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The Effect of Urbanization on the Intensity of Heavy Rainfall in the Midwestern United States

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THE EFFECT OF URBANIZATION ON THE INTENSITY OF HEAVY RAINFALL IN THE MIDWESTERN UNITED STATES

by

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Abstract

In recent years, the global population has become more concentrated in cities and this urbanization has influenced a number of changes in climate and land use. While some studies have examined how urbanization impacts precipitation, most of these studies have examined precipitation patterns rather than intensity. Increases in the intensity of precipitation can increase the risk of flooding and flash floods, which can have devastating impacts. Stage IV multi-sensor precipitation data was used to examine heavy rainfall events during the warm-season (May-September) from 2003-2017 in Midwestern cities to examine how urbanization influences rainfall intensity. NCEI precipitation data was also used to create a climatology regarding warm-season precipitation. Results show that in most cases, areas downwind of the urban environment tend to experience heavier rainfall, thus it is likely these areas experience a greater rainfall intensity. Further research regarding specific parameters of rainfall would be beneficial in understand the precipitation modification that occurs due to urbanization.

Introduction

Motivation

Over the years, the global population has been on the rise. As of 2019, there are an estimated 7.7 billion people worldwide, and this number could grow to be around 8.5 billion by 2030 (United Nations, 2019). This population has slowly become more concentrated in cities. In 1950, 30% of the world's population lived in urban areas, but by 2000 this figure raised to 47%, and is projected to rise to 60% by 2030. The process of urbanization is very advanced in the developed world, where at least 75% of the population lives in urbanized areas, and this figure is expected to increase (Collier, 2006). Despite the number of people that are located within these cities, urban areas only cover 0.2% of the earth's land surface (Collier, 2006). With such large populations living in such dense areas, it is important to understand how these areas can impact and be impacted by weather.

Urban effects on weather have been investigated by many. Phenomena such as the urban heat island, boundary layer influences, and air pollution are just some examples of how urban areas alter and influence the environment. For example, urbanization alters the physical and dynamical structure of the planetary boundary layer, which in turn influences both local weather and climate and impacts air quality (Collier, 2006). Cities can have significant influences on both regional and local climates, which is why they are important to understand, especially in an age with increased urbanization.

Precipitation is one such weather phenomenon that is altered by urbanization. Through different processes, such as boundary layer influences and urban heat islands, precipitation is altered in urban environments (Collier, 2016). Figure 1 shows one of the ways that urban areas are able to influence precipitation. The materials that are used in urban environments absorb the sun's rays and slowly warm up the surrounding air. Eventually, this heat is released and starts to rise; in many cases this warm air combines with moisture thus creating clouds and precipitation, and the prevailing winds move this precipitation to areas that are downwind of the city. Many studies that have looked at precipitation have analyzed how precipitation patterns are altered due to urbanization. Rainfall intensity alteration is one parameter that has yet to be studied in regards to urbanization. This study seeks to prove urbanization increases the intensity of heavy rainfall. In order to determine how urbanization influences the intensity of heavy rainfall, the modification that occurs in these urban areas must be determined. The key factors of this modification occur in amount and location of the precipitation. Furthermore, the location of the heaviest precipitation in relation to the urban areas must also be determined, since this provides key insight to the influence urbanization has on altering precipitation.

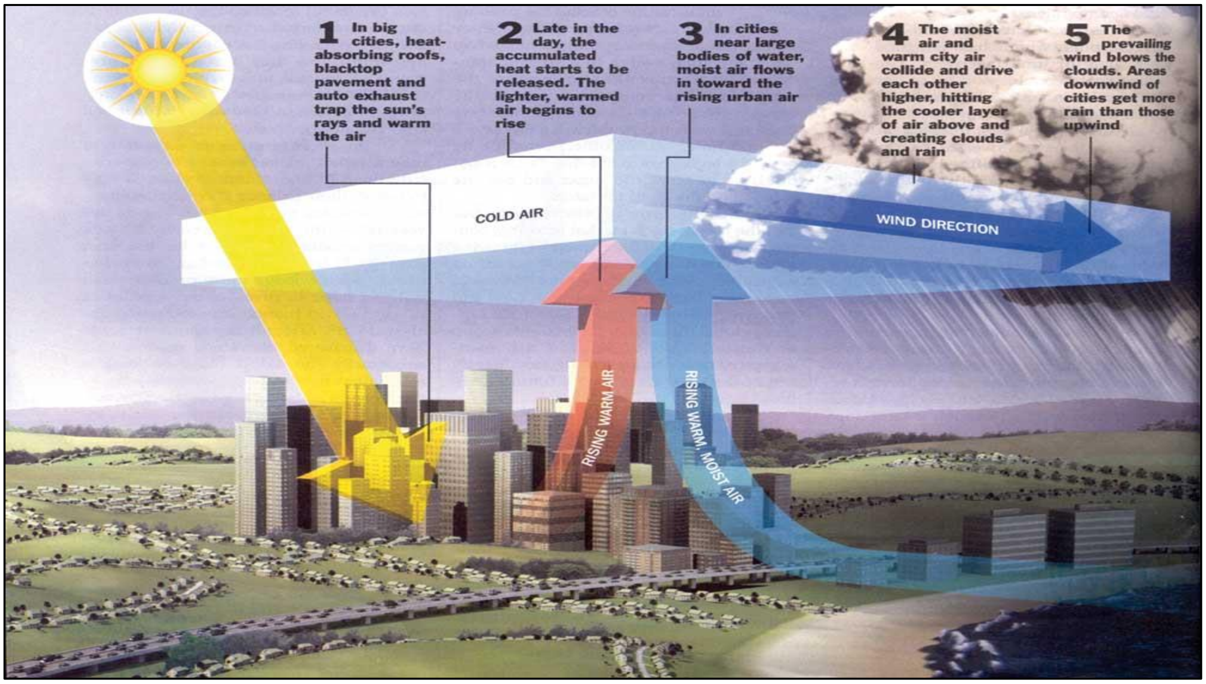

Figure 1: Image depicting how urbanization influences rainfall. The urban heat island allows more clouds to develop, thus leading to areas downwind of the city to receive more rainfall.

Past Studies

In 1971, a large-scale investigation on inadvertent weather modification was conducted in St. Louis. This research, known as the Metropolitan Meteorological Experiment (METROMEX), included mostly field work, but also utilized laboratory and atmospheric modeling (Changnon, 1971). This study focused on the study of urban-related alterations in precipitation processes and quantitative changes in surface precipitation. Huff and Changnon (1972, 1973), further examined the effect urban areas had on precipitation modification and determined that urban-related rain, thunder, and hail increases downwind of the city. These studies also indicate that urban precipitation enhancement is related to city size, industrial nuclei generation, and thermal effects.

In more recent years, there have been further investigations into how urbanization can impact precipitation events. In 2013, Yang et al. investigated the impact of urbanization on heavy convective precipitation. This study used observational and numerical modelling analyses based on the Weather Research and Forecasting (WRF) model to investigate the impact of urbanization on heavy rainfall over the Milwaukee-Lake Michigan region. The results suggest that urbanization plays a large role in precipitation distribution. Another study conducted a climatology of urbanization impacts on summer heavy rainfall events over the eastern United States and determined that the frequency of heavy rainfall events has a positive bias towards urban environments and that there is an increasing trend in rainfall amounts downwind of urban-rural boundaries. Additionally, results suggest that the urbanization signature is becoming detectable in rainfall climatology (Niyogi et al., 2017).

In their analysis of urbanization impacts on summer rainfall, Niyogi et al. (2017) analyzed rainfall data for the eastern United States by evaluating both the amount and frequency of heavy rainfall events. This research used topography-corrected Parameter-Elevation Regressions on Independent Slopes Model (PRISM) to produce estimates of precipitation on a monthly time-scale. This climatology also quantified urbanization based on population data from two different projects, the Gridded Population of the World, version 3 (GPWv3) and the Global Rural-Urban Mapping Project (GRUMP). Niyogi et al. (2017) also used rainfall data obtained from the National Climatic Data Center (NCDC), known known as the National Centers for Environmental Information (NCEI). The methodology outlined by Niyogi et al. (2017) provides a basis for the research that was used in this study.

All of these studies provide excellent insight to how much of an influence urban environments can have on different weather phenomena, especially precipitation. However, some of these studies are fairly outdated and others only focus on specific aspects of precipitation modification, such as pattern changes or rainfall climatology.

Methods

Precipitation Intensity Analysis

Stage IV precipitation data collected from the National Centers of Environmental Prediction (NCEP) was analyzed. The Stage IV analysis is based on the multi-sensor hourly and 6-hourly Stage III analysis produced by the 12 River Forecast Centers in the continuous United States, which is then mosaicked into the national Stage IV precipitation product. This product is available hourly, 6-hourly, and 12-hourly, but this project used the 6-hour analyses (Lin, 2011). The 6-hourly analyses were used for this project because it provides more insight than the 12-hourly analyses, but is a reasonable amount of data to work with compared to the hourly analyses, which would be overwhelming for the scope of this project. The Stage IV data for this project covered the warm season months, defined as May through September, for a 15-year period. This 15-year period extends from 2003 to 2017. This data was analyzed using the Grid Analysis and Display System (GrADS) through different computer scripts (see Appendix). Ten different urban cities in the Midwestern United States were examined, and locations of maximum precipitation greater than two inches in a six-hour period were recorded for these areas. The ten cities selected for analyses are: Chicago, Dallas-Fort Worth, Des Moines, Indianapolis, Kansas City, Minneapolis, Oklahoma City, Omaha, Saint Louis, and Wichita. The Midwestern United States was the region of interest for this research due to the fact that there are fewer topographical influences that can modify precipitation in comparison to other regions. Using the recorded maxima maps depicting where the maximum rainfall occurred in relation to the city were created; these maps show where the heaviest rainfall typically occurs, taking both magnitude of the rainfall amount and frequency of occurrences into account.

Precipitation Climatology

Due to the fact that the Stage IV analysis only covers a 15-year period, further climatological data is required. In order to fully understand the influences of urbanization, National Centers for Environmental Information (NCEI) precipitation data was also used. The NCEI data was collected for a 51-year period prior to the Stage IV data, spanning from 1953 to 2003, for three different stations in each of the examined urban areas. One station was upwind of the city, one of the stations was in the city center, and one of the stations was downwind of the city. Each station selected had at least 90% coverage or the time period or more; given the specific locations of interest, the length of the time period, and the nature of the weather stations, not every station had full coverage of the climatology. Using the warm season (May to September) precipitation data from the Global Summary of the Month dataset from each station, frequencies of which station has the highest rainfall total were calculated for each station. Additionally, the warm season rainfall totals were averaged for each year and plotted in a time series. This data was used to create a better understanding of how urbanization has influenced precipitation events, as well as provide a climatological basis for the Stage IV analysis.

Results

Stage IV Analysis

For six of the ten cities analyzed, the heaviest rainfall, in both frequency and magnitude, took place downwind of the city in the southeast portion of the analyzed area. In this particular study, downwind was assumed to be the area to the southeast of all of the cities based off of general synoptic patterns, rather than climatological winds. Three of the cities all had some of the heaviest rainfall located southwest of the city. Saint Louis had one of the most distinct areas of heaviest rainfall intensity downwind of the city, as seen in Figure 2. Chicago (Figure 3), Des Moines (Figure 4), Oklahoma City (Figure 5), and Wichita (Figure 6) all also had the heaviest rainfall to the southeast of the city center. Indianapolis had some of the heaviest rainfall downwind of the city, but also a second area of heavy rainfall located upwind of the city, which can be seen in Figure 7. While this bullseye could possibly be due to the urban effects of Indianapolis, there is also the possibility of this region being influenced by the Chicago urban impacts. Omaha (Figure 8) had a maximum located downwind of the city, however the heaviest rainfall occurred to the southwest of the city. Similarly, Kansas City (Figure 9) had the area of heaviest rainfall located to the southwest of the city; there was also a much smaller maximum located directly north of the city, but it is much smaller compared to the one located to the southwest. As seen in Indianapolis, Minneapolis, seen in Figure 10, also had two areas of heaviest rainfall; one maximum in located to the southwest and the other is located directly east of the city center. Dallas-Fort Worth (Figure 11) had its maximum located northeast of the city, and was the only city to have a maximum in this location.

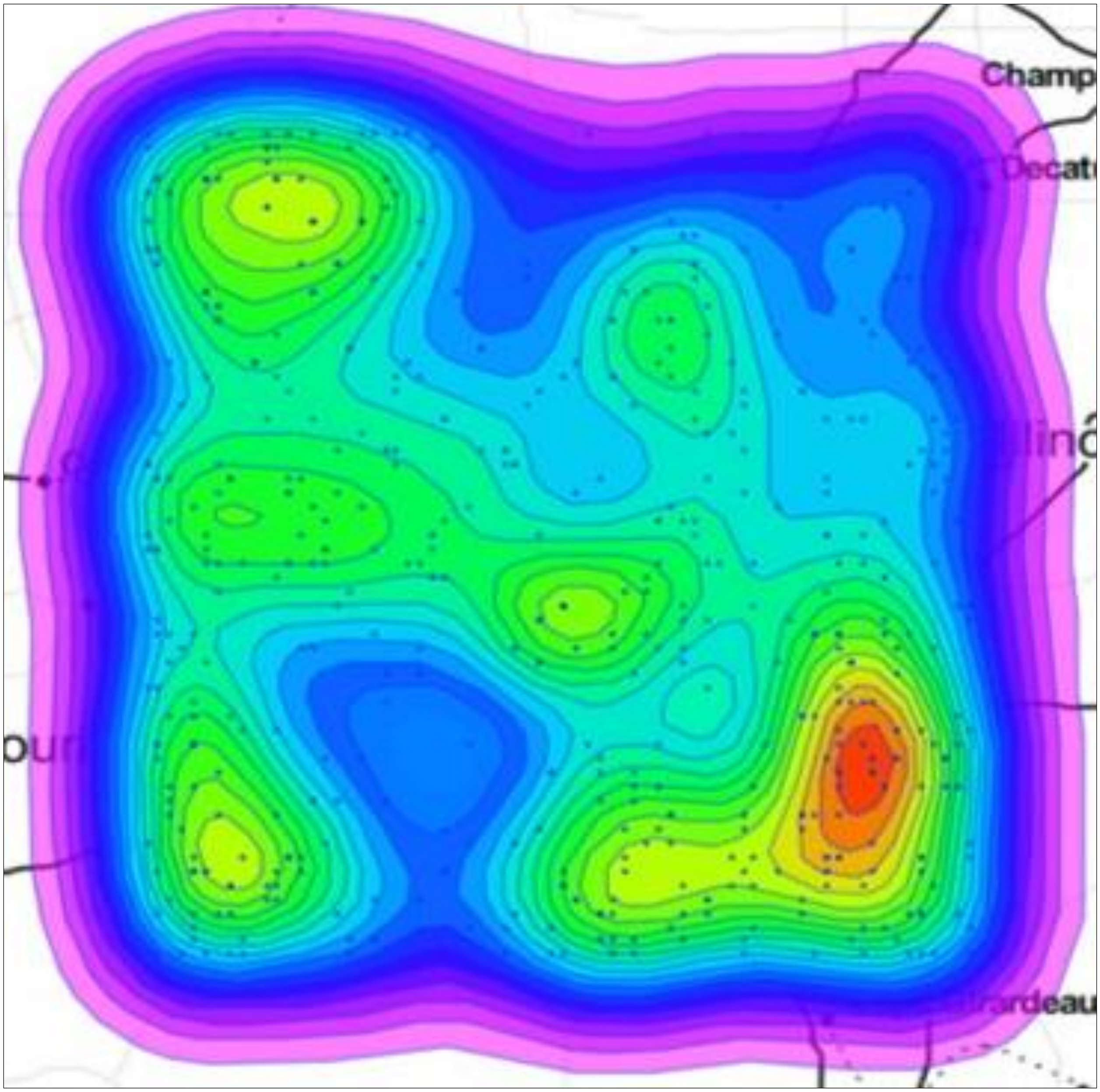

Figure 2: Map depicting maximum rainfall for Saint Louis, MO. The map accounts for both the magnitude and frequency of heaviest rainfall, with the maximum being indicated by the red shading downwind of the city. Saint Louis is located in the center of the map.

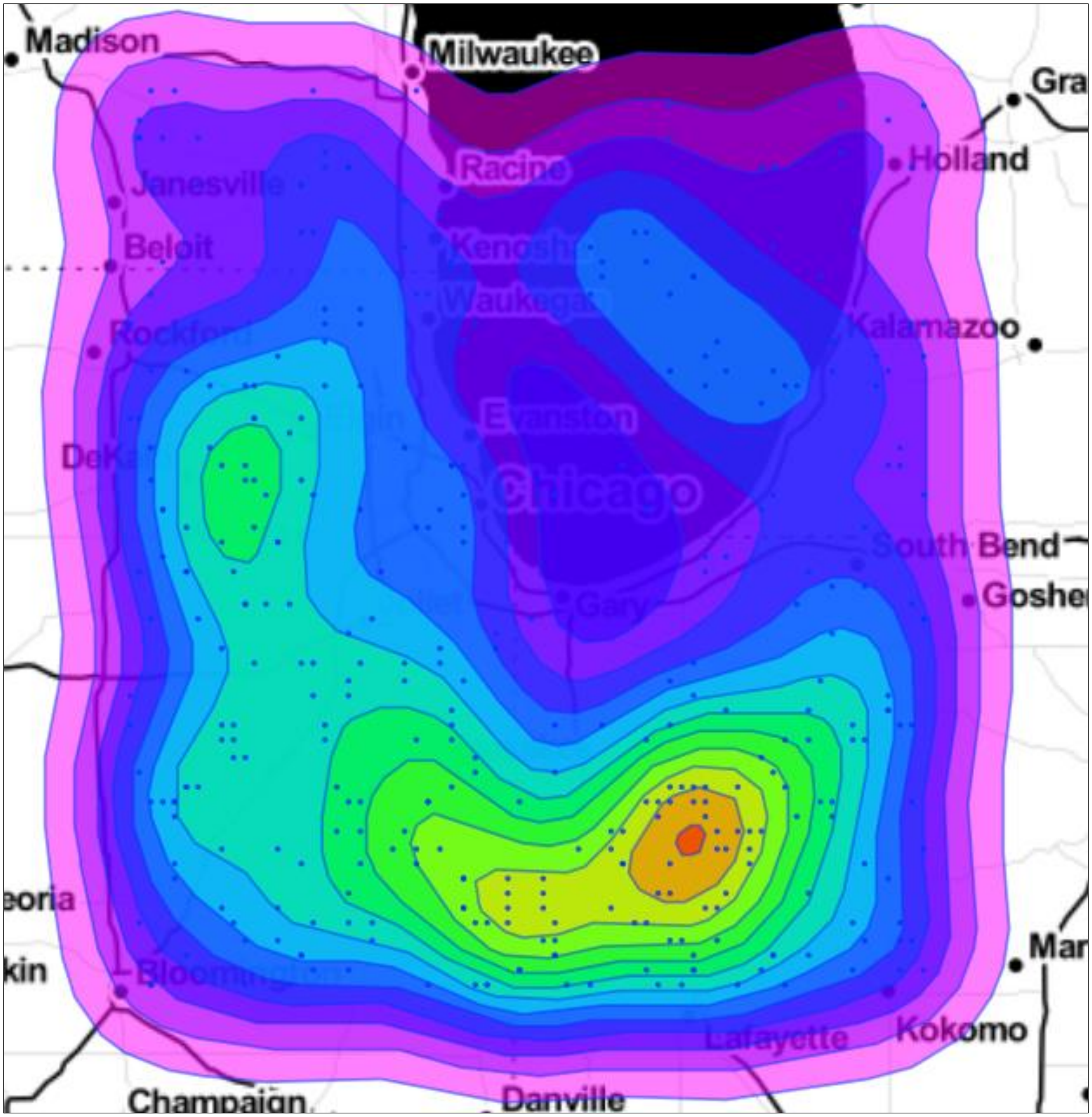

Figure 3: Map showing heavy rainfall location and magnitude for Chicago, IL. Chicago had a bullseye located downwind of the city, indicating the heaviest intensity of rainfall occured downwind of the city. Chicago is located in the center of the map.

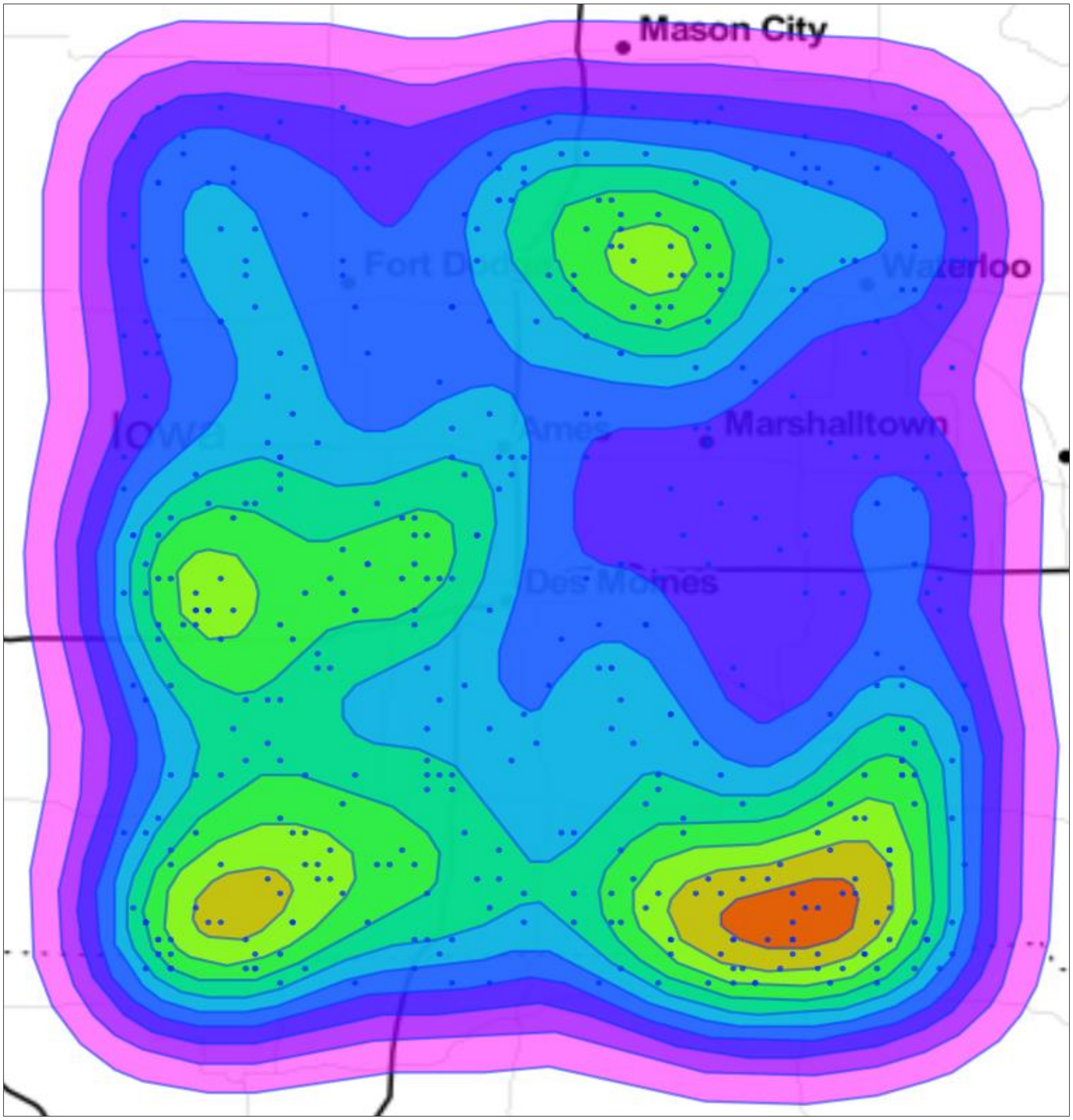

Figure 4: Map depicting the frequency and magnitude of the heaviest rainfall maxima for Des Moines, IA. Like many of the other cities, the heaviest rainfall intensity is seen downwind of the city. Des Moines is located in the center of the map.

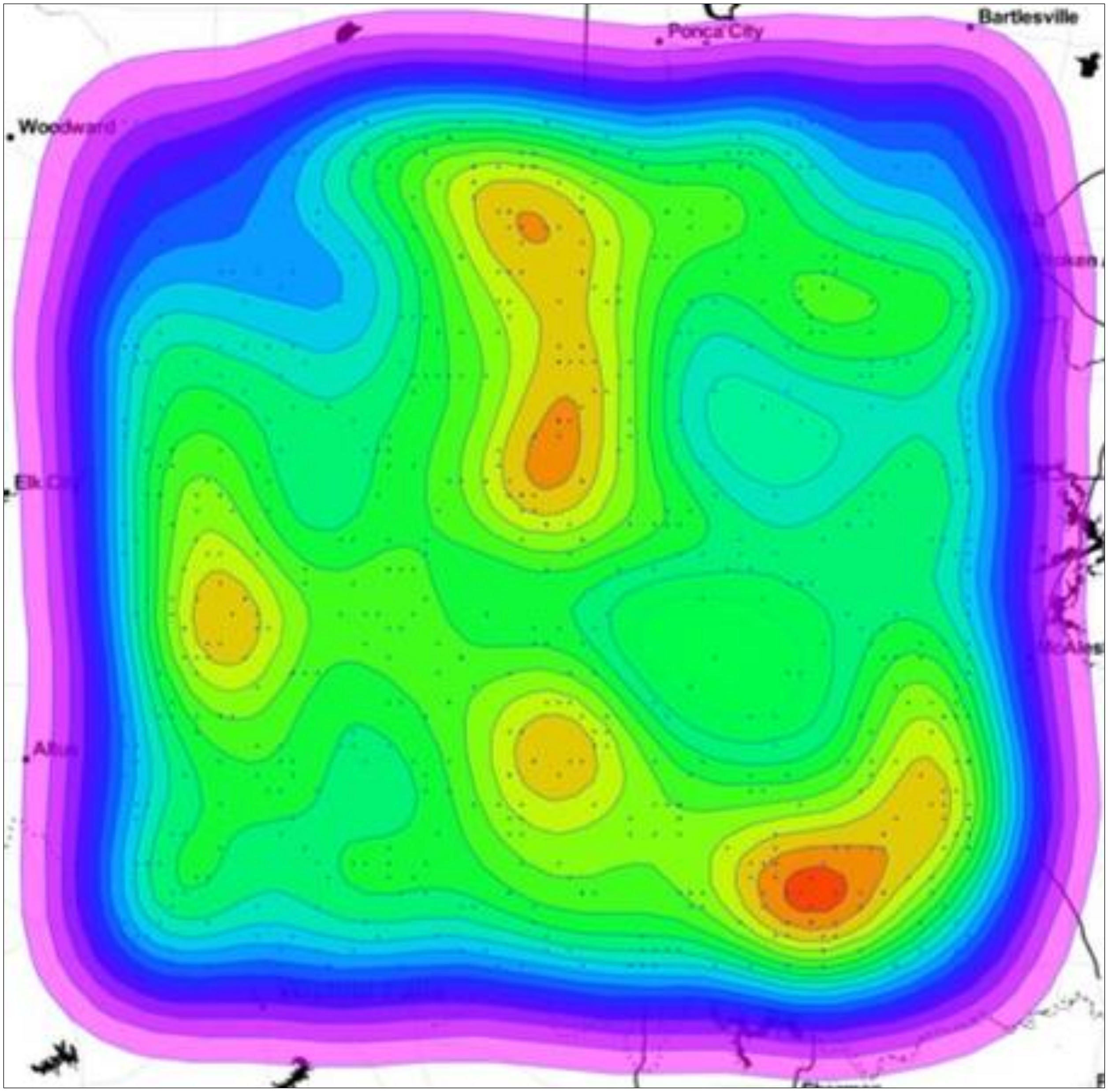

Figure 5: Map of heaviest rainfall for Oklahoma City, OK. There are a few areas of heavier rainfall, indicated by the orange bullseyes, but the heaviest rainfall, in both frequency and magnitude, is indicated by the red bullseye located southeast of the city. Oklahoma City is located in the center of the map.

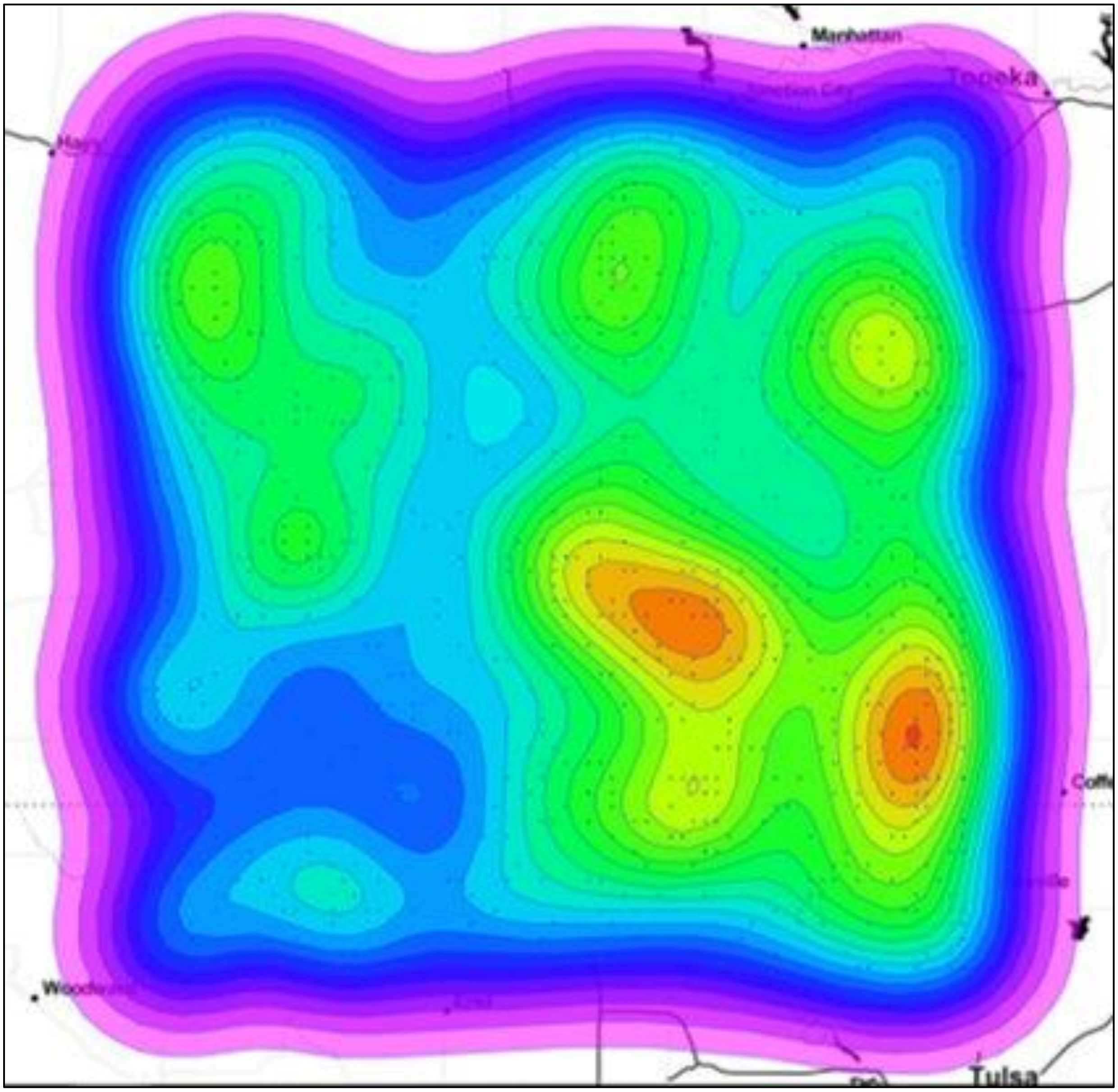

Figure 6: Map of heaviest rainfall frequency and magnitude for Wichita, KS. There are two maxima, both of which are downwind of the city. Wichita is located in the center of the map.

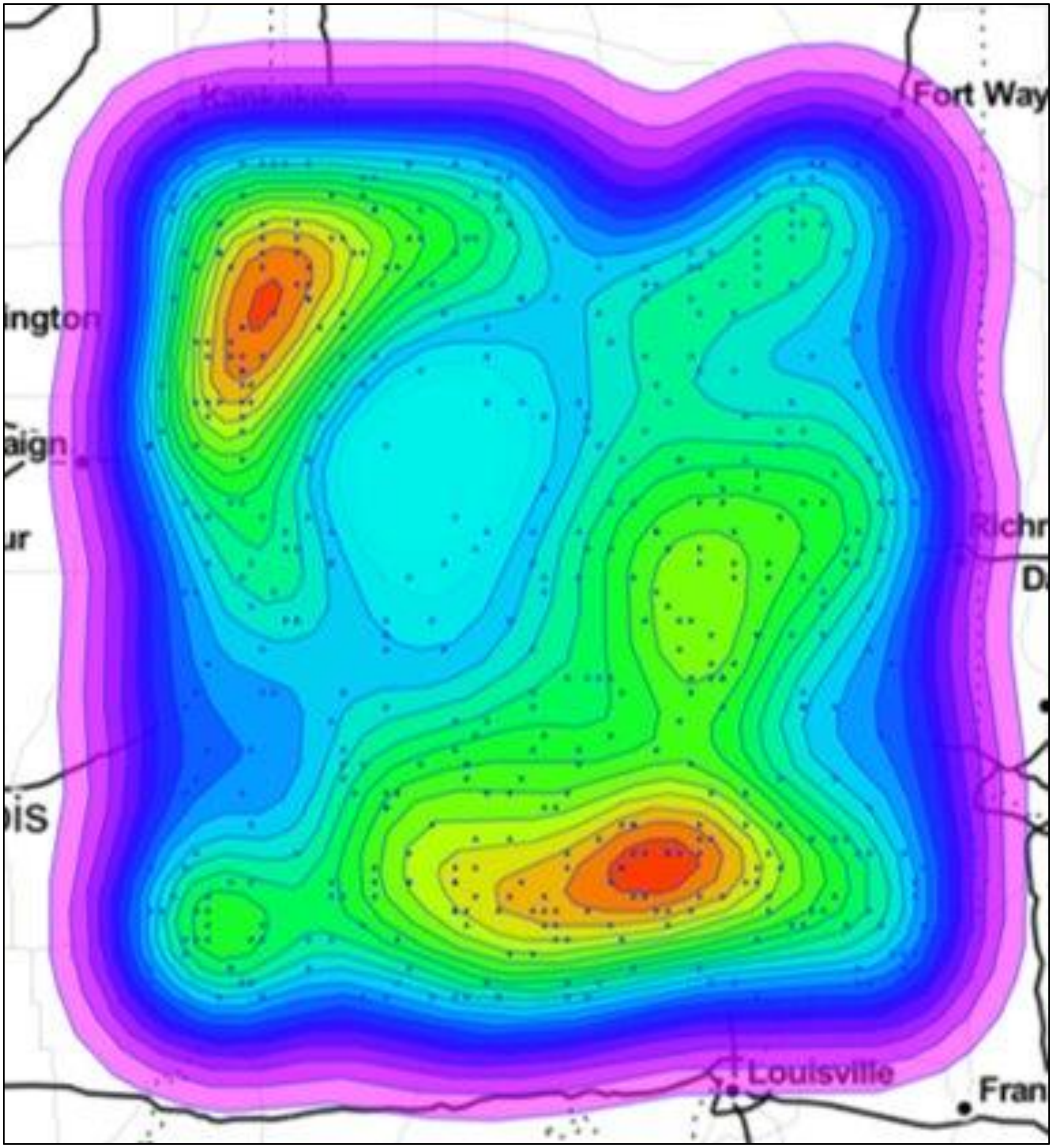

Figure 7: Map showing the frequency and magnitude of the heaviest rainfall for Indianapolis, IN. For this city, there are two very noticeable maxima, one located upwind of the city and one located downwind of the city. Indianapolis is located in the center of the map.

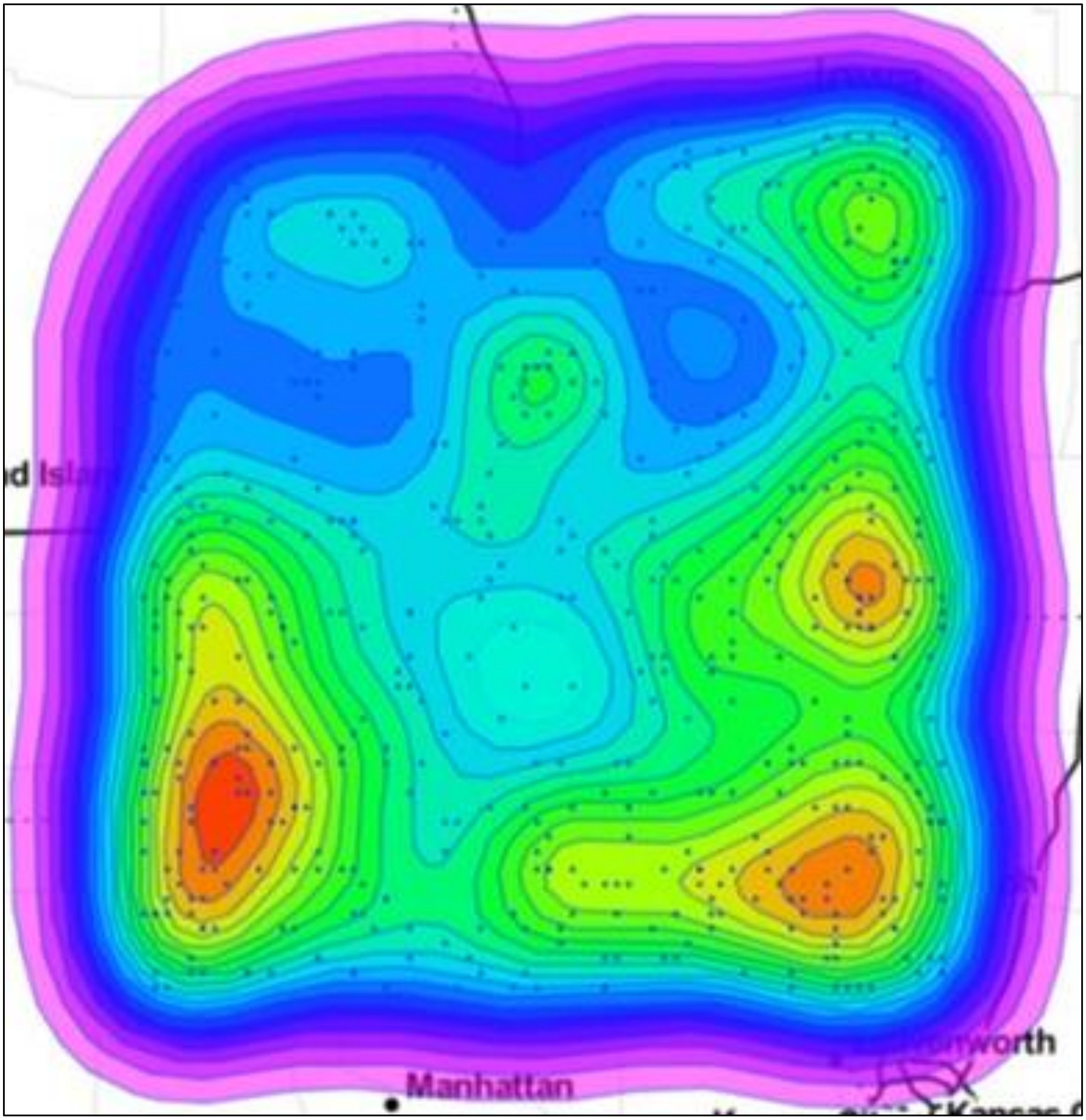

Figure 8: Rainfall map for Omaha, NE. The area of heaviest rainfall is located to the southwest of the city center, with a smaller maximum located in the southeast. Most of the cities have seen the area of heaviest rainfall southeast of the city. Omaha is located in the center of the map.

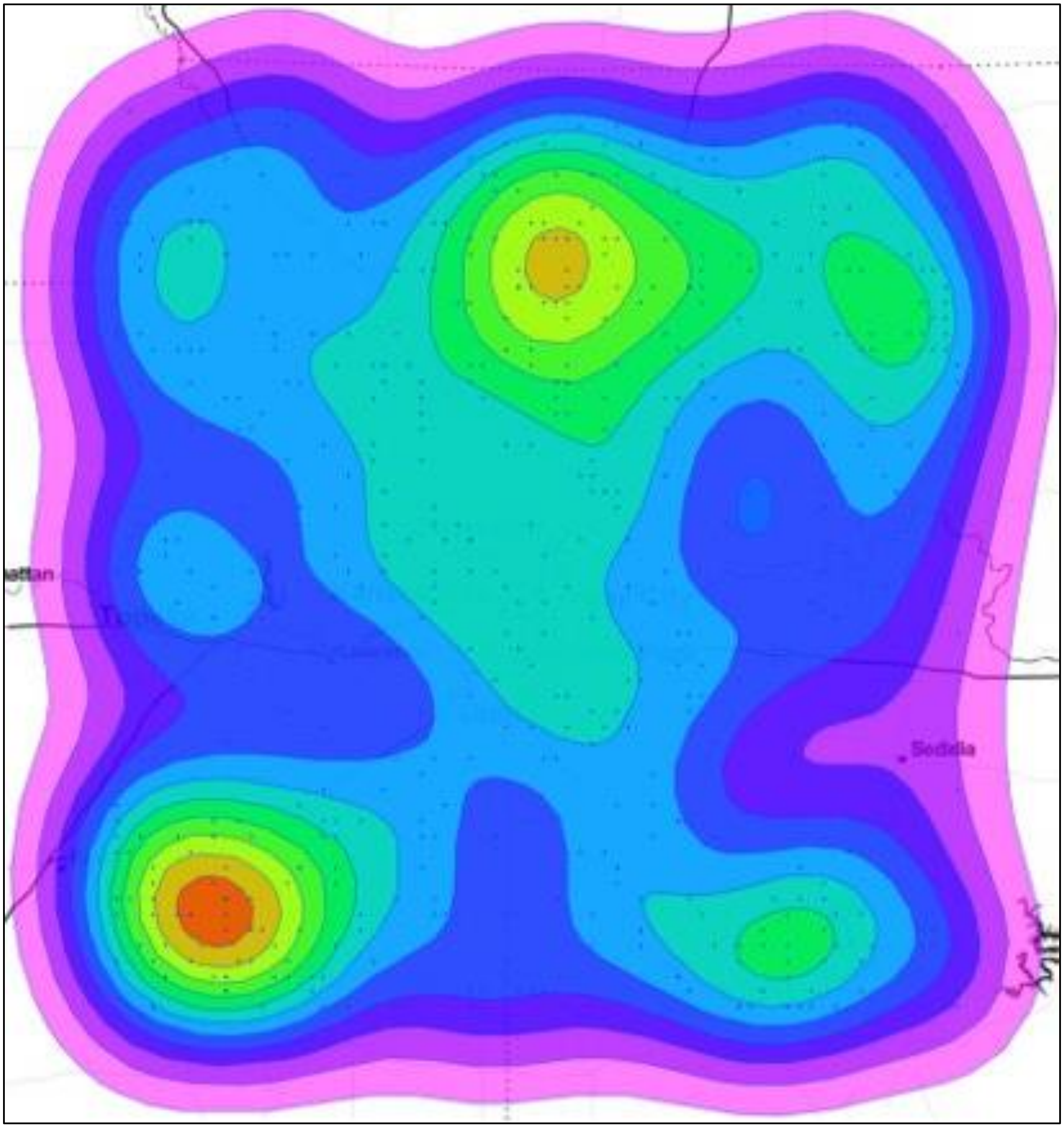

Figure 9: Map showing the heaviest rainfall frequency and magnitude for Kansas City, MO. There is a very well-defined area of heaviest rainfall located southwest of the city center. Kansas City is located in the center of the map.

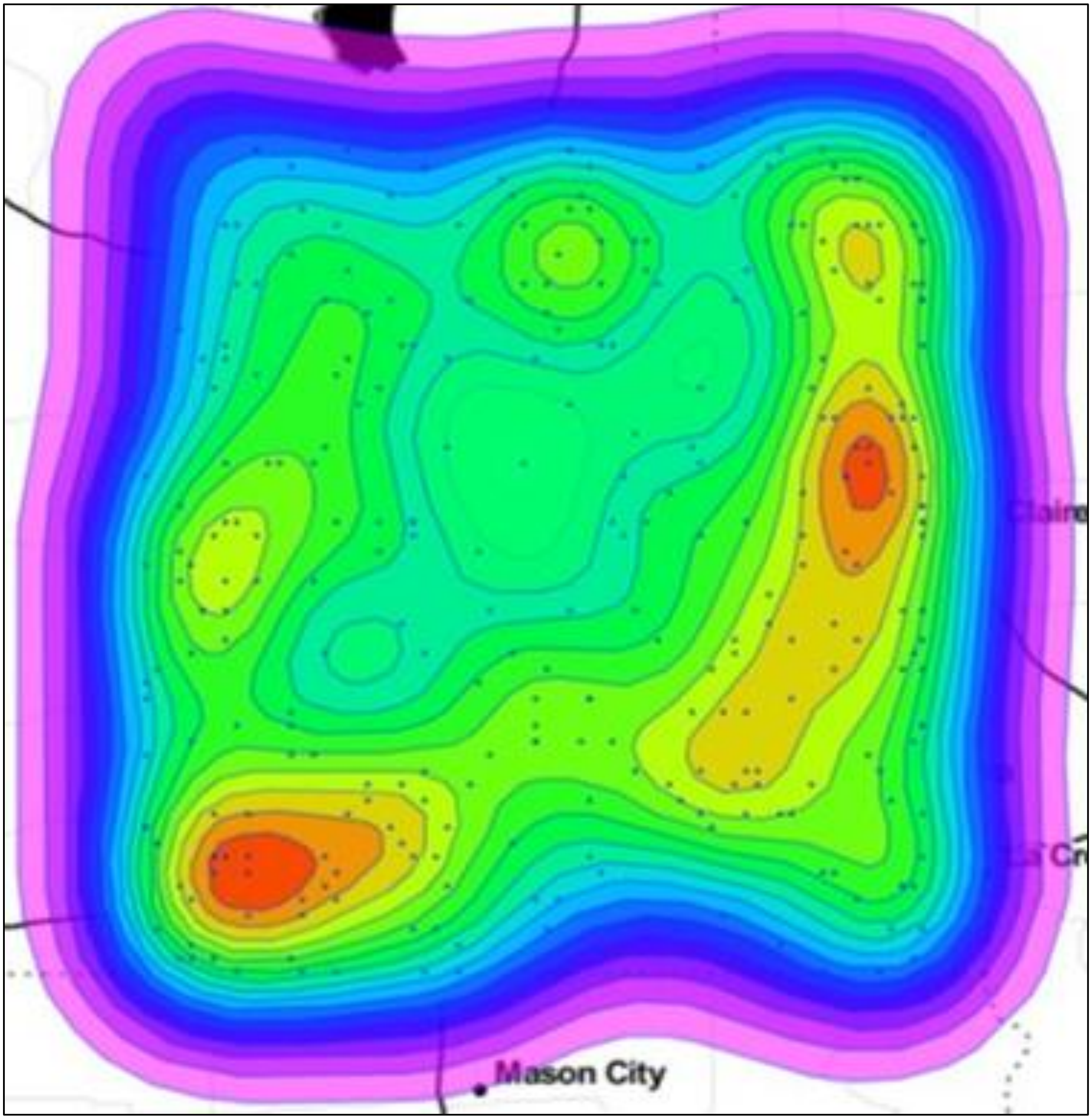

Figure 10: Map of heaviest rainfall for Minnesota, MN. There are two areas of heaviest rainfall frequency and magnitude. One is located to the southwest of the city and the other is to the direct east of the city. Minneapolis is located in the center of the map.

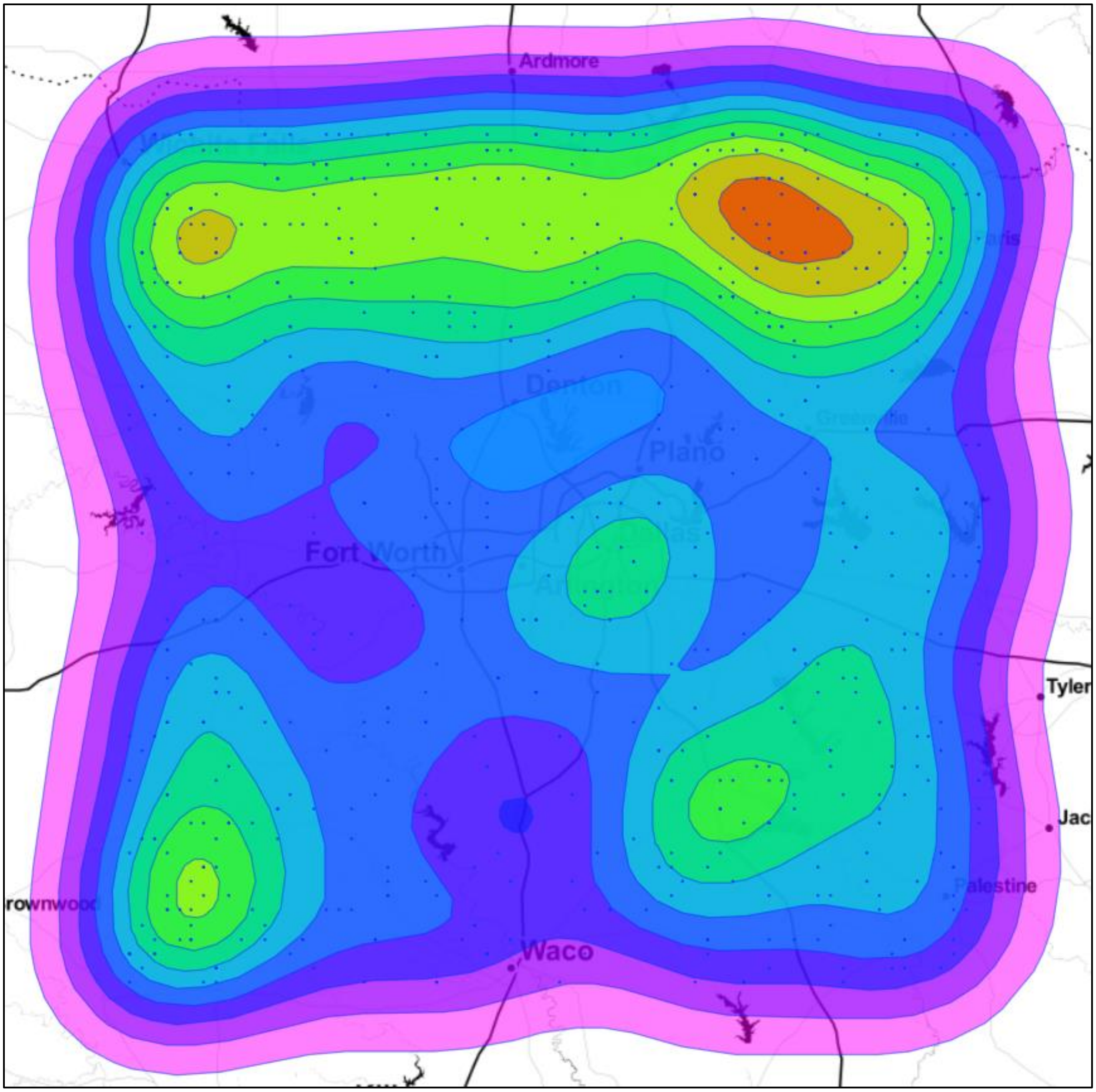

Figure 11: Map depicting the rainfall intensity for Dallas-Fort Worth, TX. The maximum heavy rainfall occurred northeast of the city. Dallas is located in the center of the map.

Precipitation Climatology

For all of the warm-season months from 1953 to 2003, the station with the highest rainfall was determined. In cases where the stations tied for the highest rainfall, it was counted in number for both of the stations; for example, if the rainfall total was tied for the downwind and upwind stations, it was counted in the total for both stations. For a majority of the cities, the downwind stations experienced more months with higher rainfall amounts compared to the other stations. For Chicago, Dallas-Fort Worth, and Saint Louis the upwind station experienced the most months with the highest rainfall values. For all of the cities, the city center station experienced the fewest months with the heaviest precipitation. The distribution of months for each station can be seen in Table 1. The distribution of the heaviest rainfall for each city can also be illustrated in Figures 12-21.

Table 1: This table shows the number of months each station had the highest rainfall amount from 1953-2003.

City	**Upwind**	**City Center**	**Downwind**
Chicago, IL	107	65	84
Dallas-Fort Worth, TX	107	65	86
Des Moines, IA	84	74	98
Indianapolis, IN	81	74	100
Kansas City, MO	99	54	103
Minneapolis, MN	89	72	94
Oklahoma City, OK	84	76	97
Omaha, NE	70	68	118
Saint Louis, MO	124	56	75
Wichita, KS	81	72	102

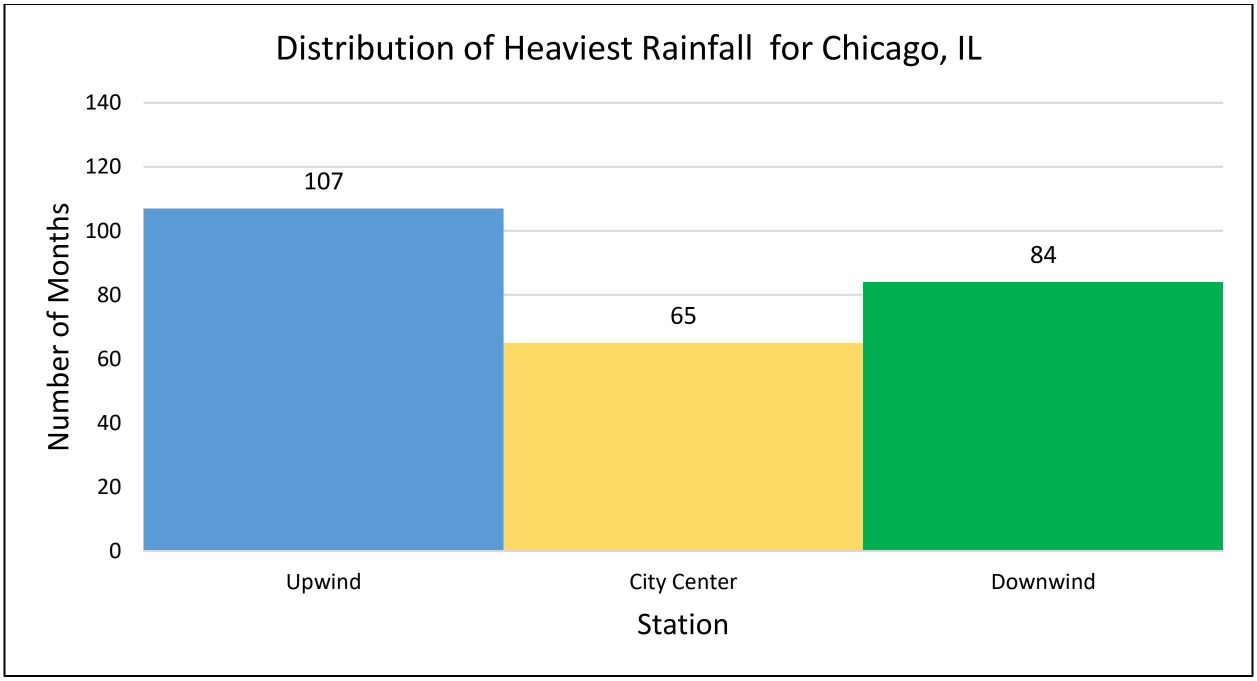

Figure 12: Distribution of heaviest rainfall for Chicago, IL. The upwind station had the most months of the heaviest rainfall.

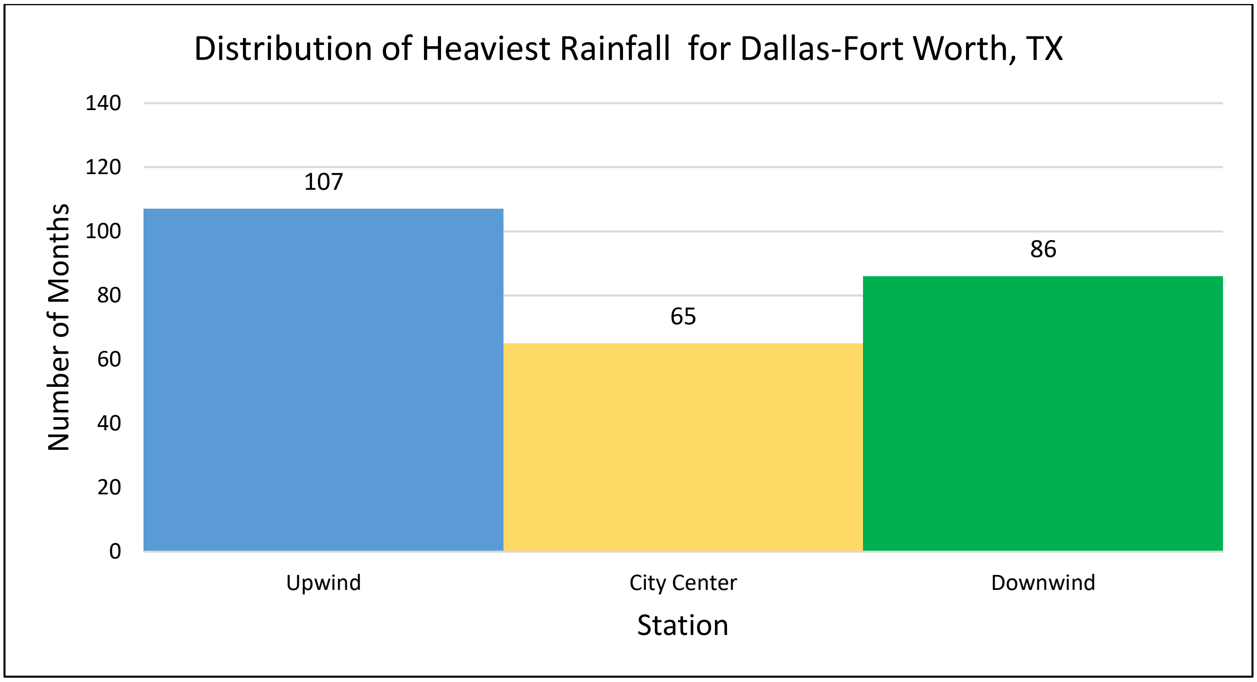

Figure 13: Distribution of the heaviest rainfall for Dallas-Fort Worth, TX. The upwind station had the most months of heaviest rainfall.

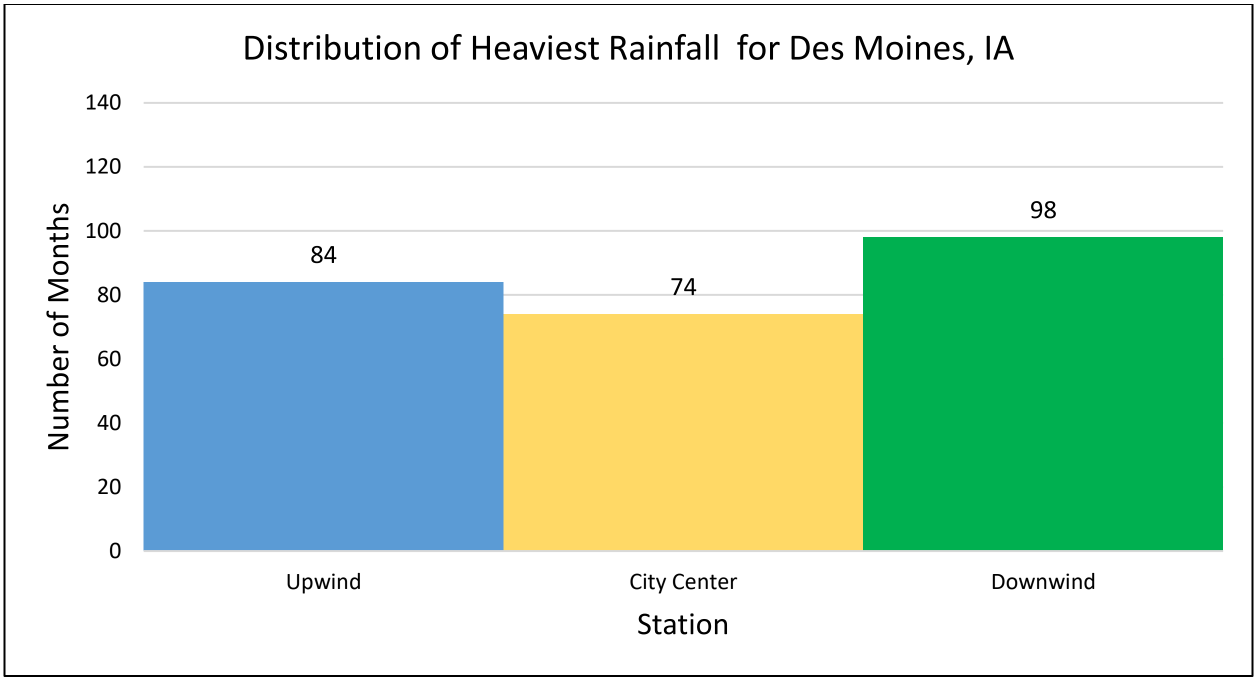

Figure 14: Distribution of the heaviest rainfall for Des Moines, IA. The downwind station had the most months of the heaviest rainfall.

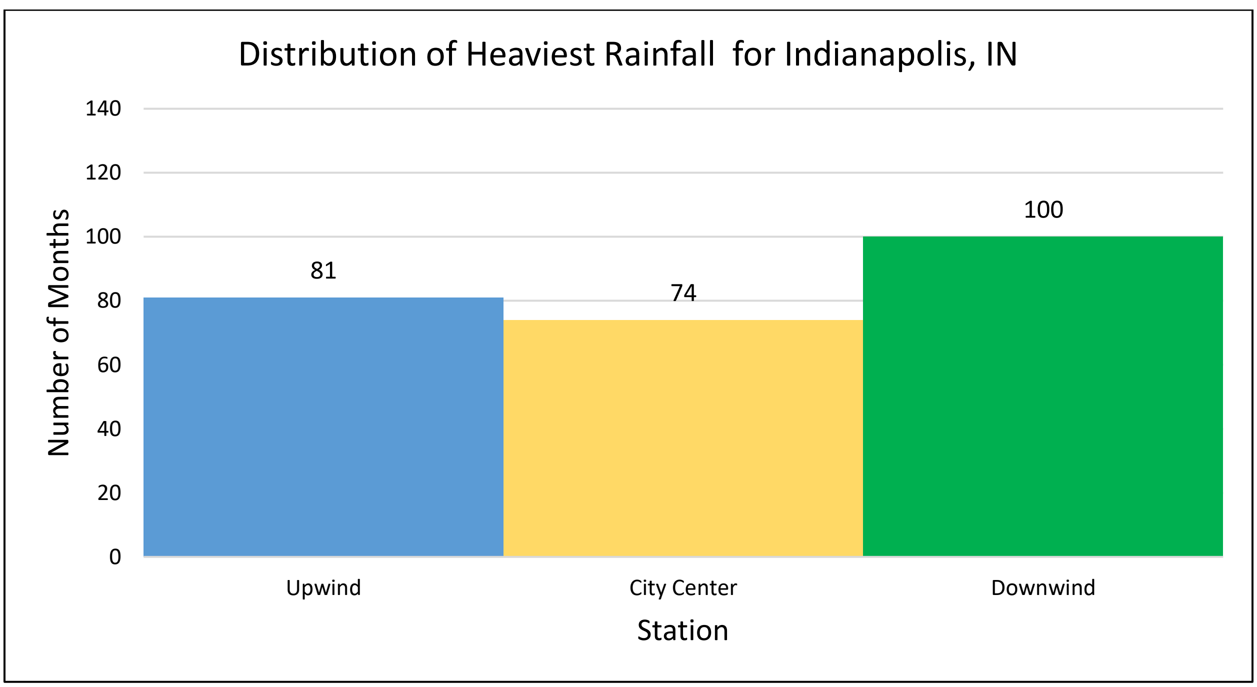

Figure 15: The distribution of the heaviest rainfall for Indianapolis, IN. The downwind station had the most months of the heaviest rainfall.

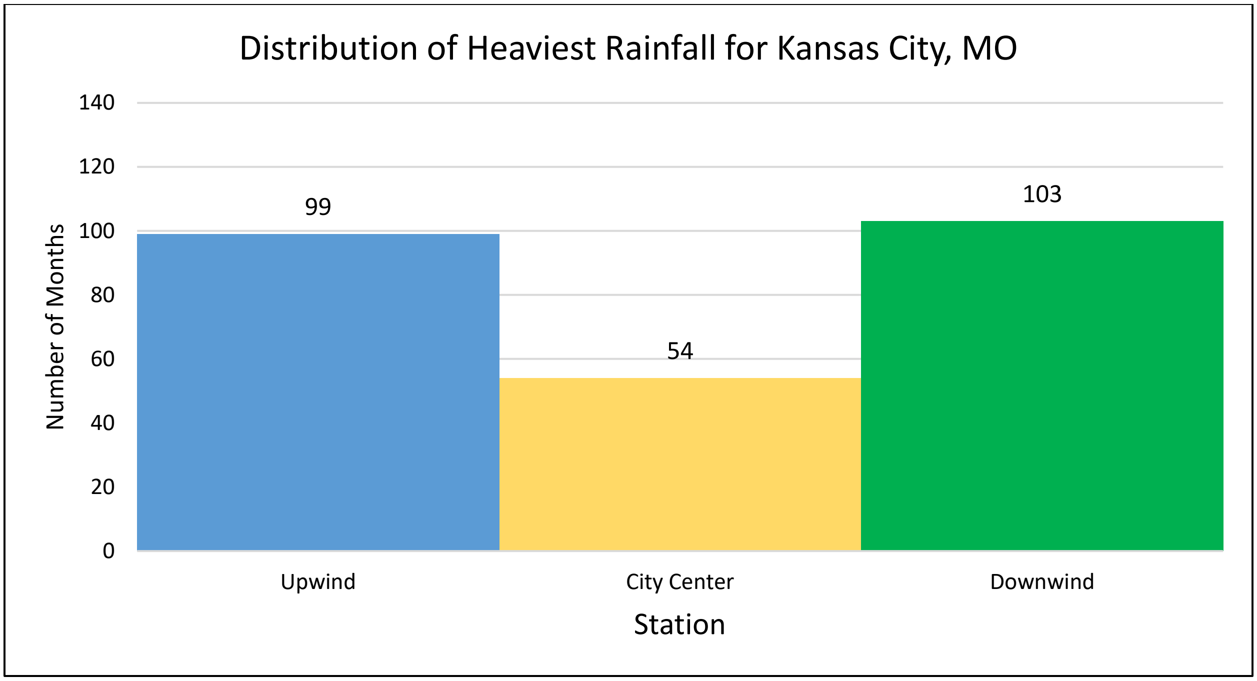

Figure 16: The distribution of heaviest rainfall for Kansas City, MO. The downwind station had the most months of the heaviest rainfall.

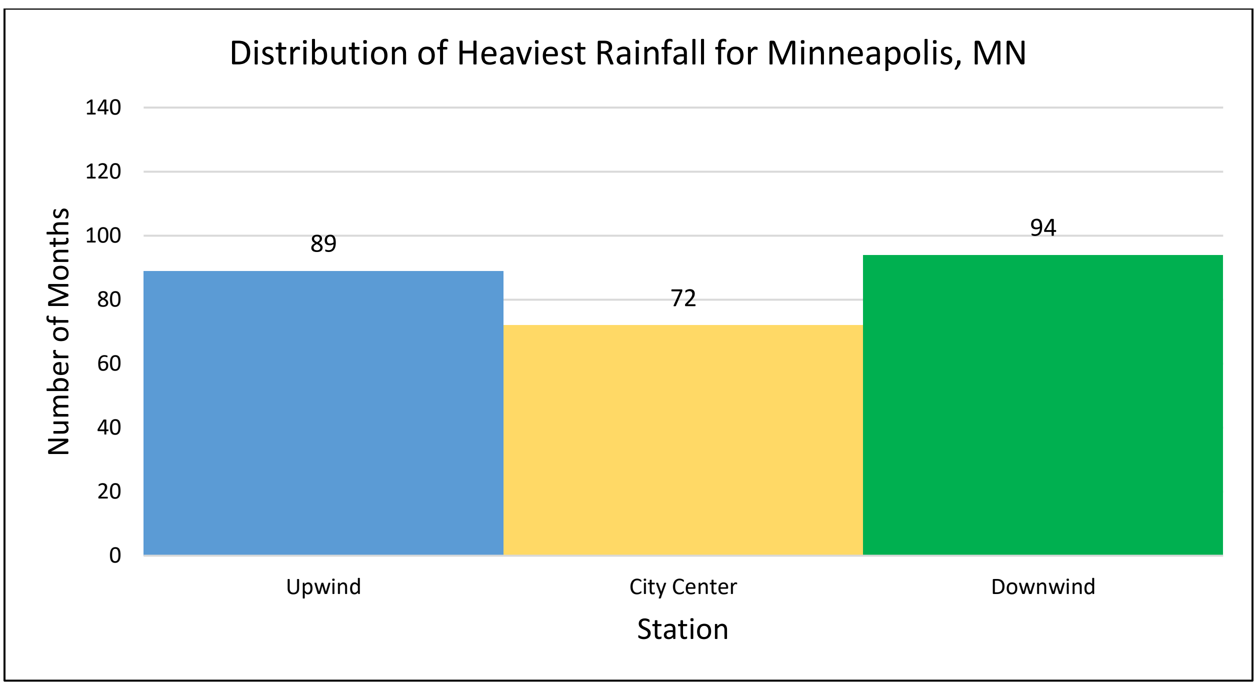

Figure 17: The distribution of heaviest rainfall for Minneapolis, MN. The downwind station has the most months with the heaviest rainfall.

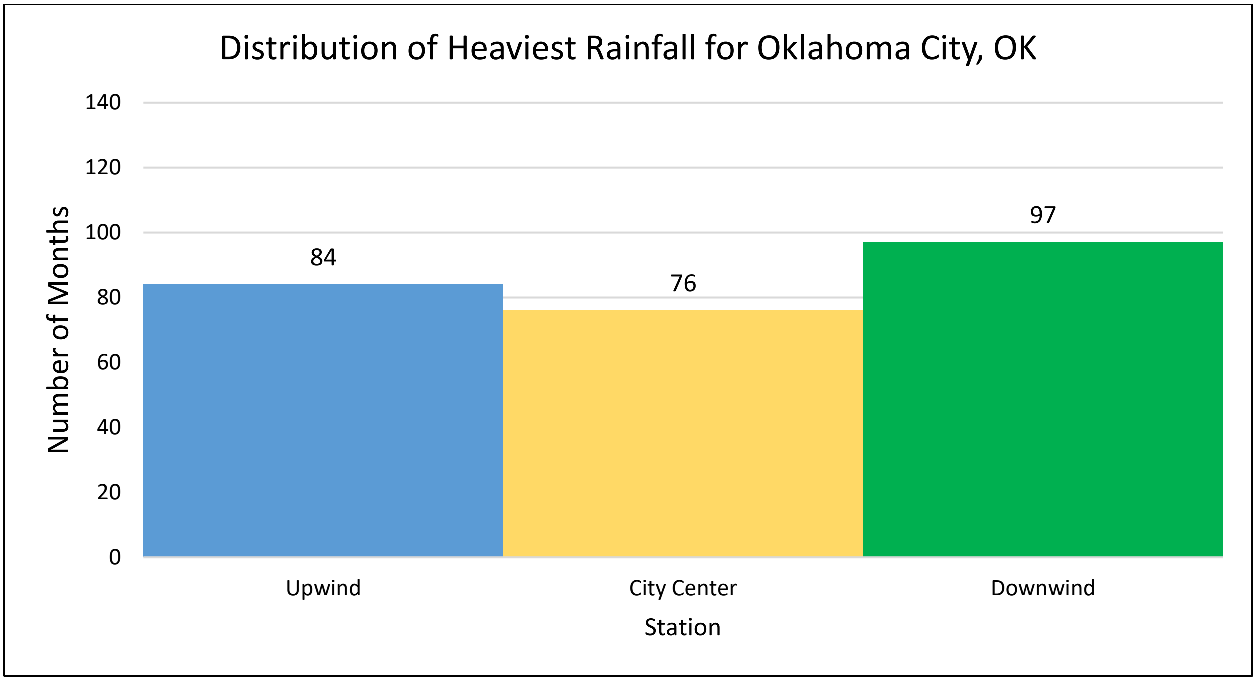

Figure 18: Distribution of the heaviest rainfall for Oklahoma City, OK. The downwind station has the most months with the heaviest rainfall.

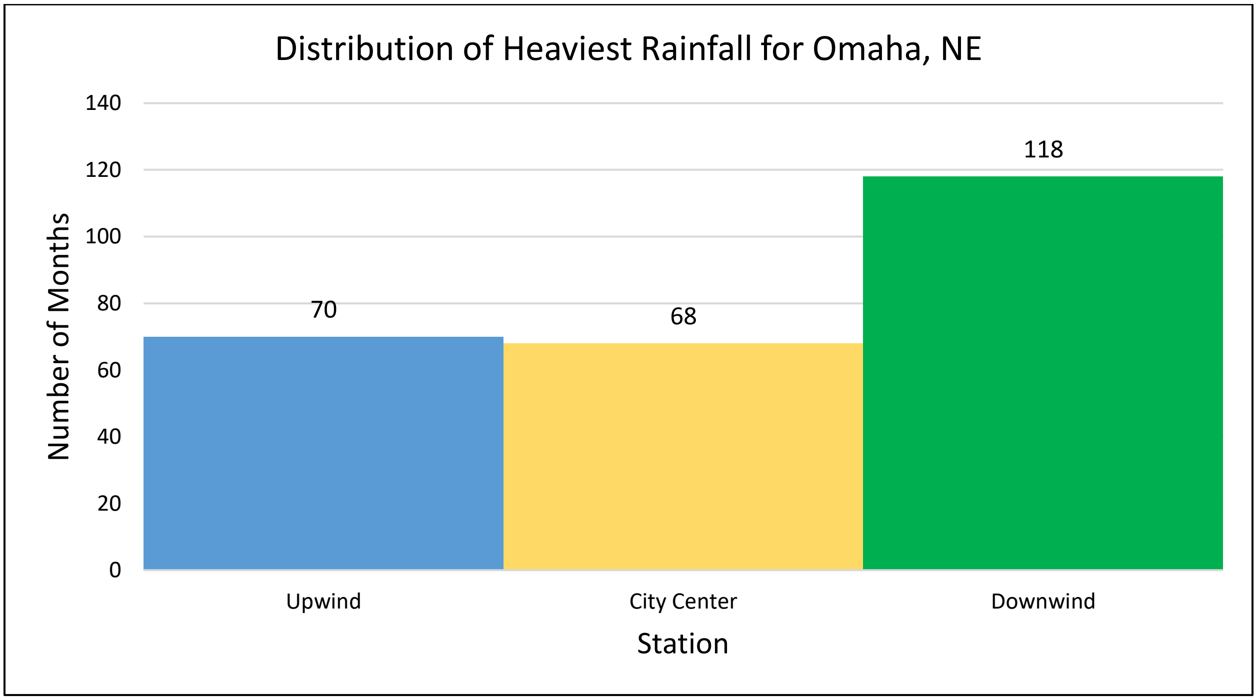

Figure 19: Distribution of heaviest rainfall for Omaha, NE. The downwind station had the most months with the heaviest rainfall.

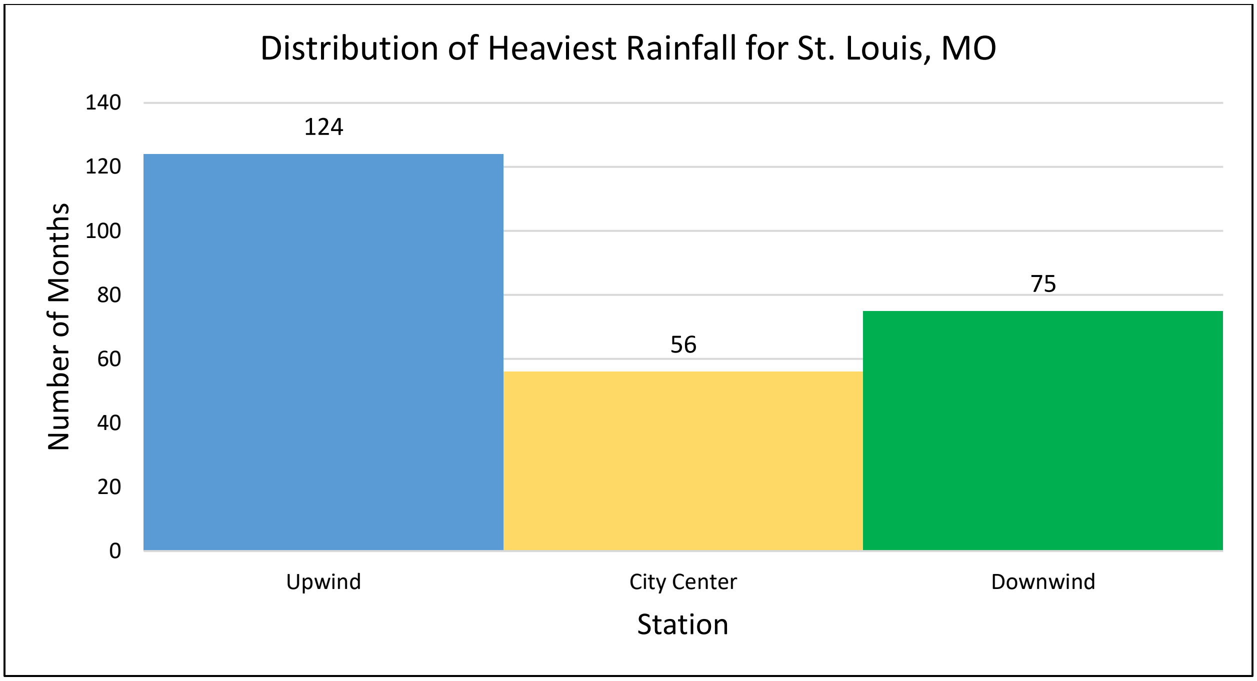

Figure 20: Distribution of heaviest rainfall for Saint Louis, MO. The upwind station had the most months with the highest rainfall.

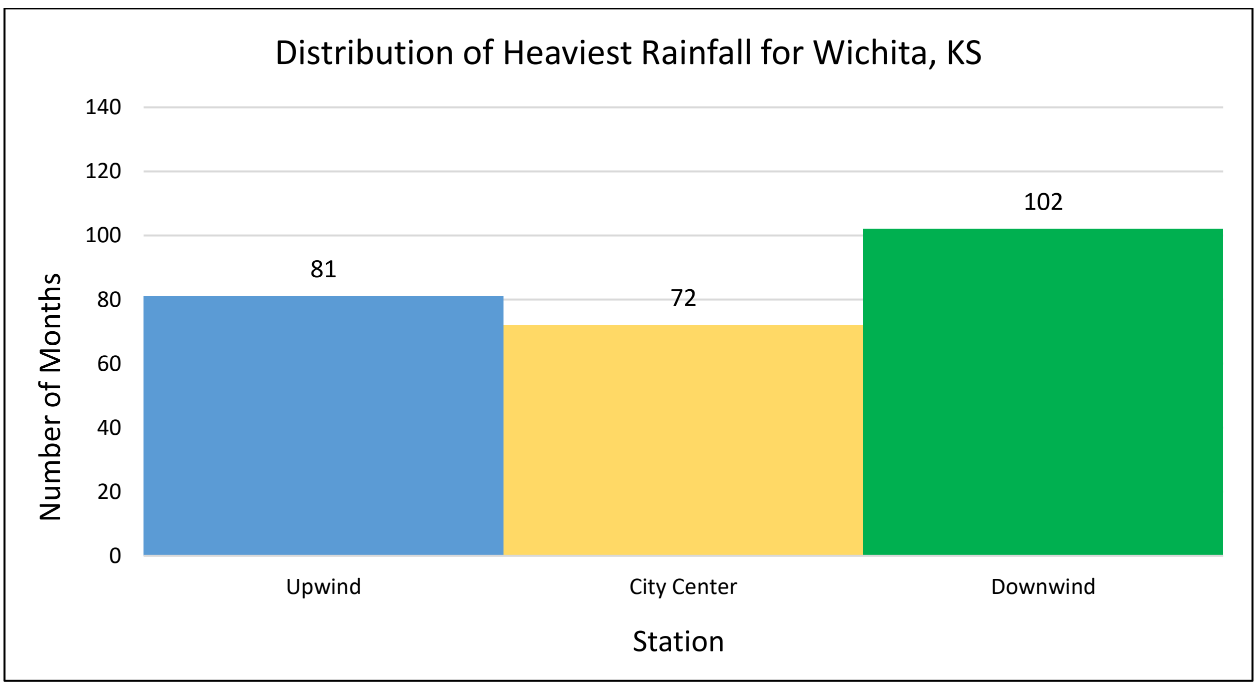

Figure 21: Distribution of heaviest rainfall for Wichita, KS. The downwind station had the most months of heaviest rainfall.

The yearly average warm-season precipitation for each station was also calculated. Since monthly precipitation data was collected, the average warm-season precipitation was the average of the precipitation amounts for the 5 warm season months (May to September). This process was repeated for each station, for each year. Figures 22-31 show the warm-season climatology for each city and station from 1953 to 2003. Table 2 shows the average rainfall for each station over the entire 51-year period. For the most part, the station that had the highest average rainfall amount corresponded to the station that had the most months of heaviest rainfall; the only exception to this is Kansas City, where the downwind station had the greatest number of months, but the upwind station had the highest average rainfall out of the three stations.

Table 2: Average rainfall from 1953 to 2003 for each station in inches

City	**Upwind**	**City Center**	**Downwind**
Chicago, IL	4.033	3.729	3.839
Dallas-Fort Worth, TX	3.142	3.084	3.133
Des Moines, IA	3.949	3.912	4.255
Indianapolis, IN	3.754	3.801	3.956
Kansas City, MO	4.567	3.809	4.441
Minneapolis, MN	3.480	3.594	3.762
Oklahoma City, OK	3.751	3.767	4.030
Omaha, NE	3.705	3.833	4.477
Saint Louis, MO	4.051	3.510	3.640
Wichita, KS	3.215	3.627	3.922

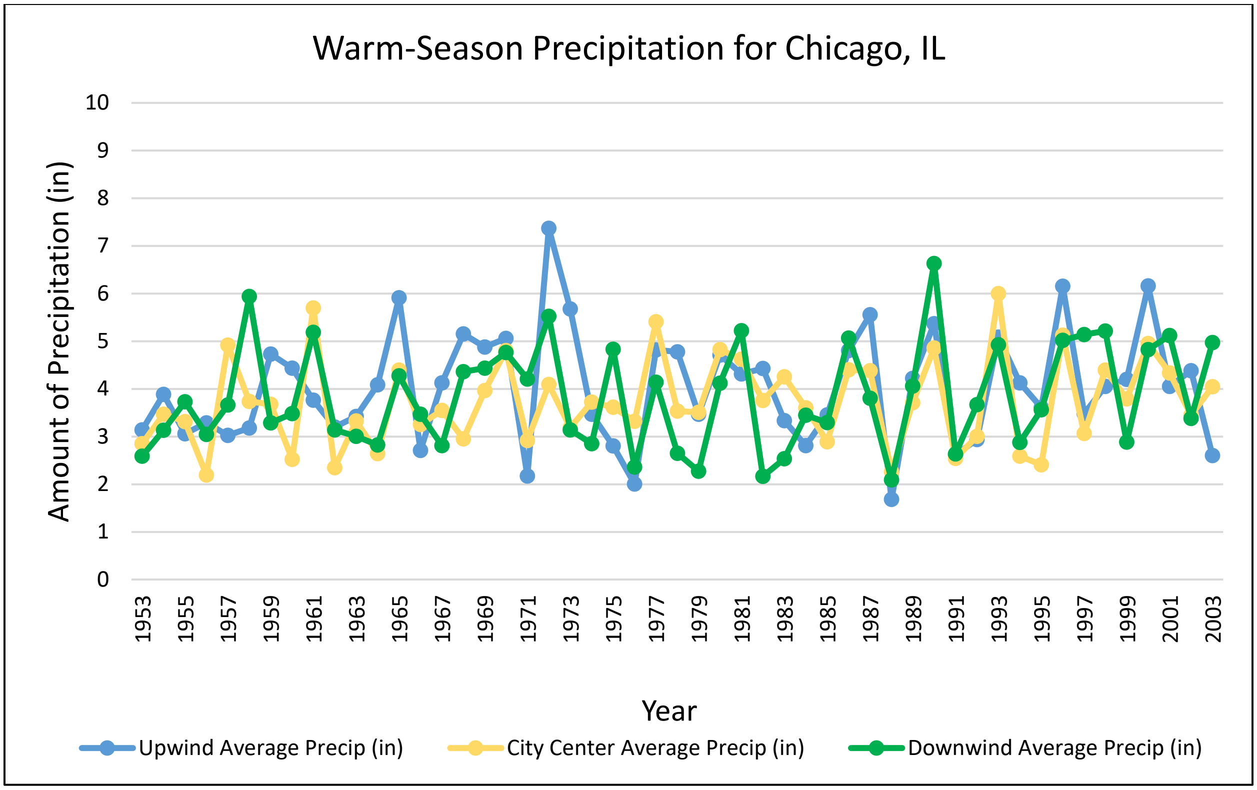

Figure 22: Warm-season precipitation climatology for Chicago, IL from 1953-2003.

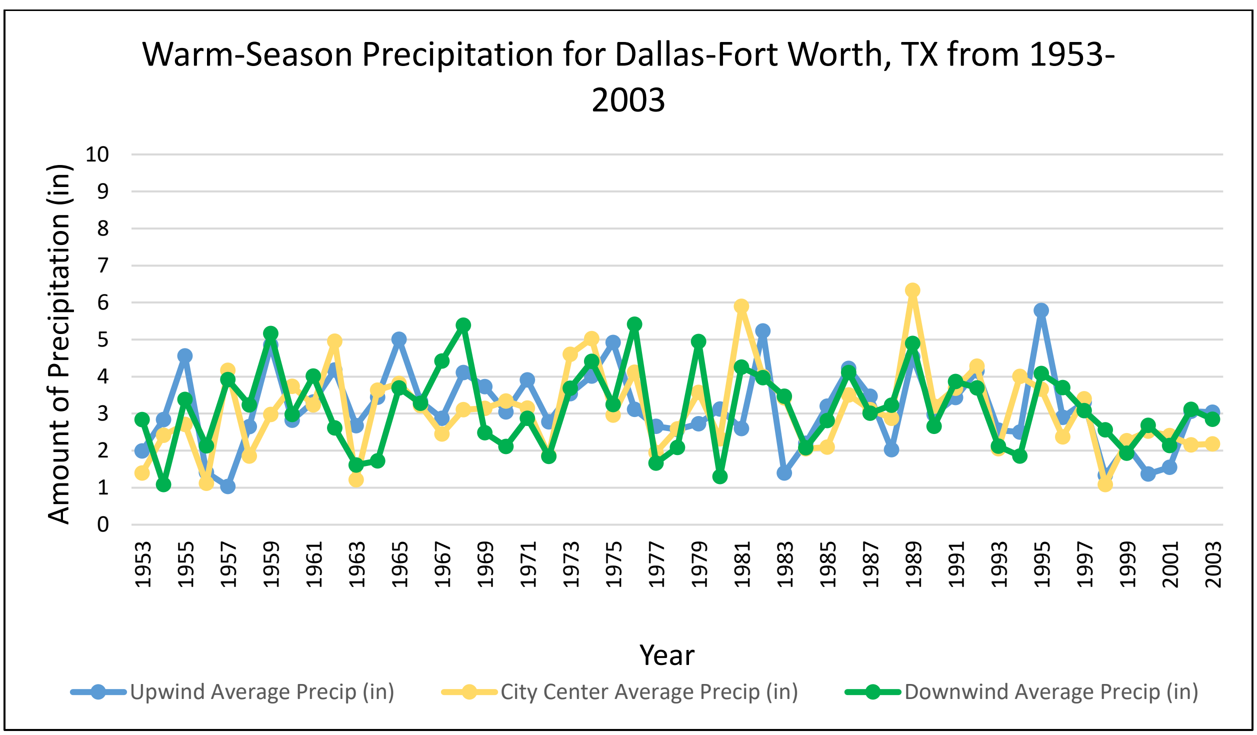

Figure 23: Warm-season precipitation climatology for Dallas-Fort Worth, TX from 1953-2003.

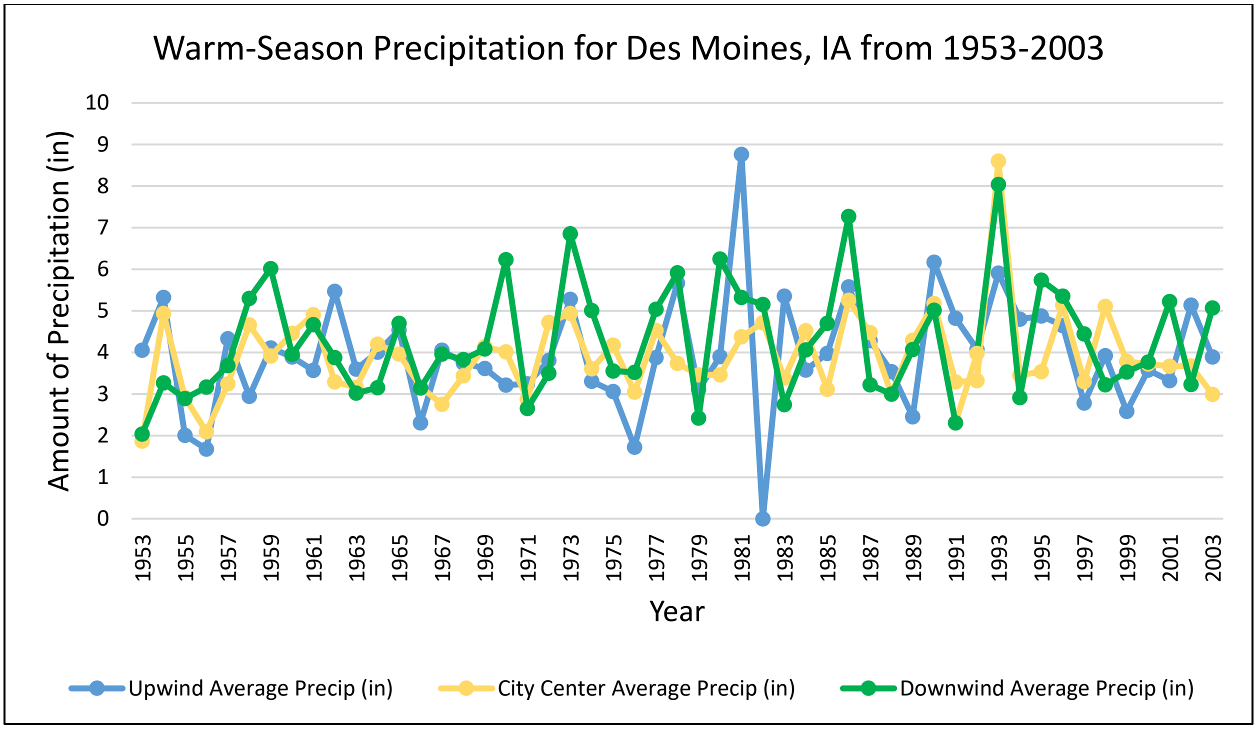

Figure 24: Warm-season precipitation climatology for Des Moines, IA from 1953-2003.

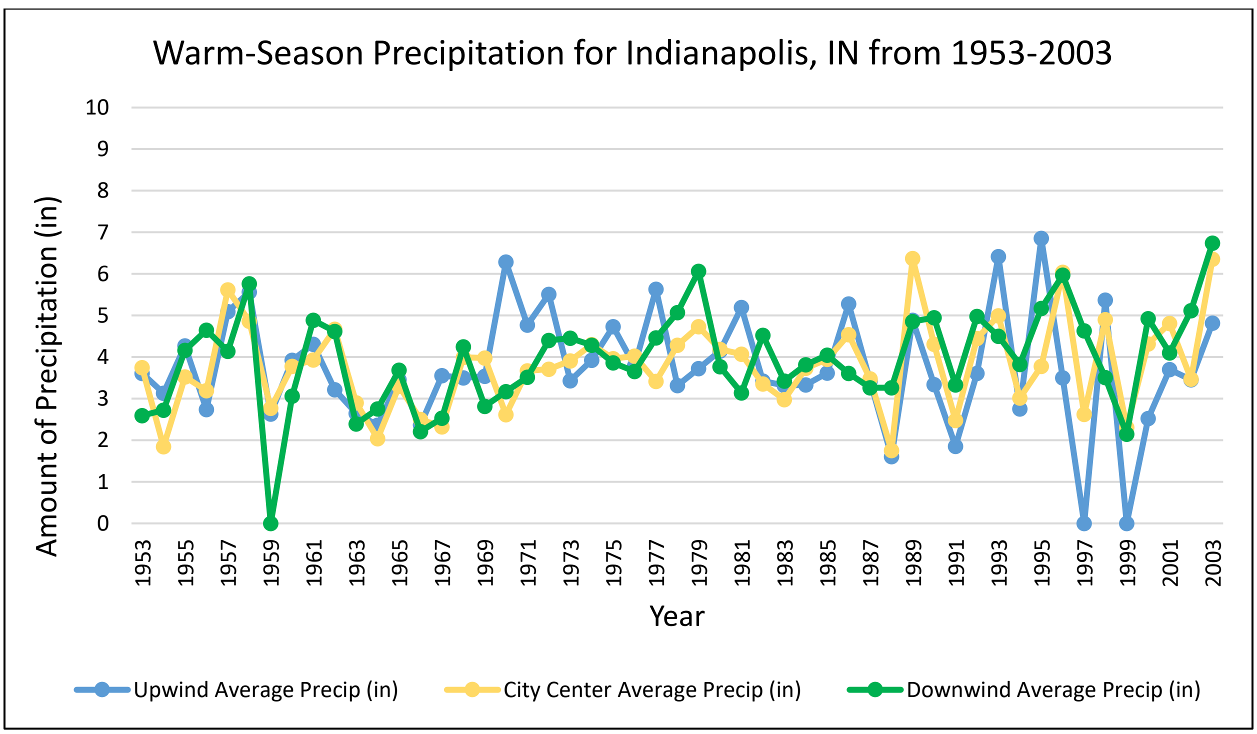

Figure 25: Warm-season precipitation climatology for Indianapolis, IN from 1953-2003.

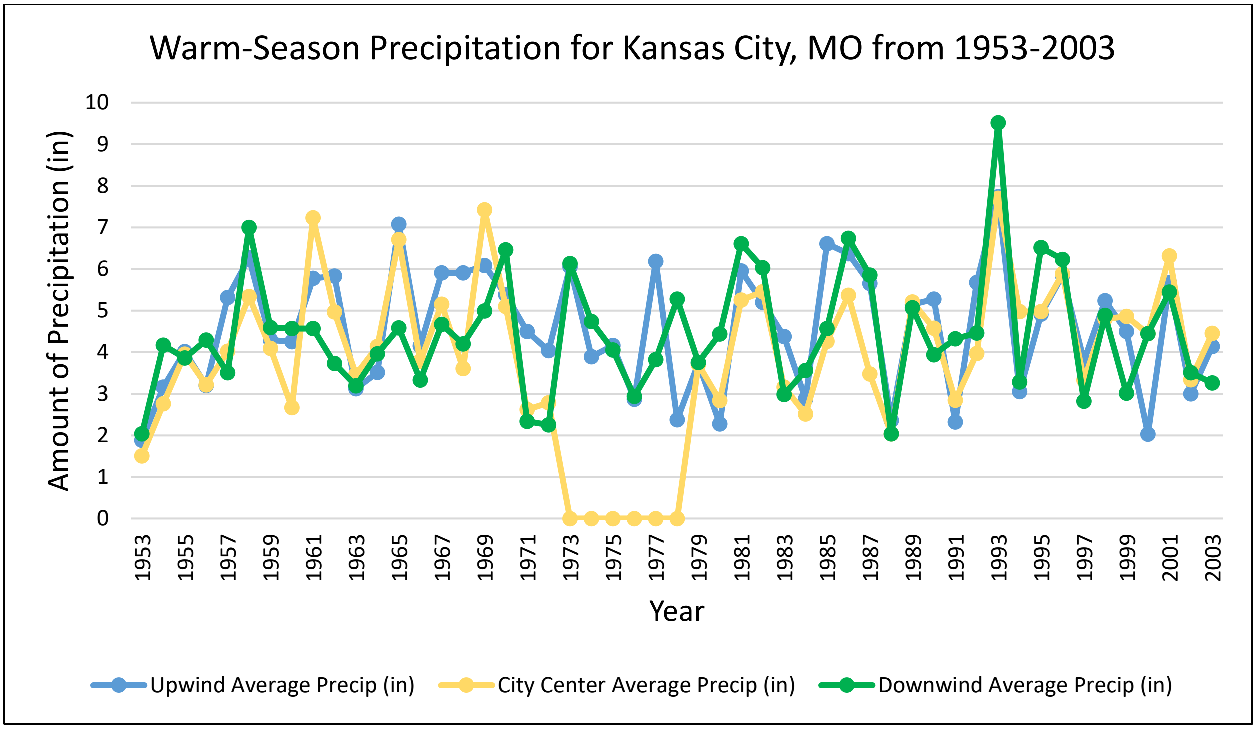

Figure 26: Warm-season precipitation climatology for Kansas City, MO from 1953-2003.

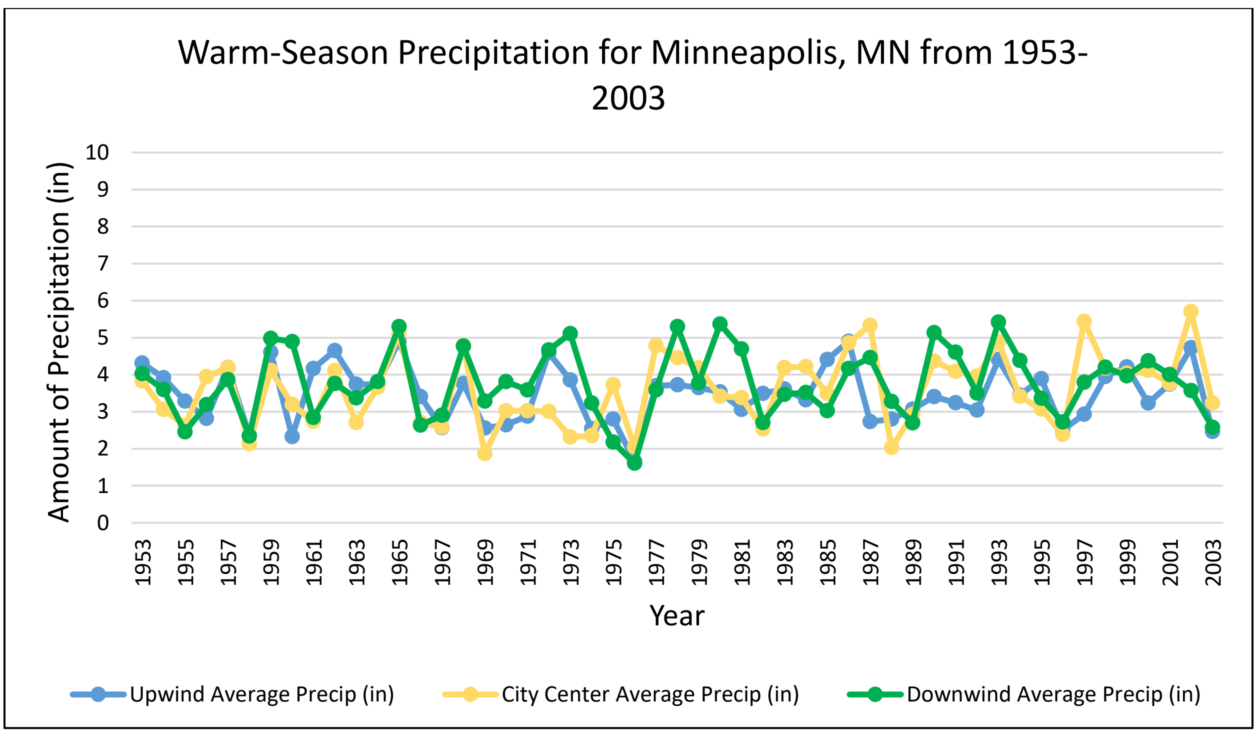

Figure 27: Warm-season precipitation climatology for Minneapolis, MN from 1953-2003.

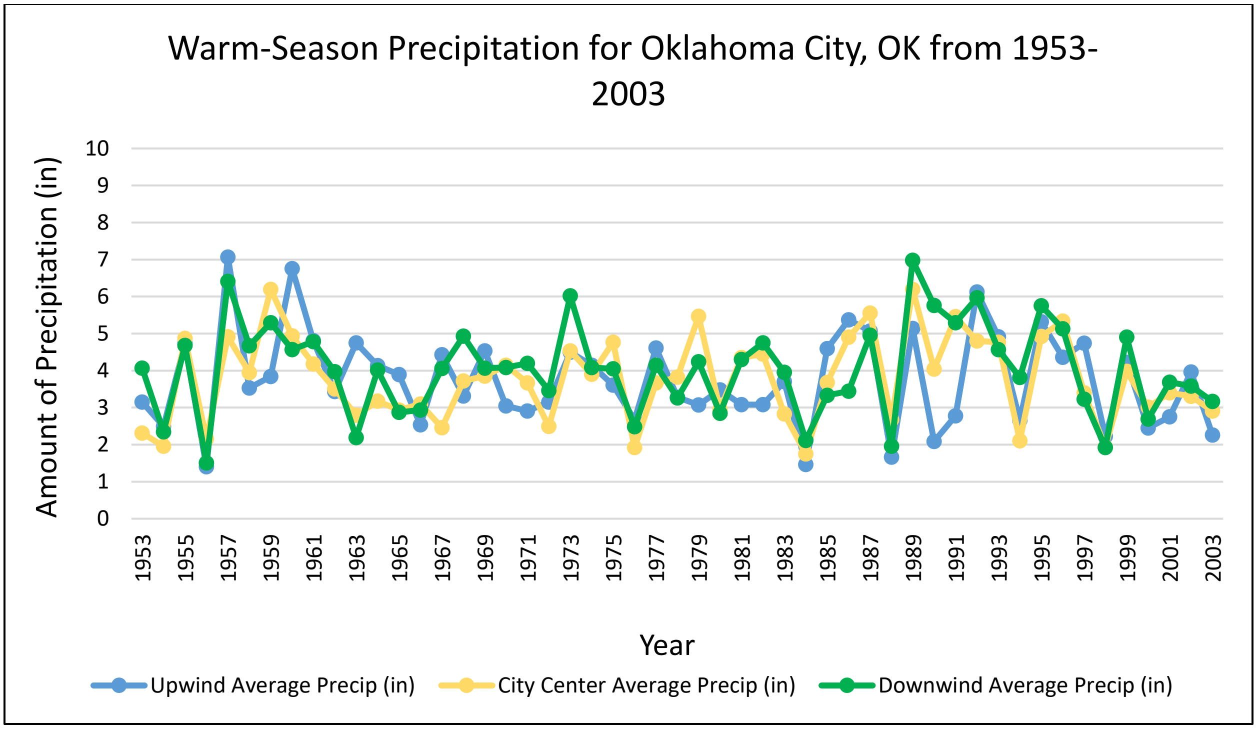

Figure 28: Warm-season precipitation climatology for Oklahoma City, OK from 1953-2003.

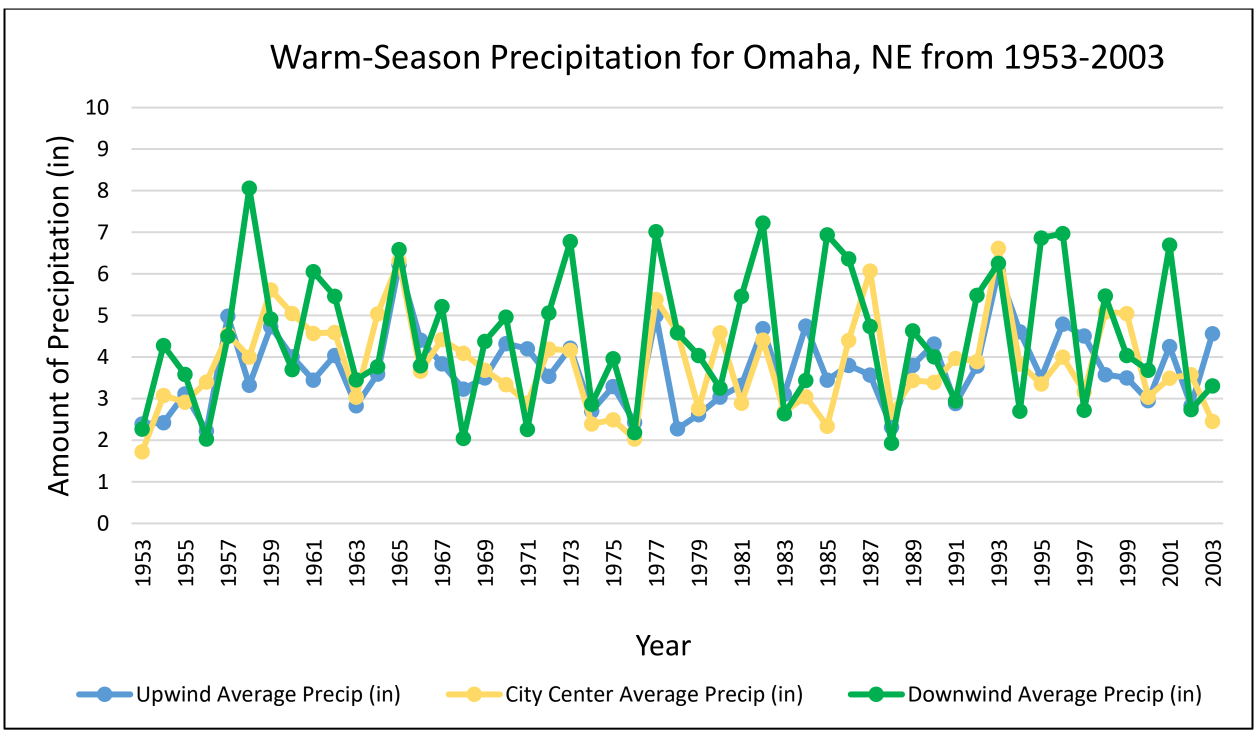

Figure 29: Warm-season precipitation for Omaha, NE from 1953-2003.

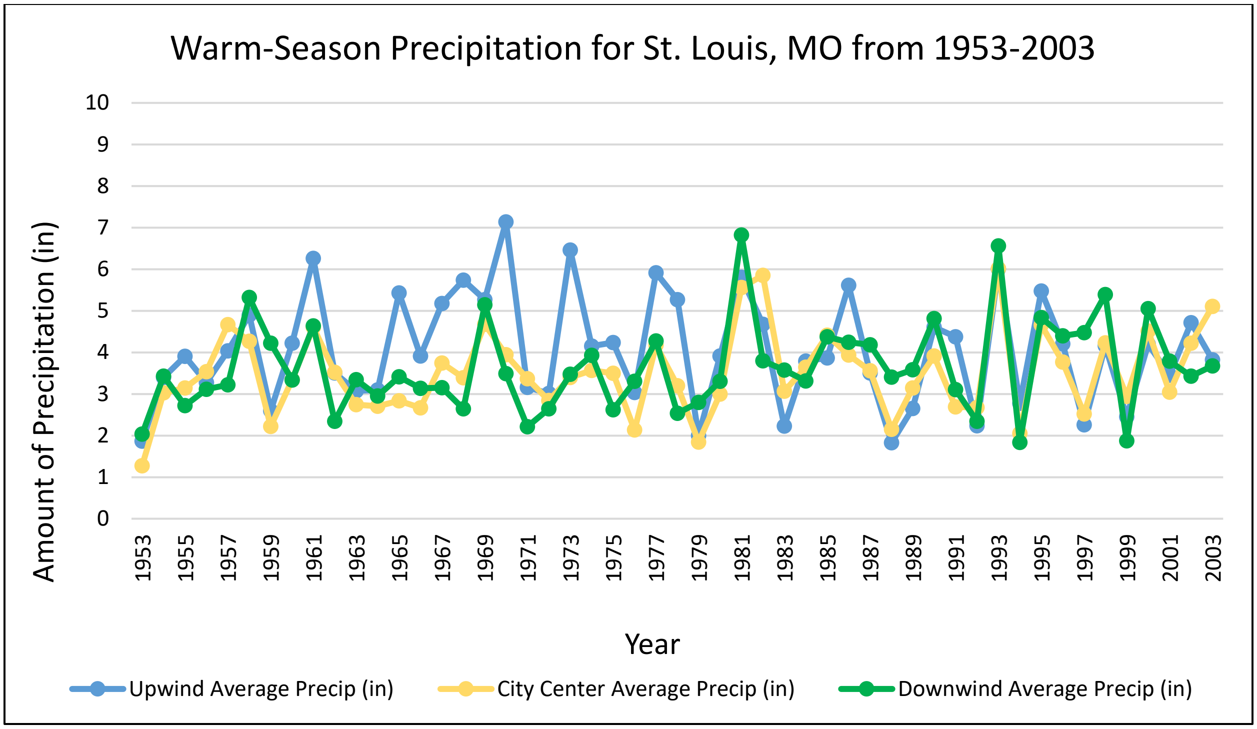

Figure 30: Warm-season precipitation climatology for Saint Louis, MO from 1953-2003.

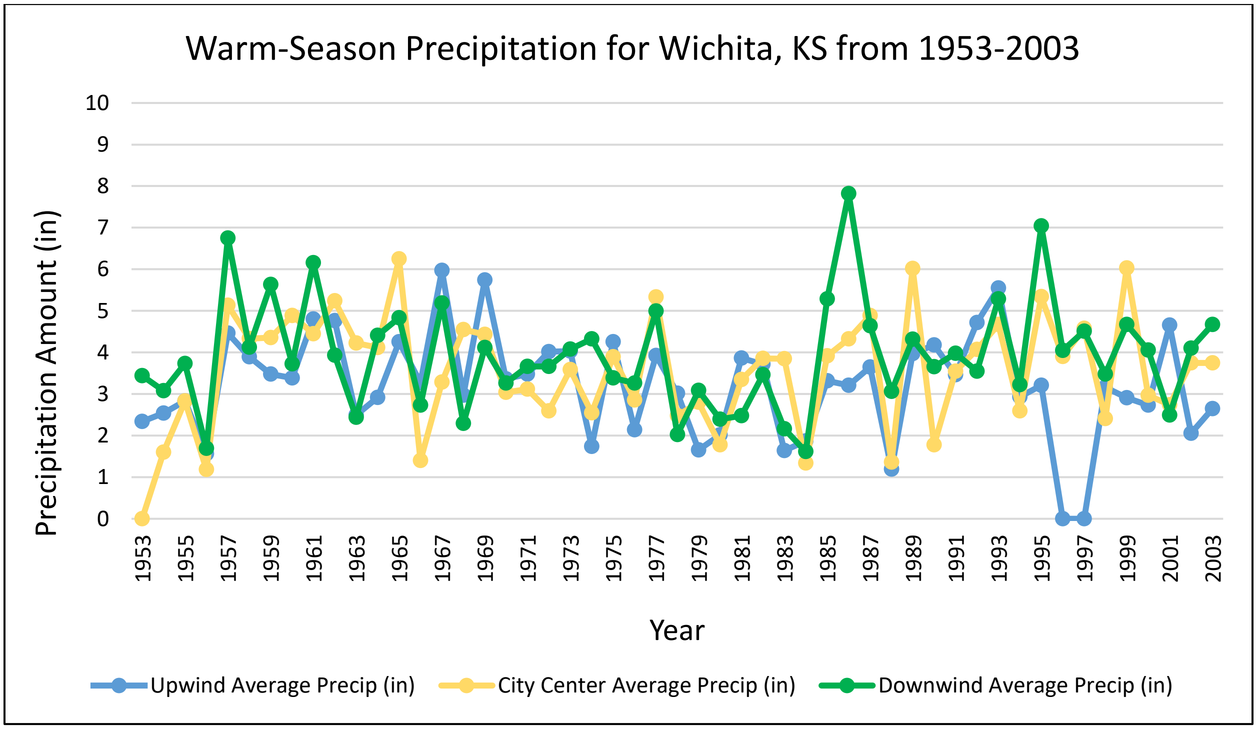

Figure 31: Warm-season precipitation climatology for Wichita, KS from 1953-2003.

Discussion

Conclusions

When looking at both the Stage IV data and the NCEI precipitation data, there appears to be heavier rainfall downwind of the urban environments. For Omaha (Figure 8, Figure 19), Des Moines (Figure 4, Figure 14), Wichita (Figure 6, Figure 21), Oklahoma City (Figure 5, Figure 18), and Indianapolis (Figure 7, Figure 15) the Stage IV data and NCEI data indicate maximum rainfall downwind of the city. The Stage IV precipitation for Minneapolis (Figure 10) indicated maximum precipitation to the southwest and west of the city, which is not quite where the downwind station is; however, the NCEI data (Table 1, Table 2) shows that the downwind station experienced the heaviest rainfall. For Chicago the Stage IV data (Figure 3) shows the heaviest rainfall downwind of the city, however the NCEI data (Table 1, Table 2) show heavier precipitation at the upwind station. The same scenario is also seen in Saint Louis; the Stage IV indicated a strong downwind maximum in the rainfall (Figure 2), but the NCEI data depicted heavier rainfall upwind of the city (Figure 20). The two data sets cover two different time periods, so that is one explanation for the differences in the Stage IV and NCEI data; additionally the Stage IV data examines heavy rainfall cases where maximum rainfall is greater than 2 inches, while the NCEI data is just the monthly precipitation, and does not separate heavy rainfall events. Dallas-Fort Worth is the other city that had the heaviest rainfall upwind of the city center (Table 1, Table 2); the Stage IV data (Figure 11) indicated precipitation maxima to the north of the city center. Kansas City is also an interesting case, since the Stage IV (Figure 9) maximum was located to the southwest of the city center; the NCEI data was also interesting because the downwind station had the most months with the heaviest rainfall for the 1953-2003 warm-season months, however the upwind station had the largest average rainfall amount (Table 2).

Every city, with the exception of Dallas-Fort Worth indicated heavier rainfall downwind of the city in comparison to the upwind and city center stations. While this data is not the only indicator of the urban influences on rainfall intensity, there is strong evidence that urbanization increases the rainfall intensity downwind of the city.

Limitations

There are several limitations to the research done in this project. Firstly, the Stage IV data only spans a 15-year period, so it is not enough to indicate specific trends and the impacts urbanization can have on heavy rainfall intensity. This study also does not have enough data to verify if the apparent increase in intensity downwind of the cities is actual due to the urban areas influencing the environment. Some of the stations were also missing some data, which may have influenced some of the findings in the precipitation climatology. Additionally, the stations chosen for each city may not actually line up with the upwind and downwind climatological patterns of each of the cities since that data was unavailable; instead the same pattern was used for each city, with upwind being to the northwest and downwind being to the southwest as this is pattern is most typical and has been used in past studies. The climatology looks at the monthly total precipitation, and does not discriminate against heavy rainfall events like the Stage IV data does, so the findings to not necessarily carry over to heavy rainfall intensity.

Further Research

In order to further understand the influences of urbanization on rainfall intensity, case studies would be extremely beneficial. Analysis of case studies would provide insight into which parameters are altered by urbanization of which of these parameters influence the precipitation intensity. Additionally, the use of radar parameters in case studies can also provide more data regarding the influences of urbanization on rainfall intensity. Polarimetric radar variables, especially specific differential phase (K_{DP}), can be used to identify rainfall intensity, and analyze difference due to urban modifications. Rainfall rates can also be used to understand rainfall intensity and the influence of urban areas on precipitation.

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Appendix

Sample GrADS script to determine the location of maximum precipitation greater than 2 inches

The latitude, longitude, and outfile name were changed based on the city

```
*GrADS Script to determine location of maximum precipitation
'set lat 37.5 40'
'set lon -92 -89'
'set mpdset hires'
outfile = 'precipout.txt'
outfile2 = 'points.out'
*Need to determine how to have script read each time value when each year has a different number of files
count = 1
while (count <= 613)
  'set t 'count
* Only want to look at areas where precipitation is >=2in (50.8mm)
* If the precipitation is >=50.8in, find the location of maximum precipitation
  'd apcpsfc'
  'd amax(apcpsfc,lon=-92,lon=-89,lat=37.5,lat=40)'
  'd amax(apcpsfc,lon=-92,lon=-89,lat=37.5,lat=40)'
  strng=result
  apcpoutstr=sublin(strng,2)
  apcp=subwrd(apcpoutstr,4)
  if (apcp >= 50.8)
      'd amaxlocx(apcpsfc,lon=-92,lon=-89,lat=37.5,lat=40)'
      strng2 = result
      xlocoutstr = sublin(strng2,2)
      xloc = subwrd(xlocoutstr,4)
      'd amaxlocy(apcpsfc,lon=-92,lon=-89,lat=37.5,lat=40)'
      strng3 = result
      ylocoutstr = sublin(strng3,2)
      yloc = subwrd(ylocoutstr,4)
      outline =count' 'apcp' 'xloc' 'yloc
      res = write(outfile2,outline,write)
      'q gr2w 'xloc' 'yloc
      strng4 = result
      xlonoutstr = sublin(strng4,1)
      lon = subwrd(xlonoutstr,3)
      ylatoutstr = sublin(strng4,1)
      lat = subwrd(ylatoutstr,6)

      record =count' 'apcp' 'lon' 'lat
      res = write(outfile,record,write)
  endif
  count = count + 1
  'clear'
endwhile
```