Floods over the U.S. Midwest: A Regional Water Cycle Perspective

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ABSTRACT

The characteristics of situations of extremely high rainfall over the midwestern region of the United States during late spring and summer are investigated from the perspective of the regional water cycle using observations and observationally based analyses. The period of May–July has the greatest mean rainfall rates of the year and higher interannual variability than the periods either before or after. This is also a critical time of year for water resources and cultivation schedules in this agriculturally important region. Large-scale floods during this time of year are usually characterized by an enhanced source of moisture evaporating from low latitudes, specifically the Caribbean Sea. This is part of a fetch of moisture that extends from the Caribbean northward along the coast of Central America, over the Yucatan Peninsula, along the east coast of Mexico and the western Gulf of Mexico, and over Texas, where it links into the Great Plains low-level jet. In fact, heavy rainfall over much of the eastern half of the United States is associated with above-average Caribbean moisture supply. There is also indication of an enhanced source of moisture from the subtropical Pacific during Midwest flood events. Drought events appear to have a different spatial pattern of water cycle variables and circulation anomalies, and are not simply equal and opposite manifestations of flood events. While not a dominant source of moisture even during extreme events, the Caribbean region seems to be part of an important link for remote moisture, supplying floods over the Midwest.

1. Introduction

Extremes in rainfall can cause problems anywhere, but they are particularly critical in agriculturally important regions. The U.S. Midwest is one such region. In the Midwest, both drought and flood can have perilous consequences for the cultivation of crops, river transportation, and the regional economy. Excessive rainfall can also hamper ground and air transportation, endanger low-lying communities, and create health hazards. Outstanding recent cases of large-scale midwestern flooding include those of late spring and summer of 1993 (Kunkel et al. 1994) and 2008 (Hoke 2009).

There have been many studies of the impacts of climatic extremes over the Midwest, particularly in the wake of the severe summer drought of 1988 and flood of 1993. Anderson et al. (2003) presented a compendium of regional modeling studies of the 1993 flood. The models consistently underforecast the intensity of the flooding, with most models limiting their domains to the contiguous United States and adjacent oceans. Pan et al. (2000) found that the large-scale anomalies in the circulation were critical for simulating the mesoscale conditions for flooding in a regional model. Giorgi et al. (1996) and Bosilovich and Sun (1999) also used regional models and found that nonlocal conditions appeared to be important for the 1993 floods. Beljaars et al. (1996) found that upstream land surface conditions over the southern Great Plains appeared to have made an important contribution to the 1993 floods. Trenberth and Guillemot (1996) found evidence for a connection between extreme precipitation cases over the central United States and both stationary wave patterns and moisture transport originating in the tropics. Cook and Vizy (2008) identified a low-level jet feature.
across the Caribbean Sea that exists year round, but only has a northward-turning branch during May–September. They failed to find a connection between this Caribbean jet and droughts in the Midwest, but Wang et al. (2007, 2008) found in modeling studies a connection linking circulation and rainfall anomalies to the intensity of the Atlantic warm pool on seasonal time scales. However, Dirmeyer and Brubaker (1999) found a connection between northward atmospheric moisture transport from the Caribbean region and the subseasonal Midwest floods during the summer of 1993. This finding was extended by Dirmeyer and Kinter (2009) to the floods of 2008, suggesting that a similar tropical moisture source supplied both of those major precipitation anomalies. Hwu et al. (1999) found that the representation of the meridional moisture flow in meteorological analyses were of vital importance for simulation of the 1993 flood.

These studies suggest there is something particular about flood situations over the central United States that connects this category of extreme events to the general circulation and the water cycle in the tropics. In this study, we examine the regional water cycle with a focus on extreme rainfall events over the Midwest. We look for dominant or systematic features of heavy rainfall events that characterize the apparent link between tropical moisture sources and midlatitude floods. Here, we use the term Midwest flood to denote a large positive rainfall anomaly over a large-scale area defined in section 3. Section 2 presents a description of the datasets used for this analysis. The characteristics of the regional water cycle for mean conditions and flood events are given in section 3, with some comparison to drought situations presented as well. A discussion of our results is presented in section 4.

2. Datasets

Although this paper presents a regional analysis, it is part of a global project to estimate the hydrologic connection through the atmosphere between precipitation over all terrestrial locations outside Antarctica, and the sources of evaporated moisture from the surface that supply that precipitation. Thus, global datasets are used in all cases.

Two gridded precipitation datasets are used in this study. Research-grade global pentad estimates are taken from the Global Precipitation Climatology Project (GPCP; Xie et al. 2003). Monthly data come from the GPCP version 2.1 Combined Precipitation Dataset (Adler et al. 2003). Soil moisture estimates are from the Climate Prediction Center’s (CPC) global soil moisture monitoring product (Fan and van den Dool 2004). There are other global soil moisture datasets besides the CPC product, but the reasonable quality of this data for water cycle applications was demonstrated by Dirmeyer et al. (2004) and Guo et al. (2007).

Estimates of the evaporative sources that are advected to locations where precipitation occurs come from the global datasets of Dirmeyer and Brubaker (2007). These are calculated using a back-trajectory tracer algorithm employing wind, moisture, and temperature data from the National Centers for Environmental Research–Department of Energy (NCEP–DOE) reanalysis (Kanamitsu et al. 2002).

For each observed precipitation event over land, a probability distribution of surface evaporation supplying that event is calculated, and results are aggregated across all events for each month over each land grid box. These data can also be used to produce estimates of precipitation recycling. The evaporative source dataset is on the same grid as the NCEP–DOE reanalysis. The precipitation and soil moisture data are interpolated to this reanalysis grid for the calculations in this paper.

Problems with reanalysis evaporation estimates are well known, and these issues were addressed in previous publications on this technique (e.g., Brubaker et al. 2001; Sudradjat et al. 2003; Dirmeyer and Brubaker 2007). Random errors have little effect on the calculation, while systematic errors will extend or retract the estimated fetch of moisture, uniformly affecting absolute estimates of recycling but having little effect on the estimates of relative changes or anomalies.

3. Climate characteristics

We focus on the northern U.S. Great Plains, specifically a region of five reanalysis grid boxes zonally by five grid boxes meridionally, as indicated in Fig. 1. This region was originally chosen because it represented the area most affected by the floods of 1993 and 2008, but we also find it to be representative of an area of relatively high precipitation variance. Figure 1 also shows the temporal standard deviation of the GPCP precipitation over most of North America from 1979 to 2007 using data at three different temporal resolutions. The calculation using the GPCP pentad data is performed over the period from 16 April to 3 August for each year (22 pentads). Monthly GPCP data from May through July are used for the other two calculations. In each case, the mean annual cycle is removed before standard deviations are calculated. For the pentad data, a centered 65-day running mean is applied to smooth the mean annual cycle.

At all three time scales, a tongue of high variance extends northward from the Gulf coast, suggesting that there is relatively high precipitation variability at these latitudes compared to elsewhere over the continent.
Our focus on May–July (MJJ) instead of a more traditional seasonal period is similarly dictated by the character of the floods in the region. Figure 2 shows the monthly mean and variance of precipitation over the box outlined in Fig. 1. The period of May–July includes the three wettest months of the year in this region. More importantly, this is a period of high interannual variance compared to the months immediately preceding and following this period. There is a secondary peak in variance during the last 3 months of the year, but it is weaker and not during as agriculturally important a time as the late spring to early summer period. This maximum in variance is a consequence of the tendency for extreme extended rainfall anomalies during this period.

In a random series, one would expect a sample of size $N$ to show $N/3$ positive local extrema and $N/3$ negative local extrema, higher or lower than the points on either side. Out of 308 months (January 1979–August 2004) of precipitation in our complete time series of moisture sources for the Midwest region, we expect about 103 each positive and negative extrema and actually find 99 positive and 98 negative. Thus, we have reduced the number of degrees of freedom in our significance calculations by 5% to account for this slight redness in the monthly time series.

The climatology of key water cycle variables and their extremes are shown in Fig. 3, with precipitation in the left column. The 29-yr mean monthly GPCP precipitation is shown in the middle panel of Fig. 3. The view has been expanded from Fig. 1 to show more of the surrounding oceans and extended southward into the tropics. There is a distinct local maximum in rainfall in excess of 4 mm day$^{-1}$ near the center of our region of interest, indicated by the red box. The mean rainfall begins to decrease as it approaches the western margin of the region. Above and below the center panel in Fig. 3 are shown the precipitation anomalies for the top and bottom 15% of all months in the sample—12 months in each composite. These may be thought of as flood and drought conditions. It is clear that the extreme wet and dry months for the upper Midwest are not equal and opposite. In

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**Fig. 1.** Temporal standard deviation of the precipitation anomalies (mm day$^{-1}$) during MJJ 1979–2007 using (top) pentad, (middle) monthly, and (bottom) 3-month means. Boxes outline the Great Plains flood region (solid) and the Caribbean Sea (dotted).

**Fig. 2.** Mean precipitation (bars) and interannual variance (connected points) for 1979–2007 over the area outline by the box in Fig. 1.
particular, the area to the southeast is anomalously dry in both situations. Wet conditions over the box are part of a broader pattern extending to the northwest and east. The driest months form an anomaly pattern that is much more circular in shape, with an extension to the southeast. These patterns are roughly consistent with those of Mo et al. (1997).

Soil wetness is shown in the right column of Fig. 3. The definitions of the wettest and driest 15% for soil wetness are based on precipitation, so the same months compose the extremes in both columns. The climatology for MJJ shows a gradient of soil wetness sweeping from high at the southeast corner of the box to low to the west. There is a clear contrast in the patterns of the soil wetness anomalies associated with the flood and drought months. Floods are characterized by a narrow arcing band of high soil moisture extending south of the box thousands of kilometers across eastern Mexico and Central America with positive anomalies over tropical South America. In the case of drought conditions, low soil moisture over the upper Midwest appears to be part of a diffuse pattern of dryness that covers a large fraction of North America. Examining the extreme months individually (not shown), there is noticeable variation in the soil moisture patterns among the driest months. On the other hand, of the flood months, 8 of the 12 show a well-defined trail of high soil moisture extending into Mexico.

The soil moisture pattern for wet conditions implies there may be a corresponding fetch of atmospheric moisture coming from the south as noted by Mestas-Nuñez et al. (2007). Figure 4 shows the evaporative moisture sources supplying rainfall over the Midwest region, exhibiting the MJJ climatology in the middle and the wettest and driest 15% of months above and below. The scales are in terms of the percentage of the total water mass evaporated from each grid cell that fell as rainfall over the outlined box. We use this normalized measure, instead of units of water mass, because there is such a large range between the total precipitation (and thus the total evaporative source) between floods and droughts. Visual comparison would be difficult otherwise. The size of the grid cells is apparent in the figures—slightly smaller than $2^\circ \times 2^\circ$. The sum of the climatology over all grid cells globally totals to 100%.

The climatological pattern shows that most of the moisture supplying rainfall over the Midwest region originates as evaporation nearby, predominantly within the area or to the west, southwest, or south, reflecting the predominant wind directions. The total percentage summed within the red box gives the recycling ratio, which
is the fraction of total rainfall that originated as evaporation within the same area, and is about 20%. There is a particularly long extension of evaporative source extending south to the western Gulf of Mexico and then southeastward over the Caribbean Sea. There is also a region of moisture source over the Pacific Ocean just off the west coast of North America. It was noted in Brubaker et al. (2001) that the Pacific climatological feature predominates during spring and is greatly reduced by July and the onset of the North American monsoon. We again see disparities between the patterns for the rainiest and driest months. During both extremes, there is below-average recycling evidenced by the predominance of brown and red colors over the northern part of the outlined box, but opposite signals over the southern part. During the driest months, there is insufficient moisture in the local (terrestrial) evaporation to support precipitation, while in the wettest months, as we will see, an external source of moisture is necessary to maintain high rainfall rates. For the driest months, there is a strong reduction in the oceanic sources of moisture and a relative increase in the proportion of terrestrial evaporation supplying what little rainfall exists over the region. Most of the terrestrial evaporation is to the south and southwest of the region. For the flood months, there is also an increase in evaporation over land to the southwest and west, but this region appears to be part of extended or enhanced areas of evaporation stretching from the main oceanic areas. In particular, there is evidence of a much stronger fetch of moisture from Texas, the western Gulf of Mexico, the Yucatan Peninsula, and the Caribbean. This region of augmented evaporative source lies on the western margin of the central tongue of moisture evident in the climatology. These characteristics were noted for the specific cases of the 1988 drought and 1993 flood by Dirmeyer and Brubaker (1999). We found no significant correlation between monthly rainfall anomalies over the Midwest region and sea surface temperatures anywhere over the globe, although there is some evidence that the Atlantic warm pool could have an impact on longer time scales (Wang et al. 2007). Figure 5 shows a scatter of the anomalies of the monthly recycling ratio over the Midwest box against precipitation anomalies over the same box. The connection between the heavy rainfall and reduced recycling is quite evident. The connection for dry conditions is a little more tenuous, as Fig. 4 and the discussion above suggest. Nevertheless, the anticorrelation is significant at $p = 0.002$. Triangles show the values for MJJ 2008, another season of extreme floods that lies outside the original analysis, but was examined by Dirmeyer and Kinter (2009). These points are not out of line with the 26-yr results (circles), but the anomaly in the recycling ratio was not significantly different from zero in 2 of the 3 months.

This result would seem to be in conflict with that of Bosilovich and Chern (2006). However, the discrepancy can be explained in terms of a difference in the moisture regime between their model climatology and the observations and reanalyses. Their study area includes the entire Mississippi River basin and is, thus, centered slightly west of ours. In addition, the GCM from which they calculate relationships between recycling and rainfall appears to have a dry bias over the Mississippi River basin (cf. their Fig. 2). Only during spring, in the far western part of the basin, is that model at or above the observed rainfall rates. In fact, warm dry biases and excess downward solar radiation are a common feature of GCMs (Dirmeyer et al. 2006). Calculating the correlation as in Fig. 5 with the Midwest box shifted west seven grid boxes ($13.125^\circ$) gives a strong positive correlation $r = 0.58$. This is characteristic of a soil-moisture-limited arid zone, which appears to extend too far eastward in the model of Bosilovich and Chern (2006).

The temporal correlation between the precipitation anomaly over the Midwest region and the fraction of the total moisture source supplying rainfall over the region
(not shown) reveals a long band of positive correlation with midwestern rainfall stretching from southern Texas across the Bay of Campeche, the Yucatan Peninsula, and covering all of the Caribbean Sea. There also appears to be a band from the Sonoran Desert–northern Sea of Cortez northwest along the coast of California to the Gulf of Alaska. Returning to Fig. 3, we see that this northwestern area is a minor contributor of moisture to the region, but the southern part may be associated with the fetches from the subtropical eastern North Pacific. Over land, there are several areas where the moisture source fraction is anticorrelated with rainfall over the box. Most prominent is a large area of the southeastern United States. When correlations are calculated separately for positive and negative precipitation anomalies only, we find that the positive correlation areas are solely associated with the wet events, consistent with Fig. 4. The northwestern area of the correlation loses prominence, but the one to the southwest remains. For the dry cases, we find a single region of negative correlation over the southeast United States, which in fact means an enhanced fraction of the evaporative source from the this region during dry conditions.

Moisture from the region of the Caribbean Sea, which we define as the area outlined by the dotted line in Fig. 1, is not only important to rainfall in the Midwest. Figure 6 shows the correlation between monthly rainfall anomalies at grid points over much of North America, and the anomalous source of evaporated moisture to the corresponding grid point from the Caribbean Sea. Shading indicates the significance level of the correlation. Much of the United States east of about 97°W shows a significant positive correlation. There are especially significant correlations over the upper Mississippi River Basin, a band along the Gulf coast and northeast over the Appalachian Mountains to the Mason–Dixon line, and also over southern Florida. West of 97°W, there are few points with strong significant correlation, indicating...

**FIG. 5.** Scatter of monthly anomalies of recycling ratio vs rainfall anomaly over the Midwest box during MJJ 1979–2004. Dashed line is a best-fit linear regression through the points, and the correlation is shown at the top of the graph. Dark circles represent the wettest 15% of months. Triangles are for MJJ 2008 and do not contribute to the best-fit line.

**FIG. 6.** Correlation between the monthly local precipitation anomaly in each grid box and the anomalous evaporative moisture source to that grid box from the Caribbean Sea during MJJ 1979–2004. Shading indicates the significance level.
a sharp divide between regions that do and do not have access to this tropical oceanic moisture source. A fetch of Caribbean moisture carried over the eastern United States is consistent with the circulation around the Atlantic subtropical ridge, particularly when it is either unusually strong or displaced anomalously toward the west.

Figure 7 shows a scatterplot of the two terms used to calculate the correlations in Fig. 6, but averaged for each month over the area outlined in the box. The positive correlation is evident. The 5 wettest months in terms of rainfall all show anomalously high sources of Caribbean moisture, and 11 of the 12 months with the highest proportions of Caribbean moisture show positive precipitation anomalies. Most outstanding is the point representing July 1993, highlighted in the upper-right portion of Fig. 7. This month has by far the largest precipitation anomaly and the largest percentage contribution of evaporated moisture from the Caribbean Sea. However, removing this outlier only reduces the correlation to 0.52, which is still significant at a chance likelihood of less than 1:400 000. These analyses show a strong connection between tropical Caribbean moisture and the heaviest precipitation events over the Midwest during late spring and summer.

An analysis of individual cases with large monthly rainfall anomalies shows that while each case is different, there tend to be common large-scale features associated with heavy rain events over much of the Midwest as well as many flood cases over the lower Mississippi River basin. Cohesive regions of large positive rainfall anomalies typically are paired with larger areas of rainfall deficits of at least 1 mm day$^{-1}$ immediately to the south or southeast. There is typically an area of anomalously low evaporative moisture source to the south of the flood area, corresponding to a greater or lesser degree to the drought region. To the south of that, typically over the subtropics or Caribbean Sea, is an area of enhanced moisture source, often penetrating northward on the western margin of the drought area.

Examining the flood cases further, we find that, for the top 15% of cases (12 months) based on rainfall over the box of interest, there are characteristics that are nearly universal but that fade quickly as we look farther down the ranked list. Figure 8 shows the precipitation and moisture source anomalies for these cases. Nearly all of the 12 flood cases exhibit an area of anomalously dry conditions to the southeast, with the two regions separated by a clear partition running southwest–northeast, like that seen in the composite in Fig. 3. There is also a band of evaporative source stretching south then southeast from the region in most cases, (marked by red arcs) like that seen in the Fig. 4 composite. Ten of the wettest cases also show an anomalous supply from the Pacific Ocean southwest of the coast of California, although this feature is usually much weaker than the western Gulf–Caribbean source. Local recycling is often suppressed (indicated by dominant brown colors over the red box in Fig. 8), and usually neighboring terrestrial moisture sources are also supplying a reduced fraction of the total moisture.

Perhaps more striking about Fig. 8 is the variability in precipitation and moisture source patterns from case to case. The composites in Figs. 3 and 4 clearly filter out much of the "noise." Nevertheless, the moisture patterns
largely correspond to regions previously identified as having significant climatological remote moisture-source contributions to the precipitation, as well as a minimum in the local evaporation contributions, during this time of year (Dirmeyer and Brubaker 2007; Anderson et al. 2009).

Table 1 shows some key statistics for these 12 cases, which are listed, like Fig. 8, in order from the largest rainfall anomaly down. As evident in the scatterplots in Figs. 5 and 7, the sign of the associated anomalies in recycling and the Caribbean moisture source are consistent with the large rainfall anomalies, but certainly do not always fall into rank with the rainfall anomaly. Ten of 12 cases have an above-average proportion of moisture from the Caribbean Sea, while all of the 12 months as well as 1 of the 2 wet months from 2008 have negative anomalies in the recycling ratio.

4. Discussion

We have identified characteristics of the heaviest rainfall events over the midwestern United States during the late spring and early summer (May–July), the period of highest mean rainfall and high variability. The spatial patterns of rainfall and their associated components of the water cycle show that extreme cases of flood and drought are not mirror images of one another. Flood cases are often associated with an anomalous transport of moisture from the subtropics or tropics, originating as evaporation from the Gulf of Mexico, eastern Mexico, or, in particular, the Caribbean Sea.

There are also asymmetries in the regional soil moisture and circulation that suggest “wet minus dry” or “dry minus wet” composites may not be useful for understanding the water cycle processes in this region. Both extreme wet and dry months over the Midwest are typically characterized by below-average recycling ratios—the fraction of precipitation originating as surface evaporation from the same location. In the case of high rainfall, this is a result of the proportionally larger importation of moisture from the subtropics and tropics compared to normal conditions. For droughts, the local lack of soil moisture and evaporation reduces the recycling ratio. Droughts are also characterized by more proximate and limited sources of moisture from the surrounding land areas. Floods tend to tap moisture evaporating from open seas.

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Fig. 8. Precipitation and evaporative moisture source anomalies for the 12 months during MJJ 1979–2004 with the greatest rainfall anomaly within the red box. Panels are ordered as in Table 1.
Table 1. The 12 wettest months from MJJ 1979–2004 over the box bounded by 36.19°–45.7135°N, 96.5625°–187.1875°W, and their associated anomalies in precipitation, recycling ratio, and Caribbean evaporative moisture source. Also shown are the averages across the 12 wettest months, and the values for June and July 2008.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date</th>
<th>Precipitation anomaly (mm day⁻¹)</th>
<th>Recycling ratio anomaly (%)</th>
<th>Caribbean source anomaly (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>July 1993</td>
<td>+3.31</td>
<td>−4.1</td>
<td>+12.3</td>
</tr>
<tr>
<td>2</td>
<td>July 1992</td>
<td>+2.64</td>
<td>−6.5</td>
<td>+1.7</td>
</tr>
<tr>
<td>3</td>
<td>May 1995</td>
<td>+2.45</td>
<td>−1.1</td>
<td>−0.4</td>
</tr>
<tr>
<td>4</td>
<td>June 1998</td>
<td>+2.24</td>
<td>−3.3</td>
<td>+2.2</td>
</tr>
<tr>
<td>5</td>
<td>June 1993</td>
<td>+2.18</td>
<td>−2.1</td>
<td>+3.0</td>
</tr>
<tr>
<td>6</td>
<td>June 2000</td>
<td>+2.12</td>
<td>−6.8</td>
<td>+5.4</td>
</tr>
<tr>
<td>7</td>
<td>May 1990</td>
<td>+2.05</td>
<td>−3.4</td>
<td>+0.8</td>
</tr>
<tr>
<td>8</td>
<td>May 2004</td>
<td>+1.80</td>
<td>−6.4</td>
<td>+3.1</td>
</tr>
<tr>
<td>9</td>
<td>June 1990</td>
<td>+1.57</td>
<td>−4.3</td>
<td>+0.8</td>
</tr>
<tr>
<td>10</td>
<td>May 1996</td>
<td>+1.56</td>
<td>−9.2</td>
<td>+0.8</td>
</tr>
<tr>
<td>11</td>
<td>May 1982</td>
<td>+1.34</td>
<td>−2.7</td>
<td>−0.3</td>
</tr>
<tr>
<td>12</td>
<td>June 1981</td>
<td>+1.29</td>
<td>−9.8</td>
<td>+2.5</td>
</tr>
<tr>
<td>Avg</td>
<td></td>
<td>+2.05</td>
<td>−5.0</td>
<td>+2.7</td>
</tr>
<tr>
<td>June 2008</td>
<td>+2.08</td>
<td>−3.7</td>
<td>+7.7</td>
<td></td>
</tr>
<tr>
<td>July 2008</td>
<td>+1.41</td>
<td>+0.5</td>
<td>+4.4</td>
<td></td>
</tr>
</tbody>
</table>

Flood events are particularly well correlated with an arcing pattern of moisture sources extending southward through Texas, the western Gulf of Mexico and eastern Mexico, the Atlantic coast of Central America, and the Caribbean Sea. This fetch of moisture, termed the Maya Express (Dirmeyer and Kinter 2009), is analogous to the Pineapple Express that brings moisture to the California coast from the oceans around Hawaii during wet winters. It appears to be related to the clockwise circulation around the Atlantic subtropical ridge during times when the ridge is either stronger than normal or displaced to the west (e.g., Wang et al. 2007, 2008). During these heavy rainfall events, this fetch of Caribbean moisture links into the Great Plains low-level jet, creating a much longer “atmospheric river” of moisture. Note that the period from May to July is not dominated by intense tropical cyclone activity; the low-latitude moisture is mainly carried northward into the Midwest by the general circulation during this time of year.

These results suggest there is a systemic feature common to most of the highest rainfall events over the Midwest—a change in the regional water cycle that brings enhanced moisture transport from regions of the inter-American Seas in the subtropics and tropics to the south of the Mississippi River basin. Figure 6 suggests that a large part of the eastern United States is hydrologically linked to the Caribbean Sea during heavy rainfall events, whereas the western Great Plains, including much of the area under and to the west of the climatological low-level jet, is not. Yet Fig. 4 suggests the low-level jet is indeed the conduit, and individual cases in Fig. 8 show a signature of how the atmospheric branch of the hydrologic cycle in the Caribbean can bring flooding moisture to the study region. This is consistent with the idea of an enhanced anticyclonic circulation feature associated with flooding, and not merely an intensification of a linear jet feature.

To determine the total anomalous contributions from various areas, one must sum up the values shown in Fig. 4 over all the grid boxes in each area. Doing that, we find, for the 15% wettest cases, the contribution from the Caribbean region increases from about 2.5% of the moisture falling as rain over the Midwest box to about 5.2%, more than a doubling. The Gulf of Mexico increases from 5.6% to 7.1%, an absolute increase of 1.5% but only a fractional increase of about a quarter. From land areas of Mexico and Central America, there is an increase from 3.8% to 5.8%. The recycling ratio drops from 20% to 15%.

If one is looking to define “important” regions as those with a dominant percentage contribution, then the Caribbean is not important. Neither is the Gulf of Mexico, nor is any single region. From the central panel in Fig. 4, it is clear that a very large box needs to be drawn to encompass half of the color, for instance. The nearby terrestrial sources are the main contributors. However, the evaporation rates there cannot support floods, as evidenced by the brown shading in the top panel in Fig. 4 that corresponds so well to the dark blue area in the central panel. Rather, the way to look at this is in the same way as for the Pineapple Express, which brings winter floods to the West Coast. Impressive atmospheric rivers are seen in water vapor imagery trailing all the way to the longitude of the Hawaiian Islands, but a calculation of the evaporative moisture sources will show that, still, the main supply is from immediately offshore and decreases with distance from the coast.

It is natural to wonder whether there may be a predictable component—identifiable precursors to Midwest floods that could give probabilistic warnings at least a couple of weeks in advance if not longer—on the subseasonal time scale. This is a topic for future research, although previous research has suggested there may significant relationships in sea surface temperatures on seasonal time scales (e.g., Wang et al. 2008). Nevertheless, it is clear that extreme large-scale flooding over the central United States is typically not a local or even a regional phenomenon, but part of a large-scale circulation change that bridges the water cycle of the tropics and midlatitudes. It also represents a critical link between weather and climate time and space scales (e.g., Ralph et al. 2004). This could be a critical mechanism for better understanding, as Cook et al. (2008) find that this circulation feature is likely to become more common in a warming climate.
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