AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL070590

Key Points:
- One of the first studies to characterize the multidimensional behavior of flood change across the United States
- Changes in frequent floods lacked geographic cohesion, with half of the streamgages experiencing no statistically significant change
- Meaningful generalizations about flood change across the United States remain elusive

Supporting Information:
- Supporting Information S1

Correspondence to:
S. A. Archfield,
sarch@usgs.gov

Citation:
Archfield, S. A., R. M. Hirsch, A. Viglione, and G. Blöschl (2016), Fragmented patterns of flood change across the United States, *Geophys. Res. Lett.*, *43*, 10,232–10,239, doi:10.1002/2016GL070590.

Received 25 JUL 2016
Accepted 15 SEP 2016
Accepted article online 17 SEP 2016
Published online 9 OCT 2016

Fragmented patterns of flood change across the United States

S. A. Archfield[1], R. M. Hirsch[1], A. Viglione[2,3], and G. Blöschl[2,3]

[1]National Research Program, U.S. Geological Survey, Reston, Virginia, USA, [2]Centre for Water Resource Systems, TU Wien, Vienna, Austria, [3]Institute of Hydraulic Engineering and Water Resources Management, TU Wien, Vienna, Austria

Abstract Trends in the peak magnitude, frequency, duration, and volume of frequent floods (floods occurring at an average of two events per year relative to a base period) across the United States show large changes; however, few trends are found to be statistically significant. The multidimensional behavior of flood change across the United States can be described by four distinct groups, with streamgages experiencing (1) minimal change, (2) increasing frequency, (3) decreasing frequency, or (4) increases in all flood properties. Yet group membership shows only weak geographic cohesion. Lack of geographic cohesion is further demonstrated by weak correlations between the temporal patterns of flood change and large-scale climate indices. These findings reveal a complex, fragmented pattern of flood change that, therefore, clouds the ability to make meaningful generalizations about flood change across the United States.

1. Introduction

As the magnitude and intensity of precipitation events increase in many areas world wide [*Kunkel et al*., 2013], there is a need to understand how these increases translate to changes in observed floods. Whereas changes in the frequency and magnitude of catastrophic floods are of obvious interest for social, ecological, and economic reasons [*Bouwer*, 2011], changes in the magnitude, duration, and volume of more frequently occurring floods have the potential to adjust alluvial channels and affect the capacity of a channel to contain flood flow [*Slater et al*., 2015].

Almost all studies of long-term global [*Kundzewicz et al*., 2005] and national [e.g., *Lins and Slack*, 1999] trends in floods have focused solely on trends in the time series of annual floods—defined as the largest streamflow that occurs in each year of observed record. The use of the annual flood has several important limitations: (1) only trends in the magnitude of the flood can be considered; (2) there is only exactly one event per year, and, therefore, multiple within-year floods are not considered; and (3) the highest flow in a given year may not even be a "flood" using common definitions of flood (e.g., overbank flow); it was merely the largest streamflow observed in that year. It has also been suggested that the focus on annual floods has confounded relations of observed flood changes to large-scale climate indices [*Hirsch and Archfield*, 2015; *Mallakpour and Villarini*, 2015] and a peaks-over-threshold (POT)-derived series of flood events could clarify relations between climate and flooding [*Hirsch and Archfield*, 2015]. A POT-derived time series of flood events includes all daily mean streamflow values that exceed a selected high streamflow value, thereby allowing for the inclusion of multiple high-streamflow events in some years and no events in other years.

Recent work across Europe [*Mediero et al*., 2015] and at regional scales [*Armstrong et al*., 2012, 2014; *Mediero et al*., 2014; *Mallakpour and Villarini*, 2015] that employed a POT approach to analyze for trends in both magnitude and frequency of floods have found a limited number of changes in floods with complex patterns of geographic cohesion [*Mediero et al*., 2015] and, in the central United States, changes to flood frequency but not magnitude [*Mallakpour and Villarini*, 2015]. No such study has been completed using a POT approach for the conterminous United States nor examined multivariate flood properties.

This study examines changes in flood frequency, magnitude, duration, and volume of flood events across the various physiographic and climate regions of the conterminous United States using time series of mean daily streamflow observed at 345 streamgages over the past 70 years (see supporting information for more details) (Figure 1). Floods are then treated as a multidimensional process, where patterns of floods in four dimensions (frequency, peak magnitude, duration, and volume) are evaluated across the United States to find distinct groupings of multidimensional flood behavior. Changes in floods are evaluated relative to a consistent base

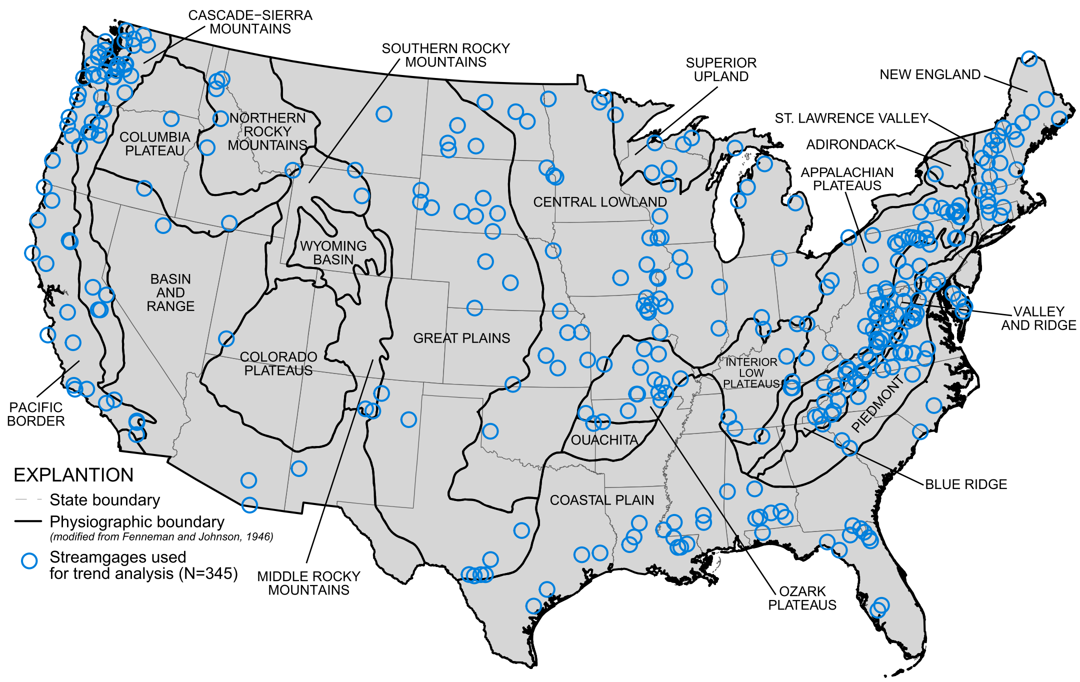

Figure 1. Streamgages to assess changes in floods across the United States. Map showing the physiographic regions of the United States [*Fenneman and Johnson*, 1946] and streamgages that are classified as having minimal development and management of water resources within the contributing watershed. These streamgages have at least 20 years of complete daily streamflow data between water years 1940 to 1969 (the “base period”), at least 20 years of complete streamflow data from water years 1970 to 2013 (the “recent period”), and at least 5 years of complete streamflow data since water year 1999 (the “very recent period”).

period in order to address questions such as whether floods are becoming more frequent, longer, or larger (either in peak or volume) (see supporting information for more details).

2. Regional Trends in the Frequency, Duration, Magnitude, and Volume of Floods

Of interest across the United States are regional changes in flood properties. At-site trend evaluations provide information only about one location on a river and, therefore, provide only limited inference about spatial patterns in floods. Regional trends were assessed in the frequency, duration, peak magnitude, and volume of flood events by 400 km by 400 km grid cells across the United States (see supporting information for more details) (Figure 2). The regional trend analysis was limited to areas with a minimum density of long-term reference streamgage records and, in aggregate, these areas encompass about 70% of the land area of the conterminous United States. The assessed areas exclude much of the southwest physiography (Figure 1), including the Basin and Range and Colorado Plateaus, as well as the Rocky Mountains and Columbia Plateau.

Across the assessed area of the United States, few significant regional trends (at $\alpha = 0.1$) are observed across the United States, and, for those flood properties that do exhibit a significant trend, the magnitude of this change over time is relatively small, with a few exceptions (Figure 2). The actual number of regions with significant trends was 11, 6, 10, and 8 for frequency, peak magnitude, duration, and volume, respectively (Figure 2). Furthermore, the number of decreasing trends and increasing trends for each of the four metrics is as follows: frequency (five decreasing, six increasing), peak magnitude (one decreasing, five increasing), duration (two decreasing, eight increasing), and volume (two decreasing and seven increasing) (Figure 2).

New England (Figure 1) shows a large, significant increase in the frequency of events per year, with increases from an average of two events per year over a base period from 1940 to 1970 to about five events per year during a more recent period from 1971 to 2013 (Figure 2a). Other areas of the county show limited significant increases or decreases in the frequency of flood events as compared to the base period; however, there are notable decreases in the frequency of flood events in Florida and in the northern Great Plains and Upper

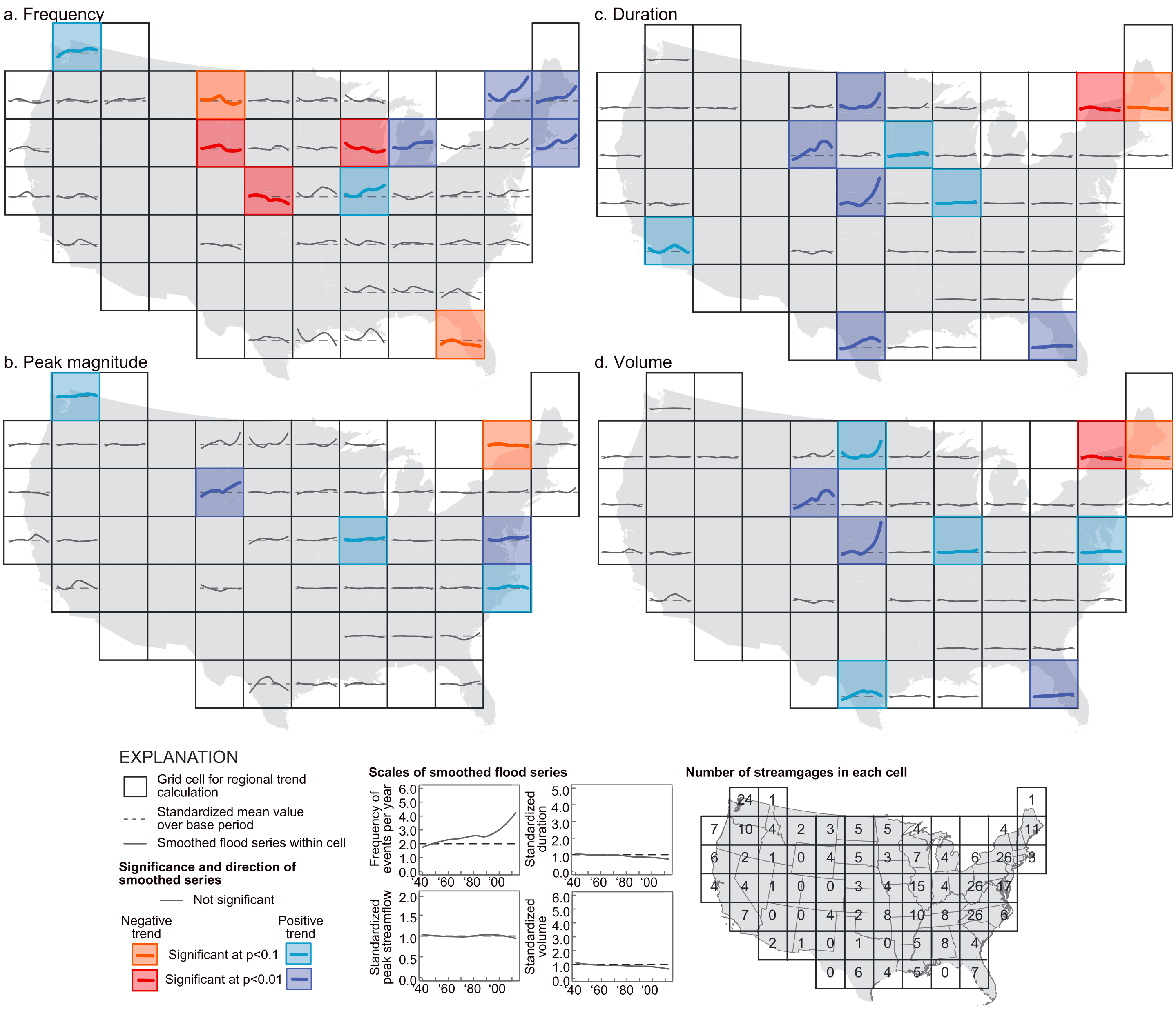

Figure 2. Regional changes in floods across the United States. Maps showing regional trends over the period 1940–2013 in the (a) frequency of flood events per year, (b) peak daily streamflow of flood events, (c) duration of flood events, and (d) volume of flood events. Each square is a grid cell of 400 km on a side. Cells with fewer than three streamgages were not included in the analysis. Significance is determined by the Regional Kendall Test [*Helsel and Frans*, 2006]. Cells are shaded based on significance and direction of trend. Each cell contains a smoothed line resulting from a locally weighted scatterplot smoothing (LOESS) regression of time versus the series of flood events for the streamgages contained within the cell. These LOESS curves are computed after standardizing the data from each site such that the mean value during the 1940–1969 base period was equal to 1.0 with the exception of the frequency of events, which were not standardized. Plots located in the explanation show the scale for each LOESS plot and the number of streamgages in each cell.

Mississippi Valley (from two events per year to one event per year) (Figure 2a). Notable increases are centered over Michigan (from two to four events per year) and the Pacific northwest (Figure 2a).

Regional changes in the peak magnitude of flood events show only statistically significant changes in 6 of the 41 grid cells. Of these, five cells show an upward trend and one cell shows a downward trend at a significance level of 0.1 (at a significance level of 0.01, two cells were found to be significant). One of those cells—located in the Great Plains (Figure 1)—shows an appreciable change in the peak magnitude of flood events, with the

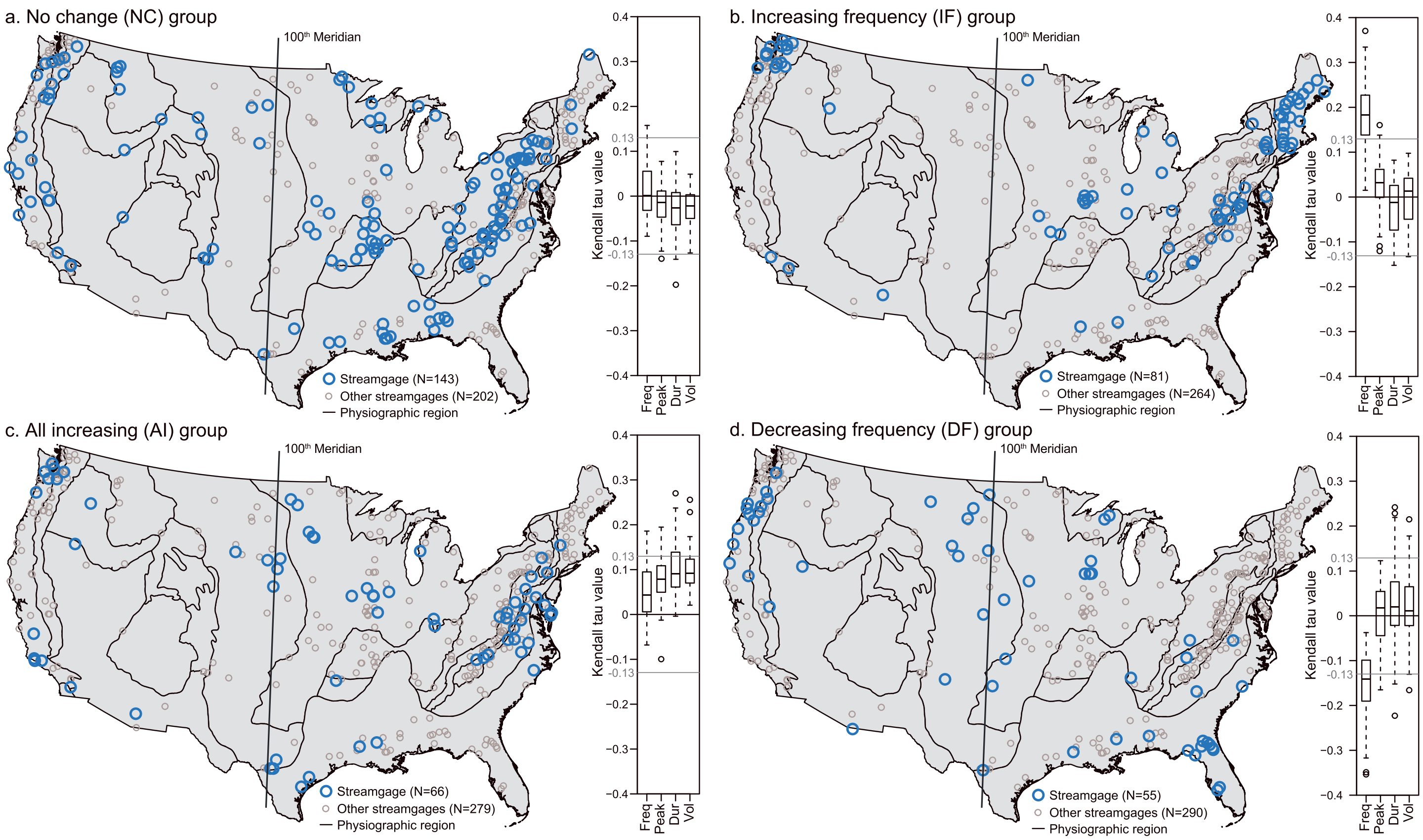

Figure 3. Streamgages experiencing similar changes in flood events. Streamgages clustered into one of four groups experiencing similar changes in the frequency (Freq), peak magnitude (Peak), duration (Dur), and volume (Vol) of flood events over the period 1940–2013 relative to a base period from 1940 to 1969 that averaged two flood events per year. Streamgages in (a) the no change (NC) group generally show no change in the flood properties; streamgages in (b) the increasing frequency (IF) group generally exhibit an increasing frequency of events; streamgages in (c) the all increasing group (AI) show increases across all flood properties; and streamgages in (d) the decreasing frequency (DF) group generally exhibit a decreasing frequency of events. Box plots of the Kendall tau values—a measure of relation between time and the flood properties—for the streamgages within each group is shown to the right of each map. A negative Kendall tau value indicates a decreasing trend; a positive value indicates an increasing trend. Correlations above values of 0.13 and below values of −0.13 (shown in grey lines) are generally significant correlations at a significance level of 0.1. Streamgages that are members of the respective cluster are shown as an open blue circle; streamgages that are part of the study but not a member of the cluster are shown as open gray circles.

mean peak magnitude of the flood events increasing 1.5 times (150%) relative to the base period (Figure 2b), meaning the present peak magnitude values were as much as 150% larger than observed during the base period.

Changes in the duration and volume of events show significant increases in the Great Plains, with durations of flood events increasing in length by 2 to 5 times (200 to 500%) relative to what was observed during the base period (Figure 2c) and volumes of flood events in this area becoming nearly 6 times greater than the average flood event volume observed during the base period (Figure 2d). Other areas of the country exhibited statistically significant changes in the duration and volume of flood events; however, the magnitudes of change in these flood properties were small (Figures 2c and 2d).

From a field significance [*Livezey and Chen*, 1983] perspective, hypothesis tests were applied to the 41 regions for each flood property to determine if the number of regions with a significant trend is greater than what could be expected by chance and if the number of regions with observed significant increasing trends is statistically different than the number of regions with observed significant decreasing trends. If one applies a significance level, α, equal to 0.1 for field significance, results were field significant (when the resulting p value is less than α) for frequency (p value = 0.0005), duration (p value = 0.0019), and volume (p value = 0.048) but not for peak magnitude (p value = 0.22). In evaluating the probability that the number of observed increasing trends is different from the number of observed decreasing trends, the results were field significant for peak magnitude (p value = 0.031) but not for frequency (p value = 1.00), duration (p value = 0.11), and volume (p value = 0.18). Therefore, three of the four flood metrics (frequency, duration, and volume) showed significantly more regions with trends than would be expected under chance; yet none of these flood metrics showed statistically significant evidence for a tendency toward increasing trends versus decreasing trends. For the remaining metric—peak magnitude—the data do not show a significantly higher number of trends than expected, but for those that were significant, there was a strong propensity toward increasing trends versus decreasing.

Much of the United States has not experienced significant change in any of the flood properties, with the exception of New England and the northern Great Plains and Upper Mississippi Valley (Figure 2). The northern Great Plains and Upper Mississippi Valley appear to show significant but small decreases in the frequency of flood events and large increases in the peak, duration, and volume of flood events (Figure 2). New England exhibits the opposite behavior, showing large, significant increases in the frequency of flood events and significant (but small) decreases in the peak, duration, and volume of flood events (Figure 2).

3. Geographic Cohesion of Trends

The multidimensional nature of these trends was explored using cluster analysis [*Venables and Ripley*, 2002; *Olden et al*., 2012; *Tan et al*., 2006], combining similar patterns of increases or decreases in the frequency, duration, peak magnitude, and volume of flood events into four distinct groups (see supporting information for more details): (1) streamgages generally show no change (i.e., streamgages generally showing very little change and most changes being nonsignificant) in any of the flood properties (NC, no change) (Figure 3a); (2) streamgages generally exhibit only an increasing frequency of events (IF, increasing frequency) (Figure 3b); (3) streamgages showing increases across all flood properties (AI, all increasing,) (Figure 3c); and (4) streamgages generally exhibit only a decreasing frequency of events (DF, decreasing frequency) (Figure 3d). Box plots (Figure 3) of the clustering variables—the Mann Kendall tau value [*Helsel and Hirsch*, 2002] measuring correlation between time and the respective flood property—describe the behavior of the observed changes in floods. Based on the significance tables for the Kendall tau correlation coefficient, values between ±0.13 are not significant at the level of 0.1 for records of 74 years duration. For records that are slightly shorter, such as 60 years, the critical values of tau are at about ±0.145. As such, when the boxplot for a given flood property is largely contained between these bounds, one can generally conclude that within that group, trends in that given flood property are not significant (Figure 3). For example, the AI group shows a tendency toward increases in all flood properties although very few of them are statistically significant (Figure 3c). Two groups had streamgages showing significant trends in increasing frequency (group IF; Figure 3b) or decreasing frequency (group DF (Figure 3d)) with no strong tendency toward positive or negative trends for peak magnitude, duration, and volume. Of note, in the IF and DF groups, all tau values were positive or negative, respectively, even if the tau value was not significant. In addition to considering the behavior of floods within the four groups, it is interesting to note that no clusters exhibited widespread decreasing trends in duration, peak magnitude, and volume of the flood events.

Across the United States, there is an apparent lack of geographic cohesion within the clusters; however, some regional patterns can be observed. The NC group (Figure 3a) has the largest membership, containing nearly 40% of the streamgages, and these are scattered across the United States. In the eastern United States, all but three streamgages located in New England physiographic region belong to the IF group (Figure 3b), which shows strong increases in the frequency of flood events and is consistent with the regional analysis of trends (Figure 2a). Yet in other portions of the eastern United States, a mixed pattern emerges. In the Appalachian Plateaus (Figure 1), approximately half of the streamgages belong in the NC group (Figure 3a) whereas most streamgages in the nearby Valley and Ridge, Blue Ridge, and Piedmont (Figure 1) are evenly mixed across the NC, IF or AI groups (Figures 3a–3c). Further south, in the eastern portion of the Coastal Plain (Figure 1), all but one streamgage belongs in the DF group (Figure 4d), contrasting the increased frequency of flooding in the northeast United States to the decreased frequency of flooding observed in the southeast United States.

Streamgages located in the central United States also do not appear to group in a cohesive spatial pattern; however, nearly all streamgages in the Ozark Plateaus and Superior Upland (Figure 1) have membership in the NC group (Figure 3a). Streamgages located in the Central Lowland (Figure 1) have streamgages in each of the four groups and even closely located streamgages have membership in different groups with the exception of streamgages in the northern portion of the Central Lowland, which mostly belong in the AI

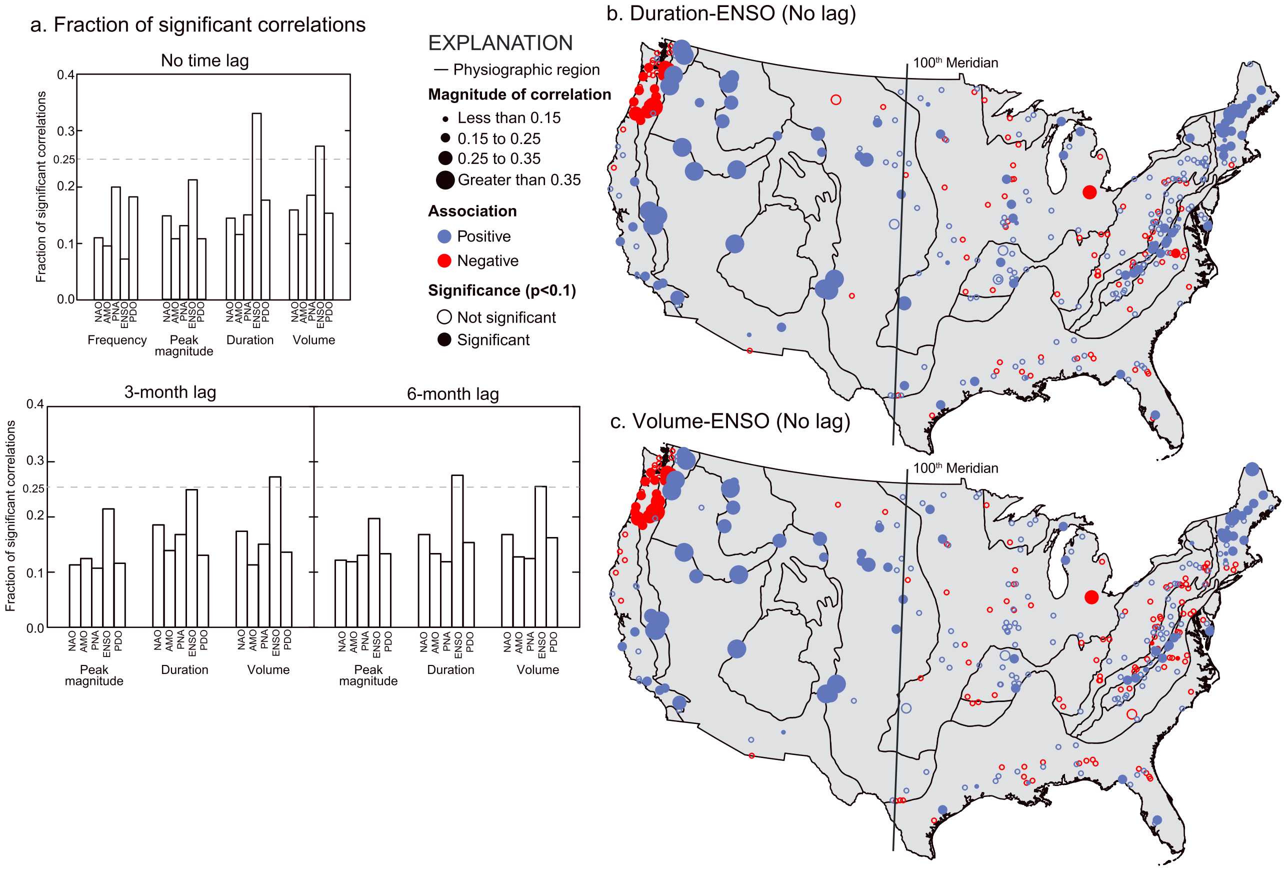

Figure 4. Relations between flood events and large-scale, quasiperiodic climate indices. Fractions of significant Spearman rho correlation values (a) with no lag between the time series of flood frequency, peak magnitude, duration, and volume of flood events with each of five large-scale, quasiperiodic climate indices: North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Pacific North American (PNA) Oscillation, El Niño Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO), and fraction of significant Spearman rho correlation values between the time series of peak magnitude, duration, and volume of flood events using the preceding 3 month and 6 month values of the climate indices. Maps (b and c) showing the correlations between the flood property and climate index series with no lag that were found to show significant relations at more than 25% of streamgages.

group. For the streamgages within this localized region, the average number of days of streamflow over the threshold tripled when compared to the average number of days of streamflow over the threshold that occurred prior to 1970. Streamgages in the Great Plains (Figure 1) have membership in each of the groups with the exception of the IF group. In the northern and southern Rocky Mountains (Figure 1) nearly all streamgages belong to the NC group (Figure 3a); too few streamgages are located in the Columbia Plateau, Basin and Range, and Colorado Plateaus to make any regional observations about group membership (Figure 1).

Much like the eastern portion of the United States, there are stronger regional patterns in the western portion of the United States than in the central United States. Streamgages belonging in the NC group are located along the entire stretch of the west coast of the United States (Figure 3a); however, streamgages belonging to the IF or AI group are confined to the northernmost portion (Figure 3b), and streamgages belonging to the DF group are mainly located in the middle portion, just below the northernmost streamgages (Figure 3c). This clear demarcation in the behavior of floods in the northwest United States (increasing frequency or all increasing flood properties in the northern portion and decreasing frequency in middle portion) was unexpected for such a relatively small region. Most of the streamgages in the southern portion of the West Coast fall into the NC group with a few streamgages belonging to the IF or AI groups.

4. Relation of Trends to Large-Scale, Quasiperiodic Climate Indices

The relation of large-scale, quasiperiodic ocean/atmosphere oscillations to flood events is not well understood [*Merz et al.*, 2014]. This lack of understanding may be due, in part, to the general practice of relating annual flood series—rather than the POT series—to these patterns [*Hirsch and Archfield*, 2015]. Quasiperiodic oscillations can often be represented by climate indices such as the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), Pacific North American (PNA) Oscillation, El Niño–Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO). To this end, the time series of frequency, peak magnitude, duration, and volume of flood events at each streamgage were correlated to the NAO, AMO, PNA, ENSO, and PDO. The details of this analysis can be found in the supporting information.

Correlations are generally low (Figure 4a) and not significant. For most flood property-climate index pairs, the fraction significant was near the significance level of α equals 0.1 (Figure 4a). A few pairs stand out as being at least twice as large: frequency correlated with PNA or PDO, and duration, peak magnitude, and volume correlated with ENSO (Figure 4a). Field significance [*Livezey and Chen*, 1983] was not calculated because of the potentially large intersite correlations among nearby streamgages. In two of these cases the fraction of streamgages with significant correlations was over two and a half times the individual significance level of α equals 0.1 (Figure 4a): (1) duration and ENSO, and (2) volume and ENSO. The cross correlations between 1, 2, 3, 4, 5, and 6month lags between the flood event and the preceding *n* month climate index value (where $n = 1, 2, 3, 4, 5$, or 6) were also computed. For this analysis, we chose to examine the 1–6 month lags between the flood event and the preceding *n* month climate index value (where $n = 1, 2, 3, 4, 5$, or 6). The lagged correlations between the frequency of flood events were not further examined, as this is an annual series and the climate indices are already averaged over the year before computing the correlations. Only results for the 3 month and 6 month lags are shown because similar results were observed across all lags, which are also consistent with what was observed when no lag was considered: the relation between ENSO and duration and ENSO and volume remains the two relations for which approximately 25% of streamgages have significant correlations. The correlations for these pairings were mapped to evaluate any regional patterns in these relations (Figures 4b and 4c). Nearly all other relations between a given climate index and flood property across all lags have significant correlations approximately equal to what one would expect by chance given a significance level of 0.1.

Widespread regional patterns are evident in correlations between ENSO and duration and volume (Figures 4b and 4c), extending west from the Great Plains to the Cascade-Sierra Mountains (Figure 1); nearly all of the streamgages located in this area have significant, positive correlations greater than 0.25. Streamgages close to the 100th meridian—commonly used demarcation line separating arid climates to the west and subhumid climates to the east—show the strongest tendencies toward increasing volume and duration of floods. A substantial climate and hydrologic shift has been documented in this region [*Ryberg et al*., 2014] with an extreme wet period persistent over the past two decades. Paleohydrologic data indicate previous episodes of similar wet regimes, suggesting that this is a large-scale quasiperiodic phenomenon [*Ryberg et al*., 2016]. Significant, positive but lower magnitude correlations are observed in New England and, to a lesser extent, in the Valley and Ridge and Blue Ridge regions. By contrast, the Pacific Northwest has significant, low, and negative correlations between ENSO and duration and volume. Aside from these particular examples (Figures 4b and 4c), there is little evidence to suggest strong relations between most large-scale, quasiperiodic climate indices and the flood properties examined in this study.

5. Conclusions

Anticipated changes in flood frequency and magnitude due to enhanced greenhouse forcing are not generally evident at this time over large portions of the United States for several different measures of flood flows. Statistically significant regional trends in flood properties are observed more than what would be expected by chance alone, but the directions of these trends do not present a coherent spatial pattern. Many regions show no particular indications in changes in flood properties, while some others show specific patterns of changing flood properties. However, even within a given region of the nation, the changes exhibited can be very different in watersheds that are in close proximity to each other. Aside from New England, this analysis shows little geographic cohesion from a physiographic perspective and, apart from the El Niño–Southern Oscillation (ENSO), the climate indices do not show widespread, strong correlations with flood events. The fragmented patterns of flood change suggest that the catchment scale may be the resolution at which to understand and attribute these patterns, as the regional or global explanatory variables examined here appear to hold only a small amount of explanatory power.

The metrics of flooding used in this study are just a few of the many that warrant examination over time. The relationships between landscape properties, climate variations and trends, and the generation of floods are highly complex [*Hall et al.*, 2014; *Viglione et al.*, 2016]. Continuing research aimed at identifying climate-related trend signals in flood records is one part of an overall strategy needed to increase the ability to forecast the trajectory of flood conditions that is needed to guide natural resource and natural hazard planning and management over the coming decades.

Acknowledgments
Financial support has been provided by the U.S. Department of the Interior WaterSMART Program, the U.S. Geological Survey National Research Program and also partly provided by the European Research Council, FloodChange project (ERC Advanced grant 291152). The authors declare no competing financial interests. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Information about potential streamgages to use in the study was obtained from *Falcone et al.* [2010] and available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml. Streamflow data were obtained from the U.S. Geological Survey National Water Information System available at 10.5066/F7P55KJN. Climate index data were downloaded from the National Oceanic and Atmospheric Administration Earth System Research Laboratory at http://www.esrl.noaa.gov/psd/data/climateindices/list/.

References

Armstrong, W. H., M. J. Collins, and N. P. Snyder (2012), Increased frequency of low-magnitude floods in New England, *JAWRA J. Am. Water Resour. Assoc.*, *48*(2), 306–320, doi:10.1111/j.1752-1688.2011.00613.x.

Armstrong, W. H., M. J. Collins, and N. P. Snyder (2014), Hydroclimatic flood trends in the northeastern United States and linkages with large-scale atmospheric circulation patterns, *Hydrol. Sci. J.*, *59*(9), 1636–1655, doi:10.1080/02626667.2013.862339.

Bouwer, L. M. (2011), Have disaster losses increased due to anthropogenic climate change?, *Bull. Am. Meteorol. Soc.*, *92*(1), 39–46, doi:10.1175/2010BAMS3092.1.

Falcone, J. A., D. M. Carlisle, D. M. Wolock, and M. R. Meador (2010), GAGES: A stream gage database for evaluating natural and altered flow conditions in the conterminous United States, *Ecology*, *91*(2), 621–621, doi:10.1890/09-0889.1.

Fenneman, N. M., and D. W. Johnson (1946), Physical divisions of the United States, U.S. Geological Survey, 1:7,000,000.

Hall, J., et al. (2014), Understanding flood regime changes in Europe: A state of the art assessment, *Hydrol. Earth Syst. Sci.*, *18*, 2735–2772, doi:10.5194/hess-18-2735-2014.

Helsel, D. R., and L. M. Frans (2006), Regional Kendall test for trend, *Environ. Sci. Technol.*, *40*(13), 4066–4073, doi:10.1021/es051650b.

Helsel, D. R., and R. M. Hirsch (2002), *Statistical Methods in Water Resources*, *Techniques of Water-Resources Investigations Book 4*, Chap. A3., U.S. Geological Survey. [Available at http://pubs.usgs.gov/twri/twri4a3/.]

Hirsch, R. M., and S. A. Archfield (2015), Flood trends: Not higher but more often, *Nat. Clim. Change*, *5*(3), 198–199, doi:10.1038/nclimate2551.

Kundzewicz, Z. W., D. Graczyk, T. Maurer, I. Pińskwar, M. Radziejewski, C. Svensson, and M. Szwed (2005), Trend detection in river flow series: 1. Annual maximum flow/Détection de tendance dans des séries de débit fluvial: 1. Débit maximum annuel, *Hydrol. Sci. J.*, *50*(5), 707–810, doi:10.1623/hysj.2005.50.5.797.

Kunkel, K. E., T. R. Karl, H. Brooks, J. Kossin, J. H. Lawrimore, D. Arndt, L. Bosart, D. Changnon, S. L. Cutter, and N. Doesken (2013), Monitoring and understanding trends in extreme storms: State of knowledge, *Bull. Am. Meteorol. Soc.*, *94*(4), 499–514.

Lins, H. F., and J. R. Slack (1999), Streamflow trends in the United States, *Geophys. Res. Lett.*, *26*(2), 227–230, doi:10.1029/1998GL900291.

Livezey, R. E., and W. Y. Chen (1983), Statistical field significance and its determination by Monte Carlo techniques, *Mon. Weather Rev.*, *111*(1), 46–59, doi:10.1175/1520-0493(1983)111<0046:SFSAID>2.0.CO;2.

Mallakpour, I., and G. Villarini (2015), The changing nature of flooding across the central United States, *Nat. Clim. Change*, *5*(3), 250–254, doi:10.1038/nclimate2516.

Mediero, L., D. Santillán, L. Garrote, and A. Granados (2014), Detection and attribution of trends in magnitude, frequency and timing of floods in Spain, *J. Hydrol.*, *517*, 1072–1088, doi:10.1016/j.jhydrol.2014.06.040.

Mediero, L., et al. (2015), Identification of coherent flood regions across Europe by using the longest streamflow records, *J. Hydrol.*, *528*, 341–360, doi:10.1016/j.jhydrol.2015.06.016.

Merz, B., et al. (2014), Floods and climate: Emerging perspectives for flood risk assessment and management, *Nat. Hazards Earth Syst. Sci.*, *14*(7), 1921–1942, doi:10.5194/nhess-14-1921-2014.

Olden, J. D., M. J. Kennard, and B. J. Pusey (2012), A framework for hydrologic classification with a review of methodologies and applications in ecohydrology, *Ecohydrology*, *5*(4), 503–518, doi:10.1002/eco.251.

Ryberg, K. R., W. Lin, and A. V. Vecchia (2014), Impact of climate variability on runoff in the north-central United States, *J. Hydrol. Eng.*, *19*(1), 148–158, doi:10.1061/(ASCE)HE.1943-5584.0000775.

Ryberg, K. R., A. V. Vecchia, F. A. Akyüz, and W. Lin (2016), Tree-ring-based estimates of long-term seasonal precipitation in the Souris River Region of Saskatchewan, North Dakota and Manitoba, *Can. Water Resour. J.*, 1–17, doi:10.1080/07011784.2016.1164627.

Slater, L. J., M. B. Singer, and J. W. Kirchner (2015), Hydrologic versus geomorphic drivers of trends in flood hazard, *Geophys. Res. Lett.*, *42*, 370–376, doi:10.1002/2014GL062482.

Tan, P., M. Steinbach, and V. Kumar (2006), *Introduction to Data Mining*, 769 pp., Pearson Addison Wesley, Boston, Mass.

Venables, W. N., and B. D. Ripley (2002), *Modern Applied Statistics With S*, 4th ed., Springer, New York.

Viglione, A., B. Merz, N. Viet Dung, J. Parajka, T. Nester, and G. Blöschl (2016), Attribution of regional flood changes based on scaling fingerprints, *Water Resour. Res.*, *52*, 5322–5340, doi:10.1002/2016WR019036.