



# CLIMATE IN THE HEARTLAND

HISTORICAL DATA AND FUTURE PROJECTIONS FOR THE HEARTLAND REGIONAL NETWORK

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# Climate in the Heartland: Historical Data and Future Projections for the Heartland Regional Network

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## 1 Introduction

In recent decades, cities in the Great Plains have confronted an increasing frequency of extreme and damaging weather events. Historical climate patterns are changing, with hotter temperatures, exceptional floods and droughts, and erratic weather events. These factors affect city governments' ability to maintain normal daily operations and meet citizens' needs.

Weather has always affected municipal government operations. Heavy rainfall and floods, for example, have impacts that ripple across departments. Police and fire departments experience an increase in call volume, accompanied by decreased access throughout the city and more hazardous working conditions. Public infrastructure is at risk of damage, and water treatment facilities must deal with poorer water quality. Solid waste operations must process greater quantities of debris, and services such as public transportation can be disrupted. Other hazardous weather events, such as tornadoes, wind, hail, drought, heat waves, and winter storms come with their own range of impacts.

Over the past century, governments evolved to their environmental contexts, establishing policies, procedures, organizational structures, and budget allocations adaptive to their particular climate conditions. In recent years, as weather anomalies have become more frequent, governments have had to work harder and smarter to fulfill their routine obligations while responding to an increasing number of weather disasters. A recent spate of 100- and even 500-year floods in Great Plains cities has left governments scrambling to protect public safety in the short term and rebuild and repair infrastructure and facilities in the long term.

Yet, despite the effects already felt by many communities, some of the expected impacts of climate change have not yet emerged. Therefore, there is a need to evaluate historical and recent climate data and future climate change projections so that cities have sufficient opportunity to prepare for a changing climate in their strategic and operational planning.

While some work has been done to examine projected climate change impacts regionally, existing information is insufficient for municipal planning purposes for two reasons. First, the information is not specific enough. Most data are regional – applicable, for example, to the Midwest or the southern Great Plains. While there are commonalities across regions, climate change will vary among localities, and cities need data specific to their communities. Second, the existing data is generally conveyed in terms of metrics that are intended for meteorologists rather than local governments. There is a need for metrics that will help government departments plan for issues such as infrastructure or staffing needs. The present report begins to fill this gap.

The goal of this report is to assist participating cities as they prepare for climate change impacts, adapting their operations to better serve citizens in a changing environment. Historical climate data and future climate projections are provided to each city to inform municipal staff and elected officials of weather conditions that are anticipated to exceed historical bounds. Climate data are expressed in terms that are applicable to municipal leadership and management.

## 1.1 Participating Cities

Participating cities are all members of the Heartland Regional Network of the Urban Sustainability Directors Network (USDN) and include:

- Iowa City, IA
- Columbia, MO
- Lincoln, NE
- Lawrence, KS
- Oklahoma City, OK

## 1.2 Partnerships

This project was a partnership between municipal sustainability directors, state climatologists, and other experts in climate science, with work contracted to consultants for data analysis and report preparation. Participants in the project include the following people.

### Sustainability Directors

- Brenda Nations, Iowa City, IA
- Barbara Buffaloe, Columbia, MO
- Milo Mumgaard, Lincoln, NE
- Eileen Horn, Lawrence, KS
- T.O. Bowman, Oklahoma City, OK

### State Climatologists and Climate Scientists

- Gary McManus, State Climatologist, Oklahoma Climatological Survey
- Margret Boone, Program Manager, Oklahoma Climatological Survey
- Patrick E. Guinan, Missouri State Climatologist, University of Missouri
- Mary Knapp, Service Climatologist, Kansas State University
- Martha D. Shulski, Director, High Plains Climate Center, University of Nebraska
- Eugene S. Takle, Director, ISU Climate Science Program, Iowa State University

### Consultants

- Chris Anderson, Assistant Director, ISU Climate Science Program, Iowa State University
- Jennifer Gooden, Environmental and Sustainability Consultant

## 1.3 Funding

This project was made possible by the Urban Sustainability Directors Network (USDN), which provided funding for a Regional Network Collaboration Project. USDN funding paid for a 1.5-day collaboration workshop in Iowa City, IA, in November 2014, during which state climatologists, climate scientists, and local government sustainability directors met to determine which data were useful to governments needed and available from climate scientists. The funding also covered personnel costs for the principal investigator for 1.5 months and a sustainability consultant for 1.25 weeks.

## 2 Methods

### 2.1 Introduction to Methods

This project was designed to supplement existing climate change data for the Heartland Regional Network area. Resources such as the National Climate Assessment (NCA) (Walsh and Wuebbles 2014) provide information about future impacts expected across regions of the United States. The NCA and other projects utilize global climate models (GCMs), which employ advanced computer modeling techniques provided with scenarios of global human greenhouse gas emissions (Nakićenović et al. 2000) to project future atmospheric conditions based on known factors and a variety of variables. While useful for discerning trends over broad areas, GCMs do not provide sufficiently localized data for municipal planning. For example, in the NCA, projections are regionalized to the northern Great Plains and southern Great Plains, with little data available at a finer grain. In addition, global-scale scenarios are developed from societal variables to which the GCMs respond. Scenarios are generally based on those adopted by the Intergovernmental Panel on Climate Change (Nakićenović et al. 2000), a program of the World Meteorological Organization and the United Nations Environment Program. These allow models to be adjusted based on different scenarios for factors such as future international policy collaboration and carbon emissions. Results from each model are applicable when the scenario is applicable.

The present project utilized GCMs but applied two additional techniques to make the data more usable for local governments. First, the project used not just one but nine GCMs, averaging results together. This means that the data are an average of different models and different scenarios, allowing climate scientists to identify signals that are strongest across a range of circumstances. The process used here is based on work done by Hayhoe (2014), which utilizes methods that are transparent and publicly accessible. Second, the present project uses a technique known as downscaling, which allows climate projections to be obtained from GCMs at a finer-grained, local scale (Stoner et al. 2013). More information about the modeling process used in this report is included in the Discussion.

### 2.2 Climate Metrics

Because the production of localized data for government planning is a new activity, output metrics were selected before extracting data from climate models output archives. These metrics were decided upon at a 1.5-day meeting of local government sustainability directors, university climate scientists, and state climatologists in November 2014. At this meeting, government directors described what types of data would be useful for planning purposes, and climate scientists described what was feasible with available data. It was determined that the following factors would be reported.

#### Climate Metrics Reported

Climate Condition	Climate Metric	Municipal Concern
<b>Annual and Seasonal Temperature</b>	Average, maximum, and minimum temperatures	General climate conditions
<b>Annual and Seasonal Precipitation</b>	Average rainfall	General climate conditions
<b>Last Spring Frost and First Fall Frost</b>	Dates when minimum temperature is less than 32°F	Parks and recreation; employees working outdoors; insect vectors
<b>Heat Waves</b>	Average, maximum, and minimum temperatures over a the hottest 3-day time period each year	Energy demand; public health
<b>Cold Waves</b>	Minimum temperature over the coldest 3-day time period each year	Energy demand; public health
<b>Heavy Rainfall</b>	Days with rainfall >1.25" Days with rainfall >4.00" Amount of rainfall in wettest 5-day period Amount of rainfall in wettest 15-day period	Stormwater management; floodplain planning; emergency response; infrastructure design
<b>Snowstorms</b>	Days with snowfall >3.0" Days with snowfall >6.0" Days with snowfall >12.0" Amount of snowfall in heaviest 3-day period	Snow and ice management; public safety; electricity and phone service outages
<b>Thaw/Freeze Cycles</b>	Days with temperatures >45°F followed by days <28°F	Street repair; parks and recreation; urban forest management

Climate metrics are further defined in Appendix B: Climate Metrics and Definition of Terms.

Some of the climate metrics for this report are not part of the standard data products provided by state climatologists or regional climate centers. To fill the void, university climate scientists developed analysis procedures in R code (open source statistical analysis software) and applied procedures to station data provided by state climatologists. The R code may be integrated into existing analyses by state climatologists and regional climate centers. State climatologists were welcomed to perform the analysis with their own software as well. The outcomes of the analysis procedure were data plots and data tables that were shared with the state climatologists who used the outputs as guidance in preparing historical climate variability narratives.

With climate metrics, special attention was given to whether future projected climate metrics fall outside the historical range. This determination was made by calculating the 10<sup>th</sup> percentile and 90<sup>th</sup> percentile values of the historical record. The future projection was determined to be outside the normal historical range if its value fell below the 10<sup>th</sup> percentile or above the 90<sup>th</sup> percentile. Throughout this report, projections such as these are described as outside the normal historical range or above the most extreme years (i.e., hottest, coldest, wettest, driest, etc.) of the historical record.

### 2.3 Historical Summaries

In each participating state, the state climatologist and/or his or her affiliates participated in this project by providing a narrative description of historical climate data for both the city's official weather station and the climate division in which the city is located. For each city, the official weather station is shown on a map and identified by latitude and longitude.

In this report, any disparities between station and climate division data are noted in the historical climate variability summaries.

Some damaging weather events were excluded from this analysis, if, for example, the historical data were unreliably collected (e.g., tornado, wind, and hail), historical data were collected over a very short period of time (e.g., radar estimates of hourly rainfall), or climate change projection data are not yet possible for these damaging weather events (e.g., tornado). Tornado projections are particularly difficult to determine because human-caused climate change may not affect all factors that cause a tornado. For instance, among other factors, a storm's intensity is affected by humidity and wind shear, which is the change in wind direction and speed with height of the storm that is often present when a tornado forms. Humidity is expected to increase, which will elevate thunderstorms' intensity, but it is not known if wind shear in thunderstorms will be affected.

#### **Station Data**

A representative weather station was selected for each municipality by the state climatologist. The quality of the station reports depends on the length of the station data series, with longer series capturing more variability; the extent to which the station has remained in one place and its immediate surroundings have remained unchanged; and regular maintenance of the weather station. State climatologists are responsible for climate data collection and data quality control and have a complete record of the station location and maintenance history, making them the best resource for determining the quality of station weather data. [See Discussion for more information about considerations in dataset selection.]

#### **Climate Division Data**

Because weather stations represent a single location, station data sometimes include isolated and rare damaging weather events not experienced widely in the area. Examining the context beyond the immediate city prevents interpretation of isolated events as broader changes in climate conditions. The best scale for looking at area context is the city's climate division, as this unit ensures that local anomalies are not overgeneralized yet avoids inclusion of climate variability across larger regions. Climate divisions were first established in the 1940s by the United States Weather Bureau and were aligned either by crop district or drainage basin. The data are aggregated over many weather stations within a climate division. Climate division data have been used by the National Climatic Data Center to assess large-scale climate change with respect to a long period of record. Climate division data are used for all cities in this report except Columbia, as addressed in that section.

### 2.4 Climate Projection Summaries

Climate change projection summaries were produced by climate scientists at Iowa State University utilizing data from the Coupled Model Intercomparison Project 3 (CMIP3), an internationally organized standard experimental protocol for studying the global climate's response to anthropogenic greenhouse gas increases. The CMIP3 was the basis for the Intergovernmental Panel on Climate Change Assessment Review 4, released in 2007. Our data products utilize nine global climate models (CCSM3, CGCM3, CNRM, ECHAM5, ECHO, GFDL2.1, HadCM3, HadGEM, and PCM), producing simulations of climate response to multiple specified future greenhouse gas emissions scenarios. Three scenarios were used for this study, reflecting different levels of international cooperation on emissions reduction resulting in scenarios with emissions rates that have moderate reductions (Scenario A1B), little to no reductions (A2), and increases (A1FI). The projections, therefore, detect signals that are robust across various circumstances.



In order to provide downscaled projections, the CMIP3 output was downscaled to stations with long-term weather reports using the Asynchronous Regional Regression Model as described in Stoner et al. (2013). This approach was recently used as the basis for a downscaled climate model data for the City of Austin, TX, on which the present study was partially based. The primary methodological difference is that Hayhoe (2014) used CMIP5 CGM data, which were the basis for the Intergovernmental Panel on Climate Change Assessment Review 5, released in 2013. The downscaled data from CMIP5 were constructed specifically for the Austin report and were not available in the Midwest. However, the CMIP3 data have not been determined to be of lower quality than CMIP5.<sup>1</sup>

Output data were summarized over two future 30-year periods, 2021-2050 and 2051-2080. Tabular summaries were distributed to state climatologists for review. Note that many of the figures showing climate change projections include data for three time periods: 1981-2010, 2021-2050, and 2051-2080. Data for 1981-2010 are actual recorded values, while data for 2021-2050 and 2051-2080 are the output of climate model projections. The broader data ranges for 1981-2010 values, compared to the others, are an artifact of the different data sources.

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<sup>1</sup> The upper bound emissions scenarios used in this report (CMIP3 A1FI) and Austin's report (CMIP5 RCP8.5) are very similar. The main difference between the reports is the lower bound of the emissions scenario in the Austin report (CMIP5 RCP4.5) is much lower than this report's lower bound (CMIP3 A1B). The CMIP5 RCP4.5 scenario is an aggressive carbon reduction scenario that assumes stabilization of emissions by 2050 and reduction thereafter, requiring substantial international cooperation that does not yet exist. The CMIP3 A1B scenario assumes less international collaboration, with emissions stabilization near 2100.

### 3 Results

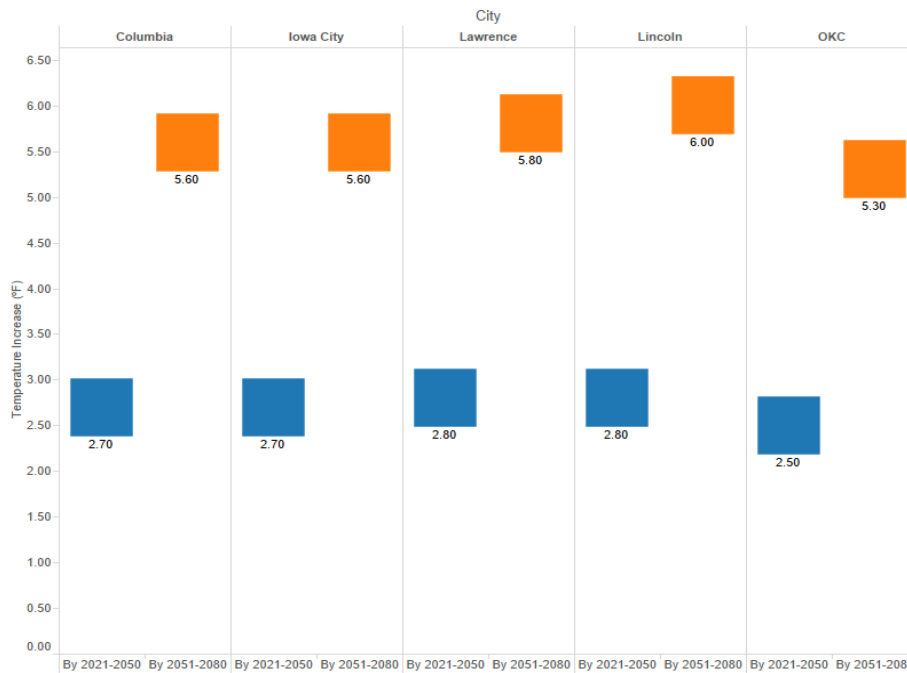
Results common to the region are presented first, followed by results specific to each municipality.

#### 3.1 Regional similarities

Similarities among the municipalities point to planning concerns that may benefit from broad alliances in the region. Historical and projected changes common throughout the region are discussed below.

- *Annual temperature* is projected to increase substantially for each municipality. For every city in the study, the 30-year average annual temperature in 2051-2080 is projected to exceed all but the hottest years from 1981-2010, and some cities will exceed this threshold by 2021-2050. This means that the average temperature in most future years will be higher than extremes that have recently occurred on average only once per decade.
- *Spring temperature* has increased in recent years in all municipalities. It is projected to increase further, in many cases at a rate in excess of recent change, and in many municipalities it will exceed all but the hottest spring temperatures on the historical record.
- *Summer temperature* has increased in many municipalities, with Columbia and Lawrence being the exceptions. In all municipalities it is projected to increase and exceed the top 10% of hottest summer temperatures on record.
- *Date of last frost in spring* has already shifted earlier in all municipalities except Lincoln. In all municipalities, the future projection data show an earlier date for the typical last frost in spring.
- *Date of first frost in fall* has shifted later in all municipalities, with the exception of Columbia and Lincoln. In all municipalities, future projection data show later date for first frost in fall.
- *Hottest 3-day maximum temperature* and *hottest 3-day minimum temperature* are projected to increase substantially for each municipality, indicating more extreme heat waves. However, cities' experiences in recent years show little commonality.
- *Spring precipitation* has increased recently in all municipalities except Oklahoma City. In the future, it is projected to increase in all municipalities except Oklahoma City.
- *Excessive daily rainfall* is projected to increase substantially in Iowa City, Columbia, and Lawrence, but recent historical increase is evident only in Iowa City and Columbia.

Temperature Increases from 1981-2010 Annual Averages

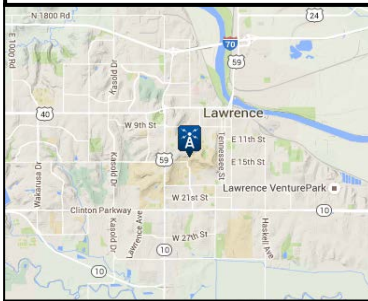


#### 3.2 Results for each city

The following sections describe the results of the present research for each of the participating municipalities.

## 7 Lawrence, Kansas

Figure KS1



Lawrence station location is indicated by radio tower symbol.  
Global Historical Climate Network ID USC0014459 (38.9583°N, -92.2513°W); [Source](#).

Recent change has been observed in summer warming, particularly at night, and warmer and wetter spring seasons. In recent years, summer rainfall has been volatile, with heavy precipitation in the 1990s followed by very low precipitation in the 2000s. Looking forward, climate change projections show the emergence of a substantial increase in temperature. At the projected rate, beyond the next decade, the average annual temperature will exceed the hottest years in the normal historical temperature range. Temperature is projected to increase several degrees during winter, spring, and summer, especially during heat waves. Projections of rainfall show continued increase in spring and winter but indicate no clear pattern for summer.

### 7.1 Historical Climate Variability

Lawrence is in a sub-humid continental climate zone, described as temperate with extremes of heat, cold, and precipitation.

The climate station in Lawrence is located [add location]. It has a period of record from 1890 to present and has been located with a similar exposure through the period. Since 1980, Lawrence has had annual high, low, and average temperature of 66.4°F, 46.2°F, and 56.3°F, respectively. Annual average rainfall and snowfall have been 38.80" and 17.0", respectively. Monthly temperatures reach their maximum in July with an average of 90°F and minimum in January at

20°F. Monthly rainfall peaks in June with 5.16" and is driest in January with 1.06" of precipitation. The record daily temperatures range over 139°F, from -25°F to 114°F, and maximum daily rainfall is 7.23". Lawrence accumulates on average 4,864 heating degree days and 1,155 cooling degree days per year.

### 7.2 Recent Weather Changes

In recent years, Lawrence has experienced seasonal changes in weather. These changes are summarized in the following table.

Recent Changes in Seasonal Weather

Season	Recent Changes
<b>Summer</b>	Fewer cool summers and more frequent hot summers due to higher minimum temperatures More frequent warm nights
<b>Fall</b>	Mixed temperature pattern; drier weather Average date of first frost is 9 days later
<b>Winter</b>	Milder winters with fewer sub-zero days
<b>Spring</b>	Increase in mild and wet springs April freeze more frequently occurs after a mild February and March

In addition, the last three decades have seen changes in the frequency of hazardous weather events. These changes are summarized in the following table.

Recent Changes in Damaging Events

Damaging Event	Recent Changes
<b>Heat Waves</b>	Higher average temperature and average minimum temperature in hottest 3-day period
<b>Cold Waves</b>	Higher average minimum temperatures in coldest 3-day period Fewer sub-zero temperatures
<b>Heavy Rainfall</b>	More years with frequent high intensity rainfall (8 days or more with >1.25"/day) Higher frequency of unusually high rainfall over wettest 5-day period (>6.28") Higher frequency of unusually high rainfall over wettest 15-day period (>10.25")
<b>Late/Early Freeze</b>	Likelihood unchanged, but complicated by warm spring temperatures
<b>Tornado, Wind, Hail</b>	Inconsistencies in reporting are more pronounced than long-term changes in frequency

### 7.3 Historical Context

To identify recent changes in weather, data from the past three decades were compared to the previous historical record. Here, the past three decades are generally defined as 1981-2010, though more recent data are incorporated into the analysis when available.

Temperature change has been uneven in Lawrence. Change has been most pronounced during the winter, with the 1981-2010 mean temperature being 1.2°F warmer than the 1890-1980 average. However, this increase is due to the increase in the low (nighttime) temperatures rather than the high temperatures, which have actually been 0.7°F cooler in winter, on average. There are also fewer days with sub-zero temperatures.

The average summer temperature for 1981-2010 is 0.6°F higher than the 1890-1980 average. More warm summers have occurred, and cool summers are not as common. In last 30 years, Lawrence has experienced four of the 10 hottest summers dating to 1893, but none of the 10 coolest summers. Like winter, summer temperature increase is primarily due to an increase in minimum rather than maximum summer temperature. Five of the 10 warmest average minimum temperatures have occurred since 1981, while only two of the average maximum temperatures rank in the top 10 warmest.

While spring temperatures are higher, fall temperatures are slightly cooler. However, year-to-year variability of temperature for these transition seasons is much larger than summer. One of the potential problems from this pattern is a mild spring coupled with a typical last spring freeze date. This causes vegetation to break dormancy early when it is more vulnerable to freeze damage.

#### Historic Temperature with Trendline

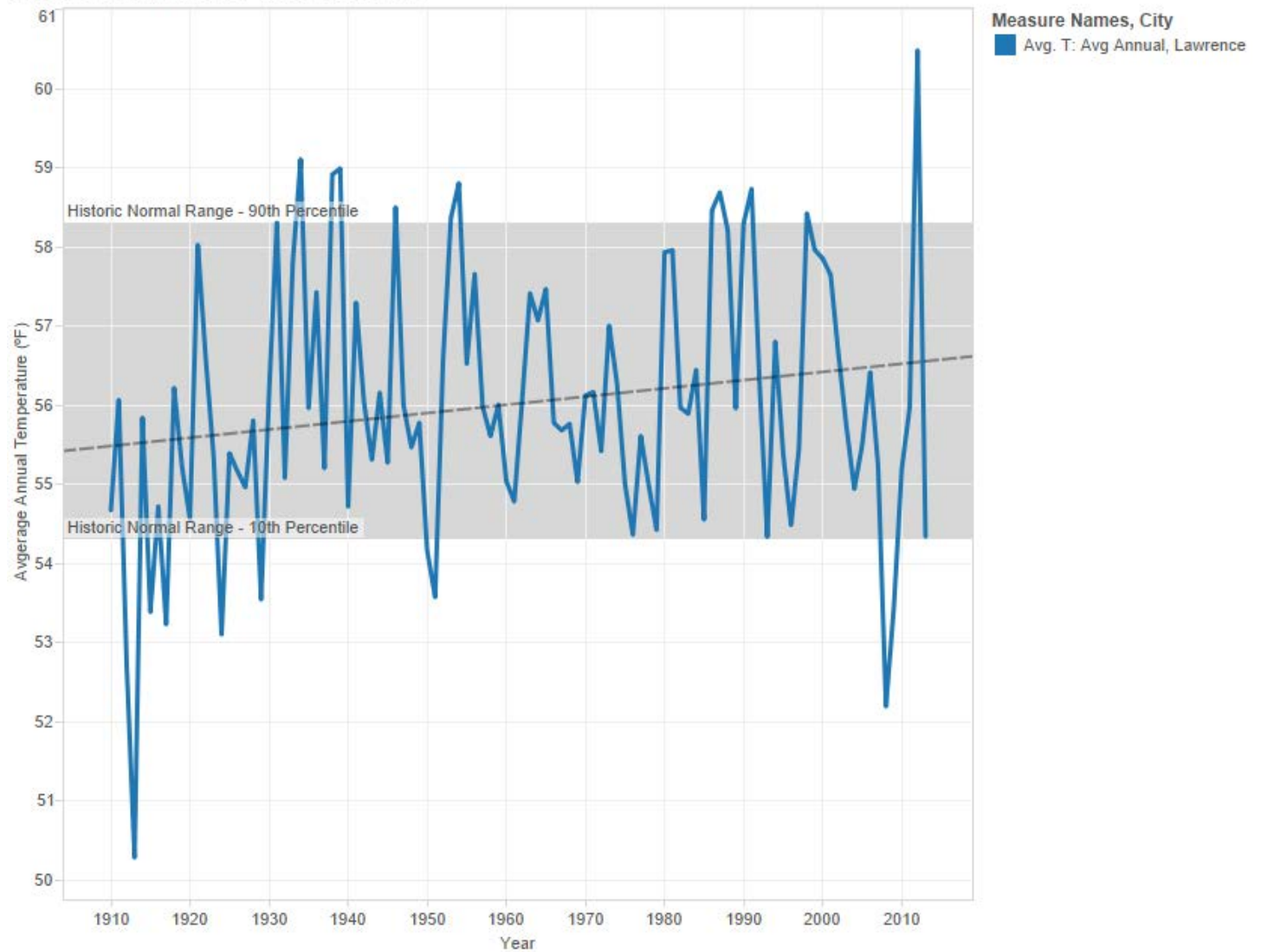


Figure KS2. Recorded annual average precipitation with trendline.

Heating degree days have decreased substantially due to recent increase in winter temperatures, and cooling degree days have increased slightly due to recent increase in spring temperatures. This has implications in future energy demands, as seasonal demand peaks shift.

Spring and fall freeze dates have also changed. Compared to 1890-1980, in 1981-2010 the last day in spring with low temperature  $<32^{\circ}\text{F}$  was one week earlier, and, in fall, the first day with low temperature  $<32^{\circ}\text{F}$  was one week later. However, the spring freeze date in the last few years has occurred much later in the spring than the average date. This is a clear reminder that the volatility of daily spring temperature is larger than the volatility of spring season temperature averages and is large enough that any single year can be substantially different from the average of recent years.

Rainfall change is pronounced in daily and extreme multi-day to seasonal rainfall. Frequency of wet spring and number of wet days per year are higher. The average number of days with rainfall  $>1.25''$  has not substantially changed. However, in the recent 30-yr period, Lawrence has experienced 4 of the top 10 years for number of days  $> 1.25''$ .

Precipitation trends in Lawrence have shown increased rainfall. Frequencies of wet spring seasons and overall number of wet days per year is higher. The 1985-2014 period averaged 13% more days with rainfall  $\geq 1.25''$  compared to the 1890-1984 period. Moreover, there has been a 40% increase in events  $\geq 2.00''$  and 118% increase for  $\geq 3.00''$ . The frequency of 5-day and 15-day periods with unusually high rainfall ( $\geq 6.25''$  and  $\geq 9.0''$ , respectively) has also increased over the past few decades, compared to the long-term trend.

Historic Precipitation with Trendline

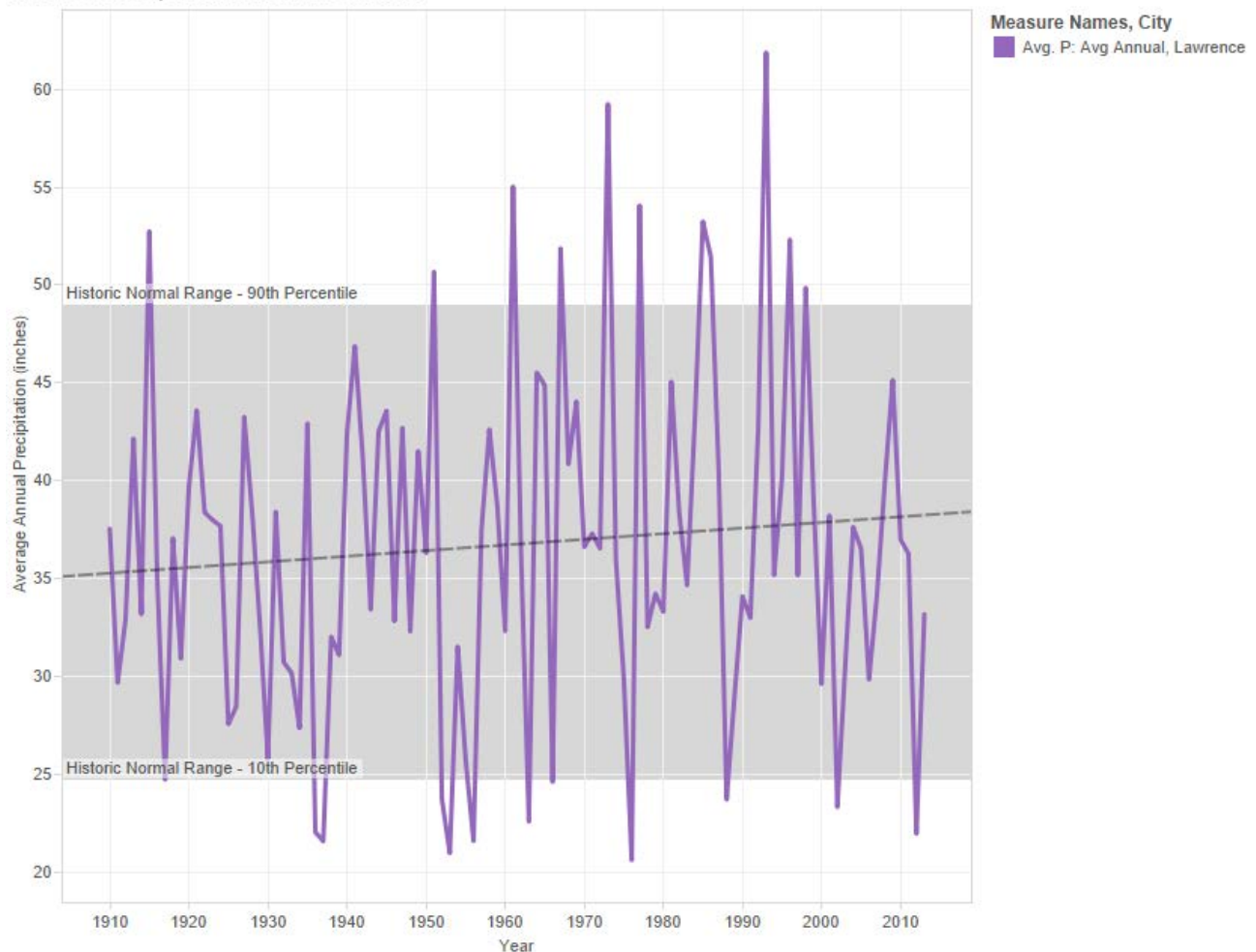


Figure KS3. Recorded annual average precipitation with trendline.

The average annual maximum of 5-day and 15-day rainfall events has increased slightly. In addition, for both accumulation periods, the frequency of rainfall events at or above the 90<sup>th</sup> percentile has increased. This is significant because it is not single-day maximum rainfall creates high stream flow events, but rather the increase in the total amounts during multi-day events.

## 7.4 Area Context

Lawrence is located in the East Central Kansas Climate Division (CD6), and records show there is little difference between the climate in Lawrence and the surrounding area. In both cases, precipitation has been higher in all seasons, with the greatest increase in the spring months. There are some slight differences in January and February, where the division data had higher precipitation totals during these months, while recent trends in Lawrence showed lower precipitation totals in January and February. No division data are available for snowfall, but in Lawrence the pattern appears to be inconsistent. Overall the 1981-2010 period averages less total snow by month and by year. However, this average is made up of extremes: seasons with little snow followed by heavy snow events. While 10 of the 15 years with lowest snowfall have occurred since 1980, six of the 15 snowiest seasons have also occurred since that date.

# Kansas

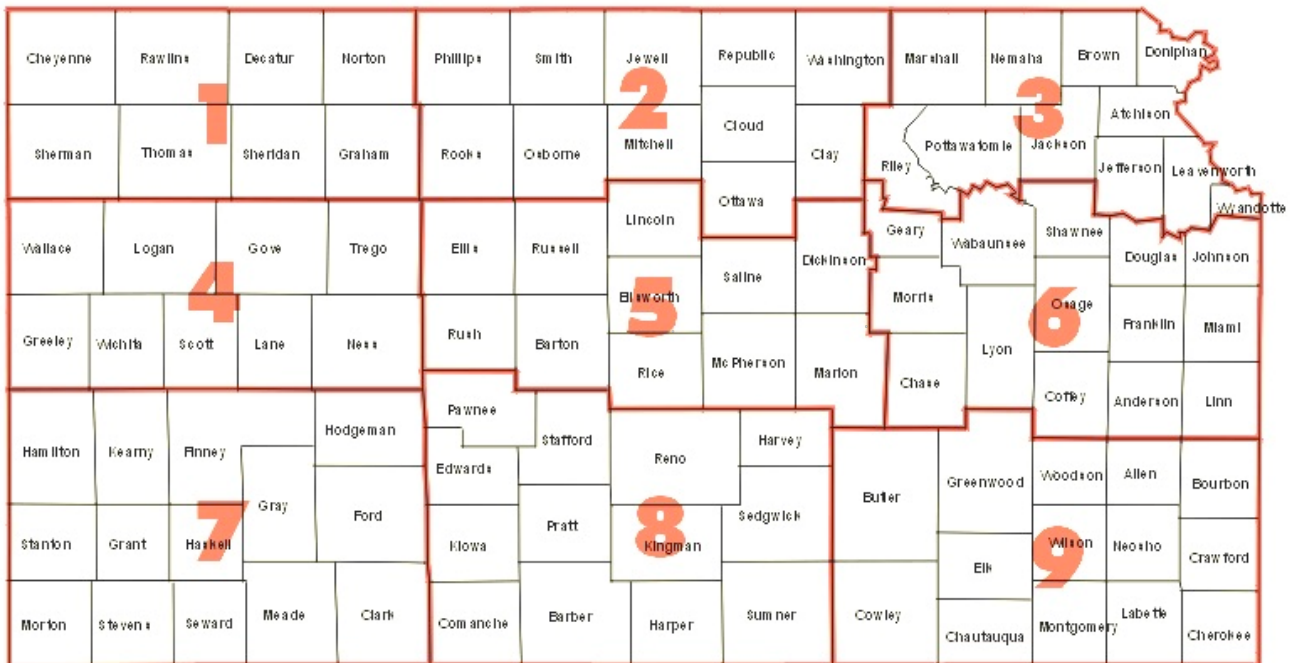


Figure KS4. Climate divisions; [Source](#).

## 7.5 Recent Change in Weather Hazards

Weather hazards threaten Lawrence's infrastructure and the safety and well being of its population, and these hazards have become more numerous since 1981. Lawrence's risk profile has expanded rather than narrowed due to both an increased frequency of some hazardous weather conditions and an increased range of weather conditions. Recent changes that have expanded the risk profile include:

- Increase in the frequency of warm nights
- During heat waves, a trend toward hotter nights, higher average temperature, and higher heat index
- Increase in number of days with extreme rainfall
- Increase in frequency of extremely wet spring seasons, precipitation in the late winter, and increased accumulation during multi-day (5-day and 15-day) heavy rainfall events

Other weather threats have been less frequent in recent years but are projected to emerge going forward. Recent data series are too short to discern a permanent change in these weather threats, but with 10 to 20 years of monitoring, it may be possible to conclude exposure to the following threats has changed:

- Late spring freeze
- Early fall freeze
- Extremely cold waves

Additional study is needed to conclude with certainty the impact of the urban heat island effect on changes in summer minimum temperature, as well as the average and minimum temperatures during heat waves.

## 7.6 Climate Projections

Lawrence's annual temperature is projected to increase substantially. In the future, the 30-year average temperature is projected to be well above the 90<sup>th</sup> percentile of the normal historical temperature range. Annual precipitation is expected to change very little.

### Temperature

Temperature is expected to increase substantially by the 2050s and beyond with much of the projected change occurring during spring, summer, and winter. By 2021-2050, the average annual temperature is projected to exceed the historical range and continue to increase into 2051-2080. This is a much faster rate of increase than measured in the recent historical change.

Temperature increase is largest in summer and winter with the average summer and winter temperature in 2021-2050 projected to nearly equal what is currently the threshold of the top 10% hottest years.

Historic Temperature and Future Projections

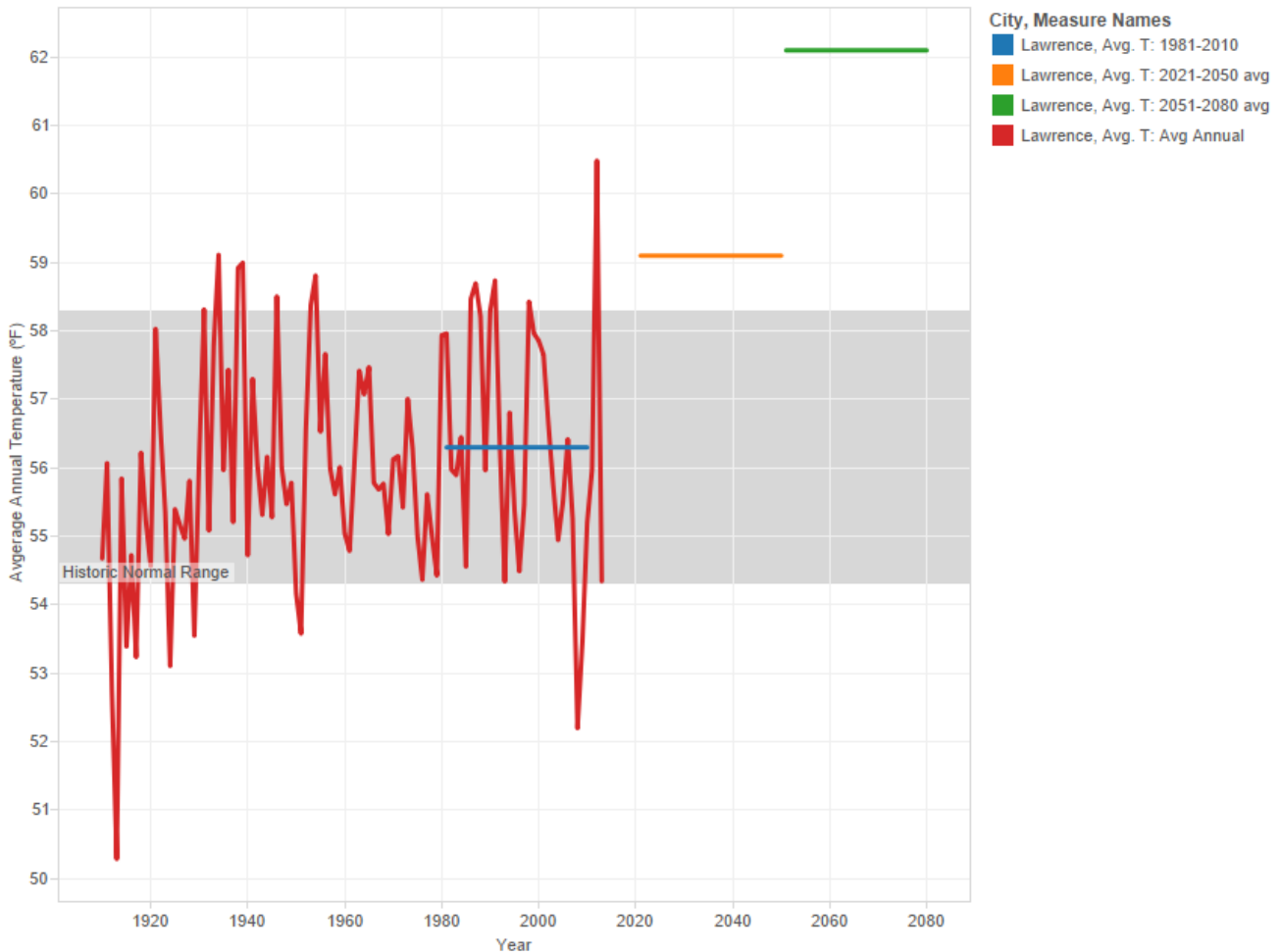


Figure KS5 illustrates the difference in annual temperature in the past and future. The line shows recorded temperatures from the historic record, and the 1981-2010 average is calculated from recorded temperatures. The 2021-2050 and 2051-2080 averages are calculated from climate models.

## Precipitation

Precipitation is projected to increase modestly in the future, which is consistent with recent changes in weather patterns. In the last three decades, average precipitation has increased from 36.5" to 38.8", though most of the wet recent years occurred in the 1990s, while very low years of precipitation have occurred since 2000. The increase in projected precipitation is largest in spring, while summer and fall are projected to have variable change in average precipitation.

### Historic Precipitation and Future Projections

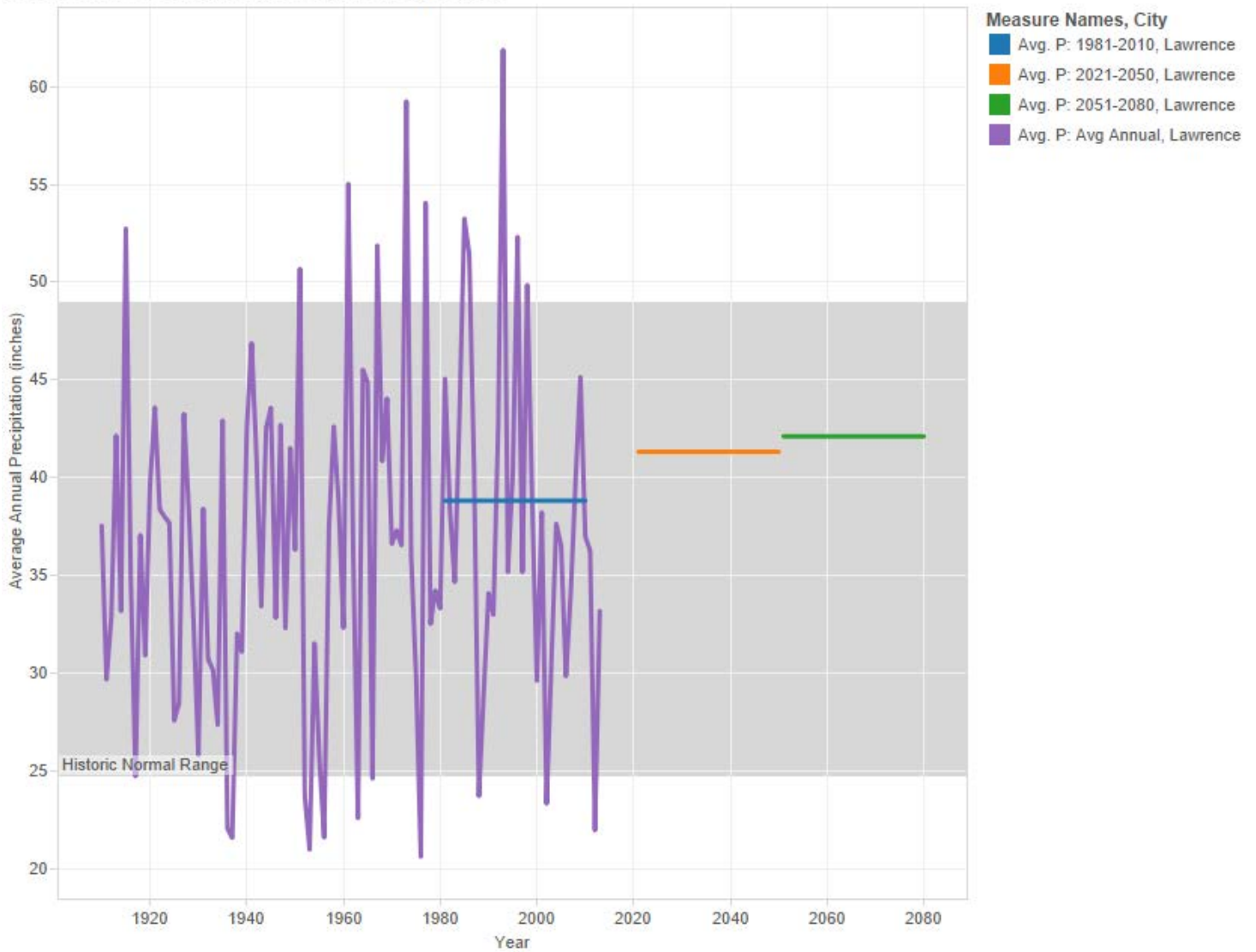


Figure KS6 illustrates the difference in annual precipitation in the past and future. The line shows recorded precipitation from the historic record, and the 1981-2010 average is calculated from recorded precipitation. The 2021-2050 and 2051-2080 averages are calculated from climate models.



## Data

The following tables show projection data for temperature, precipitation, and hazardous events in the coming decades, relative to the last 30 years.

### Projected Changes in Climate

Season	Metric	1981-2010	2021-2050	2051-2080
Annual	Average	56.3°F	59.1°F	62.1°F
	Maximum	66.4°F	69.3°F	72.5°F
	Minimum	46.2°F	48.8°F	51.7°F
	Precipitation	38.8"	41.3"	42.1"
Summer	Average	77.6°F	80.6°F	83.8°F
	Maximum	87.7°F	90.8°F	94.2°F
	Minimum	67.6°F	70.4°F	73.4°F
	Precipitation	13.8"	14.1"	13.4"
Fall	Average	57.7°F	59.0°F	61.2°F
	Precipitation	9.6"	10.3"	10.7
	Frost Date	October 31	November 4	November 7
Winter	Average	33.4°F	36.6°F	40.0°F
	Maximum	42.8°F	46.2°F	49.9°F
	Minimum	24.0°F	27.1°F	30.1°F
	Precipitation	3.8"	4.4"	4.4"
Spring	Average	56.1°F	59.6°F	63.0°F
	Precipitation	11.7"	12.7"	13.7"
	Frost Date	April 3	March 27	March 20

### Projected Changes in Hazardous Events

Damaging Event	Metric	1981-2010	2021-2050	2051-2080
Heat Waves	3-day average	87.8°F	91.0°F	94.7°F
	3-day maximum	99.4°F	103.0°F	107.2°F
	3-day minimum	77.0°F	79.7°F	83.0°F
Cold Waves	3-day minimum	0.4°F	4.7°F	9.1°F
Heavy Rainfall	Days > 1.25"	7 days	8 days	9 days
	Days > 4.00"	1 day per 10 years	1 day per 4 years	1 day per 3 years
	5-day	4.8"	5.2"	5.5"
	15-day	7.2"	7.8"	8.3"
Thaw/Freeze	Days > 45°F followed by days < 28°F	4.3 times per year	4.2 times per year	3.9 times per year

The following summary describes all climate change impacts, noting consistency, or lack thereof, with recent changes. See Discussion for information about the relationship between consistency and confidence.

- *Spring temperature* has recently increased by 0.6°F from 55.5°F to 56.1°F. It is projected to increase at a faster rate to 59.6°F in 2021-2050 and 63.0°F in 2051-2080.
- *Summer temperature* is projected to increase from 77.6°F in 1981-2010 to 80.6°F in 2021-2050 to 83.8°F in 2051-2080. The projected average annual temperature exceeds the historical threshold of 80.5°F for the 10% hottest summers. Recent historical change has been due almost entirely to increased nighttime temperatures.
- Change in *winter temperature* has been negligible. In the future it is projected to increase from 33.4°F in 1981-2010 to 36.7°F in 2021-2050 to 40.0°F in 2051-2080.
- *Date of last frost in spring* has recently shifted three days earlier (April 6 to April 3). It is projected to move earlier in the year by more than one week (March 27) in 2021-2050 and more than two weeks (March 20) in 2051-2080.
- *Date of first frost in fall* has recently shifted two days later (October 29 to October 31). It is projected to be five days later by 2021-2050 (November 4) and eight days later by 2051-2080 (November 7).
- The *hottest 3-day maximum* is projected to increase substantially. In 2021-2050, the maximum average temperature of the hottest 3-day period is expected to increase to 103.0°F, and further increase to 107.2°F is projected in 2051-2080. This is in

the opposite direction of recent change, which has seen a decrease in the maximum temperature of the hottest 3-day period, from 100°F to 99.4°F.

- The *hottest 3-day minimum* has recently increased by 0.7°F from 76.3°F to 77.0°F. It is projected to increase substantially. In 2021-2050, the minimum average temperature of the hottest 3-day period is projected to be 79.7°F and increase further to 83.0°F in 2051-2080.
- *Fall precipitation* has recently increased substantially by 1.2" from 8.4" to 9.6". It is projected to increase to 10.3" in 2021-2050 and to 10.7" in 2051-2080.
- *Summer precipitation* is projected to remain unstable. It has recently increased by 1.1" from 12.7" to 13.8". The year-to-year variation of summer rainfall is large, and this recent increase is relatively small compared to year-to-year variation. Variability is projected to continue, with an increase to 14.1" projected in 2021-2050 and a decrease to 10.3" projected in 2051-2080.
- *Spring precipitation* has recently increased substantially by 1.5" from 10.2" to 11.7". It is projected to continue to increase at about the same rate to 12.7" in 2021-2050, then to 13.7" in 2051-2080. Of all seasonal rainfall projections, projected spring rainfall approaches most closely the historical threshold for the 10% wettest years, which is 15.2".
- *Excessive rainfall* is projected to increase. The amount of rainfall during the annual maximum 5-day and 15-day rainfall is projected to increase. This is the same direction of change as the recent historical change.



## 9 Discussion

### 9.1 Interpretation

The purpose of this report is to present climate projection data in terms of metrics that are readily applicable. This information includes sections on the level of scientific confidence in these metrics, as well as sources of uncertainty.

#### Confidence

For municipal planning purposes, it is important to understand the level of scientific confidence in future climate projections. Confidence levels can be determined by comparing the direction of change in the historical climate and future projection data. Highest confidence should be assigned when change is in the same direction in both data sets. When this happens, it means that recent change has factors going forward that may support further change in the same direction.

Confidence levels arise from the fact that normal historical climate range should be used to plan for the next decade; whereas, future climate projection data should be used for planning further into the future. The confidence level associated with different combinations of recent and projected direction of change is provided in the table below.

**Confidence Levels for Climate Projections beyond the Next Decade**

	No Predicted Change	Predicted Increase	Predicted Decrease	Legend
No Recent Change	No Change	Increase	Decrease	High Confidence
Recent Increase	No Change	Increase	Decrease	Moderate Confidence
Recent Decrease	No Change	Increase	Decrease	

#### Uncertainty

There is a degree of uncertainty in any projection exercise. With climate projection, uncertainty arises from four sources, all of which are relevant to long-range municipal climate planning. The largest source of uncertainty is human behavior, particularly the amount of greenhouse gas emissions.<sup>8</sup>

- *Natural variability*, which causes temperature, precipitation, and other aspects of climate to vary from year to year and even decade to decade
- *Scientific uncertainty*, as it is still uncertain exactly how much the Earth will warm in response to human emissions and global climate models cannot perfectly represent every aspect of Earth's climate
- *Scenario uncertainty*, which results from the unpredictability of human behavior, particularly regarding policies on greenhouse gas emissions, as future climate change will continue in response to human activities that have not yet occurred
- *Local uncertainty*, which results from the many factors that interact to determine how the climate of one specific location, such as Austin, will respond to global-scale change over the coming century.

This project has addressed these sources of uncertainty in the following ways.

- To address uncertainty from *natural variability*, the climate projections are summarized over two future 30-year periods, 2021-2050 and 2051-2080. Natural variability is an important source of uncertainty in the next two decades. Recent trends that are consistent with projected climate change in 2021-2050 are the strongest indicators of future climate conditions. Consistency, or lack thereof, between recent trends and future projections has been noted for each city.
- *Scientific uncertainty* is addressed by selecting projections from nine global climate models (CCSM3, CGCM3, CNRM, ECHAM5, ECHO, GFDL2.1, HadCM3, HadGEM, and PCM). Differences between the models are indicative of the limitations of scientific ability to simulate the climate system. Scientific uncertainty is an important source of uncertainty in

<sup>8</sup> Much of the content in this section is derived, paraphrased, or quoted with permission from Hayhoe (2014).

determining the magnitude and sometimes even the direction of projected changes in average precipitation, as well as dry days and extreme precipitation.

- *Scenario uncertainty* is addressed by selecting climate model projections under three future greenhouse gas emissions scenarios. The greenhouse gas emissions scenarios reflect different levels of international cooperation on emissions reduction resulting in scenarios with emissions rates that have moderate reductions (Scenario A1B), little to no reductions (A2), and increases (A1FI). Should greenhouse gas reductions be pursued aggressively, resulting in a significant reduction in atmospheric carbon, the future change summarized in this document may no longer be reasonable for planning. Through 2015, the observed trend in global emissions is most similar to A1FI scenario.
- Finally, *local uncertainty* is addressed by use of global climate model simulations downscaled to stations with long-term weather reports using the Asynchronous Regional Regression Model as described in Stoner et al. (2013). The data used for downscaling is the same data utilized to produce the historical weather reports in this document. These projections are based on a single location. In the future, to generate robust projections for planning purposes, it is recommended that a similar analysis be conducted for all long-term weather stations in the municipal area.

In addition to the uncertainty inherent in predicting the future, data sets must also be examined for validity. The ability to detect change in the historical weather record is the fundamental concern of climatologists, who have identified the following concerns regarding data validity.

- *Data record length*: A short data record makes it more difficult to ascertain whether recent weather extremes are outside the range of past extremes and whether recent change is large compared to past variability. Data record length is reported for each city, and, where the record is short, it is compared to a longer record from the nearby area.
- *Weather station conditions*: If the landscape surrounding a weather station becomes more urban, the record can reflect an increase in temperature due to changing land use, an increase that is not present where the landscape has remained rural. This is known as the urban heat island effect, and, where applicable, it can challenge data validity. Similarly, change in vegetation, such as from forest to cropland, can alter humidity and temperature. This has been addressed by comparing each station’s data with data from the surrounding area.
- *Change in location*: When a station is moved, particularly from a higher to lower elevation or an urban to rural setting, the temperature and humidity can change substantially. Where this situation occurred, a nearby weather station with stable location was utilized instead.
- *Change in instrumentation or reporting procedure*: The time of reporting for daily maximum and minimum temperature has changed from afternoon to morning, and the instrumentation used for reporting has changed in some stations. This can alter the average maximum and minimum temperature by a degree or more.

This project addressed data validity by utilizing a team that included university climate scientists, who worked on the projections, in collaboration with state climatologists, who have set standards for data quality and control procedures of historical station data. For each municipality’s historical report, the state climatologist selected the best available long-term record and situated any change in the municipality’s record within the context of regional change.

The downscaled data used in this report were generated by the Asynchronous Regional Regression Model (Stoner et al. 2013). The following criteria were applied when selecting this dataset for downscaled climate projections.

### Considerations in Selecting Downscaled Climate Datasets

Consideration	Comments
<b>Temporal and Spatial Characteristics</b>	Downscaled data available as daily data at locations of historical weather data.
<b>Accuracy</b>	Downscaled climate data has been evaluated against historical station data.
<b>Methodological Assumptions</b>	Fixed parameter assumptions have been evaluated by the perfect model framework developed at the Geophysical Fluid Dynamics Laboratory ( <a href="http://gfdl.noaa.gov/esd_eval_stationarity_pg1">http://gfdl.noaa.gov/esd_eval_stationarity_pg1</a> ).
<b>Uncertainty</b>	Downscaled climate data adequately samples uncertainty from natural variability, scientific uncertainty, human uncertainty, and local uncertainty.
<b>Availability</b>	Downscaled climate projections database was immediately available to our project through direct provision by Katharine Hayhoe, Texas Tech University High Performance Computing Center.
<b>Use in other Assessments</b>	The downscaled climate projection database has been used in assessments by other municipalities and federal agencies. This ensures we are using a well-reviewed data set and can draw from and contribute to learning of its best uses.

## 9.2 Application

Specific, localized climate projection information is useful information to local governments. The recorded record shows the climate throughout the Great Plains shows the climate was relatively stable for a long period, and government functions evolved to operate within that range. However, as cities have seen in recent years, when extreme weather events push the climate outside the normal range, it puts stressors on government organizations to respond to significant weather events while continuing to provide regular services. The impacts are immediate (e.g., personnel safety), medium range (e.g., cleanup and restoration), and long range (e.g., planning for infrastructure development).

While there are multiple ways to utilize this information, the particular strategy is outlined here based on recent work completed in Oklahoma City. This strategy is ideal for cities with limited staff time to dedicate to a project, as it does not require ongoing committee work. The method involves determining how current weather affects departmental operations and extrapolating to ascertain how the impacts will change over time.

Once support is obtained for the study, steps involved in this process include the following.

1. Develop a list of critical government functions that may be affected by weather. This should be done by staff who are familiar with municipal operations and may also include a review of other cities' plans. In Oklahoma City, critical functions included public safety, water utilities, solid waste, infrastructure, public facilities, public transportation, and personnel. An "other" category captured impacts that did not fit within these groupings.
2. Create a list of departmental representatives with operational knowledge about these government functions, particularly how they are affected by weather events.
3. Make a list of specific effects that may occur within each of the departments associated with the critical government functions. For example, in public safety, impacts may include personnel safety, response times, and call volume, among others.
4. Make a list of the weather events that impact operations.
5. Utilize the list of specific effects and list of weather events to create tables in preparation for interviews with departmental representatives. A sample table is included in
6. Schedule and conduct 30-90-minute interviews with departmental representatives. Utilize the tables as a starting point, but emphasize that not every cell must be completed and request support in identifying other important impacts not listed. It is useful to appoint one person as an interviewer and one as a notetaker. Begin with an assessment of how weather currently affects government functions, and follow with questions about how changing conditions may alter the impacts. (Note: if climate projections are not available at the time of interviews, as was the case in Oklahoma City, questions can be asked hypothetically. Future impacts can be extrapolated from current impacts once climate projections are received.)
7. Record interview notes. After the interview, organize notes, tagging impacts by the weather type and government function affected. Make note of general impacts on government, which may be the same regardless of the nature of the disaster. Note that impacts may be positive, negative, neutral, or mixed.
8. Prepare report and disseminate. Utilize information to develop an action plan to mitigate negative impacts. Incorporate results into other long-range plans, such as the comprehensive plan, hazard mitigation plan, capital improvement plan, or climate adaptation plan.

Utilizing this methodology, the City of Oklahoma City has completed an impact analysis of present and future climate conditions. For more information, contact the Sustainability Office at [sustainability@okc.gov](mailto:sustainability@okc.gov).

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## Appendix A: Regional Changes in Temperature

Several broad similarities were apparent in the historical and projection data for cities in this report. Much of this consistency arises from the fact that they are all in the Great Plains region of the United States. Examining broad spatial patterns is useful because it helps explain these similarities. The National Climate Assessment 2014 (NCA 2014) (Walsh and Wuebbles 2014) contains information about two temperature metrics of relevance in this report: projection of change in future annual temperature and historical change in daily maximum and minimum temperature.

Two emissions scenarios analyzed in this report are included in NCA 2014, the A2 and A1B scenarios.<sup>9</sup> The A2 scenario is considered a “business as usual” scenario, while A1B is a scenario in which the rate of increase of greenhouse gas concentration is slowed slightly. The broad pattern illustrates why projections of temperature change are similar among the municipalities.

In Figure X, the projection of annual temperature change for 2071-2099, relative to 1970-1999, is shown for the A2 and A1B scenarios. The A2 scenario shows greater change than A1B in annual temperature. Importantly, the pattern of change is similar for most of the central United States. For the A2 scenario, the entire central United States is 8-9°F warmer; whereas, for the A1B scenario, the south central United States is warmed 5-6°F but the north central United States is warmed 7-8°F. This broad pattern of future change is the reason annual temperature increases well beyond the historical bounds of annual temperature are projected unequivocally for all municipalities in this report.

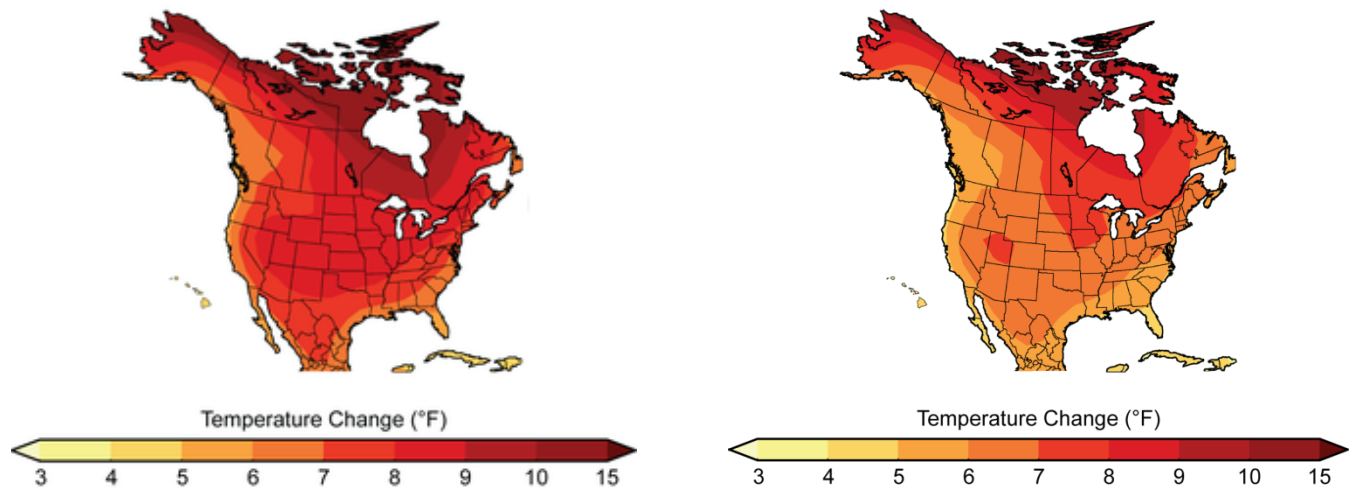


Figure A1: SRES projected change in surface air temperature at the end of this century (2071-2099) relative to the end of the last century (1970-1999). (Figure source: NOAA NCDC / CICS-NC).

At times, the direction of future change may be opposite of recent change, even over a broad region. For example, NCA 2014 summarized trends in annual maximum and annual minimum temperature (Figure C2) (Menne and Williams 2009; Walsh and Wuebbles 2014)<sup>10</sup> and showed that annual maximum temperature has had decreasing trend over large portions of Iowa, Missouri, and Nebraska and mixed trend over Kansas and Oklahoma, although future projections predict a warming trend (Figure X). Annual minimum temperature is more consistent, with an increasing trend everywhere except southeastern Oklahoma.

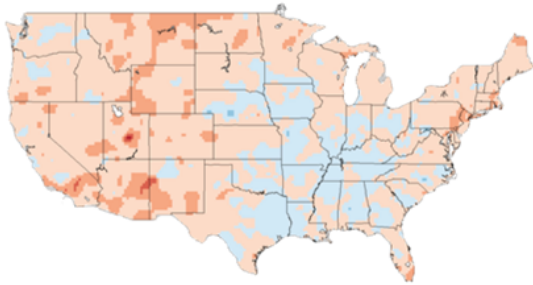
These figures, taken together, illustrate that mean annual temperature increase in the future (Figure X [1<sup>st</sup> image]) will be an emerging trend for most of the central United States, whereas to date only annual minimum temperature has increased (Figure X [2<sup>nd</sup> image]).

<sup>9</sup> The scenarios are described under National Climate Assessment 2014 Supplemental Message 5 and in Figure 19, available at the following URL: <http://nca2014.globalchange.gov/report/appendices/climate-science-supplement#statement-38715>

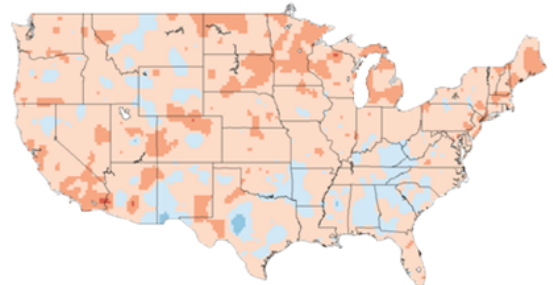
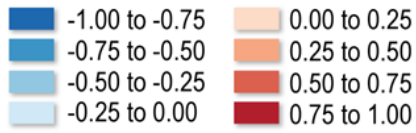
<sup>10</sup> Descriptions of data and figures are available from National Climate Assessment 2014 Climate Science Supplement, using the following URL: <http://nca2014.globalchange.gov/report/appendices/climate-science-supplement#statement-38713>.

Maximum Temperature  
1895-2011

Minimum Temperature  
1895-2011



°F per Decade



°F per Decade

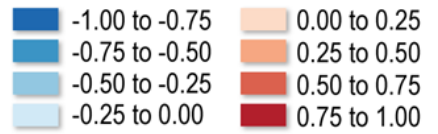


Figure A2: Trends in Maximum and Minimum Temperatures adjusted. Caption: Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Figure source: updated from Menne et al. 2009).



## Appendix B: Climate Metrics and Definition of Terms

Several factors influenced the choice of climate metrics (TABLE X). For example, a standard meteorological definition doesn't exist for heat waves, but studies of the 1995 Chicago heat wave have identified 3-day temperature as an indicator of human survival. Similarly, concerning rainfall, engineers use 1.25" as a threshold for infiltration for storm water, and climatologists list maximum of 1-day and 5-day rainfall among internationally agreed upon extreme weather metrics.

The data in the climate data sets consists of daily entries for maximum temperature, minimum temperature, and precipitation. Metrics are combinations of these values and are defined in the table below. Seasonal averages follow the meteorological seasons:

- Summer values are averaged over June, July, and August.
- Fall values are averaged over September, October, and November.
- Winter values are averaged over December, January, and February.
- Spring values are averaged over March, April, and May.

### Climate Metrics Definitions

Metric	Computation
<b>Seasonal Accumulation or Average</b>	Sum over days during meteorological season. For seasonal average, divide sum by number of days. Days included in each season are: Summer, days 152-243; Fall, days 244-334; Winter, days 335-365 and (following year) days 1-59; Spring, days 60-151.
<b>Cooling Degree Days</b>	Annual accumulation of difference between daily average temperature and 65°F when daily average is above 65°F. Daily average temperature above 65°F indicates the need for air conditioning to maintain indoor temperature of 70°F. Annual accumulation indicates the amount of demand for air conditioning over the entire year.
<b>Heating Degree Days</b>	Annual accumulation of difference between daily average temperature and 65°F when daily temperature is below 65°F. Daily average temperature below 65°F indicates the need for heating to maintain indoor temperature of 70°F. Annual accumulation indicates the amount of demand for heating over the entire year.
<b>Spring Frost Date</b>	Prior to July 1 <sup>st</sup> , latest day of minimum temperature less than 32°F
<b>Fall Frost Date</b>	After July 1 <sup>st</sup> , latest day of minimum temperature less than 32°F
<b>Heat Waves</b>	Annual maximum of running 3-day average maximum temperature; annual maximum of running 3-day average temperature
<b>Cold Waves</b>	Annual minimum of running 3-day average minimum temperature
<b>Thaw to Freeze</b>	Average daily temperature changes from >45°F to <28°F
<b>Moderate Warm to Freeze</b>	Average daily temperature changes from the range of 32°F-45°F to below 28°F
<b>Number Rainfall Days Greater than Threshold</b>	Annual sum of days exceeding 1.25" and 4.0"
<b>Number Snowstorm Days Greater than Threshold</b>	Annual sum of days with snow exceeding 3.0", 6.0", 9.0", and 12.0"
<b>Maximum 5-day Rainfall</b>	Annual maximum of running 5-day rainfall

<b>Maximum 15-day Rainfall</b>	Annual maximum of running 15-day rainfall
<b>Maximum 3-day Snowfall</b>	Annual maximum of running 3-day snowfall
<b>Top 10% of Years; 90<sup>th</sup> Percentile</b>	Years are sorted from lowest to highest; threshold is the value above which there are 10% of the years
<b>Bottom 10% of Years; 10<sup>th</sup> Percentile</b>	Years are sorted from lowest to highest; threshold is the value below which there are 10% of the years



# Appendix C: Sample Interview Table

The table on following pages is representative of the type of table used in departmental interviews in Oklahoma City. Weather events are listed in rows, and potential functions impacted by weather are listed in columns. This example was utilized for an interview with the fire department.

	Personnel safety	Response times	Call volume	Road access	Elderly & vulnerable	Facilities, Equip, Budget
Floods, flash floods						
Heavy rainfall						

	Personnel safety	Response times	Call volume	Road access	Elderly & vulnerable	Facilities, Equip, Budget
Tornadoes						
Hail						

	Personnel safety	Response times	Call volume	Road access	Elderly & vulnerable	Facilities, Equip, Budget
Longer frost-free season						
Warmer Winters						

	Personnel safety	Response times	Call volume	Road access	Elderly & vulnerable	Facilities, Equip, Budget
Heat waves						
Drought						

	Personnel safety	Response times	Call volume	Road access	Elderly & vulnerable	Facilities, Equip, Budget
Wildfire/ brush fire						
Winter ice storms, blizzards						



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