Berghuijs, W. R., Aalbers, E., Larsen, J., Trancoso, R., & Woods, R. (2017). Recent changes in extreme floods across multiple continents. *Environmental Research Letters*, *12*(11), [114035]. https://doi.org/10.1088/1748-9326/aa8847

Environmental Research Letters

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To cite this article: Wouter R Berghuijs *et al* 2017 *Environ. Res. Lett.* **12** 114035

View the article online for updates and enhancements.

Environmental Research Letters

OPEN ACCESS

RECEIVED
2 May 2017

REVISED
20 July 2017

ACCEPTED FOR PUBLICATION
24 August 2017

PUBLISHED
16 November 2017

LETTER

Recent changes in extreme floods across multiple continents

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Keywords: flood, global hydrology, natural hazard, hydro-climate

Abstract

Analyses of trends in observed floods often focus on relatively frequent events, whereas changes in rare floods are only studied for a small number of locations that have exceptionally long observational records. Understanding changes in rare floods is especially relevant as these events are often most damaging and influence the design of major structures. Here, we provide an assessment of changes in the largest flood events (∼0.033 annual exceedance probability) observed during the period 1980–2009 for 1744 catchments located in Australia, Brazil, Europe and the United States. The occurrence of rare floods in spatial aggregate shows strong temporal variability and peaked around 1995. During the 30 year period, there are overall increases in both the frequency and magnitude of extreme floods. These increases are strongest in Europe and the United States, and weakest in Brazil and Australia. Physical causes of the reported short-term variability and longer-term changes in extreme floods currently remain elusive, because the key drivers vary between catchments. Nonetheless, this approach provides the basis for a more spatially representative assessment of changes in extreme flood occurrence.

1. Introduction

Increasing greenhouse gas concentrations generally result in a warmer atmosphere able to hold more moisture at saturation, leading to increasing observed and predicted rainfall extremes [1–4]. It is therefore expected that the magnitude and frequency of flooding will increase with a warming climate [5–7]. However, the sign, magnitude and spatial manifestation of regional and global flood changes in both past and future decades remain largely unknown as there is profound disagreement between predicted flood trends, which are uncertain but generally increasing [8–12], and the large variability in observed global flood trends in recent decades, which can be either increasing or decreasing [6, 7, 13–16]. This apparent mismatch suggests purely relying on uncertain model predictions [17], or superimposing extreme precipitation trends onto floods, is invalidated by several confounding factors, such as: (i) changes in other climatic factors that control flood conditions (e.g. evaporation and snowmelt) [18, 19], (ii) the dependence on antecedent conditions, which themselves are not always extreme [20], and (iii) the impact of changing catchment templates (e.g. river channels and land use) on which climate-driven changes in flood behavior may occur [5, 6, 21]. Closely monitoring runoff observations, which integrates all these factors, is therefore of key importance to understanding the changing nature of floods.

Studies of observed trends generally focus on flood events with some regularity over time (e.g. annual or bi-annual peaks) [14, 22–25]. Understanding changes in frequently occurring maximum river flows is useful. However, this does not necessarily provide information on extreme and infrequent floods that can be far more

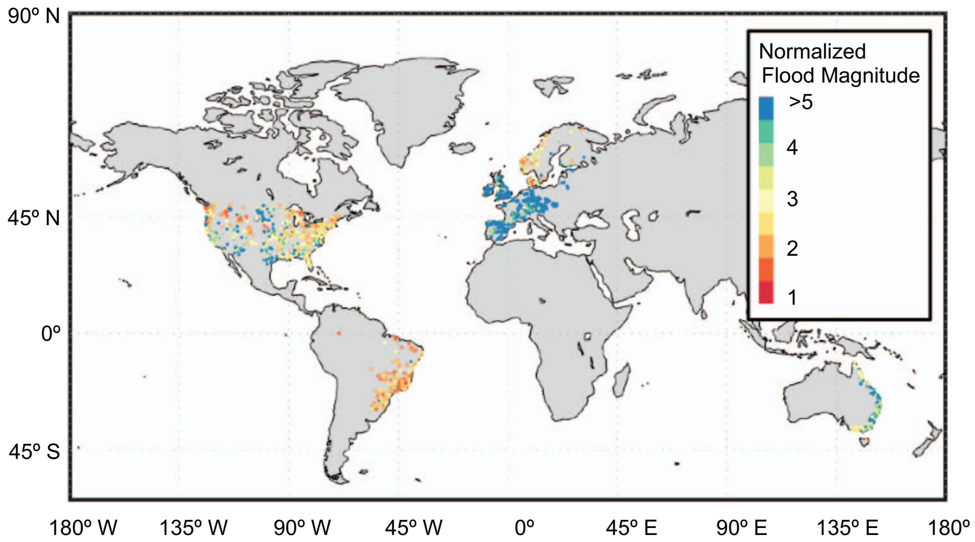

Figure 1. Location of stream gauges and the relative magnitude of the largest flood events. The 1744 stream gauges used in this study are spread across four continents as indicated by the colored markers. The color indicates the magnitude of the maximum daily flow rate during the entire 30 year period compared to the mean maximum annual flow rate of the same catchment. This normalized flood magnitude indicates the relative magnitude of the studied extreme floods compared to the mean of commonly studied annual flood peaks. In large parts of South America, the more humid parts of the United States, and Scandinavia, the maximum events are comparable in size with annual flood peaks. In Australia, most of Europe, and the more arid central part of the United States the 1/30 year floods are much bigger than the annual flood peaks.

destructive. Our ability to examine changes in extreme floods (e.g. annual exceedance probability < 0.05) is currently confined to locations with exceptionally long flow records and pre-instrumental flow estimates [26]. Long records are necessary to allow a sufficient number of extreme events for trend analysis. Consequently, it is unclear if findings from this small number of rivers, such as no increasing trends in extreme floods in Europe [27] or a high sensitivity of flood magnitude to changes in climate [28, 29], are representative of the majority of river systems around the world. Thus, the nature of regional and global changes in extreme floods is mostly unknown.

If mostly unidirectional changes in the frequency and magnitude of extreme floods exist (e.g. as predicted [8–12]), it should be possible to detect such changes using observational records that, despite having limited temporal coverage, encompass a much greater spatial footprint of many rivers across the globe. Although the changing characteristics of extreme floods for individual rivers cannot be determined given the limited number of extreme events per catchment, aggregating the data over a large number of locations can provide robust information on the changing nature of extremes across larger regions or a large number of catchments [30]. Such a regional approach is needed given that a systematic test of recent changes in extreme floods across multiple continents is currently not available. Aiming to fill this knowledge gap, we assess changes in the frequency and magnitude of extreme flood events, defined here as the largest observed daily flow rate during the period 1980–2009 (i.e. ~0.033 annual exceedance probability) for catchments located in diverse landscapes and climates in Australia, Brazil, Europe, and the United States.

2. Methods

2.1. Data

Daily streamflow observations for the period 1980–2009 are used from 309 catchments located in eastern Australia, 671 catchments in the continental United States, 244 catchments in Brazil, and 520 catchments located in Europe (figure 1). The extreme events we studied (i.e. the maximum flood in a 30 year period) are orders of magnitude larger than mean flow rates, and, on average 3.9 times larger than the mean annual flood peaks (figure 1). These catchments range in size from ~1–10 000 km^2, and do not have any major dams affecting river flow, although some catchments in Brazil may have a higher degree of regulation. More information can be found in previous studies that used these catchments [31–34]. Catchments with more than 15% missing data are removed from the data set.

2.2. Quantifying changes in floods

For each catchment, we determined the time of occurrence of the single largest daily flow rate in the 30 year period. In order to consider independent extreme events only (i.e. not consider multiple floods driven by the same synoptic system), extreme flows from neighboring catchments (gauges less than 100 km apart) within a 7 day period are counted only once. Modifying this distance (50–250 km) did not change the results significantly. We then split the data into two periods

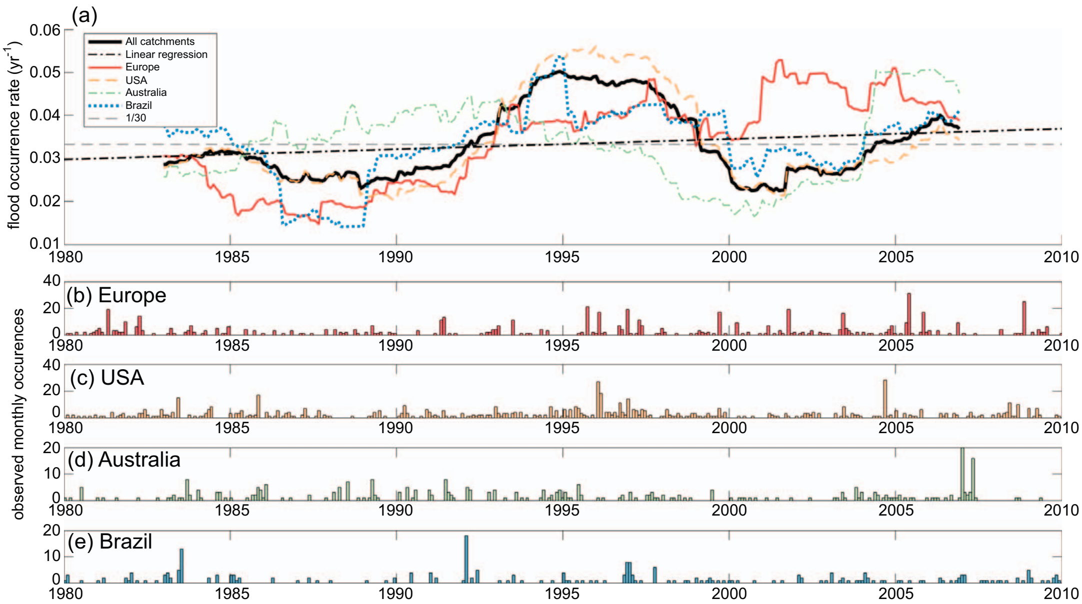

Figure 2. Occurrence rate of each catchment's largest flood. The 5 year moving average of the annual probability that a certain flood magnitude is observed, shown per region and for all catchments (*a*). Time of occurrence of each catchment's single largest flood is shown for Europe (*b*), United States (*c*), Australia (*d*), and Brazil (*e*).

of equal length ($t_1 = 1980-1994$, $t_2 = 1995-2009$) and counted the total number of occurrences (n_1, n_2) of the maximum flood per period per continent and for all catchments. The change in flood occurrence is:

$$\Delta n = \left(\frac{n_2}{n_1} - 1\right) \cdot 100\%. \quad (1)$$

The probability that floods have increased is calculated using a chi-square test where the null hypothesis, H_0, is no change in the likelihood of flood occurrences (i.e. $n_1 = n_2$):

$$\chi^2 = \sum \frac{(n_2 - (n_1 + n_2)/2)^2}{(n_1 + n_2)/2}. \quad (2)$$

The likelihood of accepting H_0 (indicating the likelihood of no increase in maximum flow occurrence) is calculated as the p-value.

To quantify how flood size changed over time, we compared per catchment the magnitude of the maximum daily flow rate of period t_1 (Q_1), with the magnitude of the maximum daily flow rate for the period t_2 (Q_2):

$$\Delta Q_2 = \left(\frac{Q_2}{Q_1} - 1\right) \cdot 100\% \quad (3)$$

and its reciprocal form indicating the increase of Q_1 compared to Q_2:

$$\Delta Q_1 = \left(\frac{Q_2}{Q_1} - 1\right) \cdot 100\%. \quad (4)$$

A Kolmogorov–Smirnov test rejects at a $p = 0.05$ significance level that the population of all catchments (and per continent) ΔQ is normally distributed, suggesting a non-parametric statistical test is needed to determine whether ΔQ_1 and ΔQ_2 originate from the same distribution (which implies no change in flood magnitude) or from different distributions (which implies a change in flood magnitude). The two distributions are compared to one another, because a single ΔQ distribution is skewed towards a flood increase, because it has a (theoretical) lower limit of zero and a (theoretical) upper limit of infinity. We therefore used a two-sided Wilcoxon signed rank-test [35] (which makes no prior assumptions on the shape of studied distributions) to quantify the likelihood that the median of ΔQ_1 is equivalent to the median of ΔQ_2 to assess whether changes in flood magnitude are significant.

3. Results and discussion

We display the 5 year moving average of overall and continental extreme flood occurrence rates (figure 2(*a*)) based on the timing of the largest daily flow event of each catchment during the 30 years of observations (figures 2(*b*)–(*e*)). Overall, and per continent, the frequency of extreme floods, i.e. the fraction of catchments experiencing their maximum flood at a certain moment, shows considerable temporal variability. If these extreme floods were fully independent both spatially and temporally, the expected frequency would be 0.033 yr^{-1}. Yet, all regions have flood occurrence rates that differ substantially from this mean rate (figure 2(*a*)), indicating extreme flooding is clustering in time at regional scales. The overall occurrence rate shows substantial temporal variations, with a notable peak in extreme flood occurrence rates

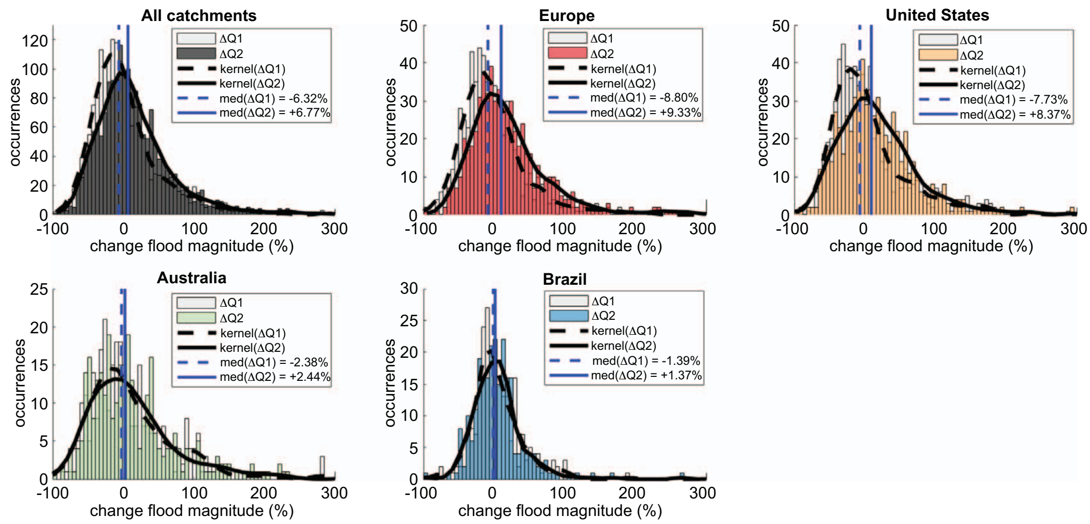

Figure 3. Changes in flood magnitude of each catchment's largest flood. To quantify how floods changed in magnitude we compare the magnitude of the maximum flow events of period t_1 (Q_1) to the magnitude of maximum for the subsequent period t_2 (Q_2) using ΔQ_1 and ΔQ_2 (see equations (3) and (4)), for all catchments, and per continent. Smoothed versions of the histograms are displayed by kernel density estimations. The changes in magnitude are shown for Europe, United States, Australia, and Brazil.

around 1995. Such identification of flood-rich and flood-poor periods has been used before to understand the dynamics of flood regimes [e.g. 7, 16, 27, 36–38]. A simple linear trend suggests this multi-continental rate has also increased over time (figure 2(*a*)). This means more catchments have experienced their most extreme floods more recently. To further test this apparent non-stationarity in flood occurrences, we split the data into two periods of equal length ($t_1 = 1980–1994$, $t_2 = 1995–2009$) and calculate the relative difference in flood occurrences between the two periods. The total number of occurrences of extreme floods increased by 26.6% across all catchments (equation (1), figure 2), where a chi-squared significance test rejects ($p < 0.001$) the null-hypothesis of no change in flood probability (equation (2)). This indicates that across multiple continents the frequency of extreme floods has increased, with the caveat that the significance level and percentages of this increase will change when other temporal or spatial intervals are used given the strong temporal and regional variability (figure 2). For example, the relative occurrence of maximum floods in the three consecutive 10 year periods between 1980–2009 is 28.9%, 36.6% and 34.5%, which is consistent with the overall increase of floods during the 30 year period and a peak in the 1990s.

The relative increases in the occurrence of extreme floods are strongest in the Northern Hemisphere regions. In Europe, the flood occurrence rate increased by 44.4% ($p < 0.001$), whereby the most recent 15 years have many more floods than in the period before 1995. Flood occurrences in the United States increased by 21.4% ($p = 0.030$), but temporal variations are much stronger, with the flood occurrence rate peaking around halfway through the 1990s. Flood occurrence increases are smaller and less significant within the Southern Hemisphere, with increases of 11.6% in Australia ($p = 0.335$), and 14.0% in Brazil ($p = 0.301$) (equations (1) and (2)). Both Australia and Brazil also have less pronounced increases in flood occurrence compared to the flood increases in Europe, with a much larger influence from temporal variability on the regional pictures of extreme flooding. The regional percentages and significance levels of these increases may also change when data are aggregated into alternative time intervals.

Given these changes in the frequency of extreme floods, we next ask whether these increases in frequency are also associated with a significant increase in the magnitudes of extreme events. A comparison of the maximum daily flow rate of both t_1 and t_2 within each catchment can indicate the percentage increase (or decrease) of flood magnitudes between the two periods. Applying equation (3) to all catchments, we find that the multi-continental aggregated extreme floods (ΔQ_2) have a median increase of 6.77% in magnitude (figure 3(*a*)). A two-sided non-parametric Wilcoxon signed rank-test indicates the median flood increase of ΔQ_2 is significantly larger than the median of ΔQ_1 ($p < 0.001$). This means that peak flows for the largest floods were significantly higher in the period 1995–2009 than they were in the previous 15 years. Again, hemispheric differences in these changing extreme flood magnitudes exist (ΔQ_2, figures 3(*b*)–(*e*)); with flood magnitudes increasing relatively strongly in the United States (+8.4%, $p < 0.001$) and Europe (+9.9%, $p < 0.001$), while increases for the other continents are less strong or not significant: Australia (+2.4%, $p = 0.753$) and Brazil (+1.4%, $p = 0.456$).

While the above analyses do not inform the magnitude of change expected within individual catchments, they do indicate that at continental and multi-continental scales there is strong temporal variability as well as increasing trends in both the magnitude and frequency of extreme flood events. This regional picture of extreme flooding is important since it is rarely assessed, because measures of extreme floods are usually obtained by extrapolating the rating curves and therefore are likely to contain uncertainties [39]. However, our spatially aggregated approach looks at relative differences, which reduces the influence of the observation uncertainty of extreme floods. The extreme events we studied are orders of magnitude larger than mean flow rates, and, on average 3.9 times larger than the mean annual flood peaks. Although these extreme events will have been implicitly contained within previous studies that focused on annual flood peaks, or peaks over threshold analyses, trends in these more frequent flood peaks do not necessarily correspond with changes in the behavior of extreme floods. For Europe, our reported increases in extreme flood occurrence rates and magnitudes are consistent with the observed increase in the inundated area and news coverage on rare floods over the past decades [40]. In contrast, there is no clear overall trend of observed annual flood peaks across Europe [23]. For the United States, the most recent decade had lower extreme flood occurrence rates than midway through the 1990s. Trends in annual flow peaks are highly variable [13, 14], and only very frequently occurring (i.e. bi-annual) flood peaks in the Midwest have been identified to show a clear increasing frequency in recent decades [24]. For Australia, we observe a clear increase in extreme floods from ~2004 onwards (figure 2), although this begins prior to the end of overall drought conditions around 2009 [41]. Therefore, the smaller increase in extreme flood events in Australia may be influenced by the lower likelihood of flood conditions during the prolonged multiyear drought. Importantly, while extreme floods for individual river basins have been studied in Brazil [42–44], our study also provides the first assessment of extreme flood changes over multiple catchments in South America. These results therefore highlight the need for more regional-based assessments of changes in extreme flooding, since this is the scale at which the impacts of these changes will be managed and mitigated against.

Understanding the physical causes behind these recent changes in extreme floods is a crucial next step before we can assess the degree to which our findings are representative of other regions and future conditions [45, 46]. The hydrological time-series we used is relatively short and catchments (with some exceptions, e.g. in Brazil) have minimal human influence. Consequently, we consider it unlikely that engineering and land-cover changes are the dominant cause of the changes in the flood signal. Both climatic variability and long-term shifts in climatic conditions can be considered more viable drivers of the observed evolution in extreme flood occurrence rates and changes in flood magnitude. Changes in flood magnitudes in individual rivers [29, 47], as well as across larger regions [48, 49] have been linked to climate variability. Although we cannot yet provide attribution for the observed recent changes in extreme floods, an overarching causality is likely to remain elusive as flood-generating mechanisms vary strongly between catchments [20], and there are many potential causes of flood change that will also vary between catchments and time periods. The difficulty in attributing physical causes is also compounded by the fact that changing characteristics of extreme floods for individual rivers cannot be determined, and the mechanisms generating more frequently occurring (e.g. annual) flood peaks are likely to differ from those that generate the most extreme events. When simulation models are used, attribution can also be challenging, because of the substantial uncertainty in model simulations of floods [6–11, 17], especially the most extreme ones.

4. Conclusions

For the first time, we are able to quantify multi-continental changes in the frequency and magnitude of extreme floods. The spatially aggregated approach does not allow for determining changes at individual catchments, but the data suggest that in addition to strong temporal variability there have been increases during 1980–2009 in both the magnitude and frequency of regional extreme floods. These increases have been strongest in Europe and the United States, and weaker in Australia and Brazil. Such flood changes have significant societal relevance as these extreme events are often most damaging [50], influence the design of major structures [46], and shape the riparian environment [51]. Moreover, impacts at the regional scales assessed here are more relevant for extreme flood management and mitigation, but are usually not captured by traditional flood analysis. The studied catchments cover many regions, but due to data limitations do not include some of the most flood-prone regions of the world (e.g. Southeast Asia [50]), and are not necessarily representative of future conditions. However, the approach provided here can easily be extended to these regions as data become available. Future research focused on understanding the cause of these changes will allow more reliable predictions of the future extreme floods, especially for the large areas of the globe that remain poorly monitored.

Acknowledgments

The National Water Agency of Brazil (Agencia Nacional de Aguas) provided streamflow data of the Brazilian catchments (www.snirh.gov.br/hidroweb). The State government water monitoring agencies of Queensland (www.dnrm.qld.gov.au/water/water-monitoring-and-data/portal), New South Wales (http://realtimedata.water.nsw.gov.au/water.stm), Victoria (http://data.water.vic.gov.au/monitoring.htm), and Tasmania (http://wrt.tas.gov.au/wist/ui#fopt) provided streamflow data for the Australian catchments. Andrew Newman (NCAR) provided data for the US catchments (http://ral.ucar.edu/projects/hap/flowpredict/subpages/modelvar.php). Most of the European records are part of the United Nations Educational, Scientific and Cultural Organization's (UNESCO) European Water Archive, which includes data provided by the European sub-network (EURO-Flow Regime from International Experiment and Network Data (FRIEND). Comments by two anonymous reviewers helped us to improve this manuscript.

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