Contribution of daily contiguous rainfall areas to warm season precipitation in the north central United States

by

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ABSTRACT</th>
<th>iii</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Thesis Organization</td>
<td>2</td>
</tr>
<tr>
<td>CHAPTER 2. LITERATURE REVIEW</td>
<td>3</td>
</tr>
<tr>
<td>CHAPTER 3. CONTRIBUTION OF DAILY CONTIGUOUS RAINFALL AREAS TO WARM SEASON PRECIPITATION IN THE NORTH CENTRAL UNITED STATES</td>
<td>10</td>
</tr>
<tr>
<td>Abstract</td>
<td>11</td>
</tr>
<tr>
<td>Introduction</td>
<td>12</td>
</tr>
<tr>
<td>Data and Methods</td>
<td>12</td>
</tr>
<tr>
<td>Results</td>
<td>19</td>
</tr>
<tr>
<td>Discussion and Conclusions</td>
<td>35</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>37</td>
</tr>
<tr>
<td>References</td>
<td>38</td>
</tr>
<tr>
<td>CHAPTER 4. CONCLUSIONS AND FUTURE WORK</td>
<td>41</td>
</tr>
<tr>
<td>Conclusions</td>
<td>41</td>
</tr>
<tr>
<td>Future Work</td>
<td>42</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>44</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>45</td>
</tr>
</tbody>
</table>
ABSTRACT

Increases in damage associated with floods in the North Central U.S. call for a better understanding of the precipitation events that lead to these floods. Analysis of long records of historical observations of regional precipitation provides an opportunity to document both the basic characteristics and trends in temporal and spatial precipitation characteristics. Previous studies with this goal have used relatively short time scales, station data with coarse, non-uniform resolution with no regard to the spatial patterns or correlation among stations.

I use a dataset developed as input to the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 1994, 1996) by Maurer et al. (2002) which uses both horizontal interpolation and elevation corrections. This produces a $1/8^\circ$ grid of daily precipitation from 1950 through 2010 over the entire coterminous United States (CONUS). The North American Regional Reanalysis (NARR) reported by the National Center for Environmental Prediction (NCEP) will also be used to analyze specific meteorological variables that are not available in the VIC dataset. A procedure called the method for object-based diagnostic evaluation (MODE) will allow me to identify precipitation events of certain contiguous size and rainfall depth.

Research performed for completion of this thesis has led me to the following findings: 1) $90^{th}$ percentile precipitation events, while not characterized as extreme, actually contribute 50-70% of the total warm season precipitation events in the North Central United States. 2) A $90^{th}$ percentile event, depending on the location within the region of interest, is either $\frac{1}{4}”$ or $\frac{1}{2}”$ of total daily precipitation. 3) $90^{th}$ percentile events have increased from the first to the second half of the past 61 years. 4) The main environmental indicators of these rainfall events are Convective Available Potential Energy (CAPE) and water vapor flux convergence, which provide insight into the characteristics of warm season precipitation in the region. 5) These $90^{th}$ percentile events are quite common and can happen many times per month during the warm season. 6) These events, more often than not, occur in a series on consecutive days within a narrow corridor rather than as an isolated event which can lead to potential flooding problems.
CHAPTER 1. GENERAL INTRODUCTION

Introduction

Flooding has become a greater concern for residents of Iowa and other parts of the North Central United States in the past two decades. Many cities and towns across the country have seen increased rainfall totals and intensities which have led to the occurrence of more flooding events. A paper by Karl et al. (1998) states that since 1910, precipitation has increased by about 10% in the contiguous United States and that over half (53%) of that increase is due to increases in 90th percentile or higher precipitation events. The year 1993 was a record year for flooding across the state of Iowa and significant flooding occurred in Cedar Rapids in 2008 and Ames in 2010. In 2011, large early warm season precipitation totals in the Upper Missouri River Basin contributed to extensive flooding on Iowa’s western border along the Missouri River and elsewhere in the Midwest as well. These historic floods caused extensive property damage amounting to enormous financial losses (Mutel et al. 2010).

The precipitation characteristics in the North Central United States are the focus of this paper due to the importance of precipitation events in the region to much of the Midwestern United States. The Iowa Flood Center (www.iowafloodcenter.org) is seeking a better understanding of the meteorological conditions and their precursors to better understand the physics of flood events and to develop prediction tools that will provide communities and residents of Iowa more lead time in preparing for these events.

This thesis describes an attempt to utilize a high resolution gridded precipitation dataset as well as reanalysis data to gain a historical perspective of the precipitation characteristics of the North Central United States. Precipitation regimes, or meteorological conditions that exist when consecutive precipitation events occur over the same area, are important to understand in order to identify precipitation events that lead to flooding. The better the past is understood, the more confident we can be about predictions in the future.
Thesis Organization

The organization of this thesis follows the format of a journal article. Chapter 1 includes a general introduction to the thesis, followed by Chapter 2 which contains a detailed literature review of warm season precipitation characteristics. Chapter 3 is a paper to be submitted to a scientific journal and Chapter 4 is the general conclusion, which outlines the major findings of this research. Anticipated future work is also discussed followed by acknowledgements and references cited.
CHAPTER 2. LITERATURE REVIEW

Using observed station data to analyze precipitation characteristics in the United States has been done on many occasions. Karl et al (1998) used observed station data to evaluate secular trends of precipitation amount, frequency, and intensity in the United States. They found that since 1910, precipitation in the contiguous United States has increased by about 10%. Over half of this increase (53%) can be attributed to positive trends in the upper 10 percentiles (90th percentile or above) of the precipitation distribution. An increase in the number of days with precipitation was also found.

Kunkel et al. (2012) also use an observed station dataset to analyze meteorological causes of the secular variations in observed extreme precipitation events in the coterminous United States. Data from 935 stations over the period of 1908-2009 were used. Extreme daily precipitation was defined for each station as a 1 in 5-yr recurrence. The threshold ranged 25 mm in the western interior states to 250 mm along the Gulf of Mexico. This study used the observed station data to create a 1° by 1° gridded dataset of rainfall (grid average is the average rainfall from stations within the 1° by 1° grid cell) in order to account for the large spatial variation in station density and provide a more even representation of areas. This gridded dataset was used to identify contiguous rainfall areas for each day which the authors call a contiguous precipitation region (CPR). This was done by identifying the grid point with the greatest precipitation for each day and then searching for adjacent grid points that had daily precipitation values >12.5mm. The search was continued until the values were lower than that threshold resulting in a region that consisted of contiguous grid points, all with precipitation values greater than 12mm, entirely surrounded by grid points with <12.5mm. The number of extreme daily events that occurred within the CPR was counted, and only a very few were not associated with a CPR. A cause was then assigned to each of the CPR’s. The authors identify the single largest cause of extreme precipitation events in the US to be frontal, accounting for about 54% of all events.

Changes in intense precipitation over the Central United States were discussed by Groisman et al. (2012), who found increases in intense precipitation events and a decrease in
moderately heavy precipitation events in this region. This research uses two data sources - an hourly precipitation dataset with 3,076 stations augmented by a daily precipitation dataset with 5,885 long-term daily cooperative (COOP) stations. The criterion for being classed as a long term station was that it must have 25 years of data within the period from 1948-2009. The authors only consider precipitation events which led to daily totals of >12.7 mm. Results of this research show increases in the frequency of days with intense precipitation as well as multiday extreme rain events of up to 40% in the last 31 years.

Mesoscale convective complexes (MCCs) were first identified and defined by Maddox (1980). It was found that MCC systems frequently occur over the central United States and often persist for over 12 hours. These systems are defined by physical characteristics that can be observed in enhanced infrared (IR) satellite imagery. There are several criteria including size, duration, and shape of the cloud shield. A cloud shield with a continuously low IR temperature \(\leq 32^\circ C\) must have an area \(\geq 100,000 \text{ km}^2\) and the interior cold cloud region with temperature \(\leq 52^\circ C\) must have an area \(\geq 50,000 \text{ km}^2\). These size criteria must be met for \(\geq 6\) hours and the eccentricity (minor axis/major axis) must be \(\geq 0.7\) at the time of maximum extent (when the continuous cold cloud shield reaches maximum size).

The idea of precipitation “corridors”, a series of convective rainfall events, repeatedly occurring over an interval of a few days along a narrowly defined path has been discussed on several occasions. In a paper by Tuttle and Davis (2005), the authors define and attempt to better understand the nature of warm season precipitation corridors in the central United States as well as the environmental factors that lead to their formation. Using a US national composite radar dataset and RUC model analyses, the warm seasons (July-August) from 1998-2002 were examined to analyze the properties of corridors and environmental factors that are important for determining when and where they develop. A precipitation corridor was defined as a series of precipitation events in which the day-to-day change of latitude is no more than \(\pm 4^\circ\). The cumulative rainfall of these events was anywhere from 8-50cm with a modal value of 15cm.

Convection for these events showed the expected association with areas of enhanced CAPE and strong low-level shear. The strongest association, however, was to the exit region
of the low-level jet (LLJ). Enhanced vertical motion and frontogenesis can occur at the northern terminus of the LLJ from the deformation flow that occurs there. Also, as the LLJ increases in strength, a higher percentage of convection is being locally forced. This leads to increased precipitation in these areas. High low-level winds (>10 m s\(^{-1}\)) was also noted as being important in the maintenance of convection.

These phenomena tend to propagate in a southerly direction (Tuttle and Davis, 2005), and if a watershed is orientated north to south, the second storm in a series could add large amounts of precipitation over an area that already has swollen rivers and tributaries from the first system that occurred upstream. An example of this happening was in Ames, Iowa in August 2010. A series of heavy precipitation events occurred consecutively over northwest to southeast oriented watersheds. The storms tracked right along the watersheds from the northwest to the southeast, raining on already swollen streams which ultimately led to extensive flooding in Ames and surrounding areas. A situation similar to this happened in the city of Cedar Rapids, Iowa in 2008 when heavy rain on multiple days, already saturated soils, and swollen streams from upstream heavy precipitation combined to produce a record breaking flood. Water from heavy rainfall upstream from Cedar Rapids on June 8, 2008 flowed downstream and combined with more heavy precipitation falling farther downstream in the watershed on June 12. This succession of storms and their respective rises in river levels combined to create a rapid rise and one extremely large peak flow in the city of Cedar Rapids on June 13. The Cedar River crested at 31.12 feet, over 19 feet above flood stage of 12 feet, causing extensive damage (Mutel et al., 2010).

Another paper that discusses a series of convective weather events is Kane and Fritsch (1987). In the article discussing precipitation characteristics of mesoscale convective weather systems (MCWSs), the authors state that under certain synoptic conditions, MCWSs tend to occur in a series. A grouping of MCWSs is considered a series if the precipitation patterns of two or more MCWSs overlap by more than 20% and if each subsequent event begins (precipitation starts) 12 h or less following dissipation (precipitation ends) of the previous event. These series of convective complexes (SCCs) are of significant concern with
regard to the hydrologic impact they can have on a region. Severe flooding can result from an SCC occurring over a single watershed.

A paper by Carbone (2001) discusses the predictability of warm season precipitation episodes. Here, these “episodes” are defined as time-space clusters of heavy precipitation that often occur in a sequence as a result of organized convective systems such as squall lines, MCC’s, or MCS’s. These episodes tend to display coherent rainfall patterns that are characteristic of propagating events. The data used to analyze these events include Geostationary Operational Earth Satellite (GOES) data from 1998-2000 and WSR-88D radar data from 1997-2000. The results of this paper indicate that coherent rainfall events on the order of 1000 km in zonal span and 1 day duration occur almost once per day during the warm season. Many of these events exceed the zonal extent and duration that is normally associated with MCC’s and are believed to be compound events, a coherent succession of convective systems, referred to as episodes. The visible dissipation and subsequent regeneration of convective rainfall within an episode suggests a causal relationship among successive systems and therefore the possibility of intrinsic predictability.

Several reports have examined the contribution of mesoscale convective weather systems to warm season precipitation in the US. One of the most notable is by Fritsch and Kane (1986). This study includes the contribution of both mesoscale convective systems (MCSs) and mesoscale convective complexes (MCCs) from 1982 and 1983 as identified by annual summaries (Rodgers et al., 1983, 1985). MCSs are MCC-type or MCC-like events which for various reasons, such as insufficient size or duration, did not meet the MCC criteria established by Maddox (1980). MCSs were included in the study as the precipitation characteristics of MCSs were not very different from that of MCCs (Kane et al., 1985). The two types of mesoscale phenomena were combined to be identified as mesoscale convective weather systems (MCWSs). Precipitation data were from 24-h precipitation charts from the Heavy Precipitation Branch at the National Meteorological Center and hourly reports from the National Climate Data Center. In total, 106 MCWSs were analyzed consisting of 74 MCCs and 32 MCSs. The years 1982 and 1983 were used to characterize a “normal” year (1982) and a “dry” year (1983). The authors determined that 30-70% of April through
September precipitation could be attributed to these systems in 1982. In 1983, the drought year, parts of at least 10 states received >25% of their warm season precipitation from MCWSs. Even though the total amount of precipitation was less for the drought year of 1983, the percentage of warm season precipitation provided by MCWSs did not change significantly. The authors conclude that if the warm season of 1982 is typical of MCWS rainfall, then these systems are the dominant warm season precipitation producing systems over much of the Midwest.

A paper by Ashley et al. (2003) also addresses the issue of the contribution of warm season precipitation from Mesoscale Convective Complexes alone. This report used the MCC summaries compiled between 1978 and 1999 of which 15 years were used. Other data used in this report include an NCDC hourly precipitation dataset and an 8-km resolution radar dataset from NASA from 1997-1998. The warm season was defined here as May through August as 86% of the events analyzed occurred within this four-month period. Results of this paper indicate that 8-18% of warm season precipitation in parts of the Great Plains comes from MCCs. There is a high degree of variability to this however, and in any given year, some locations can receive up to 40% of their warm season precipitation from these events. The results of Ashley et al. are quite different from those of Fritsch and Kane but this is probably due to the fact that Ashley used many more years in the study and the fact that the criteria were restricted to only MCCs and did not include MCSs.

The precipitation life cycle of the Mesoscale Convective Complex was analyzed by McAnelly and Cotton (1988). Hourly precipitation data from 1977-1983 as well as GOES satellite data were used in this study. The GOES satellite data were used to identify 122 MCCs, and the US hourly precipitation dataset was used to evaluate the precipitation resulting from these events. It was found that the average MCC produced a rainfall depth of 10.8 mm over an area of 3.2*10^5 km^2. They also found that 36% of MCC precipitation occurred at a rate <7.6 mm hr^{-1} and 45% occurred at a rate <10.2 mm h^{-1}.

An early release paper by Hitchens et al., (2011) examined an object oriented characterization of extreme precipitation-producing convective systems in the United States. The data used in this study include Stage II (ST2) hourly radar-derived precipitation from
1996-2010. This is a multi-sensor product that augments radar-derived precipitation data with gauge measurements. This study focused on extreme precipitation events in the 99th percentile, or >55.4 mm hr$^{-1}$. Of the 3,484 events analyzed in the time period, they found that 71% occurred in the months of June, July, and August. These events were also found to peak in the afternoon to evening hours between 19 and 02 UTC. The average size of these events was 7,000 km$^2$ with a rainfall intensity of 69 mm hr$^{-1}$. Table 2-1 below gives an overview of the literature reviewed for this thesis.

Table 2-1. An overview of literature reviewed including author and year of publication, data source, event criteria and a summary of main findings

<table>
<thead>
<tr>
<th>Paper</th>
<th>Data Source</th>
<th>Event Criteria</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maddox (1980)</td>
<td>GOES Infrared Satellite data</td>
<td>Area of $\leq 32^\circ$ cloud shield $\geq 100,000$ km$^2$</td>
<td>Definition of Mesoscale Convective Complex (MCC)</td>
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<tr>
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<td></td>
<td>Area of $\leq 52^\circ$ cloud shield $\geq 50,000$ km$^2$</td>
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<td></td>
<td>Areas must be satisfied for $\geq 6$ h</td>
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<td></td>
<td></td>
<td>Eccentricity (minor axis/major axis) $\geq 0.7$ at maximum extent</td>
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<td>Hitchens et al., (2011)</td>
<td>Stage II (ST2)- radar derived hourly precipitation data</td>
<td>Precipitation events in the 99th percentile $&gt;55.4$mm/hr$^{-1}$</td>
<td>Average event: 7000km$^2$ and 69 mm/hr max # of events in June, July, August between 19 and 02 UTC</td>
</tr>
<tr>
<td>Fritsch and Kane, (1986)</td>
<td>Satellite, radar, hourly and daily gauge data for 1982 and 1983</td>
<td>Mesoscale Convective Weather Systems MCWS’s(including MCS’s and MCC’s)</td>
<td>30-70% of warm season precipitation (April through September) can be attributed to MCWS’s</td>
</tr>
<tr>
<td>Kane and Fritsch, (1987)</td>
<td>Satellite, hourly and daily precipitation gauge data for 1982 and 1983</td>
<td>Mesoscale Convective Weather Systems MCWS’s (MCS’s and MCC’s)</td>
<td>Average area producing $\geq 26$mm = 96,000 km$^2$, average total precipitation= 16.1mm, average maximum precipitation= 102mm.</td>
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<tr>
<td>Source</td>
<td>Data Description</td>
<td>Precipitation Characteristics</td>
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<td>Ashley et al., (2003)</td>
<td>MCC summaries from 1978-87, 92-93, 97-98 (satellite data), NCDC hourly precipitation dataset, 8km, 15 min NASA radar data 1997-1998</td>
<td>8-18% of warm season (May through August) precipitation is from MCC’s (average of all years and locations) Locally,</td>
<td></td>
</tr>
<tr>
<td>McAnelly and Cotton, (1988)</td>
<td>GOES Satellite data, US hourly precipitation, 1977-1983 warm seasons (June through August)</td>
<td>Mesoscale Convective Complex (MCC) Average area of 320,000 km², average rain depth of 10.8mm 36% of MCC precipitation &lt;7.6mm/hr 45%&lt; 10.2 mm/hr</td>
<td></td>
</tr>
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<td>Groisman et al. (2012)</td>
<td>3,076 hourly precipitation stations &amp; 5,885 long term daily cooperative stations (1949-2009)</td>
<td>&gt;12.7 mm daily total rainfall Increases in intense precipitation by up to 40% in 31 years</td>
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<tr>
<td>Kunkel et al. (2012)</td>
<td>935 long term daily cooperative stations (1908-2009) gridded to 1° by 1°</td>
<td>spatially contiguous rainfall areas with a 1 in 5 year recurrence interval The largest single cause of extreme precipitation in the U.S. is an extratropical cyclone near a front (54%)</td>
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<tr>
<td>Karl et al. (2008)</td>
<td>182 daily observed precipitation stations (1910-1996) averaged into 1° by 1° grid cells</td>
<td>Percentiles of daily precipitation (5th, 10th, 15th, etc…) Precipitation has increased 10% since 1910 due greatly to increases in precipitation &gt;90th percentile</td>
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CHAPTER 3

Contribution of daily contiguous rainfall areas to warm season precipitation in the
north central United States

by

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Abstract

Predicting flooding events, both in time and magnitude is an extremely difficult task for both meteorologists and hydrologists. A good understanding of the spatial and temporal precipitation characteristics of a region, particularly in the warm season, is very important for flood forecasting and preparation. Long records of historical observations of precipitation can provide deep understanding of seasonal precipitation. Previous studies of precipitation characteristics in the Central U.S. have used relatively short time scales and station data with coarse, non-uniform resolution and little regard to the spatial patterns or correlation among stations. The authors attempt to improve understanding by using a longer time series and a high resolution, gridded precipitation dataset.

The primary data set used is a gridded ($\frac{1}{8}^\circ$) and interpolated observed daily precipitation dataset that spans 61 years (1950 through 2010) over the entire contiguous United States (CONUS) to characterize the warm season (April through September) precipitation in the North Central United States. This dataset was originally developed for the Variable Infiltration Capacity (VIC) hydrologic model, Liang et al. (1994, 1996) by Maurer et al. (2002) and will herein be called the VIC dataset. The North American Regional Reanalysis (NARR) by the National Center for Environmental Prediction (NCEP) will also be used to analyze certain meteorological variables that are not available in the VIC dataset. To help analyze this data, a procedure called the method for object-based diagnostic evaluation (MODE) will be used to identify precipitation events of certain contiguous size and depth.

Results of this paper indicate that 90th percentile precipitation events contribute 50-70% of warm season precipitation in the North Central U.S. The main environmental indicators of these less extreme rainfall events are Convective Available Potential Energy (CAPE) and water vapor flux convergence. These 90th percentile events are quite common and can happen several times per month during the warm season. Precipitation events in the 90th percentile have increased in the last 61 years and these events, more often than not, occur in a series on consecutive days within a narrow corridor rather than as an isolated event.
1. Introduction

Floods are of increasing concern for residents of the Midwest including Iowa. Many cities and towns have experienced increased rainfall totals and intensities (Groisman et al. 2012, Karl et al. 1998). The year 1993 was a record year for flooding across the state of Iowa and significant flooding occurred in Cedar Rapids in 2008 and Ames in 2010. In 2011, large early warm season precipitation totals in the Upper Missouri River Basin contributed to extensive flooding on Iowa’s western border along the Missouri River and elsewhere in the Midwest. These historic floods caused extensive property damage amounting to enormous financial losses (Mutel et al, 2010). Numerous smaller, less destructive floods have occurred in these areas over the past 20 years or so as well. Precipitation characteristics relevant to floods in the north central United States are the focus of this paper. The Iowa Flood Center (www.iowafloodcenter.org) is seeking a better understanding of the meteorological conditions and their precursors to better understand the physics of flood events and to develop prediction tools that will provide communities and residents of Iowa more lead time in preparing for these events.

This paper utilizes a high-resolution gridded precipitation dataset to gain a historical perspective of flood-relevant precipitation characteristics of the north central United States. Using data that is gridded over a long period provides insight into spatially correlated precipitation events. Precipitation regimes, or meteorological conditions that exist when consecutive precipitation events occur over the same area, are important to conditions that lead to flooding. NARR reanalysis data is utilized to evaluate a few key meteorological variables associated with these events.

2. Data and Methodology

The primary observational dataset used in this research is a gridded, interpolated precipitation dataset by Maurer et al. (2002) that spans the years from 1950 through 2010 providing 61 years of daily precipitation data for the entire coterminous United States.
(CONUS). These data were originally used by Maurer in the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994, 1996) and in this paper will be called the VIC dataset.

The observed precipitation data used to create this gridded dataset comes from the daily precipitation totals from the National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer (Co-op) network of stations which has an average density of one station per 700 km$^2$.

The precipitation data were gridded to the $1/8^\circ$ degree resolution by the synergraphic mapping system (SYMAP) algorithm of Shepherd (1984). This algorithm interpolates data points using a modified inverse distance weighting solution. While inverse distance weighting is a good approach to interpolation, as the number of data points becomes large, computation time increases exponentially and can therefore become impractical. The general method also only takes into account distance between points and not direction leading to other errors Shepherd (1968). To help remedy the computation problem, Shepherd uses a method called “selecting nearby points” which eliminates computations with data points that are distant from the point of interest. A minimum of four and maximum of ten nearest (by horizontal distance) data points are selected. Direction and slope were also taken into account to improve the quality of the interpolation by accounting for terrain. Also to account for local variations due to complex terrain, the gridded daily precipitation data were scaled to match the long-term average of the Parameter-elevation Regressions on Independent Slopes Model (PRISM). The PRISM dataset is a comprehensive dataset of 12 monthly means for 1961-90 that is statistically adjusted to capture local variations due to complex terrain.

To accomplish the terrain scaling, 12 scale factors for each grid scale, one for each month, were generated where each scale factor was the ratio of the PRISM mean monthly precipitation for 1961-90 to the mean monthly gridded, unscaled co-op station precipitation for 1961-90. This dataset may have some underestimation of precipitation in areas with large amounts of annual snow because the PRISM data do not include an adjustment for precipitation gauge undercatch which can be significant for snowfall measurements.
(Goodison et al. 1998). This alone should not affect the results of this research as it is solely concerned with warm season precipitation, which in this case is considered the months from April through September. Other effects of the interpolation method are evident in the dataset. Grid points where weather observing stations are located can be seen to have heavier weighting and therefore slightly higher precipitation amounts than surrounding grid points.

One of the tools used to analyze this dataset was Model Evaluation Tools’ (MET) method for object-based diagnostic evaluation (MODE; documentation and other information is available online at http://www.dtcenter.org/met/users/docs/users_guide/MET_Users_Guide_v3.1.pdf). MODE is an object-based verification tool that is generally used to compare gridded forecasts to gridded observations. However, MODE can be used to compare any two fields as long as they are on a common grid, even if the two fields are identical. In our research, the daily precipitation dataset was compared to itself in order to identify contiguous precipitation objects (events) of certain accumulation and size. These “objects” can be thought of as a region of interest where in this case a certain amount of precipitation fell over a contiguous area.

Daily rainfall objects, or contiguous areas of ≥¼” and ≥½” or greater daily accumulation, were identified using the MODE software. These thresholds of precipitation were chosen because they correspond to a 90th percentile daily total at locations within the region of interest. Due to the smoothing effect of interpolation and the use of the entire warm-season, the thresholds for 90th percentile daily totals are lower than reported from station data alone. For example, Groisman et al. (2001) report the July 90th percentile threshold from station data in the central and northern Plains is ~30 mm (1.2”) and ~ 20 mm (0.8”).

Then, all large objects, here defined as containing 675 contiguous grid points or 97,200 km² were found for the same accumulation thresholds. Kane and Fritsch (1987) found that large mesoscale convective weather systems producing over 26 mm of total precipitation were, on average, 96,000 km² in total area.
When the MODE analysis was completed, several statistics were computed from the output. The goal was to determine the frequency of these events and therefore their importance and contribution to warm season precipitation. The average number of large and all objects per year were identified. The contribution of these events to warm season, here defined as April 1st through September 30th, precipitation was also calculated by comparing these event objects to total warm season precipitation. The ratio of large events to the total number of events at each precipitation threshold was calculated to determine what role the larger, more widespread systems played in the warm season totals. These statistics were calculated for the entire 61-year period from 1950-2010. A precipitation comparison between the first half (1950-1979) and the second half (1980-2010) of the dataset was also made to determine whether 90th percentile events had increased or decreased.

When the analysis for the entire conterminous United States (CONUS) was completed, MODE was used to perform an analysis on five point locations in the North Central United States. Because of the relatively sharp gradient of warm season precipitation in this region, we wanted to get a good representation of locations that have different seasonal rainfall totals. The locations identified represent these seasonal rainfall differences and include a point in central Montana-Porphyry Peak, south central North Dakota (Bismarck), south central Nebraska (Kearney), north eastern Colorado (Akron), and central Iowa (Ames). Figure 3-1 below shows the five locations overlain on a map of average warm season precipitation in the United States to illustrate the locations’ position relative to the precipitation gradient. Time lags of precipitation events in the 90th percentile were computed at these locations at time periods of 1 day, 3 days, 7 days, and 30 days to gain a perspective of the number of events expected on a daily, weekly, and monthly basis. Provided that a 90th percentile event occurred on a certain day, the average number of events occurring again within the given time lag was computed.

The warm season was also split up at each of these point locations to determine if the frequency of daily 90th percentile events had changed from the first 30 years to the second 31 years. To determine if the changes in frequency of 90th percentile events were statistically significant, the data at each point location were put through a two-sample t-test.
Fig. 3-1. Point locations analyzed in the MODE analysis (stars) overlain on a map of average warm season precipitation in the United States.

Data from the North American Regional Reanalysis (NARR) from the National Center for Environmental Prediction (NCEP) were used to determine atmospheric conditions during each precipitation event. The NCEP NARR is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain, Mesinger et al. (2006). It incorporates both observations and model simulation through a 3-hour assimilation cycle and because of this is superior in its representation of precipitation over the CONUS (Bukovsky et al., 2006). This dataset is available for years 1979-2010 at 3-hr intervals and 32-km resolution. The fact that the NARR is not available before 1979 is one of the reasons we chose the VIC dataset to analyze warm season precipitation. While other studies have analyzed precipitation on a shorter timescale, we wanted to use as much precipitation data as possible, and using the VIC dataset that starts in 1950 added an extra 29 years of available data.
We identified the days on which objects occurred over the CONUS so that analysis of conditions could be performed only on those days. It was also impractical to analyze atmospheric conditions at every 3-hr interval on the days that events occurred. The VIC dataset starts and ends each Julian day at 12Z, which is 6 LST in the Midwest. Studies have shown that much of the warm season precipitation is nocturnal in the central United States, Wallace (1975). So, to get a likely representation of the conditions on each day a precipitation event occurred, NARR data were analyzed at 12Z at the beginning of the day of interest (called 12Z before), 0Z, which is 1900 LST of that day, and 12Z at the end of the day (called 12Z after) of interest. Variables analyzed at each grid point include convective available potential energy (CAPE),

\[
CAPE = \int_{z_{LFC}}^{z_{LFC}} g \left( \frac{T_{par} - T_{env}}{T_{env}} \right) dz
\]

convective inhibition (CIN), water vapor flux convergence (WVCONV),

\[
WVCONV = \frac{1}{g} \int_{p_1}^{p_2} (\vec{V} \cdot q \cdot \nabla) dp
\]

water vapor increment (WVINC), and precipitable water (PWAT).

\[
PWAT = \frac{1}{g} \int_{p_1}^{p_2} (q) dp
\]

CAPE is a measure of positive buoyancy of an air parcel and a good indicator of the possibility of convection. CIN is calculated in the same manner as CAPE and is essentially the opposite of CAPE, a measure of the negative buoyancy of an air parcel. Water vapor flux convergence describes the movement of moist air into a region and the increase or decrease in moisture density due to convergence or divergence. Water vapor increment describes moisture added to the model when precipitation exists in the observed data and the model does not have enough moisture to produce precipitation. Precipitable water is the total atmospheric water vapor contained in a vertical column of unit cross-sectional area between
any two specified atmospheric levels. These variables were averaged for each 90\textsuperscript{th} percentile precipitation event to provide a general perspective of the conditions leading to those events.

To facilitate the corridor analysis, we set up one large quadrant and four smaller quadrants around each point location analyzed in the North Central U.S. The quadrants extend +/- 2.5° longitude and +/- 2° latitude in accordance with the corridor study by Tuttle and Davis (2005). This creates a 4° wide latitude band and a 5° wide longitude band around each point location which we call a corridor.

The occurrence of an object within a corridor is then defined by the occurrence of a 90\textsuperscript{th} percentile event at one grid point within a quadrant. This was done to determine the frequency of occurrence of 90\textsuperscript{th} percentile events within the corridors and how often events occur in succession within a corridor. The smaller (2.5° by 2°) quadrants surrounding each grid point were used to determine if certain orientations of precipitation-producing weather systems were preferred within the larger corridors. Corridor events that produce precipitation within a corridor on more than one consecutive day were also identified to determine their frequency. The averages of yearly frequency of events producing precipitation on 2, 3, 4, 5, 6, and 7 consecutive days were calculated as well to determine how common these events are at each point location. The warm season was then split up into the first half (April 1 through June 30) and second half (July 1 through September 30) and analyzed separately to determine if there was a seasonality preference to the occurrence of consecutive corridor days. Figure 3-2 below shows the corridor analysis setup including the orientations identified.
Fig. 3-2. Corridor analysis setup showing the quadrants (2.5° longitude by 2° latitude) that were developed around each point location as well as the orientations that were analyzed

3. Results

From the average total warm season precipitation in the VIC data, precipitation events in the 90th percentile were identified for the locations of interest in the North Central United States. The timing of heavy rainfall is often more important than whether it is an extreme rainfall rate. This is clearly illustrated by the 2008 Cedar Rapids flood (Mutel et al., 2010) when the arrival of a flood crest coincided with a night of heavy though not extreme rainfall. The unfortunate timing was responsible for ~70% of the record stream flow. More generally, flood damage is more highly correlated with multi-day rainfall than extreme rainfall on a single day (Pielke et al., 1999). Therefore, we decided to focus on heavy rather than extreme precipitation events that may occur in succession. A plot of warm season precipitation for the United States is shown in Fig. 3-3. We have found that these 90th percentile events contribute 50-70% of total warm season precipitation in these areas (Fig. 3-4a and Fig. 3-4c).
In central Montana, northeastern Colorado, and south-central North Dakota, a precipitation event in the 90th percentile is one that produces approximately 6.4 mm or ¼” of total daily rainfall. For the locations in south-central Nebraska and central Iowa, a 90th percentile event is one that produces twice that – 12.7 mm or ½” (Fig. 3-4b and Fig. 3-4d below).

Fig. 3-3. Warm season (April – September) precipitation over the United States
All 90th percentile events are considered, but those that produce precipitation over a very large spatial area are of greatest concern. The larger the event, the more rainfall volume accumulates which leads to greater runoff into streams and rivers and poses a greater risk for flooding. To characterize a large event, a size threshold of 675 gridpoints (97,200 km²) was used. We use this area to evaluate large daily contiguous rainfall areas because it implies mesoscale to synoptic scale processes were responsible for the rainfall pattern. Results indicate that at the locations of interest in Montana, North Dakota, Nebraska, and Colorado, 30-50% of precipitation above ½” comes from large object events while 50-60% comes from large object events at the location in Iowa. The percentage is even greater for ¼” events where 60-70% of precipitation from this threshold comes from large events in the Montana,
North Dakota, Nebraska, and Colorado while 70-90% comes from large object events in Iowa and farther South. Results also show that 40-60% of all $\frac{1}{2}''$ producing daily rain events are large in the locations in Montana, North Dakota, Nebraska, and Colorado and 50-70% are large in central Iowa. For $\frac{1}{4}''$ producing daily rain events, 70-90% are large in the same four locations and 80-100% are large in central Iowa. Figure 3-5 shows the fraction of warm season precipitation above $\frac{1}{2}''$ and $\frac{1}{4}''$ that come from large objects, as well as the fraction of $\frac{1}{2}''$ and $\frac{1}{4}''$ events that are large.

![Maps showing precipitation patterns](image)

Fig. 3-5. Plots showing (a) the fraction of warm season precipitation over $\frac{1}{2}''$ that comes from large objects, (b) the fraction of $\frac{1}{2}''$ precipitation events that are large, (c) the fraction of warm season precipitation over $\frac{1}{4}''$ that comes from large objects (d) the fraction of $\frac{1}{4}''$ precipitation events that are large.

Also of interest is whether these 90$^{th}$ percentile events are increasing. Results indicate that 90$^{th}$ percentile rainfall has increased by 10-20% in many locations in the United States. Figure 3-6 (a) below shows percent difference in the frequency of $\frac{1}{2}''$ events for the
last 31 years (1980-2010) – the first 30 years (1950-1979) being +10-20%. Figure 3-6 (b) is a plot which shows whether or not ½” events have increased or decreased. Figure 3-6 (c) shows percent difference in the frequency of ¼” events being +0-10% in much of the region with few areas showing a decrease, while Fig. 3-6 (d) shows whether or not ¼” events have increased or decreased. A distinct area of increased ½” and ¼” precipitation in the central US can be seen most clearly in plots (b) and (d).

Fig. 3-6. Plots showing (a) the percent difference in the frequency of ½” precipitation events from the last 31 years to the previous 30 years, (b) whether or not the frequency of ½” precipitation has increased (white) or decreased (black) at each grid point, (c) the percent difference in the frequency of ¼” precipitation events from the last 31 to years to the previous 30 years, and (d) whether or not the frequency of ½” precipitation has increased (white) or decreased (black) at each grid point.

The change in 90th percentile precipitation frequency was also calculated at each individual point location identified in this study. Four of the five locations showed an increase in 90th percentile precipitation between the first and second half of the record. The
location in central Montana showed the largest increase in 90th percentile precipitation of 12.4%. The location in central Iowa showed an increase of 12.2%. The locations in northeastern Colorado and south central Nebraska showed increases of 7.4% and 9.0% respectively. The only location that showed a decrease in the number of 90th percentile events is the point in south central North Dakota with a 2.9% decrease. These results are shown graphically in Fig. 3-7. Results of the t-test show that the increase observed at the point in central Montana is statistically significant at a 95% confidence interval and the increase observed at the point in central Iowa is statistically significant at a 94% confidence interval. The other locations were not found to be statistically significant to levels close to the locations in Montana and Iowa.
Fig. 3-7. Plots showing (a) percent change in 90th percentile precipitation at central Montana location (b) percent change in 90th percentile precipitation at north eastern Colorado location (c) percent change in 90th percentile precipitation at south central North Dakota location (d) percent change in 90th percentile precipitation at south central Nebraska location (e) percent change in 90th percentile precipitation at central Iowa location.
Results of the point analysis indicate that when a 90\textsuperscript{th} percentile event occurs in central Montana, another 90\textsuperscript{th} percentile event occurs on the very next day approximately 36\% of the time, within the next 3 days 50\% of the time, within the next 7 days 80\% of the time and within the next 30 days, the location should experience 3 more 90\textsuperscript{th} percentile events.

In south central North Dakota, a 90\textsuperscript{th} percentile event happens on the next day about 40\% of the time, within the next 3 days 60\% of the time, within the next 7 days 80\% of the time, and within the next 30 days the location should experience 3 more 90\textsuperscript{th} percentile events.

At the location in south central Nebraska, a 90\textsuperscript{th} percentile event occurs 38\% of the time on the next day, 50\% of the time within the next 3 days, 60\% of the time within the next 7 days, and within the next 30 days, the location should experience 2 more 90\textsuperscript{th} percentile events.

In northeastern Colorado, a next-day 90\textsuperscript{th} percentile event occurs approximately 20\% of the time, within the next three days 30\% of the time, within the next 7 days 50\% of the time, and within the next 30 days, the location should experience 2 more 90\textsuperscript{th} percentile events.

In central Iowa, a next-day 90\textsuperscript{th} percentile event occurs approximately 30\% of the time, within the next three days 40\% of the time, within the next 7 days 60\% of the time, and within the next 30 days the location should experience 2 more 90\textsuperscript{th} percentile events.

These results are important to understand because if the climatology of the locations begins to change, changes may be seen in the number of 90\textsuperscript{th} percentile events that occur per week or per month. The plots in Figs. 3-8 through 3-11 below show the results described above.
Fig. 3-8. Probability of a 90th percentile event on the next day following a 90th percentile event in (a) central Montana, (b) northeastern Colorado, (c) south central North Dakota, (d) south central Nebraska, and (e) central Iowa.
Fig. 3-9. As in Fig. 3-8 except for a 3-day lag
Fig. 3-10. As in Fig. 3-9 except for a 7-day lag
Fig. 3-11. As in Fig. 3-10 except for a 30-day lag
The goal of the NARR analysis was to determine the variability of precipitation regimes of 90th percentile events across the north central United States. When the analysis was completed, several observations shed some light on the atmospheric conditions present (or absent) on days when these precipitation events took place.

An elevation of CAPE was seen at every location at 0Z on the day of a 90th percentile event. When a 90th percentile event occurred in central Montana, the peak CAPE was at 0Z, and CAPE existed at the other analysis points as well. CAPE in central Montana was almost non-existent when an event occurred at any of the other locations. Relative to the other locations, the elevation of CAPE in central Montana was minimal.

An elevation of water vapor convergence occurred at 0Z when there was a 90th percentile event at all four locations. However, the peak water vapor flux convergence was seen at 12Z after in Nebraska and Iowa. This added moisture flux is most likely due to the presence of the Low Level Jet (LLJ) that is frequent in the central United States during the warm season months (Higgins et. al. 1997). The authors found a distinct association between the LLJ and nocturnal precipitation and moisture flux. The LLJ showed its peak amplitude and frequencies at 6Z and 12Z, so a peak at 12Z of water vapor flux convergence that is shown in the NARR analysis is not surprising.

When there was strong water vapor convergence in central Montana, there was water vapor divergence in Colorado and the central plains. Peak water vapor flux convergence in Iowa (at 12Z after) corresponded to water vapor divergence at every other point location in the north central U.S. These observations can be seen in Figs. 3-12 and 3-13 below. CAPE and water vapor flux convergence seemed to be key environmental indicators.
Fig. 3-12. Plots showing convective available potential energy (CAPE) (J·kg⁻¹) at 12Z before (far left), 0Z (center), and 12Z after (far right) for all five locations: Central Montana, South Central North Dakota, Northeastern Colorado, South Central Nebraska, Central Iowa.
Fig. 3-13. As in figure 3-6 but for water vapor flux convergence ($kg \cdot (m^2)^{-1} \cdot s^{-1}$)
Results of the corridor portion of this study indicate that in fact there aren’t any preferences in orientation of precipitation events in the corridors analyzed. Each orientation, N-S, E-W, NW-SE, and SW-NE showed an almost equal number of events. The total number of precipitation events in each corridor was fairly uniform across all point locations with an average of 45% of warm season days experiencing a 90th percentile event within the corridor. When precipitation did occur within a corridor, it was more likely than not that the event was a successive corridor event, or an event that produced precipitation on more than one consecutive day. An average of only 7.4% of rainfall days occurred in isolation, where a 90th percentile event occurred after a day when no rainfall was experienced, and no rainfall occurred the day after. These results are outlined in Table 3-1 below.

Table 3-1: Detailed data of the entire warm season corridor analysis

<table>
<thead>
<tr>
<th>Location</th>
<th>Percentage of warm season days per year that experienced a 90th percentile event</th>
<th>Percentage of 90th percentile events that occurred in isolation</th>
<th>Percentage of 90th percentile events that occurred consecutively</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Montana</td>
<td>45%</td>
<td>9%</td>
<td>91%</td>
</tr>
<tr>
<td>South Central North Dakota</td>
<td>42%</td>
<td>6%</td>
<td>94%</td>
</tr>
<tr>
<td>South Central Nebraska</td>
<td>43%</td>
<td>9%</td>
<td>91%</td>
</tr>
<tr>
<td>Northeastern Colorado</td>
<td>49%</td>
<td>6%</td>
<td>94%</td>
</tr>
<tr>
<td>Central Iowa</td>
<td>47%</td>
<td>7%</td>
<td>93%</td>
</tr>
</tbody>
</table>

The frequency of successive events within a corridor for a given length of time documents how long a series of events lasts when it occurs. On average over the four locations, there are 5.6 2-day corridor events per warm season, 4.3 3-day corridor events, 2.6 4-day corridor events, 1.7 5-day corridor events, 1.1 6-day corridor events, and the chance of having a 7 day long corridor event is 78%. Table 3-2 below shows the result of analyzing the average number of 2-7 day corridor events for each location over the warm seasons of the 61 year time series.
Table 3-2: Detailed information on the average number of consecutive corridor events for a given number of consecutive days

<table>
<thead>
<tr>
<th></th>
<th>2 day</th>
<th>3 day</th>
<th>4 day</th>
<th>5 day</th>
<th>6 day</th>
<th>7 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Montana</td>
<td>4.7</td>
<td>3.7</td>
<td>2.4</td>
<td>1.6</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>South Central North Dakota</td>
<td>4.8</td>
<td>3.5</td>
<td>2.3</td>
<td>1.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>South Central Nebraska</td>
<td>6.8</td>
<td>4.5</td>
<td>2.5</td>
<td>1.9</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Northeastern Colorado</td>
<td>4.5</td>
<td>3.8</td>
<td>2.7</td>
<td>1.8</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Central Iowa</td>
<td>7</td>
<td>4.75</td>
<td>3.1</td>
<td>1.95</td>
<td>1.1</td>
<td>.78</td>
</tr>
</tbody>
</table>

When the warm season was split up into two time periods (April 1 through June 30 and July 1 through September 30), the same statistics were calculated as for the entire warm season. The results of this analysis indicate that at three of the point locations, Montana, Colorado, and North Dakota, more 90th percentile events occur within the corridors in the first half of the warm season than the second half with Montana showing the largest difference between the two time periods. The locations in Nebraska and Iowa show a slightly higher number of events during the second half. Table 3-3 below outlines these results in more detail.

Table 3-3: Details on the percent of 90th percentile events that occur in first and second halves of the warm season

<table>
<thead>
<tr>
<th></th>
<th>Percentage of events in first half of warm season (April 1 through June 30)</th>
<th>Percentage of events in the second half of warm season (July 1 through September 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Montana</td>
<td>61%</td>
<td>39%</td>
</tr>
<tr>
<td>South Central North Dakota</td>
<td>51%</td>
<td>49%</td>
</tr>
<tr>
<td>South Central Nebraska</td>
<td>47%</td>
<td>53%</td>
</tr>
<tr>
<td>Northeastern Colorado</td>
<td>52%</td>
<td>48%</td>
</tr>
<tr>
<td>Central Iowa</td>
<td>45%</td>
<td>54%</td>
</tr>
</tbody>
</table>

4. Discussion and Conclusions

In order to examine the characteristics of 90th percentile contiguous precipitation events in the North Central United States, the authors use a 61-year gridded (12-km) observed daily precipitation dataset (VIC dataset) as well as data from the NARR reanalysis. The method for object-based diagnostic evaluation (MODE) was used to identify precipitation events of a given contiguous size and depth threshold in order to highlight the
fact that these events are not isolated but rather widespread and cover large swaths of land. Point correlation analysis was done on five locations in the North Central United States to analyze daily, weekly, and monthly frequency of 90th percentile events at those locations. Finally, a corridor analysis was done on each location to determine how often consecutive rainfall events occur within a narrow band around the locations specified.

The principle findings of this paper include:

- A 90th percentile daily rainfall event in the much of the North Central United States can be characterized by ¼” or ½” of total daily accumulation.
- 90th percentile precipitation events actually contribute 50-70% of total warm season precipitation in much of the North Central United States.
- 90th percentile events have increased in frequency between the first and second half of the past 61 years at many locations throughout the North Central U.S.
- Statistically significant increases in 90th percentile precipitation have occurred in central Montana and central Iowa between the first and second half of the past 61 years.
- Convective available potential energy (CAPE) and water vapor flux convergence are key environmental indicators for these 90th percentile events. Elevated levels of CAPE and water vapor flux convergence existed at all locations when a 90th percentile precipitation event occurred there.
- Point correlation lag analysis indicates that 90th percentile precipitation events are quite common throughout the North Central United States on a daily, weekly, and monthly basis. Increases in the number of these events on any timescale could have a large hydrologic impact on a region.
- Results of the corridor analysis indicate that most (91-94%) of 90th percentile events occur in a series within a defined corridor (2.5° longitude by 2° latitude). This analysis also suggests that, historically, at three of the locations analyzed, more of these events occur in the first half of the warm season than the second half. Any shift in the seasonality of these events could also have large hydrologic impacts.
Using a gridded, interpolated dataset of daily observed precipitation station data provided a unique opportunity to highlight the importance of less extreme rainfall in the 90th percentile to warm season precipitation totals in the north central United States. An extensive time series of data and the use of analysis techniques such as MODE helped to better understand these precipitation events. The results of this research indicate that less extreme events may play a more important role in the threat of flooding than previously thought, especially when considering that these events tend to occur on multiple consecutive days. It is shown that 90th percentile events have increased, and if they continue to do so, their contribution to warm season precipitation may increase as well, leading to higher flood damage as a result.

These results expand upon other studies by using a longer record (61 years) of observed precipitation data than many others, a dataset that is gridded to high resolution (1/8°) and interpolated, and by focusing on less extreme 90th percentile precipitation. While Groisman et. al. (2012) use a similar time series of 62 years (1948-2009), the data is not gridded or interpolated to account for the correlation between stations, and only days with intense precipitation are analyzed. Kunkel et. al. (2012) also use a long time series of 102 years (1908-2009) and a gridded dataset, but the grid resolution is lower (1° by 1°), there is no interpolation (just station averaging within a grid box), and only days with totals >12.5mm are analyzed.

5. Acknowledgements

The authors thank the Iowa Flood Center for providing support for this research.
6. References


CHAPTER 4: CONCLUSIONS AND FUTURE WORK

Conclusions

This thesis examined the characteristics of 90th percentile contiguous precipitation events in the North Central United States. A 61-year gridded, interpolated observed daily precipitation dataset was used as well as data from the NARR reanalysis. The method for object-based diagnostic evaluation (MODE) was used to identify precipitation events of a given size and depth threshold. Point correlation analysis was done on five locations in the North Central United States to look at daily, weekly, and monthly frequency of 90th percentile events at those locations. Finally, a corridor analysis was done on each location to determine how often consecutive rainfall events occur at the locations specified.

The main results of this paper include:

- A 90th percentile daily rainfall event in the much of the North Central United States can be characterized by ¼” or ½” of total daily accumulation.
- 90th percentile precipitation events actually contribute 50-70% of total warm season precipitation in much of the North Central United States.
- 90th percentile precipitation events have increased from the first to the second half of the 61-year period at many locations within the North Central United States.
- Statistically significant increases in 90th percentile precipitation have occurred in central Montana and central Iowa between the first and second half of the past 61 years.
- Convective available potential energy (CAPE) and water vapor flux convergence are key environmental indicators for these 90th percentile events. Elevated levels of CAPE and water vapor flux convergence existed at all locations when a 90th percentile precipitation event occurred there.
- Point correlation lag analysis indicates that 90th percentile precipitation events are quite common throughout the North Central United States on a daily, weekly, and
monthly basis. Increases in the number of these events on any timescale could have a large hydrologic impact on a region.

- Results of the corridor analysis indicate that most (91-94%) of 90th percentile events occur in a series within a defined corridor (2.5° longitude by 2° latitude). This analysis also suggests that, historically, at three of the locations analyzed, more of these events occur in the first half of the warm season than the second half. Any shift in the seasonality of these events could also have large hydrologic impacts.

This thesis highlights the importance of less extreme rainfall in the 90th percentile to warm season precipitation totals in the North Central United States. Using a high-resolution gridded, interpolated dataset of daily observed precipitation station data provided a unique opportunity to analyze an extensive time series of data and use unconventional analysis techniques such as MODE. Using the gridded dataset also made utilizing NCEP NARR data for point analysis possible.

**Future Work**

Now that a good understanding has been gained of the warm season precipitation characteristics over the last 61 years, it will be desirable to attempt to predict what changes may occur in the future. Data from the North American Regional Climate Change Assessment Program (NARCCAP) may be used to evaluate regional atmospheric conditions. NARCCAP produces high resolution climate change simulations over North America in order to investigate regional scale climate change projections by utilizing regional climate models. Smaller domains over regions of North America have been developed for regional analysis as well. The data is available for retrospective reanalysis-driven simulations from 1979-2004. This simulation period could be compared to the same time period in the VIC dataset to see how well the climate model predicted historical events. NARCCAP data is also available for global climate model (GCM) driven current and future climate projections (1971-2000) and (2038-2070). This would be useful to see how warm season precipitation could continue to change in the future.
It may also be beneficial to look at the precipitation data on a smaller scale as well, such as a specific watershed. This could be accomplished by delineating a watershed and evaluating the observed precipitation characteristics within it. Evaluating precipitation totals and timing of past events within a watershed could provide more insight into how stream flows within the watershed are affected by certain daily precipitation events. The use of a gridded, interpolated dataset to do this would be advantageous over using 1 or 2 stations unevenly distributed throughout a watershed. This method might yield better results in a watershed with no precipitation gauges as well.
ACKNOWLEDGEMENTS

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REFERENCES


