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The tale of flooding over the central United States

Iman Mallakpour
University of Iowa

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THE TALE OF FLOODING OVER THE CENTRAL UNITED STATES

by
Iman Mallakpour

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degree in Civil and Environmental Engineering in the
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The University of Iowa

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Thesis Supervisor: Professor Gabriele Villarini

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

Iman Mallakpour

has been approved by the Examining Committee for
the thesis requirement for the Doctor of Philosophy degree
in Civil and Environmental Engineering at the August 2016 graduation.

Thesis Committee: ___________________________________
Gabriele Villarini, Thesis Supervisor

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A. Allen Bradley

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Witold F. Krajewski

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Keith Schilling

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Larry J. Weber

To my mom, Mina, my father, Shadpour, my sisters, Adeleh and Freshteh, and my brother-in-law, Hossein.

The world does not begin or end today	امروز نه آغاز و نه انجام جهان است
Sad and happy hide behind one curtain	اي بس غم و شادي كه پس پرده نهان است
If you're on the path don't despair of the distance	گر مرد رهي غم مخور از دوري و ديري
Arrival is the art of stepping through time	داني كه رسيدن هنر گام زمان است
A seasoned traveler on the road to love's door	تو رهرو ديرينه سرمنزل عشقي
Your blood leaves its mark on every step	بنگر كه زخون تو به هر گام نشان است
Still water soon sinks into the earth	آبي كه برآسود زمينش بخورد زود
But the river rolling grows into a sea	دريا شود آن رود كه پيوسته روان است

Hushang Ebtehaj (Translated by Mojdeh Marashi & Chad Sweeney)
The Art of Stepping Through Time

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ABSTRACT

The central United States is a region of the country plagued by frequent catastrophic flooding (e.g., flood events of 1993, 2008, 2011, 2013, and 2014). In the twentieth and twenty-first centuries, flooding has taken a devastating societal and economic toll on the central United States, contributing to dozens of fatalities and causing billions of dollars in damage. Moreover, previous studies have shown that flood damage has been increasing over the past century across this region, and seems to foreshadow a future increase in flood activity. Despite these large repercussions, the use of historical records to ascertain the changes over time in flooding has thus far proved inconclusive. It is therefore of paramount importance to examine whether the characters (i.e., magnitude and frequency) of recent flooding are different from the long-term averages over the central United States. The results of this thesis are based on long-term discharge records at 774 U.S. Geological Survey sites and show limited evidence suggesting increasing or decreasing trends in the magnitude of flood peaks over the study region. In contrast, there is much stronger evidence of increasing frequency of flood events. While the detection of changes in flood characteristics is essential, it is also of critical importance to start exploring what caused these changes. Therefore, in addition to the aforementioned investigation on the stream flow records, precipitation records were used to inspect whether possible changes in flood characteristics can be linked to the changes in heavy precipitation characteristics. The results indicate that there is a stronger signal of change in the frequency rather than in the magnitude of heavy precipitation events, similar to what found for the discharge records. Given that heavy precipitation is responsible for the observed changes in flooding, further analyses were performed to examine the climatic driving forces that are responsible for the observed changes in the frequency of precipitation, and consequently flooding at the seasonal scale; particular emphasis was paid to the role played by the Atlantic and Pacific Oceans. The results of this dissertation indicate that changes in the climate system play a significant role in explaining the variations in the frequency of heavy precipitation and flooding over the central United States at both the seasonal and sub-seasonal scales. The Pacific North American (PNA) teleconnection pattern was found to play a particularly prominent role. Therefore, these results suggest that recent observed changes in the frequency of flood events over the central United States can be largely attributed to changes in the frequency of heavy precipitation events, which were in turn driven by changes in the climate system.

PUBLIC ABSTRACT

Rivers are one of the most important natural resources for human activities, particularly for the agricultural communities of the central United States. In this predominantly agricultural region of the country, a large concentration of the population are clustered near rivers. However, settling near rivers comes with increased vulnerability to flooding. Floods are extreme hydrological events that occur periodically, and humankind refer to them as a natural hazard. In the twentieth and twenty-first centuries, the central United States has been affected by a series of large floods such as those that occurred in 1993, 2008, 2011, 2013 and 2014. These events had adverse societal consequences including agricultural losses, decreased food production and displacement of communities/people, leading to economic losses reaching billions of dollars. Therefore, it is of the utmost importance to examine whether the magnitude and/or frequency of flood events have been changing over the most recent decades. Moreover, to interpret the possible changes in the occurrence of flood events and to investigate future changes in flooding, it is crucial to take a step forward to investigate the possible causes and drivers of the observed changes. The results of this dissertation, highlighting the detection, attribution, and drivers of the possible changes in flooding, provide important insights into flooding characteristics and conditions over the central United States. The insight gained from this work can provide basic information that has the potential to improve future water management and planning for the central United States.

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CHAPTER 1 INTRODUCTION

> "That stated time had arrived. […] The weather was frightful to behold! [...] All day long the South Wind blew, blowing fast and then the flood came, overwhelming the people like an attack […] Six days and seven nights came the wind and flood, the storm flattening the land […] I looked around all day long, quiet had set in and all the human beings had turned to clay! The terrain was as flat as a roof. "
>
> The Epic of Gilgamesh, tablet 11, approximately 2700 BCE

Living alongside rivers has always been one of the first and sought-after options because of the close proximity to one of the most important natural resources (e.g., for irrigation and drinking water, communications and transportation, fertile soils). However, settling near rivers also comes with the possibility of flooding. Although flood events can provide an important source of water, especially in arid and semiarid regions of the world (e.g., transport of nutrients, water sources for near stream riparian systems, maintaining water levels of reservoirs; e.g., Mallakpour, 2011, Simpson and Meixner, 2012, Simpson et al., 2013), the primary effects of flood events are mostly negative (e.g., fatalities, destruction of infrastructure near rivers, erosion and water quality issues, changes in the morphology of the rivers). For example, just in 2013, 9819 people lost their lives due to flooding and the total economic damages were about $52.4 billion worldwide (Guha-Sapir et al., 2014). In 2014, although fewer people were killed by flood-related disasters (3634), flooding still accounted for the highest number of deaths due to natural disasters globally (Guha-Sapir et al., 2015).

Flood events occur periodically depending on factors such as the intensity and amount of precipitation, the morphology of the river, topography and soil type, land use and land cover (e.g., Funk, 2006, Ashley and Ashley, 2008). Garner et al. (2015) indicated that weather and climate conditions are the drivers of flood events, and basin characteristics control and moderate the occurrence of flood events. Flooding can occur over a wide range of spatial scales, from 1 to 10^5 km^2, and over temporal scales on the order of hours to several months (Stahl and Hisdal, 2004, Garner et al., 2015).

Floods are extreme hydrological events that humankind tends to refer to as a "natural hazard." Flooding is also one of the most common natural hazards in the United States. The National Weather Service (NWS) estimated that flooding is responsible for billions of dollars in damage and about 100 flood-related fatalities on average every year in the United States (NWS, 2014) over the 1914-2013 period. In recent years, flood-related fatalities have ranked second among weather-related hazards in the United States (e.g., Ashley and Ashley, 2008). The central United States, in particular, is plagued by large flood events, especially over the most recent decades (e.g., 1993, 2008, 2011, 2013, 2014), with flood damage in excess of several billion dollars and numerous fatalities (e.g., Hicks and Burton, 2008, Otto, 2009, Smith and Katz, 2013, NCDC, 2015). For example, approximately 80% of flood economic damage and 40% of flood-related deaths in 2008 occurred in the central United States (NWS, 2014). During the June 2008 Midwest flood alone, 24 people lost their lives, 140 were injured (Dirmeyer and Kinter, 2009) and the total economic damages were of approximately $11 billion (Xiao et al., 2013, NCDC, 2015). The Mississippi and Missouri flooding of April-June 2011 caused economic losses on the order of $5 billion and 12 fatalities (NCDC, 2015). Because of all these devastating flood events over the central United States, there has been a large interest in analyzing the observed streamflow records to detect variability in flood magnitude and/or frequency (e.g., Lins and Slack, 1999, Schilling and Libra, 2003, Lins and Cohn, 2011, Villarini et al., 2011b, Hirsch and Ryberg, 2012, Slater et al., 2015).

Although damage from flood events varies from year to year (e.g., Downton et al., 2005, NWS, 2014), previous studies have shown that flood damage has been increasing over the past century (e.g., Pielke and Downton, 2000, Downton et al., 2005, Gall et al., 2011). Part of the increase in flood damage is due to the growth in human activities over flood-prone regions (Pielke and Downton, 1999, Peterson et al., 2013). However, modeling studies point to an intensification of the hydrological cycle under projected climate warming (e.g., Voss et al., 2002, Held and Soden, 2006, Huntington, 2006), with increasing frequency of extreme events, such as heavy rainfall and flooding (e.g., Voss et al. 2002, Milly et al. 2002, 2005, Christensen and Christensen, 2003, IPCC, 2012).

Despite these modeling results, detecting changes in the flood records has been highly elusive. The Intergovernmental Panel on Climate Change (IPCC) report (Hartmann et al., 2013) concluded that “there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods at a global scale.” Similar contrasting conclusions were reached by a number of observational studies examining changes in flood magnitude over the central United States (e.g., Changnon and Demissie, 1996, Lins and Slack, 2005, Novotny and Stefan, 2007, Schilling and Libra, 2003, Zhang and Schilling, 2006, Villarini et al, 2009, 2011b). Studies such as Lins and Slack (1999, 2005) were not able to find statistically significant trends in peak flow at the majority of the stations they considered. On the other hand, Gebert and Krug (1996) performed analyses at a much more local scale (Driftless Area of Wisconsin) and found a decreasing trend in the annual peak flow data. Increasing trends were reported in studies such as Groisman et al. (2001) over the eastern part of the United States, Olsen et al. (1999) over the northern part of the Upper Mississippi basin and Novotny and Stefan (2007) over the Red River, the Minnesota River, and Mississippi River basins.

Furthermore, design of hydraulic structures (e.g., dams, bridges, sewer systems) and, more generally, current methods for flood frequency analysis and forecasting in the United States are based on the stationary assumption (IACWD, 1982, Salas and Obeysekera, 2014). This assumption means that the probability distribution is not changing over time (Brillinger, 2001), and the distribution of past observed events is representative of possible future conditions. Otherwise stated, a stationary time series is one that is free of any gradual, abrupt and periodic changes (Salas, 1993). However, in recent years there have been numerous studies investigating the validity of the stationary assumption (e.g., Hejazi and Markus, 2009, Vogel et al., 2011, Villarini et al., 2009, 2011b, Mallakpour and Villarini, 2016b, Slater et al., 2015), and most of them arrived at the similar conclusion that the stationary assumption is no longer valid. In an era that presumes that "the stationary assumption is dead" (Milly et al., 2008), potential changes in peak flow over the central United States could have very large economic and social repercussions (e.g., fatalities, agricultural losses, property losses, water quality issues). Therefore, with elusive and contrasting results regarding possible changes in flooding and questions regarding the assumption of stationarity, it is of paramount importance to perform an extensive and detailed analysis of changes in flood characteristics across the central United States over the most recent decades.

While detection of changes in flood characteristics (i.e., magnitude and frequency) is important, it is also imperative to investigate future changes in these same characteristics. It is therefore of critical importance to go beyond the simple detection of changes in flood time series, and to start investigating what caused these changes. Attribution of causes represents the procedure that leads to the establishment of the most likely causes for the observed changes. Changes in regional flooding behavior reflect the combined influence of climate, stream dynamics, and watershed characteristics. Peterson et al. (2013) indicated that similar spatial patterns can be observed by investigating the presence of trends in flooding and associated changes in the total annual precipitation series. Similarly, Ryberg et al. (2012) indicated that changes in precipitation are the primary driver for changes in flood magnitude over the North Central United States. From a more process-oriented perspective, Villarini et al. (2013a) indicated that large flood events over the Mississippi River basin and more generally over the central United States are products of heavy rainfall over an extended period of time. Villarini et al. (2011b) discussed that flood events over Nebraska, Kansas and Iowa are related to summer time convective systems, and flood events over the northern part of the central United States are due to snow melting and rain-on-snow events. Lavers and Villarini (2013) found that atmospheric rivers are responsible for some of the largest flood events over large areas of the central United States. By focusing on flood impacts, Ashley and Ashley (2008) reported that most flood-related deaths in the United States are due to flash flooding resulting from heavy precipitation. In addition, they indicated that flood-related deaths in the eastern part of the United States are higher because of the higher number of heavy precipitation events that occur each year. Here, I will start by considering changes in precipitation (in particular at the high end of the distribution) as the main culprit to explain changes in the flooding.

The IPCC (2012) reported that extreme precipitation events have been increasing since 1951 over many locations in the mid-latitudes. These increases have been observed even in regions where a decreasing trend in the total annual precipitation was detected (IPCC, 2012). An upward trend in extreme precipitation has been observed for the past decades over the United States in general (e.g., Karl et al., 1996, 2009, Karl and Knight, 1998, Kunkel et al., 1999, 2003, Gershunov and Cayan, 2003, Groisman et al. 2001, 2005, Higgins and Kousky, 2013, Anderson et al., 2015), and over the central United States in particular (e.g., Angel and Huff, 1997, Groisman et al. 2012, Villarini et al., 2013a, Stevenson and Schumacher, 2014). Karl and Knight (1998) found that total precipitation increased by 10%, and that most of this increase came from the upper ten percent of the daily precipitation distribution. Overall, the increase in the frequency and intensity of heavy rainfall is an apparent characteristic over the United States during the past 50 years (Karl et al., 2009). Groisman et al. (2012) indicated that days with heavy precipitation account for almost 70% of annual rainfall over the central United States. Angel and Huff (1997) found an increasing trend in heavy precipitation and they indicated that rainfall stations in this region are "more likely to experience their heaviest rainfall events in more recent years." Indeed, because a warmer atmosphere can hold more water vapor, computer models of future climate include a pronounced increase in the heaviest rainfall events (e.g., Allen and Soden, 2008, Sillmann et al., 2013). Therefore, future projections of precipitation are predicting a higher rate of change in the frequency of precipitation (Monier and Gao, 2014) with the highest change in extreme precipitation over the Northwestern and Northeastern United States (Meehl et al., 2005).

Given that rainfall is responsible for the observed changes in flooding, I will investigate why rainfall has been changing. My hypothesis is that the observed changes in rainfall over the central United States are associated with climatic variability related to the influence of the Atlantic and Pacific Oceans. Coupled oceanic-atmospheric variations can happen on interannual, decadal and multidecadal timescales (e.g., Tootle et al., 2005) resulting in seasonal, annual, and decadal changes in the hydrologic processes (e.g., Andersen and Shepherd, 2013). Redmond et al. (2002) indicated that fluctuations in the spatial and temporal distribution of extreme hydrologic events are due to fluctuations in climate variability. Indeed, climate variability can affect the jet streams and storm tracks that are controlling extreme hydrological events (e.g., flood, heavy precipitation, drought; e.g., Andersen and Shepherd, 2013). Climate indices such as the North Atlantic Oscillation (NAO; e.g., Hurrell, 1995), the Southern Oscillation Index (SOI; e.g., Ropelewski and Jones, 1987), the Pacific Decadal Oscillation (PDO; e.g., Mantua et al., 1997), the Atlantic Multidecadal Oscillation (AMO; e.g., Enfield et al., 2001), the Arctic Oscillation (AO; e.g., Thompson and Wallace, 1998, 2000) and the Pacific-North American pattern (PNA; e.g., Leathers et al., 1991) are metrics that can be used to describe the state and variation in the climate system, with particular emphasis on the Atlantic and Pacific Oceans.

There is a growing number of studies examining the relationship between hydrological processes and climate variability. These studies show that low frequency climate variability to some extent can control precipitation (e.g., Leathers et al., 1991, Enfield et al., 2001, Durkee et al., 2008), groundwater level (e.g., Kuss and Gurdak, 2014), streamflow (e.g., Enfield et al., 2001, Tootle et al., 2005, Tootle and Piechota, 2006, Sagarika et al., 2015), and drought (e.g., McCabe et al., 2004). Contrasting results have been found regarding the relationship between streamflow and climate variability in the continental United States. McCabe and Wolock (2014) investigated spatial and temporal changes in the streamflow characteristics throughout the United States. In general, they found weak correlations between mean annual streamflow and the climate indices they examined (i.e., El Niño–Southern Oscillation (ENSO), PDO, AMO, PNA and NAO). The authors indicated that temporal changes in mean annual streamflow were not predictable by climate indices. However, Tootle et al. (2005) evaluated the streamflow responses to four climate indices (PDO, NAO, AMO, and ENSO) and found that they can influence the streamflow variability over the continental United States. Indeed, they concluded that potentially valuable information for streamflow forecasters and water managers can be provided by investigating the relationship between climate indices and streamflow conditions. While in the past the relationship between discharge and climate was explored, the focus was on average annual streamflow, annual maxima or volume, rather than on the frequency of flood events as in this thesis.

If the relationship between climate variability and flood events can be unraveled as hypothesized above, then it may help us understand and predict future flood conditions. In other words, understanding the relationship between climate variability and flooding could improve future water management. Interannual to decadal climate predictions have been gaining attention for short-term decision-making, flood defense and water planning (e.g., Wang et al., 2014). A number of studies have shown that large-scale climate indices can be used to forecast streamflow (e.g., Tootle and Piechota, 2004, Wernstedt and Hersh, 2002, 2004, Hamlet and Lettenmaier, 1999, Kalra and Ahmad, 2009, Risko and Martinez, 2014). Piechota and Dracup (1999) used ENSO for long-range streamflow forecasting over the Pacific Northwest region of the United States. Hamlet and Lettenmaier (1999) showed that climate indices such as PDO and ENSO can be used to predict the Columbia River streamflow with a lead time of six months. Hsieh et al. (2003) developed a framework to make long-range streamflow predictions using tropical Pacific sea surface temperature (SST), PNA, and PDO, along with local precipitation.

However, one of the challenges in using large-scale climate indices to forecast streamflow is choosing the optimal climate indices (Risko and Martinez, 2014). Kalra and Ahmad (2009), for instance, used ENSO, NAO, PDO and AMO for 3-year lead time streamflow forecasting over the Upper Colorado River Basin, and indicated that ENSO and NAO were the best set of climate indices for predicting streamflow over that region. The reliability of flood predictions is heavily dependent on the accuracy of the predictions of climate indices.

To summarize, the focus of my thesis is the detection and attribution of changes in flooding across the central United States. I view this as a hierarchy of problems which can be addressed with the following hypotheses:

-Flood frequency over the central United States has been changing over the past 50+ years;

-The changes observed in flooding are mostly driven by changes in heavy rainfall;

-The changes in heavy rainfall and flooding are largely driven by changes in the climate system related to the influence of the Atlantic and Pacific Oceans.

The results of this proposed research will provide important insights into flooding characteristics and conditions over the central United States. While the focus of the proposed research is on flooding over this region and on understanding of the major drivers of change in flood characteristics, the result and methodology will provide basic information that can be applied for water resources planning and management both over this region and across other areas.

CHAPTER 2 DATA

2.1. Introduction

Long-term historical records are key to understand the past and provide valuable information about possible future changes. In this chapter, I introduce and present the different datasets that I will use throughout the remaining chapters of this thesis.

2.2. Study area and stream flow data

This thesis focuses on heavy rainfall and flooding across the central United States, defined here as the region including 14 states: North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Illinois, West Virginia, Kentucky, Ohio, Indiana, and Michigan (Figure 2-1). I use daily streamflow records from 774 U.S. Geological Survey (USGS) stream gauges that have at least 50 years of data that end no earlier than 2011, and with a gap no larger than two years (Figure 2-1, panels b and c). A year counts as complete when streamflow data are available for at least 330 days (less than 10% missing days). From these 774 stream gauges, 43 of them are located in North Dakota, 45 in South in Dakota, 54 in Nebraska, 69 in Kansas, 50 in Missouri, 68 in Iowa, 42 in Minnesota, 50 in Wisconsin, 89 in Illinois, 32 in West Virginia, 26 in Kentucky, 63 in Ohio, 75 in Indiana, and 68 in Michigan. Overall, there is a good density of stations, allowing me to have an overall good characterization of the changes in flood hydrology over the central United States at large. Even though the focus of this study is on stations with at least 50 years of data, most of the stations have 60 to 80 years of data, providing a comprehensive view of discharge over the second half of the 20th century and into the first decade of the 21st century.

Over the central United States, there is a marked seasonality in the annual maximum daily discharge records (Figure 2-2, panels a-d) and the seasonality of the flood events exceeding a high threshold to give two events per year on average (Figure 2-2, panels e-h); with almost similar seasonal patterns between the two datasets. Between 50% and 90%+ of flood events tend to occur during spring over the majority of the study region, especially in the north part of the study area. These flood events are largely driven by snowmelt, rain-on-snow or rain on frozen ground, as well as by extratropical cyclones and atmospheric rivers. During the summer, the largest fraction of flood events is concentrated over the western part of the domain, where mesoscale convective systems tend to be responsible for these events. Fall is the season with the smallest contributions to the flood seasonality. Finally, up to about 50% of the flood events tends to occur in the winter in the southeastern part of the study region (i.e., southern Illinois, Indiana, Kentucky, Ohio and West Virginia), with atmospheric rivers playing a dominant role (e.g., Lavers and Villarini, 2013). For a more detailed and extensive characterization of flood seasonality across this area, consult Villarini (2016) and Berghuijs et al. (2016).

2.3. Hydrometeorological data sets

Precipitation analyses are based on the unified Gauge-Based daily observation data from 1948 to 2012. This data set is available from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) with no missing data over the contiguous United States (Higgins et al., 2000). This product has a horizontal grid resolution of $0.25^{\circ} \times 0.25^{\circ}$ and contains daily precipitation information from more than 8000 stations over the contiguous United States (Higgins et al., 2007, Higgins and Koiusky, 2013). The seasonality of the annual maximum daily precipitation (Figure 2-3, panels a-d) and the seasonality of the days exceeding the 95th percentile of the precipitation distribution (Figure 2-3, panels e-h) show a marked seasonality over the study domain, with some differences and similarities with respect to what observed for flooding (Figure 2-2). The largest seasonal contribution to extreme precipitation over this area is in the summer, with more than half of the annual extremes occurring in this season. Spring, on the other hand, shows a much weaker contribution, and mostly limited to North and South Dakota and Kansas. These results are different from what observed for flooding, where snowmelt played a critical role in controlling the upper tail of the distribution, in particular in the northern Great Plains. On the other hand, the precipitation results for fall and winter tend to mirror those for flooding: weak contribution to extremes in the fall, while the largest fractions are concentrated in the south-eastern part of the domain in the winter. In another study examining in details changes in extreme precipitation over the continental United States (Mallakpour and Villarini, 2016a), I checked whether there have been changes in the seasonality of extreme precipitation during the second half of the 20th century and the first decade of the 21st century; overall I found very limited empirical evidence suggesting that the seasonality of extreme precipitation has been changing over the past 60+ years.

The temperature data used for some of the analyses in Chapter 3 is based on gridded monthly mean surface air temperatures by the University of Delaware (Willmott and Robeson, 1995). This observation-based gridded product has a grid resolution of 0.5° latitude/longitude degrees. I obtained this dataset from the NOAA's website (http://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html) for the period of 1948-2011.

To connect the results from the statistical analyses to the physical processes in Chapters 4 and 5, I use integrated vapor transport (IVT) and 500-mb geopotential height (GPH). IVT (kg m^{-1} s^{-1}) is a quantity that describes the total amount of transported water vapor to a location, and is calculated by integrating specific humidity, zonal and meridional winds across different atmospheric levels (e.g., from the surface to 300 hPa; Neiman et al., 2008, Lavers and Villarini, 2013, Nayak et al., 2016). IVT magnitude is computed as:

$$IVT = \sqrt{\left(\frac{1}{g}\int_{surface}^{300} qudp\right)^2 + \left(\frac{1}{g}\int_{surface}^{300} qvdp\right)^2} \tag{2.1}$$

where g is the acceleration due to gravity (m s^{-2}), q is specific humidity (kg kg^{-1}), dp is the pressure difference between two pressure levels, u is zonal wind (ms^{-1}) and v is meridional wind (ms^{-1}). Here IVT is computed from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset for the 1948-2012 period. NCEP-NCAR also represents the source of information for the 500-mb GPH. The GPH represents the height of the pressure surface, and is given by

$$GPH = \frac{\Phi(z)}{g_0} = \frac{1}{g_0}\int_0^z gdz \tag{2.2}$$

where Φ(z) is geopotential at height z and g_0 is the globally averaged acceleration due to the gravity on the surface of the Earth (Wallace and Hobbs, 2006). The use of 500-mb GPH is because most of the weather system and moisture transport mechanisms follow the winds at this level.

2.4. Climate indices

The streamflow and precipitation data are complemented by different climate indices reflecting the state of the Atlantic and Pacific Oceans (see analyses in Chapters 4-5). The ocean and atmosphere are dynamic systems; coupled together, they structure a complex, ever-changing system that governs our planet's climate (e.g., Hidore et al., 2009). Climate variability in the coupled oceanic-atmospheric system causes variability in the atmospheric flow (e.g., Sheridan, 2003), which is one of the main reasons for the variability of climatic patterns. Climate indices are metrics that can be used to describe the state and variation in the climate system. Researchers use quantities related to the oceanic-atmospheric system such as SST and sea level pressure (SLP) to calculate these indices, which are then used to investigate the influence of coupled oceanic-atmospheric variations on the climate and weather. Here I will focus on some of the most widely indices to characterize the connection between climate and hydrometeorological events.

The NAO index is one of the leading modes of inter-annual to decadal timescale variability in the oceanic-atmospheric system and describes the large-scale change in the atmospheric mass over the North Atlantic Ocean (Hurrell, 1995). The negative (positive) NAO values represent weaker (stronger) than average pressure centers over the subtropical high and subpolar low regions, which result in weaker (stronger) westerly winds (e.g., Hurrell, 1995, Sheridan, 2003, Kuss and Gurdak, 2014). Traditionally, NAO is calculated using the normalized SLP anomaly difference between the Azores and Iceland (e.g., Hurrell, 1995, Stenseth et al., 2003, Portis et al., 2001). However, the downside of using the traditional NAO is that the pressure differences between the subtropical high and subpolar low regions are much more pronounced during the winter season. Because here I do not limit my analyses to the winter season, I use the "mobile" NAO index based on Portis et al. (2001), which is a seasonally and geographically changing NAO index. I calculated the "mobile NAO" index for the 1948-2012 period, by subtracting the normalized SLP anomalies at the locations of the North Atlantic Ocean where SLP between subtropical and subpolar shows the maximum negative correlation [consult Portis et al. (2001) for more information]. The monthly mean SLP data that are used to calculate the "mobile NAO" index are based on NCEP–NCAR reanalysis.

The ENSO index used in this study is based on the SOI index, which can be determined by using the SLP differences between Tahiti and Darwin (e.g., NOAA, 2015, Ropelewski and Jones, 1987, Trenberth, 1984). The negative (positive) values of the SOI represent El Niño (La Niña) episodes in the Pacific Ocean (NOAA, 2015). The SOI index was obtained from the NOAA CPC (http://www.cpc.ncep.noaa.gov/data/indices/soi) for the period of 1951-2012.

The PDO index is the mode of climate variability related to decadal to inter-decadal variability in the atmospheric system (Mantua et al., 1997). This index is defined based on the monthly SST over the Pacific Ocean, north of 20° N after the global mean SST has been removed (e.g., Mantua et al., 1997, Mantua and Hare, 2002). This index consists of positive (warm) and negative (cold) phases where each phase can last from 20 to 30 years (e.g., Tootle et al., 2005). Hamlet and Lettenmaier (1999) indicated that the effects of the positive (negative) phase of the PDO are similar to the impacts of El Niño (La Niña) episodes. The PDO index was downloaded from the CPC website (http://www.esrl.noaa.gov/psd/data/correlation/pdo.data) for the period of 1948-2012.

The AMO index is a mode of climate variability identified as a natural leading pattern of the low-frequency SST variability over the North Atlantic Ocean from 0° to 70°N (e.g., Enfield et al., 2001, Tootle et al., 2005). Enfield et al. (2001) indicated that this mode can control the strength of the thermohaline circulation over the Atlantic Ocean and has an oscillation on the order of 60-80 years. This index also consists of two phases, positive and negative. The positive phase of AMO have been associated with warmer North Atlantic SST and larger Atlantic warm pool (AWP), in comparison with the negative phase of AMO (Enfield et al., 2001, McCarthy et al., 2015). The AMO index was downloaded from the CPC website (http://www.esrl.noaa.gov/psd/data/correlation/amon.us.data) for the period of 1948 to 2012.

The PNA index is a prominent natural mode of climate variability over the Pacific Ocean and North America (e.g., Wallace and Gutzler, 1981, Leathers et al., 1991). This climate mode can describe the variation of the jet streams in the Northern Hemisphere's mid-latitudes, particularly over North America (Wallace and Gutzler, 1981, Leathers et al., 1991). The PNA index is calculated by using the mean of normalized mid-latitudes 500-mb GPH height anomalies over the Pacific Ocean and North America. Leathers et al. (1991) indicated that the PNA index has a strong connection with the surface weather over the United States. This index is characterized by a positive phase that reflects above normal GPH near Hawaii and near Alberta and below normal GPH located in the Aleutian low and Florida. Studies (e.g., Leathers et al., 1991, Notaro et al., 2006) have shown that the positive phase of PNA is associated with above average temperature and below average precipitation over the eastern United States. On the other hand, the negative phase of PNA shows below (above) average GPH values over the western (eastern) side of the United

States, leading to wind flow that is more zonal over the United States (e.g., Sheridan, 2003). The negative phase of the PNA index has been associated with cooler temperatures and above average precipitation over the eastern United States (Leathers et al., 1991, Notaro et al., 2006). The monthly and daily values of the PNA index was obtained from the CPC website (http://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml) for the period 1950-2012.

Finally, the AO index is a climate index that describes the circulation of the atmosphere around the Arctic (e.g., Thompson and Wallace, 1998, 2000). Studies have shown that this circulation influences storm tracks, polar jet movement, air mass and moisture exchange between the polar regions and the mid-latitudes, over a temporal scale ranging from a week to decades (e.g., Ambaum et al., 2001, Knight et al., 2008, Hu and Feng, 2010, Kellner and Niyogi, 2015). This climate mode is one of the major sources of climate variability over the large areas of the northern hemisphere, and it presents a center of action over the Arctic and antagonistic anomalies over the mid-latitude (Thompson and Wallace, 1998, 2000, Deser, 2000). The AO index is calculated using the first leading empirical orthogonal function (EOF) of the 1000-mb height anomalies over the North Hemisphere, north of 20°N (Thompson and Wallace, 1998, 2000, Hu and Feng, 2010). The negative (positive) values of the AO are associated with weaker (stronger) than average polar vortex over the Arctic, leading to weaker (stronger) upper-level westerly winds (e.g., Hu and Feng, 2010, Kellner and Niyogi, 2015). The daily AO index was obtained from the CPC website (http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml) for the period 1950-2012.

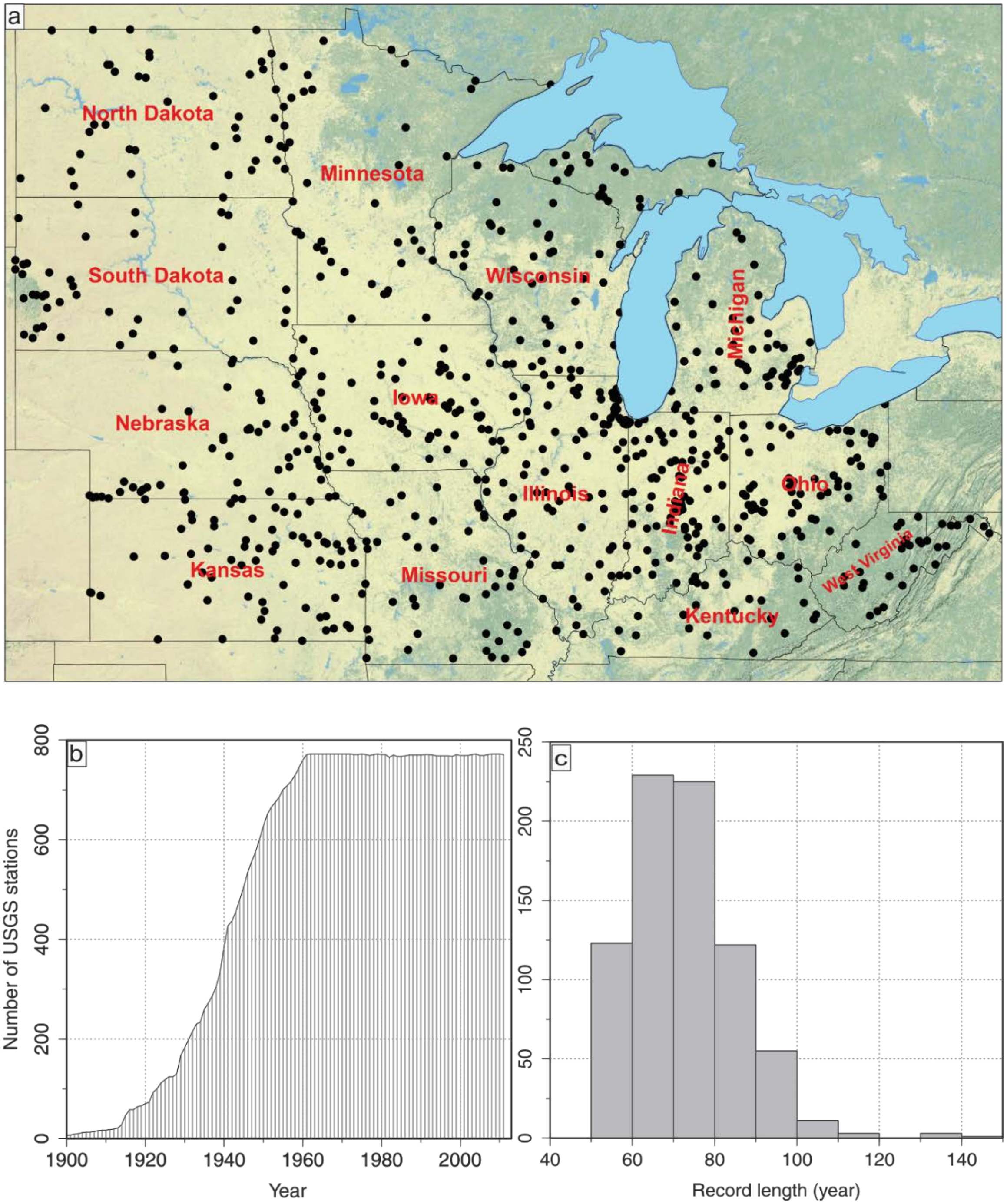

Figure 2-1: (a) Map showing the study area and the location of the 774 U.S. Geological Survey (USGS) stations (black circles) used in this study. (b) Number of available stations in a given year. (c) Histogram showing the length of record (in years) for all the stations used in this study.

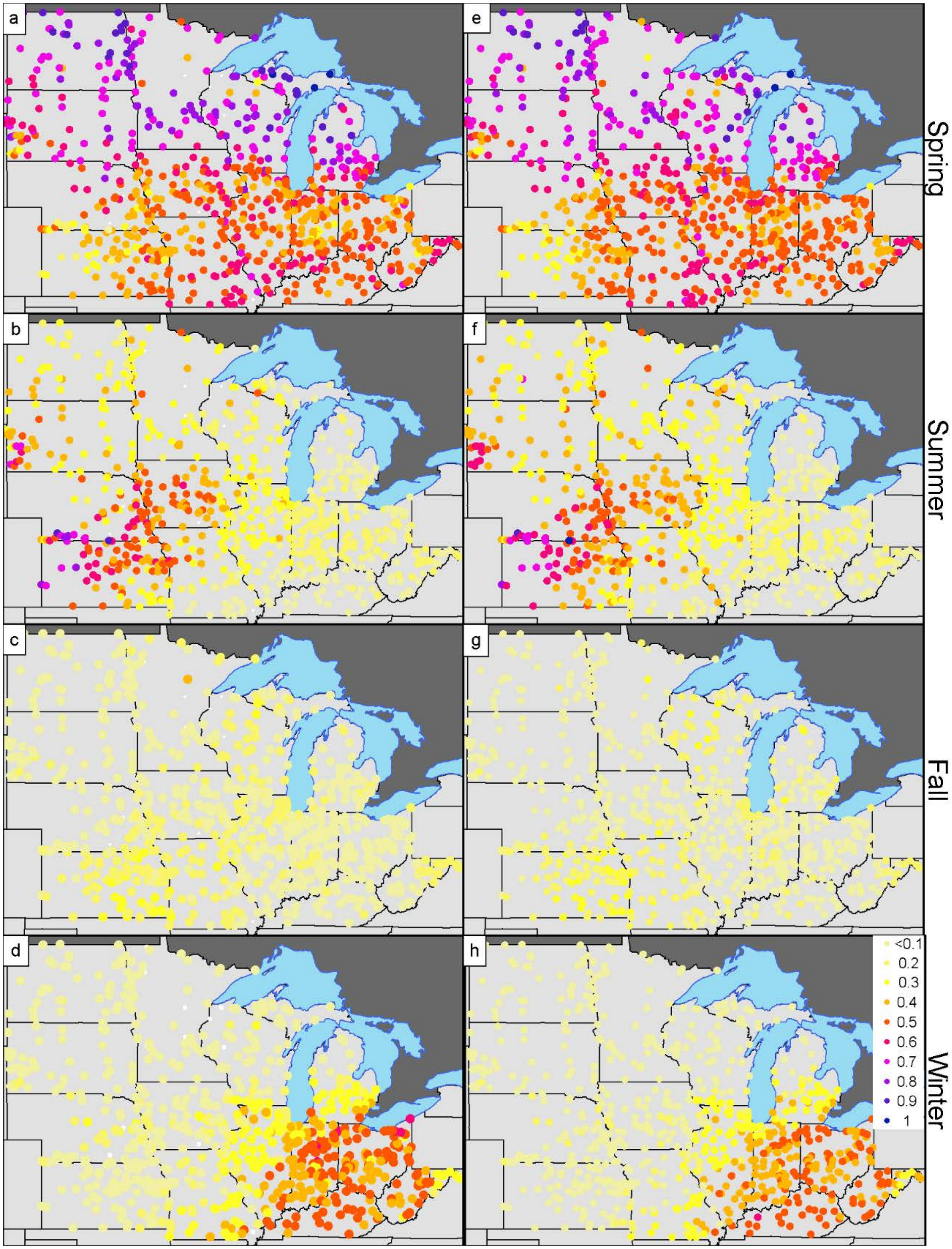

Figure 2-2: Fractional contribution of the different seasons to the seasonality of annual maximum daily discharge records (a-d) and frequency of flood events (e-h).

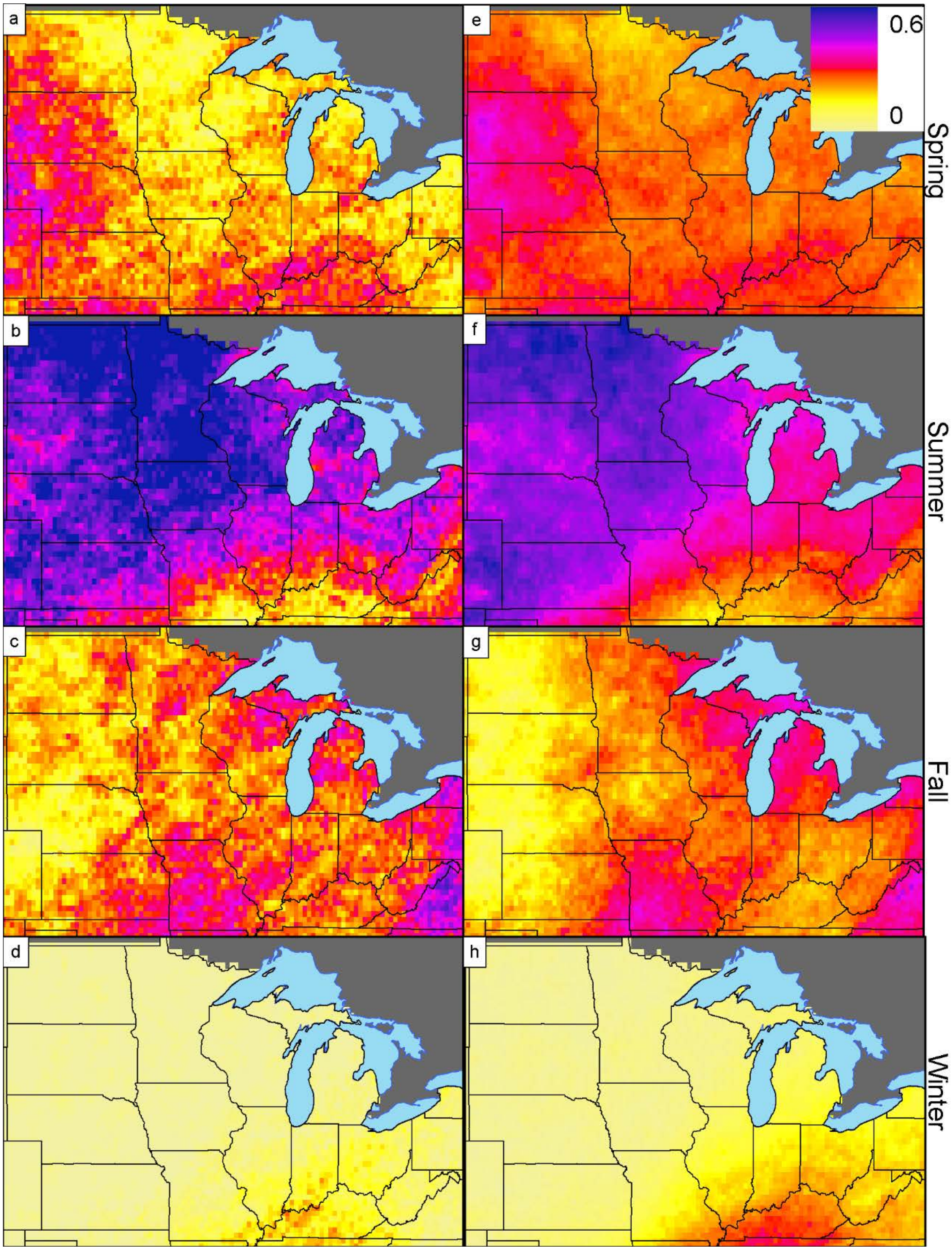

Figure 2-3: Fractional contribution of the different seasons to the seasonality of annual maximum daily rainfall records (a-d) and frequency of precipitation (e-h).

CHAPTER 3 THE CHANGING NATURE OF FLOODING ACROSS THE CENTRAL UNITED STATES[1]

3.1. Introduction

This chapter is devoted to examining whether the magnitude and/or frequency of flood events has remained constant or has been changing in recent decades over the central United States. As mentioned in Chapter 1, the central United States has experienced a series of large flood events over the twentieth and early twenty-first centuries, with significant adverse societal consequences (e.g., decreased food production, displacement of communities/people, economic losses, and fatalities).

Numerous modeling studies point to an intensification of the hydrological cycle under projected climate warming (e.g., Voss et al., 2002, Held and Soden, 2006, Huntington, 2006), with increasing frequency of extreme events, such as heavy rainfall and flooding (e.g., Voss et al., 2002, Milly et al., 2002, 2005, Christensen and Christensen, 2003, IPCC, 2012). However, a number of observational studies that examined changes in the magnitude of annual maximum peak discharge over the central United States, were not able to show that the magnitude of flood events is changing (e.g., Lins and Slack, 1999, 2005, Douglas et al., 2000, Novotny and Stefan, 2007, Villarini et al, 2009). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) (Stocker et al., 2013) concluded that "there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods at a global scale." Therefore, use of historical records to determine changes over time in flooding has proved inconclusive.

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[1] Adapted from Mallakpour, I., and G. Villarini, The changing nature of flooding across the central United States, *Nature Climate Change*, 5, 250-254, 2015.

However, the question remains: is the character of recent flooding truly distinct from the long-term averages, or is it simply an artifact of our relatively short collective memory? With elusive results regarding possible changes in flood characteristics, it is essential to perform an extensive analysis of changes in flooding over the central United States.

Therefore, I use different approaches (i.e., block maximum, peak-over-threshold) to detect the possible changes in the magnitude and/or frequency of flood events over recent decades. If either or both of these attributes have changed over time, it is imperative to understand the underlying mechanisms that are responsible for the observed behavior. Because a warmer atmosphere can hold more moisture (the Clausius-Clapeyron relation), a pronounced increase in intense rainfall events is included in models of future climate (Sillmann et al., 2013). Thus, in this chapter, I will examine if and where the magnitude and/or the frequency of flood events has been changing, and, if so, what the possible reasons would be.

3.2. Methods

To detect changes in the magnitude of flood peaks and annual maximum daily rainfall, I use a block maximum approach; according to this approach, a block could represent either the entire year or a season, and the largest daily value within each block is extracted for each stream gauge station (or each pixel for the rainfall analysis). I use the nonparametric Mann-Kendall test (e.g., Mann, 1945, Kendall, 1975) to investigate the presence of monotonic patterns. This test has been widely used to examine the presence of monotonically increasing/decreasing trends in hydrometeorological data (e.g., Pryor et al., 2009, Alexander and Arblaster, 2009, Villarini et al., 2009, 2011b, Westra et al., 2013, Anderson et al., 2015). For the Mann-Kendall test applied to the block maximum time series of discharge or rainfall, the null hypothesis (H_0) is that there is no change in the magnitude of flood peaks / extreme rainfall. The alternative hypothesis (H_a) is that there is a monotonic trend in the magnitude of the time series of interest.

On the other hand, I use a peak-over-threshold (POT) approach to examine changes in the frequency of flood and heavy rainfall events. According to this method, I select a threshold value and calculate the number of events exceeding this value. Unlike the block maximum approach, which identifies only one event per block (e.g., year, season), the POT method allows setting a high threshold to consider a wider range of events (e.g., Lang et al., 1999). Here, I select the threshold for flood events so that I have, on average, two events per year to focus on the larger flood events. This means that, if I examine a record with 50 years of data, I set a threshold so that I have 100 events over the study period. Moreover, to avoid counting the same event multiple times (this is particularly true for larger watersheds), I allow only one peak within a 15-day period, centered on the day of occurrence of the flood peak. For rainfall, I set a threshold that is equal to the 95th percentile of the rainfall distribution at each pixel.

As a result of the discrete nature of the data, I used Poisson regression to ascertain whether or not there are trends in the number of flood or heavy rainfall events. Poisson regression is a type of regression in which the response variable is discrete and follows a Poisson distribution (e.g., Dobson, 2001). In this case, counts in year i (N_i) have a conditional Poisson distribution with the rate of occurrence (λ_i) as follows:

$$P(N_i = k|\lambda_i) = \frac{e^{-\lambda_i} \cdot \lambda_i^k}{k!} \quad (k = 0, 1, 2, \ldots) \tag{3.1}$$

at each USGS stations or rainfall pixels, I examine the presence of a statistically significant increasing or decreasing trend by means of Poisson regression model:

$$\lambda_i = \exp(\beta_0 + \beta_1 \cdot i) \tag{3.2}$$

where β_0 and β_1 are the coefficients to estimate via maximum likelihood. A statistically significant monotonic trend is expected when the coefficient for time (β_1) is statistically different from zero. A positive (negative) value of β_1 points to an increasing (a decreasing) trend in the number of flood or rainfall events over time. For all of the statistical analyses, I set the significance level to be 5%.

Here I present the result of the trend analyses for the flood characteristics (i.e., magnitude and frequency) for two cases:

1- For the entire available record length at each station.

2- For the 1962-2011 time period that is common for all the sites given that I selected stations with at least 50 years of data ending no earlier than 2011 (see details in Chapter 2).

Because the final goal of this chapter is to go beyond the simple detection of changes in flood events, and to start exploring what causes these observed changes, an analysis of stream gauges with the similar starting and ending dates can be a better representative of the most likely causes across a network of stream gauges.

3.3. Results and discussion

3.3.1. Detecting changes in the flood records

The lack of evidence for an increase in peak discharge becomes clearer when examining trends in the magnitude of the annual maximum daily discharge data for 774 USGS stream gauge stations across the central United States over the common 1962-2011 time period (Figure 3-1 A) and on the entire available record length at each station (Figure 3-2 A). Over most of the study area, no statistically significant trends are identified. Therefore, this data analysis does not suggest that the annual peak discharge magnitude has been increasing or decreasing over most of the twentieth and early twenty-first centuries. When examining changes in the magnitude of annual maxima for the entire record length available at each sites, I find that 247 (31%) of the stations show a statistically significant change in the magnitude of flood events. The signal becomes even weaker when I analyze the magnitude of flood events over the common 1962-2011 time period: overall, 158 (20%) of the stations exhibit statistically significant changes in the magnitude of flood peaks, and of these, 101 (13%) are characterized by a trend toward increasing flood magnitude, with many of them concentrated in the greater Chicago area. These results are consistent with previous studies (e.g., Lins and Slack, 2005, Villarini et al., 2009, 2011b, Schilling and Libra, 2003, Peterson et al., 2013), which also failed to detect widespread evidence of changing flood magnitude over the central United States.

The results change markedly, however, when I use a POT approach to examine changes in the frequency of flood events. As shown in Figure 3-1 B and Figure 3-2 B, when analyzed in this manner, the frequency of flood events has been changing over much of the central United States, with spatially contiguous regional changes. When analyzing the stations for their entire available record length, there are 308 (40%) sites with increasing trends in the frequency of flood events, and 93 (12%) with decreasing trends. Moreover, when I examine the station data over the common 1962-2011 time period, I find that 264 (34%) stations present an increasing trend in the frequency of flood events, while 66 (9%) decreasing trends. In both cases, there is a very spatially coherent region with increasing flood frequency that ranges from North Dakota south to Iowa and Missouri and east into Illinois, Indiana, and Ohio. This swath is bordered to the southwest (Kansas and Nebraska) and to the northeast (northern Minnesota, Wisconsin, and Michigan) by areas with decreasing flood frequencies. Overall, these analyses have revealed that the largest flood peaks have not been significantly changing over this broad belt of the central United States, but, rather, the region has been experiencing a greater number of flood events (Figure 3-1 and Figure 3-2).

These more widespread increasing trends in the frequency of flood events is also apparent when viewed in the context of a subset of 68 "pristine" stream gauging stations (Figure 3-3). These stations are based on Hirsch and Ryberg (2012), and represent stream gages draining watersheds with "little or no reservoir storage or urban development (less than 150 persons per square kilometer in 2000)". Overall, there are 22 (32%) stations with statistically significant trends in the magnitude of flood events (Figure 3-3 A) and 34 (50%) with significant trends in the frequency of flood events (Figure 3-3 B), when I examine the stream gauges for the entire available record length. The results based on the common 1962-2011 time period show that there are 9 (13%) stations with statistically significant trends in the magnitude of flood events (Figure 3-3 C) and 25 (37%) stream gages with significant trends in the frequency of flood events (Figure 3-3 D). Therefore, the findings in Figure 3-3 illustrate that the results concerning a stronger signal of change in the frequency rather than the magnitude of flood events persist in the “pristine” watersheds and cannot be solely ascribed to the human modifications of the watersheds.

I have also examined changes in flood frequency and magnitude at the seasonal scale (Figure 3-4 and Figure 3-5). During the spring and summer seasons (which represent the period of the year with the largest fraction of flood events over the majority of the study region; Figure 2-2), 46 (6%) stations present statistically significant increasing trends in the magnitude of flood events during spring, while 227 (30%) in the summer. These numbers are relatively consistent even if I focus on the entire record length rather than only the 1962-2011 period: 86 (11%) stations show increasing trends in the magnitude in the spring (Figure 3-5 A), while 212 (27%) in the summer (Figure 3-5 B). These high numbers are driven by the stations in the western part of the study region, which is also an area with minimal summer contribution to the total seasonality of flooding (Figure 2-2 b).

On the other hand, increases in the frequency of flood events in spring and summer (Figure 3-4, and Figure 3-5, panels E-F) closely resemble the corresponding results at the annual scale (Figure 3-1 and Figure 3-2). Overall, 138 (17%) of the stations are exhibiting statistically significant changes in spring and 215 (28%) of the stations in summer when analyzing the stations for the common 1962-2011 time period. When I examine the stream gauges for the entire available record length, there are 248 (32%) stations with statistically significant changes in spring and 278 (35%) stream gages with significant trends in summer. These results are particularly relevant because of the geographic regions in which these trends are found and the relationship to the seasonality of flooding (Figure 2-2, e-f). Fall and winter, on the other hand, exhibit a more muted signal compared to spring and summer (Figure 3-4 and Figure 3-5), particularly in regions with minimal contributions to the flood seasonality (Figure 2-2, panels c, d, g, and h).

3.3.2. Attribution of observed changes

Up to this point, the results of my work indicate increases in the frequency but not in the magnitude of historic flood events in the central United States over most of the twentieth century and the first decade of the twenty-first century. Here, I examine what the possible reasons for these changes may be. Secular changes in regional flood behavior reflect the integration of climate, stream dynamics, and watershed characteristics. I begin by examining the changes in heavy rainfall at the annual scale (Figure 3-6). Similar to the analyses performed for flood events, I examine temporal variability in the annual maximum daily rainfall (Figure 3-6 A) and in the number of days exceeding the 95th percentile of the rainfall distribution (Figure 3-6 B). Overall, only limited evidence suggests changes in the magnitude of heavy rainfall, a finding consistent with previous studies (e.g., Pryor et al., 2009, Villarini et al., 2011a) and in line with what I found for flooding (Figure 3-1 A and Figure 3-2 A).

A stronger tendency towards increases in the frequency of heavy rainfall days (Figure 3-6 B) is apparent over most of the region, similar to the findings in previous studies (e.g., Pryor et al., 2009, Villarini et al., 2011a, 2013a). Moreover, the fact that I observe the largest changes in the frequency rather than in the magnitude of heavy rainfall is generally consistent with what I found for flood events. There are, however, regional differences in terms of the sign of the change. The frequency of flooding has been increasing over large areas from the Dakotas to Iowa, Illinois, and Ohio, with decreasing trends existing to the northeast and southwest. These changes in rainfall are generally in the same direction across most of the central United States, with the exception of Nebraska and Kansas where the frequency of heavy rainfall days has been increasing while the frequency of flood events has been decreasing. These differences can be associated with declining water tables that were caused by groundwater withdrawal and the construction of ponds and terraces, particularly in western Kansas (e.g., Rasmussen and Perry, 2011). Rasmussen and Perry (2001) used 88 stations in Nebraska, Kansas and Oklahoma, where they found that 18 (4) stations had statistically significant decreasing (increasing) trends in peak flows, where most of the stations with decreasing trends concentrated in western Kansas and southwestern Nebraska, similar to what I have found here.

I also consider the attribution of changes in flood events at the seasonal scale in light of changes in rainfall and temperature. These seasonal analyses provide more insight into flood-generating processes and enable the evaluation of the conclusions I reached using annual data. At the seasonal scale, the changes in the frequency of heavy rainfall event (Figure 3-7, E-H) are generally stronger than those changes in magnitude (Figure 3-7, A-D). When compared to flooding, the seasonality of heavy rainfall (Figure 2-3) exhibits some differences with respect to that of flooding (Figure 2-2). The most notable difference is the pronounced peak in summer rainfall in contrast to the spring/summer for flooding. Most of the flood peaks in the northern part of the central United States tend to occur in the spring and are associated with snow melt, rain falling on frozen ground, and rain-on-snow events (e.g., Villarini et al., 2011b, Peterson et al., 2013, Olsen et al., 1999, Villarini, 2016). In addition, Peterson et al. (2013) and Pederson et al. (2011) indicated that earlier snow melting and changes in the rain-to-snow ratio were reported in areas of the United States in which snow-melt events are the major flood agent. In addition, I have also examined the seasonal temperature records to identify possible trends and to explore the connection between temperature and flood events. Spring represents the season with the strongest increases over most of the northern part of my region (Figure 3-8). Trends of rising temperature yield an increase in available energy for snow melting, and the observed trends in increasing flood frequency over the Dakotas, Minnesota, Iowa, and Wisconsin can, consequently, be related to both increasing temperature and rainfall (Pederson et al., 2011). During the summer, the largest fraction of flood peaks is concentrated over Kansas and Nebraska, for which the decreasing trends can be explained in terms of the declining water tables caused by groundwater withdrawal and the construction of ponds and terraces (Rasmussen and Perry, 2001). The contribution of the fall season to the flood seasonality is limited, even though the observed changes match those areas in heavy rainfall (e.g., at the border between the Dakotas and Minnesota). During winter, most of the flood activity is concentrated over the south/southeastern part of the study region, with atmospheric rivers being a major flood agent (Lavers and Villarini, 2013).

Generally, the results for flooding match the patterns of heavy rainfall. In addition to examining the changes in heavy precipitation, I have also considered changes in annual (Figure 3-9) and seasonal (Figure 3-10) total precipitation. These additional analyses further support the overall conclusions about the relationship between precipitation and flood frequency over this area.

3.4. Conclusions

The main objective of this chapter was to examine the changes in the frequency and magnitude of flooding over the central United States during the last 50 years. For this, I analyzed the annual and seasonal daily streamflow records at 774 stream gauge stations with at least 50 years of record and ending no earlier than the year 2011. The key results of this chapter can be summarized as follows:

1- By inspecting the presence of monotonic trends in the annual maximum daily discharge records, only a small number of stations revealed a statistically significant trend. Thus, I find limited evidence pointing to changes in the size of flood peaks over the central United States. Similar results are obtained when maximum daily discharge at the seasonal scale is examined.

2- To examine observed changes in the frequency of flooding, I used the peaks-over-threshold method. The result indicates that the frequency of flood events has been increasing over a large area of the central United States. In addition, I have examined changes in flood frequency at the seasonal scale, where I get a similar result to what was observed at the annual scale. This is especially true in spring and summer, which are the seasons with the largest contributions to the flood seasonality.

3- By analyzing the flood frequency and magnitude at the seasonal and annual scales, I showed that while observational records present limited evidence toward changes in the magnitude of flood peaks, stronger evidence points to increasing trends in the frequency of flooding. Therefore, the results of this chapter reveal that changes in flooding over the central United States are not due to the increase in the size of the flood peaks, but rather to the increase in the frequency of these events.

4- By integrating river discharge and regional climate data, I have found that changes in flood behavior along rivers over the central United States can be largely attributed to concomitant changes in rainfall and temperature, with changes in the land surface potentially amplifying this signal (Yang et al., 2013, Ryberg et al., 2014, Villarini and Strong, 2014). Largely, the results for flooding match the patterns of heavy rainfall with the exception of Nebraska and Kansas. The findings of this chapter, therefore, provide a physical explanation for the stronger observed changes in the frequency rather than the magnitude of flood events over this area. However, a direct attribution of these changes in discharge, precipitation, and temperature to human impacts on climate represents a much more complex problem that is daunting to address using only observational records (e.g., Hegerl and Zwiers, 2011, Hirsch, 2011).

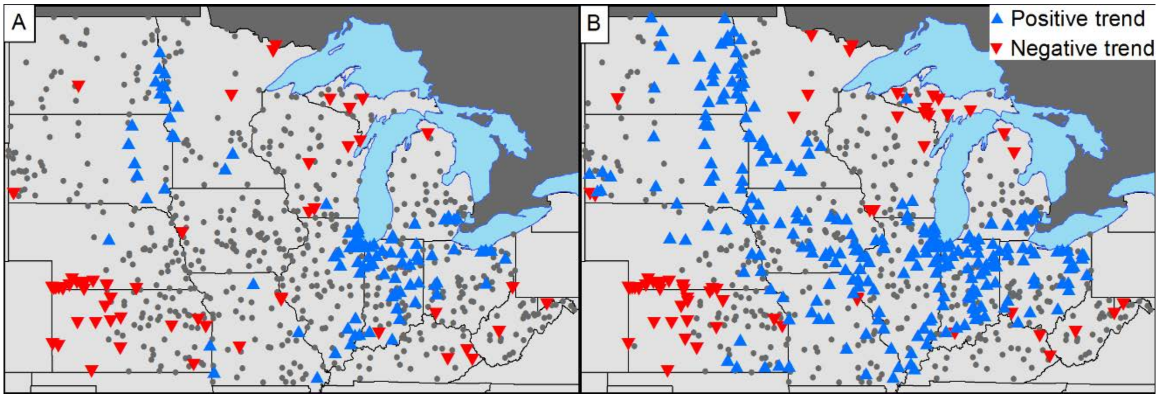

Figure 3-1: These maps summarize the results for trends in the magnitude (panel A) and frequency (panel B) of flood events at the annual scale. The blue (red) triangles indicate the location of the stations with increasing (decreasing) trends at the 5% level. The grey circles refer to the location of the stations that did not experience statistically significant changes (at the 5% level). These results refer to the common 1962-2011 time period.

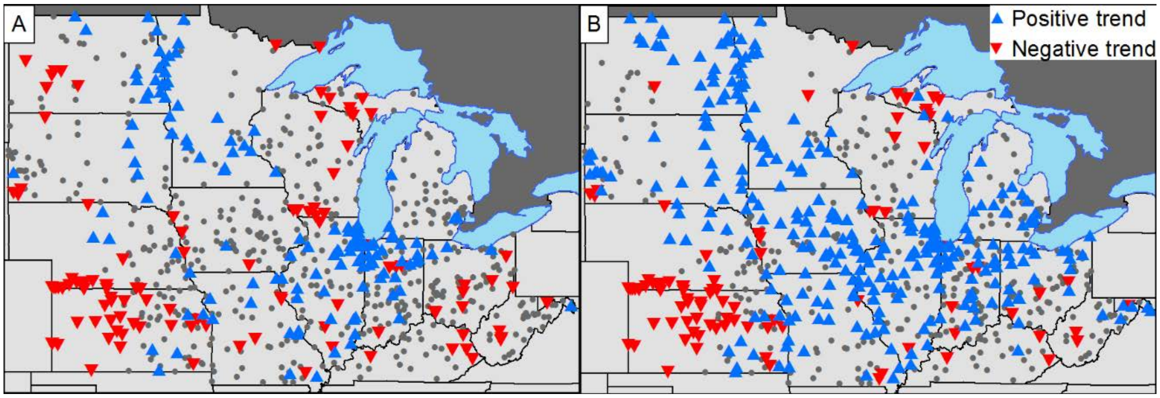

Figure 3-2: Same as Figure 3-1 but for the entire record length for each station.

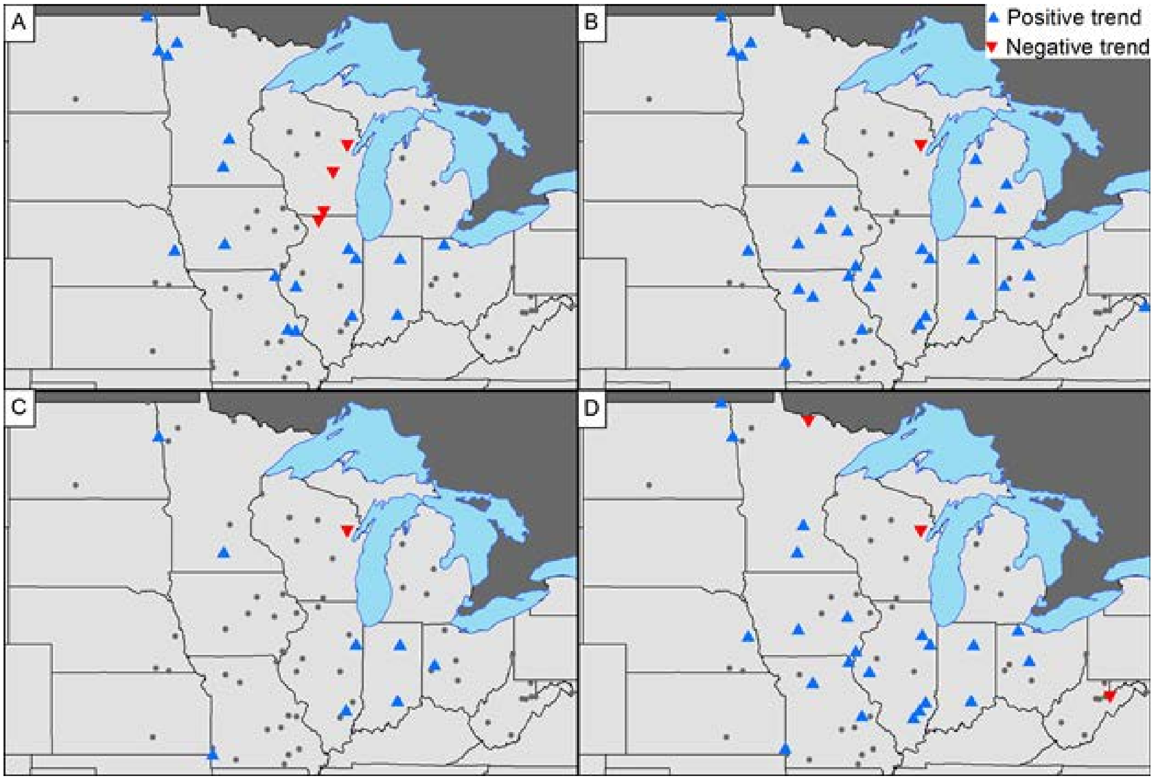

Figure 3-3: Same as Figure 3-1 but it summarizes the results for trends in the magnitude (panels A and C) and frequency (panels B and D) of flood events for 68 "pristine" stations in Hirsch and Ryberg (2012). The results in panels A and B are based on the entire available record length at each station, while those in panels C and D are based on the common 1962-2011 time period.

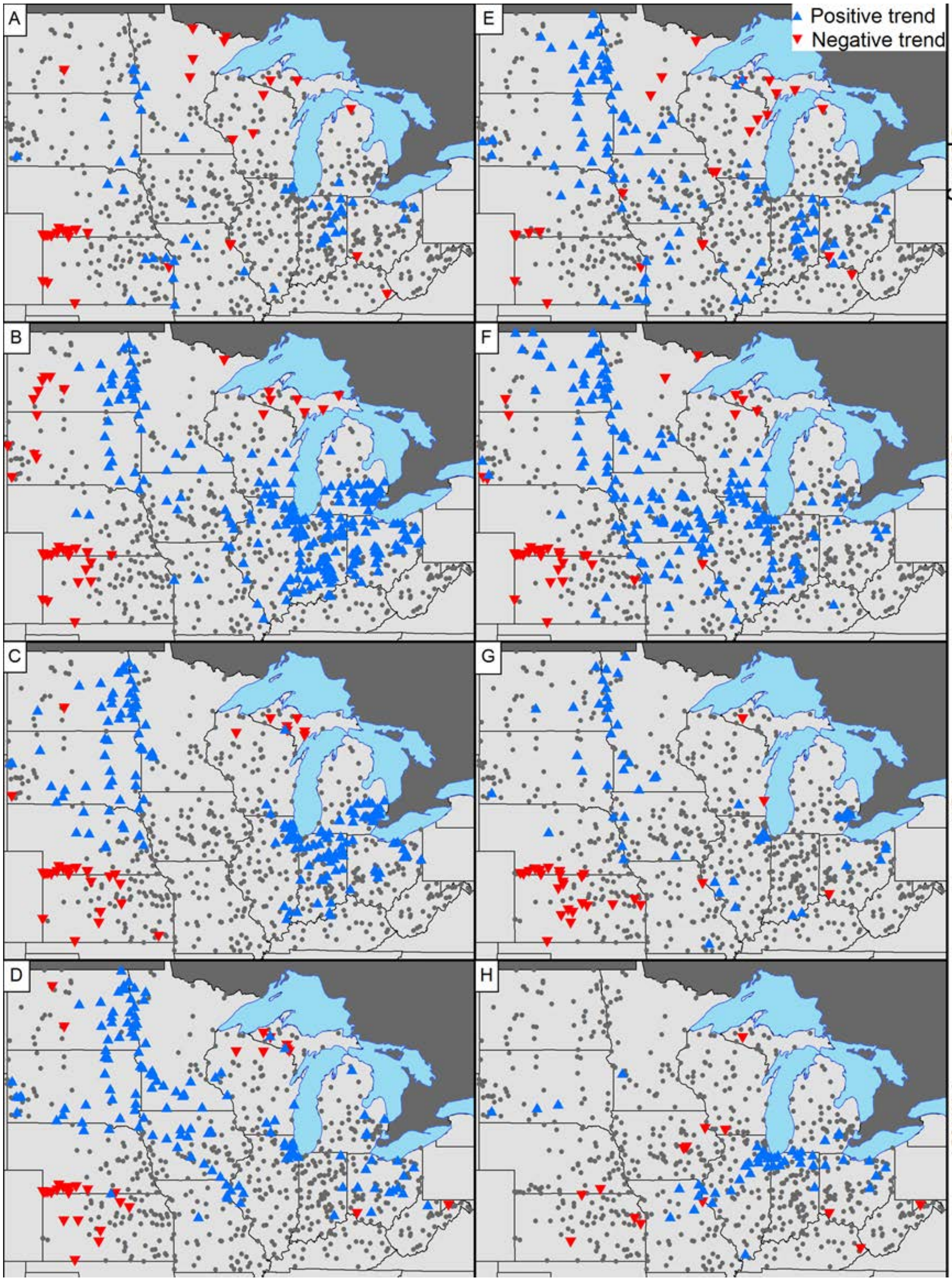

Figure 3-4: Same as Figure 3-1 but these maps summarize the results for trends in the magnitude (A-D) and frequency (E-H) of flood events at the seasonal scale. Analyses are performed over the common 1962-2011 time period.

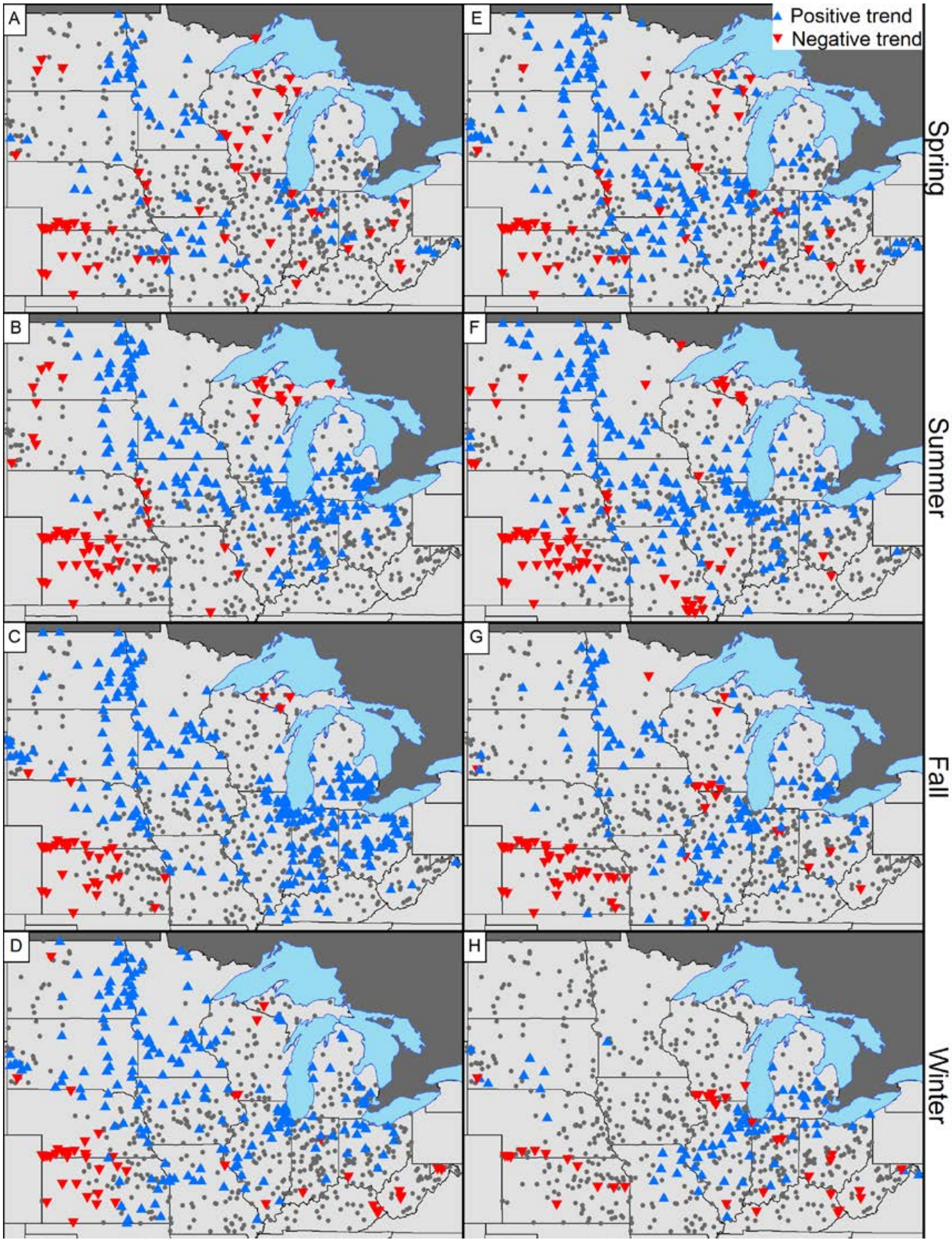

Figure 3-5: Same as Figure 3-4 but for the entire record length available at each location.

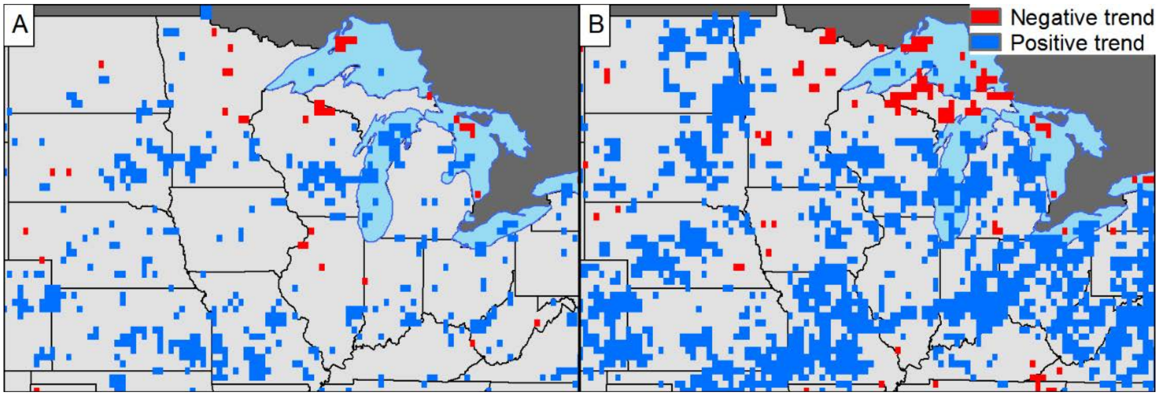

Figure 3-6: The maps summarize the results for trends in the magnitude (panel A) and frequency (panel B) of heavy rainfall events at the annual scale. The blue (red) pixels indicate locations with increasing (decreasing) trends at the 5% level. The grey pixels refer to the locations that did not experience statistically significant changes (at the 5% level).

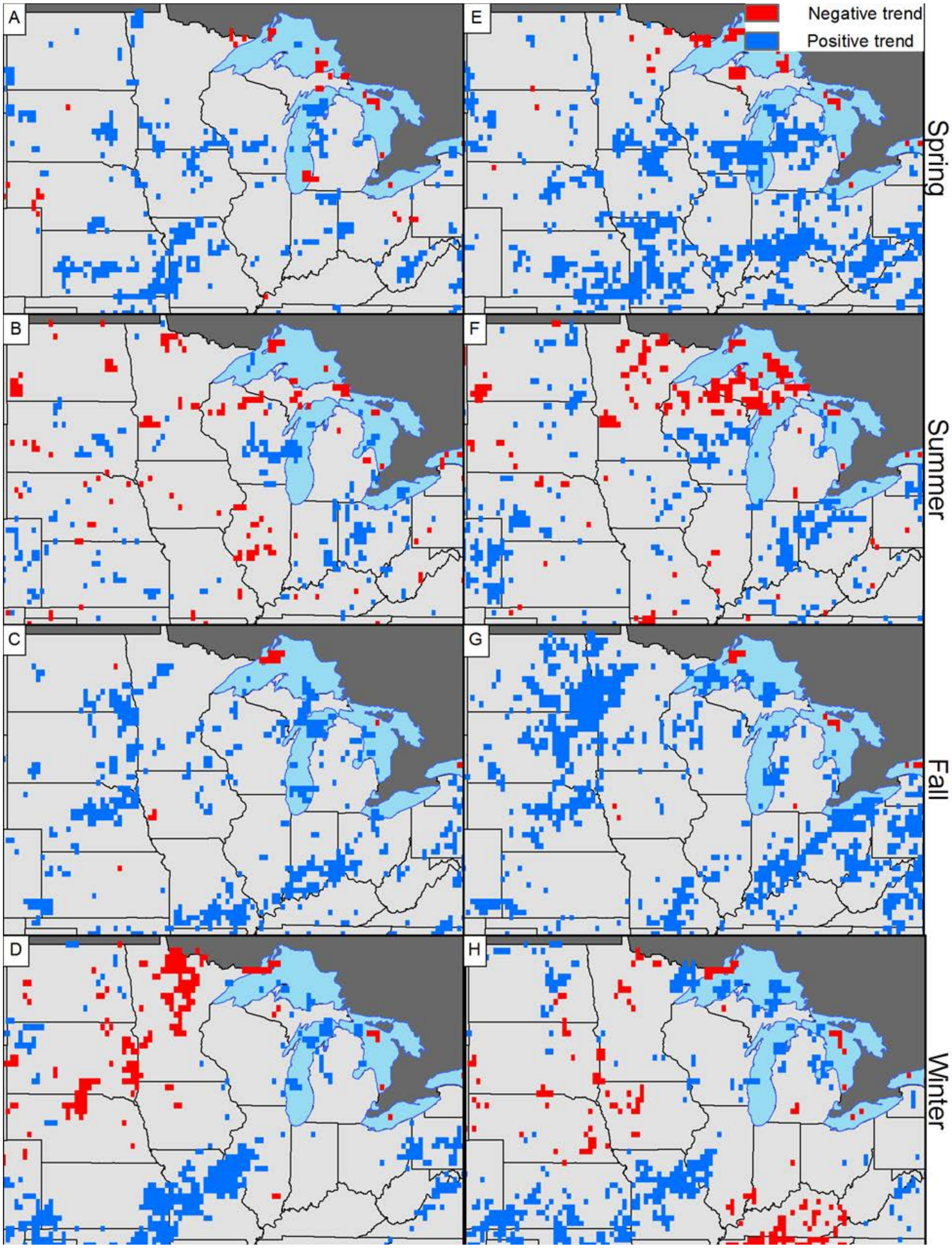

Figure 3-7: Same as Figure 3-6 but these maps summarize the results for trends in the magnitude (A-D) and frequency (E-H) of heavy rainfall events at the seasonal scale.

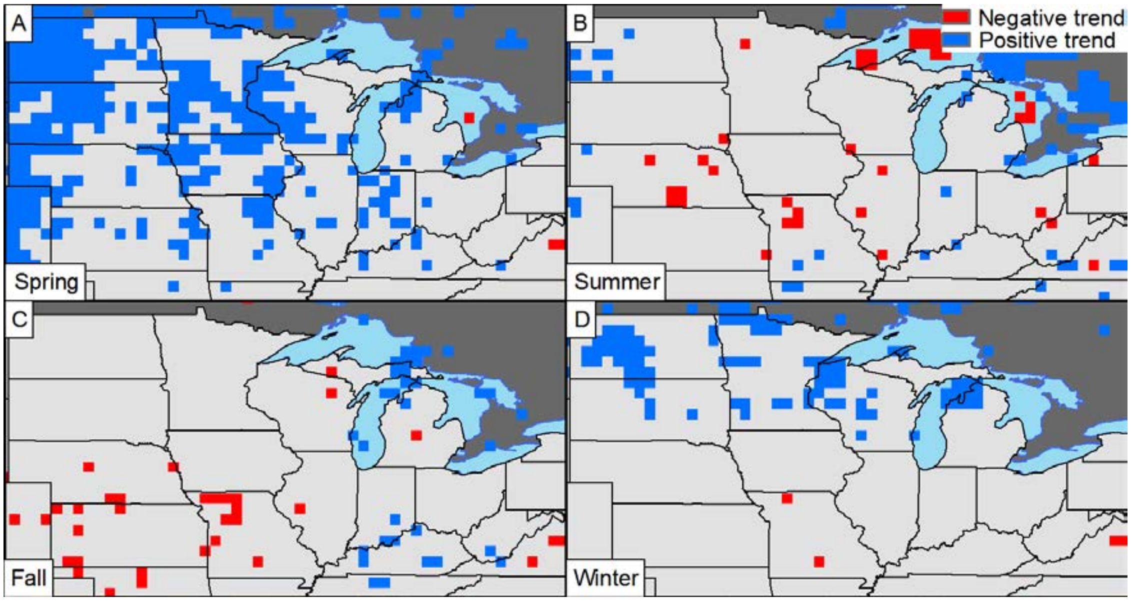

Figure 3-8: Maps showing the presence of trends in the seasonal temperature over the 1948-2011 time period. The blue (red) pixels indicate locations with increasing (decreasing) trends. Results are significant at the 5% level.

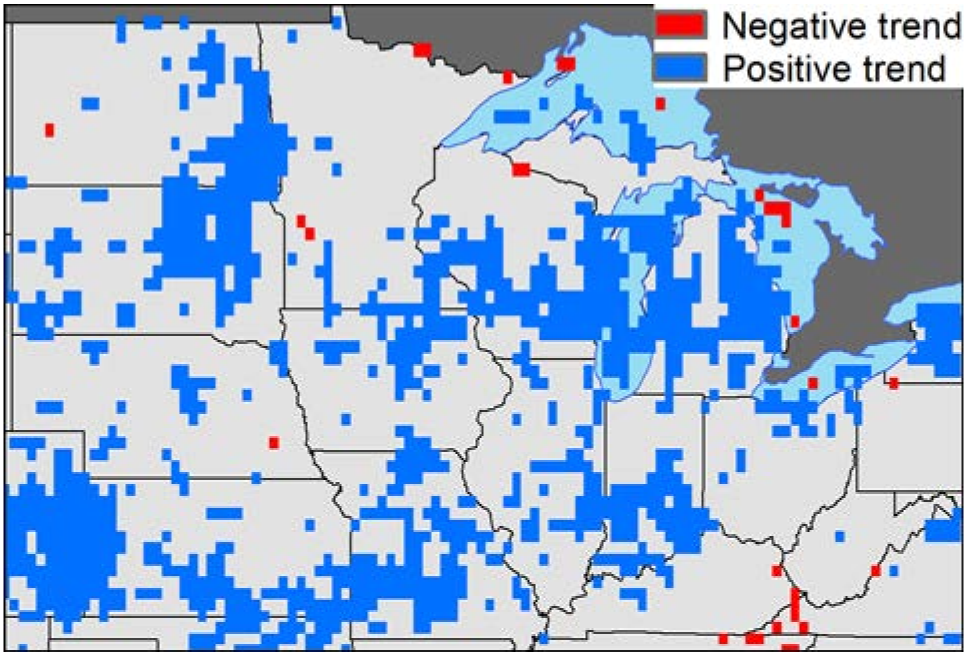

Figure 3-9: Maps showing the presence of trends in the annual precipitation over the 1948-2012 time period. The blue (red) pixels indicate locations with increasing (decreasing) trends at the 5% level.

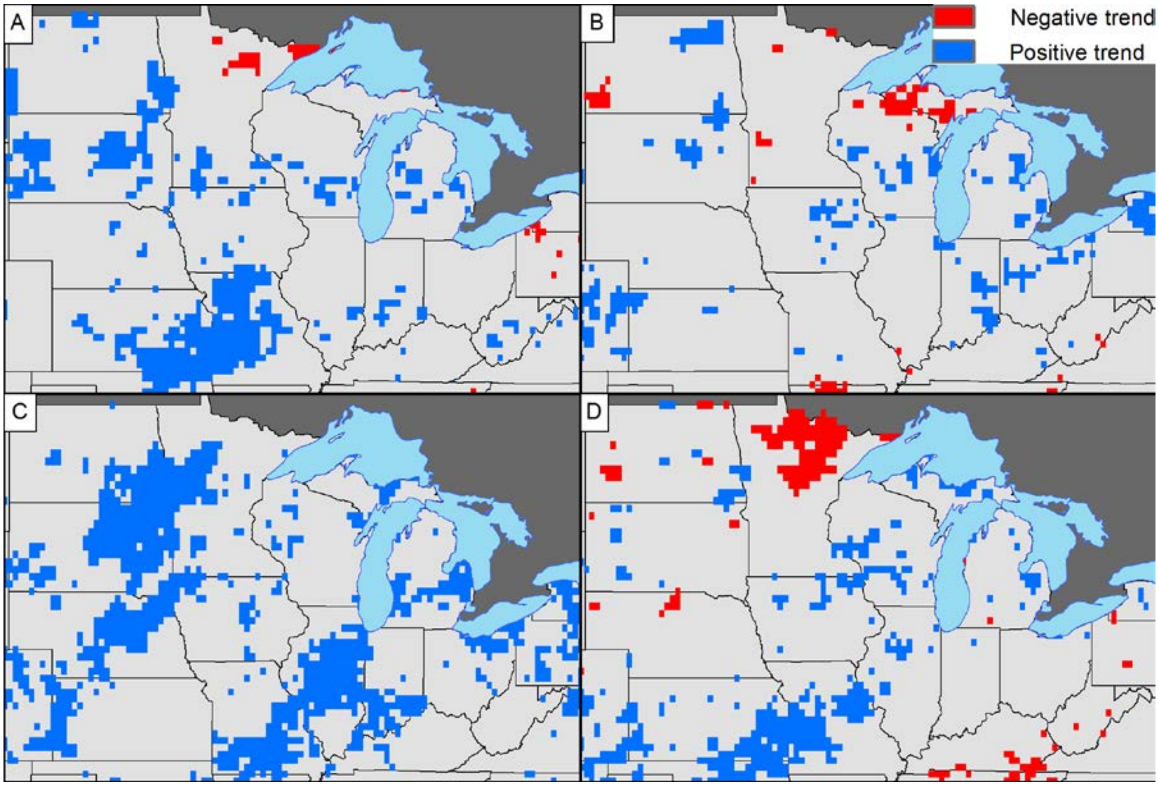

Figure 3-10: Same as Figure 3-9 but for the results at the seasonal scale.

CHAPTER 4 EXAMINING THE RELATIONSHIP BETWEEN FLOODING AND LARGE-SCALE CLIMATE INDICES OVER THE CENTRAL UNITED STATES[2]

4.1. Introduction

In Chapter 3, I showed that over the past 50+ years, it is not an increase in the magnitude but in the frequency of flood events that is detectable from the observational records over the central United States. In addition, I described that these changes can be largely related to changes in the frequency of heavy precipitation events. The next question to address in this chapter is then: why has the frequency of precipitation, and consequently flooding, been changing over the second half of the 20th century and into the first decade of the 21st century? Here I will examine whether and to what extent these observed changes can be explained by the variability in the climate system related to both the Atlantic and Pacific Oceans.

There are different meteorological, hydrological and climatological mechanisms that bring moisture that can produce flooding (i.e., tropical cyclone, convection, thunderstorm, frontal passages, SST anomalies, and jet streams) (Hirschboeck, 1988). Hirschboeck (1988) classified these mechanisms based on the difference in time and space scales as "proximate" (direct and immediate climatic causes) and "ultimate" (climatic mechanisms operating at larger and longer scales) factors. For example, a series of warm season convective systems over a period of two weeks were identified as the "proximate" cause of the 2008 Midwest flood (e.g., Coleman and Budikova, 2010, Budikova et al.,

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[2] Adapted from Mallakpour, I., and G. Villarini, Examining the relationship between flooding and large-scale climate indices over the central United States, *Advances in Water Resources,* 92, 159-171, 2016.

2010, Smith et al., 2013). However, the excess moisture for these series of storms was brought by the "ultimate" mechanisms such as the Great Plains Low Level Jet (GPLLJ), which interacted with a strong North American jet (e.g., Coleman and Budikova, 2010, Budikova et al., 2010, Smith et al., 2013). Higgins et al. (1997) examined the role played by the GPLLJ in transporting moisture leading to precipitation over the central United States (see also Nayak et al. (2016)). SST anomalies in the North Atlantic, SST anomalies in the Pacific, and GPLLJ are among the factors that can cause extreme flooding over this area (e.g., Lavers and Villarini, 2013, Patricola et al., 2015). Coleman and Budikova (2010) examined the climatological causes of the 2008 Midwest flood and indicated that a mixture of different large-scale oceanic-atmospheric circulation brought moisture that produced the 2008 flooding.

In this chapter, I examine the relationship between the frequency of flood events/heavy precipitation events and large-scale climate indices over the central United States using five indices reflecting the influence of the Atlantic and Pacific Oceans. These climate indices are the NAO, the SOI, the PDO, the AMO, and the PNA. Each of the above-mentioned climate indices has the potential to describe certain spatial and temporal aspects of the climate variability. Climate variability can affect and control the jet streams and storm tracks that are controlling extreme hydrological events (e.g., flood, heavy precipitation, drought; e.g., Andersen and Shepherd, 2013). If I can identify a statistically significant relationship between the frequency of flood /heavy precipitation events and large-scale climate indices, then it would have the potential to help understand and predict future flood conditions. In other words, understanding the relationship between climate variability and flooding could have the potential to improve future water management and the preparation against these catastrophic events. Inter-annual to decadal climate predictions have been gaining attention for short-term decision making, flood defense, and water planning (e.g., Wang et al., 2015). However, the reliability of flood predictions is heavily dependent on the accuracy of the predictions of climate indices. A number of studies have shown that large-scale climate indices can be used to forecast streamflow (e.g., Sankarasubramanian and Lall, 2003, Kwon et al., 2008, Hamlet and Lettenmaier, 1999, Kalra and Ahmad, 2009, Risko and Martinez, 2014). For instance, Kwon et al. (2008) used a hierarchical Bayesian modeling framework to investigate the seasonal forecasting of flooding events in Montana using climate indices such as ENSO and PDO. However, one of the challenges in using large-scale climate indices to forecast streamflow is choosing "the optimal" set of climate indices (e.g., Risko and Martinez, 2014). The final goal of this chapter is to find the "optimal" set of climate indices that can describe the relationship between climate and the seasonal frequency of flood events over the central United States.

4.2. Methods

To calculate the frequency of flood events over the central United States, the peaks-over-threshold method is used. Similar to what done in the previous chapter, the threshold is selected to give on average two flood events per year, with no more than one event in a 2-week time window (to not allow for counting the same events multiple times). For detecting the changes in the frequency of heavy precipitation, I use the peaks-over-threshold method as well. The threshold is selected based on the 95th percentile of the precipitation distribution at each pixel (e.g., Villarini et al., 2013a). After setting the thresholds for streamflow and precipitation, I count the number of events that exceeded the threshold in every season for each grid cell or stream gage location.

I use Poisson regression to investigate the relationship between climate indices (predictors) and the number of flood and heavy precipitation events (predictands). Poisson regression represents an appropriate statistical method because the response variable (i.e., number of flood events, number of heavy precipitation events) is in the form of count data and has a discrete nature. The key assumptions to use the Poisson regression are that the response variables are independent and following a Poisson distribution (e.g., Dobson 2001, Fox, 2015). The Poisson probability distribution can be written as follows:

$$P\left(N_{ij} = k \middle| \lambda_{ij}\right) = \frac{e^{-\lambda_{ij}} \cdot \lambda_{ij}^{k}}{k!} \quad (k = 0, 1, 2, \ldots) \tag{4.1}$$

where N_{ij} represents the number of events in a particular season j of year i, and λ_{ij} is the rate of occurrence parameter which is a nonnegative random variable.

For each of the USGS stations or precipitation pixels, I evaluate the presence of a statistically significant relationship between the frequency of flood events and climate indices by fitting a Poisson regression model. The rate of occurrence parameter λ_{ij} depends linearly on the climate indices (by means of a logarithmic link).

$$\lambda_{ij} = \exp\left(\beta_{0,j} + \beta_{1,j} \cdot C_{ij}\right) \tag{4.2}$$

where C_{ij} is value of climate index in the j^{th} season of the i^{th} year, and β_0 and β_1 are the coefficients to estimate via maximum likelihood.

Here the focus is on statistical relationships that are significant at the 5% and 10% levels; this means that I will focus on coefficients β_1 in equation 4.2 that are different from zero at the 5% and 10% levels. A positive (negative) value of β_1 indicates that, on average, I would expect an increase (decrease) in the number of flood or precipitation events for an increase in the value of the climate index.

I use the multiple Poisson regression model to find the optimal climate index or set of climate indices that can describe the temporal variability in the seasonal frequency of flood events over the central United States. For each of the USGS stations or precipitation pixels, I consider all the models that represent all the possible combinations of predictors (from one to five climate indices), for a total of 31 different models. Then the best model is selected based on two criteria: first, I select a subset of models for which all the estimated coefficients for each of the climate indices are different from zero at the 10% significant level. Then I select as the final model out of this subset the one with the smallest value of the Akaike information criterion (AIC; Akaike, 1974).

As described in Chapter 2 (Section 2.3), the period of availability for each of the climate indices is slightly different. In performing the multiple Poisson regression, my focus is on the common period from 1951 to 2011. In addition, all the climate indices are available at the monthly scale. In performing our seasonal analyses, I average the monthly values to the season of interest (Winter: December-January-February; Spring: March-April-May; Summer: June-July-August; Fall: September-October-November). All the calculations are performed in R (R Development Core Team, 2014).

4.3. Results and discussion

4.3.1. Relationship between each climate index and the frequency of flooding and heavy precipitation events

Figure 4-1 (panels a-d) displays the statistically significant results of the relationship between flood frequency and PDO over the central United States. Overall, 20% (27%) of the stations present statistically significant relationships at the 5% (10%) significant level in winter and spring, while 20% (30%) occur in the summer, and 11% (19%) in the fall. More important than the raw numbers describing the percent of stations showing statistically significant results is the geographical pattern of the relationship between PDO and frequency of flooding. During spring, a broad region from southern Minnesota to Kansas shows a positive relationship between PDO and the frequency of flooding, while there is a negative tendency in northern Minnesota, Wisconsin, and Michigan. During the summer, PDO and flood events are generally positively related in a swath from Ohio and Indiana, across Illinois and Iowa and into southern Minnesota. During the fall, the clearest clusters are in Wisconsin, southern Illinois, and Missouri. Finally, in the winter, there is a large area encompassing West Virginia, Ohio, Kentucky, and eastern Illinois with a negative relationship between PDO and the number of flood events. Figure 4-1 (panels e-h) presents the results of the relationship between heavy precipitation frequency and PDO. For all the seasons, there are striking similarities (both in terms of geographic location and sign) with what I found for flooding (Figure 4-1, panels a-d). The fact that I find significant relationships between PDO and flooding is consistent with previous studies (e.g., Nigam et al., 1999, Tootle et al., 2005) where they observed a statistically significant link between PDO and the annual streamflow variability for the upper to middle Mississippi River basin.

Figure 4-2 (panels a-d) presents the results of the relationship between flood frequency and NAO. Overall, 15% (25%) of the stations present statistically significant relationships at the 5% (10%) significant level in the spring, 33% (40%) occur in the summer, 8% (15%) in the fall, and 6% (10%) in the winter. During spring, the frequency of flooding is negatively related to the NAO index mostly west of Wisconsin and Illinois; on the other hand, there is a positive relationship in Michigan and Indiana. During the summer, about 31% (38%) of the stations exhibit a statistically significant negative relationship at the 5% (10%) significant level with NAO over a broad region from the Dakotas to Indiana and Ohio. On the other hand, the link between NAO and flood frequency is weak for fall and winter. Figure 4-2 (panels e-h) shows the results of the relationship between heavy precipitation frequency and NAO. Overall, the results are similar to what discussed for flooding. These results are in line with Tootle et al. (2005), where they observed a significant negative relationship between NAO and average annual streamflow variability over the upper to the middle Mississippi River Basin. Also, studies have found a strong connection between the strength of the GPLLJ and the negative phase of the NAO (e.g., Weaver and Nigam, 2008, Coleman and Budikova, 2010). Weaver and Nigam (2008) tied the negative NAO with heavy precipitation over the U.S. Midwest. Coleman and Budikova (2010) showed that NAO was in a strong negative phase during the summer flood of 2008 over the U.S. Midwest.

Figure 4-3 (panels a-d) presents the results of the relationship between flood frequency and AMO. Here 16% (23%) of the stations show a statistically significant relationship at the 5% (10%) significant level in the spring, 15% (24%) in the summer, 13% (21%) in the fall, and 8% (15%) in the winter. During spring, two distinct clusters of stations were identified: the eastern portion of the study region shows a positive relationship while the western region displays a negative relationship. During the summer, about 98% (102 stations) of all the stations that are revealing a statistically significant relationship at the 5% significant level are showing a positive relationship. These stations are located in the areas from the Dakotas into Illinois, Indiana, and Ohio; overall, this pattern resemble what discussed for the NAO (Figure 4-2b), but weaker. During fall, the central part of the study area displays a cluster of stations with a negative relationship. During winter, the signal of the relationship between AMO and flood frequency is weak, with a limited spatially coherent area in the southern part of the study region. Overall, the results for the AMO are weaker than what observed for the NAO and PDO. Figure 4-3 (panels e-h) shows the results of the relationship between heavy precipitation frequency and AMO, with findings and conclusions similar to the results for flooding. Overall, my findings are consistent with published results; Enfield et al. (2001) examined the seasonality of the correlation between precipitation and AMO and found that the summer season showed the highest significant correlations. Tootle et al. (2005) found areas with a statistically significant positive link between AMO and streamflow variability for the upper and middle Mississippi River basin. Also, McCabe and Wolock (2014) found weak and mostly negative correlations between AMO and annual streamflow over the central Unites States.

Figure 4-4 (panels a-d) displays the results of the relationship between flood frequency and SOI. Overall, 14% (22%) of the stations exhibit a statistically significant relationship at the 5% (10%) significant level in the spring, 11% (19%) in summer, 11% (18%) in the fall, and 7% (13%) in the winter. In general, the relationship between SOI and flood frequency is weak in all the seasons. However, the most coherent geographical relationship can be found during spring, where I can identify three clusters of stations: the central and southwestern portion of the study region with a negative relationship, the eastern region with a positive relationship and the northwestern part of the study region with a positive relationship. Tootle et al. (2005) found that the strongest link between streamflow variability and ENSO can be observed in Florida, Arizona, Southern California and the Pacific Northwest, not over the central United States. Figure 4-4 (panels e-h) shows that the results of the relationship between heavy precipitation frequency and SOI are similar to what discussed for flooding. Villarini et al. (2011a) examined the relationship between annual maximum rainfall and SOI over the U.S. Midwest, where they could not found noticeable statistically significant spatial patterns between extreme rainfall and SOI in this region.

Finally, Figure 4-5 (panels a-d) displays the results of the relationship between flood frequency and PNA. Statistically significant results were found in different locations for each season. Overall, 20% (27%) of the stations present a statistically significant relationship at the 5% (10%) significant level in the spring, 26% (33%) in the summer, 31% (42%) in the fall, and 28% (36%) in the winter. Among all the climate indices considered in this study, the relationship between PNA and flood frequency is the most dominant one. During spring, the southwestern portion of the study region shows a strong positive relationship between flood frequency and PNA. During the summer, there is an extended region that ranges from North Dakota to Iowa and Missouri, and east into Wisconsin, Illinois, Indiana, and Ohio showing a negative relationship. For the fall, there is a pronounced negative relationship over the study area, especially strong over the south-west / north-east swath from Kansas to Michigan and Ohio. For winter, a strong negative relationship between PNA and flood frequency can be observed over the southeastern part of the study area, from southern Missouri into Michigan, Ohio and West Virginia. Figure 4-5 (panels e-h) shows the results for the relationship between the frequency of heavy precipitation and PNA. Overall, the conclusions I can draw about the influence of PNA on the frequency of heavy precipitation are markedly similar to what mentioned for the frequency of flooding. This pattern is similar to what was found by McCabe and Wolock (2014) regarding the relationship between PNA and average annual streamflow over the northern United States where they found a negative correlation between average streamflow and PNA over the eastern part of the study region. Moreover, these results are consistent with Ning and Bradley (2015), who found a negative correlation between the number of days with precipitation larger than 10 mm and PNA during the winter season. In addition, Coleman and Budikova (2010) indicated that the negative phase of the PNA during winter is related to more precipitation and higher average streamflow over the Ohio River Valley region.

4.3.2. Identification of the relationship between the frequency of flooding and heavy precipitation and climate indices using multiple Poisson regression

In Section 4.3.1 I examined the relationship between the frequency of heavy precipitation and flooding and each of the climate indices. While several interesting patterns were identified, there were also areas that seemed to be controlled by two or more climate indices (e.g., PDO and PNA in the winter). Here I perform multiple Poisson regression to identify the dominant climate indices for each season.

Table 4-1 and Figure 4-6 summarize the results of the multiple Poisson regression. Overall, the regression models that contain PNA as one of the covariates are the ones that can better describe the variability in the frequency of flooding in all four seasons. During spring, depending on the location, the variability in the frequency of flooding can be driven by at least one of the five climate indices. The models that contain at least one or a subset of the NAO, PDO, and PNA as a covariate can generally define the relationship between flood frequency and climate indices in the summer. During fall, there is a clear negative relationship between PNA and the frequency of flooding, while the PDO is positively related. For winter, there is a pronounced negative relationship over the southern part of the central United States between the frequency of flooding and PNA. In Section 4.3.1 I have investigated the relationship between each of the climate indices and the frequency of flooding: I found that both PNA (Figure 4-1 d) and PDO (Figure 4-5 d) were significantly related to the frequency of flooding over the region from Kansas to Michigan and West Virginia. The results in Figure 4-6, however, point to PNA as the major driver over the majority of the stations within this area, with PDO no longer identified as a significant predictor.

I have also extended these analyses to the frequency of heavy precipitation events (Figure 4-7). Overall, the findings for streamflow can be transferred to heavy precipitation, with PNA being the dominant climate mode across much of the study domain and for all the seasons. The main difference is for the fall season, in which the strongest relationship between flooding and PNA is in the southeastern part of the domain while the frequency of heavy rainfall is related to PNA in the northwestern part of the study area. A possible explanation can be found in the seasonality of flooding over this region with the fall season contributing very little to the overall number of heavy rainfall and flood events (e.g., Villarini, 2016).

To a large extent, for all the seasons and across much of the study area, I found that the relationship between heavy precipitation and flooding with PNA is the dominant one. Mostly, this relationship has a negative sign, indicating that, on average, I would expect an increase in the number of flood or heavy precipitation events during the negative phase of PNA. To investigate the physical mechanisms responsible for these findings, I examine the seasonal anomalies in IVT, 500-mb GPH, and in the frequency of heavy precipitation and flood events during the negative phase of PNA (Figure 4-8). The results show that there is an anomalously high transport over the central and south-eastern United States during the negative phase of PNA (Figure 4-8, left column; see also Leathers et al. (1991) and Harding and Snyder (2015)). This is particularly true in the spring and winter, even though weaker but positive IVT anomalies are still present over the study region. These patterns in moisture transport are also tied to the anomalies in 500-mb GPH (contour lines in Figure 4-8), with a high pressure area (ridge) over the southeastern United States and low pressure region (trough) over much of the western United States. The same regions with strong positive IVT anomalies are associated with an above-average frequency of heavy rainfall and flooding (Figure 4-8, middle and right panels). Therefore, these results indicate that during the negative phase of PNA, there is large moisture transport leading to an increasing frequency of heavy precipitation and flooding.

The fact that I see similar spatial and temporal patterns in terms of the relationship between climate indices and heavy precipitation and flooding allows me to infer that the variability in the frequency of flood events across the central United States are tied to variability in the climate system through their effects on heavy precipitation.

4.4. Conclusions

In this chapter, I have examined the relationship between climate variability and the frequency of flood and heavy precipitation over the central United States during the second half of the 20th and the first decade of the 21st centuries. I have analyzed the seasonal daily streamflow records for 774 USGS streamflow gages with at least 50 years of data. Because of the discrete nature of these data, I used Poisson regression to describe the relationship between climate indices and the response variable (frequency of flood or frequency of heavy precipitation). Five climate indices (NAO, SOI, PDO, AMO, and PNA) were used to examine these relationships.

The results of this study indicate that the climate variability of both the Atlantic and Pacific Oceans can affect the frequency of flooding events over the central United State, with each of the climate indices that can describe certain spatial and temporal features of the relationship between climate variability and frequency of flooding. Among all the climate indices, the relationship between PNA and flooding was overall the most dominant one. The sign of the relationship between PNA and flood frequency was mostly negative, indicating that a more positive (negative) value of PNA would result in a decrease (increase) in the frequency of flooding. The remaining four climate indices, on the other hand, showed a weaker and less spatially coherent signal.

In addition to analyzing the relationship between the frequency of flooding and climate indices, I also examined the relationship between climate indices and the frequency of heavy precipitation events. The results of this chapter indicate that the variability of the Atlantic and Pacific Oceans can influence the heavy precipitation frequency over the central United States in a manner very similar to what is found for flooding. I have found that PNA was the dominant climate mode, and the sign of the relationship between PNA and heavy precipitation frequency was largely negative. These results can be explained in terms of above average moisture transport over the study area, leading to an increased frequency of heavy rainfall and flood events. Moreover, these results are consistent with Harding and Snyder (2015), who showed that during the negative phase of PNA, there is a higher amount of moisture transported over the central United States through the GPLLJ. Thus, the variation in the climate system is affecting the transport and availability of moisture. In general, when there is excess moisture in the system, that excess moisture can cause heavy precipitation, which then can lead to flooding.

To sum it up, the issue of changes in the frequency of flood events can be viewed as a hierarchy of problems. In fact, flood frequency over the central United States has been changing over the past 50+ years. These changes in the frequency of flooding are mostly driven by changes in heavy precipitation. Finally, the changes in heavy precipitation and flooding are largely driven by climate variability related to the influence of the Atlantic and Pacific Oceans.

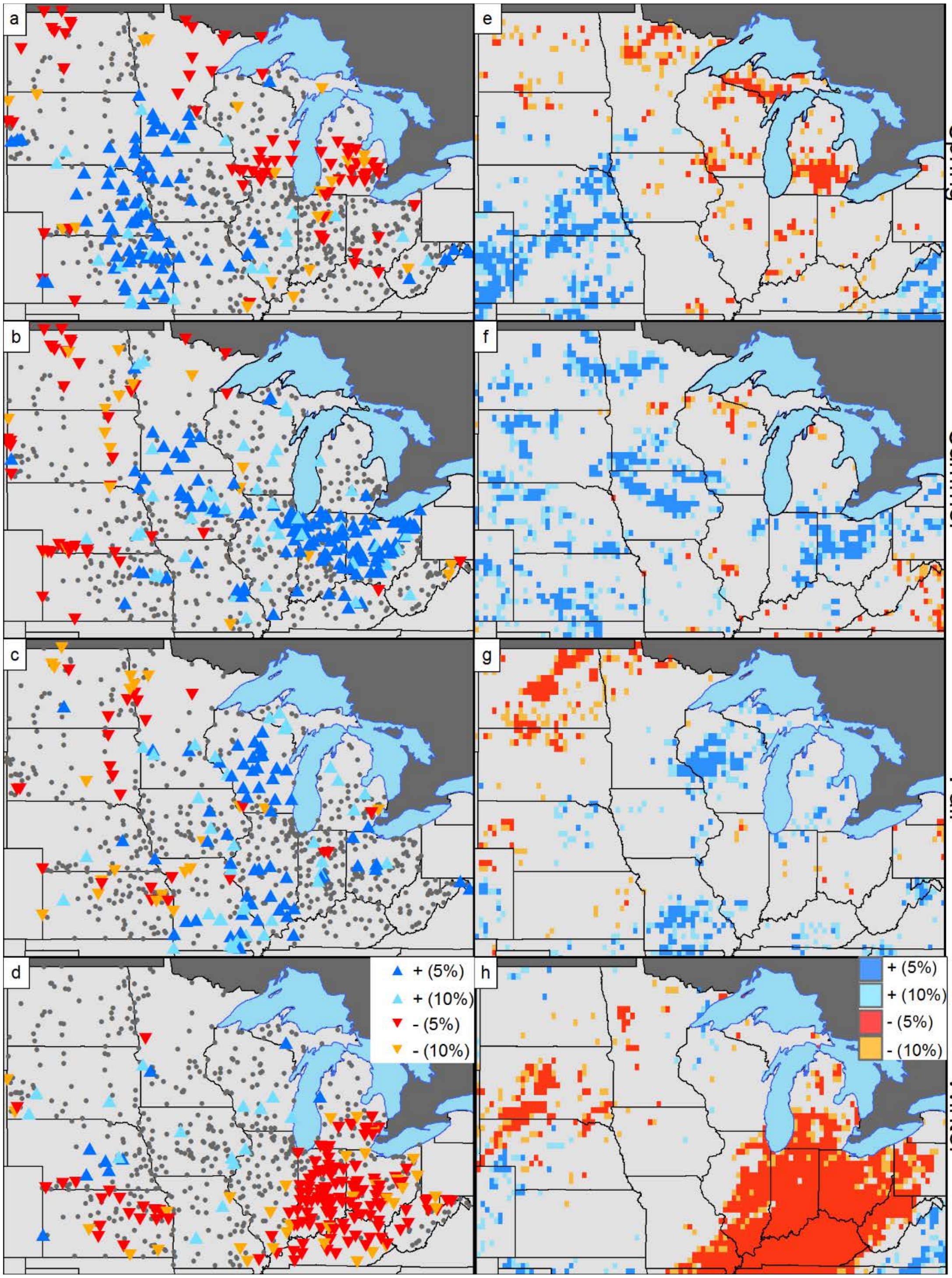


Figure 4-1: Maps summarizing the results for relationship between PDO and (a-d) the frequency of flooding and (e-h) the frequency of heavy precipitation events. The red

(orange) colors indicate a statistically significant negative relationship at the 5% (10%) level; the dark (light) blue colors show a statistically significant positive relationship at the 5% (10%) level. The grey circles refer to locations that did not show a statistically significant relationship significant at the 10% level.

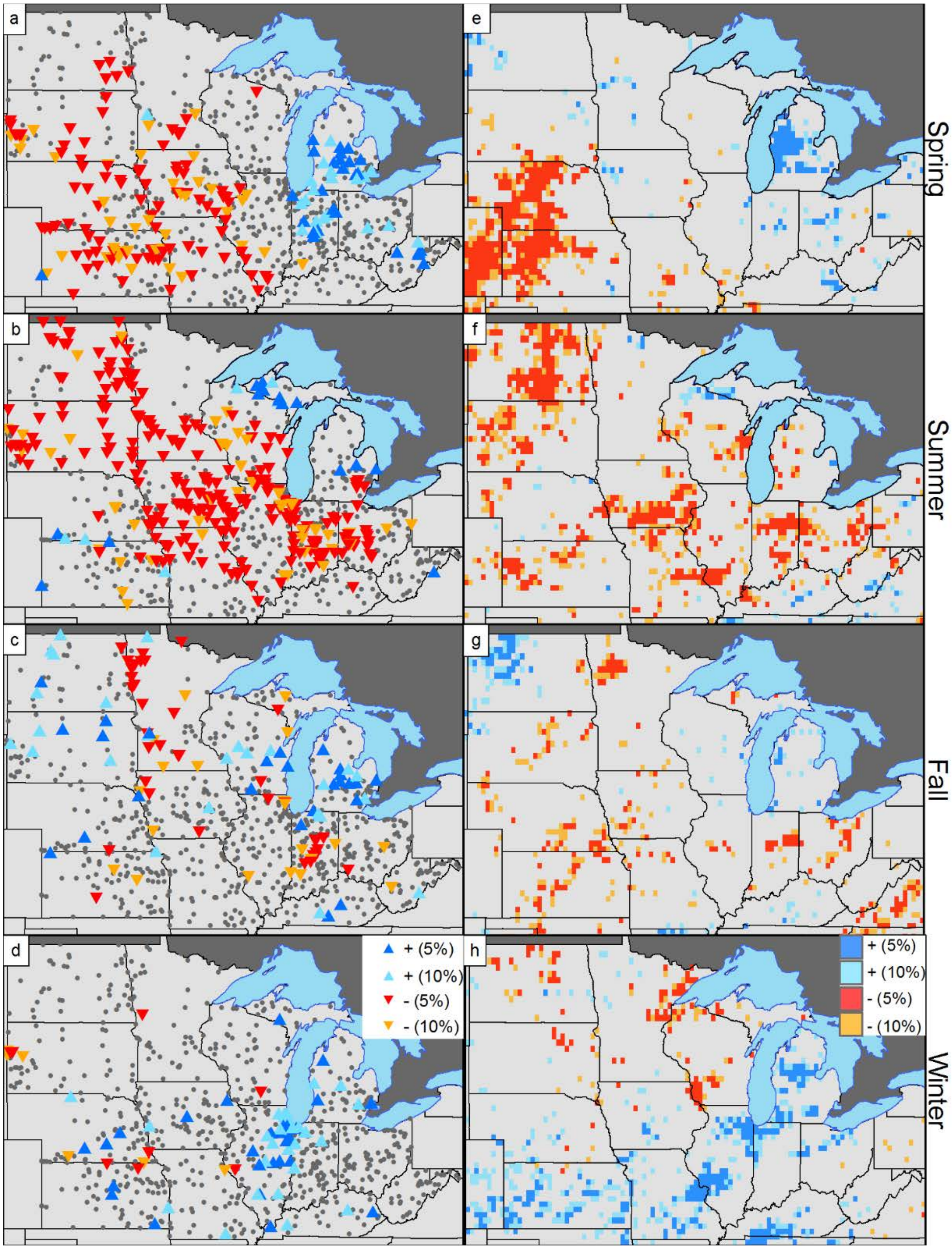


Figure 4-2: Same as Figure 4-1 but for the NAO index.

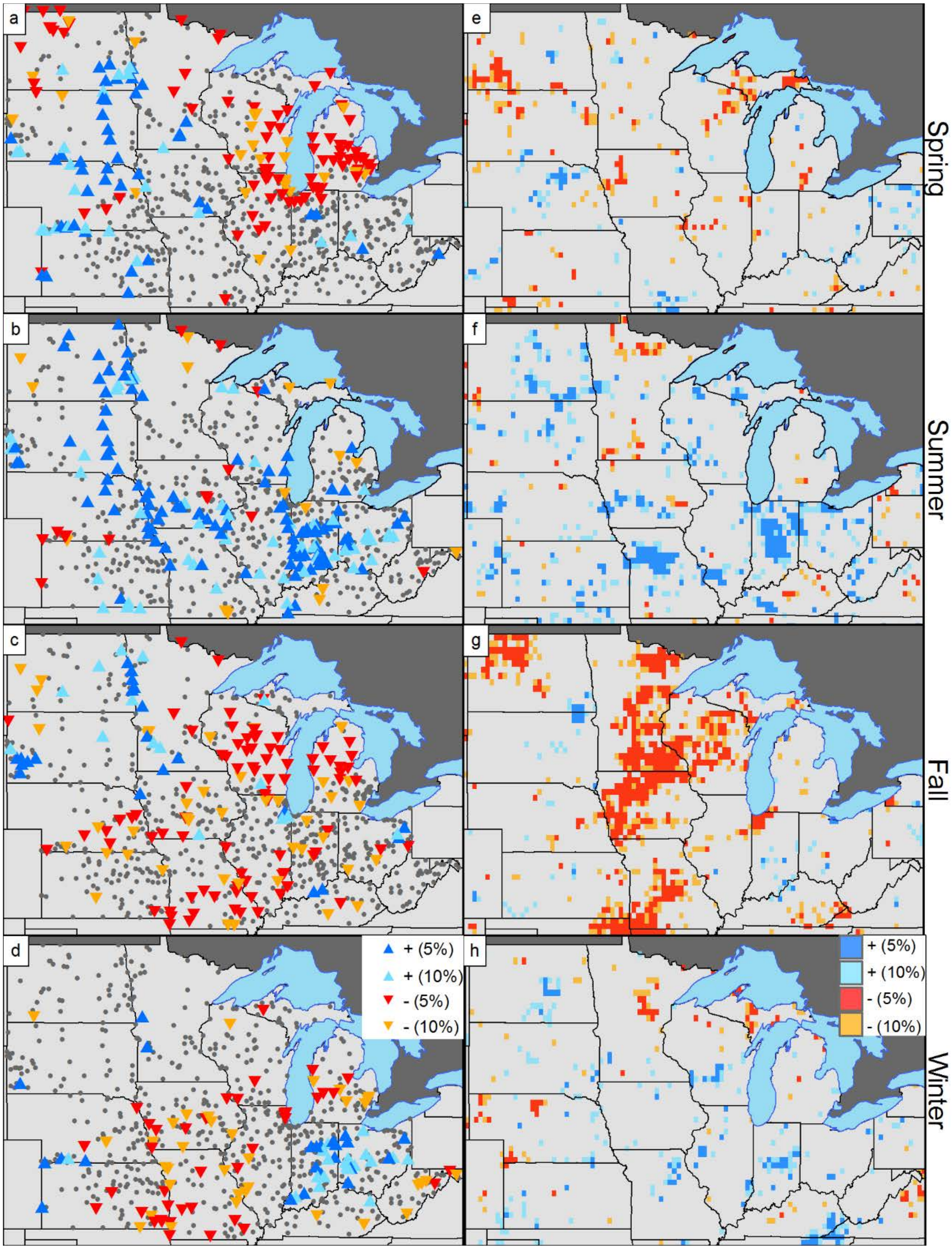


Figure 4-3: Same as Figure 4-1 but for the AMO index.

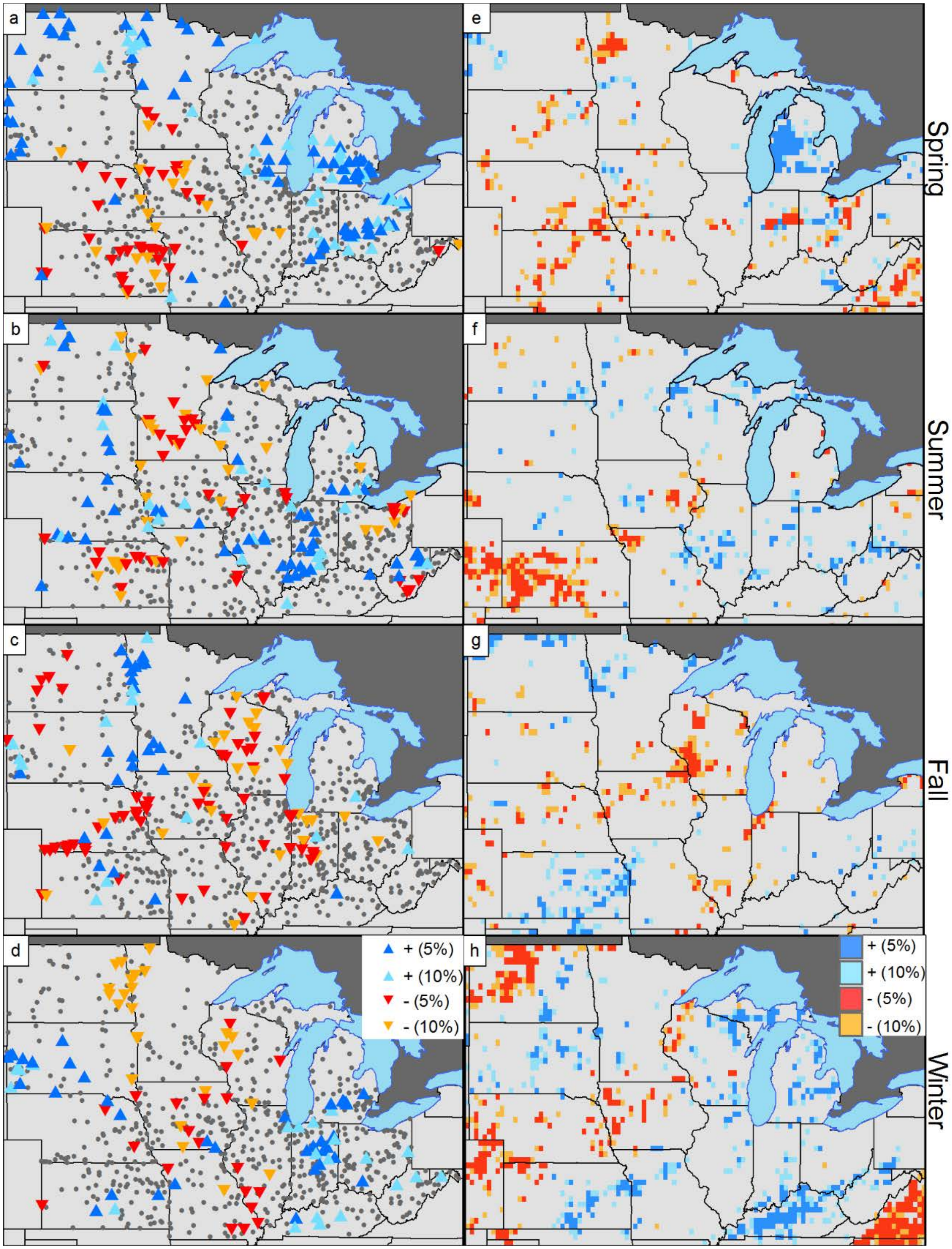


Figure 4-4: Same as Figure 4-1 but for the SOI index.

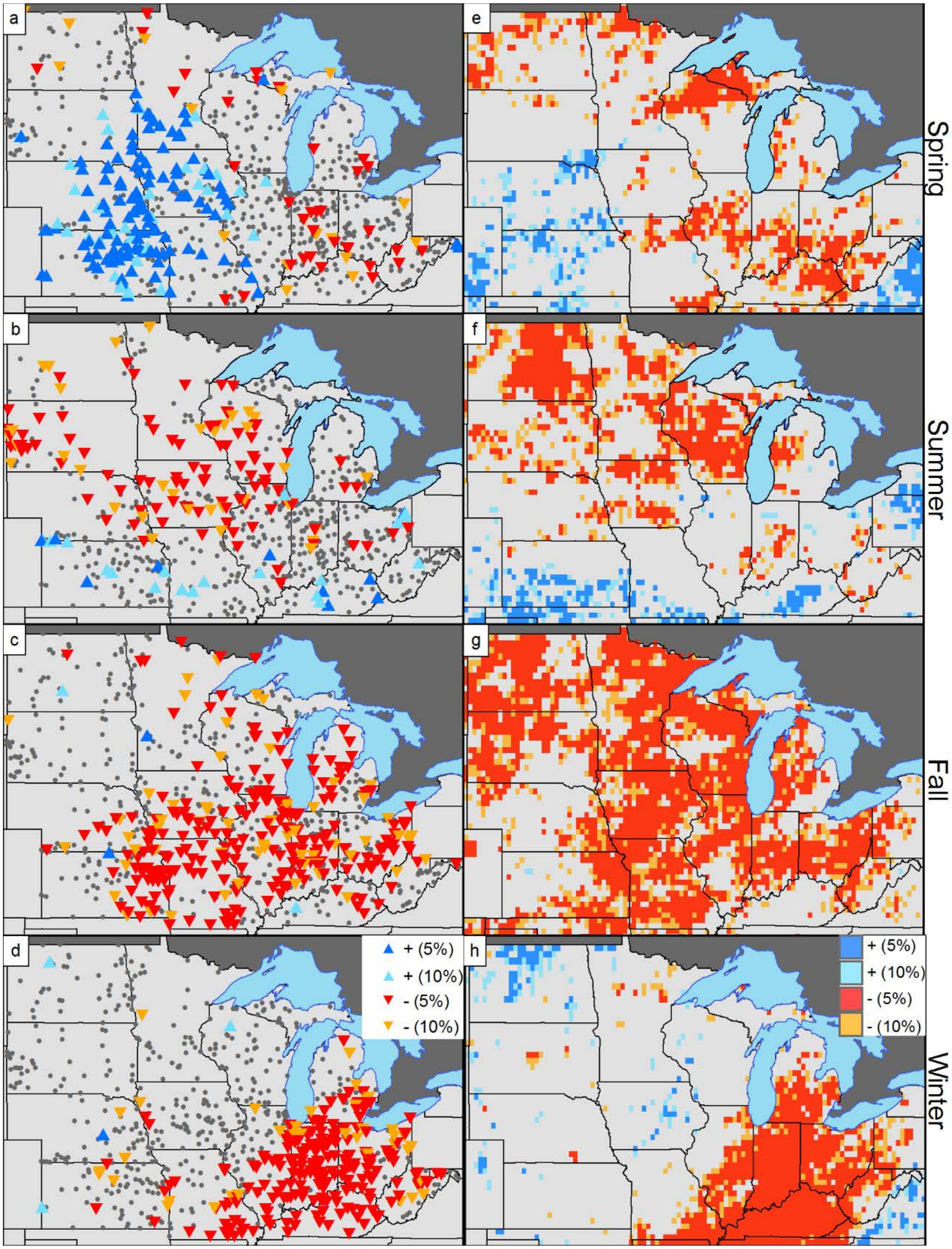


Figure 4-5: Same as Figure 4-1 but for the PNA index.

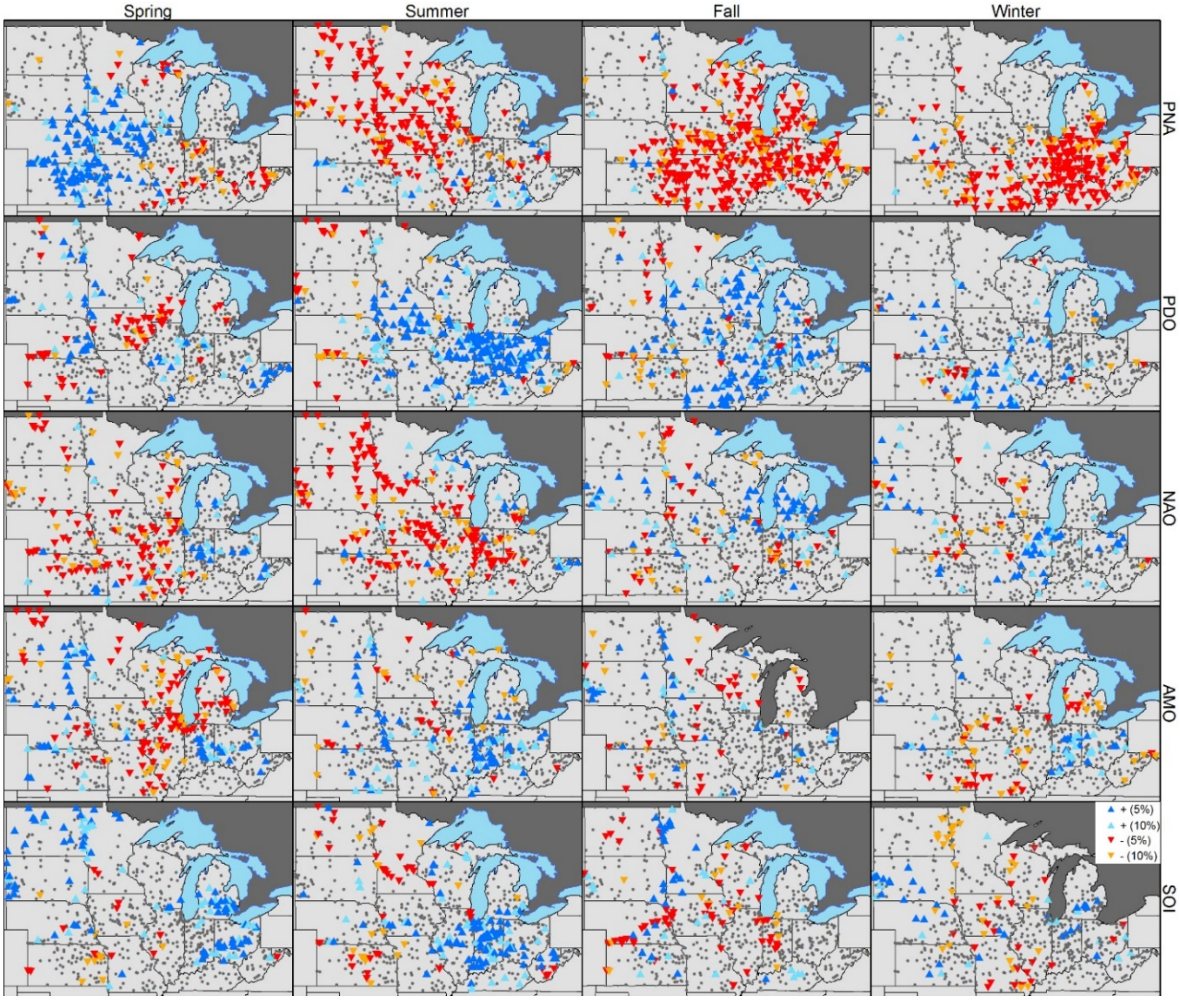


Figure 4-6: Maps showing the results of the multiple Poisson regression for the frequency of flood events. The red (orange) colors indicate a statistically significant negative relationship at the 5% (10%) level. The dark (light) blue colors show a statistically significant positive relationship at the 5% (10%) level. The grey circles refer to the location of the stations that did not show a statistically significant relationship at the 10% significant level.

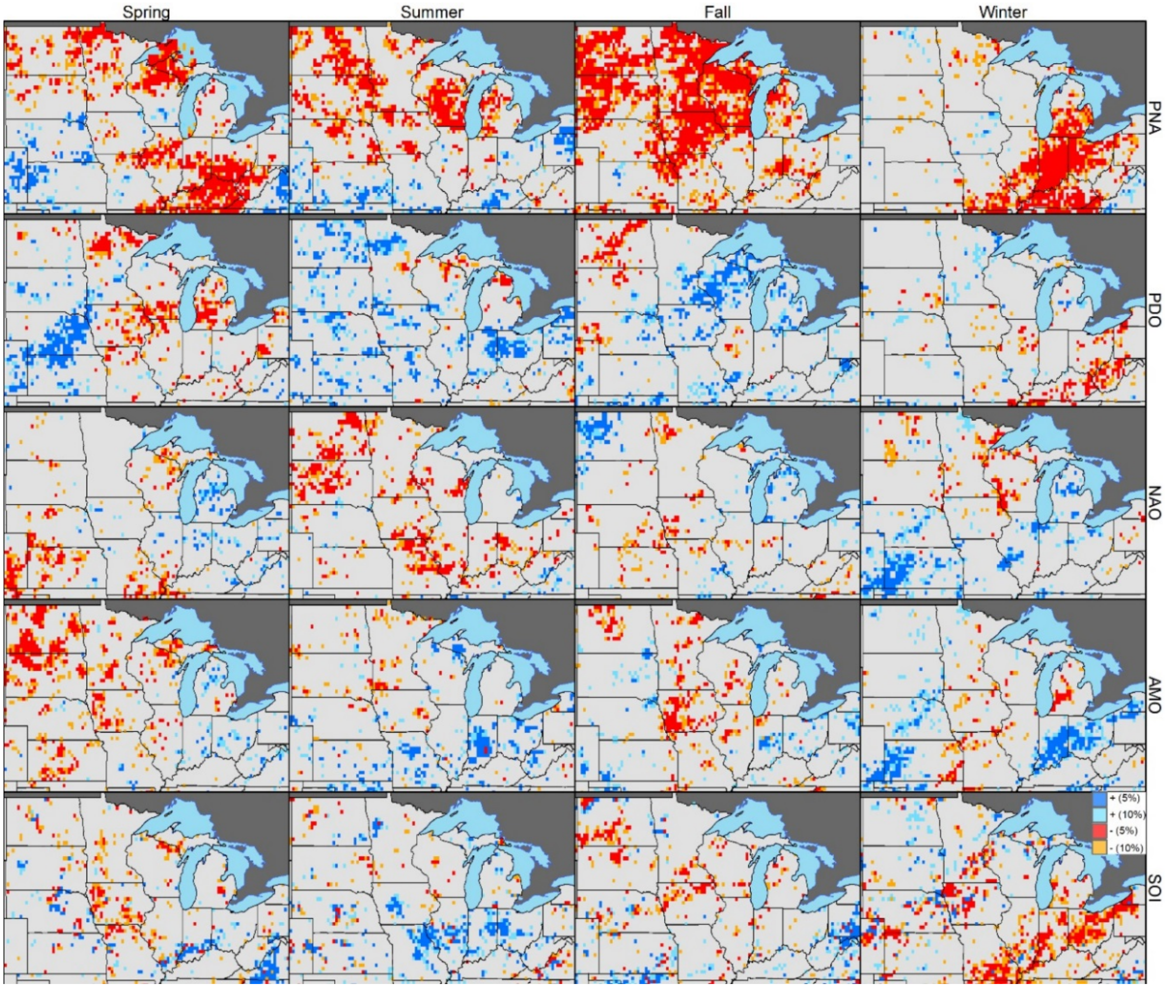


Figure 4-7: Same as Figure 7 but for the frequency of heavy precipitation events.

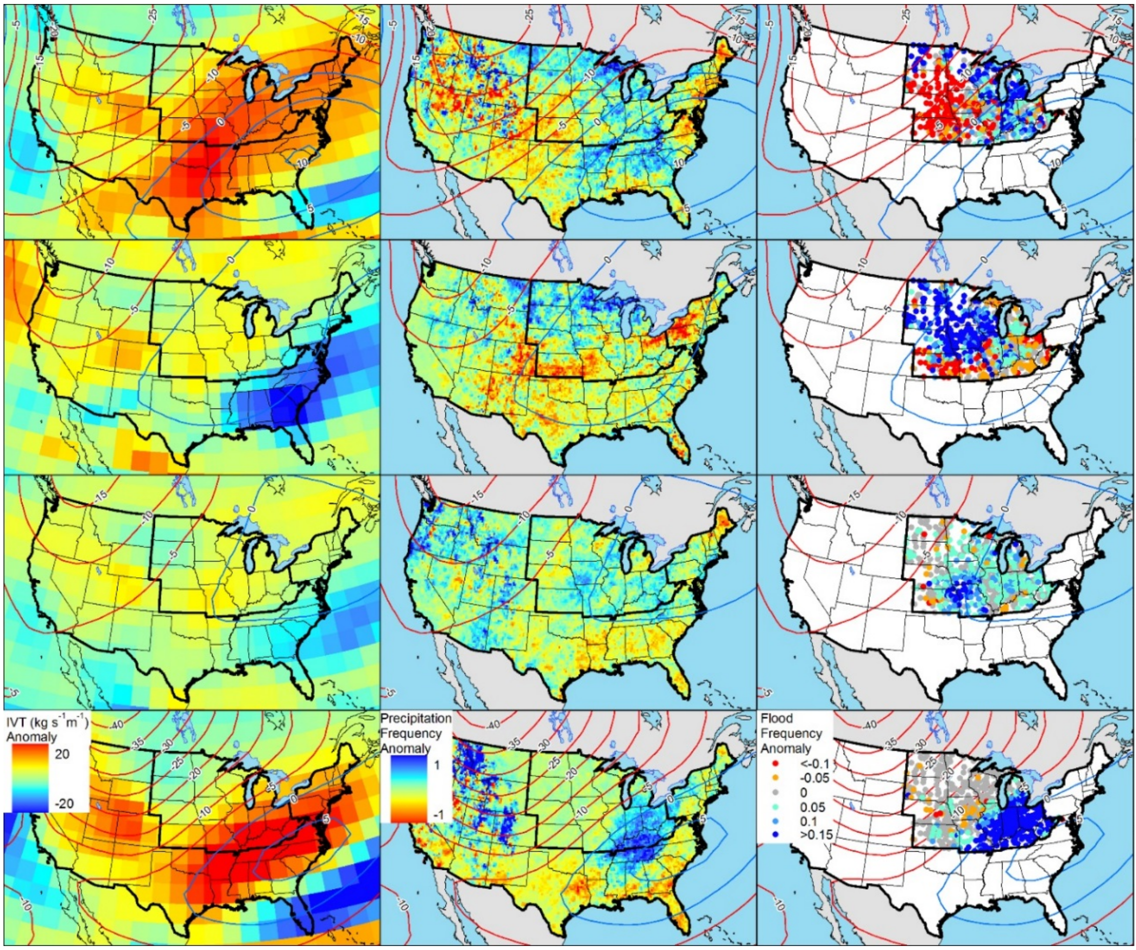


Figure 4-8: Maps showing the IVT anomaly (left column), heavy precipitation frequency anomaly (middle column) and flood frequency anomaly (right column) during the negative phase of PNA. In all these maps, the blue (red) contours represent positive (negative) 500-mb GPH anomalies (m). Anomalies are calculated for each season with respect to the 1980-2010 base period.

Table 4-1: Summary of the fraction of stream gage stations with a statistically significant (10% level) relationship with each of the climate indices based on the multiple Poisson regression.

	Spring		Summer		Fall		Winter	
	Positive	Negative	Positive	Negative	Positive	Negative	Positive	Negative
PNA	0.19	0.07	0.05	0.27	0.01	0.45	0.01	0.36
PDO	0.08	0.08	0.28	0.05	0.21	0.05	0.08	0.03
NAO	0.05	0.16	0.04	0.25	0.09	0.07	0.08	0.04
AMO	0.09	0.15	0.13	0.05	0.05	0.07	0.05	0.08
SOI	0.16	0.02	0.16	0.07	0.06	0.10	0.06	0.07

CHAPTER 5 THE ROLE OF CLIMATE IN CONTROLLING THE OCCURRENCE OF FLOOD AND HEAVY PRECIPITATION EVENTS ACROSS THE CENTRAL UNITED STATES AT THE SUB-SEASONAL SCALE

5.1. Introduction

By investigating the past changes in the frequency and magnitude of flood events in Chapter 3, I found that stronger evidence is pointing to changes in the frequency rather than in the magnitude of flooding. In particular, the strongest signal of change was for increasing trends. This indicates that a larger number of flood events have been experienced across the central United States over the second half of the twentieth and the first decade of the twenty-first centuries. The occurrence of a flood event depends on multiple factors related to the climate, stream dynamics, and watershed characteristics. However, as showed in Chapter 3, the findings for flooding can be largely linked to changes in the frequency of heavy precipitation events, with other drivers tied to human modifications of the catchments playing a more limited impact. While the detection of changes in flood and heavy precipitation characteristics (i.e., magnitude and frequency) is important, it is also critical to start investigating the driving forces that are responsible for the observed changes. By improving our understanding of the factors responsible for these changes, we are going to be in a potentially better position to improve our capabilities of predicting and projecting flood events.

Most of the studies in the literature has linked detected changes in extreme precipitation and flooding to either climate changes that have been caused by human-induced global warming (e.g., Milly et al., 2002, Min et al., 2011, Zhang et al., 2013, Fischer and Knutti, 2015) or natural variability in the climate system (e.g., Jain and Lall, 2001, Sankarasubramanian and Lall, 2003, Gershunov and Cayan, 2003, Kunkel, 2003, Higgins et al., 2007, Deser et al., 2012, Yu et al., 2016). For instance, Fischer et al. (2013) discussed that one of the main sources of uncertainty in the prediction of extreme events is the role of climate variability, especially on a timescale ranging from several decades to sub-seasonal. Redmond et al. (2002) indicated that fluctuations in the spatial and temporal distribution of extreme hydrologic events are due to climate fluctuations. Yu et al. (2016) investigated the relationship between extreme precipitation events and climate variability over the contiguous United States with data that was available for the period of 1979-2013. They mentioned that, despite the discussion that anthropogenic activity can be responsible for the observed changes in extreme precipitation events, their results point to climate variability as the main reason for the observed increase in extreme precipitation over the recent three decades. Furthermore, studies have shown that climate variability can affect the jet streams and storm tracks, which can cause changes in the atmospheric moisture content and transport patterns (e.g., Jain and Lall, 2001, Andersen and Shepherd, 2013, Villarini et al., 2011a). For instance, in both the 1993 and 2008 flood events over the central United States, atmospheric circulation and climate condition were favorable for bringing higher than average moisture from the Gulf of Mexico and Atlantic Ocean to the central United States (e.g., Dirmeyer and Kinter, 2009, Coleman and Budikova, 2010, Budikova et al., 2010, Smith et al., 2013, Lavers and Villarini, 2013).

In Chapter 4, I investigated the relationship between climate variability and flood and heavy precipitation frequency over the central United States at the seasonal scale. Those results revealed that the climate variability of both the Atlantic and Pacific Oceans can affect the frequency of precipitation, and consequently flooding, over the central

United States. However, all the analyses were geared toward the modeling of the total number of events within a given season. I did not consider how these events occurred within the season: did they occur at regular intervals, randomly or in clusters? In general, the fact that extreme events cluster in time can have a great impact on a number of fields as well as important societal and economic repercussions. For instance, Mumby et al. (2011) examined the temporal clustering of North Atlantic tropical cyclones and its effect on coral reefs. They found that the observed clustered behavior in tropical cyclones has a less detrimental impact on reef health than assuming independent events. By accounting for temporal clustering of hurricane occurrences in the vicinity of Florida, Jagger and Elsner (2012) were able to improve the retrospective forecasts of these storms. Vitolo et al. (2009) discussed the potential effects of clustering of extreme events for the insurance/reinsurance industry and explained that, given the same total losses from an individual event or from a cluster of events (before reinsurance), the cost to an insurance company after reinsurance from a cluster of events can be higher than from a single event.

Therefore, the goal of this chapter is to examine the nature of the occurrence of heavy precipitation and flood events (e.g., random, clustered), and whether it is possible to identify the climatic drivers responsible for the observed changes in the frequency of these events over the central United States at the sub-seasonal (daily) scale. My hypothesis is that extreme hydrometeorological events tend to cluster in time, with the clustering that is driven by changes in the climate state. To be able to test this hypothesis, I cannot use a modeling framework that is based on Poisson processes, that are memoryless and for which the occurrence of one event does not bear any information related to the occurrence of subsequent ones. Therefore, I here resort to Cox processes (Cox, 1972) to model the occurrence/non-occurrence of flood and heavy precipitation events over the central United States (e.g., Smith and Karr, 1983, 1986, Villarini et al., 2013b). Cox processes are widely used in biostatistics and can be viewed as a generalization of Poisson processes with a randomly varying rate of occurrence. In the hydrometeorological community, there have been few studies that used the Cox processes to model the occurrence of flood (e.g., Smith and Karr, 1986, Futter et al., 1991, Villarini et al., 2013b) and rainfall events (e.g., Smith and Karr, 1983, 1985). Smith and Karr (1983) introduced a point process framework based on Cox processes to investigate rainfall occurrences in the Potomac River basin where they found that clustering was an important feature of rainfall occurrences over their study region. Smith and Karr (1986) developed a flood frequency approach based on the Cox regression model to extract information related to occurrence/non-occurrence of flood events depending on time-varying predictors. They found that snow pack and soil moisture can control the occurrence of flood events over the North Branch of the Potomac River. More recently, Villarini et al. (2013b) used the Cox regression model for investigating temporal clustering of flood events over Iowa, and found that the occurrence of flood events can be described in terms of PNA and NAO at several stations.

Rather than assuming that flood and heavy precipitation events occur independently of the occurrence of previous events (as in Poisson processes), Cox processes allow accounting for the potential presence of temporal clustering. Under clustering, there is an alternation of quiet and active periods, in which the occurrence of an event has information about possible future events (Smith and Karr, 1985, 1986, Villarini et al., 2013b). Similar to Villarini et al. (2013b), I refer to a clustered process as one that is not Poisson. In particular, flooding and heavy precipitation can exhibit a concentration of events in a particular period of the year, which can be described by a Poisson process with a seasonally varying rate of occurrence. This inhomogeneous Poisson process does not represent what I mean by clustered process, as it can be represented by a Poisson process under an appropriate transformation of the time axis, with the arrival time of the events that can be described by an exponential distribution. On the other hand, the time clock that characterizes the occurrence of events in a Cox model is not one with constant speed, but one that sometimes moves faster and sometimes slower (Zhou, 2001).

In Chapter 4, I showed that the occurrence of heavy precipitation and flood events at the seasonal scale are controlled by PNA. Here, I will complement the PNA with the AO, because this climate mode has been tied to the occurrence of atmospheric rivers, which exert a major control on hydrometeorological extremes over this area (Nayak and Villarini 2016). Moreover, Hu and Feng (2010) linked variability in the summertime rainfall over the central United States to the AO. In addition, Kellner and Niyogi (2015) have shown that AO can describe variability in rainfall and temperature and consequently, corn production over the central United States.

The result of this chapter, highlighting the relationship between observed climate variability and frequency of heavy precipitation and flood events at the daily time scale, will increase our understanding of what controls the occurrence of these extremes over the central United States, and has the potential to provide essential insight information for short-term forecasting of heavy precipitation and flooding events.

5.2. Methods

Similar to Chapters 3 and 4, I use a peak-over-threshold (POT) approach to identify the occurrence of heavy precipitation and flood events (e.g., Katz et al., 2002, Davison and Smith, 1990, Villarini et al., 2013b). To identify heavy precipitation events, a threshold is set based on the 95th percentile of the empirical precipitation distribution at each pixel. Flood events are identified based on the threshold that gives on average two flood events per year, with no more than one event in a 2-week time window that is centered on the day of occurrence of the flood event to avoid counting the same event multiple times. After setting the thresholds for streamflow and precipitation, I determine the occurrence of events based on the values that exceeded the threshold for each grid cell or stream gage location.

In this study, the point process models for the occurrence of heavy precipitation and flood events are based on Cox processes and regression. Cox regression (Cox, 1972) is the model that can describe a Cox process with a time-varying rate of occurrence that is depending on covariate processes. The rate of the occurrence λ of the day t (t = 1,…, 365) of i^{th} year can be written as follows:

$$\lambda_i(t) = \lambda_0(t) \cdot exp\left[\sum_{j=1}^{m} \beta_j Z_{ij}(t)\right] \tag{5.1}$$

where this equation shows that the rate of occurrence is the product of two quantities, the baseline hazard $\lambda_0(t)$, which is a non-negative function of time, and the exponential part, including $Z_{ij}(t)$, which is j^{th} time-varying covariate process for the i^{th} year, and β_j, which is the coefficient for the j^{th} covariate with j=1, …, m and m represents the total number of events (e.g., Kleinbaum and Klein, 2012). This model is a semiparametric one, because the baseline hazard function is parametrically unspecified and the covariates are linearly related to the hazard function (Cox, 1972, Kleinbaum and Klein, 2012).

In addition to examining whether the occurrence of flood and heavy precipitation events can be explained with models that have only AO or PNA as the covariate, I also used a set of Cox regression models in which both climate indices are considered as potentially useful covariates. For that, at each of the USGS stations or precipitation pixels, I consider five different possible models; these models are a base model with no climate indices (the model reduces to baseline hazard), a model with only AO as covariate, a model with only PNA as predictor, a model including both AO and PNA, and a model that includes both AO and PNA and the interaction term between them. Then the best model is selected based on the smallest value of the Akaike information criterion (AIC; Akaike, 1974). In this chapter, if the selected model is different from the base model, I focus on the coefficients β_j that are different from zero at the 5% and 10% levels. A positive (negative) value of β_j, on average, would result in an increase (decrease) in the value of the rate of occurrence for a positive value of the climate index. Note that to better capture longer time of influence of AO and PNA, I used averaged values of each of these climate indices over the previous 7 days for all the analyses.

5.3. Results and discussion

5.3.1. PNA or AO as covariate

In this section, I consider the Cox regression models in which each climate predictor is considered in isolation. The results in Figure 5-1 (top panels) are for the PNA, while those in the Figure 5-1 (bottom panels) are for AO. Let me begin with flooding and PNA (Figure 5-1 a). Overall, 42% (46%) of the stations exhibit a negative relation between

PNA and the occurrence of flood events at the 5% (10%) significance level and 5% (8%) show a positive relation. A strong negative relationship between PNA and the occurrence of flood events can be seen over the eastern part of the study region, from Minnesota into Michigan, Iowa, Wisconsin, Indiana, Illinois, Missouri, Kentucky, Ohio and West Virginia. On the other hand, positive values can be observed over the southwestern part of the study region, including Nebraska and Kansas. Figure 5-1 b shows the results of the relation between the occurrence of heavy precipitation events and PNA at sub-seasonal scale. Overall, the results are similar to those discussed for flooding. The negative relation between PNA and the occurrence of heavy precipitation events can be identified over the eastern portion of the study region, whereas the southwestern region displays a positive relation. These results are in line with what I found in Chapter 4, where the sign of the relationship between the frequency of flood and heavy precipitation events with PNA was mostly negative especially over the eastern part of the central United States. Harding and Snyder (2015) showed that during the negative phase of PNA there is a higher amount of moisture transported to the central United States. Moreover, Coleman and Budikova (2010) indicated that the negative phase of the PNA is associated with higher than average precipitation and streamflow over the Ohio River Valley region.

Figure 5-1 c presents the results of the relation between the occurrence of flood events and AO. Overall, I find that for 27% (35%) of the stations, the rate of occurrence of flood events is a function of AO at the 5% (10%) significance level. Of these, 24% (30%) are characterized by a positive relation between AO and the occurrence of flood events at the 5% (10%) significance level, with many of them concentrated in the southeastern part of the study region, including West Virginia, Ohio, Kentucky, Illinois, Indiana, and northern Michigan. Figure 5-1 d presents the results of the relation between the occurrence of heavy precipitation events and AO, where there are striking similarities (both in terms of geographic location and sign) with what I have just described for flooding. The eastern part of the study region shows a positive relationship between AO and occurrence of heavy precipitation events while the western region displays a negative relation. The fact that I find a significant relation between AO and the occurrence of heavy precipitation events is consistent with previous studies (e.g., Hu and Feng, 2010, Kellner and Niyogi, 2015) where they observed a statistically significant link between AO and seasonal rainfall variability over the central United States. Moreover, these results are also consistent with Nayak and Villarini (2016), who found that AO and PNA are important predictors in explaining the frequency of atmospheric rivers over this area.

5.3.2. PNA and AO as covariates

In the previous section, I find that the occurrence of flood and heavy precipitation events over the eastern part of the central United States can be explained by PNA and AO, with the coefficient β for the former (latter) that was negative (positive). Over the western part of the study region, on the other hand, the sign of the coefficient for AO is negative while for PNA is positive. However, I considered these two predictors separately, and I cannot conclusively say if one of them is the dominant one, or whether they both play an equally important role. I address this issue in this section by allowing both of these predictors to be selected.

Figure 5-2 displays the results of the Cox models for which the rate of occurrence of heavy precipitation and flood events is a linear function of AO and/or PNA (by means of logarithmic link function). Out of 774 stations, there are 233 (28%) stations where the base model (a model with a constant rate of occurrence) has the smallest AIC. For the remaining 555 (72%) stream gaging stations, the models with the smallest AIC are those including at least one of the climate indices (Figure 5-2 a and c). From these 555 stations, there are 54 stations for which an interaction term is presented in the final selected model with the smallest AIC (Figure 5-2 e). Qualitatively, the results for heavy precipitation events are similar to the flooding ones (Figure 5-2 b, d and f).

In general, the Cox models that contain PNA as one of the covariates are the ones that can describe the occurrence of flood and heavy precipitation events over the majority of the study region (Figure 5-2 a and b). This result is in line with what I found in Chapter 4, where the Poisson regression models that contain PNA as one of the predictors were able to explain the variability in the frequency of flooding and heavy precipitation events at the seasonal scale. Overall, 40% (44%) of the stations exhibit a negative relationship between PNA and the occurrence of flood events at the 5% (10%) significance level (Figure 5-2 a). These stations are concentrated across the eastern part of the study region, including northern Minnesota, eastern Iowa, Michigan, Wisconsin, Indiana, Illinois, Missouri, Kentucky, Ohio and West Virginia. Moreover, 5% (7%) of the stream gaging stations show a positive relation at the 5% (10%) significance level, and they are located over the western side of the study region (Figure 5-2 a). Figure 5-2 c shows the models that contain AO as one of the predictors that can affect the occurrence of flooding over the central United States. Overall, 16% (21%) of the stream gaging stations show a positive relation between AO and the occurrence of flood events at the 5% (10%) significance level. Most of these stations are located in the southeastern part of the study region. In addition, 3% (5%) of stations reveals a negative relationship between the occurrence of flood events and AO at the 5% (10%) significance level. Most of them are located in Nebraska, Kansas, and Iowa.

By expanding the analyses to heavy precipitation events, the conclusions I can draw about the influence of PNA and AO on the occurrence of heavy precipitation events are rather similar to those mentioned for flooding (Figure 5-2 b and d). Overall, there is a pronounced negative relation between the occurrence of heavy precipitation events and PNA over the eastern part of the central United States. On the other hand, the western part of the study region displays a positive relation between PNA and the occurrence of heavy precipitation events. For the relation between AO and the occurrence of heavy precipitation events, the sign of the coefficient is positive over the eastern part of the study region, while the sign of the coefficient is negative over the western part of the central United States.

Up to this point, I have found that the occurrence of heavy precipitation events, and consequently flooding events, depend linearly on AO and/or PNA over a vast portion of the central United States. To examine the physical mechanisms responsible for these findings, I investigate both the IVT and 500-hPa GPH anomalies on the days that heavy precipitation events occurred and seven days prior to the events (Figure 5-3). Figure 5-3 a shows the results for a grid cell for which a Cox model including AO as the only covariate can describe the occurrence of heavy precipitation events; at this location, the IVT anomalies are overall positive, while the GPH ones are negative. Figure 5-3 b shows the results for a case where the base model (i.e., no covariates were selected) had the smallest AIC value; this pixel is located in the transition zone between positive and negative GPH anomalies. The picture changes noticeably when I examine the anomalies in IVT and GPH for locations in which PNA was retained as an important predictor, either in combination with AO (Figure 5-3 c) or alone (Figure 5-3 d). In both cases, the results reveal that there is an anomalously high IVT, showing a higher than average transport of moisture to the area where the grid cell is located. This can be tied to the anomalies in 500-mb GPH, where the positive values of the GPH anomaly that represent warmer and wetter conditions located over the examined locations. Similar to my findings in Chapter 4, the results illustrate that there is a large moisture transport leading to the occurrence of heavy precipitation events during the negative phase of PNA. Overall, the negative PNA is associated with persistent and longer zonal planetary waves that on the average transport considerably more water vapor over the central United States (Leathers et al., 1991, Harding and Snyder, 2015). A warmer and wetter condition has the potential to generate a higher number of heavy precipitation events that can then lead to more frequent flood events.

5.3.3. Sensitivity analysis to the threshold selection

The flood analyses in the previous two sections were based on a threshold of an average of two flood events per year; on the other hand, to identify the heavy precipitation events, I selected a threshold corresponding to the 95th percentile of the empirical precipitation distribution at each pixel. In this section, I perform the same set of simulations as in Section 5.3.1, for both flooding and heavy precipitation to investigate the sensitivity of the results to the thresholds selection. Figure 5-4 a-d and Figure 5-4 e-h present the statistically significant results of the relation between the occurrence of flood events and PNA, and AO, respectively. In these sets of simulation, the threshold varies from an average of 1 to 5 events per year. The results are markedly similar to what discussed in Section 5.3.1 (Figure 5-1 a and c) both in terms of geographic location and sign of the relation between the occurrence of flood events and the covariate processes. I also used the Cox model to examine the influence of AO (Figure 5-5 a) and PNA (Figure 5-5 b) on heavy precipitation occurrence for the case that the threshold is selected based on the 90th percentile of the precipitation distribution at each pixel; once again, the results are similar to what discussed in Section 5.3.1 (Figure 5-1 b and d). Based on these results, it is clear that the observed findings are not dependent upon the threshold used to identify heavy precipitation and flood events, but rather they represent a real characteristic of extreme hydrometeorological events over this area.

5.4. Conclusions

In this chapter, I have investigated if and how climate variability can affect the occurrence of flood and heavy precipitation events across the central United States at the sub-seasonal scale. Cox regression models with time-dependent predictors were used to investigate the potential relation between the occurrence of flood and heavy precipitation events and two climate indices (PNA and AO). The main findings of this chapter can be summarized as follows:

1- By investigating the models for which the rate of occurrence of flood and heavy precipitation events were a function of AO or PNA, I have found that these two climate play an important role over large areas of the central United States. In particular, I have found that there are regional differences, with an enhanced likelihood of having a flood or heavy precipitation events during the negative phase of the AO and the positive phase of PNA in the western part of the study region. The results for the eastern part of the domain exhibited opposite dependencies, with the positive phase of AO and the negative phase of the PNA that were more conducive to the occurrence of these hydrometeorological extremes.

2- I expanded my analysis to a set of possible models to find the climate index or set of climate indices that could describe the occurrence of flood and heavy precipitation events adequately, including a base model for which the model reduces to the baseline hazard. There were about two-thirds of the stations, for which the models that describe the occurrence of flood events included AO and/or PNA as the selected covariates (based on the AIC as penalty criterion). The same conclusions were reached when I expanded the analyses to heavy precipitation events. Overall, the models that include PNA as one of the covariates were the models that could describe the occurrence of flood and heavy precipitation events over large areas of the central United States. These results can be explained in terms of above average moisture transport over the study region, especially during the negative phase of PNA, causing the occurrence of heavy precipitation, and consequently flooding events.

3- The results of this chapter show that AO and/or PNA could explain the temporal clustering in the occurrence of flood events in over 72% of the stream gage stations across the central United States. Indeed, the rate of occurrence process was found to be dependent on the climate covariate processes over a vast area of the central United States. This would point to the temporal clustering of flooding and heavy precipitation events as an important feature of the flood and heavy precipitation events, with this behavior being controlled by climate variability. The insight gained from this work could be used to improve prediction systems, with the improved understanding of the relationship between climate variability and the occurrence of heavy precipitation and flooding. Thus, by being able to forecast PNA and AO, these modeling results can be used to investigate whether a certain period of time at a given location will be more active or quiet in term of flooding and heavy precipitation events.

4- I examined the sensitivity of the results to different selected thresholds for the occurrence of flood and heavy precipitation events. The overall results and conclusions were largely insensitive to the selected threshold.

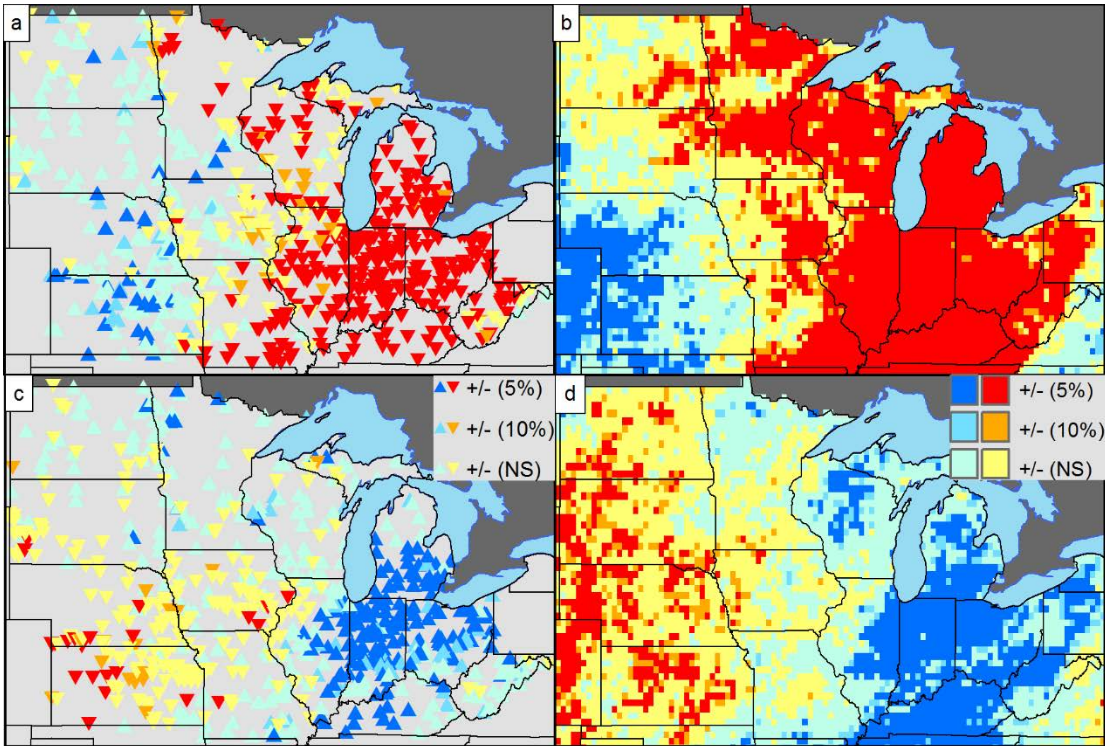
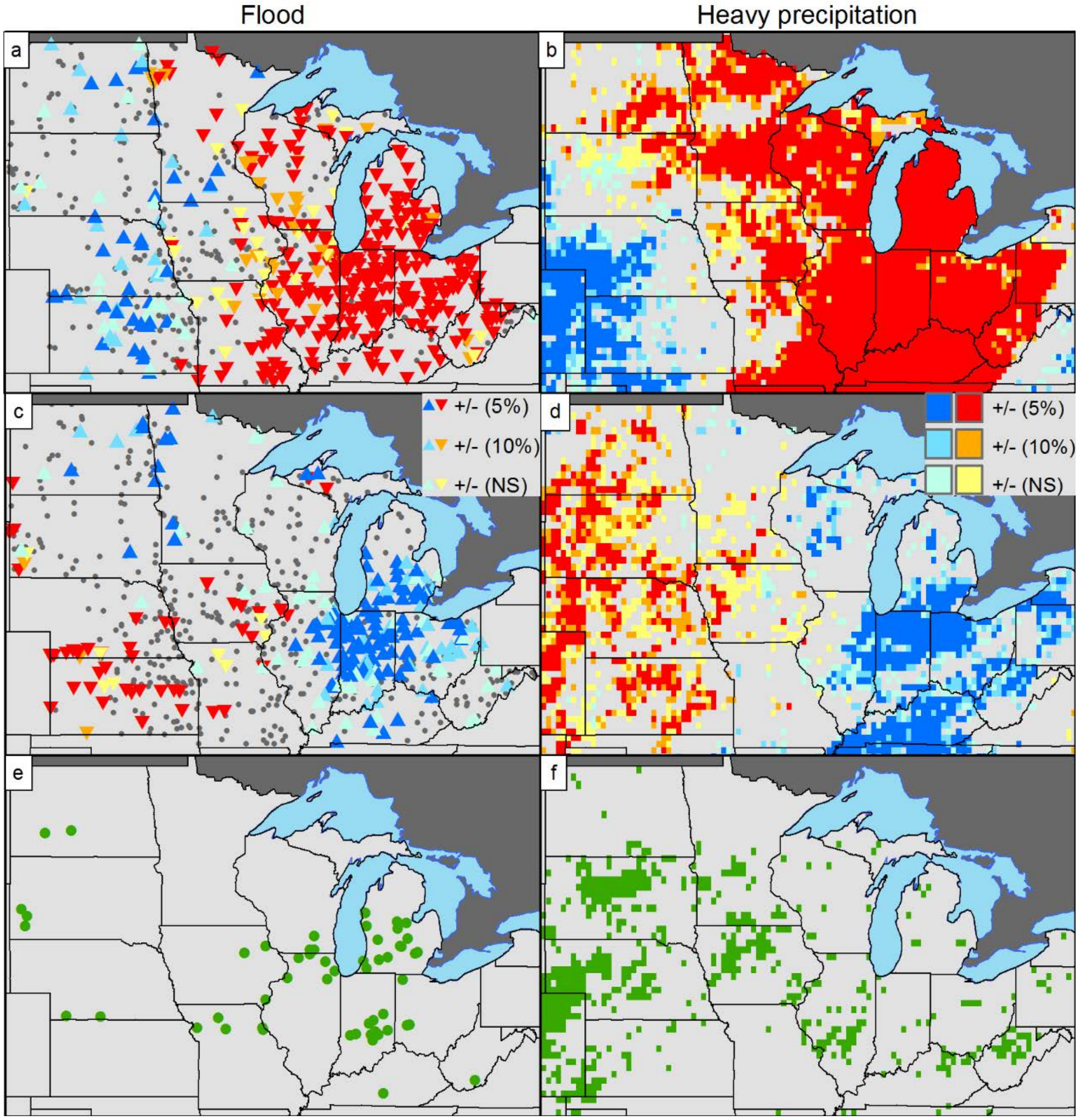


Figure 5-1: Maps showing the results for the relation between the occurrence of (a) flood events and PNA, (b) heavy precipitation events and PNA, (c) flood events and AO, (d) heavy precipitation events and AO at the sub-seasonal scale over the central United States. The red (orange) colors indicate a statistically significant negative relationship at the 5% (10%) level; the dark (light) blue colors show a statistically significant positive relationship at the 5% (10%) level. The yellow (cyan) color show the results for the non-significant negative (positive) relations.



Flood

Heavy precipitation

Figure 5-2: Maps showing the results of the best Cox model (selected based on the smallest AIC) for which PNA (top panels) and AO (middle panels) are retained as a significant covariates in the final models. The green colors in the bottom panels show the location of the final models that includes an interaction term. The grey circles in panels a and c refer to locations that the climate index is not maintained as an important covariate. The red (orange) colors indicate a statistically significant negative relationship at the 5% (10%) level; the dark (light) blue colors show a statistically significant positive relationship at the

5% (10%) level. The yellow (cyan) colors show the results for the non-significant negative (positive) relations.

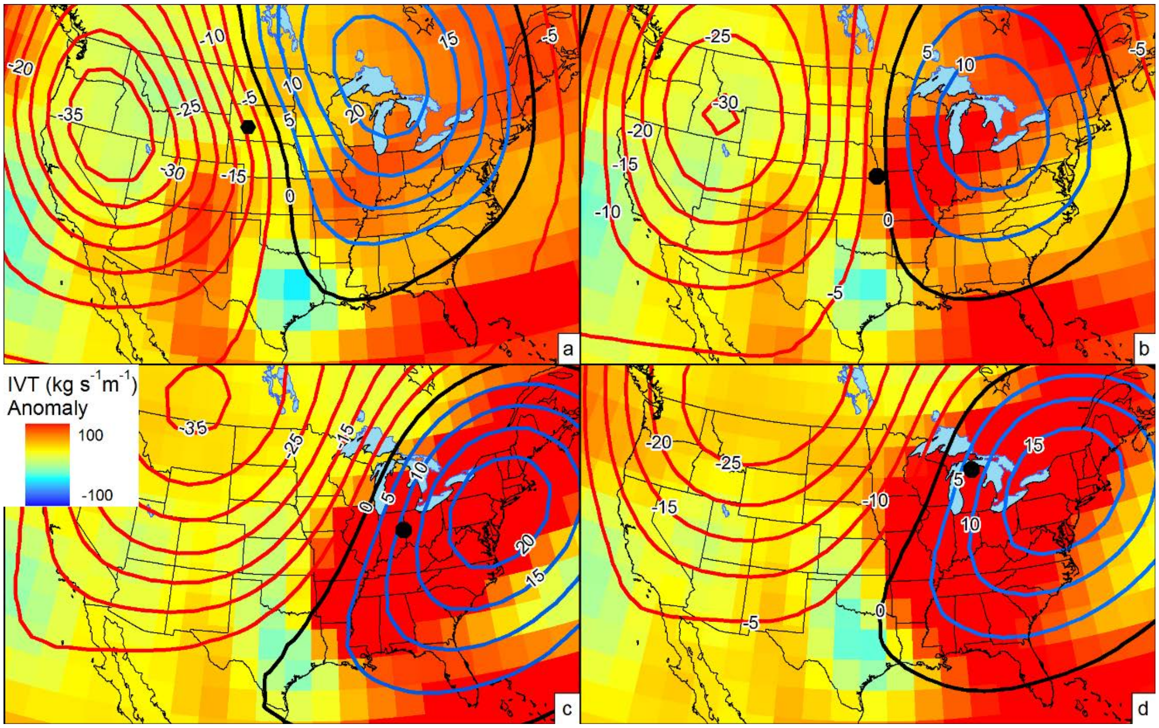


Figure 5-3: Maps showing the IVT and GPH anomalies corresponding to four different locations (black circles) for which different Cox regression models were selected to describe the occurrence of heavy precipitation events: (a) a model with AO as the only covariate; (b) a model in which neither of the covariates were selected; (c) a model including both AO and PNA; (d) a model with PNA as the only predictor. In all the panels, the blue (red) contours represent positive (negative) 500-mb GPH anomalies (m) on the days of the occurrence of the events and seven days prior to the events, while the underlying colored fields show the IVT anomalies. Anomalies are calculated for each day with respect to the 1980-2010 base period.

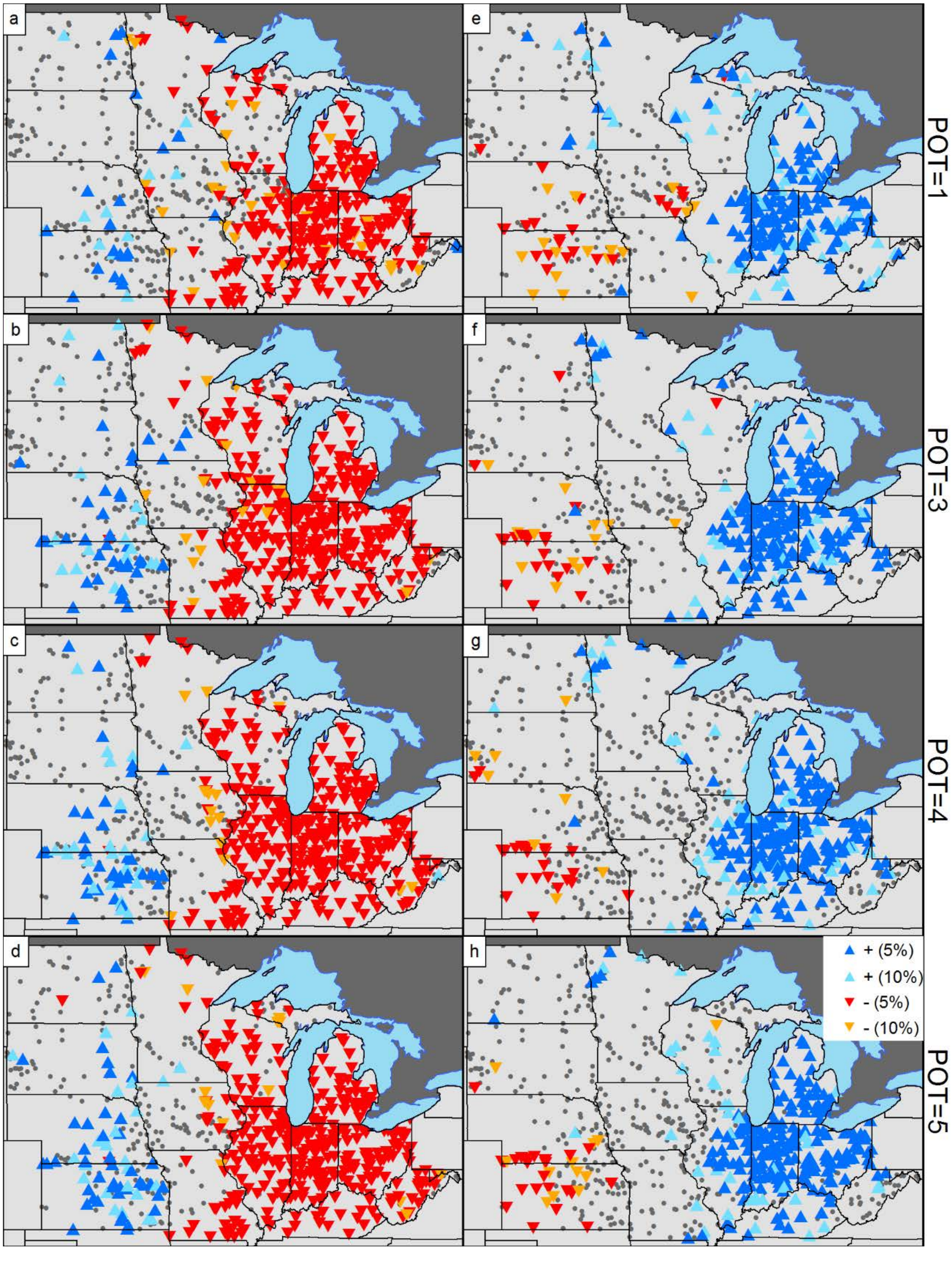


Figure 5-4: Maps summarizing the sensitivity of the results to the thresholds selection for the relation between the occurrence of flood events and PNA (left panels) and AO (right

panels) at the sub-seasonal scale over the central United States. The red (orange) colors indicate a statistically significant negative relationship at the 5% (10%) level; the dark (light) blue colors show a statistically significant positive relationship at the 5% (10%) level. The grey circles refer to the location of the stations that did not show a statistically significant relationship at the 10% significant level.

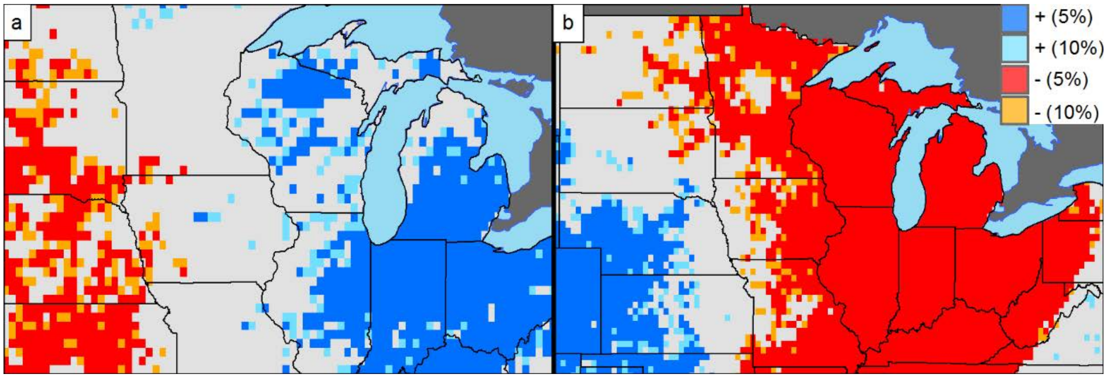


Figure 5-5: Maps showing the results for the relation between the occurrence of heavy precipitation events and (a) AO and (b) PNA at the sub-seasonal scale when the threshold is selected based on the 90th percentile of the empirical precipitation distribution. The red (orange) colors indicate a statistically significant negative relationship at the 5% (10%) level; the dark (light) blue colors show a statistically significant positive relationship at the 5% (10%) level.

CHAPTER 6 SUMMARY AND CONCLUSION

As discussed in the Introduction, flooding over the central United States has large societal and economic impacts, with loss of human lives and billions of dollars in damage. Because of these large repercussions, it is of the utmost importance to examine whether the magnitude and/or frequency of flood events have been changing over the twentieth and early twenty-first centuries. Therefore, there has been a lot of interest in analyzing streamflow records to detect variability in flood magnitude and/or frequency (e.g., Lins and Slack, 1999, Schilling and Libra, 2003, Lins and Cohn, 2011, Villarini et al., 2011b, Hirsch and Ryberg, 2012, Slater et al., 2015). Many of these studies did not show significant changes in flooding characteristics, particularly in flood magnitude. However, in analyzing precipitation data, numerous studies over the past decades have shown an increasing trend in the frequency and/or magnitude of extreme precipitations over the United States (e.g., Karl et al., 1996, 2009, Karl and Knight, 1998, Madsen and Figdor, 2007, Groisman et al., 2001, 2004, 2012, Kunkel et al., 1999, 2008, 2013, Alexander et al., 2006, Higgins and Kousky, 2013). Also, previous studies have shown that flood damage has been increasing over the past century (e.g., Pielke and Downton, 2000, Downton et al., 2005, Gall et al., 2011). In addition, modeling studies point to an intensification of the hydrological cycle under projected climate warming (e.g., Voss et al., 2002, Held and Soden, 2006, Huntington, 2006), with increasing frequency of extreme events, such as heavy rainfall, flooding and drought (e.g., Voss et al., 2002, Milly et al., 2002, 2005, Christensen and Christensen, 2003, IPCC, 2012).

Because studies of the historical records to determine changes in flooding have thus far proved inconclusive, in Chapter 3, I used different approaches (i.e., block-maximum and peak-over-threshold) to investigate whether the characteristics of recent flooding are different from the long-term averages over the central part of United States. To address this research question, I analyzed annual and seasonal daily streamflow records from 774 USGS streamflow stations over the central United States. The study area included North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Illinois, West Virginia, Kentucky, Ohio, Indiana, and Michigan. The focus was on 774 USGS stream gages with long records (i.e., at least 50 years of data) ending no earlier than 2011.

I found limited evidence suggesting an increasing or decreasing trend in the magnitude of flood peaks over this area. In contrast, there was much stronger evidence of an increasing frequency of flood events. Therefore, the results of this work support the argument that over the past 50+ years the largest flood peaks have not really become larger, but that there has been a larger number of flood events.

Flood events happen when a stream system has excess water. Although there is evidence showing that part of the increase in the flood damage noted in the previous studies is related to growth in human activity in flood hazard regions (e.g., Pielke and Downton, 1999, Pielke, 1999, Peterson et al., 2013), extreme precipitation still plays a critical role. Indeed, different hydrometeorological processes (e.g., mesoscale convective systems, snowmelt events, tropical and extratropical cyclones, atmospheric rivers) contribute to flood events in different seasons and locations over the contiguous United States. Therefore, in Chapter 3, I also examined changes in heavy precipitation as a possible reason for explaining observed changes in flooding over the central United States. Similar to the analysis of flood events, there is a stronger signal of change in the frequency rather than in the magnitude of heavy precipitation events. Overall, by examining the precipitation records, I was able to link the increasing trend in the frequency of flood events to similar patterns in heavy precipitation over the central United States.

To this end, I found that changes in flood characteristics could be largely attributed to related changes in heavy precipitation. By assuming that this relationship holds outside the study region, I have examined the precipitation records to infer what changes in flooding across the United States may be. Figure 6-1 a summarizes the results of an analysis related to the presence of trends in annual maximum precipitation records. Overall, there is a limited number of pixels showing statistically significant changes in the magnitude of heavy precipitation: overall, 10% (8%) of grid cells show statistically significant increasing (decreasing) trends in the magnitude of heavy precipitation.

While the signal of change in the magnitude is relatively weak, it becomes much stronger when I examine changes in the frequency of heavy precipitation (Figure 6-1 b). About 30% of the grid cells over the contiguous United States display an increasing trend in the frequency of heavy precipitation, and 10% of grid cells reveal a decreasing trend. Therefore, the frequency of extreme precipitation has been increasing over large regions of the contiguous United States; the most notable exception is the Northwest, where the frequency of extreme precipitation has decreased over the past 65 years. Consequently, these results indicate that while most of the contiguous United States regions are not experiencing stronger storms, they have been experiencing a larger number of heavy precipitation events.

The analyses in Figure 6-1 lead to an interesting question for the future work. Is it possible that changes in the frequency rather than in the magnitude of flood events are not just confined to the central United States, but represent a widespread characteristic of flood events across the continental United States that can be attributed to the changes in heavy precipitation events? To answer this question, analyses using the methodology detailed in this thesis should be performed.

While identifying the changes in flood and heavy precipitation characteristics reported in Chapter 3 is important, it is also imperative to start inspecting the driving forces that are responsible for the observed changes. In Chapter 4, I examined the climatic driving forces that are responsible for the observed changes in flood frequency over the central United States at the seasonal scale. The results revealed that climate variability from both the Atlantic and Pacific Oceans can play a significant role in explaining the variations in the frequency of flooding over the central United States. Among the different climate indices considered here, PNA was found to play a dominant role.

The findings about the nexus between climate variability and the frequency of flood events were extended to examine climate controls on heavy precipitation over the same area. I found that the variability of the Atlantic and Pacific Oceans influenced the frequency of heavy precipitation events in a manner similar to what was found for flooding, both in terms of geographic regions and seasonality. Therefore, these results suggest that the recent observed changes in the frequency of heavy precipitation and flood events over the central United States can be largely attributed to variability in the climate system.

The findings and methodology of Chapter 4 could provide the foundation for a number of additional lines of research. For instance, the insight gained from this work could be used to improve seasonal prediction systems. Indeed, an improved understanding of the relationship between climate variability and flooding could provide basic information to improve future water management. In particular, by skillfully forecasting

PNA values over a season of interest we would be able to have information related to the number of flood events that could be expected at a given location.

These analyses were extended to the sub-seasonal scale to examine how flood and heavy precipitation events were distributed within a season. I accomplished this by using Cox processes to describe the temporal clustering of flood events. As indicated, under clustering, there is an alternation of quiet and active periods, with the fact that one event has occurred that changes the probability of another event to occur later on. Thus, in Chapter 5, I developed Cox regression models to examine the climatic driving forces responsible for the observed changes in the flood and heavy precipitation frequency over the central United States at the sub-seasonal scale. The results reported in Chapter 5 indicate that variations in the climate system play a critical role in explaining the occurrence of flood and heavy precipitation events at the sub-seasonal scale over the central United States. These results highlight that the rate of occurrence depends on covariate processes over a broad area of the central United States. In other words, temporal clustering is present and it is driven by climate variability. The findings of Chapter 5 increase our understanding of the causes responsible for the occurrence of heavy precipitation and flood events over the central United States. The information gained in that chapter can provide essential knowledge for short-term forecasting of heavy precipitation and flooding events, which could be useful for water resources planning and management.

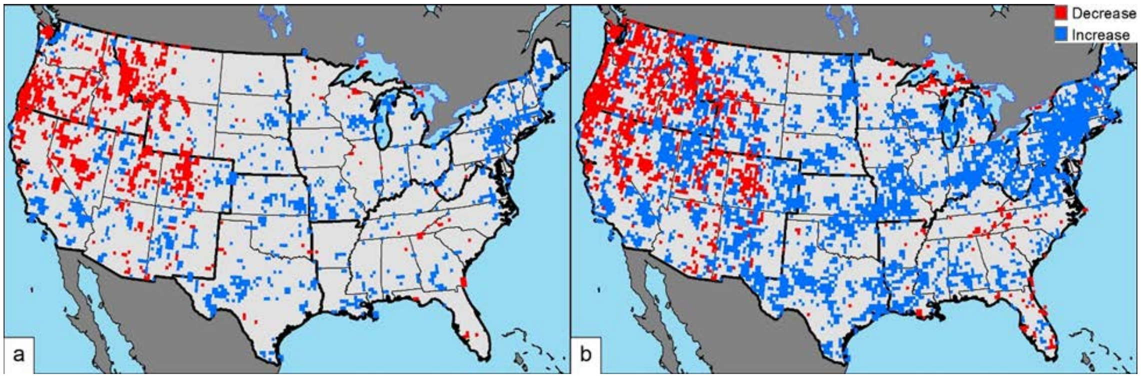


Figure 6-1: Maps showing the results for statistically significant trends (5% level) in the magnitude (a) and frequency (b) of heavy precipitation. Analyses are performed at the annual scale. Blue (red) pixels show grid cells with an increasing (decreasing) trend. Adapted from Mallakpour and Villarini (2016a).

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