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# Precipitation Patterns and Trends in the Metropolitan Area of Milwaukee, Wisconsin

## **Abstract**

This study investigated changes in mean and extreme precipitation in the metropolitan area of Milwaukee, Wisconsin in an attempt to find the effects of urban areas on precipitation patterns. Precipitation data were obtained from a gridded (8-km spacing) historical climatic dataset for Wisconsin for 1950-2006. The Mann-Kendall test and the Sen's slope test were applied to investigate temporal trends. Monthly wind directions were examined against monthly precipitation patterns. Main findings from the study include the following: (1) Annual precipitation significantly increased in the northern part of the study area during 1950-2006, whereas extreme precipitation showed virtually no trends; (2) The metropolitan area showed a distinctive center of low precipitation in selected months; (3) Extreme precipitation showed a more localized pattern than annual precipitation; and (4) Wind directions reasonably explained the spatial distributions of monthly precipitation with respect to the urban area. The results suggest signals of urban influence on precipitation, which need to be corroborated by more detailed investigation on precipitation characteristics.

## **Keywords**

precipitation, urban climatology, climate change, Milwaukee, trend analysis, gridded data

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## 1. INTRODUCTION

Climate change is arguably one of the most significant challenges facing the human society. Because of high population density and infrastructure, cities can be more subject to adverse impacts of climate change than the countryside. As a well-known feature of urban meteorology, the urban heat island phenomenon is likely to intensify with climate change as recent studies suggest (e.g. McCarthy et al. 2010; Wilby 2008). It is also widely reported that other atmospheric variables such as precipitation, wind, and humidity can result in different patterns in urban areas compared to the countryside (Landsberg 1981 pp. 177-210). Naturally, it is of scientific and practical interest whether such different patterns will change in the future with climate change. Precipitation was of particular interest in this study, because both excess and lack thereof significantly affect human life and infrastructure in cities.

In the second half of the 20<sup>th</sup> century, studies theorized or empirically demonstrated that urban environments can alter mesoscale convective circulation which results in changes of precipitation patterns (e.g. Changnon 1981; Changnon and Huff 1986; Changnon et al. 1991; Changnon et al. 1976; Dixon and Mote 2003; Huff and Changnon 1986; Huff and Changnon 1973). Lowry (1998) and Shepherd (2005) provide an extensive review of current research on urban effects on precipitation, and Shepherd (2005 pp. 5-6) summarized possible mechanisms for urban effects on precipitation into: enhanced convergence due to increased surface roughness, urban heat island phenomena and related thermal perturbation, enhanced condensation nuclei from aerosols, and bifurcating or diverting of precipitation systems by the urban canopy. However, answers are not very conclusive on which mechanism plays which role in specific cases (Shepherd 2005). The actual intensity of urban induced precipitation needs to be investigated per urban area due to differences in orography, location, land use, urban morphology, meteorological situation, emitted aerosols, etc. (Schlünzen et al. 2010). Therefore, it is necessary to investigate precipitation changes for each urban area in its unique context.

There is certainly a need for precipitation research with regard to both climate change and urban effects for Milwaukee, the largest city in the state of Wisconsin. It is vulnerable to flooding due to intense rainfall events, but there has not been much research for Milwaukee. In the current article, the spatial and temporal patterns of precipitation were investigated for the metropolitan area of Milwaukee, as a first step to explore climate change effects on urban precipitation. The study was partly motivated by the fact that Serbin and Kucharik (2009) produced a gridded daily temperature and precipitation dataset for Wisconsin for the period 1950-2006 at an 8-km resolution. Such a high-resolution long-term data have not been available for the area. A dense network of rain gages became available only after the 1980s by the Milwaukee Metropolitan Sewerage District. The spatial resolution of the dataset is fine enough to contain multiple grid points in a mid size urban area like Milwaukee, and regular grid spacing is often preferred for examining extreme precipitation events (Ou et al. 2013), which is part of this article. Milwaukee is also a challenging place in this type of research due to its lakeshore location. Lake-breeze frontal movement is influenced by the urban heat island effect (Keeler and Kristovich 2012), which adds complexity to the aforementioned mechanisms. Therefore, previous studies on precipitation in the Milwaukee area had short time frames

(e.g. Yang et al. 2014; Yang et al. 2013). In this context, the present study examined the long-term spatial pattern of precipitation in the metropolitan area of Milwaukee. Specifically, it compared the overall precipitation between different sections of the metropolitan area and examined temporal trends of annual and extreme precipitation across the region.

## 2. MATERIALS AND METHODS

### 2.1 STUDY AREA

The study area (Figure 1) encompasses Milwaukee County and a roughly drawn 24 km buffer around it. The buffer distance was determined to include three grid points in one direction. Milwaukee County was selected to be representative of the urban area and will be referred to as Metro Milwaukee in this article. The ‘Metro Milwaukee’, as identified by the U.S. Census Bureau, is comprised of five counties (Milwaukee, Waukesha, Racine, Washington, and Ozaukee), but I selected Milwaukee County as the metro area for the study because only this area is mainly comprised of urban land cover.

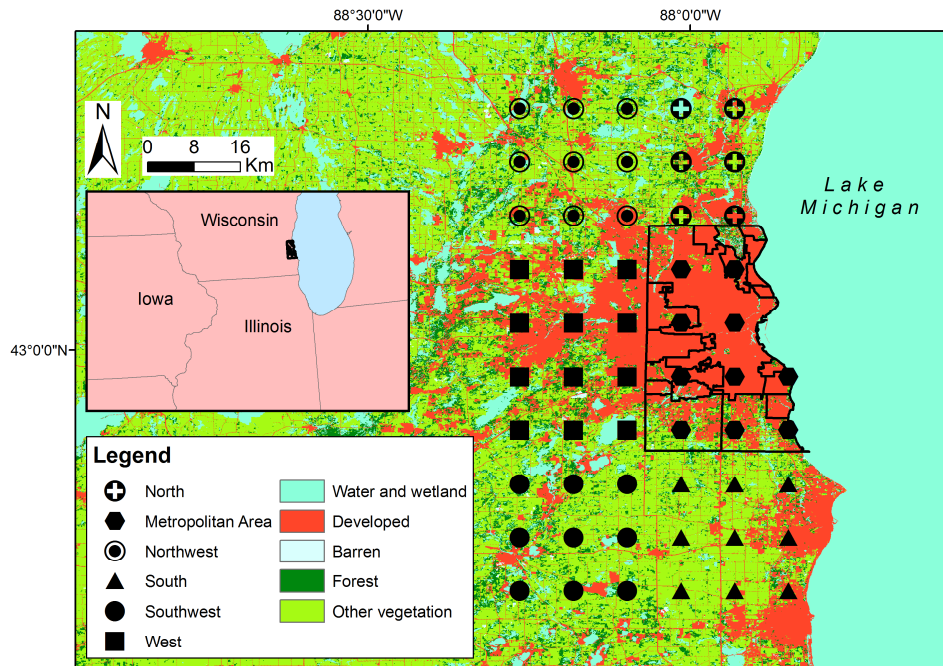


Figure 1. Boundaries of Milwaukee County and cities in the county (black lines), grid points selected for each of the 6 groups from the high-resolution gridded historical climatic dataset, and reclassified land cover data from the US Geological Survey 2006 National Land Cover Dataset.

Annual total precipitation for the Milwaukee area is averaged at about 828 mm. Seasonally, June, July, and August are the wettest months, with more than 90 mm per month, and February is the driest month. Temperature-wise, daily maximum temperature is about 13 °C, and daily minimum temperature is under 3 °C as annual average according to the historical gridded data (Serbin and Kucharik 2009). June, July, and August are the warmest months, and December, January, and February are the coldest months.

## 2.2 DATA

The high-resolution gridded daily precipitation data created by Serbin and Kucharik (2009) were downloaded from a server located at the University of Wisconsin-Madison. The gridded dataset is based on daily observations of total precipitation for 1950-2006. The observation stations data were interpolated to an 8-km (0.0833° latitude × 0.0833° longitude) grid using an inverse distance weighting spatial interpolation algorithm. Daily precipitation data from a total of 176 observation stations within Wisconsin and stations within a 70-km buffer from the state border were included in the interpolation process. The location of the observation stations is shown on a map on page 744 of their article, and only several are located in Metro Milwaukee.

Daily precipitation data from 90 grid points were extracted, encompassing Metro Milwaukee and approximately a 24 km buffer around it. The study area is comprised of a rectangle of 9 latitudinal and 10 longitudinal grid points ranging 42.62-43.37° latitude and 87.6-88.26° longitude. Furthermore, to gain a better insight into spatial differences within the study area, the 90 grid points were initially divided into 9 different groups, similarly to Schlünzen et al. (2010): Northwest, North, Northeast, West, Metro, East, Southwest, South, and Southeast. The border of each group and the number of included grid points is based on the boundary of Metro Milwaukee and the lake shoreline. Therefore, the number of grid points in each group varied from 6 to 14 points. It should be noted that data over Lake Michigan are more error-prone because there are no weather stations. Therefore, they were eventually excluded from the analysis, and the remaining groups are shown in Figure 1.

Annual and monthly averages of predominant wind directions for the time period 1948-1990 were obtained from the Wisconsin State Climatology office (<http://www.aos.wisc.edu/~sco/climhistory/stations/mke/milwind.html>).

## 2.3 METHODS

Analysis methods adopted in the study includes the following: (1) Mann-Kendall test for trend to determine the significance of the temporal trend of precipitation; (2) Sen's slope to calculate the slope of precipitation changes; (3) spatial interpolation of the gridded data for visualization of spatial pattern; and (4) calculation of precipitation statistics.

The Mann-Kendall (Kendall 1975; Mann 1945) test for trend was used to investigate the temporal trend for the historical time period 1950-2006. The non-parametric rank-based test is very often used to test randomness against trend (Mitchell et al. 1966) and does not assume any specific data distribution form, which makes it powerful and popular

for testing trends in hydrometeorological time series (Toreti et al. 2009; Zhang et al. 2009; Zhang et al. 2005). For this research the procedure described by Manly (2009) was used (see Appendix).

The strength of precipitation trend was evaluated by calculating the Sen's slope. The Sen's slope test is a non-parametric test of trend and calculates the slope based on a linear model to estimate the trend (Sen 1968). Equations are available in Appendix.

To visualize the spatial pattern of precipitation, daily data were aggregated to monthly or annual scales and interpolated from grid points to surface using an inverse squared distance weighting algorithm available in ArcGIS 10. The purpose of the spatial interpolation was not to estimate precipitation values between grid points but only to display the spatial pattern effectively.

As a statistic of precipitation to represent the entire study area, we calculated 'representative precipitation (RP)' using a similar approach to that used by Schlünzen et al. (2010). In this research, the RP was calculated as the median of all the grid points in the study area. The RP was used to analyze differences in precipitation within the study area by comparing the RP to the precipitation value at individual grid points or groups. The 95<sup>th</sup> percentile values of daily precipitation amounts larger than 1 mm each year were used as an index of extreme precipitation.

### **3. RESULTS**

#### **3.1 ANNUAL PRECIPITATION**

Figure 2 portrays the regional differences within the study area, the difference between each group and the RP (828 mm). The northern regions of the study area (groups: Northwest and North) received less annual precipitation than the RP. The North region, right above Metro Milwaukee, received the least amount of precipitation. The average precipitation in the southern regions (groups: Southwest and South) was higher than the RP. Both Metro Milwaukee and the area to the west showed a slightly higher precipitation (ca. 2 mm). Precipitation in Metro Milwaukee was overall closest to the RP.

Figure 3 shows the slope and significance of trend for annual total precipitation ( $\alpha = 0.05$ ). The strongest increasing trends were found northwest of Metro Milwaukee and the south side of Metro Milwaukee. Significant increases occurred in North, Northwest, and eastern half of Metro. Only two grid points, in the far southwest corner, showed a negative trend, but these trends were not statistically significant. Overall, whether statistically significant or not, increasing trends are predominant in this region. Such similar trends across the region suggest that the difference in precipitation between urban and non-urban areas did not result from global climate change (Yang et al. 2014).

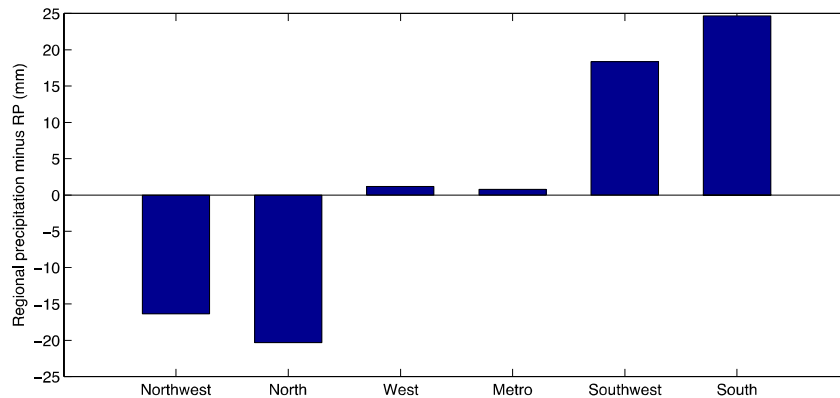


Figure 2. Difference between annual precipitation of each group and the representative precipitation during 1950-2006

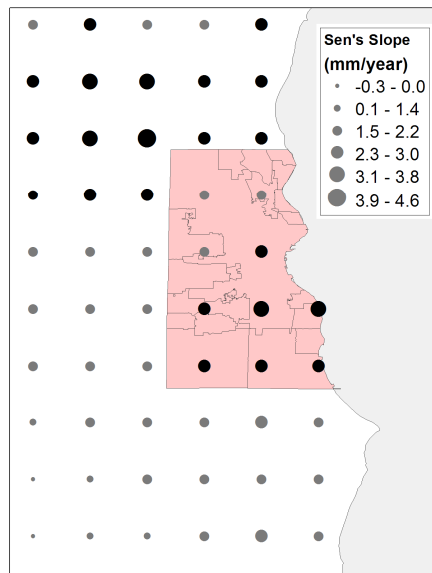


Figure 3. Results from the Sen's slope test for trend of annual precipitation. Black marks indicate statistically significant trends and grey ones insignificant according to the Mann-Kendall test

### 3.2 MEAN MONTHLY PRECIPITATION

The spatial distribution of mean monthly precipitation averaged over the time period 1950-2006 is shown in Figure 4 (January-June) and Figure 5 (July-December). In December and January, high precipitation centers over the metropolitan area spread southeastward, and the driest areas were found in the northwestern regions of the study area. In February, March and April, the northwestern part of the study area was the driest, and the southeastern region the wettest. In May through August, the driest areas moved northeastward, and the wettest areas were found in the southwest (June) or west (July and

August). A distinguished center of low precipitation over Metro Milwaukee was observed in May, July, September, October, and November. Overall, the regional pattern found in Figure 2 varied substantially by season, possibly reflecting different precipitation mechanisms.

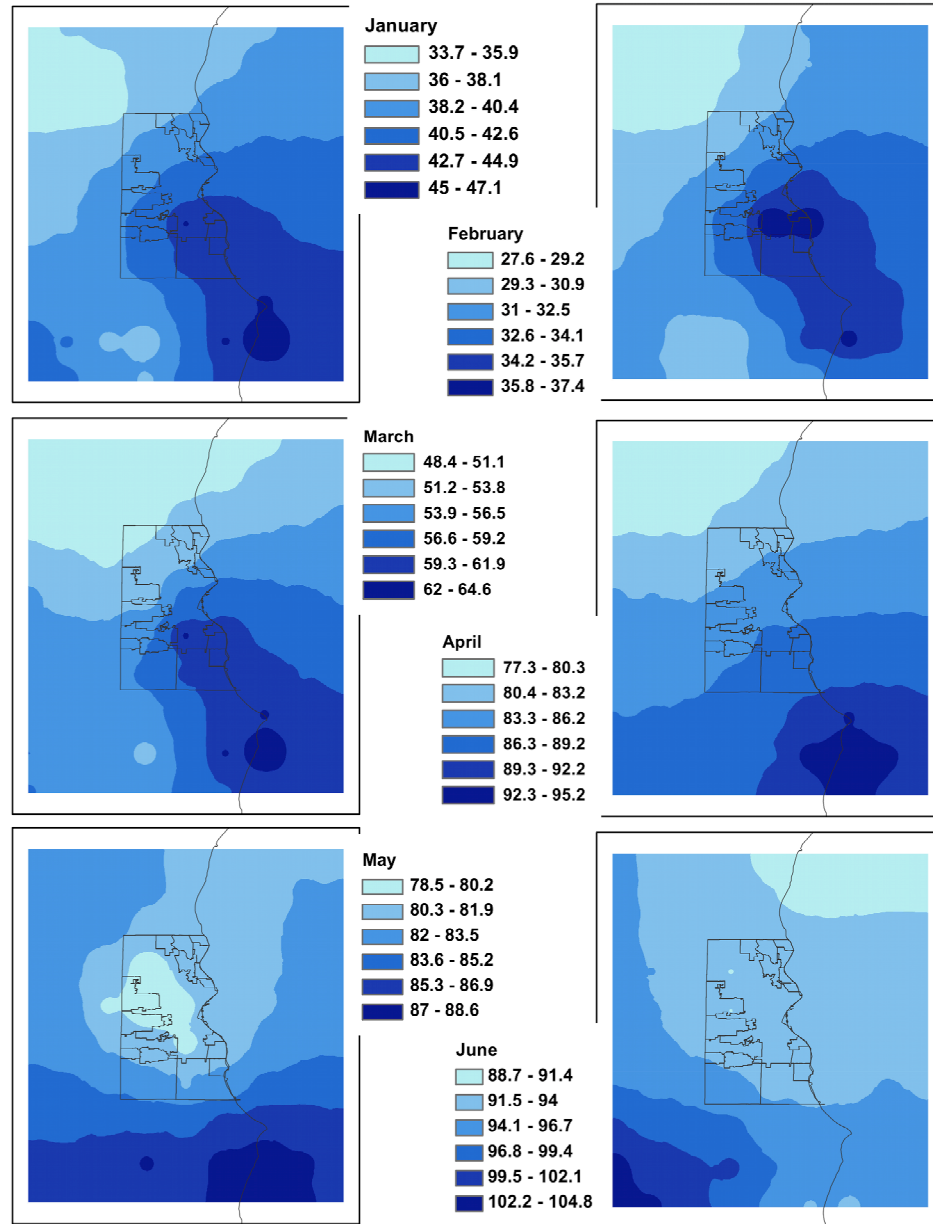


Figure 4. Spatial distribution of mean monthly precipitation (mm) during 1950-2006 for January-June. Data over Lake Michigan may be ignored.



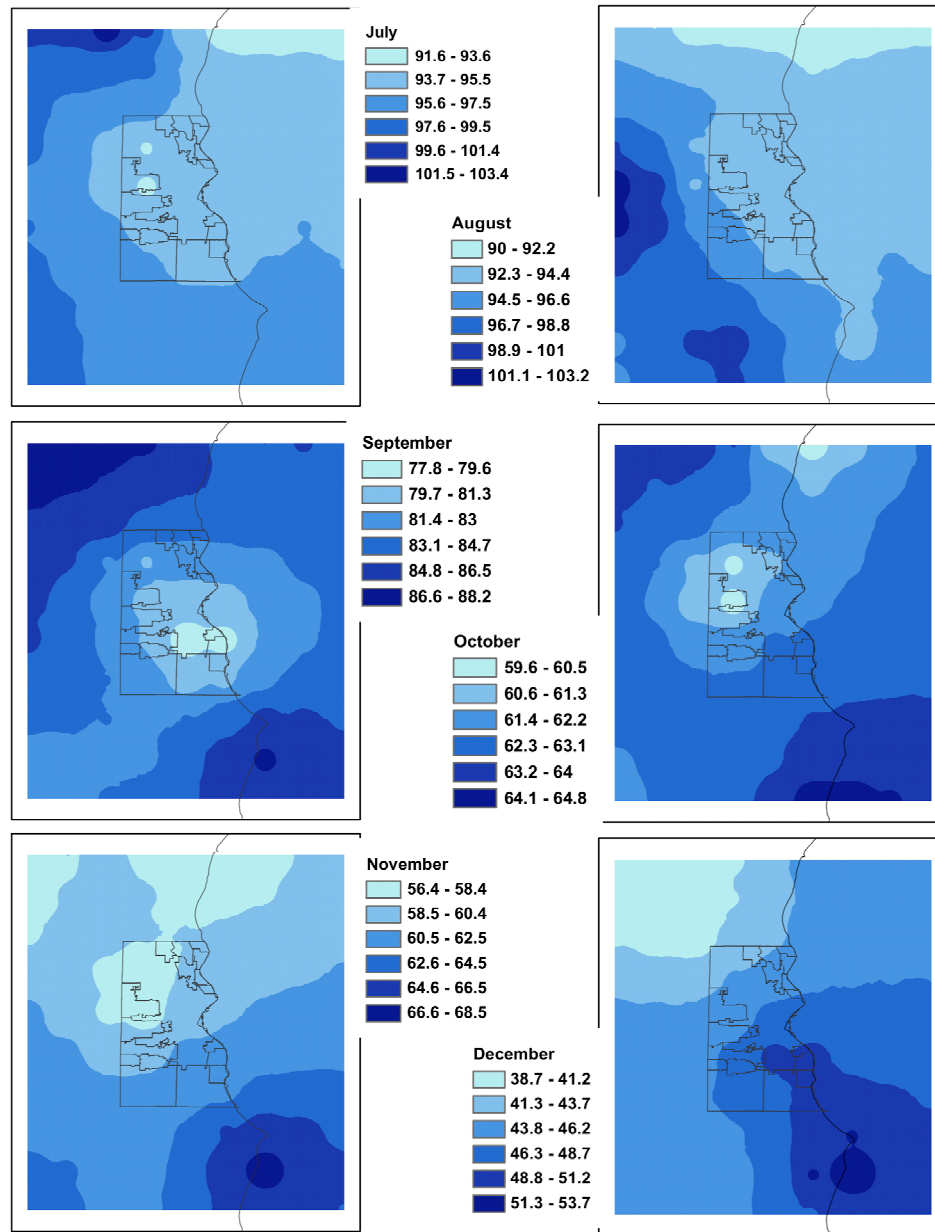


Figure 5. Spatial distribution of mean monthly precipitation (mm) during 1950-2006 for July-December. Data over Lake Michigan may be ignored.

### 3.3 EXTREME PRECIPITATION INDEX

Figure 6 portrays the spatial distribution of the 95<sup>th</sup> percentile daily precipitation. Several concentric circles were found over the land area, indicating a more localized pattern of extreme precipitation than monthly precipitation. Its inter-annual variability was not as

drastic as annual precipitation, with a range of approximately 12-15 mm. The highest precipitation occurred in the southeastern parts of the study area and the lowest to the northeast and east over Lake Michigan. When it comes to temporal trend, virtually no significant trends were found (not shown).

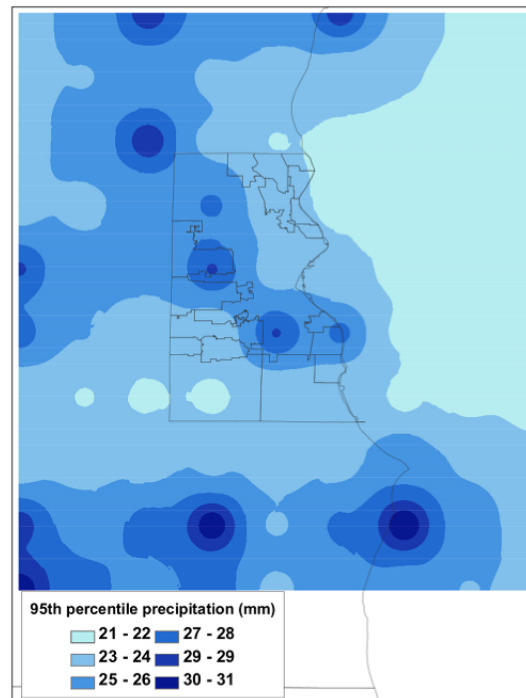


Figure 6. Spatial distribution of the 95<sup>th</sup> percentile daily precipitation averaged for 1950-2006. Data over Lake Michigan may be ignored.

### 3.4 PRECIPITATION AND WIND DIRECTION

In the study, the highest precipitation was found in the southern regions of the study area and the lowest in the northwestern and northern regions. The highest average annual precipitation is located downwind of Metro Milwaukee. The averaged annual wind is a west-northwest wind (Table 1). The high precipitation located to the south of the study area could be partially due to urban effects enhancing the precipitation magnitude.

Similar patterns are found for the monthly precipitation. In winter (December-February), high precipitation amounts are shown in the southeastern portion of Metro Milwaukee and in the southeastern parts of the study area. The predominant wind direction in winter is west-northwest. In March and April, the wettest areas are found in the southeastern corner of the study area. In May, the highest precipitation occurs in the southern regions. The predominant wind pattern for March is west-northwest which could explain the high center of precipitation southeast of Metro Milwaukee. In April and May, the wind predominantly comes from the north-northeast. This might explain the shift from the concentrated high precipitation in the southeastern corner towards the more

widespread precipitation in the southern regions. In June, the highest precipitation is found in the southwest and the predominant wind direction is north-northeast. This once again puts the highest precipitation amounts at the downwind side of Metro Milwaukee. In July to September, the wind predominantly comes from the southwest and south-southwest. During these months the highest precipitation is found in the southwest and western regions. In November, the predominant wind again comes from the west-northwest and the southeastern regions experience the highest precipitation.

Table 1. Predominant wind direction based on annual and monthly averages for the time period 1948-1990

<b>Month</b>	<b>Average wind direction</b>
Annual mean	West-northwest
January	West-northwest
February	West-northwest
March	West-northwest
April	North-northeast
May	North-northeast
June	North-northeast
July	Southwest
August	Southwest
September	South-southwest
October	South-southwest
November	South-southwest
December	West-northwest

## 4. DISCUSSION

### 4.1 SCALE OF RESEARCH

The present study analyzed decades long daily precipitation data over the metropolitan area of Milwaukee and its surroundings that covers 55 grid points. This temporal and spatial scale is unique compared to other studies, particularly some recent ones for Milwaukee. This article reports higher annual precipitation downwind side of the metro area and dry centers in downtown in some months of the year. It also found an uneven distribution of the 95<sup>th</sup> percentile daily precipitation even within metro Milwaukee. This finding is complemented by the work of Yang et al. (2013). They found that rainfall was higher in the metro area from selected flood-producing storms since the 1990s. Their analysis is based on individual storms, and such a result is in line with the aggregated data shown in Figure 6 of this article. Higher amounts of extreme precipitation in the metro area may be attributed to the urban heat island effect (Yang et al. 2014). Heavy rain storms increased in frequency in Chicago suggestively due to influences of the city and Lake Michigan (Changnon and Westcott 2002). Even though the metropolitan area of Chicago is larger than Milwaukee, it has a very similar climatic and landscape setting,

thus suggesting a similar mechanism for Milwaukee. However, this article suggests that such effects become negligible for total precipitation even at the monthly time scale.

The dry centers over Metro Milwaukee in warmer months warrant further investigation at finer time scales using numerical modeling. Niyogi et al. (2011) examined 91 summertime thunderstorm cases over a ten-year period to find changes in storm structure over urban areas in Indianapolis, and such an approach may help explain the dry centers found in this article.

This article analyzed an extreme precipitation index, measured as the 95<sup>th</sup> percentile of daily precipitation amount each year, in greater detail than Choi et al. (2013). As mentioned above, it was higher in the core of Metro Milwaukee than around its edge. However, during the 57-year period, it showed no significant trend. Decreasing trends are predominant in the northern part of Wisconsin, but increasing trends are sporadic location-wise across the state (Choi et al. 2013). Based on the statewide trend, it is speculated that urban growth did not influence the trend of extreme precipitation. It is thought that the trend occurred as a result of larger-domain processes.

## **4.2 DATA SOURCE**

The present study used a gridded dataset of observed precipitation available at a daily time scale. Its 8-km spatial resolution allowed spatial analysis over a metropolitan area, but was not fine enough to identify individual storms and their tracks. Therefore, even though some signals of urban-induced precipitation were found, the study could not draw strong conclusions on them. Some studies used remote sensing data (e.g. Hand and Shepherd 2009; Bentley et al. 2010; Kishtawal et al. 2010; Ashley et al. 2012) and generally focused on particular types of precipitation, such as warm-season rainfall or thunderstorms. Like the present study, they present how urban areas ‘appear’ to influence precipitation to different degrees. The cause-effect relationship is better explained by numerical simulations (e.g. Molders and Olson 2004; Gero et al. 2006; Shepherd et al. 2010; Miao et al. 2011).

Because the dataset has been gridded from weather station data, it is likely that the intensity of extreme rainfall events has been underestimated, and very low precipitation events have been overrepresented. However, gridded data are known to be suitable for examining overall trends and variability of extreme precipitation (King et al. 2013). The use of gridded data in the present study was inevitable because a dense network of rain gauges was not available before the 1990s. Extreme precipitation indices can be either gridded after being calculated from station data or calculated from gridded precipitation data. The two methods produce quite a large difference, particularly with larger grid cells (Ou et al. 2013), and in the present study, the latter was inevitably adopted. Considering that the grid spacing is much finer than those (0.5-4°) of Ou et al. (2013), the difference would have been much smaller for the present study.

## 5. CONCLUSIONS

The present study investigated observed precipitation patterns and changes around the metropolitan area of Milwaukee, Wisconsin. The patterns and changes were investigated at annual and monthly scales using the historical gridded (8-km spacing) daily precipitation data for 1950-2006. The study suggests that the trend of annual total and extreme precipitation during 1950-2006 was largely a result of processes occurring over large domains. However, the spatial pattern in and around the metropolitan area reveals signs of urban effects, particularly at the monthly scale, corroborated by general wind directions. The signs of urban effects differed between extreme precipitation and monthly totals, suggesting different mechanisms for urban effects on precipitation.

## APPENDIX

### MANN-KENDALL TEST FOR TREND

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sign}(x_i - x_j)$$

where for a series  $x_n$  the test statistic  $S$  is the sum of the signs of the differences between any two observations, and where  $\text{sign}(z)$  is 0 when  $z$  is zero, 1 when  $z$  is positive and -1 when  $z$  is negative.

If series of values in a random order, the expected value of  $S$  is zero and the variance  $VS$  is given as follows:

$$VS = n(n-1)(2n+5)/18$$

Whether  $S$  is significantly different from zero can be tested by using the  $Z$  statistic, which is given as follows:

$$\begin{aligned} &\text{if } S > 0 \\ &Z = \frac{S-1}{\sqrt{VS}} \\ &\text{else} \\ &Z = \frac{S+1}{\sqrt{VS}} \end{aligned}$$

$Z$  follows the standard normal distribution, and a positive  $Z$  value indicates a positive trend and a negative one indicates a negative trend in a two-sided test for trend. In this case the  $Z$  values were converted to probabilities of observing larger absolute  $Z$  values. In order to show the significance of a trend the  $p$  value was calculated as follows:

$$p = 2 \Phi (-|Z|)$$

where  $\Phi$  is the normal cumulative distribution function.

### SEN'S SLOPE

The Sen's slope estimator calculates the slope (S) of the data x as follows:

$$S = \text{median}(y)$$

$$y = \left( \frac{x_i - x_j}{i - j} \right) \quad i = 1, 2, 3, \dots, N \text{ and } i < j$$

If there are  $n$  values of  $x$  in the time series we get as many as  $N = n(n-1)/2$ . The slope of the time series is given in proportional values based on the size of the data values.

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