26.25	27.85	27.00	26.91	27.36	--	41.68	40.35	41.09	40.39	40.67	40.45	40.33
Cabin Creek	--	--	--	--	--	26.20	26.33	26.35	--	--	--	--	--	38.78	38.96	38.35
Canon City	29.46	29.63	29.51	28.54	29.36	29.04	28.69	--	40.75	41.34	41.17	41.31	40.62	40.90	40.34	--
Castle Rock	--	--	--	--	--	27.84	--	27.77	--	--	--	--	--	40.78	--	39.96
Cheesman	27.46	29.49	28.72	28.76	29.14	28.57	27.99	28.25	39.73	42.13	40.65	41.82	40.86	40.73	40.79	40.48
Cherry Creek Dam	--	--	--	--	28.75	27.23	--	28.54	--	--	--	--	41.08	41.26	--	41.33
Climax	--	--	--	--	25.67	25.54	26.36	26.85	--	--	--	--	37.90	38.45	39.00	38.84
Colorado Springs Municipal Airport	--	--	--	26.58	27.30	27.20	27.40	27.31	--	--	--	40.33	39.52	39.76	39.87	39.25
Cripple Creek	--	--	28.45	--	--	--	--	--	--	--	39.70	--	--	--	--	--
Denver Lowry AFB	--	--	--	25.50	--	--	--	--	--	--	--	39.45	--	--	--	--
Denver Stapleton	--	--	--	25.70	26.74	26.93	26.71	27.19	--	--	--	39.69	39.52	40.07	40.08	39.97
Denver Weather Service Office City	25.25	26.19	25.56	25.32	26.15	--	--	--	38.04	39.74	38.61	39.27	38.71	--	--	--
Dillon 1 E	25.70	27.38	27.28	27.17	27.00	26.29	25.87	26.47	38.87	40.29	39.71	39.93	39.94	39.79	39.13	38.98
Edgewater	26.86	28.04	28.52	27.49	--	--	--	--	39.65	42.06	41.48	41.58	--	--	--	--
Elbert	--	--	--	--	--	27.68	20.98	--	--	--	--	--	--	40.40	--	--
Elk Creek 1	23.97	--	--	--	--	--	--	--	35.16	--	--	--	--	--	--	--

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Estes Park	28.47	26.68	27.14	25.92	--	26.39	26.44	--	39.94	39.37	40.24	39.12	--	39.03	39.31	--
Evergreen	--	--	--	--	--	26.75	27.11	27.93	--	--	--	--	--	39.65	39.34	39.42
Florissant Fossl Bed	--	--	--	--	--	--	--	29.33	--	--	--	--	--	--	--	40.28
Fort Collins	24.31	25.37	25.08	24.68	25.49	25.66	26.22	26.30	36.96	38.36	37.66	38.36	37.62	38.09	38.39	37.79
Fort Lupton 2 SE	25.72	26.75	26.12	27.27	26.95	--	--	--	39.38	41.44	40.17	41.21	39.48	--	--	--
Fort Morgan	22.79	25.37	24.95	24.30	25.24	25.17	25.49	25.96	35.99	39.02	37.96	38.83	38.45	39.24	39.42	38.70
Fraser	23.97	25.25	26.40	25.28	25.21	--	--	26.31	37.35	38.90	39.50	39.23	38.25	--	--	39.40
Georgetown	--	--	--	27.41	--	--	--	--	--	--	--	41.21	--	--	--	--
Grand Lake 1 NW	--	--	--	25.45	26.20	26.06	27.21	28.08	--	--	--	39.32	39.04	39.25	40.51	40.31
Grand Lake 6 SSW	--	--	--	24.60	24.83	24.58	24.84	26.02	--	--	--	38.61	38.01	38.10	38.31	38.69
Grant	--	--	--	--	--	27.86	27.29	28.11	--	--	--	--	--	40.11	39.33	39.73
Greeley	25.26	26.22	25.45	24.51	--	--	--	--	38.82	40.92	39.73	39.45	--	--	--	--
Greeley UNC	--	--	--	--	--	26.73	26.36	26.54	--	--	--	--	--	39.54	39.44	38.96
Green Mountain Dam	--	--	27.30	26.94	27.40	26.98	25.66	25.90	--	--	40.15	40.83	40.65	40.28	39.23	38.93
Grover 10 W	24.86	25.19	24.94	24.61	26.07	--	--	--	38.05	40.63	38.64	39.13	39.10	--	--	--
Hohnholz Ranch	--	--	--	--	--	--	--	26.23	--	--	--	--	--	--	--	39.35
Hot Sulphur Springs 2 SW	--	--	--	--	26.03	--	--	--	--	--	--	--	40.07	--	--	--
Hourglass Reservoir	--	--	--	--	--	--	--	27.07	--	--	--	--	--	--	--	40.19
Idaho Springs	25.40	25.97	27.34	26.69	27.72	--	--	--	36.76	38.11	39.69	40.17	39.26	--	--	--
Kassler	28.18	29.20	28.43	28.15	28.08	27.44	26.93	27.83	39.62	40.91	40.29	40.92	39.75	40.05	39.83	40.22
Kauffman 4 SSE	--	--	26.11	25.42	26.37	26.09	--	--	--	--	39.37	39.76	39.08	39.94	--	--
Kremmling	--	--	--	--	--	--	--	25.90	--	--	--	--	--	--	--	39.46
Lake George 8 SW	--	--	--	--	27.91	27.09	26.20	27.44	--	--	--	--	39.84	39.75	39.35	39.48
Lake Moraine	25.22	25.39	24.33	26.77	--	--	--	--	36.49	38.56	36.52	39.32	--	--	--	--
Lakewood	--	--	--	--	--	26.25	26.45	27.01	--	--	--	--	--	39.41	39.51	39.43
Leadville Lake CO Airport	--	--	--	26.20	27.07	--	--	27.44	--	--	--	40.63	40.02	--	--	39.91
Limon 10 SSW	--	26.49	25.89	26.40	27.31	--	--	--	--	40.63	38.95	40.66	40.02	--	--	--

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Limon WSMO	--	--	--	25.37	26.28	25.94	25.90	--	--	--	--	39.46	38.83	39.31	39.34	--
Lindon 5 WNW	--	--	--	--	--	--	--	25.53	--	--	--	--	--	--	--	38.62
Littleton	--	--	--	--	--	--	27.02	--	--	--	--	--	--	--	38.68	--
Longmont 2 ESE	26.46	26.73	26.01	25.35	26.25	26.25	26.68	27.07	39.33	40.12	38.85	39.65	38.89	39.66	39.92	39.76
Loveland 2 N	--	--	--	--	--	--	--	26.49	--	--	--	--	--	--	--	38.24
Monument 2 WSW	27.00	28.28	27.98	28.29	--	--	--	--	39.95	42.18	40.38	41.78	--	--	--	--
Monument	--	--	--	--	--	--	--	27.19	--	--	--	--	--	--	--	39.62
Mount Evans Research Station	--	--	--	--	--	--	--	25.78	--	--	--	--	--	--	--	37.96
Nederland 2 NNE	--	--	--	--	--	25.87	--	--	--	--	--	--	--	38.51	--	--
New Raymer 21 N	--	--	--	--	--	--	--	24.50	--	--	--	--	--	--	--	37.13
New Raymer	--	--	--	--	--	26.23	26.33	25.97	--	--	--	--	--	40.27	40.15	38.22
Northglenn	--	--	--	--	--	--	--	27.30	--	--	--	--	--	--	--	39.59
Nunn	--	--	--	--	--	--	26.40	--	--	--	--	--	--	--	40.28	--
Parker 6 E	--	26.63	26.68	27.41	28.78	27.74	27.49	--	--	40.82	40.15	41.45	40.65	40.66	40.49	--
Red Feather Lakes 2 SE	--	--	--	24.98	--	--	25.75	--	--	--	--	39.44	--	--	39.37	--
Rush 1 N	--	--	--	--	28.55	--	26.91	--	--	--	--	--	40.57	--	39.56	--
Ruxton Park	--	--	--	--	27.01	25.54	26.13	24.98	--	--	--	--	38.16	38.37	38.24	36.89
Spicer	25.49	25.48	--	--	25.29	25.22	25.46	25.75	39.00	39.49	--	--	38.58	38.80	39.01	38.82
Strontia Springs Dam	--	--	--	--	--	--	--	27.40	--	--	--	--	--	--	--	39.14
Sugarloaf Reservoir	--	--	--	25.87	--	--	26.18	26.35	--	--	--	39.32	--	--	39.41	39.04
Twin Lakes Reservoir	--	--	--	--	--	26.31	--	--	--	--	--	--	--	39.11	--	--
Vail	--	--	--	--	--	--	--	26.35	--	--	--	--	--	--	--	39.46
Victor	28.11	--	--	--	--	--	--	--	40.02	--	--	--	--	--	--	--
Walden	--	--	25.76	24.96	25.34	25.40	25.90	26.70	--	--	39.69	39.24	39.29	39.77	40.26	39.90
Waterdale	26.77	26.71	25.95	25.68	27.06	25.27	26.26	26.62	37.99	39.89	38.87	39.55	39.06	38.48	39.30	38.78
Wheat Ridge 2	--	--	--	--	--	--	--	28.10	--	--	--	--	--	--	--	40.10
Wiggins 7 SW	--	--	--	--	27.11	--	--	--	--	--	--	--	40.17	--	--	--
Williams Fork Dam	--	--	--	--	--	--	--	26.79	--	--	--	--	--	--	--	39.77

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name		Fall								Winter							
	Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Allenspark 2 NNW		--	--	--	30.31	28.63	29.79	--	--	--	--	--	20.17	17.47	18.75	--	--
Antero Reservoir		--	--	--	--	--	29.78	29.47	30.49	--	--	--	--	--	17.86	17.84	19.12
Arriba		--	29.16	29.56	--	--	--	--	--	--	16.23	15.89	--	--	--	--	--
Bailey		--	--	32.03	32.74	32.09	30.43	29.05	29.40	--	--	21.05	22.04	20.54	19.99	18.98	18.78
Berthoud Pass		--	--	--	--	--	27.25	--	--	--	--	--	--	--	16.56	--	--
Bond		--	--	--	--	30.44	--	--	--	--	--	--	--	15.73	--	--	--
Boulder		28.87	29.89	28.60	30.58	29.94	28.60	29.15	29.56	18.24	18.23	17.19	19.87	18.51	18.63	18.74	18.69
Briggsdale		--	--	--	--	--	--	27.56	27.48	--	--	--	--	--	--	15.31	15.52
Brighton 3 SE		--	--	--	--	--	--	28.63	28.29	--	--	--	--	--	--	16.30	16.96
Buckhorn Mountain 1 E		--	--	--	--	--	--	--	29.54	--	--	--	--	--	--	--	19.91
Buena Vista 2 S		--	32.20	--	32.97	32.90	--	30.88	30.77	--	21.13	--	21.55	20.83	--	20.41	20.24
Byers 5 ENE		--	29.91	29.68	29.64	29.60	28.75	28.69	28.94	--	17.40	17.03	18.16	16.94	16.42	15.91	16.51
Cabin Creek		--	--	--	--	--	29.35	28.95	29.64	--	--	--	--	--	19.18	20.10	20.26
Canon City		31.63	31.11	32.13	31.70	31.64	30.50	30.17	--	21.94	20.39	21.44	22.24	20.81	20.93	19.47	--
Castle Rock		--	--	--	--	--	30.33	--	30.88	--	--	--	--	--	19.92	--	20.33
Cheesman		30.96	33.00	32.20	32.94	32.41	31.32	31.20	30.76	20.98	21.89	21.39	22.45	21.40	21.34	21.34	20.81
Cherry Creek Dam		--	--	--	--	31.05	29.78	--	31.00	--	--	--	--	18.89	18.95	--	19.89
Climax		--	--	--	--	29.01	29.04	29.01	29.98	--	--	--	--	17.85	18.38	19.20	19.39
Colorado Springs Municipal Airport		--	--	--	29.98	29.59	28.51	29.03	29.10	--	--	--	20.17	17.91	17.82	17.82	18.91
Cripple Creek		--	--	31.79	--	--	--	--	--	--	--	20.98	--	--	--	--	--
Denver Lowry AFB		--	--	--	29.06	--	--	--	--	--	--	--	18.79	--	--	--	--
Denver Stapleton		--	--	--	29.10	29.33	28.56	28.46	28.93	--	--	--	18.58	17.04	17.79	16.99	18.15
Denver Weather Service Office City		27.73	28.98	28.68	28.88	28.63	--	--	--	16.82	17.56	17.09	18.72	17.24	--	--	--
Dillon 1 E		28.98	30.43	30.63	31.52	30.30	29.65	28.82	29.29	16.51	18.12	18.61	19.71	17.67	17.62	18.04	18.38
Edgewater		28.94	30.11	30.34	31.75	--	--	--	--	18.09	18.19	18.24	20.52	--	--	--	--
Elbert		--	--	--	--	--	30.09	--	--	--	--	--	--	--	19.43	19.24	--
Elk Creek 1		27.52	--	--	--	--	--	--	--	17.94	--	--	--	--	--	--	--

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name	Fall								Winter							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Estes Park	29.78	30.86	30.88	29.90	--	29.14	28.82	--	19.20	19.10	19.43	19.33	--	18.42	19.15	--
Evergreen	--	--	--	--	--	29.44	29.13	30.35	--	--	--	--	--	20.46	20.34	21.03
Florissant Fossl Bed	--	--	--	--	--	--	--	31.55	--	--	--	--	--	--	--	21.16
Fort Collins	26.29	27.78	27.55	27.74	27.36	26.80	26.99	27.40	14.30	15.42	15.18	16.68	15.44	15.80	15.98	16.89
Fort Lupton 2 SE	27.01	28.50	28.23	29.68	28.69	--	--	--	14.03	15.18	14.91	17.89	15.62	--	--	--
Fort Morgan	25.26	27.63	26.91	26.88	27.48	26.88	27.21	27.60	11.92	13.59	13.21	14.43	13.64	13.44	13.31	14.61
Fraser	27.60	29.00	29.32	29.18	28.30	--	--	28.33	15.42	16.20	17.06	16.53	14.98	--	--	15.98
Georgetown	--	--	--	31.41	--	--	--	--	--	--	--	20.48	--	--	--	--
Grand Lake 1 NW	--	--	--	30.04	29.55	29.02	29.36	30.26	--	--	--	16.96	16.33	16.48	17.85	18.41
Grand Lake 6 SSW	--	--	--	28.58	28.18	27.67	27.29	28.52	--	--	--	14.97	13.75	13.97	14.70	14.88
Grant	--	--	--	--	--	29.43	28.61	29.46	--	--	--	--	--	18.25	18.06	18.87
Greeley	27.74	28.80	28.22	27.35	--	--	--	--	13.93	14.89	14.35	14.95	--	--	--	--
Greeley UNC	--	--	--	--	--	27.55	27.23	27.43	--	--	--	--	--	15.29	14.55	15.36
Green Mountain Dam	--	--	30.25	30.53	30.28	29.20	26.96	27.58	--	--	16.09	16.15	15.02	14.96	13.88	14.35
Grover 10 W	27.41	28.58	28.30	27.90	28.71	--	--	--	14.80	15.26	15.16	16.43	16.10	--	--	--
Hohnholz Ranch	--	--	--	--	--	--	--	28.67	--	--	--	--	--	--	--	16.95
Hot Sulphur Springs 2 SW	--	--	--	--	29.30	--	--	--	--	--	--	--	13.28	--	--	--
Hourglass Reservoir	--	--	--	--	--	--	--	30.34	--	--	--	--	--	--	--	19.52
Idaho Springs	27.35	28.69	30.62	30.89	30.60	--	--	--	17.43	17.57	19.49	20.49	19.78	--	--	--
Kassler	30.39	31.96	31.40	31.42	30.48	29.24	29.22	30.11	19.66	20.74	19.83	21.41	19.14	19.15	18.20	19.82
Kauffman 4 SSE	--	--	29.09	28.62	28.54	27.81	--	--	--	--	16.39	16.71	15.90	15.75	--	--
Kremmling	--	--	--	--	--	--	--	27.73	--	--	--	--	--	--	--	12.57
Lake George 8 SW	--	--	--	--	30.46	29.67	29.20	30.41	--	--	--	--	17.40	17.33	16.10	18.31
Lake Moraine	29.10	29.95	29.38	31.21	--	--	--	--	19.53	19.08	19.25	21.80	--	--	--	--
Lakewood	--	--	--	--	--	28.41	28.61	29.23	--	--	--	--	--	17.98	17.89	19.19
Leadville Lake CO Airport	--	--	--	30.70	30.30	--	--	29.88	--	--	--	18.97	19.17	--	--	19.63
Limon 10 SSW	--	29.22	28.80	29.39	29.94	--	--	--	--	16.71	15.73	18.49	17.44	--	--	--

Table 8. Average Decadal Daytime Seasonal Temperatures (°C) from 1920-1990

Station Name	Fall								Winter							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Limon WSMO	--	--	--	28.70	28.60	27.41	28.01	--	--	--	--	18.03	16.44	16.12	15.77	--
Lindon 5 WNW	--	--	--	--	--	--	--	27.53	--	--	--	--	--	--	--	15.17
Littleton	--	--	--	--	--	--	27.31	--	--	--	--	--	--	--	17.36	--
Longmont 2 ESE	28.38	29.14	28.59	28.68	28.45	27.74	28.12	28.80	16.34	17.03	16.08	17.35	15.84	15.94	15.76	17.28
Loveland 2 N	--	--	--	--	--	--	--	27.76	--	--	--	--	--	--	--	17.04
Monument 2 WSW	30.47	32.01	32.01	32.32	--	--	--	--	20.19	20.23	20.53	22.25	--	--	--	--
Monument	--	--	--	--	--	--	--	28.44	--	--	--	--	--	--	--	18.45
Mount Evans Research Station	--	--	--	--	--	--	--	28.31	--	--	--	--	--	--	--	17.86
Nederland 2 NNE	--	--	--	--	--	28.51	--	--	--	--	--	--	--	18.04	--	--
New Raymer 21 N	--	--	--	--	--	--	--	26.12	--	--	--	--	--	--	--	14.98
New Raymer	--	--	--	--	--	27.68	28.03	26.91	--	--	--	--	--	14.68	15.05	15.35
Northglenn	--	--	--	--	--	--	--	29.10	--	--	--	--	--	--	--	18.49
Nunn	--	--	--	--	--	--	27.36	--	--	--	--	--	--	--	15.26	--
Parker 6 E	--	30.28	31.02	31.32	31.56	30.01	29.88	--	--	18.29	17.87	20.24	20.14	19.19	18.40	--
Red Feather Lakes 2 SE	--	--	--	30.73	--	--	27.94	--	--	--	--	18.95	--	--	17.73	--
Rush 1 N	--	--	--	--	30.78	--	28.52	--	--	--	--	--	19.27	--	17.11	--
Ruxton Park	--	--	--	--	29.68	28.15	28.77	28.13	--	--	--	--	19.60	17.92	19.43	18.32
Spicer	28.34	28.12	--	--	28.46	27.90	27.56	28.06	16.31	14.75	--	--	14.82	14.95	15.65	15.31
Strontia Springs Dam	--	--	--	--	--	--	--	29.43	--	--	--	--	--	--	--	18.80
Sugarloaf Reservoir	--	--	--	29.89	--	--	28.92	28.82	--	--	--	18.81	--	--	18.89	18.92
Twin Lakes Reservoir	--	--	--	--	--	29.35	--	--	--	--	--	--	--	17.99	--	--
Vail	--	--	--	--	--	--	--	28.27	--	--	--	--	--	--	--	15.17
Victor	32.37	--	--	--	--	--	--	--	22.31	--	--	--	--	--	--	--
Walden	--	--	28.82	28.69	28.56	28.05	28.01	28.64	--	--	15.18	15.03	14.06	14.20	15.89	16.22
Waterdale	28.55	29.02	28.68	29.24	28.89	26.76	27.71	28.36	17.04	17.08	16.75	18.37	17.12	15.97	16.78	17.93
Wheat Ridge 2	--	--	--	--	--	--	--	30.25	--	--	--	--	--	--	--	20.12
Wiggins 7 SW	--	--	--	--	28.99	--	--	--	--	--	--	--	15.37	--	--	--
Williams Fork Dam	--	--	--	--	--	--	--	28.85	--	--	--	--	--	--	--	14.54

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Allenspark 2 NNW	--	--	--	12.14	12.23	12.56	--	--	--	--	--	22.79	22.29	22.18	--	--
Antero Reservoir	--	--	--	--	--	9.51	9.65	10.84	--	--	--	--	--	20.08	20.96	21.07
Arriba	--	10.05	10.05	--	--	--	--	--	--	23.16	22.08	--	--	--	--	--
Bailey	--	--	10.46	9.94	9.77	10.13	9.92	10.96	--	--	20.29	20.33	20.11	19.64	20.07	20.64
Berthoud Pass	--	--	--	--	--	12.22	--	--	--	--	--	--	--	24.69	--	--
Bond	--	--	--	--	9.91	--	--	--	--	--	--	--	20.17	--	--	--
Boulder	11.93	12.54	12.49	12.82	13.13	12.29	12.92	13.03	23.40	24.10	24.18	25.35	24.82	23.70	23.61	23.08
Briggsdale	--	--	--	--	--	--	9.19	9.51	--	--	--	--	--	--	20.90	21.45
Brighton 3 SE	--	--	--	--	--	--	10.89	10.62	--	--	--	--	--	--	22.62	22.30
Buckhorn Mountain 1 E	--	--	--	--	--	--	--	13.68	--	--	--	--	--	--	--	25.38
Buena Vista 2 S	--	12.35	--	12.39	12.43	--	12.98	12.22	--	22.05	--	22.69	22.75	--	23.42	22.24
Byers 5 ENE	--	10.74	10.61	10.17	9.92	9.14	10.27	10.58	--	23.32	22.44	22.41	21.87	21.30	22.18	22.35
Cabin Creek	--	--	--	--	--	14.22	13.91	11.74	--	--	--	--	--	24.93	24.67	22.57
Canon City	13.35	14.66	13.64	13.02	13.70	13.45	13.71	--	24.46	26.34	25.15	25.33	25.31	25.26	24.88	--
Castle Rock	--	--	--	--	--	10.88	--	12.10	--	--	--	--	--	21.90	--	23.02
Cheesman	11.01	11.24	10.42	10.66	9.94	9.21	10.50	7.85	22.63	23.06	21.54	21.62	20.99	19.75	21.06	17.72
Cherry Creek Dam	--	--	--	--	10.50	10.60	--	10.98	--	--	--	--	22.02	21.98	--	22.31
Climax	--	--	--	--	13.18	11.94	12.44	12.13	--	--	--	--	24.54	24.24	25.16	24.31
Colorado Springs Municipal Airport	--	--	--	11.94	12.19	12.86	12.87	12.99	--	--	--	24.40	24.28	24.77	24.70	24.34
Cripple Creek	--	--	13.79	--	--	--	--	--	--	--	24.61	--	--	--	--	--
Denver Lowry AFB	--	--	--	11.98	--	--	--	--	--	--	--	25.22	--	--	--	--
Denver Stapleton	--	--	--	11.45	11.16	11.57	12.62	12.45	--	--	--	24.29	23.12	23.38	24.58	24.05
Denver Weather Service Office City	12.68	13.26	13.33	12.95	13.65	--	--	--	24.70	26.00	25.30	25.80	25.72	--	--	--
Dillon 1 E	7.46	8.00	8.58	7.78	9.19	10.09	10.54	10.78	17.94	18.34	17.93	17.80	19.63	19.82	20.67	20.33
Edgewater	10.39	11.82	12.64	11.22	--	--	--	--	21.77	23.84	23.79	22.76	--	--	--	--
Elbert	--	--	--	--	--	10.15	4.67	--	--	--	--	--	--	21.57	--	--
Elk Creek 1	7.30	--	--	--	--	--	--	--	17.52	--	--	--	--	--	--	--

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Estes Park	11.46	12.42	12.76	11.55	--	11.72	12.36	--	21.23	22.51	21.76	21.13	--	20.98	21.99	--
Evergreen	--	--	--	--	--	9.68	10.47	10.59	--	--	--	--	--	19.83	21.06	20.70
Florissant Fossl Bed	--	--	--	--	--	--	--	10.76	--	--	--	--	--	--	--	20.49
Fort Collins	9.32	10.28	9.96	9.60	10.20	10.77	11.31	11.74	20.97	22.25	21.24	21.72	22.01	22.35	22.73	22.50
Fort Lupton 2 SE	10.15	10.70	10.32	9.62	9.35	--	--	--	22.06	22.76	21.64	21.93	21.11	--	--	--
Fort Morgan	7.41	8.84	9.52	8.93	9.25	9.77	10.24	10.24	20.17	21.83	21.67	22.07	21.81	22.42	22.85	22.84
Fraser	7.79	7.30	8.48	6.88	5.74	--	--	8.57	17.21	17.03	17.42	16.63	16.34	--	--	17.79
Georgetown	--	--	--	13.68	--	--	--	--	--	--	--	24.94	--	--	--	--
Grand Lake 1 NW	--	--	--	8.40	8.58	8.80	10.49	11.06	--	--	--	17.57	18.21	18.74	19.97	20.07
Grand Lake 6 SSW	--	--	--	9.17	8.99	9.17	9.83	9.88	--	--	--	20.27	20.32	20.22	20.86	20.27
Grant	--	--	--	--	--	11.35	11.81	12.51	--	--	--	--	--	20.88	22.04	21.97
Greeley	8.32	9.05	9.26	8.95	--	--	--	--	20.66	21.32	21.08	21.49	--	--	--	--
Greeley UNC	--	--	--	--	--	10.50	10.75	11.56	--	--	--	--	--	21.86	22.35	22.68
Green Mountain Dam	--	--	10.16	10.43	10.44	10.48	10.77	10.89	--	--	19.75	20.85	21.19	20.82	21.03	20.31
Grover 10 W	8.23	9.33	9.33	8.33	9.48	--	--	--	19.82	21.87	20.98	20.71	21.52	--	--	--
Hohnholz Ranch	--	--	--	--	--	--	--	9.51	--	--	--	--	--	--	--	18.88
Hot Sulphur Springs 2 SW	--	--	--	--	8.18	--	--	--	--	--	--	--	18.73	--	--	--
Hourglass Reservoir	--	--	--	--	--	--	--	12.75	--	--	--	--	--	--	--	23.16
Idaho Springs	11.82	12.63	11.54	10.93	11.22	--	--	--	22.35	23.34	21.41	21.16	21.10	--	--	--
Kassler	11.08	12.64	12.16	11.85	11.79	11.87	11.32	11.35	23.52	25.03	24.30	24.60	24.10	24.22	23.50	23.46
Kauffman 4 SSE	--	--	8.66	7.73	8.80	9.04	--	--	--	--	20.24	20.14	20.89	20.99	--	--
Kremmling	--	--	--	--	--	--	--	10.16	--	--	--	--	--	--	--	19.68
Lake George 8 SW	--	--	--	--	10.66	10.94	11.18	11.57	--	--	--	--	22.94	22.49	23.37	23.08
Lake Moraine	13.17	13.36	13.87	13.48	--	--	--	--	23.94	24.08	25.02	24.38	--	--	--	--
Lakewood	--	--	--	--	--	12.24	12.48	12.19	--	--	--	--	--	24.24	24.14	23.47
Leadville Lake CO Airport	--	--	--	12.48	12.61	--	--	11.92	--	--	--	24.16	23.40	--	--	21.50
Limon 10 SSW	--	10.45	10.29	9.71	9.78	--	--	--	--	22.86	22.24	22.56	22.27	--	--	--

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Spring								Summer							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Limon WSMO	--	--	--	8.87	9.19	9.83	10.25	--	--	--	--	22.18	22.15	22.01	22.50	--
Lindon 5 WNW	--	--	--	--	--	--	--	9.60	--	--	--	--	--	--	--	21.96
Littleton	--	--	--	--	--	--	12.66	--	--	--	--	--	--	--	23.83	--
Longmont 2 ESE	9.08	9.73	9.82	9.40	9.85	10.37	10.42	9.45	20.34	21.22	20.76	21.20	21.20	21.59	22.10	20.62
Loveland 2 N	--	--	--	--	--	--	--	11.10	--	--	--	--	--	--	--	22.22
Monument 2 WSW	11.92	12.08	12.66	12.11	--	--	--	--	22.95	23.67	23.80	24.20	--	--	--	--
Monument	--	--	--	--	--	--	--	12.62	--	--	--	--	--	--	--	23.47
Mount Evans Research Station	--	--	--	--	--	--	--	13.75	--	--	--	--	--	--	--	24.02
Nederland 2 NNE	--	--	--	--	--	10.46	--	--	--	--	--	--	--	19.89	--	--
New Raymer 21 N	--	--	--	--	--	--	--	8.72	--	--	--	--	--	--	--	20.86
New Raymer	--	--	--	--	--	8.69	8.24	9.53	--	--	--	--	--	20.92	20.87	21.79
Northglenn	--	--	--	--	--	--	--	12.16	--	--	--	--	--	--	--	22.98
Nunn	--	--	--	--	--	--	9.71	--	--	--	--	--	--	--	21.64	--
Parker 6 E	--	9.43	10.40	10.75	10.59	11.61	13.01	--	--	21.39	22.06	23.52	22.73	23.85	25.11	--
Red Feather Lakes 2 SE	--	--	--	10.63	--	--	11.45	--	--	--	--	21.65	--	--	21.58	--
Rush 1 N	--	--	--	--	9.86	--	11.91	--	--	--	--	--	22.25	--	22.79	--
Ruxton Park	--	--	--	--	11.99	11.29	10.37	10.84	--	--	--	--	21.88	21.31	20.69	21.20
Spicer	8.75	10.56	--	--	9.57	9.29	9.95	10.92	19.19	20.44	--	--	19.87	18.88	19.79	19.68
Strontia Springs Dam	--	--	--	--	--	--	--	7.55	--	--	--	--	--	--	--	18.46
Sugarloaf Reservoir	--	--	--	10.58	--	--	11.26	11.72	--	--	--	22.00	--	--	22.38	22.19
Twin Lakes Reservoir	--	--	--	--	--	9.25	--	--	--	--	--	--	--	20.53	--	--
Vail	--	--	--	--	--	--	--	11.62	--	--	--	--	--	--	--	19.90
Victor	14.43	--	--	--	--	--	--	--	25.37	--	--	--	--	--	--	--
Walden	--	--	10.56	9.01	8.45	9.59	9.79	10.40	--	--	19.63	18.64	18.68	18.78	19.33	19.38
Waterdale	9.30	10.00	9.92	9.17	9.81	10.60	10.18	10.50	19.72	20.88	20.29	19.95	20.79	21.73	21.27	21.18
Wheat Ridge 2	--	--	--	--	--	--	--	11.39	--	--	--	--	--	--	--	22.03
Wiggins 7 SW	--	--	--	--	8.37	--	--	--	--	--	--	--	20.78	--	--	--
Williams Fork Dam	--	--	--	--	--	--	--	8.87	--	--	--	--	--	--	--	18.92

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Fall								Winter							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Allenspark 2 NNW	--	--	--	15.30	15.44	14.55	--	--	--	--	--	8.22	6.58	6.74	--	--
Antero Reservoir	--	--	--	--	--	10.17	10.59	10.89	--	--	--	--	--	-1.08	-2.41	-0.99
Arriba	--	12.16	12.38	--	--	--	--	--	--	1.29	1.28	--	--	--	--	--
Bailey	--	--	12.02	11.24	11.51	10.77	10.70	11.61	--	--	2.40	3.63	2.31	2.85	1.53	3.08
Berthoud Pass	--	--	--	--	--	15.55	--	--	--	--	--	--	--	5.17	--	--
Bond	--	--	--	--	10.66	--	--	--	--	--	--	--	-0.68	--	--	--
Boulder	13.37	14.47	14.72	15.37	14.89	13.61	14.03	14.43	4.01	4.30	4.65	6.59	4.80	4.75	4.75	5.23
Briggsdale	--	--	--	--	--	--	9.33	9.99	--	--	--	--	--	--	-1.39	-0.46
Brighton 3 SE	--	--	--	--	--	--	11.35	11.24	--	--	--	--	--	--	0.93	1.34
Buckhorn Mountain 1 E	--	--	--	--	--	--	--	16.30	--	--	--	--	--	--	--	7.61
Buena Vista 2 S	--	12.56	--	14.13	14.31	--	13.52	12.71	--	2.69	--	5.67	4.45	--	4.41	4.17
Byers 5 ENE	--	12.21	11.96	11.94	11.77	9.70	10.79	11.26	--	1.01	1.29	2.61	0.52	-1.12	-0.10	0.70
Cabin Creek	--	--	--	--	--	16.75	16.46	14.61	--	--	--	--	--	8.01	8.15	5.64
Canon City	15.25	16.84	15.63	15.20	15.99	14.95	14.34	--	5.91	6.95	5.66	6.81	5.65	5.40	4.81	--
Castle Rock	--	--	--	--	--	10.93	--	13.13	--	--	--	--	--	1.53	--	4.04
Cheesman	13.36	13.14	12.25	12.20	12.27	10.31	11.71	8.60	3.29	2.97	1.66	3.57	1.50	0.40	1.03	-0.48
Cherry Creek Dam	--	--	--	--	12.13	11.99	--	12.39	--	--	--	--	1.56	2.13	--	2.75
Climax	--	--	--	--	16.62	15.55	15.80	15.27	--	--	--	--	6.45	5.52	5.46	5.22
Colorado Springs Municipal Airport	--	--	--	14.04	14.66	14.19	14.30	14.24	--	--	--	4.55	3.57	3.97	4.23	4.58
Cripple Creek	--	--	16.41	--	--	--	--	--	--	--	6.40	--	--	--	--	--
Denver Lowry AFB	--	--	--	14.42	--	--	--	--	--	--	--	4.65	--	--	--	--
Denver Stapleton	--	--	--	13.51	12.60	12.51	13.20	13.21	--	--	--	3.91	1.73	2.44	2.99	3.59
Denver Weather Service Office City	14.43	15.29	15.17	15.20	15.74	--	--	--	4.42	5.00	5.03	6.31	5.17	--	--	--
Dillon 1 E	8.93	9.47	9.58	9.16	11.86	11.75	12.19	12.03	-3.09	-1.27	-0.79	-0.15	0.77	1.49	1.64	1.87
Edgewater	11.48	13.16	13.59	12.63	--	--	--	--	1.79	2.93	4.11	4.44	--	--	--	--
Elbert	--	--	--	--	--	11.01	--	--	--	--	--	--	--	0.79	1.29	--
Elk Creek 1	9.00	--	--	--	--	--	--	--	-0.35	--	--	--	--	--	--	--

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Fall								Winter							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Estes Park	13.57	14.85	14.08	13.25	--	13.24	13.90	--	6.70	7.00	5.75	7.41	--	6.34	5.84	--
Evergreen	--	--	--	--	--	10.32	11.05	11.46	--	--	--	--	--	1.52	2.31	2.27
Florissant Fossl Bed	--	--	--	--	--	--	--	11.64	--	--	--	--	--	--	--	1.74
Fort Collins	10.33	10.98	10.51	10.50	11.38	11.37	11.68	12.17	-0.27	-0.03	-0.45	0.91	0.76	1.15	1.24	2.58
Fort Lupton 2 SE	11.51	11.75	11.15	10.63	9.91	--	--	--	0.71	0.73	0.45	1.34	-1.01	--	--	--
Fort Morgan	8.51	9.24	10.06	9.56	9.78	9.43	10.20	11.11	-3.58	-3.66	-2.44	-1.66	-2.74	-2.56	-1.92	-0.58
Fraser	8.97	7.94	8.34	6.71	6.78	--	--	9.06	-1.54	-2.77	-2.15	-2.73	-5.35	--	--	-1.94
Georgetown	--	--	--	17.06	--	--	--	--	--	--	--	9.21	--	--	--	--
Grand Lake 1 NW	--	--	--	9.49	10.32	10.34	12.04	12.18	--	--	--	0.29	-0.40	0.04	2.10	2.50
Grand Lake 6 SSW	--	--	--	11.76	12.23	11.93	12.74	12.23	--	--	--	0.18	-0.33	-0.09	0.48	-0.13
Grant	--	--	--	--	--	12.77	13.14	13.55	--	--	--	--	--	4.48	4.45	4.66
Greeley	8.93	8.79	8.82	8.97	--	--	--	--	-3.09	-3.22	-2.90	-1.67	--	--	--	--
Greeley UNC	--	--	--	--	--	10.47	10.96	11.92	--	--	--	--	--	0.20	0.14	1.95
Green Mountain Dam	--	--	11.02	12.07	12.91	12.30	12.27	11.70	--	--	0.04	1.59	0.50	1.00	0.63	0.60
Grover 10 W	10.18	11.61	11.29	10.78	12.24	--	--	--	-0.48	0.50	1.03	1.20	1.14	--	--	--
Hohnholz Ranch	--	--	--	--	--	--	--	10.00	--	--	--	--	--	--	--	1.82
Hot Sulphur Springs 2 SW	--	--	--	--	9.63	--	--	--	--	--	--	--	-2.41	--	--	--
Hourglass Reservoir	--	--	--	--	--	--	--	15.36	--	--	--	--	--	--	--	7.09
Idaho Springs	14.20	15.03	13.19	12.92	13.41	--	--	--	6.02	6.15	4.60	6.13	4.82	--	--	--
Kassler	13.27	14.77	14.27	14.48	14.21	13.32	12.33	12.91	2.95	3.45	3.11	4.80	2.89	2.65	1.94	2.14
Kauffman 4 SSE	--	--	9.82	9.39	10.54	10.13	--	--	--	--	0.02	0.51	-0.01	0.08	--	--
Kremmling	--	--	--	--	--	--	--	9.46	--	--	--	--	--	--	--	-3.10
Lake George 8 SW	--	--	--	--	13.42	12.62	13.41	13.42	--	--	--	--	0.25	-0.19	-1.56	-0.20
Lake Moraine	16.40	16.30	17.45	16.49	--	--	--	--	7.65	6.78	7.70	8.71	--	--	--	--
Lakewood	--	--	--	--	--	13.72	13.42	13.37	--	--	--	--	--	3.92	3.87	4.48
Leadville Lake CO Airport	--	--	--	15.79	15.30	--	--	13.65	--	--	--	6.41	5.23	--	--	3.70
Limon 10 SSW	--	12.06	11.90	11.46	12.32	--	--	--	--	1.29	1.40	1.69	0.86	--	--	--

Table 9. Average Decadal Nighttime Seasonal Temperatures (°C) from 1920-1990

Station Name	Fall								Winter							
Year	1920	1930	1940	1950	1960	1970	1980	1990	1920	1930	1940	1950	1960	1970	1980	1990
Limon WSMO	--	--	--	10.17	10.25	10.98	11.47	--	--	--	--	-0.02	-1.09	0.47	1.09	--
Lindon 5 WNW	--	--	--	--	--	--	--	10.65	--	--	--	--	--	--	--	0.35
Littleton	--	--	--	--	--	--	11.94	--	--	--	--	--	--	--	2.37	--
Longmont 2 ESE	9.53	10.11	10.36	9.98	10.66	10.42	10.17	9.73	-0.97	-0.96	-0.80	0.27	-0.40	0.06	-0.62	-0.05
Loveland 2 N	--	--	--	--	--	--	--	11.69	--	--	--	--	--	--	--	1.79
Monument 2 WSW	13.86	14.12	15.37	14.77	--	--	--	--	4.56	4.32	5.45	6.53	--	--	--	--
Monument	--	--	--	--	--	--	--	14.30	--	--	--	--	--	--	--	5.47
Mount Evans Research Station	--	--	--	--	--	--	--	16.25	--	--	--	--	--	--	--	7.32
Nederland 2 NNE	--	--	--	--	--	11.64	--	--	--	--	--	--	--	4.00	--	--
New Raymer 21 N	--	--	--	--	--	--	--	10.16	--	--	--	--	--	--	--	0.53
New Raymer	--	--	--	--	--	9.61	8.90	10.57	--	--	--	--	--	-1.08	-1.74	0.34
Northglenn	--	--	--	--	--	--	--	13.21	--	--	--	--	--	--	--	3.77
Nunn	--	--	--	--	--	--	9.84	--	--	--	--	--	--	--	-0.89	--
Parker 6 E	--	10.14	11.69	12.38	12.24	13.78	15.17	--	--	-0.41	0.31	3.20	1.27	3.54	5.21	--
Red Feather Lakes 2 SE	--	--	--	13.76	--	--	13.26	--	--	--	--	5.87	--	--	5.37	--
Rush 1 N	--	--	--	--	12.20	--	12.49	--	--	--	--	--	0.76	--	2.79	--
Ruxton Park	--	--	--	--	14.46	12.86	11.96	12.93	--	--	--	--	4.81	4.53	2.81	3.98
Spicer	10.46	12.13	--	--	11.66	9.91	11.51	11.99	1.70	2.27	--	--	1.74	1.74	2.31	2.99
Strontia Springs Dam	--	--	--	--	--	--	--	8.17	--	--	--	--	--	--	--	-1.22
Sugarloaf Reservoir	--	--	--	13.73	--	--	14.21	14.60	--	--	--	1.47	--	--	4.00	4.29
Twin Lakes Reservoir	--	--	--	--	--	12.42	--	--	--	--	--	--	--	1.50	--	--
Vail	--	--	--	--	--	--	--	12.04	--	--	--	--	--	--	--	2.45
Victor	18.27	--	--	--	--	--	--	--	9.41	--	--	--	--	--	--	--
Walden	--	--	10.65	9.17	9.70	9.67	10.51	11.12	--	--	1.30	0.79	-0.24	1.15	1.23	1.63
Waterdale	10.06	10.77	10.43	10.29	11.55	11.78	11.05	11.62	-0.15	0.53	0.54	1.69	1.01	1.66	0.28	1.53
Wheat Ridge 2	--	--	--	--	--	--	--	11.85	--	--	--	--	--	--	--	3.12
Wiggins 7 SW	--	--	--	--	9.13	--	--	--	--	--	--	--	-2.27	--	--	--
Williams Fork Dam	--	--	--	--	--	--	--	9.46	--	--	--	--	--	--	--	-3.04

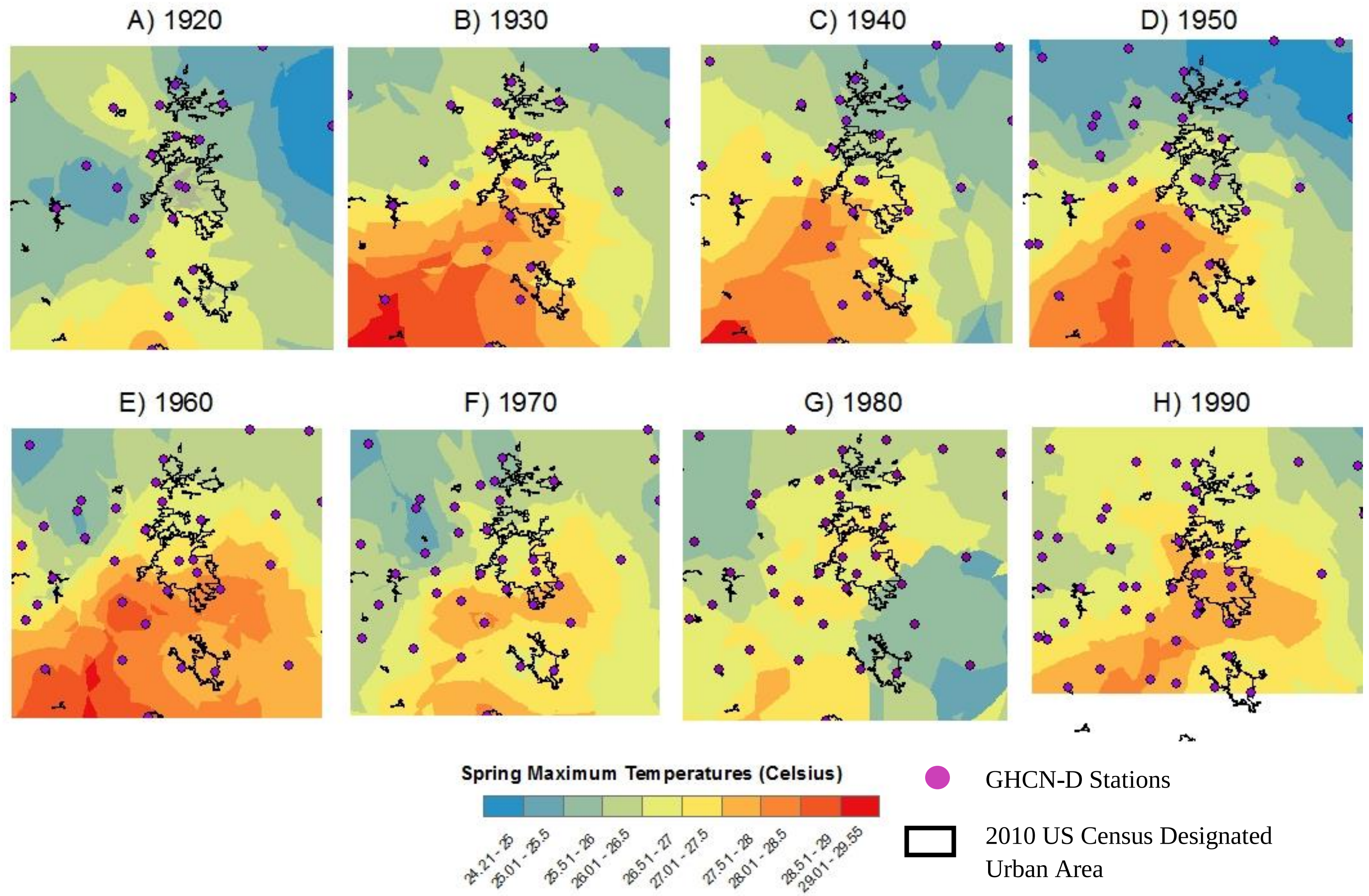


Figure 7. Average Decadal Spring Maximum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

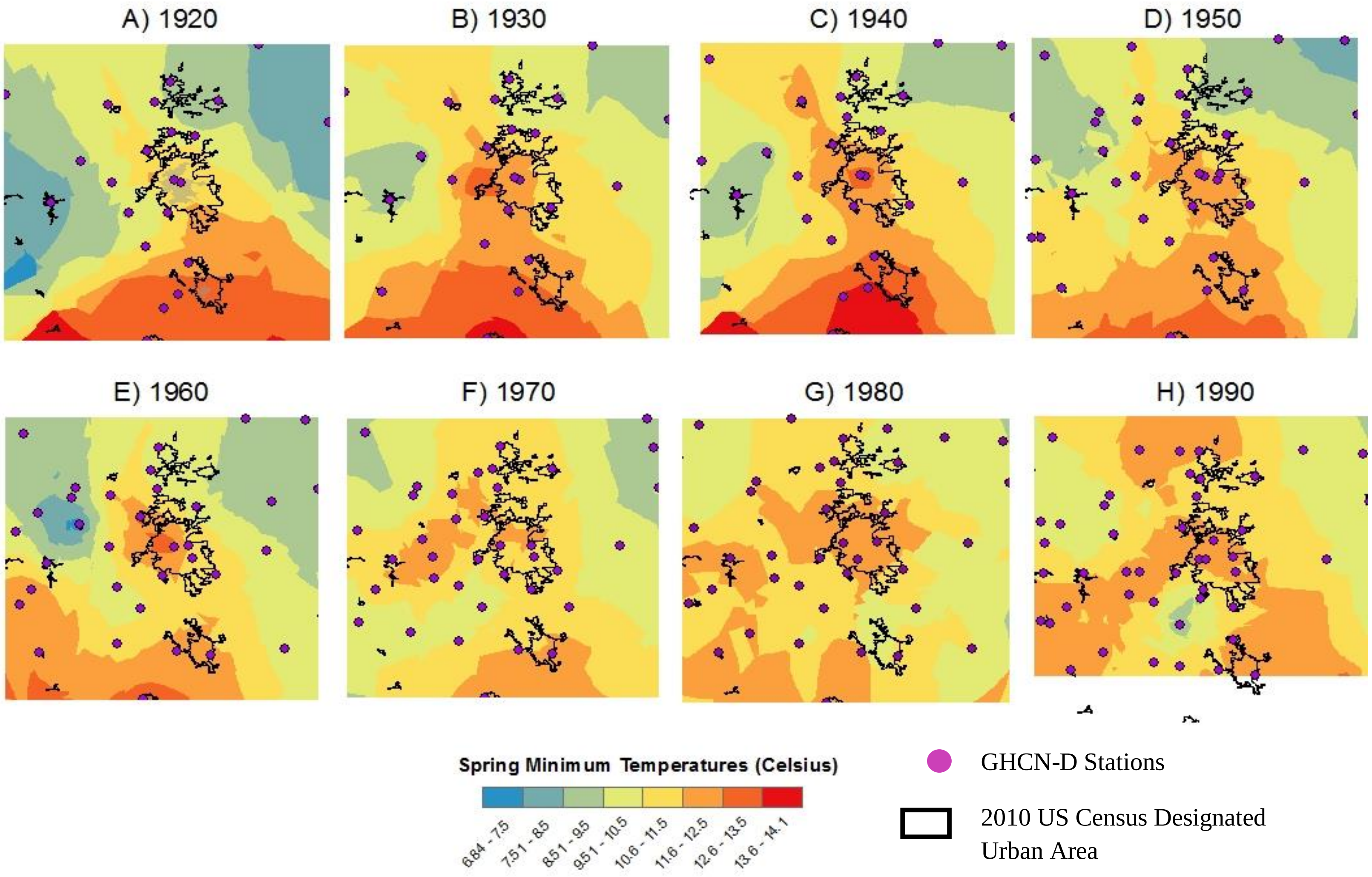


Figure 8. Average Decadal Spring Minimum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

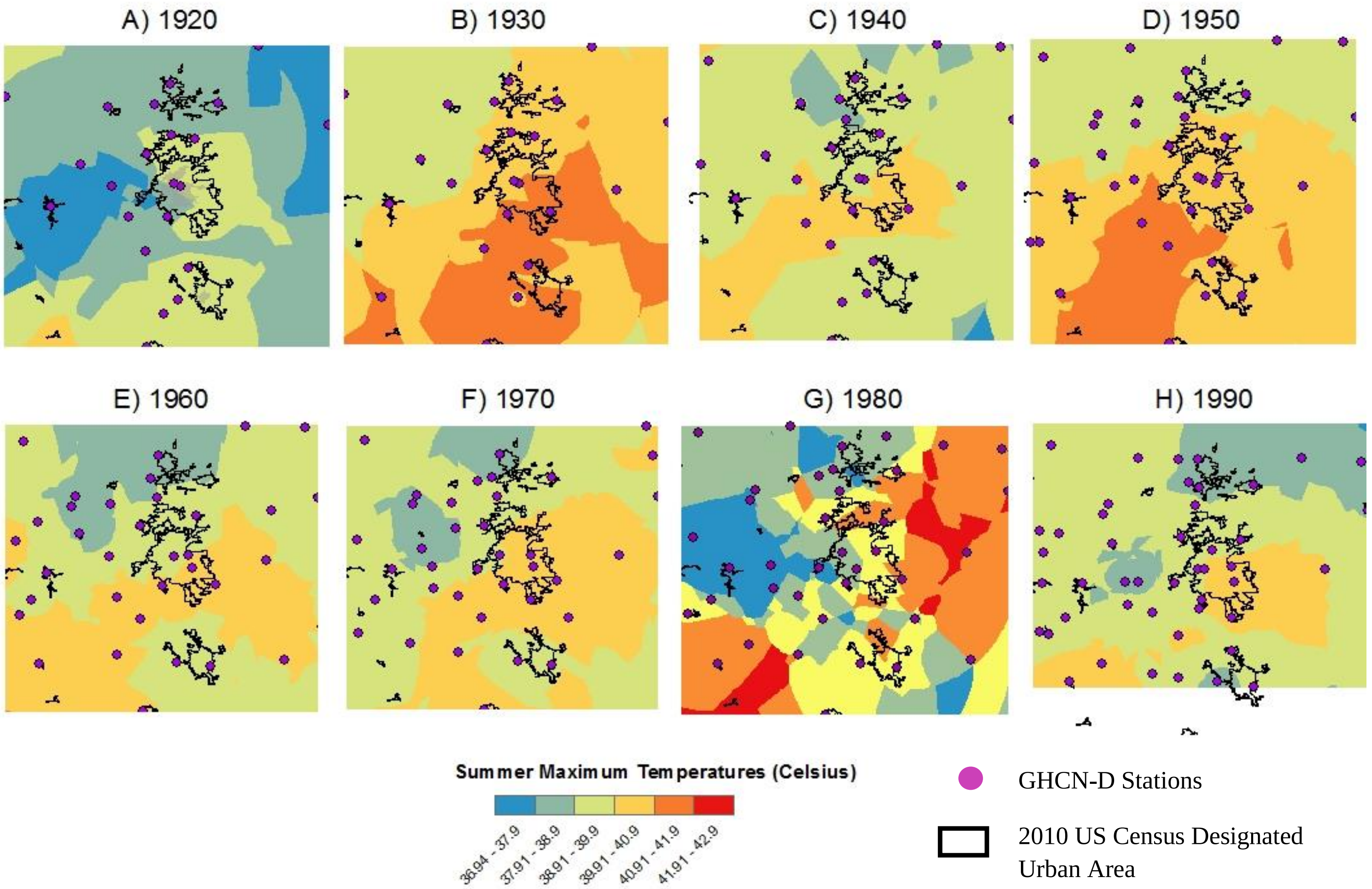


Figure 9. Average Decadal Summer Maximum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

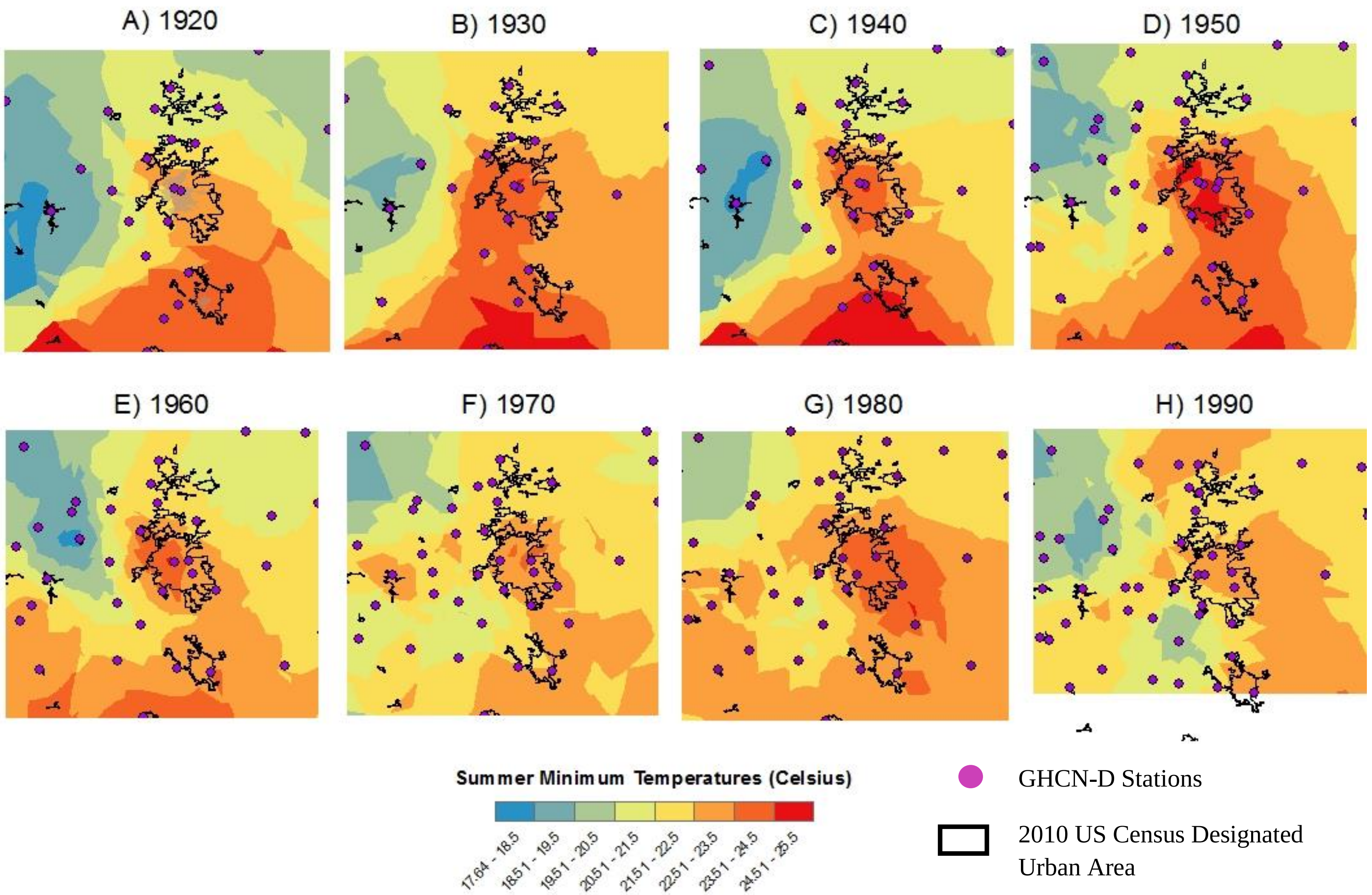


Figure 10. Average Decadal Summer Minimum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

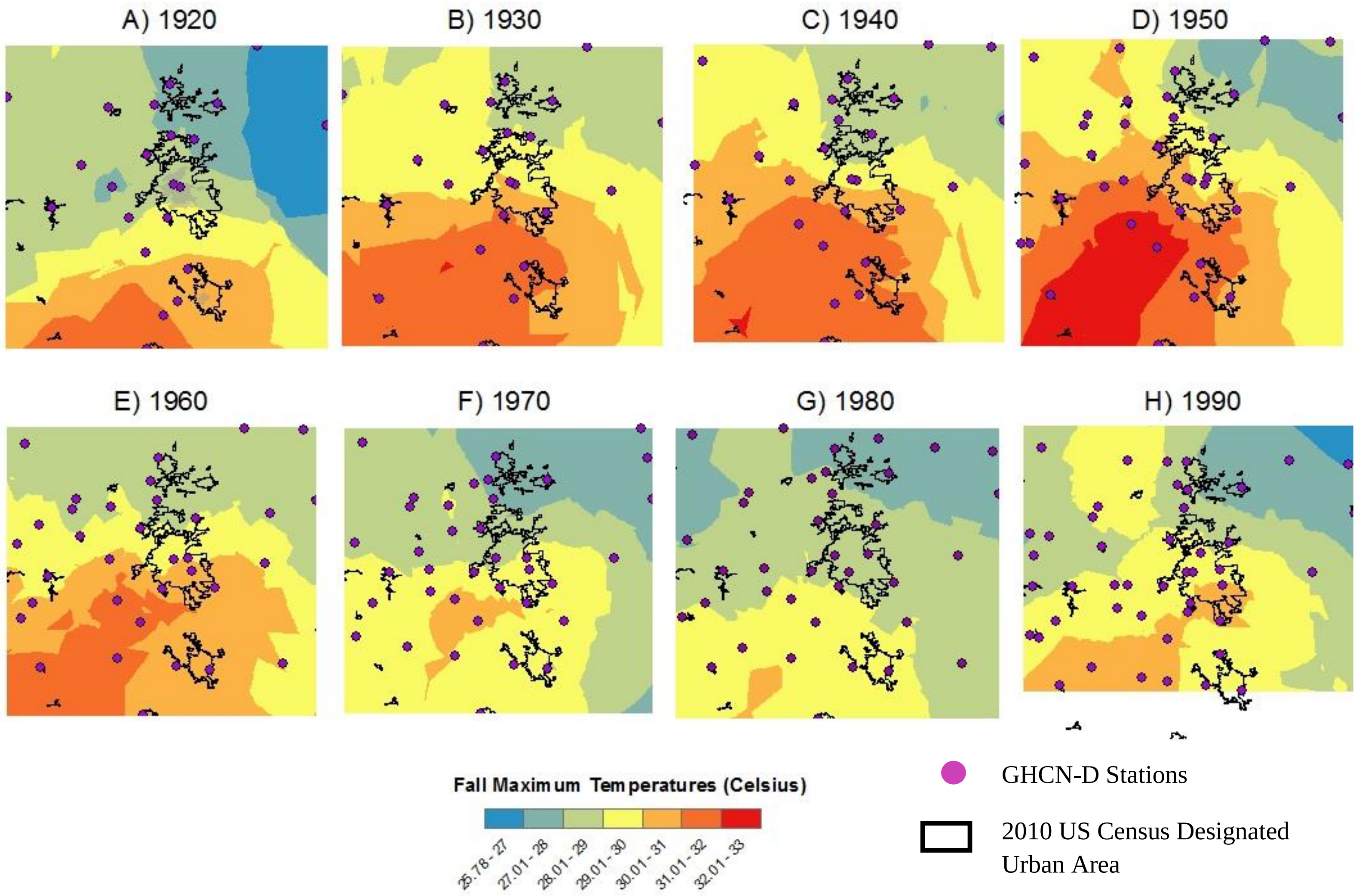


Figure 11. Average Decadal Fall Maximum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

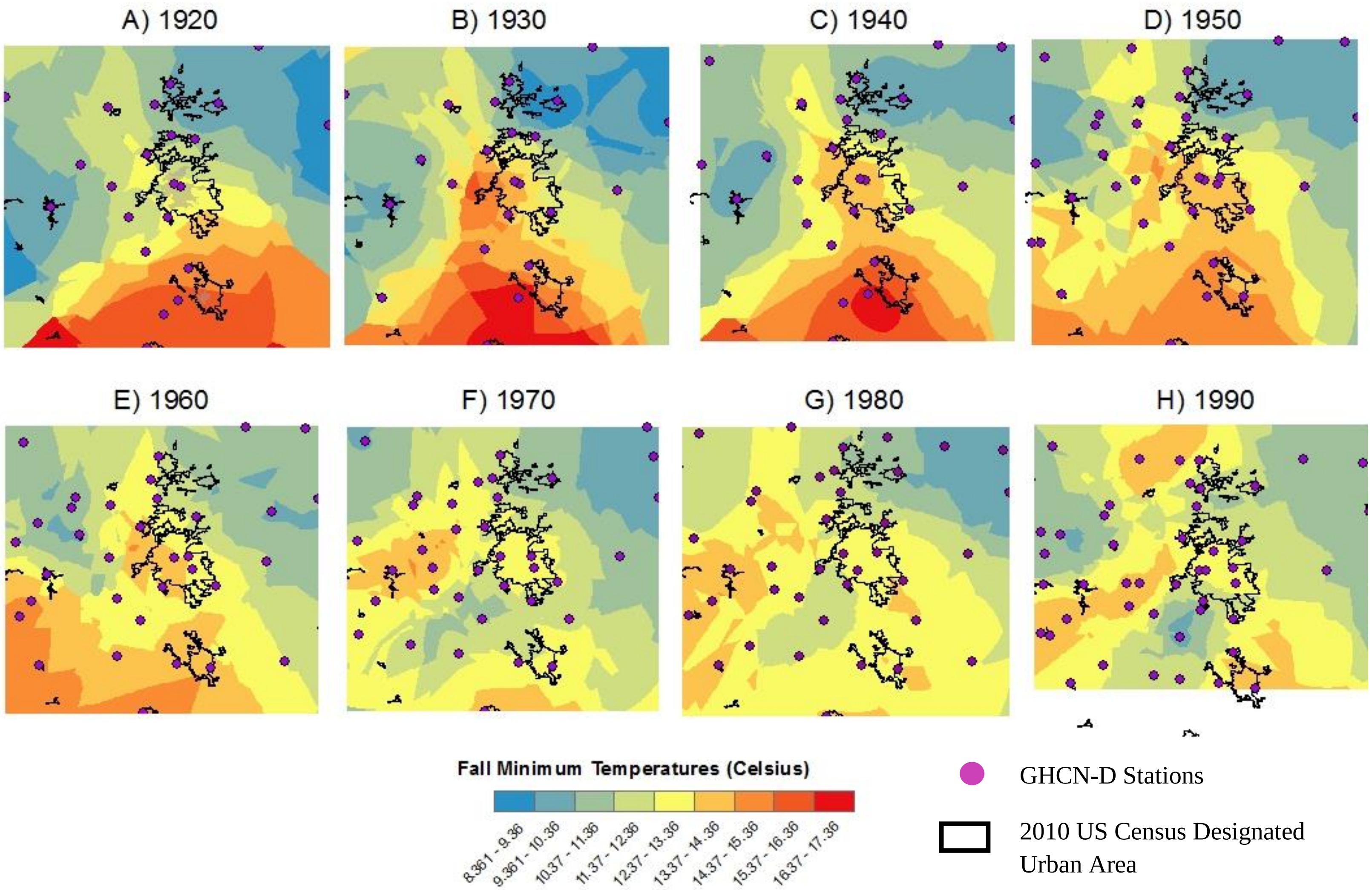


Figure 12. Average Decadal Fall Minimum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

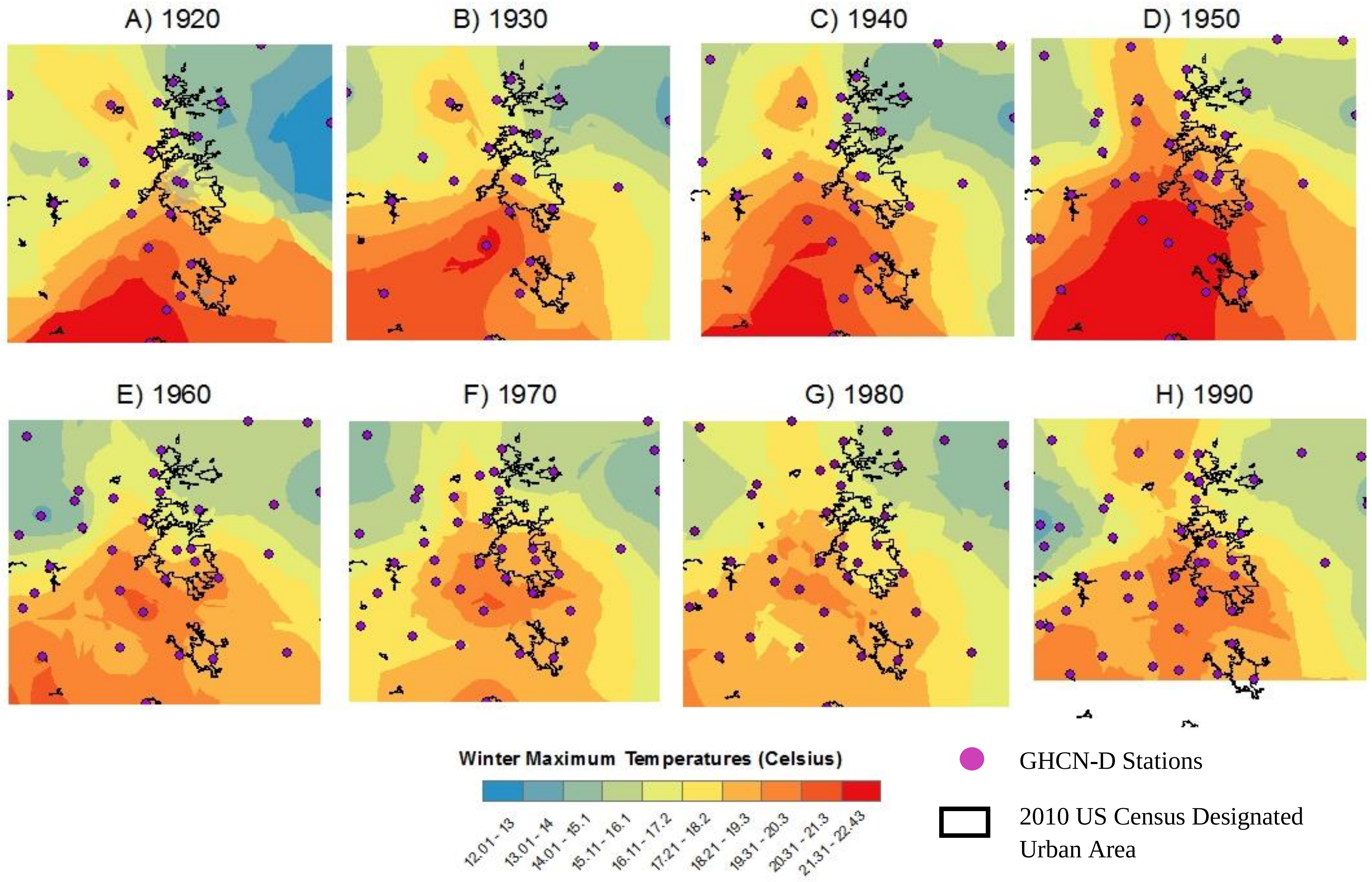


Figure 13. Average Decadal Winter Maximum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

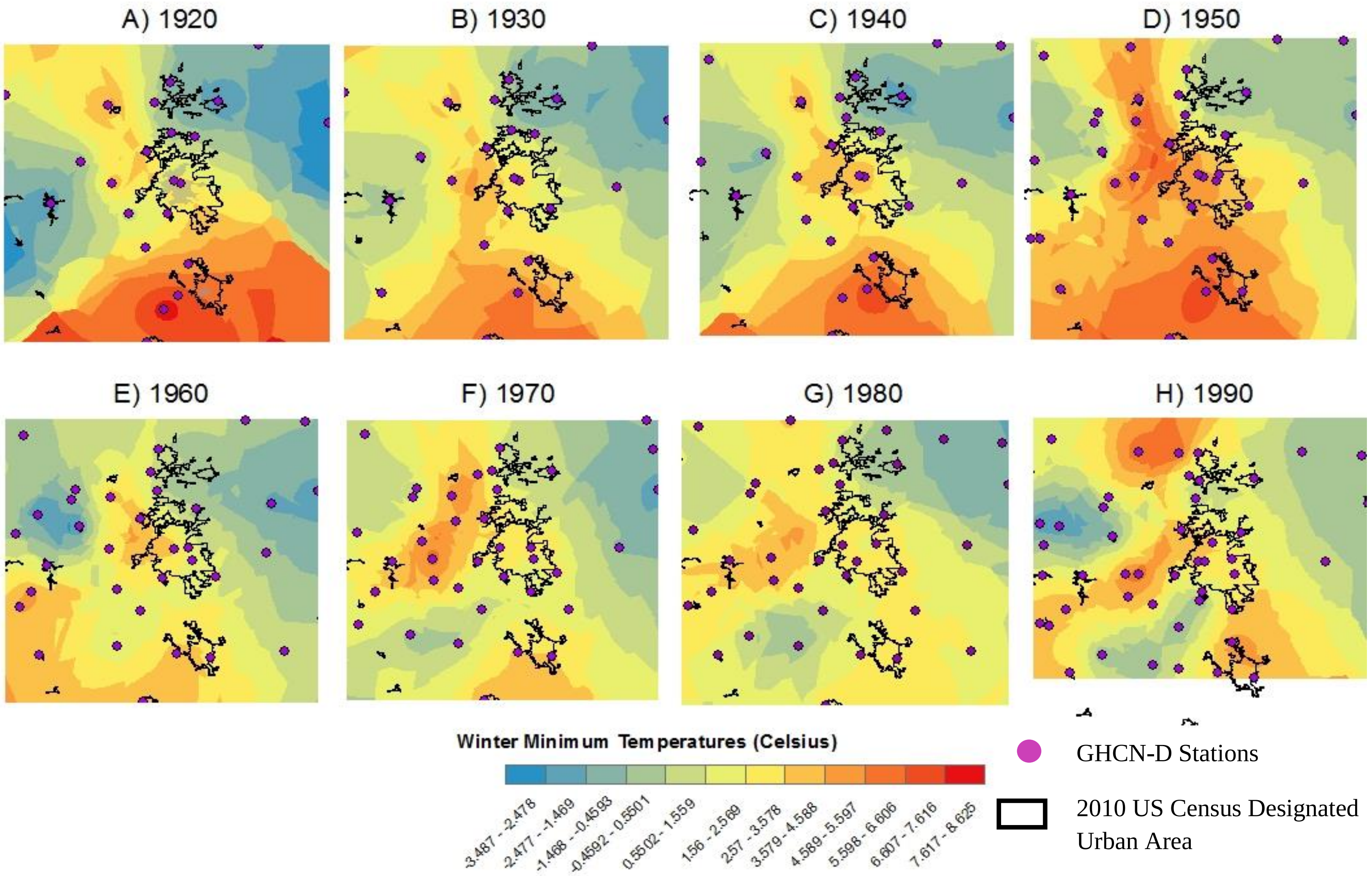


Figure 14. Average Decadal Winter Minimum Interpolated Temperature Surfaces 1920-1990 (A-H) with the 2010 U.S. Census Urban Areas

4.3 Change in Temperature and Precipitation

For the pre-urban and urban precipitation and temperature analysis three different interpolated surfaces were made for the annual and each season (Figures 15-19); two temperature maps showing the exact change in temperature for both T_{max} and T_{min} and a map showing the percent change in precipitation were made. Tables 10-12 shows the percent change at each station for T_{max}, T_{min}, and Precipitation between the two time periods. The results for each season and variable are discussed.

During spring, daytime temperatures (Fig. 15) increased from pre-urbanization to the urban time period in the northern part of Denver extending the northernmost edge of the study area. Along the western and eastern edges there was also a slight increase. Over Colorado Springs and southern Denver there was roughly no change. A small portion in the southwest corner saw a decrease in daytime temperatures. The minimum or nighttime temperatures during spring (Fig. 15) saw an increase in the central, northern, and eastern regions. Just west of Denver extending to the western edge is an area where temperatures have reduced since the urbanization of Denver. The spring season has seen an overall decrease in precipitation (Fig. 15) since the middle of the century with the driest areas being to the east and west of Denver. The smallest decrease was west of Colorado Springs and north of Denver.

Daytime summer temperatures (Fig. 16) have seen a general increase across the whole study area. A band extending from east of Denver down into Colorado Springs did not see any change. The largest increase in daytime temperatures is west of Fort Collins extending south to the west of Denver and down to the southwest corner of the region.

Nighttime temperatures (Fig. 16) decreased just west of Denver, in a small area north of Denver and a small area east of Denver. Increases were found over the southeastern part of Denver, Fort Collins, the southeast and northeast corners of the region, and also in two spots on the western border of the study area. Precipitation (Fig.16) was found to increase the greatest in a region east of Denver over the plains and in the southwestern corner. The largest decreases were found north and northwest of Denver and southwest of Colorado Springs.

Fall maximum temperatures (Fig. 17) increased west of Denver and over northern Denver. Decreases were found from southern Denver down through Colorado Springs to the southern border of the study area. Nighttime temperatures (Fig. 17) increased in the whole eastern half of the region. Decreases were found west of Denver. Precipitation (Fig. 17) has increased the greatest in the southwest corner during fall. There was little to no change found over the center of the region. The largest decrease in precipitation is in the northwest corner.

Winter daytime temperatures (Fig. 18) have increase over northern Denver and up into Fort Collins. Decreases in temperature are east of Denver and south through Colorado Springs. Nighttime temperatures (Fig. 18) have increased in the eastern half of the study area and decreased just west of Denver. Precipitation (Fig. 18) has increased southwest and north of Denver. Precipitation amounts decreased the most along the eastern edge of the study region.

Overall the study area has seen daytime temperatures (Fig. 19) decrease south of Denver into Colorado Springs. Daytime temperatures increased north of Denver and along both the east and west edges of the study area. Nighttime temperatures (Fig. 19) have increased along the whole eastern half of the study region. Temperatures have decreased at night west of Denver. The precipitation (Fig. 19) has increased west of Colorado Springs and generally decreased everywhere else in the study area.

The results of the t-tests show that each season had statistically significant changes in daytime and nighttime temperatures. Significant changes in precipitation were found in fall, spring, and winter. The list of stations that had significant change between the two time periods and for which season is showed in Table 13. These stations are also displayed in Figures 15-19 using the green triangle symbol.

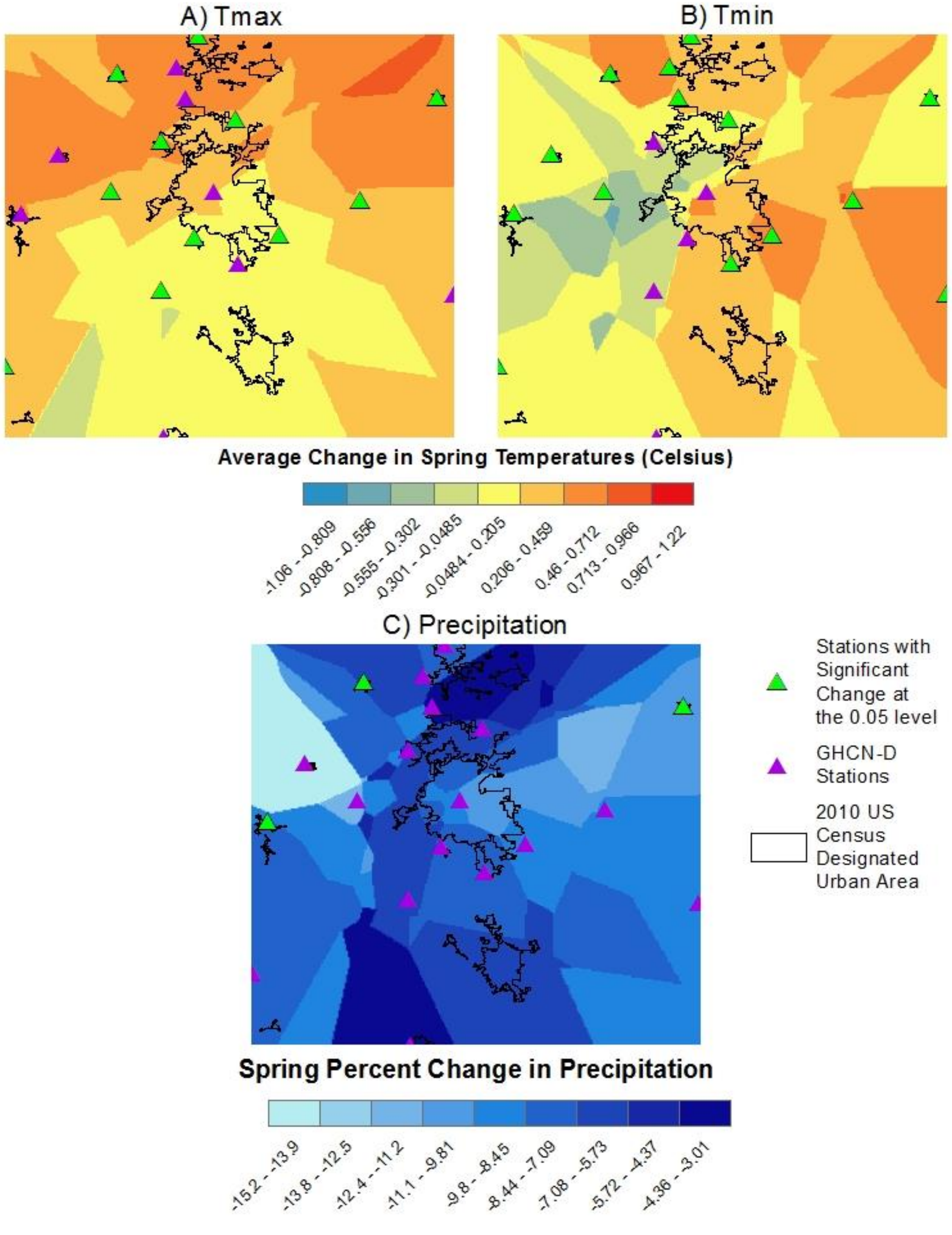


Figure 15. Average Change in Spring Maximum (A), Minimum (B) Temperatures and Percent Change in Precipitation (C) from Pre-Urban (1893-1950) to Urban (1951-2011)

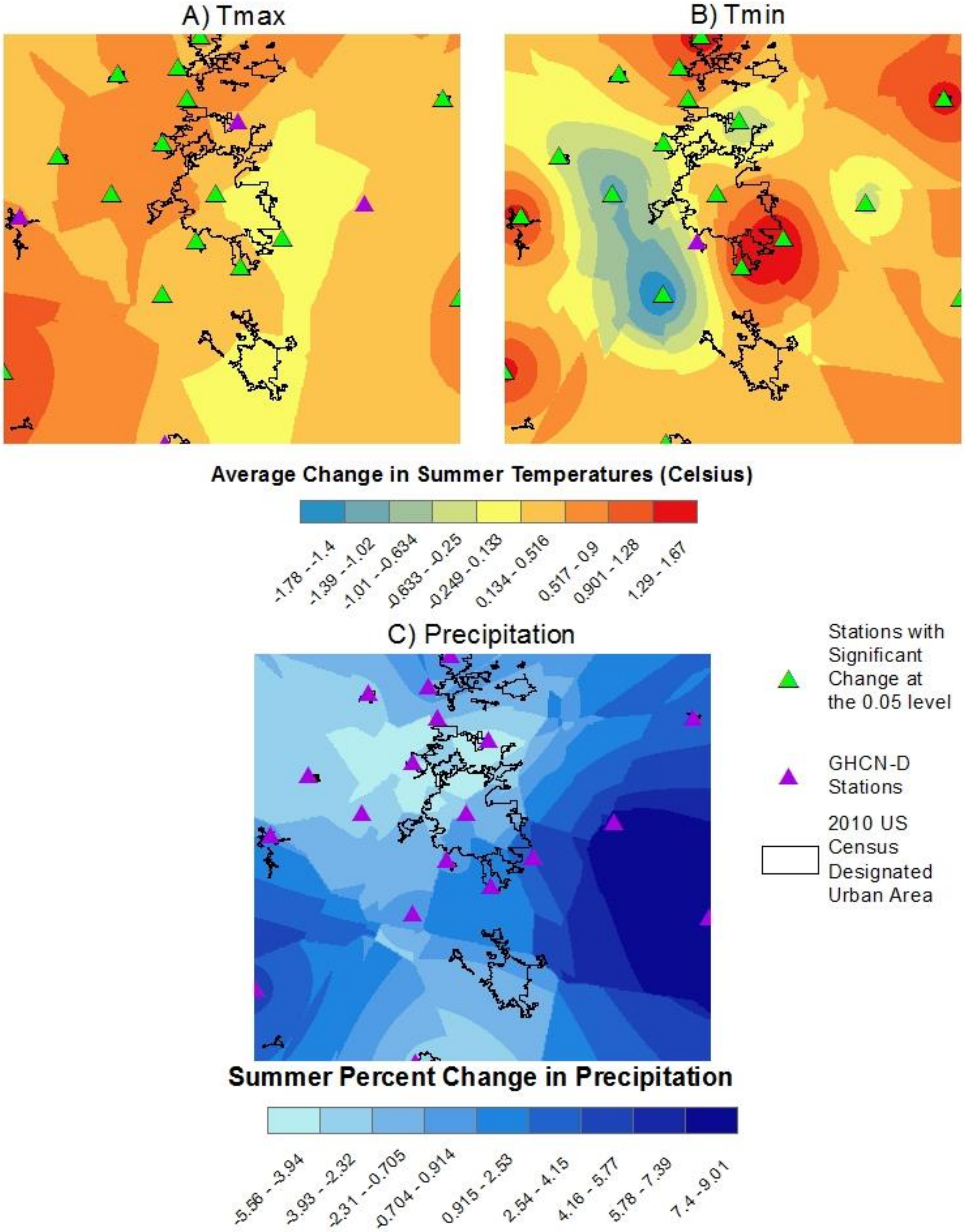


Figure 16. Average Change in Summer Maximum (A), Minimum (B) Temperatures and Percent Change in Precipitation (C) from Pre-Urban (1893-1950) to Urban (1951-2011)

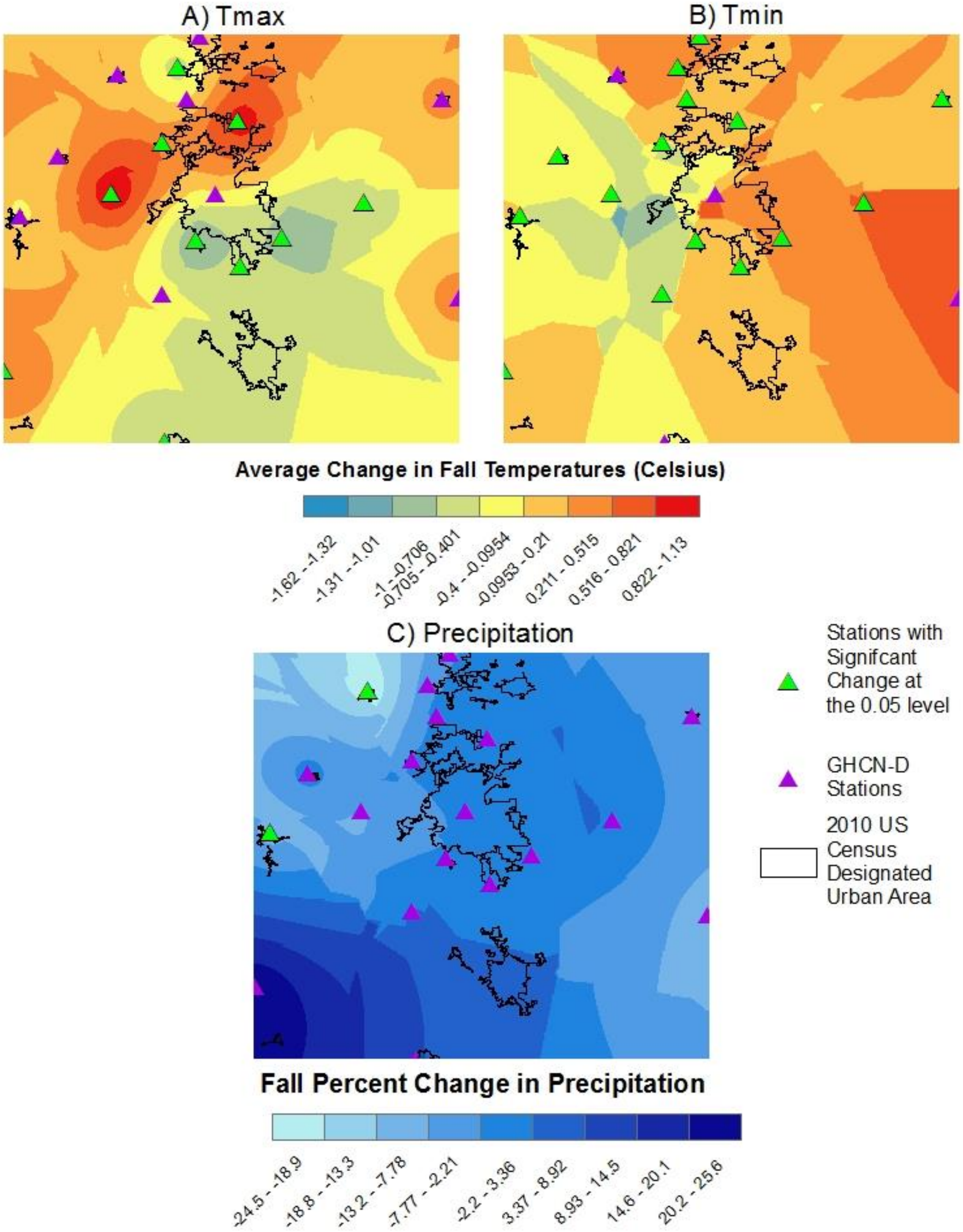


Figure 17. Average Change in Fall Maximum (A), Minimum (B) Temperatures and Percent Change in Precipitation (C) from Pre-Urban (1893-1950) to Urban (1951-2011)

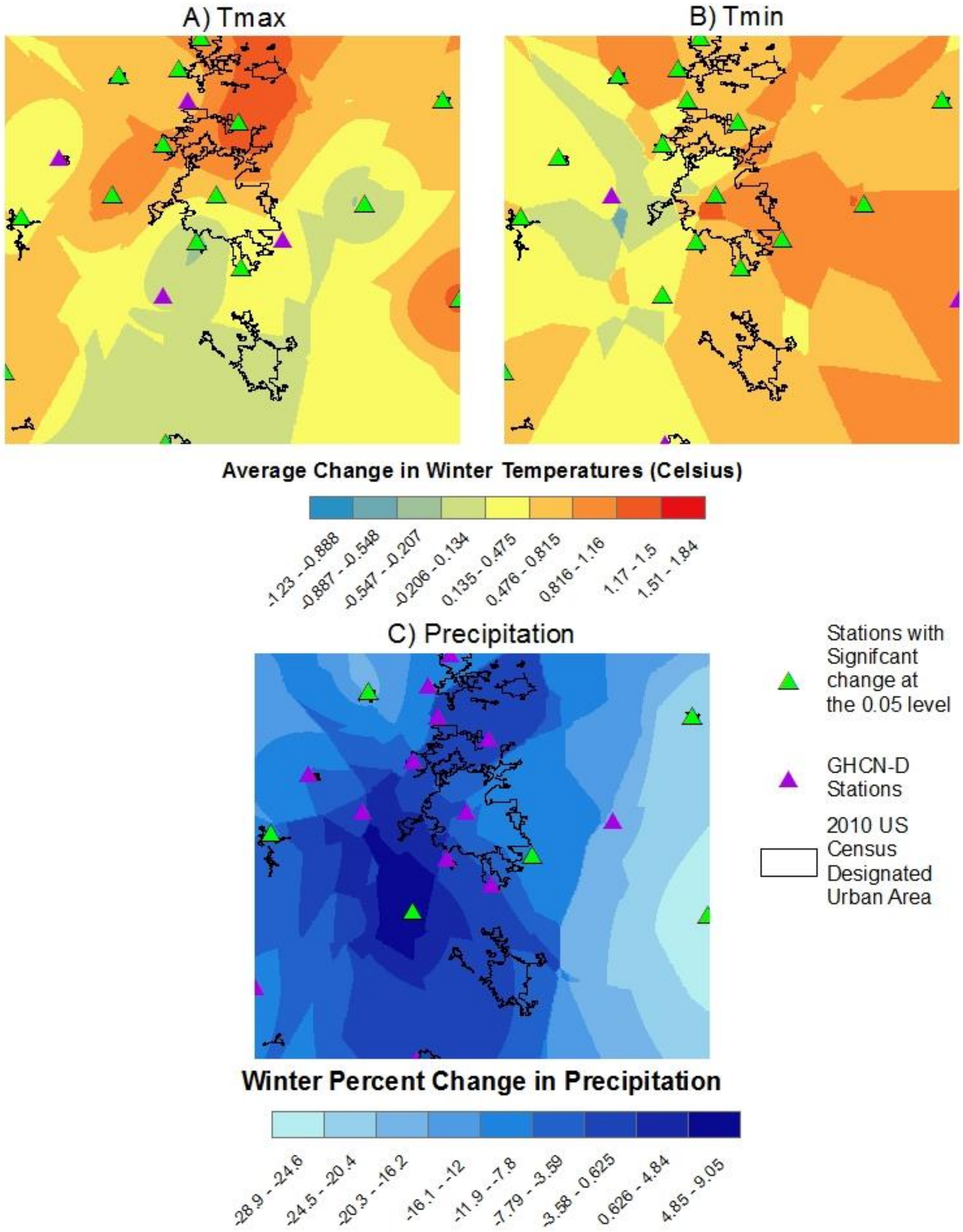


Figure 18. Average Change in Winter Maximum (A), Minimum (B) Temperatures and Percent Change in Precipitation (C) from Pre-Urban (1893-1950) to Urban (1951-2011)

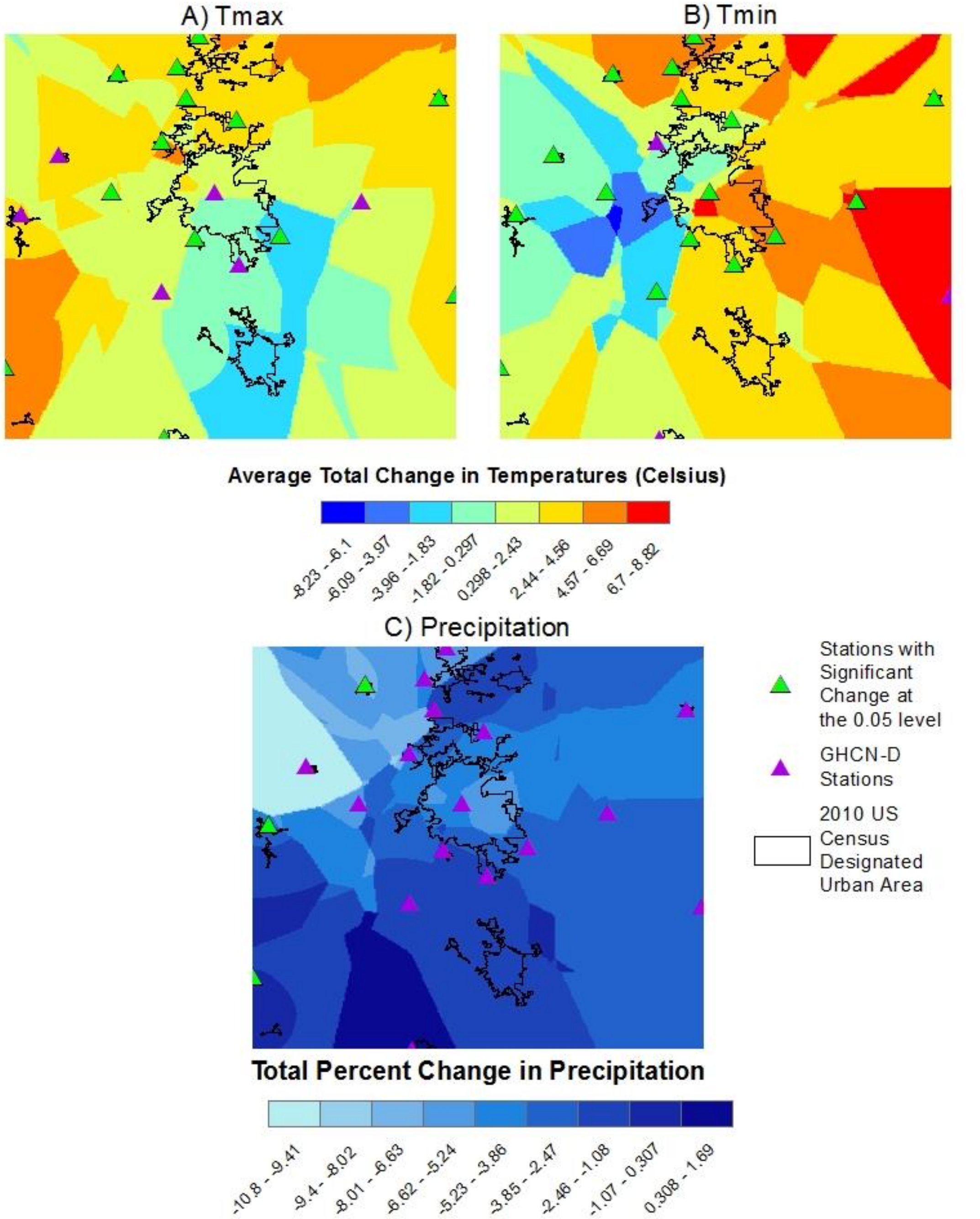


Figure 19. Average Total Change in Maximum (A), Minimum (B) Temperatures and Percent Change in Precipitation (C) from Pre-Urban (1893-1950) to Urban (1951-2011)

Table 10. Change in Average Maximum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Spring			Summer		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	15.85	17.15	8.20	28.05	29.49	5.14
Buena Vista 2 S	13.24	13.83	4.46	24.38	26.29	7.84
Byers 5 ENE	16.55	17.10	3.33	30.76	30.64	-0.41
Canon City	18.83	18.56	-1.42	30.45	30.40	-0.17
Castle Rock	15.71	15.94	1.48	27.79	28.32	1.90
Cheesman	14.87	15.03	1.05	26.98	27.49	1.92
Denver Weather Service Office City	15.36	15.40	0.27	28.48	28.77	1.00
Dillon 1 E	9.22	9.04	-1.97	22.19	22.13	-0.27
Estes Park	11.46	11.89	3.72	24.11	24.31	0.86
Fort Collins	15.01	16.27	8.37	27.67	28.58	3.30
Fort Lupton 2 SE	16.56	17.28	4.37	30.60	30.74	0.44
Fort Morgan	16.38	16.88	3.02	29.81	30.54	2.45
Fraser	8.29	8.44	1.85	21.51	21.91	1.84
Idaho Springs	11.75	12.55	6.80	23.79	24.90	4.64
Kassler	17.88	16.98	-5.05	29.56	29.46	-0.33
Limon 10 SSW	15.77	15.97	1.27	28.65	29.56	3.17
Longmont 2 ESE	16.73	16.84	0.63	29.63	30.04	1.38
Parker 6 E	15.03	15.61	3.85	28.80	28.44	-1.27
Waterdale	16.34	16.18	-0.98	28.58	29.06	1.67

Table 10 Continued. Change in Average Maximum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Fall			Winter		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	18.48	18.94	2.48	7.25	8.22	13.39
Buena Vista 2 S	15.84	16.25	2.60	4.23	5.06	19.57
Byers 5 ENE	19.68	19.04	-3.24	7.21	6.66	-7.63
Canon City	21.02	20.46	-2.66	10.41	10.12	-2.77
Castle Rock	18.93	18.36	-2.99	7.13	7.61	6.62
Cheesman	18.31	18.07	-1.28	7.84	7.71	-1.62
Denver Weather Service Office City	18.23	18.11	-0.65	6.95	7.61	9.55
Dillon 1 E	12.41	12.21	-1.60	0.05	0.44	766.87
Estes Park	14.57	14.75	1.26	3.45	4.19	21.24
Fort Collins	17.44	17.61	0.95	5.26	6.53	24.13
Fort Lupton 2 SE	18.11	19.19	5.97	5.09	6.92	35.97
Fort Morgan	18.49	18.77	1.51	4.76	5.36	12.59
Fraser	11.56	11.63	0.56	-1.03	-1.14	-10.95
Idaho Springs	14.51	15.70	8.14	3.85	5.33	38.30
Kassler	20.39	19.31	-5.31	9.39	8.71	-7.25
Limon 10 SSW	18.26	18.74	2.62	5.50	7.11	29.41
Longmont 2 ESE	18.85	18.69	-0.84	6.56	6.86	4.55
Parker 6 E	19.05	18.21	-4.40	6.65	7.01	5.36
Waterdale	18.64	18.01	-3.39	6.67	7.02	5.26

Table 10 Continued. Change in Average Maximum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Annual		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	17.47	18.57	6.31
Buena Vista 2 S	14.24	15.42	8.30
Byers 5 ENE	18.63	18.40	-1.21
Canon City	20.24	20.01	-1.11
Castle Rock	17.60	17.63	0.17
Cheesman	16.98	17.12	0.80
Denver Weather Service Office City	17.31	17.45	0.81
Dillon 1 E	11.12	10.99	-1.15
Estes Park	13.46	13.70	1.72
Fort Collins	16.39	17.32	5.69
Fort Lupton 2 SE	17.70	18.59	5.03
Fort Morgan	17.28	17.98	4.01
Fraser	10.15	10.23	0.77
Idaho Springs	13.47	14.57	8.14
Kassler	19.32	18.67	-3.37
Limon 10 SSW	17.21	17.90	4.01
Longmont 2 ESE	17.95	18.18	1.30
Parker 6 E	17.67	17.36	-1.76
Waterdale	17.83	17.62	-1.20

Table 11. Change in Average Minimum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Spring			Summer		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	2.12	2.26	6.74	13.59	13.41	-1.38
Buena Vista 2 S	-3.79	-2.84	25.18	5.95	7.48	25.59
Byers 5 ENE	0.48	0.08	-83.44	12.63	12.16	-3.76
Canon City	2.84	2.74	-3.52	14.02	14.49	3.38
Castle Rock	-1.95	-0.60	69.12	9.05	10.61	17.14
Cheesman	-2.19	-3.47	-58.79	9.08	7.29	-19.71
Denver Weather Service Office City	2.75	3.02	10.06	15.01	15.54	3.58
Dillon 1 E	-9.37	-7.75	17.32	0.71	2.23	213.84
Estes Park	-3.37	-2.64	21.50	6.31	6.70	6.10
Fort Collins	-0.21	1.26	694.44	11.13	12.73	14.37
Fort Lupton 2 SE	0.64	-0.30	-147.22	12.35	11.78	-4.61
Fort Morgan	0.02	1.31	6111.92	12.52	14.04	12.16
Fraser	-9.10	-10.41	-14.35	0.28	-0.20	-172.53
Idaho Springs	-2.54	-3.48	-36.61	7.78	6.52	-16.14
Kassler	1.25	1.08	-13.31	13.55	13.46	-0.66
Limon 10 SSW	-0.50	-1.14	-125.84	11.43	11.61	1.62
Longmont 2 ESE	-0.13	0.30	331.23	10.98	11.72	6.75
Parker 6 E	-1.78	-0.36	79.56	10.08	11.77	16.68
Waterdale	-0.24	0.03	111.41	10.10	11.11	9.95

Table 11. Continued. Change in Average Minimum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Fall			Winter		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	4.09	3.77	-7.99	-5.99	-5.43	9.25
Buena Vista 2 S	-2.76	-1.87	32.26	-12.51	-11.09	11.33
Byers 5 ENE	1.99	1.06	-46.69	-8.88	-9.61	-8.21
Canon City	4.39	4.27	-2.56	-5.19	-5.31	-2.29
Castle Rock	-0.81	0.23	127.85	-11.31	-9.36	17.27
Cheesman	-0.22	-2.13	-871.71	-10.44	-12.01	-15.03
Denver Weather Service Office City	4.70	4.96	5.55	-5.44	-4.55	16.37
Dillon 1 E	-8.04	-6.12	23.83	-19.18	-16.37	14.64
Estes Park	-1.23	-0.99	19.14	-8.91	-8.26	7.30
Fort Collins	0.46	1.84	302.62	-10.35	-8.20	20.81
Fort Lupton 2 SE	1.66	0.41	-75.24	-9.13	-9.69	-6.15
Fort Morgan	0.71	1.50	111.15	-11.67	-10.40	10.88
Fraser	-8.32	-9.97	-19.82	-19.25	-21.01	-9.16
Idaho Springs	-0.47	-1.61	-244.73	-8.96	-9.09	-1.43
Kassler	3.27	2.81	-13.98	-7.48	-7.83	-4.76
Limon 10 SSW	1.22	0.94	-22.94	-9.61	-9.53	0.83
Longmont 2 ESE	0.24	0.53	124.75	-10.78	-9.76	9.42
Parker 6 E	-0.64	1.45	328.57	-11.53	-8.52	26.15
Waterdale	0.48	1.20	147.34	-9.65	-8.96	7.14

Table 11. Continued. Change in Average Minimum Temperature between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Annual		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	3.51	3.61	2.90
Buena Vista 2 S	-3.40	-2.06	39.42
Byers 5 ENE	1.63	0.96	-40.86
Canon City	4.11	4.18	1.64
Castle Rock	-1.03	0.29	128.15
Cheesman	-0.93	-2.54	-174.43
Denver Weather Service Office City	4.31	4.73	9.75
Dillon 1 E	-8.85	-6.96	21.27
Estes Park	-1.75	-1.37	21.85
Fort Collins	0.30	1.97	566.27
Fort Lupton 2 SE	1.48	0.60	-59.85
Fort Morgan	0.30	1.70	476.52
Fraser	-9.04	-10.40	-15.03
Idaho Springs	-1.05	-1.94	-85.16
Kassler	2.68	2.43	-9.33
Limon 10 SSW	0.77	0.52	-31.64
Longmont 2 ESE	0.09	0.77	741.42
Parker 6 E	-0.72	1.14	257.89
Waterdale	0.43	0.92	113.97

Table 12. Change in Average Precipitation between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Spring			Summer		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	21.58	20.07	-7.00	15.48	15.46	-0.09
Buena Vista 2 S	7.05	7.29	3.39	10.64	11.89	11.75
Byers 5 ENE	15.10	13.90	-7.95	15.08	16.83	11.55
Canon City	11.96	10.69	-10.64	15.12	13.80	-8.77
Castle Rock	16.28	15.19	-6.66	19.35	18.80	-2.81
Cheesman	13.10	13.43	2.53	17.98	18.97	5.55
Denver Weather Service Office City	14.44	12.51	-13.41	11.09	11.00	-0.78
Dillon 1 E	14.94	10.56	-29.29	13.31	13.20	-0.84
Estes Park	17.28	12.62	-26.97	17.88	16.22	-9.31
Fort Collins	16.53	16.26	-1.62	12.94	14.23	9.96
Fort Lupton 2 SE	13.22	11.66	-11.79	12.51	11.15	-10.94
Fort Morgan	14.41	12.36	-14.21	16.01	16.19	1.13
Fraser	15.57	14.34	-7.89	14.31	14.44	0.95
Idaho Springs	13.30	12.63	-5.09	17.75	16.15	-9.05
Kassler	19.94	18.11	-9.20	14.60	14.25	-2.42
Limon 10 SSW	12.71	11.68	-8.05	17.76	19.87	11.86
Longmont 2 ESE	13.96	14.76	5.73	12.52	11.32	-9.58
Parker 6 E	14.29	12.83	-10.18	15.45	16.76	8.51
Waterdale	17.32	16.86	-2.62	14.54	15.39	5.85

Table 12. Continued. Change in Average Precipitation between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Fall			Winter		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	11.60	11.69	0.73	6.39	6.39	-0.03
Buena Vista 2 S	4.84	6.37	31.64	3.81	3.27	-14.18
Byers 5 ENE	7.22	7.63	5.62	3.75	3.43	-8.33
Canon City	6.56	7.10	8.27	4.19	3.92	-6.30
Castle Rock	8.32	8.46	1.71	4.91	5.19	5.73
Cheesman	8.08	8.59	6.29	3.86	4.70	21.67
Denver Weather Service Office City	7.41	7.33	-1.15	4.28	4.01	-6.29
Dillon 1 E	10.61	8.67	-18.31	11.17	8.12	-27.28
Estes Park	11.46	7.64	-33.37	6.84	3.84	-43.90
Fort Collins	8.60	8.47	-1.58	3.93	3.67	-6.76
Fort Lupton 2 SE	7.00	7.22	3.15	3.29	3.21	-2.52
Fort Morgan	7.21	6.73	-6.63	2.64	1.97	-25.25
Fraser	10.84	11.96	10.36	12.81	14.11	10.20
Idaho Springs	8.96	7.91	-11.69	3.72	4.03	8.38
Kassler	11.15	10.84	-2.81	6.29	5.81	-7.61
Limon 10 SSW	6.94	6.06	-12.74	3.63	2.11	-41.92
Longmont 2 ESE	7.85	7.99	1.76	3.56	3.48	-2.31
Parker 6 E	7.26	7.22	-0.58	3.63	2.59	-28.70
Waterdale	9.60	9.34	-2.71	4.08	4.14	1.56

Table 12. Continued. Change in Average Precipitation between the Pre-Urban (1893-1950) time period and the Urban (1951-2011) time period at GHCN-D stations for Spring, Summer, Fall, Winter, and Annual

	Annual		
Station	Pre-Urban (°C)	Urban (°C)	Percent Change
Boulder	13.89	13.49	-2.88
Buena Vista 2 S	6.56	7.22	10.05
Byers 5 ENE	10.42	10.48	0.52
Canon City	9.44	9.00	-4.69
Castle Rock	12.24	12.04	-1.71
Cheesman	10.76	11.50	6.88
Denver Weather Service Office City	9.31	8.72	-6.37
Dillon 1 E	12.53	10.15	-18.98
Estes Park	13.41	10.09	-24.78
Fort Collins	10.51	10.69	1.74
Fort Lupton 2 SE	9.05	8.30	-8.25
Fort Morgan	10.06	9.41	-6.49
Fraser	13.37	13.73	2.64
Idaho Springs	10.99	10.25	-6.74
Kassler	13.00	12.29	-5.45
Limon 10 SSW	10.30	9.98	-3.08
Longmont 2 ESE	9.51	9.44	-0.75
Parker 6 E	10.42	9.91	-4.97
Waterdale	11.50	11.48	-0.13

Table 13. GHCN-D stations with Statistically Significant Change in Precipitation and Temperature at the 0.05 Level

Station	Variable	Total	Spring	Summer	Fall	Winter
Boulder	PPT					
	Tmax	✓	✓	✓	✓	✓
	Tmin			✓	✓	✓
Buena Vista 2 S	PPT	✓				
	Tmax	✓	✓	✓	✓	✓
	Tmin	✓	✓	✓	✓	✓
Byers 5 ENE	PPT					
	Tmax		✓		✓	✓
	Tmin	✓	✓	✓	✓	✓
Canon City	PPT					
	Tmax	✓			✓	✓
	Tmin			✓		
Castle Rock	PPT					
	Tmax			✓	✓	✓
	Tmin	✓	✓	✓	✓	✓
Cheesman	PPT	✓				✓
	Tmax		✓	✓		
	Tmin	✓		✓	✓	✓
Denver Weather Service Office City	PPT					
	Tmax			✓		✓
	Tmin	✓		✓		✓
Dillon 1 E	PPT	✓	✓		✓	✓
	Tmax					✓
	Tmin	✓	✓	✓	✓	✓
Estes Park	PPT	✓	✓		✓	✓
	Tmax	✓	✓	✓		✓
	Tmin	✓	✓	✓		✓
Fort Collins	PPT					
	Tmax	✓	✓	✓		✓
	Tmin	✓	✓	✓	✓	✓

Table 13. Continued GHCN-D stations with Statistically Significant Change in Precipitation and Temperature at the 0.05 Level

Station	Variable	Total	Spring	Summer	Fall	Winter
Fort Lupton 2 SE	PPT					
	Tmax	✓	✓		✓	✓
	Tmin	✓	✓	✓	✓	✓
Fort Morgan	PPT		✓			✓
	Tmax	✓	✓	✓		✓
	Tmin	✓	✓	✓	✓	✓
Fraser	PPT					
	Tmax			✓		
	Tmin	✓	✓	✓	✓	✓
Idaho Springs	PPT					
	Tmax	✓	✓	✓	✓	✓
	Tmin	✓	✓	✓	✓	
Kassler	PPT					
	Tmax	✓	✓	✓	✓	✓
	Tmin	✓			✓	✓
Limon 10 SSW	PPT					✓
	Tmax	✓		✓		✓
	Tmin		✓	✓		
Longmont 2 ESE	PPT					
	Tmax	✓		✓		
	Tmin	✓	✓	✓	✓	✓
Parker 6 E	PPT					✓
	Tmax	✓	✓	✓	✓	
	Tmin	✓	✓	✓	✓	✓
Watedale	PPT					
	Tmax	✓		✓	✓	✓
	Tmin	✓	✓	✓	✓	✓
Total	PPT	✓	✓			
	Tmax			✓	✓	✓
	Tmin					

5.0 Discussion

5.1 Current Urban Heat Island

The calculated averages for T_{max} and T_{min} for the decade of 2000-2009 show a statistical difference between urban and rural sites. The magnitude or the difference between T_u and T_r shows there is indeed an urban heat island over the Denver metropolitan area evident all year long. The interpolated surface visually shows how there is a bubble of warmer air centered over the major urban areas of Denver.

As expected the urban heat island is most pronounced graphically and numerically during summer nights. T_u-T_r was larger for summer nights than any other season at 4.22°C. Visually, the interpolated surface map shows the warmest temperatures concentrated over the urban corridor for T_{min}. The daytime summer temperatures visually show warm temperatures over the whole study area. There is a centralized area of highest temperatures right over downtown Denver. This also shows a UHI present during summer days although it is not as large as the nighttime UHI. Previous research has found the UHI to be most evident during the summer nights (Huff and Changnon 1972; Gallo and Owen 1999) therefore the results of this study corroborate with the results found in other cities.

Winter daytime had the second largest UHI magnitude at 3.95 °C. Winter has the second largest urban heat island for the year possibly due to the addition of anthropogenically generated heat. This urban heat island could possibly be gaining some strength from the anthropogenic heat generation. Because Denver can reach uncomfortably low temperatures during the winter, energy is used to heat buildings during this time of year. It is possible the retention of solar radiation is not the main driver behind the winter UHI. A study done during the winter in Minneapolis, Minnesota found that if there is at least 5 centimeters of snow on the ground the magnitude of the UHI increased by 1°C during the day and 0.5°C at night (Malevich and Klink 2011). This was because of the insulating behavior of the snow at night and the high albedo during the day (Malevich and Klink 2011). This could possibly be the case in Denver. The snow on the ground during winter could be amplifying the UHI to be at its second largest for the whole year at 3.95°C during the day and 3.85°C during the night. Although there is less of an obvious visual UHI during winter, warm air can be seen encompassing all of the Denver urban area.

The other season to display an obvious visual UHI over Denver is during spring nighttime. A bubble of warmer area is located right over the Denver urban area. The magnitude of the UHI during this season was third largest after summer at 3.87°C. Spring is also rather cool in Denver so this UHI could be so visually distinct due to the addition of anthropogenic heat just like winter. The region also receives the maximum amount of precipitation this time of year. Often this falls in the form of snow. Due to the warmer surfaces in the city the snow will melt faster than in non-urban settings. This leads to widely different albedos between urban and rural surfaces. Urban environments are going to absorb more radiation due to the reduced snow cover causing the surface temperature to rise. This could possibly be why there are distinctly higher temperatures over the urban corridor of the Front Range during spring.

While fall does have urban areas that have calculated warmer temperatures than rural areas, there is no distinct visual urban heat island for either T_{max} or T_{min}. Winter T_{min} and Spring T_{max} also did not show visual UHIs either but they both have calculated UHIs. This could be the result of needing a finer resolution in the scale to bring out distinct temperature differences in the maps.

The overall average magnitude of the UHI in Denver for the whole year is higher than the average magnitude found in studies of other cities. The Denver UHI raises temperatures by 3.57°C during the day and 3.82°C at night. Other studies have shown the average increase in air temperatures to be around 2°C due to the UHI (Taha 1997b; Changnon 1976, 1981). Denver's higher UHI magnitude could be attributed to the higher amount of insolation compared to other cities or possibly because many of the rural sites are located in agricultural areas where artificial irrigation is prominent. The surface water will lower rural air temperatures causing the urban-rural temperature difference to be exaggerated.

5.1.1 Limitations

The major limitation in the current UHI analysis in Denver is over the classification of the rural and urban sites. As Stewart and Oke (2012) point out there have been discrepancies over what should be classified as urban or rural for years. The term *urban* has no single objective definition as it varies from city to city. What is described as urban in one city may not be the same in another city. It is impossible to set a universal definition physically, thermally, or by its surface properties. In many cities the demarcation between urban and rural is no longer a clear divide as cities are becoming more decentralized (Stewart and Oke 2012). According to Hawkins *et al.* (2004) urban effects depend on both the landcover changes taking place at the site, but also the changes taking place at the rural site it is being compared to. For this study I used the United States Census designation, which bases the classification solely on population. The land use or land cover of the site was not taken into consideration. Using surrounding landcover instead of population might result in different classifications for each station.

5.2 Urban Heat Island 1920s-1990s

It first must be noted when examining historical temperatures that the amount of surface water can greatly affect air temperatures as discussed in the introduction. Years of drought can bring higher than normal temperatures and years with ample rain will be cooler than normal. Therefore it is imperative that we first look at the dry and wet periods for the study region. Years of drought in Colorado include the 1930s, 1950s, most of the 1970s, and the 2000s. The 1920s, 1940s, 1980s and 1990s were all decades of higher than normal precipitation. The 1960s had alternating years of very dry and very wet (McKee *et al.* 2000). The 1930s and the 1950s interpolated surface maps consistently displayed the warmest temperatures for almost all seasons. The drought could be the reason for this. The most recent decade of 2000-2009 has been the warmest decade on record and therefore the temperatures reflect this across all seasons.

The warmer temperatures that appear in the southern portion of all seasons through 1920-1950 are an anomaly that cannot be explained in this paper. It could have been the result of a change in instrumentation, errors in collection, or something environmental. Whether these readings are accurate or not they distort evidence of current and past urban heat islands.

Springtime T_{min} shows warm temperatures over Denver that expands in spatial extent through the decades. The UHI almost disappears during the 1970s. This was a decade of drought conditions so this is surprising. T_{max} on the other hand does not have such a continuous pattern. The warm air from the south continues to travel northward, but this temperature increase is not due to the urban areas of Denver. It is not until the 1990s that a noticeable bubble around the urban area begins to form. Spring holds a lot of variability in weather conditions for the Denver area so it is not surprising there is not a definitive pattern amongst the years for this season.

Another highly variable season in Colorado is fall in which neither the T_{max} nor the T_{min} show a pattern of a UHI forming over the city. Besides the unusually warm southern temperatures from 1920-1960 the temperatures are rather continuous through the 80 year analysis with some slight variations that are not attributed to the expansion of urban areas.

Winter does not show much a UHI forming as the city expanded except for the later decades of daytime temperatures. Starting in 1950 the warmer temperatures begin to envelope Denver’s urban core. This could possibly be due to the increase in anthropogenic heating discussed earlier. Winter nighttime temperatures do not show a distinct visual UHI forming over the years.

While the nighttime summer maps show that the Denver urban area does have a region of continuously warm temperatures over it through the decades I believe this can be attributed to a UHI present all the way back to 1920. While there was not as much impervious surfaces as there are today there was still enough to cause a noticeable difference in temperatures between the city and rural areas, particularly at night. The extent of warm air expands as time progresses indicating this is due to the expansion of urbanized areas. The summer daytime temperature on the other hand do not present a noticeable pattern over 1920-2000 that can be attributed to an urban heat island.

5.2.1 Limitations

The main limiting factor in the 1920-2000 UHI analysis was the incongruity of the stations used in each decadal analysis. It was not possible to find enough GHCN-D stations that had temperature readings from 1920-2009. Therefore different stations were used to create the interpolated surface maps for each decade. There could be slight biases between the stations that could ultimately be skewing the data for each decade. Undocumented changes in temperatures measurements and records could also be contributing to the large southern warm air anomaly from 1920-1950.

Also using the environmental lapse rate (ELR) of 6.4°C/km could be too general for the complex slopes present in the study area. According to Minder *et al.* (2010) the ELR is far too high when compared to actual lapse rates in mountainous environments. They found the mean lapse rate to be substantially smaller at 3.95°C/km. It also differs widely throughout the year not staying constant through the seasons. The smallest lapse rate was found during late summer and the largest was found in spring (Minder *et al.*

2010). The ELR used in this study is constant throughout the year and does not take into account seasonal or spatial variability.

5.3 Change in Temperature and Precipitation

The springtime changes in daytime temperature between Pre-Urban and Urban show a noticeable increase in temperatures in the north and along the edges of the study area. It is surprising that the meteorological station located in the very center of Denver did not have a significant increase in temperature. Both to the east and west of Denver there was significant change. I was not expecting such drastic changes to the west of Denver. This area should not be impacted by urbanization so therefore this change is being caused by some other variable. Fort Collins showed an increase in temperature that could be correlated with the urban area. Colorado Springs surprisingly did not show any change in temperature but this could be due to the lack of GHCN-D stations in that area. Nighttime temperatures again show no significant change within Denver, but substantial change to the west and east. A noticeable decrease in nighttime temperatures was found to the west while a noticeable increase in temperatures was found over the eastern plains. The decrease could be due to elevation changes within the stations or by environmental variables. The increase to the east of Denver could be due to the carryover of heat from the urban center due to wind. Both Fort Collins and Colorado Springs showed an increase in temperatures since 1950 that might be from the expansion of heat retaining surfaces.

Overall, there was a decrease in springtime precipitation between the pre-urban and urban time period. The largest decrease was to the west of Denver. The most likely reason for this large decrease is a change in elevation of the nearby reporting stations between the two time periods. There is a decrease in precipitation to the east of Denver extending out into the plains. This could possibly be caused by the city although this behavior is unlike the UHI-induced precipitation found in most other cities. There is a chance this decrease could be the result of the urban area. Rosenfeld (2000) suggests that the increased presence of condensation nuclei due to pollution can cause a decrease in precipitation downwind of cities. These pollution condensation nuclei create a greater number of droplets but do not stimulate coalescence therefore a reduction in precipitation can occur. This could be occurring during this season. Especially since this is the time of year the Denver metro area receives its largest amount of precipitation. On the other hand spring is a highly variable season for precipitation and it is not surprising that such drastic changes were found. Spring can be substantially different year to year so it is probable this played out in the 20 year average.

The other highly variable season fall, showed similar results as to spring. The minimum temperatures increased in the northern region and along the western and eastern edges. There was a slight cooling over south Denver and Colorado Springs. The warming to the north can possibly be connected with urban areas, but the warming to the west would not be. This could be caused by a change in elevation of the stations between the two time periods. Fall nighttime temperatures showed an increase all along the urban corridor and extending to the east. A very warm spot is evident in the middle of the Denver urban area indicating this is due to the UHI. The areas that have cooled over the past 60 years are located to the west of Denver. The change in precipitation does show an increase in some areas and also some decreases. There were only two stations that had significant changes and these might be due to elevational changes during the reporting history. The increases in the southwest corner are most likely not attributed to any urban area. Around the urban areas and downwind of them there does not appear to be much change indicating the UHI is not influencing precipitation rates during fall.

Winter changes in T_{max} show a general increase in temperatures, except for an area south of Denver extending into Colorado Springs. All but one of the fifteen statistically signification stations showed an increase in daytime temperatures. The largest increase during the day is north of Denver extending up into Greeley. There has been a lot of growth in this area so it is not surprising there is an increase in temperatures here. T_{min} show increases in temperature over Denver and the eastern half of the study region. The largest increase is located right over Denver. This is what I expect to find with the presence of an urban heat island. The same decreases to the west of Denver that were found during spring and fall are also found in winter. Precipitation has increased slightly to the southwest of Denver. This could possibly be caused by the bifurcation of storms due to the vertical profile of Denver. Bornstein and LeRoy (1990) found that preexisting storms moving towards a city tending to split and move around it causing increases in precipitation along the edges. This could be the case here. The storm is being pushed south of the major urban area causing an increase in precipitation to the southwest of Denver and northwest of Colorado Springs. A band extending north to south from east of Denver to the eastern border of the study area has seen a substantial decrease in winter precipitation. These stations are located on a relatively flat area so elevation changes would not be an issue in this case. Unfortunately this area is too sizeable and too far from the urban center to be explained alone by the presence of urban areas, but could be amplified by Rosenfeld's (2000) theory of decreasing precipitation downwind due to an increase in smaller condensation nuclei. This decrease is more likely driven by synoptic scale changes in weather patterns. Overall in winter there does not appear to be UHI-induced precipitation.

Summer daytime temperatures have increased across the whole study region except for a band east of Denver that extends south to Colorado Springs that saw no change. All but three of the stations saw significant changes. Summer nighttime temperature changes show the formation of a UHI over Denver, Fort Collins, Buena Vista, and Dillon to the far west. These three urban areas show significant increases in temperature from the Pre-urban time period. This is a classic urban heat island. As discussed previously, the UHI is most evident during summer nights and this is the case here. There has been substantial urban and suburban development located in the southern metropolitan area right where the T_{min} increase has occurred. This could be caused by the presence of impervious surfaces that were not there 70 years ago. The changes in precipitation during summer do indicate a possible urban heat island induce precipitation. While it is not significant, there has been a 7-9% increase in precipitation downwind of the major urban centers of Denver and Colorado Springs. The major increase in precipitation is directly downwind of the highest increase in nighttime temperatures found around southern Denver. This increase in precipitation could be caused by the newly formed urban areas in this region. Smaller increases were found closer to the eastern edge of the city and downwind of Fort Collins that could also be related to the presence of the urban areas. There has been an overall decrease in precipitation over north Denver and to the west of Denver. Bornstein and LeRoy (1990) found a decrease in precipitation over the downtown urban area due to bifurcation of preexisting storms around the city. It is possible this decrease in precipitation over north and central Denver can be attributed to the vertical build-up of the city.

The overall annual change in T_{max} showed an increase in temperatures to the north and a decrease in the south. It is surprising there is a decrease over Colorado Springs because this city has expanded since the 1950s as well. This decrease is likely explained by the fact that there are few reporting stations for that area with none directly inside the city. The meteorological conditions from farther away are being used to predict the temperatures over Colorado Springs and this is the most probable reason for this odd decrease over a highly urbanized area. The decrease in T_{min} to the west of Denver could be explained by elevational changes in the stations recording history. The increases in T_{min} to the east of all urbanized areas could be the increase in air temperatures due to the UHI. Overall the precipitation has decreased over the study region. The only area of increase is located to the west of Colorado Springs. This is very surprising given there were more drought years in the pre-urban time period and there were more wetter than normal years in the urban time period. I would expect to see an overall increase in precipitation for the whole region. This was not the case. The area of increased precipitation is not likely the result of Denver’s UHI. The largest decrease in precipitation located to the west of Denver is probably due to elevational changes of the recording station and not to the UHI. There is a strip of larger decreases over central Denver extending to the eastern border. This could be the result of the increased smaller cloud condensation nuclei that decreases precipitation downwind of cities.

While it is impossible to tell if the changes in precipitation are caused alone by the urban heat island around Denver it is a good indicator that the UHI is playing a role. Other factors that could be influencing the change could be an increase in aerosols, the vertical profile of the city interacting with storms, or changes in synoptic scale weather patterns. It is notable that there is indeed an increase in precipitation downwind of Denver and Colorado Springs during the summer months similar to previous studies.

5.3.1 Limitations

Any site that changed elevation drastically during the time periods can cause substantial error in both precipitation and temperature readings because the data were not standardized to any set elevation. An increase in elevation could relate to higher precipitation readings and vice-a-versa. For example the Estes Park GHCN-D site elevation varied by 180 meters with the highest elevation corresponding with the pre-urban time period and the lowest elevation readings were in the latest decade. Coincidentally it was the pre-urban time period at Estes Park that had higher precipitation rates as well. The increase in temperature between the time periods could be explained by the decrease in elevation as well. At the Dillon site, the variation in elevation was around 210 meters. The highest elevations were mainly in the later time period while the lowest elevations were around the earlier time period. Despite this the pre-urban time period still had higher precipitation rates than the urban.

It was surprising to find statistically significant results in both temperature and elevation west of Denver and the urban areas. Since there is little urbanized land in the mountains I was expecting to find negligible change in both temperature and precipitation. As discussed these changes could be the result of errors in the collection of the data or it could be a sign of changes in the larger overall meteorological patterns for the Front Range.

Having more GHCN-D sites would have provided a higher accuracy to this study. The 19 points used in the precipitation analysis cover a large areal extent. Having more data points would lend to more accurate interpolation surfaces. UHI-induced changes in precipitation might not be clearly apparent with only 19 stations.

6.0 Conclusion

Overall this study shows Denver, Colorado does exhibit an urban heat island during the decade from 2000-2009. By finding the average rural and urban temperatures for the Denver metro area the magnitude of the UHI was calculated for the 2000-2009 time period. The strongest UHI, as expected, was found during summer nights although every season revealed there was some form of a UHI present all year long. Looking at historical interpolated temperature surfaces it is possible to see the UHI increasing in extent and magnitude through the decades for some seasons. During spring and fall there does not appear to be a significant pattern indicating the growth of the urban heat island. There did appear to be some error or anomaly in the data collection from the 1920s-1950s due to the large substantially warmer region encompassing the southern portion of the study area.

It was also determined the urban heat island around Denver might be causing a downwind increase in precipitation during the summer months. The increase is not statistically significant, but nonetheless indicates a pattern of increasing rainfall amounts. This can have substantial effects on the agricultural community to the east of Denver and their water usage. The large statistically significant decrease during the winter to the east of the city is too large to be attributed to the UHI alone, but it could be playing a role or amplifying this decrease. The statistically significant results found to the west of Denver indicate this could be caused by error from changes in elevation or movement of the GHCN-D sites. There has been an overall decrease in precipitation for the study region of 4.4%.

6.1 Future Research

The overall decrease in precipitation for the region is reason for future research. In an area that is so heavily dependent on scarce water resources any increase or decrease will trigger changes in water use and allocation strategies. Changes in the historical data collection needs to be looked at to see if any significant changes have been made that could be affecting the readings. It would be helpful to normalize the precipitation data so that the error caused by changes in elevation would no longer be skewing the results. Looking at changes in the number of precipitation events, when during the week the precipitation events occur, raindrop size, diurnal patterns, and intensity of storms should also be considered.

More analysis should be done on the landcover or land use at each of the meteorological stations. Looking closely at the landcover changes at the urban and rural sites rather than using a population category to classify the sites as urban or rural might yield different results as well. Calculating the magnitude of the UHI for each decade could be done as well to see if there has been an increase in the difference between rural and urban sites. This could be done by using the United States Geological Survey's designations for urban and rural landcover.

Using an automobile traverse through the city to measure the urban heat island would be beneficial. This would allow for a more accurate determination of the spatial extent of the UHI. An automobile traverse would also allow for more detail in mapping the range of the magnitude from city center to the suburbs.

Bibliography

2010 TIGER/Line Shapefiles [machine-readable data files]/ prepared by the U.S. Census Bureau, 2012

Aggarwal, R. M., Guhathakurta, S., Grossman-Clarke, S., and Lathey V. (2012), How do variations in Urban Heat Islands in space and time influence household water use? The case of Phoenix, Arizona, *Water Resour. Res*., 48, W06518, doi:10.1029/2011WR010924

Akbari, H., Rosenfeld, A., Taha, H. (1989). Recent developments in heat island studies: technical and policy, *Proc. Workshop on Saving Energy and Reducing Atmospheric Pollution by Controlling Summer Heal Islands*, Berkeley, CA (Feb. 23–24, 1989), pp. 14–20

Akber, A., Al-Awadi, E. and Ghoneim H. (2001). Water resources management in developing countries: A case study from Kuwait. *Integrated Water Resource Management*, ed. M. A. Mariño and S. P. Simonovic, 213–20. International Association of Hydrological Sciences (IAHS) Publication no. 272. Wallingford, Oxfordshire, U.K.: IAHS Press.

Altman, P., Lashof, D., Knowlton, K., Chen, E., Johnson, L., and Kalkstein L., (2012). Killer summer heat: Projected death toll from rising temperatures in America due to climate change. NRDC Issue Brief, May 2012 IB:12-05-C

Balling, R., and Brazel, S. (1987). Recent changes in Phoenix summertime diurnal precipitation patterns. *Theoretical and Applied Climatology*, 38, 50–54.

Balling, R.C. and Gober P. (2007). Climate variability and residential water use in the city of Phoenix, Arizona. *J. Appl. Meteor. Climatol*., 46, 1130–1137.

Basist, A., Bell, G.D, Meentemeyer, V. (1994). Statistical relationships between topography and precipitation patterns. *J. Climate*, 7, 1305–1315. doi: http://dx.doi.org/10.1175/1520-0442(1994)007<1305:SRBTAP>2.0.CO;2

Baumann, P. R. (2009). Urban heat island lesson, *Geocarto International*, 24:6, 473– 483

Berdahl, P. and Bretz, S., (1997). Preliminary survey of the solar reflectance of cool roofing materials. *Energy and Buildings*, 25, 149–158.

Blandford, T. R., Humes, K.S., Harshburger, B.J., Moore, B.C., Walden, V.P., and Hengchun, Y. (2008). Seasonal and synoptic variations in near surface air temperature lapse rates in a mountainous basin. *Journal of Applied Meteorology & Climatology* 47, no. 1: 249 –261

Bornstein, R. and Lin, Q. (2000). Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmos. Environ*. 34:507–516.

Bornstein, R., and LeRoy, M., (1990). Urban barrier effects on convective and frontal thunderstorms. Extended Abstracts, Fourth Conference on Mesoscale Processes, Boulder, CO, *Amer. Meteor. Soc*., 120 –121

Borys, R. D., D. H. Lowenthal, S. A. Cohn, and W. O. J. Brown. (2003). Mountain and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett*. 30.1538, doi:10.1029/2002GL016855.

Borys, R. D., Lowenthal, D. H. and Mitchell, D. L. (2000). The relationships among cloud microphysics, chemistry and precipitation rate in cold mountain clouds. *Atmos. Environ*. 34:2593–2602.

Bouvette, T., J. L. Lambert, and P. B. Bedient, (1982) Revised rainfall frequency analysis for Houston. *Journal of Hydraulic Engineering,* Vol. 109, No. 6, June 1983, pp. 930 –932

Brazel AJ, Selover N.J., Vose RJ, Heisler G.J. (2000) The tale of two climates -- Baltimore and Phoenix urban LTER sites. *Climate Research.* 15:123–135.

Burian, S. J., and J. M. Shepherd, (2005). Effects of urbanization on the diurnal rainfall pattern in Houston: *Hydrological Processes*. 19, 1089–1103.

Changnon, S. A. (1968). The La Porte anomaly: Fact or fiction? *Bulletin of the American Meteorological Society* 49:4–11

Changnon, S. A. (1976). Inadvertent weather modifications. *Water Resourc. Bull*., 12: 695

Changnon, S. A. (1981). METROMEX: A review and summary. *Meteor. Monogr.18*, No. 40, Amer. Meteor. Soc.,

Changnon, S. A., (2003). Urban modification of freezing-rain events. *Journal of Applied Meteorology*, 42(6), 863–870.

Chow, W.T.L. and Brazel, A.J. (2012). Assessing xeriscaping as a sustainable heat island imitigation approach for a desert city. *Build. Environ*., 47: 170–181

Chow, W.T.L., Brenna, D., and Brazel, A.J. (2012). Urban heat island research in Phoenix, Arizona theoretical contributions and policy applications. *Bulletin of the*

American Meteorological Society 93(4): 517–530, doi: http://dx.doi.org/10.1175/BAMS-D-11-00011.1

Chow, W.T.L., Pope, R.L., Martin, C.A., Brazel, A.J. (2011) Observing and modeling the nocturnal park cool island of an arid city: Horizontal and vertical impacts. *Theor. Appl. Climatol*., 103: 197–211, doi:10.1007/s00704-010-0293-8

Cities of the United States. 5th ed. Vol. 2: The West. "Denver: Geography and Climate." Detroit: Gale, 2006. 269. *Gale Virtual Reference Library.* Web. 22 Mar. 2013

Cities of the United States. 5th ed. Vol. 2: The West. "Denver: History." Detroit: Gale, 2006. 269–270. *Gale Virtual Reference Library*. Web. 22 Mar. 2013.

Cotton, W. R., and R. A. Pielke. (1995). Human impacts on weather and climate. Cambridge, U.K.: Cambridge University Press.

Denver Water. Planning for an Uncertain Future. Accessed March 23, 2013 http://www.denverwater.org/SupplyPlanning/DroughtInformation/UncertainFuture/

DeWitt, J., Brennan, M., (2001). Taking the heat. *Imaging Notes* 16 (6), 20–23.

Diem, J. E., and Brown, D.P. (2003). Anthropogenic impacts on summer precipitation in central Arizona, U.S.A. *The Professional Geographer*, 55 (3), 343–355.

Dixon, P. G., and Mote, T. L. (2003). Patterns and causes of Atlanta's urban heat island-initiated precipitation. *Journal of Applied Meteorology*, 42, 1273–1284. doi: http://dx.doi.org/10.1175/1520-0450(2003)042<1273:PACOAU>2.0.CO;2

DRCOG, (2011). *Metro Vision 2035 Plan*. 1–45

Durre, I., M. J. Menne, B. E. Gleason, T. G. Houston, and R. S. Vose, (2010). Comprehensive automated quality assurance of daily surface observations. *Journal of Applied Meteorology and Climatology*, 49, 1615–1633.

El Arabi, N. E. (1999). Problems of groundwater quality related to the urban environment in Greater Cairo. *Impacts of urban growth on surface water and groundwater quality*, ed. J. B. Ellis, 29–37. International Association of Hydrological Sciences (IAHS) Publication no. 259. Wallingford, Oxfordshire, U.K.: IAHS Press

Ellis, A. W., M. L. Hildebrandt, W. M. Thomas, and H. J. S. Fernando. (2000). Analysis of the climatic mechanism contributing to the summertime transport of lower atmospheric ozone across metropolitan Phoenix, Arizona, USA. *Climate Research* 15:13–31

El-Sharif, A. R. (1985). Water supply problems of Riyadh, Saudi Arabia. *GeoJournal* 11:239–43

Elvidge, C. D., C. Milesi, J. B. Dietz, B. T. Tuttle, P. C. Sutton, R. Nemani, and J. E. Vogelmann. (2004). U.S. constructed area approaches the size of Ohio. Eos., *Trans. Amer. Geophys. Union* 85:233.

Esri (2011) What is Empirical Bayesian Kriging? *ArcGIS Help 10.1*

Gallo, K. P. and T. W. Owen. (1999). Satellite-based adjustments for the urban heat island temperature bias. *J. Appl. Meteor*. 38:806–813.

Golden, J.S., D. A. Hartz, A. J. Brazel, G. Luber, and P. Phelan, (2008). A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006. *Int. J. Biometeor*., 52, 471–480

Guhathakurta, S., and P. Gober, (2007). The impact of the Phoenix urban heat island on residential water use. *J. Amer. Plann. Assoc*., 73, 317–329.

Guhathakurta, S., and P. Gober, (2010). Residential land use, the urban heat island, and water use in Phoenix: A path analysis. *J. Plann. Educ. Res.*, 30, 40–51

Harnack, R. P., and H. E. Landsberg. (1975). Selected cases of convective precipitation caused by the metropolitan area of Washington, DC. *Journal of Applied Meteorology*, 14:1050–60.

Hawkins, T.W., Brazel, A.J., Stefanov, W.L., Bigler, W., and Saffell, E.M. (2004). The Role of rural variability in urban heat island determination for Phoenix, Arizona. *J. Appl. Meteor.*, 43, 476–486. doi: http://dx.doi.org/10.1175/1520-0450(2004)043<0476:TRORVI>2.0.CO;2

Hidalgo, H.G. (2004) Climate precursors of multidecadal drought variability in the western United States. *Water Resources Research*, 40 (2004), p. W12504

Hjemfelt, M. R., (1982). Numerical simulation of the effects of St. Louis on mesoscale boundary layer airflow and vertical motion: Simulations of urban vs. non-urban effects. *Journal of Applied Meteorology*, 21, 1239–1257.

Howard, L., (1833). The climate of London. Vol. 1. Harvey and Darton, 348 pp.

Hudson, J. G., and P. R. Frisbie. (1991). Surface cloud condensation nuclei and condensation nuclei measurements at Reno, Nevada. *Atmospheric Environment* 25A:2285–99.

Huff, F. A. and S. A. Changnon. (1972). Climatological assessment of urban effects on precipitation at St. Louis. *J. Appl. Meteor*. 11:823–842.

Huff, F. A. and S. A. Changnon. (1972). Urban effects on daily rainfall distribution. Preprints, *Second National Conf. on Weather Modification*, Santa Barbara, CA, *Amer. Meteor. Soc.*, 215–220.

Huff, F.A. and Changnon, S.A. (1973). Precipitation modification by major urban areas. *Bulletin of the American Meteorlogical Society* 54: 1220–1232

IPCC (2008). Technical Paper of the Intergovernmental Panel on Climate Change and Water [Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof, (eds.)] IPCC Secretariat, Geneva, 210 pp.

Kahn, M. E., (2009). Urban growth and climate change. *Annual Review of Resource Economics,* 1, 333–49

Karamouz, M., S. Torabi, B. Zahraie, S. Araghi-Nejhad, and M. Shahsavari. (2001). An integrated approach to water resources development of the Tehran region in Iran. *Journal of the American Water Resources Association* 37:1301–11.

Karl T.R., Diaz H.F., Kukla G. (1988). Urbanization: its detections and effect in the United States climate record. *Journal of Climate,* 1(11): 1099–1123

Kim, Y-H. and J-J. Baik. (2002). Maximum urban heat island intensity in Seoul. *J. Appl. Meteor.* 41:651–659

Konopacki, S., and Akbari, H. (2000) Energy savings calculations for heat island reduction strategies in Baton Rouge, Sacrameno, and Salt Lake City. ACEEE Summer Study on Energy Efficiency in Buildings, August 2000, Pacific Grove, California

Laaidi, K., Zeghnoun, A., Dousset, B., Bretin, P., Vandentorren, S., Giraudet, E., and Beaudeau, P. (2012). The impact of heat islands on mortality in Paris during the August 2003 heat wave. *Environmental Health Perspectives*, 120(2):254–259

Landsberg, H. E. (1956). The climate of towns. Man's Role in Changing the Face of the Earth, W. L. Thomas, Ed., University of Chicago Press, 584–603.

Landsberg, H.E., (1981). The Urban Climate. *International Geophysics Series,* Vol. 28. New York: Academic Press.

Larson, M. K.. (1986). Potential for subsidence fissuring in the Phoenix, Arizona, USA, area. In Land subsistence, ed. A. I. Johnson, L. Carbognin, and L. Ubertini, 291–99. International Association of Hydrological Sciences (IAHS) Publication no. 151. Wallingford, Oxfordshire, U.K.: IAHS Press.

Loose, T. and R. D. Bornstein. (1977). Observations of mesoscale effects on frontal movement through an urban area. *Monthly Weather Review*. 105:563–571

Lowry, W. (1998) Urban effects on precipitation amount. *Progress in Physical Geography* 22: 477–520

Lukas, J. (2012). Drought and climate change in Colorado: What can we expect? Presentation. Natural Resources Seminar Series from Colorado Mesa University, Grand Junction, CO, October 8, 2012

Mahoney, K., Alexander, M.A., Thompson, G., Barsugli , J.J., and Scott, J.D. (2012). Changes in hail and flood risk in high-resolution simulations over Colorado's mountains. *Nature Climate Change*, 2, 125–131 doi:10.1038/nclimate1344

Malevich, S.B., and Klink, K., (2011). Relationships between snow and the wintertime Minneapolis urban heat island. Journal of Applied Meteorology and Climatology 50 (9): 1884

McKee, T.B., Doesken, N.J., Kleist, J., Shrier, C.J., Stanton, W.P., (2000). A history of drought in Colorado: Lessons learned and what lies ahead. *Water in the Balance* Report No. 9

Menne, Matthew J., Imke Durre, Russell S. Vose, Byron E. Gleason, Tamara G. Houston, (2012) An overview of the global historical climatology network-daily database. *J. Atmos. Oceanic Techn*ol., 29, 897–910. doi: http://dx.doi.org/10.1175/JTECH-D-11-00103.1

Mills, G., (2008). Luke Howard and the climate of London. *Weather* 63(6): 153–157

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia, (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438, 347–350.

Minder, J., Mote, P., and Lundquist, J. (2010). Surface temperature lapse rates over complex terrain: Lessons from the Cascade Mountains. *Journal of Geophysical Research*. 115:14

Mitchell, J.M. (1961). The temperature of cities. *Weatherwise*, 14: 224–229

Modaihsh, A. S. (1997). Characteristics and composition of the falling dust sediments on Riyadh City, Saudi Arabia. *Journal of Arid Environments* 36:211–23

Molders, N. and M. A. Olson. (2004). Impact of urban effects on precipitation in high latitudes. *J. Hydrometeor*. 5:409–429.

Myrup, L.O. (1969) A numerical model of the urban heat island. *Journal of Applied Meteorology* 8: 908–918

Oke, T. R. (1987). *Boundary Layer Climates.* 2d ed. Routledge, 435 pp

Oke, T.R. (1973). City size and the urban heat island. *Atmospheric Environment*, 7:769–779

Orville, R. E., G. R. Huffines, J. Nielsen-Gammon, R. Zhang, B. Ely, S. Steiger, S. Phillips, S. Allen, and W. Read, (2001) Enhancement of cloud-to-ground lightning over Houston, Texas. *Geophys. Res. Lett*., 28, 2597–2600.

Parton, W.J., Gutman, M.P., Travis, W.R. (2003). Sustainability and historical land-use change in the great plains: The case of eastern Colorado. *Great Plains Research* 13:97–125

Peng, R.D., Bobb, L.F., Tebaldi, C., McDaniel, L., Bell, M.L., and Dominici, F. (2011). Toward a quantitative estimate of future heat wave mortality under global climate change. *Environ. Health Perspect*. 119: 701–706

Peterson T.C., Vose R.S. (1997). An overview of the global historical climatology network database. *Bull Am Meteorol Soc* 78:2837–2849

Peterson T.C., Vose R.S., Razuvaev V.N., Schmoyer R.L. (1998). GHCN quality control of monthly climate data. *Int J Climatol* 18:1169–1179

Piechota, T. Timilsena, J., Tootle, G., Hidalgo, H., (2004). The western US drought: how bad is it? *Eos* 85 (32) 301–304

Pielke Sr., R. A., J. Nielsen-Gammon, C. Davey, J. Angel, O. Bliss, N. Doesken, M. Cai, S. Fall, D. Niyogi, K. Gallo, R. Hale, K. G. Hubbard, X. Lin, H. Li, and S. Raman, (2007) Documentation of uncertainties and biases associated with surface temperature measurement sites for climate change assessment. *Bull. Amer. Meteor. Soc*., 88, 913–928.

Pielke Sr., R. A., T. Stohlgren, L. Schell, W. Parton, N. Doesken, K. Redmond, J. Moeny, T. McKee, and T. G. F. Kittel, (2002). Problems in evaluating regional and local trends in temperature: An example from eastern Colorado, USA. *Int. J. Climatol*., 22, 421–434.

Principal Investigators of Project METROMEX. (1976). METROMEX update. *Bull Amer Meteorol Soc*, 57: 304–308

Pulwarty, R., K. Jacobs, and R. Dole, (2005). The hardest working river: Drought and critical water problems on the Colorado. *Drought and Water Crises: Science, Technology and Management*, D. Wilhite, Ed., Taylor and Francis Press, Boca Raton, FL, pp. 249–285

Quattrochi, D. A. and Luvall, J. C. (2006) The Need for High Spatial Resolution Multispectral Thermal Remote Sensing Data In Urban Heat Island Research. *American Geophysical Union*, Fall Meeting 2006, abstract #H31G-04

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld. (2001). Aerosols, climate, and the hydrological cycle. *Science* 294:2119–2124.

Raufer, R. K. (1997). Particulate and lead air pollution control in Cairo: Benefits valuation and cost-effective control strategies. *Natural Resources Forum* 21: 209–19

Ray, A., Barsugli, J., and Averyt, K. (2008). Climate change in colorado: a synthesis to support water resources management and adaptation. Boulder, Colorado, *CU-NOAA Western Water Assessment*

Robaa, S. M. (2003). Urban-suburban/rural differences over Greater Cairo, Egypt. *Atmosfera* 16:3. 157–171.

Rose, L. S., Stallins, J. A., and Bentley, M. L. (2008): Concurrent cloud-to-ground lightning and precipitation enhancement in the Atlanta, Georgia (United States), Urban Region. *Earth Interactions*, 12(11) 1–30

Rosenberger, M. S., and P. W. Suckling. (1989). Precipitation climatology in the Pittsburgh urban area during late spring and summer. *Southeastern Geographer* 29:75–91

Rosenfeld, D. (1999). TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett*. 26:3105–3108.

Rosenfeld, D. (2000). Suppression of rain and snow by urban air pollution. *Science* 287:1793–1796.

Rozoff, C., W. R. Cotton, and J. O. Adegoke, (2003): Simulation of St. Louis, Missouri, land use impacts on thunderstorms. *Journal of Applied Meteorology*, 42, 716–738.

Sanderson, M., and R. Gorski. (1978). The effect of metropolitan Detroit on precipitation. *Journal of Applied Meteorology* 17:423–27.

Shahmohamadi, P., A. I. Che-Ani, K. N. A. Maulud, N. M. Tawil, and N. A. G. Abdullah. (2011). the impact of anthropogenic heat on formation of urban heat island and energy consumption balance, *Urban Studies Research*, vol. 2011, 2011. doi:10.1155/2011/497524

Shaqour, F. (1994). Hydrogeologic role in sinkhole development in the desert of Kuwait. *Environmental Geology* 23:201–8.

Shepherd, J. M. and S. J. Burian. (2003). Detection of urban-induced rainfall anomalies in a major coastal city. *Earth Interactions* 7. [Available online at http://EarthInteractions.org].

Shepherd, J. M., H. Pierce, and A. J. Negri. (2002). Rainfall modification by major urban areas: Observations from spaceborne rain radar on the TRMM satellite. *J. Appl. Meteor*. 41:689–701.

Shepherd, J.M. (2005a): A review of current investigations of urban-induced rainfall and recommendations for the future. *Earth Interactions*. 9(12) 1–26

Shepherd, J.M. (2005b) Making rain: Do cities impact precipitation? *Weatherwise* 58(5)

Shepherd, J.M., (2006): Evidence of urban-induced precipitation variability in arid climate regimes. *Journal of Arid Environments*. 67, 607–628

Sohrabpour, M., M. Athari, H. Mirzaee, and S. Rostami. (1999). Elemental concentration of the suspended particulate matter in the air of Tehran. *Environment International* 25:75–81

Stewart, I. D., T. R. Oke, (2012). Local Climate Zones for Urban Temperature Studies. *Bull. Amer. Meteor. Soc.*, 93, 1879–1900. doi: http://dx.doi.org/10.1175/BAMS-D-11-00019.1

Summit Economics and The Adams Group. (2009). Water and the Colorado Economy.

Taha, H. (1988) Site-specific heat island simulations: Model development and application to microclimate conditions. LBL Report No. 26105 M. Geogr. Thesis University of California

Taha, H. (1997a). Modeling the impacts of large scale albedo changes on ozone air quality in the South Coast Air Basin, *Atmos. Environ*. 31(11): 1667–1676; also available as Rep. No. LBL-36890 Lawrence Berkeley National Laboratory, Berkeley, CA

Taha, H. (1997b). Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings* 25(2):99–103

Taha, H., Akbari, H., Rosenfeld A., (1989) Vegetation microclimate measurements: the Davis project. Lawrence Berkeley Lab. Rep., 24593

Taha, H., Akbari, H., Rosenfeld A., (1991). Heat island and oasis effects of vegetative canopies: Micrometeorlogical field measurements. *Theor. Appl. Climat*., 44:123

Taha, H., D. Sailor, H. Akbari (1992) High albedo materials for reducing cooling energy use. Berkeley, CA Lawrence Berkeley Lab. Rep. 31721 UC-350

Taha, H., H. Akbari, D. Sailor, R. Ritschard (1992). Causes and effects of heat islands: sensitivity to surface parameters and anthropogenic. Berkeley CA Lawrence Berkeley Lab. Rep. 29864

Tayanç, M., M. Karaca, and O. Yenigün. (1997). Annual and seasonal air temperature trend patterns of climate change and urbanization effects in relation to air pollutants in Turkey. *J. Geophys. Res*. 102:D2. 1909–1920.

Thielen, J., W. Wobrock, A. Gadian, P. G. Mestayer, and J-D. Creutin. (2000). The possible influence of urban surfaces on rainfall development: A sensitivity study in 2D in the meso-gamma scale. *Atmos. Res*. 54:15–39.

Thurow, C. (1983). Improving street climate through urban design. *American Planning Association*

Trenberth, K.E., (1983): What are the Seasons? *Bull. Amer. Meteor. Soc*., 64, 1276–1282. doi: http://dx.doi.org/10.1175/1520-477(1983)064<1276:WATS>2.0.CO;2

U.S. Census Bureau (2010). 2010 Census Urban Area Facts. Accessed April 16, 2013 http://www.census.gov/geo/reference/ua/uafacts.html

U.S. Census Bureau (2010). Table 2. Annual Estimates of the Population of Combined Statistical Areas: April 1, 2000 to July 1, 2009 (CBSA-EST2009-02), Source: U.S. Census Bureau, Population Division

United Nations Department of Economic and Social Affairs/Population Division (UNDESA), (2012). World Urbanization Prospects: The 2011 Revision. United Nations Publication ESA/WP/224

Willmott, C. J., and Matsuura, K. (1995). Smart interpolation of annually averaged air temperature in the United States. Journal of Applied Meteorology 34:2577– 2586.