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On the unseasonal flooding over the Central United States during December 2015 and January 2016

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A B S T R A C T

The unseasonal winter heavy rainfall and flooding that occurred during December 2015–January 2016 had large socio-economic impacts for the central United States. Here we examine the climatic conditions that led to the observed extreme precipitation, and compare and contrast them with the 1982/1983 and 2011/2012 winters. The large precipitation amounts associated with the 1982/1983 and 2015/2016 winter flooding were linked to the strongly positive North Atlantic Oscillation (NAO), with large moisture transported from the Gulf of Mexico. The anomalous upper-level trough in the 1982- and 2015- Decembers over the western United States was also favorable for strong precipitation by leading the cold front over the central United States. In contrast, the extremely positive NAO in December 2011 did not lead to heavy rainfall and flooding because the Azores High center shifted too far westward (like a blocking high) preventing moisture from moving towards the central and southeastern United States.

1. Introduction

The unseasonal 2015/2016 winter flooding along the Mississippi River had large societal and economic repercussions, with at least 50 fatalities due to the severe weather and flooding across the central United States and over one billion dollars in losses (NOAA, 2016; USGS, 2016). The flooding resulted from strong precipitation events with more than 500 mm of rain in the period from December 12 to December 31, 2015 (USGS, 2016). Much of the rainfall during this period was concentrated in two pulses (14–17 and 26–29 December 2015), with the second one that was stronger and longer lasting (Fig. 1). The first and second pulses are mainly caused by a stationary front and a cold front, respectively (NOAA, 2017). The daily precipitation during the two pulses was characterized by heavy precipitation over broad regions of the central and southeastern United States (Figs. S1–2). Fig. 2 shows the U.S. Geological Survey (USGS) stream gages which recorded an annual maximum daily discharge during December 2015 and January 2016. There are large areas of the central (Iowa, Missouri, Arkansas, Oklahoma, Illinois, Indiana, and Ohio) and southeastern United States (Alabama, Georgia, South Carolina, and Tennessee) which recorded annual maximum peaks during this period, with discharge values that were close or exceeded the record values in Missouri, Illinois, Arkansas, Tennessee, Mississippi and Louisiana (NOAA, 2016). In Missouri alone, there were 16 flood-related fatalities, and the City of St. Louis (Fig. 2b) and 37 counties were declared Federal Disaster Areas because of this flooding (NOAA, 2016; USGS, 2016). On 31 December 2015, due to the second pulse of rainfall (Fig. 1) the discharge for the Mississippi River at St. Louis (USGS 07010000) exceeded the major flood level established by the National Weather Service (Fig. 2b and Table S1) and was above the minor flood level for about two weeks. The goal of this work is to provide an understanding of the large-scale environmental conditions that led to these flood events.

Previous studies found that the North Atlantic Oscillation (NAO) and the Pacific-North American pattern (PNA) exerted large influence on the precipitation variability in the United States with regional characteristics, particularly for the winter season (e.g., Archambault et al., 2008; Coleman and Rogers, 2003; Henderson and Robinson, 1994; Hurrell, 2002; Hurrell and Deser, 2009; Leathers et al., 1991). NAO is a major large-scale climate mode of atmospheric variability over the extra-tropical Atlantic Ocean, and is characterized by a north-south dipole of sea-level pressure anomalies between the Icelandic Low and the Azores High (e.g., Barnston and Livezey, 1987; Hurrell et al., 2003; Lamb and Peppler, 1987; Myoung et al., 2015; Wallace and Gutzler, 1981; Wettstein and Mearns, 2002). NAO can modulate the climatology and extreme United States precipitation and temperature at different time scales, especially in the eastern United States (e.g., Archambault et al., 2008; Hurrell, 2002; Hurrell and Deser, 2009; Ning and Bradley, 2014, 2015). PNA consists of a 500-hPa planetary-scale wave train originating from the tropical Pacific and arching towards Florida (e.g., Leathers et al., 1991; Oliver, 2005; Wallace and Gutzler, 1981), and it is

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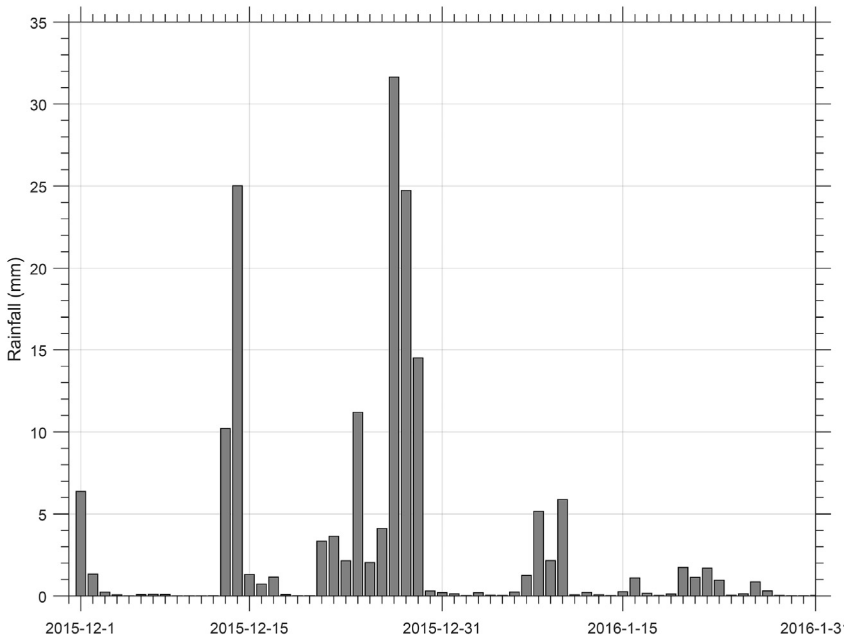

Fig. 1. The daily time series of rainfall averaged over the region (35°N–45°N, 100°W–85°W) from 1 December 2015 to 31 January 2016.

one of the most important climate modes influencing the weather and climate over the United States (e.g., Coleman and Rogers, 2003; Henderson and Robinson, 1994; Leathers et al., 1991). During the negative PNA phase, there are more and stronger rainfall events over the central United States, while the opposite is true for the positive PNA phase (e.g., Lavers and Villarini, 2013; Mallakpour and Villarini, 2016, 2017; Patricola et al., 2015; Nayak and Villarini, 2017).

While major flooding was observed along the Mississippi River and the central United States making headlines in numerous media outlets, another very wet winter occurred over this area in December 1982 (Stone and Bingham, 1991). Given these competing climate modes (i.e., NAO, PNA), we want to understand which one is the dominant one during these heavy precipitation and flood events. Improved understanding of the climate conditions associated with the 1982/1983 and 2015/2016 winter events can provide basic information critical to improve the predictability of these extremes.

2. Data

We use the daily precipitation data by the Climate Prediction Center (CPC) with has a 0.25° × 0.25° spatial resolution over the continental United States (Chen et al., 2008). NAO and PNA are calculated following the method discussed in Barnston and Livezey (1987) and are available from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml; http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna.shtml). The vertically integrated moisture flux, wind fields and geopotential height data are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA–Interim reanalysis available from 1979 to the present (Dee et al., 2011). Anomalies are defined as the departures from a long-term average (climatology).

3. Results

We focus our analyses of precipitation and relevant large-scale environmental conditions on December 2015 because it was the month with the largest amount of precipitation causing annual maximum discharge peaks over the central United States (Fig. 1). Fig. 3a shows the climatology of precipitation for the 1979–2010 Decembers, with over 300 mm of total precipitation in the eastern edge of Oklahoma, Alabama and northern Georgia. The precipitation anomalies in December 2015 feature three rainfall bands in the central and southeastern United States (Fig. 3b), consistent with what observed in terms of discharge (Fig. 2a). Panels c and d in Fig. 3 show the precipitation anomalies in December 1982 and 2011 when the NAO indices are extremely positive (Fig. 4), and highlight the differences in the rainfall amounts during those months.

To diagnose the physical mechanisms, we investigate the time series of December NAO, PNA and precipitation over the central United States precipitation (100°W–85°W, 35°N–45°N; Fig. 4). Previous studies have shown that the negative PNA is associated with large precipitation amount over the central United States (Leathers and Palecki, 1992; Leathers et al., 1991; Ning and Bradley, 2014). However, the PNA index in December 2015 is positive, suggesting that PNA should not be responsible for these extremely large precipitation amounts. NAO has a significant positive correlation with the precipitation amount in central United States for the period 1950–2015 (correlation coefficient of 0.37 significant at the 0.01 level based on *t*-test) (Fig. 4). Therefore, stronger (weaker) precipitation over the central United States is expected during the positive (negative) NAO phase. In December 2015, there was a strong NAO event, similar to that in December 1982, suggesting that the strong NAO events in the Decembers of 1982 and 2015 were partially responsible for the extremely heavy precipitation (Fig. 3, panels b and c) that caused the unseasonal flood events. Positive (negative) NAO is associated with a stronger (weaker) Azores High center over the western Atlantic, which tends to transport excessive (deficient) moisture from the Atlantic to the continental United States. Such moisture supply in winter plays a central role in modulating precipitation. In December 2011, there was an extremely strong NAO event, but the precipitation was much weaker than what observed in 1982 and 2015 (Figs. 3d and 4). Here we examine the moisture flux, geopotential height and wind fields anomalies in the Decembers of 1982, 2011 and 2015 to diagnose the physical mechanisms underlying the differences in precipitation over the central United States during these three years with large precipitation and/or NAO values.

The climatology of moisture flux in 1979–2010 and the anomalies in the Decembers of 1982, 2011 and 2015 are shown in Fig. 5. The moisture flux is vertically integrated between 1000 hPa and 300 hPa. Climatologically, the moisture transport to the continental United States in December occurs from the eastern Pacific by the subtropical jet stream and from the western Atlantic by the Azores High center (Fig. 5a), consistent with previous studies (e.g., Mo et al., 2005). In