Atmospheric Rivers and Flooding over the Central United States

DAVID A. LAVERS AND GABRIELE VILLARINI

IIHR–Hydroscience and Engineering, The University of Iowa, Iowa City, Iowa

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ABSTRACT

This paper undertakes a hydrometeorological analysis of flood events in the central United States. Vertically integrated horizontal water vapor transport over 1979–2011 is calculated in the ECMWF Interim Re-Analysis (ERA-Interim) and used in an algorithm to identify episodes of high moisture transport, or atmospheric rivers (ARs), over the central United States. The AR events are almost evenly divided among the seasons (143 during the winter, 144 during the spring, and 124 during the fall), with a minimum (40) during the summer. The annual maxima (AM) floods from 1105 basins over the period 1980–2011 are used as a measure of the hydrologic impact of the AR events. Of these basins, 470 (or 42.5%) had more than 50% of their AM floods linked to ARs. Furthermore, 660 of the 1105 basins (59.7%) had 5 or more of their top 10 AM floods related to ARs, indicating that ARs control the upper tail of the flood peak distribution over large portions of the study area. The seasonal composite average of mean sea level pressure anomalies associated with the ARs shows a trough located over the central United States and a ridge over the U.S. East Coast, leading to southerly winds and the advection of moisture over the study region. Based on the findings of this study, ARs are a major flood agent over the central United States.

1. Introduction

In recent years the central United States has experienced devastating flood events, with the summer floods of 1993 (e.g., Kunkel et al. 1994) and 2008 (e.g., Dirmeyer and Kinter 2009; Coleman and Budikova 2010; Mutel 2010; Smith et al. 2013) considered as the benchmark. Each of these events has large societal and economic impact. Estimated losses in the 1993 Midwest flood were $21 billion (all costs are given in U.S. dollars) and 48 fatalities, while the 2008 Midwest flooding caused $15 billion of damages and 24 fatalities (http://www.ncdc.noaa.gov/billions/). Given these events, and with projected climate change expected to lead to an intensification of the hydrological cycle and in particular hydrologic extremes (e.g., Held and Soden 2006; Allan and Soden 2008; O’Gorman and Schneider 2009), it is timely and necessary to assess the synoptic features of floods at a pan-central-U.S. scale to improve our hydrometeorological understanding of these events.

Over the central United States the highest rainfall rates occur during spring and summer (e.g., Dirmeyer and Kinter 2010; Villarini et al. 2011b), with most of the flood peaks occurring in the March–October period (e.g., Villarini et al. 2011a). Previous research has found three factors to be important in causing these extremes (Hu and Feng 2001, and references therein): 1) sea surface temperature (SST) anomalies in the tropical Pacific Ocean, 2) SST anomalies in the North Pacific Ocean, and 3) the Great Plains low-level jet (LLJ). It is during the spring and summer over the Great Plains of North America that the export of moisture from the tropics is at a maximum (Knippertz and Wernli 2010). Moisture is transported out of the Caribbean into the central United States by way of the northern branch of the Caribbean LLJ (Mestas-Nuñez et al. 2007), which then feeds into the Great Plains LLJ (Mestas-Nuñez et al. 2007; Dirmeyer and Kinter 2010). The linkage between the Great Plains LLJ and deep convection, and thus heavy precipitation and flooding in the central United States, has been known for some time (Higgins et al. 1997). The region of enhanced moisture transport within the LLJ is an atmospheric river (AR) colloquially named the “Maya Express” (Dirmeyer and Kinter 2009). The ARs feed moisture into regions of deep convection or mesoscale convective systems (MCSs; e.g., Anderson and Arritt 2001), with recent examples including May/June 2008 in the U.S. Midwest (Budikova et al. 2010;
Dirmeyer and Kinter 2009; Smith et al. 2013) and Tennessee in May 2010 (Moore et al. 2012). Previous research generally considers U.S. Midwest precipitation extremes only (e.g., Dirmeyer and Kinter 2010), without assessing the hydrologic impact; an exception to this is a recent study by Nakamura et al. (2013) in which a link was identified between ARs and floods in the Ohio River basin. Here we undertake a pan-central-U.S. study to investigate the strength of the link between ARs and floods, thus considering the next step in the hydrometeorological process chain. Analyses will build on previous efforts but expand to the identification of all ARs during 1979–2011 and the examination of their role as flood agents over the study area. This aim is achieved through three objectives: 1) to introduce an AR detection algorithm, based on vertically integrated horizontal water vapor transport (integrated vapor transport or IVT) using a gridded atmospheric reanalysis; 2) to compare the detected ARs with central U.S. flood occurrence; and 3) to evaluate the large-scale mean sea level pressure (MSLP) patterns that occur concurrently with the detected AR events.

2. Data and methods

The specific humidity, MSLP, and the zonal and meridional wind fields were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim, herein also called ERAIN) at a 0.7° × 0.7° resolution over 1979–2011 (Dee et al. 2011). Atmospheric reanalyses are considered to be a best estimate of the historical state of the earth’s atmosphere and are produced by assimilating meteorological/oceanic observations into numerical weather prediction (NWP) model output. The IVT was calculated from 1000 to 300 hPa in an Eulerian framework:

\[
\text{IVT} = \sqrt{\left( \frac{1}{g} \int_{1000}^{300} qu \, dp \right)^2 + \left( \frac{1}{g} \int_{1000}^{300} qv \, dp \right)^2},
\]

where \( q \) is the layer-averaged specific humidity in kg kg\(^{-1}\), \( u \) and \( v \) are the layer-averaged zonal and meridional winds in m s\(^{-1}\) respectively, \( g \) is the acceleration due to gravity, and \( dp \) is the pressure difference between two adjacent pressure levels.

The IVT fields were used in an algorithm to identify ARs impacting the central United States. Initially we determined a monthly varying IVT threshold as follows. At 1200 UTC on each day from 1979 to 2011 we extracted the maximum IVT between 85° and 100°W at 40.35°N and binned it into separate months. (We only selected the 1200 UTC time step to mitigate the effects of autocorrelation in the IVT, and the latitude of 40.35°N to ensure that the ARs penetrated deep into the central United States) As shown in Fig. 1, there is a clear seasonal cycle in the IVT values, with a maximum during the summer months. Following the results in Lavers et al. (2012) showing that the 85th percentile approximately corresponded to the IVT value of the most intense ARs, we use the 85th percentile of the IVT in each month as the threshold value for the identification of ARs (black circles in Fig. 1).

With an IVT threshold established, the following methodology was used at each 6-h time step in the ERAIN from 1979 to 2011. We calculated the IVT at grid points spanning 85° and 100°W along 40.35°N and retained the maximum IVT value. The next step was to search adjacent grid points next to 40.35°N (to the west/southwest/south/southeast) for the highest IVT. This was repeated until a total of 13 grid points were obtained (if 13 grids are taken due south of 40.35°N this would correspond to approximately 1000 km). If all points exceeded the monthly IVT threshold and the extracted grid points all occurred to the west of the 85°W meridian, then the time step was said to have an AR affecting the central United States. Moreover, only AR events that occurred for three or more time steps (18 h or more) were considered as potential flood-generating ARs (hereafter, the term AR refers to a persistent AR). Furthermore, to have independent events, two ARs were considered distinct only if they were separated by at least one day.

River basins across the central United States that had complete records of annual maxima (AM) floods for the water years of 1980–2011 were retrieved from the U.S. Geological Survey website. (The water year begins on 1 October and ends on 30 September. For example, 1980 refers to the water year of 1 October 1979–30 September 1980.) This resulted in 1105 stream gauge stations. The AM is a block maxima approach (e.g., Coles, 2001) that extracts the maximum river discharge value for each water year. We associated the AM flood with an AR if the flood occurred for three or more time steps (18 h or more) and reference adjacent grid points next to the AR.

3. Results

From 1 January 1979 to 31 December 2011 our algorithm detected 451 ARs. Figure 2 shows the IVT fields of two ARs detected by the algorithm: before the 1993 and 2008 extreme floods over the central United States. In both cases there is an AR present (as shown by the areas with heightened IVT values) that stretches for over
1000 km, with IVT values exceeding 1200 kg m$^{-1}$ s$^{-1}$ in the core of the ARs. At 0600 UTC 6 June 2008 a strong squall line was present near Cedar Rapids, Iowa (Budikova et al. 2010), and the concurrent IVT through the southern boundary of Iowa (96°–90°W at 40.35°N) was equivalent to more than 110 times the average flow of the Mississippi River at St. Louis, Missouri. The AR was located in a broader warm air mass and a cold front was situated to the west. A feature of many of the ARs that impact the central United States is a “horseshoe” IVT shape corresponding to a clockwise airflow around the subtropical (Bermuda) high pressure system (Fig. 2; see also Dirmeyer and Kinter 2010). Moisture is transported around the high pressure area over the Caribbean Sea and northward into the United States. Upon entering the United States, the moisture feeds into the Great Plains LLJ, in part causing the high IVT found over the study area.

The 1993 and 2008 flood events were not isolated cases of large floods caused by ARs. Figure 3 (left panels)
Fig. 3. (left) The number of AM floods in each season for water years 1980–2011 and (right) the number of AM in each season that are related to ARs given as a percentage.
shows the number of AM floods in each meteorological season. During winter [December–February (DJF)] there is a gradient in AM flood occurrence from the northwest to the southeast of the domain, with the northwest of the domain having relatively few AM floods. In general there are very few AM floods in the northern Midwest during DJF because 1) the rivers are often frozen, and 2) most precipitation falls as snow, causing a temporal disconnection between precipitation receipt and runoff. The vast majority of floods are confined to the spring [March–May (MAM)] and summer [June–August (JJA)] seasons. In MAM a high proportion of AM floods occur, especially in the Dakotas, Minnesota, Wisconsin, and northern Michigan, as a result of spring snowmelt. The region with the most AM floods shifts southward in JJA and is focused on Iowa, Kansas, and Nebraska. Finally, in September–November (SON) few AM floods are found, other than in the far south in Texas.

We examine the hydrologic impact of the identified ARs on floods in the central United States by determining how many of the AM floods occurred during the lifetime of an AR or up to seven days after the end of an AR. The right-hand panels of Fig. 3 show the percentage of the AM floods in a given season related to an AR with respect to the total number of AM floods in that season. In DJF the western areas of our study region have little impact of ARs on AM floods, but in the eastern regions, such as Ohio, there is a strong AR–AM link with some basins having more than 75% of their floods related to ARs (considering basins with greater than 11 floods only). In MAM there is a large AR impact on floods. Across a swath from northern Iowa/Minnesota to Lake Michigan many basins have more than 60% of their floods related to ARs; considering that some of these basins have more than two-thirds of their AM floods in MAM, this is a significant AR–AM link. The atmospheric pattern behind these results would relate to a warm sector, in which the AR is located, passing over the upper Midwest bringing warm temperatures resulting in snowmelt and possibly a rain-on-snow event, and thus a flood. In JJA the AR–AM link is weaker, but there are basins where up to 60% of the AM floods (considering basins with greater than 11 floods only) are related to ARs.

Figure 4 (top panel) displays the percentage of all AM floods that were related to an AR. A southwest–northeast-oriented line exists from the Oklahoma–Texas border to Michigan where the AR–AM link is frequently above 50%, with some basins having more than 70% of the peaks caused by ARs. The orientation of the southwest–northeast line is probably related to the most common path of ARs traveling across the central United States. This suggests that ARs have a significant role in central U.S. floods. Of the 1105 basins studied, 470 (or 42.5%) have more than 50% of their AM floods linked to ARs. To further highlight the strong AR–AM relationship, Fig. 4 (bottom panel) shows the number of the top 10 AM floods that are related to ARs in each basin. Along the aforementioned southwest–northeast line, the AR–AM link is very strong, with 6 or more of the top 10 events caused by ARs in many basins. In places such as Iowa, where the total AR–AM link is around 50% (Fig. 4a), ARs explain on average about half of the top 10 AM floods (Fig. 4 bottom panel). Therefore ARs are important flood agents over this part of the United States. Moreover, 660 of the 1105
basins (59.7%) have 5 or more of their top 10 AM floods related to ARs.

For each AR event we calculated the average MSLP (at each grid point) over its lifetime. We then calculated the MSLP anomaly pattern for that particular AR with respect to the same time period over the years 1979–2011. We then placed each MSLP anomaly field into seasonal bins and calculated a composite mean anomaly pattern for each season. The four seasonal plots are shown in Fig. 5. A striking trough (blue) and ridge (red) pattern is evident across the central United States and the North American East Coast, respectively. A similar trough–ridge pattern was found for central U.S. precipitation by Mo et al. (1997). The moisture transport within the ARs is situated in the southerly flow between these centers of action; note that this region is where the highest AR–AM relationships were found (Figs. 3 and 4).

In DJF and MAM during the lifetime of the AR events there is a signature of a positive phase of the North Atlantic Oscillation (NAO), as shown by the positive MSLP anomalies off the Iberian Peninsula and negative anomalies near Iceland. Positive pressure anomalies are also located to the south of Alaska in the Aleutian low region. These results provide the basic information on the atmospheric state during the occurrence of these events.

4. Conclusions

This study has investigated the relationship between ARs and floods in the central United States. In so doing we first introduced an algorithm to detect ARs in IVT fields across the study region and then linked the identified
ARs with 1) flood occurrence and 2) hemispheric MSLP patterns. We show that ARs are related to floods, with over 40% of the study basins having 50% of their AM floods associated with the identified ARs. A line with the strongest AR–AM relationship extends in a southwest–northeast direction from the Oklahoma–Texas border to the Great Lakes following the most common direction of AR propagation (as the ARs move around the high pressure system situated to the southeast). In nearly 60% of the basins five or more of the top 10 AM floods were related to ARs, suggesting that ARs control the upper tail of the flood peak distribution. Furthermore, the most extreme Midwest floods of 1993 and 2008 were shown to have had ARs occurring before them. The results of this study indicate that ARs can cause extensive flooding not only over the U.S. West Coast (e.g., Ralph et al. 2006; Neiman et al. 2011; Ralph and Dettinger 2012) and the United Kingdom (Lavers et al. 2011, 2012) but also over the central United States.

Hemispheric MSLP anomaly patterns revealed a trough–ridge structure over the central United States and the North American East Coast during periods of high moisture transport. The ARs were generally situated in the southerly/southwesterly flow between the trough–ridge pattern, which is where the highest AR–AM links occur (Figs. 3 and 4). A positive NAO signature was visible over the North Atlantic Ocean, especially in DJF and MAM. This is in contrast with Coleman and Budikova (2010), who found that the NAO was negative during the 1993 and 2008 flooding. Possible reasons for this discrepancy are that 1) our study has considered a seasonal composite mean of many more events and 2) we only analyze the MSLP fields for the lifetime of the ARs, and not continually through a flood episode. In fact the assessment of the daily NAO time series [see Fig. 11 in Coleman and Budikova (2010)] shows that during the strong AR that occurred on 6 June 2008 (Fig. 2 herein), the NAO was in a positive phase, which is in agreement with our results. Other modes of variability, such as the Pacific–North American (PNA) pattern, have also been connected with rainfall in the central United States. (Leathers et al. 1991; Coleman and Rogers, 2003). In Fig. 5 in DJF ARs are also associated with positive MSLP anomalies to the south of Alaska in the Aleutian low region and negative anomalies across the equatorial Pacific, suggesting a negative-type PNA pattern. Future research will develop further insights as to the influence of these and other teleconnection patterns on AR and floods over the central United States.

This study has improved the hydrometeorological understanding of flood events in the central United States by quantifying the relationship between ARs and floods. With this strong link between ARs and floods, it will be important to assess future projected changes to ARs to determine future risks from flooding over this area.

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