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The changing nature of flooding across the central United States

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In the twentieth and twenty-first centuries, flooding has taken a devastating societal and economic toll on the central United States, contributing to dozens of fatalities and causing billions of dollars in damage[1,2]. As a warmer atmosphere can hold more moisture (the Clausius–Clapeyron relation), a pronounced increase in intense rainfall events is included in models of future climate[3]. Therefore, it is crucial to examine whether the magnitude and/or frequency of flood events is remaining constant or has been changing over recent decades. If either or both of these attributes have changed over time, it is imperative that we understand the underlying mechanisms that are responsible. Here, we show that while observational records (774 stream gauge stations) from the central United States present limited evidence of significant changes in the magnitude of floodpeaks, strong evidence points to an increasing frequency of flooding. These changes in flood hydrology result from changes in both seasonal rainfall and temperature across this region.

Over the past century, the central United States (CUS) has been plagued by a series of large floods such as those that occurred in 1993, 2008, 2011, 2013 and 2014. These events had adverse societal consequences including decreased food production and displacement of communities/people, led to economic losses reaching billions of dollars[1,2], and portend future increases in flood activity. However, the question remains: is the character of recent flooding truly distinct from the long-term averages, or is it simply an artefact of our relatively short collective memory?

Use of historical records to ascertain change over time globally has thus far proved inconclusive. The Intergovernmental Panel on Climate Change[4] concluded that 'there continues to be a lack of evidence and thus low confidence regarding the sign of trend in the magnitude and/or frequency of floods at a global scale.' A number of observational studies that examined changes in the magnitude of annual maximum peak discharge over the CUS (refs 5–8) reached similar conclusions. The lack of evidence for an increase in peak discharge becomes even clearer when examining trends in the magnitude of the annual maximum daily discharge data for 774 US Geological Survey (USGS) stream gauge stations across the CUS over the common 1962–2011 time period (Fig. 1a; consult Methods for more information on how the analyses are performed). Over most of the study area, no statistically significant trends are identified; annual peak discharge magnitude has apparently not been increasing over most of the twentieth and early twenty-first centuries. Overall, 158 (20%) of these stations exhibit statistically significant changes in the magnitude of flood peaks, and of these, 101 (13% of the total number) are characterized by a trend towards increasing flood magnitude, with many of them concentrated in the greater Chicago area. These results are consistent with previous studies[5,7–10], which also failed to detect widespread evidence of changing flood magnitude over the CUS.

The results change markedly, however, when we use a peaks-over-threshold (POT) approach, in which we select discharge values exceeding a threshold that gives us two events per year on average (see Methods for more details), to examine changes in the number of flood events. As shown in Fig. 1b, when analysed in this manner, the frequency of flood events has been changing over much of the CUS, with spatially contiguous regional changes. Overall, 264 (34%) of the stations reflect an increasing frequency in the number of flood events, and 66 (9%) show decreasing trends. Note in particular the region of increased flood frequency that ranges from North Dakota south to Iowa and Missouri and east into Illinois, Indiana and Ohio. This swath is bordered to the southwest (Kansas and Nebraska) and to the northeast (northern Minnesota, Wisconsin and Michigan) by areas with decreasing flood frequencies. Overall, our analysis reveals that the largest flood peaks have not been strongly increasing in this broad belt of the CUS, but, rather, the region has been experiencing a greater number of flood events (Fig. 1). This more widespread increasing frequency in flood events defined as we have done here for POT is even more apparent when viewed in the context of a subset of 'pristine' stream gauging stations from ref. 11 for which no change in magnitude was found (Supplementary Fig. 1).

We have also examined changes in flood frequency and magnitude at the seasonal scale (Fig. 2). During the spring and summer seasons (which represent the period of the year with the largest fraction of flood events over most of the study region; Supplementary Fig. 3), 46 (6%) of the stations present statistically significant increasing trends in the spring, and 227 (30%) occur in summer. These high numbers are driven by the stations in the eastern part of our study region, which is also an area with minimal summer contribution to the total seasonality (Supplementary Fig. 3B). However, increases in the frequency of flood events in spring and summer (Fig. 2e,f) closely resemble the corresponding results at the annual scale (Fig. 1), with 138 (215) of the stations reporting statistically significant changes in spring (summer). These results are particularly relevant because of the geographic regions in which these trends are found with relation to the seasonality of flooding (Supplementary Fig. 3E,F). Autumn and winter, on the other hand, exhibit a more muted signal compared with spring and summer (Fig. 2), particularly in regions with minimal contributions to the flood seasonality (Supplementary Fig. 3C,D,G,H).

Our results, therefore, indicate significant increases in the frequency but not in the magnitude of historic flood events in the CUS. Here, we address the origins of these changes. Secular changes in regional flooding behaviour reflect the integration of climate, stream dynamics and watershed characteristics. We begin by examining the changes in heavy rainfall at the annual scale (Fig. 3). As in our analyses performed for flood events

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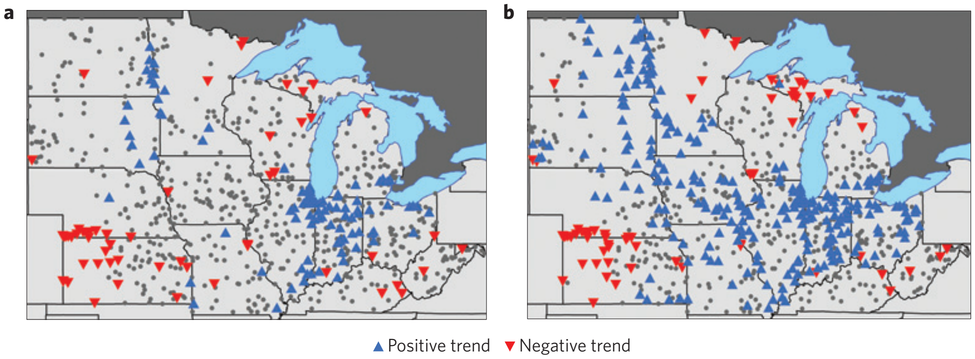

Figure 1 | Trends in the magnitude and frequency of flood events at the annual scale. a,**b**, Maps summarizing the results for trends in the magnitude (**a**) and frequency (**b**) of flood events. The blue (red) triangles indicate the location of the stations with increasing (decreasing) trends at the 5% level. There are 264 (101) stations with increasing trends in frequency (magnitude) and 66 (57) stations with decreasing trends in frequency (magnitude). The grey circles refer to the location of the stations that did not experience statistically significant changes (at the 5% level). These results refer to the common 1962–2011 time period.

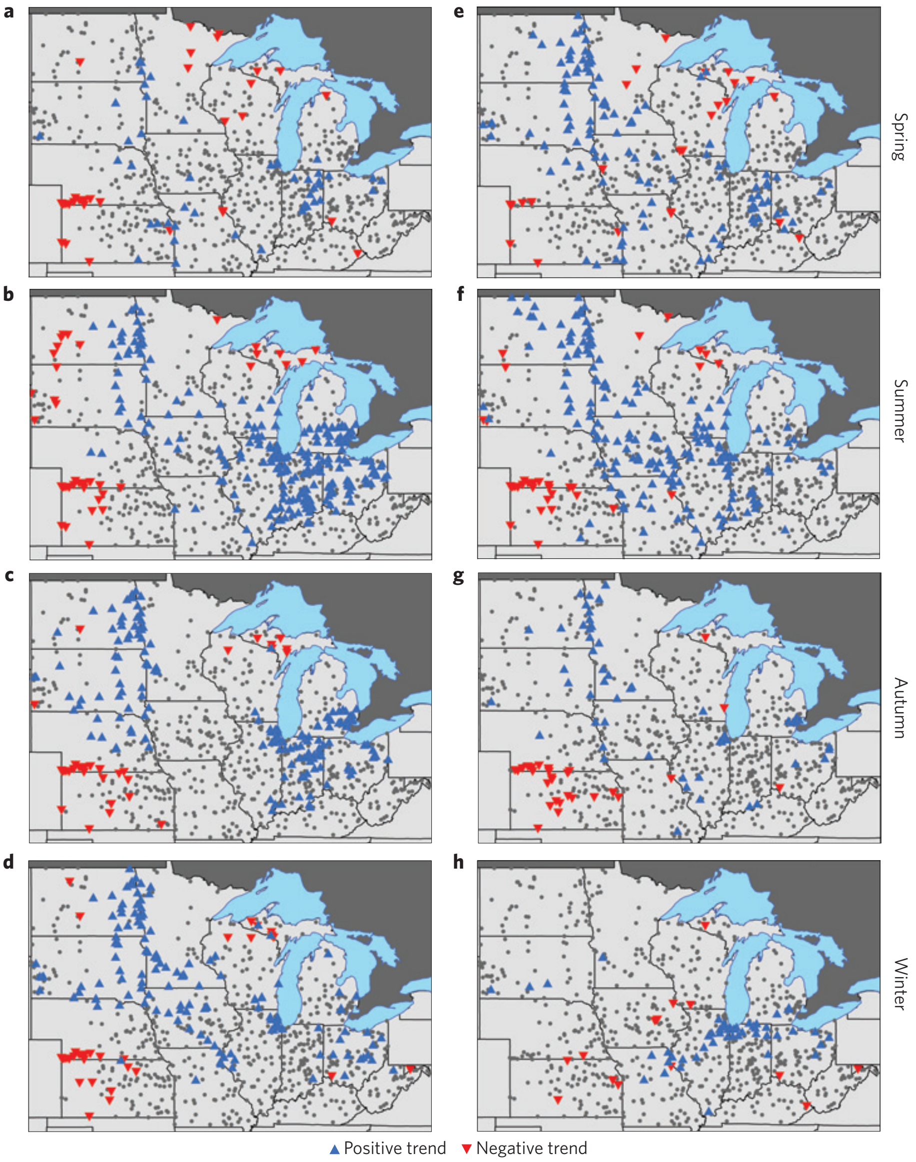

Figure 2 | Trends in the magnitude and frequency of flood events at the seasonal scale. a–**h**, Maps summarizing the results for trends in the magnitude (**a**–**d**) and frequency (**e**–**h**) of flood events. The blue (red) triangles indicate the location of the stations with increasing (decreasing) trends at the 5% level. The grey circles refer to the location of the stations that did not experience statistically significant changes (at the 5% level). Analyses are performed over the common 1962–2011 time period. The results for the entire record length are shown in Supplementary Fig. 2.

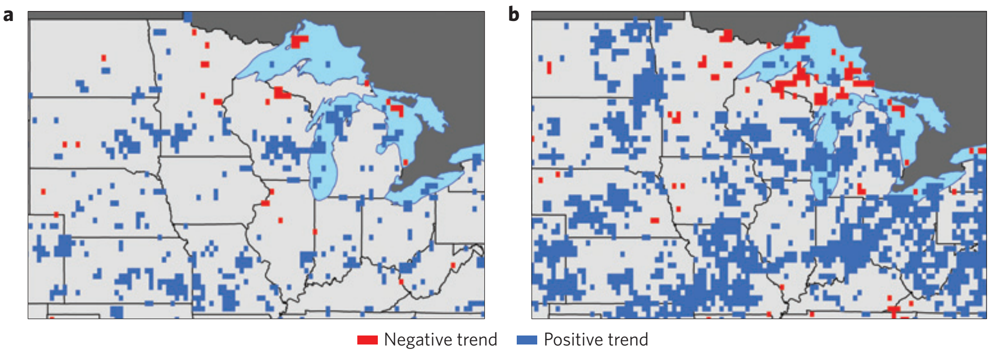

Figure 3 | Trends in the magnitude and frequency of heavy rainfall events at the annual scale. a,b, Maps summarizing the results for trends in the magnitude (**a**) and frequency (**b**) of heavy rainfall events. The blue (red) pixels indicate locations with increasing (decreasing) trends at the 5% level. The grey pixels refer to the locations that did not experience statistically significant changes (at the 5% level).

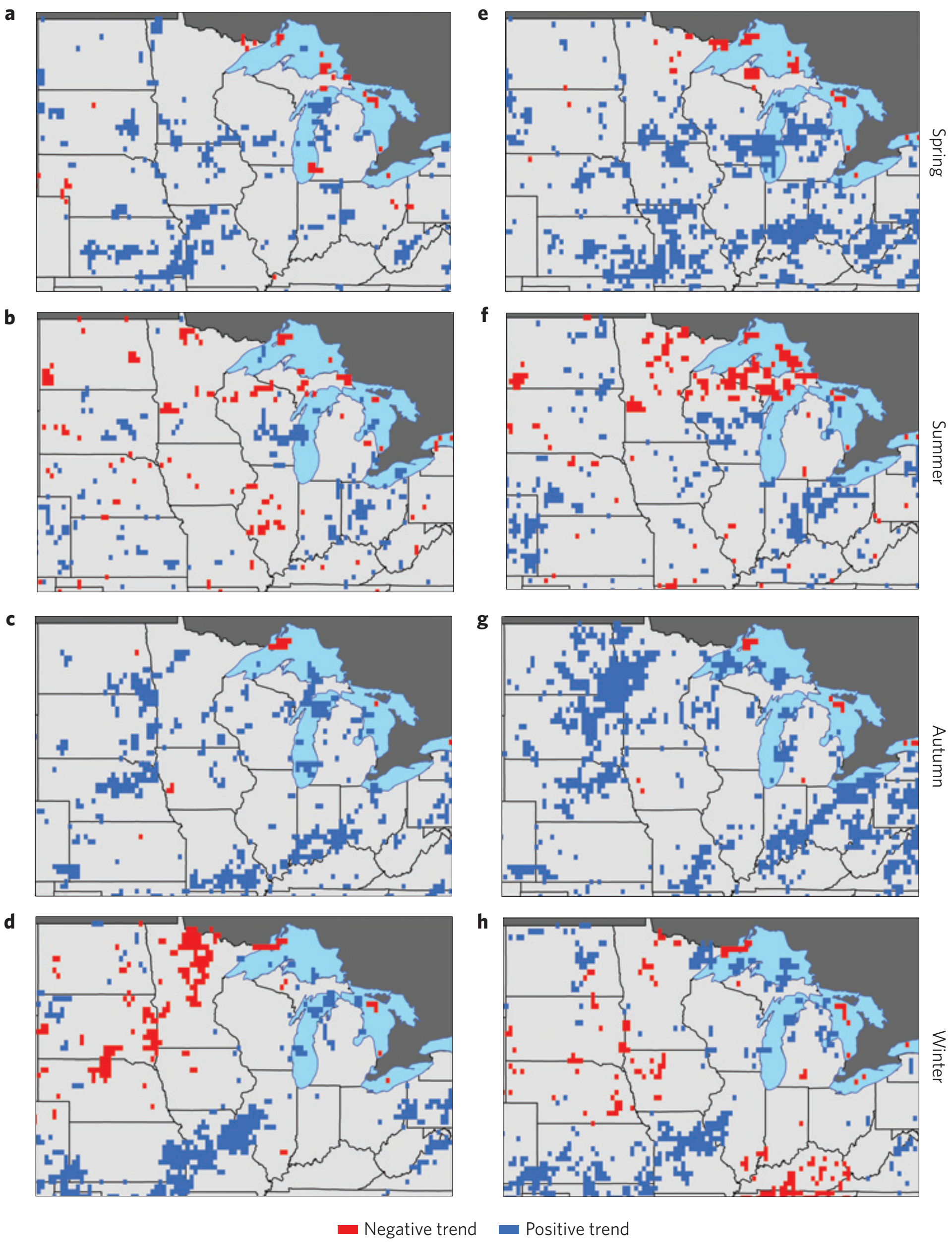

Figure 4 | Trends in the magnitude and frequency of heavy rainfall events at the seasonal scale. a–h, Maps summarizing the results for trends in the magnitude (**a–d**) and frequency (**e–h**) of heavy rainfall events. The blue (red) pixels indicate locations with increasing (decreasing) trends at the 5% level. The grey pixels refer to the locations that did not experience statistically significant changes (at the 5% level).

(consult Methods for details), we examine temporal variability in the annual maximum daily rainfall (Fig. 3a) and in the number of days exceeding the 95th percentile of the rainfall distribution (Fig. 3b). Overall, only limited evidence suggests changes in the magnitude of heavy rainfall, a finding consistent with previous studies[12,13] and in line with what we found for flooding (Fig. 1a).

A stronger tendency towards increases in the frequency of heavy rainfall days (Fig. 3b) is apparent over most of the region, similar to the findings in previous studies[12–14]. Moreover, the fact that we observe the largest changes in the frequency rather than in the magnitude of heavy rainfall is generally consistent with what we found for flood events. There are, however, differences in terms of the sign of the change. The frequency of flooding has been increasing over large areas from the Dakotas to Iowa, Illinois and Ohio, with decreasing trends existing to the northeast and southwest. These changes in rainfall are generally in the same direction across most of the CUS, with the exception of Nebraska and Kansas where the frequency of heavy rainfall days has been increasing but flood events have been decreasing. These differences can be associated with declining water tables that were caused by groundwater withdrawal and the construction of ponds and terraces, particularly in western Kansas[15].

We also consider the attribution of changes in flood events at the seasonal scale in light of changes in rainfall and temperature. These seasonal analyses provide more insight into flood-generating processes and enable the evaluation of the conclusions we reached using annual data. At the seasonal scale, the changes in heavy rainfall event frequency (Fig. 4e–h) are generally stronger than changes in heavy rainfall event magnitude (Fig. 4a–d). When compared with the flood data, the seasonality of heavy rainfall (Supplementary Fig. 4) exhibits some differences with respect to the seasonality of flooding (Supplementary Fig. 3). The most notable difference is the pronounced peak in summer rainfall in contrast to the spring/summer for flooding. Most of the flood peaks in the northern part of the CUS tend to occur in the spring and are associated with snow melt, rain falling on frozen ground, and rain-on-snow events[8,10,16]. Refs 10 and 17 indicated that earlier snow melting and changes in the rain-to-snow ratio were reported in areas of the United States in which snow-melt events are the main flood agent. We have examined the temperature record to identify possible trends and to explore the connection between temperature and flood events. Spring represents the season with the strongest increases over most of the northern part of our region (Supplementary Fig. 5A). Trends of rising temperature yield an increase in available energy for snow melting, and the observed trends in increasing flood frequency over the Dakotas, Minnesota, Iowa and Wisconsin can, consequently, be related to both increasing temperature and rainfall[17]. During the summer, the largest fraction of flood peaks is concentrated over Kansas and Nebraska, for which the decreasing trends can be explained in terms of the declining water tables caused by groundwater withdrawal and the construction of ponds and terraces[15]. The contribution of the autumn season to the flood seasonality is limited, even though the observed changes match those areas in heavy rainfall (for example, at the border between the Dakotas and Minnesota). During winter, most of the flood activity is concentrated over the south/southeastern part of the study region[18]. The results for flooding generally match the patterns for heavy rainfall. In addition to examining the changes in heavy precipitation, we have also considered changes in annual (Supplementary Fig. 6) and seasonal (Supplementary Fig. 7) precipitation. These additional analyses further support the overall conclusions about the relationship between precipitation and flood frequency over this area.

By integrating river discharge and regional climate data, we have found that changes in flood behaviour along rivers across the CUS can be largely attributed to concomitant changes in rainfall and temperature, with changes in the land surface potentially amplifying this signal[19–21]. However, a direct attribution of these changes in discharge, precipitation and temperature to human impacts on climate represents a much more complex problem that is very challenging to address using only observational records[22,23].

Methods

For this study, we use 774 USGS stream gauge daily records with at least 50 years of data ending no earlier than 2011 over the central United States, with no more than two continuous years of missing data (a year is considered missing with less than 330 days; Supplementary Figs 8 and 9). Our study region includes the following 14 states: North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Illinois, West Virginia, Kentucky, Ohio, Indiana and Michigan (Supplementary Fig. 8). We based our precipitation analyses on the unified gauge-based daily observation data[24] that is available from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) from 1948 to 2012. This daily product has a grid resolution of 0.25°. We based our temperature analyses on gridded monthly mean surface air temperatures by the University of Delaware[25] for the 1948–2011 time period. This product has a grid resolution of 0.5°.

To detect changes in the magnitude of flood peaks and annual maximum daily rainfall, we used a block maximum approach (that is, the block is either the whole year or a season) and extracted the largest daily value within each block for each stream gauge station. We used the Mann–Kendall test to test for the presence of monotonic patterns. We used a POT approach to examine changes in the frequency of flood and heavy rainfall events and selected the threshold for flood events so that we have, on average, two events per year to focus on the larger flood events. Moreover, to avoid counting the same event twice, we allow only one peak within a 15-day period. For precipitation, we set a threshold that was equal to the 95th percentile of the rainfall distribution at each pixel. As a result of the discrete nature of the data, we used Poisson regression to ascertain whether or not there are trends in the number of flood or heavy rainfall events. Note that the results in Figs 1–4 do not account for the potential presence of abrupt changes[7]. When working on the annual maximum discharge records (Supplementary Fig. 10A), we examined abrupt changes using the Lombard test[26] and applied the Mann–Kendall test over the most recent period. If no breaks were detected, then we applied the Mann–Kendall test to the entire record. If smooth or abrupt changes were detected, we applied the Mann–Kendall test only to the sub-series after the year of the change (consult Supplementary Fig. 11 for the length of these testing periods). Similarly, we used segmented regression to account for possible abrupt changes in the annual POT flood count data[27]. Similar to the block maxima results, we show the trend results for the entire record (in the case of no abrupt changes; Supplementary Fig. 10C) or based on the most recent segment (in the presence of breaks in the slope of the regression line; Supplementary Fig. 10D).

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Author contributions

G.V. conceived and designed the experiments; I.M. performed the experiments and analysed the data; I.M. and G.V. co-authored the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.V.

Competing financial interests

The authors declare no competing financial interests.