Flooding associated with predecessor rain events over the Midwest United States

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Received 7 February 2013
Accepted for publication 26 March 2013
Published 11 April 2013
Online at stacks.iop.org/ERL/8/024007

Abstract

This paper examines the severity and extent of flooding caused by six predecessor rain events (PREs) over the Midwest United States. PREs are areas of heavy rainfall that occur about 1000 km ahead of landfalling tropical cyclones. While recent studies have mostly focused on the synoptic conditions associated with PREs, little is known about the hydrologic impacts of these events.

Here, we use discharge data collected by the US Geological Survey to perform flood analyses at the regional scale. We first examine the number of stations at which a PRE caused an annual maximum flood peak. We then compute the flood ratio, defined as the ratio between the flood peak magnitude caused by the PRE and the at-site, expected 10 year flood peak magnitude. These results indicate that PREs are responsible for significant flooding over the Midwest United States, including highly populated areas like Chicago, Illinois and Detroit, Michigan.

Keywords: predecessor rainfall, flooding, Midwest US, precipitation

Online supplementary data available from stacks.iop.org/ERL/8/024007/mmedia

1. Introduction

Predecessor rain events (PREs), first described by Cote (2007), are mesoscale and sub-synoptic systems that produce heavy rainfall in excess of 100 mm d\(^{-1}\), typically located approximately 1000 km ahead of landfalling tropical cyclones (TCs). PREs develop in the equatorward entrance region of upper-tropospheric jet streaks with moisture that is advected poleward from the TC itself via a low-level jet (Bosart et al 2012). The amount of rainfall contributed by a PRE is likely to cause flooding in affected areas. If the TC itself tracks over the same vicinity as the PRE, flooding concerns escalate. As Galarneau et al (2010), hereafter ‘G10’ showed, a PRE associated with Tropical Storm Erin (2007) produced heavy rainfall in excess of 300 mm in southeastern Minnesota, with the center of circulation of the storm sitting over Oklahoma (see also Schumacher et al 2011; Schumacher and Galarneau 2012).

In Cote (2007), 47 PREs were documented in 21 TCs in the Atlantic, Caribbean, and Gulf of Mexico basins from 1998 to 2006. To be defined a PRE, it needed to be located poleward of the main body of the TC, and needed to produce rainfall rates in excess of 100 mm d\(^{-1}\). G10 expanded the study by Cote (2007) by including all TCs through 2008 east of the Rocky Mountains, and analyzed the first PRE of each TC. Finally, G10 required there be clear separation between the PRE and the main TC rain shield, and evidence that moisture from the TC is advected into the vicinity of the PRE. The combined analysis by Cote (2007) and G10 yielded 28 TCs that produced a PRE between 1995 and 2008 (consult Moore et al 2013 for an updated list). It is worth mentioning that additional studies have also shown that PREs are not unique to the United States (e.g., Wang et al 2009; Byun and Lee 2012; Meng and Zhang 2012).

Freshwater floods associated with TCs are responsible for large economic and societal repercussions (e.g., Rappaport
of the absolute discharge to the basin drainage area. A flood own historical record and takes into account the dependence ratio helps to normalize each individual stream gauge to its maximum peak flow of affected gauges from affected by a PRE event, we use discharge measurements from such as changes in land use/land cover or construction of distributions due to human modifications of these catchments, (figure 1) with at least 20 annual maximum flood peaks distribution) for all the stations within the area of PRE rainfall—maximum instantaneous flow within seven days of the PRE to the 10 year flow—is also calculated for each PRE to provide a regional perspective (figure 2). These results indicate that these events are responsible for flooding over large areas of the Midwest United States. The PRE of Hurricane Ike caused a large area of flooding to occur with stream gauges from Oklahoma to Michigan responding with a flood ratio of at least 0.75. TC Erin’s PRE also caused a number of stream gauges throughout southeastern Minnesota and southern Wisconsin to experience a flood ratio of at least 0.75. The break-down of gauges that exceeded different flood ratio thresholds is listed in table 1. It is important to note the gauge density wildly varies from state to state and even within different regions of the same state.

Comparing the 48 h precipitation to the flood ratio maps, the heaviest precipitation of each event generally fell in the same location where the most severe flooding occurred. This is expected because of the strong relation between rainfall and flooding. These results, however, also indicate that rainfall is not necessarily a good proxy for discharge because of the dependence of discharge on soil moisture conditions and land use/land cover. The largest flooding (both in terms of spatial extent and magnitude) was caused by Erin and Ike (figures 1 and 2, table 1). Hurricane Ike shows a very distinct area of heavy precipitation from Wichita, Kansas to Chicago, Illinois to Detroit, Michigan, which is where the highest flood ratios appeared. These results indicate that PREs can cause large flooding in highly populated areas of the Midwest United States.

3. Results

Figure 1 shows the 48 h storm total rainfall for the PREs that affected portions of the Midwest United States. Of these six TCs, two—Rita and Erin—produced significant precipitation for areas as far north as southern Minnesota, where storm total precipitation exceeded 200 and 300 mm, respectively. The remaining four PREs were south of Minnesota and precipitation maxed out around 200 mm for each system. The exception is TC Lili whose total PRE precipitation was less than the other five TCs. For some of these events, there is a clear separation between the track of the storm and the heavy rainfall region (e.g., Erin; figure 1(e)), while in other cases, the TC tracks near the area where the PRE just occurred (e.g., Ike; figure 1(f)). Not only are these events responsible for heavy rainfall over the Midwest United States, but they also cause extensive flooding. As shown in figure 1, there are numerous stations recording an annual maximum peak discharge in the areas affected by the PREs, matching the areas with the largest storm total rainfall. These results indicate that PREs are responsible for flooding over areas as north as southern Minnesota, Wisconsin, Iowa and Illinois. The flood ratio—maximum instantaneous flow within seven days of the PRE to the 10 year flow—is also calculated for each PRE to provide a regional perspective (figure 2). These results indicate that these events are responsible for flooding over large areas of the Midwest United States.
Figure 1. Maps showing the Stage IV 48 h PRE precipitation totals (mm) for (a) Lili (from 1 October (12 UTC) 2002 to 3 October (11 UTC) 2002). (b) Grace (from 30 August (00 UTC) 2003 to 31 August (23 UTC) 2003). (c) Matthew (from 6 October (18 UTC) 2004 to 8 October (17 UTC) 2004). (d) Rita (from 24 September (00 UTC) 2005 to 25 September (23 UTC) 2005). (e) Erin (18 August (00 UTC) 2007 to 19 August (23 UTC) 2007), and (f) Ike (from 12 September (06 UTC) 2008 to 14 September (05 UTC) 2008). The black line represents the path of the TC. The black dots indicate stream gauges that recorded an annual maximum peak during their respective water year within a week of the PRE. The gray dots signify stations that did not record an annual maximum within a week of the PRE. If data for a grid space was missing for any hour, the 48 h summation was removed to missing.

Similar conclusions hold for Erin with both the heaviest precipitation and most severe flooding occurring in southeastern Minnesota. Note that it is likely that some of the flooding from Ike represents a mix between the PRE’s and the hurricane’s contributions, given the tracking of this storm. In general, all these storms caused flooding
close to the 10 year event over large regions of the Midwest United States, highlighting the importance of PREs as flood agent over this area. Note that a flood ratio of 1.5 or 2.0 does not reflect a 15 or 20 year flood, but rather a flood whose peak flow is 1.5 or 2.0 times higher than the flow of a 10 year flood.

4. Summary and discussion

We have examined the magnitude and extent of flooding caused by predecessor rain (PRE) events associated with landfalling TCs over the Midwest United States. The main findings of this work can be summarized as follows:
(1) PREs associated with six TCs over the period 2002–8 (Hurricane Lili in 2002, Tropical Storm Grace in 2003, Tropical Storm Matthew in 2004, Hurricane Rita in 2005, Tropical Storm Erin in 2007, and Hurricane Ike in 2008) caused heavy rainfall over the Midwest United States.

(2) PREs caused annual maximum flood peaks at numerous stream gauges.

(3) The ratio between the flood peak caused by each PRE and the local 10 year flood peak is used to perform flood analyses at the regional scale. Results indicate that flooding from PREs can affect large areas. Moreover, there is a significant spatially coherent structure associated with these events related to the nature of the rainfall processes. There are also local differences due to differences in land use/land cover and soil moisture conditions. Four of the six PREs caused flooding equivalent to a 10 year flood at least at one of the stream gauges.

(4) Ike and Erin were responsible for the largest flood events (both in terms of magnitude and spatial extent). These results also highlight the role played by PREs as flood agents in highly urbanized areas, such as Chicago and Detroit.

Acknowledgment

The authors acknowledge funding by the Iowa Flood Center, IIHR–Hydroscience & Engineering.

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Table 1. Percentage (number) of gauges with 10 year flood ratios exceeding various thresholds for each of the six PRE events. It is important to note that some gauging stations themselves that were not affected by a PRE—but are within a state that was—are reported in the totals column. In addition, the gauge density wildly varies from state to state and even within different regions of the same state.

| Tropical cyclone | Flood ratio threshold | 0.01 | 0.10 | 0.25 | 0.50 | 0.75 | 1.00 | 2.00 | Total |
|------------------|-----------------------|------|------|------|------|------|------|------|------|
| Lili             | 64.8% (430)           | 29.8% (198) | 10.8% (72) | 2.3% (15) | 0.2% (1) | 0.2% (1) | 0% (0) | 664 |
| Grace            | 66.4% (225)           | 30.7% (104) | 12.4% (42) | 2.1% (7) | 0.3% (1) | 0.3% (1) | 0% (0) | 339 |
| Matthew          | 55.2% (279)           | 13.9% (70) | 3.2% (16) | 0.4% (2) | 0% (0) | 0% (0) | 0% (0) | 505 |
| Rita             | 65.3% (480)           | 22.0% (162) | 5.6% (41) | 1.5% (11) | 0.1% (1) | 0% (0) | 0% (0) | 735 |
| Erin             | 75.6% (767)           | 47.4% (481) | 31.2% (316) | 16.3% (165) | 7.4% (75) | 2.3% (23) | 0.1% (1) | 1014 |
| Ike              | 85.8% (851)           | 53.9% (535) | 37.1% (368) | 22.9% (227) | 15.0% (149) | 6.4% (63) | 0.1% (1) | 992 |

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