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Investigating the relationship between the frequency of flooding over the central United States and large-scale climate

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ABSTRACT

The aim of this study is to examine whether the climatic driving forces can describe the observed variability in the frequency of flooding over the central United States. Results are based on daily streamflow records from 774 U.S. Geological Survey (USGS) stations with at least 50 years of data and ending no earlier than 2011. Five climate indices related to both the Atlantic and Pacific Oceans are used in this study: the North Atlantic Oscillation (NAO), the Southern Oscillation Index (SOI), the Pacific Decadal Oscillation (PDO), the Atlantic Multidecadal Oscillation (AMO), and the Pacific-North American pattern (PNA). A peak-over-threshold approach is used to identify flood peaks, and the relationship between the frequency of flood events and climate indices is investigated using Poisson regression.

The results of this work indicate that climate variability can play a significant role in explaining the variations in the frequency of flooding over the central United States. Different climate modes are related to the frequency of flood events over different parts of the domain and for different seasons, with PNA playing an overall dominant role. Analyses related to flood events are extended to examine climate controls on heavy precipitation over the same area. We find that the variability of the Atlantic and Pacific Oceans can influence the frequency of heavy precipitation days in a manner similar to what was found for flooding. Therefore, these results suggest that the recent observed variability in the frequency of flood events and heavy precipitation over the central United States can be largely attributed to the variability in the climate system.

1. Introduction

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), with large economic and social repercussions (e.g., fatalities, agricultural losses, flood losses, water quality issues). For example, $34 billion in economic damage and 48 fatalities were caused by the 1993 Midwest flooding (NCDC, 2015). During the June 2008 Midwest flood, 24 people lost their lives, 140 were injured (Dirmeyer and Kinter, 2009), and the total economic damages were in excess of $11 billion (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 flooding 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, Mallakpour and Villarini, 2015).

Recently, Mallakpour and Villarini (2015) 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. They also found that these changes can be largely related to changes in the frequency of heavy precipitation events. The next question to address 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? Our hypothesis is that the variability in the climate system related to both the Atlantic and Pacific Oceans can influence the frequency of flooding and heavy precipitation over the central United States.

There are different meteorological, hydrological and climatological mechanisms that bring moisture that can produce flooding (i.e., tropical cyclone, convection, thunderstorm, frontal passages, sea surface temperature (SST) anomalies, and jet streams)

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(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., 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) showed 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 the central United States (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.

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). Coupled oceanic-atmospheric variations can occur at different time scales, from intra-annual to inter-annual, to decadal and inter-decadal (e.g., Tootle et al., 2005). Climate variability at these timescales is known as low frequency, as opposed to synoptic to seasonal climate variability which is commonly referred to as high frequency. Low frequency 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 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).

In this study, we examine the relationship between the frequency of flood 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 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), and the Pacific-North American pattern (PNA; e.g., Leathers et al., 1991). Each of the above-mentioned climate indices has the potential to describe certain spatial and temporal aspects of the climate variability.

There are 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 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 (i.e., 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 study.

The goal of our study is to examine whether there is any relationship between climate variability and the frequency of flooding over the central United States. If we can identify such a relationship as hypothesized above, 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 our 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, we have to keep in mind that 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” ones (e.g., Risko and Martinez, 2014). Kalra and Ahmad (2009) used ENSO, NAO, PDO and AMO for 3-year lead time streamflow forecasting over the Upper Colorado River Basin; they indicated that ENSO and NAO were the best set of climate indices for predicting annual streamflow over that region. Here we want 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.

The rest of this paper is organized as follows. In the next section, we describe the observational data (streamflow, precipitation) and the climate indices. In Section 3 we briefly describe the statistical methods we use to relate the frequency of flood and precipitation events to the different climate indices, with the corresponding results presented in Section 4. We summarize the major findings of this study and conclude this paper in Section 5.

2. Data

This study focuses on the central United States, which includes North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Illinois, West Virginia, Kentucky, Ohio, Indiana, and Michigan (Fig. 1a). We 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 (Fig. 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). Even though we focus 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. Analyses are done on four seasonal blocks (spring, summer, fall, and winter). Precipitation analyses are based on unified Gauge-Based daily observation data available from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) from 1948 to 2012 (Higgins et al., 2000). This daily product has a grid resolution of 0.25°.