Author/s:
Wasko, C;Nathan, R;Stein, L;O'Shea, D

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Evidence of shorter more extreme rainfalls and increased flood variability under climate change

Conrad Wasko[1*], Rory Nathan[1], Lina Stein[2], and Declan O'Shea[1,3]

[1]Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria

[2]Department of Civil Engineering, University of Bristol, Bristol, UK

[3]Climate and Energy College, The University of Melbourne, Parkville, Victoria 3010, Australia

Correspondence

*conrad.wasko@unimelb.edu.au

Key points

Extreme rainfall has increased, with greater increases for more extreme events.

Storm volumes show lesser trends, and there is a shift to shorter rainfall events.

Flood peaks for frequent flooding have decreased across many parts of the world.

Flood peaks for rarer flood events have increased across many parts of the world.

Changes in antecedent soil moisture are modulating changes in flooding.

Key words

Flooding; Extreme rainfall; Soil moisture; Trend analysis; Climate change

Abstract

Increases in extreme rainfall intensities as a result of climate change pose a great risk due to the possibility of increases in pluvial flooding, particularly in urban and developed areas. But evidence is emerging that the observed increases in extreme rainfall are not resulting in universal increases in flooding. Indeed, on a global scale, studies consistently find more gauge stations with decreasing rather than increasing trends in the annual maxima flood magnitude. Here, we aim to improve our understanding of how rainfall and streamflow extremes are changing and why floods are not always observed to increase despite increases in rainfall extremes. To do so, we examine trends in streamflow events using 2776 stations from the Global Runoff Data Centre, with events chosen to isolate the impact of changes to their respective rainfall and antecedent soil moisture. The analysis is limited to stations with 30 years or more of active record with the majority of stations in North America, Europe, Brazil, Oceania, and southern Africa.

Consistent with physical reasoning, for more frequent events such as the annual maxima, it is found the peak 1-day rainfall event intensity is increasing approximately a rate of 6-7%/°C, with rarer event intensities increasing at a rate exceeding the Clausius-Clapeyron relation. We find that storm volumes are not increasing as greatly as the peak rainfall and storm durations are decreasing, pointing to an intensification of rainfall events and a peakier temporal pattern. While rainfall is intensifying, the magnitude of frequent floods (those expected to occur on average once per year) are in general decreasing, particularly in tropical and arid regions of the world. We find that this is likely due to a dominance of drying antecedent soil moisture conditions. However, the magnitude of rarer floods has, on average been increasing. We suggest this is because, for these rarer events, the increase in rainfall outweighs the decrease in soil moisture. Our results point to a worst of both world's scenario where small floods, responsible for filling our water supplies, are decreasing, while the large flood events which pose a risk to life and infrastructure, are increasing.

1. Introduction

Flooding is one of the most common and costliest natural disasters (Razavi et al., 2020) with increasingly more people at risk of flooding (Paprotny et al., 2018). With climate change, flood risk is expected to increase in urban areas due to intensification of extreme rainfall and a lack of pervious surfaces (Fadhel et al., 2018; Hettiarachchi et al., 2018; Jha et al., 2012). Any change in the frequency of flooding is likely to have huge economic consequences with greater flood magnitudes increasing economic losses (Arent et al., 2014; Wasko et al., 2021b) and decreases in flood magnitude threatening water security (Sharma et al., 2018). Only small changes in climate are required to have large consequences to our ecosystems and economy (Alley et al., 2003). For example, changes of 1-2°C and 10-20% in annual precipitation can cause order of magnitude changes in flooding (Knox, 1993).

Average precipitation across the globe has increased by approximately 2mm/year per decade (Hartmann et al., 2013), with a suggestion that this has primarily occurred over the tropics with decreases elsewhere (Beck et al., 2019). While changes in annual mean precipitation rates will affect antecedent moisture conditions, changes in peak or high streamflow magnitude (here termed flooding for simplicity) are expected to be driven by changes in extreme precipitation. Globally, the magnitude of extreme precipitation has increased (Donat et al., 2016; Westra et al., 2013). For daily annual maxima, the average increase of 5.9-7.7%/°C (Sun et al., 2021; Westra et al., 2013) matches the theoretical Clausius-Clapeyron (6-7%/°C) increase in the moisture holding capacity of the atmosphere due to higher temperatures (Fowler et al., 2021; Trenberth, 2011). But there is also an expectation that more extreme (rarer) daily rainfalls will increase even further (Pendergrass, 2018; Pendergrass and Hartmann, 2014) with increases above the Clausius-Clapeyron rate observed (Guerreiro et al., 2018; Wasko and Nathan, 2019) and modelled (Bao et al., 2017) for events rarer than daily annual maxima.

In contrast to the increasing trends in precipitation extremes on a global scale, regional studies of flood magnitude show very mixed trends (Archfield et al., 2016; Blöschl et al., 2019; Hall et al., 2014; Mallakpour and Villarini, 2015; Wasko and Nathan, 2019). One global investigation of trends in annual flood maxima, using 9213 stations, found the number of sites showing statistically significant decreasing trends was greater than the number of sites showing statistically significant increases (Do et al., 2017). Similar results were also found for a range of flow percentiles across the world suggesting entire flow distributions have moved either upward or downward (Gudmundsson et al., 2019). Another global study found increasing 20-year and 50-year floods in temperate climates but mostly decreases elsewhere (Slater et al., 2021). Further confounding our understanding, modelled (Do et al., 2020) and projected (Hirabayashi et al., 2013) increases in flooding are not consistent with the large number of stations exhibiting historical decreases in flood magnitudes. Global flood models project 30 year and 100 year average recurrence interval (ARI) flood increases across the majority of the globe with decreases only in limited regions of central Europe, south east Australia, and central South America (Arnell and Gosling, 2016; Dankers et al., 2014; Hirabayashi et al., 2013).

It can be expected that changes to pluvial flooding in highly urban areas may be driven by changes in precipitation extremes as there is little impervious area (Hettiarachchi et al., 2018), but this transfer function between precipitation and flooding doesn't hold in non-urban areas (Ivancic and Shaw, 2015; Sharma et al., 2018). The soil moisture state of the catchment before it rains modulates flooding (Ivancic and Shaw, 2015; Pathiraja et al., 2012) and hence the historical trend in flooding (Tramblay et al., 2019; Wasko and Nathan, 2019). Indeed monthly precipitation anomalies do not correlate well with flood anomalies (Stephens et al., 2015) and a low correlation was found between changes in precipitation extremes and changes in flooding across the U.S (Do, Mei, et al., 2020). Here, we suggest that the discrepancy between extreme rainfall trends and flood trends is, at least in part, due to (a) a lack of consistency in the magnitude of the extreme event considered (Bennett et al., 2018; Bertola et al., 2021; Wasko and Nathan, 2019), and (b) changes in the antecedent moisture conditions (Ivancic and Shaw, 2015; Sharma et al., 2018; Wasko, 2021).

Although many studies examine trends in rainfall and streamflow, few, if any studies examine trends in these variables concurrently. Moreover, historical trends in antecedent moisture are rarely studied, with trend studies focusing on either changes in mean soil moisture (Albergel et al., 2013; Feng and Zhang, 2015) or the antecedent precipitation (Woldemeskel and Sharma, 2016) as a surrogate for the actual antecedent soil moisture. Finally, with few exceptions, historical trends in events rarer than annual maxima are seldom studied (Slater et al., 2021). Here, we examine the influence of changes in extreme rainfall and soil moisture on flood magnitude, and how this influence varies with event duration and rarity. In doing so, we aim to understand why, in the absence of snowmelt, floods are not always observed to increase despite increases in rainfall extremes. Using the Global Runoff Data Centre streamflow database, we identify the antecedent soil moisture, storm volume, and peak rainfall associated with flood events. We investigate the trend in each, along with the resultant peak flood magnitude, across a range of event severities, to see whether any consistency between changes to rainfall extremes and flooding can be identified.

2. Methods

We investigate historical trends in streamflow peaks using data from the Global Runoff Data Centre (GRDC, 2015), where the storm rainfall, storm volume, and soil moisture, coincident with the flood event, were obtained from the Global Land Data Assimilation System (GLDAS) Version 2 (Rodell et al., 2004). Events are sampled on the basis of rainfall to ensure that antecedent conditions are independent from the resultant flood. A peak over threshold approach is employed to identify rainfall events and the associated flood peak, with historical trends subsequently investigated by quantile regression in order to capture variation with event rarity.

2.1 Data

Daily streamflow from the Global Runoff Data Centre (GRDC, 2015) was analysed as these have been successfully used in other global studies (Do et al., 2017; Lee et al., 2015; Milly et al., 2018; Wasko et al., 2020). Rainfall, snow fall, snow depth, snowmelt, and root zone soil moisture at the catchment outlet were extracted from the Global Land Data Assimilation System (GLDAS) Version 2 (Rodell et al., 2004) for the years 1948 to 2014. GLDAS forcings, including rainfall, are from the Global Meteorological Forcing Dataset which combines a suite of observation-based datasets with reanalysis (Sheffield et al., 2006). Hence the rainfall can be considered observed. As root zone soil moisture has been identified to be most correlated with catchment flood response (Hill and Thomson, 2019) root zone soil moisture was used as representative of the catchment soil moisture state. The model for soil moisture is a stationary deterministic process and hence will not interfere with calculated trends (Wasko and Nathan, 2019). The assumptions that outlet measurements are representative of catchment conditions, and that GLDAS is representative of gauged observations, were verified using a high-quality (observed) catchment average data set for Australia and are discussed in Section 4.3.

2.2 Event sampling

Events were selected on the basis of rainfall to ensure that the antecedent conditions are independent of the flood response. For example, sampling events on the basis of flooding will bias antecedent conditions towards wet catchment conditions. A rainfall event is identified if separated by one or more days of zero rainfall with any rainfall below 1 mm assumed to be zero. The storm volume is the sum of the rainfalls over the duration of the event, the peak rainfall is the maximum daily rainfall within the event, and the antecedent moisture (or soil moisture) is the root zone soil moisture on the day before an event commenced. The peak streamflow (or peak flow) is the maximum streamflow observed after the start of the rainfall event to five days after the end of the rainfall event or before the next event. Baseflow was removed from the streamflow using a recursive digital filter (Nathan and McMahon, 1990) meaning the peak flow response is a function of the storm rainfall and soil moisture. The total number of events for each station was equal to five times the record length, with only the largest rainfall events sampled. For example, for a site with 50 years of record, the largest 250 events are sampled and subsequently analysed. This approach ensures that exceedance percentiles are consistent between stations. To focus on the impact of changes in soil moisture on the pluvial flood process we need ensure our data set is free of snowmelt. Any event that has snow present in the precipitation, or is modelled to have snowmelt present, is removed to ensure no mixing of flood mechanisms other than the interaction of rainfall and antecedent moisture (Collins, 2019; Wasko et al., 2019). Flood drivers also vary with catchment size (Wasko and Sharma, 2017a). For example, smaller catchments are less sensitive to changes in antecedent moisture (Wasko and Nathan, 2019) with larger rainfalls (and hence floods) less likely to be influenced by soil moisture storage (Ivancic and Shaw, 2015). As a result, we restrict our analysis to catchments less than 20 000 km^2. We note that catchments smaller than 20 000 km^2 have a lag time between rainfall and streamflow of less than five days ensuring the peak flow is captured and there is a more direct link with between the rainfall and runoff. Increasing the maximum allowed lag time between the rainfall event and peak flow did not materially change the results.

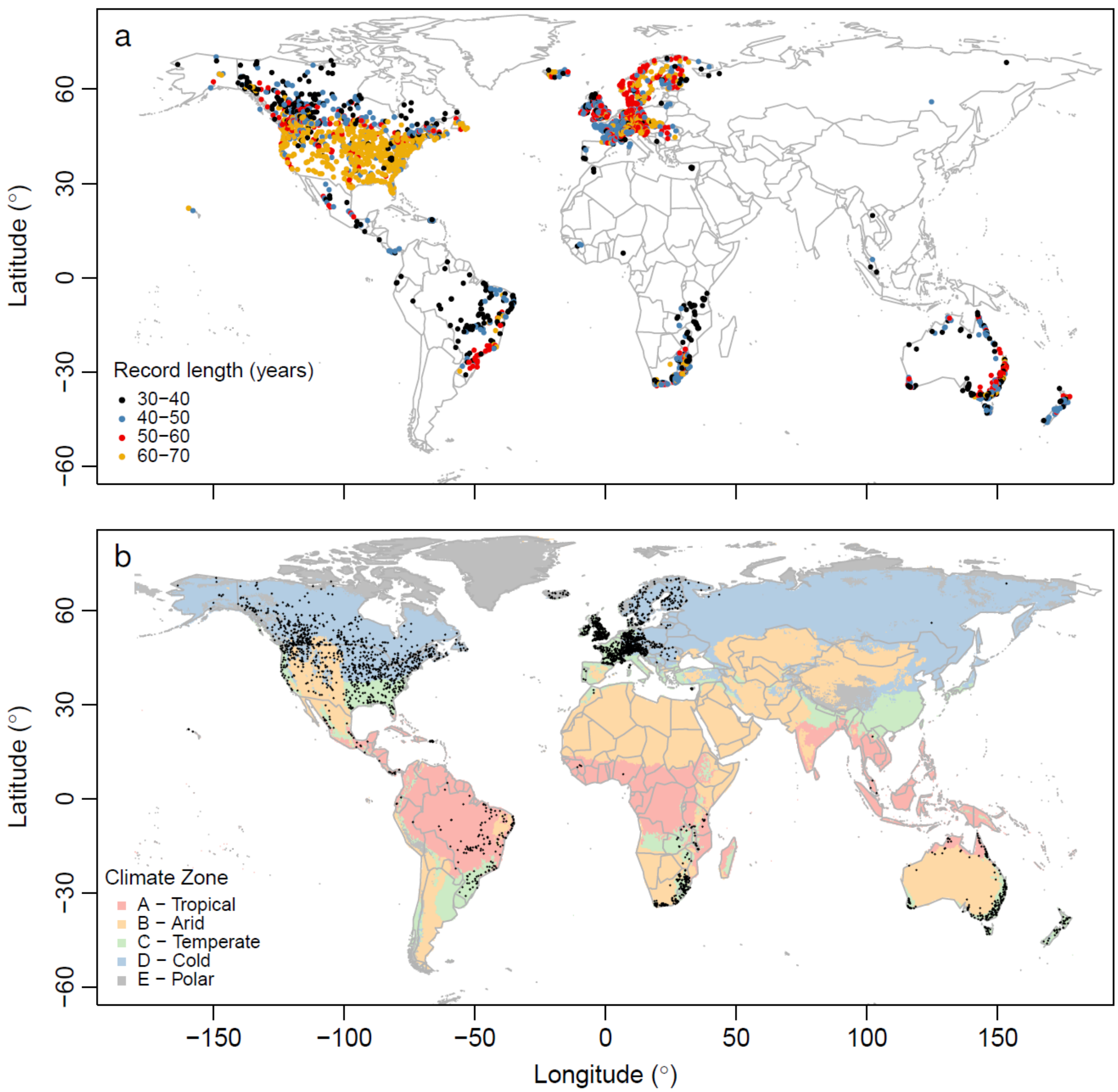

Figure 1. Station locations and record length (a) Record length (b) Station locations relative to main Köppen climate classification (Beck et al., 2019).

2.3 Station selection

To reduce the impact of drought periods, stations in highly ephemeral or arid catchments where more than 20% of events result in zero flow were omitted, as were stations with periods of zero flow greater than three years. We restricted our analysis to sites with 30 years or more of active record. In total 2776 sites were analysed with median record length of 51 years (Figure 1a) with the majority of sites located in temperate and cold Köppen climate zones across North America, Europe, Brazil, Oceania, and southern Africa (Figure 1b). The median catchment area is 1 129 km^2 and 78% of sites have a catchment area less than 5 000 km^2. Hence the majority of catchments can be considered hydrologically small. For the readers' interest the mean seasonality, calculated as a circular mean (Fisher, 1993; Wasko et al., 2020a) of the chosen events is presented in Figure S1. In the southern hemisphere sampled events generally occur in the month of peak rainfall seasonality – in the tropics the austral summer, and further south, the austral winter. In the northern hemisphere events sampled events generally occur in the boreal summer. This confirms the absence of snowmelt in the sample. We note the analysis was repeated restricting the data range to a common period (1970-2000) and to only using the "pristine" GRDC stations (those largely free of diversions and basin development) and the results were consistent with those presented here.

2.4 Calculation of Trend and Association with Flood Drivers

With the exception of the storm duration for which linear regression was used, trends for each of the peak over threshold series (peak rainfall, storm volume, soil moisture, and peak flow) were calculated using quantile regression (Hao and Naiman, 2007; Koenker, 2021; Koenker and Bassett, 1978). Quantile regression was used as it allows investigation of trends in extreme percentiles. A quantile regression was fitted between the independent response variable (y_i) and the dependent variable, time (t_i), in the units of days. Peak rainfall, storm volume, and peak flow were logarithmically transformed with the following relationship fitted:

$$\log_{10}(y_i) = \beta_0^{(q)} + \beta_1^{(q)} t_i + \epsilon_i^{(q)} \quad (1)$$

where $0 < q < 1$ is the quantile, ϵ_i is an error term with zero expectation, and *i = 1.. m* where *m* is the total number of samples for the site location. The logarithmic transform was employed to obtain residuals with zero expectation, where zero flows were set to the minimum recorded flow to allow for log transformation. Sensitivity tests showed that setting zero flows to the minimum on record had almost no influence on calculated trends.

The regression coefficients β_0 and β_1 represent a constant and the linear change in the response variable per unit change in time (*t*), respectively. A choice of *q* = 0.5 for the quantile (non-exceedance percentile) corresponds to the median tendency between the dependent variable (t_i) and response (y_i). Trends for more extreme data quantiles were investigated using quantiles (*q*) above 0.5. The trend per decade ($\Delta\%/10\text{Y}$) as a percentage was calculated using following transformation where *n* is the number of days in 10 years:

$$\Delta\%/10\text{Y} = 100 \cdot (10^{n\beta_1} - 1) \quad (2)$$

Soil moisture did not require transformation of residuals and the trend per decade is reported as the slope (β_1) of the fitted regression multiplied by the number of days in 10 years. A notional ARI was assigned to the rainfall quantile using the following equation (Stedinger et al., 1993):

$$q = 1 - \frac{1}{\lambda} \ln \left[\frac{T_a}{T_a - 1}\right] \quad (3)$$

Where *q* is the non-exceedance percentile of interest, λ is the average number of events per year, in this case 5 (Section 2.2), and T_a is the ARI in years. Finally, the association between the peak flow and the flood drivers (peak rainfall, storm volume, and soil moisture) was calculated using a Pearson correlation coefficient. The use of a rank-based Spearman correlation gave similar results.

3. Results

3.1 Association of the flood peak to event rainfall and soil moisture conditions

To assess the influence of antecedent soil moisture, peak rainfall, and storm volume on the peak flow we present the correlation of peak flow with each of these streamflow drivers in Figure 2. For a sampling frequency of five events per year the peak rainfall has a relatively low median correlation (0.12) with the peak flow. The storm volume-peak flow median correlation is slightly higher (0.28), but the highest correlation for the peak flow is with antecedent soil moisture (0.39). Peak rainfall, storm volume, and soil moisture are hence all driving the resulting peak flow, but for frequent events, on average occurring five times a year, the antecedent soil moisture is the primary driver of the flood response. Overall, the correlations changed little when sampling frequency was varied from 1 to 10 events per year on average (Figure S2).

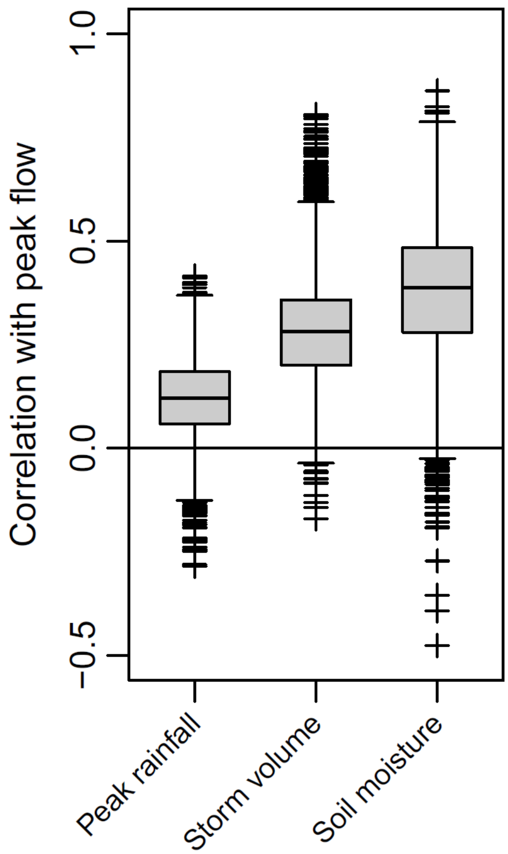

Figure 2. Correlation of peak flow with peak rainfall, storm volume, and soil moisture for each site. The boxplot whiskers extend to data which is no more than 1.5 times the interquartile range.

To quantify the magnitude of the response to change in antecedent soil moisture and rainfall the variation in peak flow resulting from different combinations of peak rainfall and soil moisture is presented in Figure 3a. To aggregate between sites, at each station the events for each variable are divided by the mean at that site with contours presenting a ‘heat map’ of antecedent soil moisture. Referring to Figure 3a, a relatively small rainfall leads to a small flow peak when the soil is dry (bottom-left). However, the same relatively small rainfall can result in a large flow peak if the catchment is wet (top-left). Hence, for the same rainfall magnitude differing catchment soil moisture before the rainfall can result in orders of magnitude difference in the flow. If the rainfall is large, a large flow will result, regardless of the soil moisture (top-right). This is because, the more extreme the rainfall event is, the less the modulating effect of the antecedent soil moisture conditions. We note, the same relationship is observed for the storm volume (Figure 3b), whereby a small difference in the soil moisture can result in order of magnitude differences in the peak flow for the same storm volume.

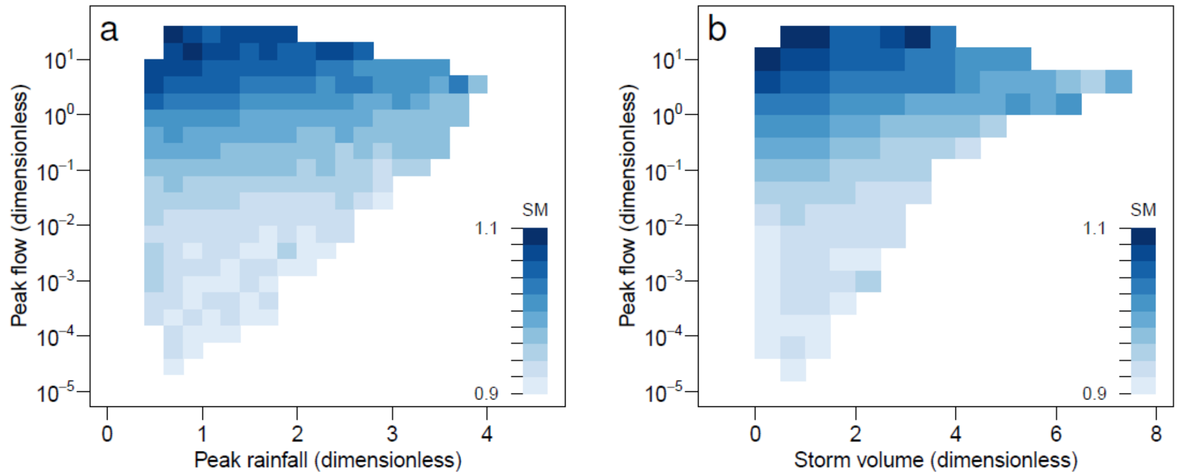

Figure 3. Relationship of pluvial flood magnitude to magnitude of flood drivers (a) Surface of antecedent soil moisture for all pairs of peak flow and peak rainfall (b) Surface of antecedent soil moisture for all pairs of peak flow and storm volume. In panel (a, b) the peak flow, peak rainfall, storm volume, and soil moisture (SM) are standardised at each site by the mean of all data at that site. Each pixel is the median of all the data points falling in that pixel. Only pixels with more than 20 points are shown. A total of 712,385 events are used for each of the plots generated.

3.2 Trends in flood drivers

Trends in frequent flooding and its drivers (peak rainfall, storm volume, and soil moisture) are presented in Figure 4 for the 50th and 95th percentile. We first focus on the results for 50th percentile in the left column. There is an almost universal increase in peak rainfall for the 50th percentile of sampled events (top-left) in the order of 0-2% per decade (Figure 4). Storm volumes show very mixed trends. For the 50th percentile storm volumes are decreasing across most of Europe, South Africa, and Australia, as well as part of the west coast of the U.S. Increases are observed in the UK and over the east and mid-west of the U.S.

On average, the 50th percentile antecedent soil moisture is decreasing (Figure 4). It needs to be noted that this is distinct from annual mean soil moisture. Although trends in antecedent root zone soil moisture exhibit a strong positive correlation of 0.78 with trends in annual mean soil moisture trends (not shown), they will not necessarily correspond. For example, although Europe exhibits historical increases in mean soil moisture (Albergel et al., 2013), antecedent soil moisture for events devoid of snowmelt has been decreasing. Here, the only regions that show increases in antecedent soil moisture are those that show increases in storm volumes, that is, the mid-west of the U.S and the U.K. (Figure 4). These regions correspond to regions that have also previously been identified as having increased flood magnitudes such as the north east U.S. (Archfield et al., 2016) and northern Europe (Blöschl et al., 2019). The bottom-left panel summarises the trends in the 50th percentile of peak flows and confirms trends presented in previous regional studies (Merz et al., 2021; Wasko, 2021). Peak flow magnitude is trending negatively in the south and western U.S., southern Europe, and the majority of the southern hemisphere. These regions coincide well with the regions of drier antecedent soil moisture conditions and reductions in storm volume presented in the panels above. The regions experiencing greater peak flow magnitudes generally correspond to the regions of wetter antecedent moisture. It appears that for frequent events, trends in the peak flow appear more linked to soil moisture with trends in peak flow bearing little resemblance to the increasing extreme rainfalls.

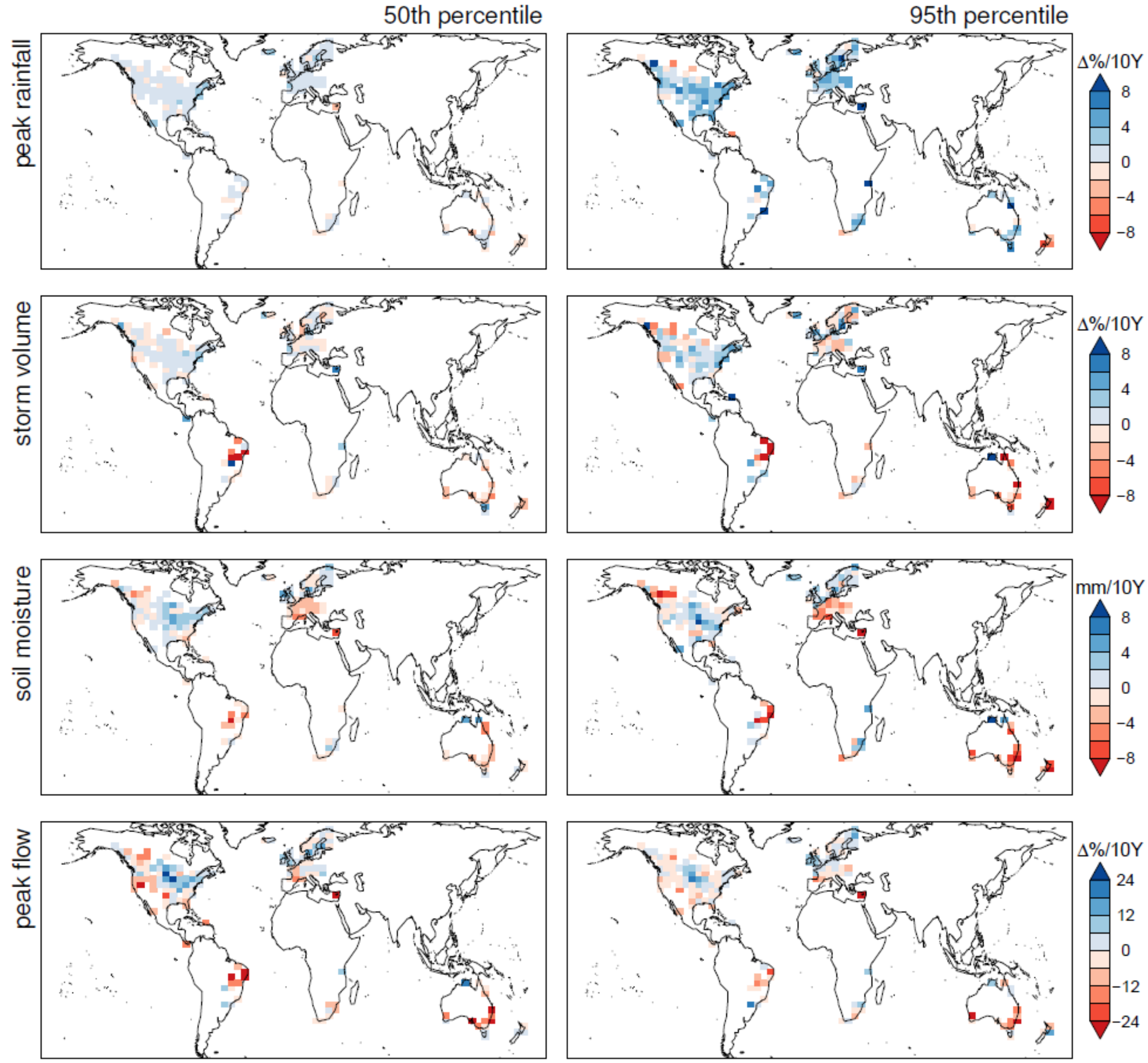

Figure 4. Trend in the 50th percentile (left column) and 95th percentile (right column) of peak rainfall, storm volume, soil moisture, and peak flow from sampled events. Blue represents a shift to wetter conditions and red towards drier conditions. Each 5° X 3° grid cell is the median trend for all the underlying stations. Only grid cells containing five or more stations are shown. Figure S3 presents individual station trends.

The right column presents the trend in the 95th percentile of sampled events. Compared to the more frequent events (left column) there are now strong increases in the magnitude of severe rainfall extremes in the order of 4-6% per decade (top-right). Storm volume trends remain similar to the 50th percentile - across Europe there is a slight drying trend and across the U.S. a slight wetting trend. Again, similar to the

50th percentile, for the 95th percentile, soil moisture has been decreasing across Australia, parts of Brazil, and southern Europe, with the only exception northern Europe, the east coast of the U.S, and northern Australia. However, flood trends differ for the 95th percentile compared to the 50th percentile. In the southern hemisphere the more severe events exhibit more positive trends in southern Africa, and less negative trends in South America and southern Australia. Similarly, the peak flow trends in the south west of the U.S. are less negative for these rarer events. Although peak flow trends do not follow peak rainfall trends, the dependence on rainfall magnitude presented in Figure 3 appears in the trends presented in Figure 4, with trends in more extreme events potentially less modulated by changes in soil moisture. The relationship between the trend in the peak rainfall, storm volume, soil moisture, and peak flow and the rarity of the event (percentile) is elucidated further in Section 3.4.

3.3 Trend in storm duration

The discrepancy between changes in the peak rainfall and storm volume requires further attention as one would expect with increasing peak rainfall that storm volumes would also increase. The results presented in Figure 4 where extreme peak rainfall is increasing but storm volume is not increasing point to a peakier temporal pattern where, to compensate for the increasing trend in the peak rainfall, the remaining rainfall in the storm is decreasing (Wasko and Sharma, 2015). A change to a peakier storm temporal pattern is equivalent and consistent with a decreasing storm duration, hence it is prudent to investigate trends in the storm duration.

The mean storm duration is presented in Figure 5a. The mean storm duration in the southern latitudes varies generally between 2-4 days but increases to 4-5 days in the tropics (and longer in Brazil) consistent with the prevalence of summer monsoonal rainfall. Across Europe, similar to the temperate climate of Australia, average storm durations of 2-4 days have been sampled. But interestingly across the Midwest of the U.S. shorter storm events indicate a prevalence of summer mesoscale convective weather systems (Prein et al., 2017).

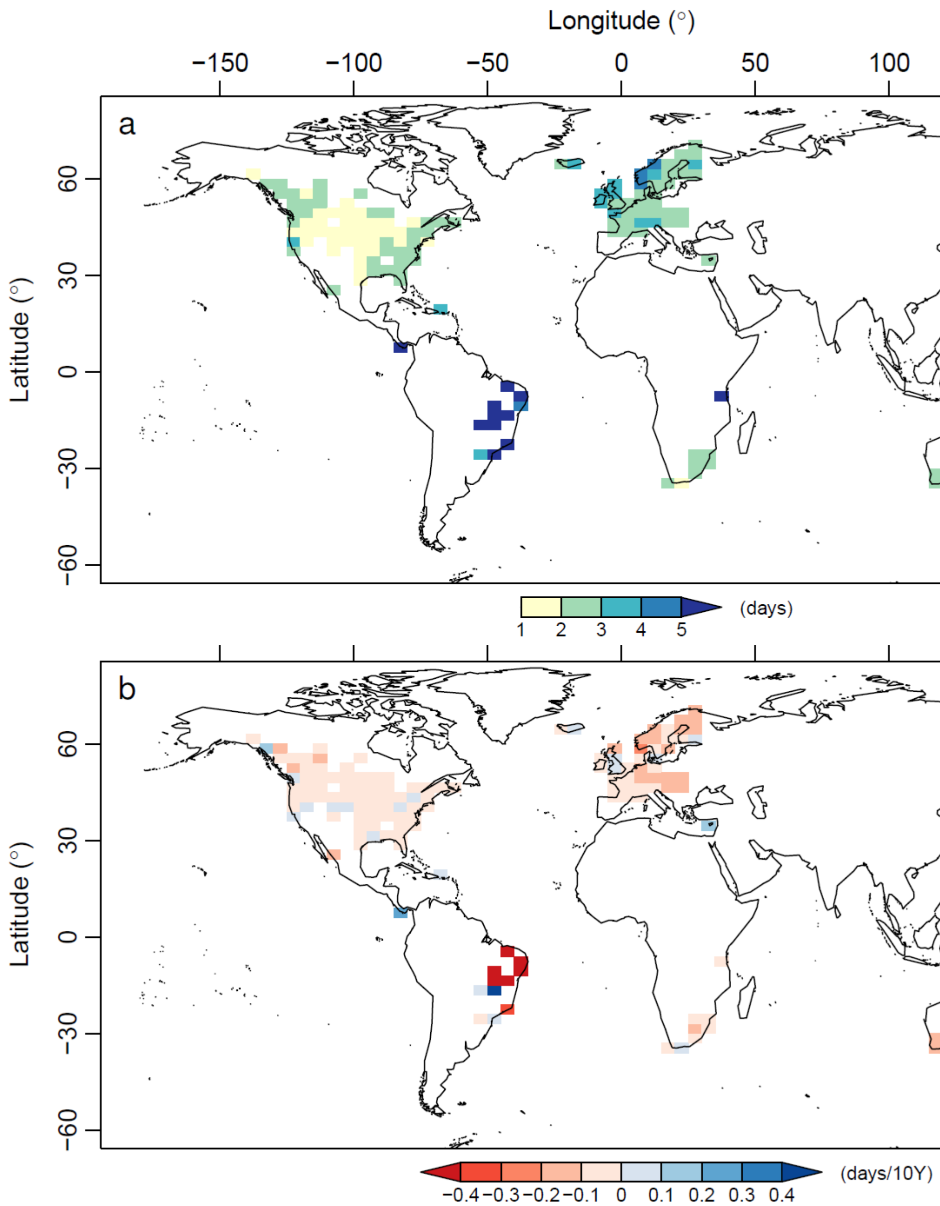

Figure 5. Event duration (a) Mean duration of events sampled (b) Linear trend in event duration. Each 5° x 3° grid cell is the median trend for all the underlying stations. Only grid cells containing five or more stations are shown. Figure S4 presents individual station trends.

The trend in storm event duration is calculated using linear regression (Figure 5b). There is an almost universal decrease in storm duration in the order of 0 to 0.2 days per decade across the globe. Some larger decreases are observed over Brazil where the largest durations are observed, however overall, the picture is very consistent: the average decrease across stations analysed is approximately 0.1 day per decade. Due to the skew of some longer events showing larger decreases, the median change is closer to -0.05 days per decade. Given that the majority of events sampled are well below 5 days in duration, this represents a substantial decreasing trend in rainfall event duration. Using different thresholds for the rainfall (above the 50th, 80th, and 90th percentile of rainfall at that station) and recalculating the trend in the storm duration did not present any evidence of greater trends with increasing event magnitude.

3.4 Variability in flood peak, storm rainfall, and antecedent soil moisture trends

To understand at what level of rarity the dominant flood driver changes (antecedent soil moisture vs peak rainfall), the median trend across all sites analysed for the peak rainfall, storm volume, and soil moisture is presented against the non-exceedance percentile of sampled events (Figure 6). The percentile is converted to a notional average recurrence interval in years using Equation 3 and is also presented in Figure 6 for reference. The three panels present a repetition of the sampling described in Section 2.2 progressively restricting the sample to shorter maximum rainfall event durations. As presented in Figure 4 there is a strong, consistent positive trend in the peak rainfall that increases with event rarity, and this trend is consistent across event durations (Figure 6). Assuming an increase in global temperature over land of 0.2°C per decade, daily annual maxima increase at approximately the Clausius-Clapeyron rate of 6-7%/°C similar to previous studies (Guerreiro et al., 2018; Westra et al., 2013). Events rarer than this however are increasing at a much greater rate that exceeds the Clausius-Clapeyron scaling rate.

Focusing on the left-most panel which presents results that do not restrict the event duration, storm volumes show mixed trends and hence on average the trend is approximately zero. There is little evidence for increasing peak flows, with a much larger variability in the streamflow response (wider confidence intervals) relative to the peak rainfall trend. Despite increases in peak rainfall across all recurrence intervals average peak flow is decreasing for frequent events. It is only for the more extreme rainfalls above the 98th percentile, recurrence intervals rarer than approximately 10 to 20 years, the median peak flow trend is positive. This points to more frequent flood magnitudes decreasing while rarer flood magnitudes are increasing.

As we progressively reduce the duration of the storm event sample to events of seven days or less (centre panel) and three days or less (right panel), the peak one-day rainfall becomes a greater fraction of the total storm volume and an increasing trend in the storm volume emerges (Figure 6). The increasing trend in the storm volume is stronger the rarer the event, as well as the shorter the storm duration. A pattern in the flood trends also emerges, whereby the peak flows are increasing in response to the increase in storm volumes, but they do not exceed the storm volume increase due to the average decrease in antecedent soil moisture. As the threshold of what was considered rainfall (here 1mm) was increased, the events being sampled become larger and more extreme, also resulting in increasing storm volumes in response to the increasing extreme rainfalls. Despite increasing storm volumes for larger events, storm durations continue to shorten (Section 3.3).

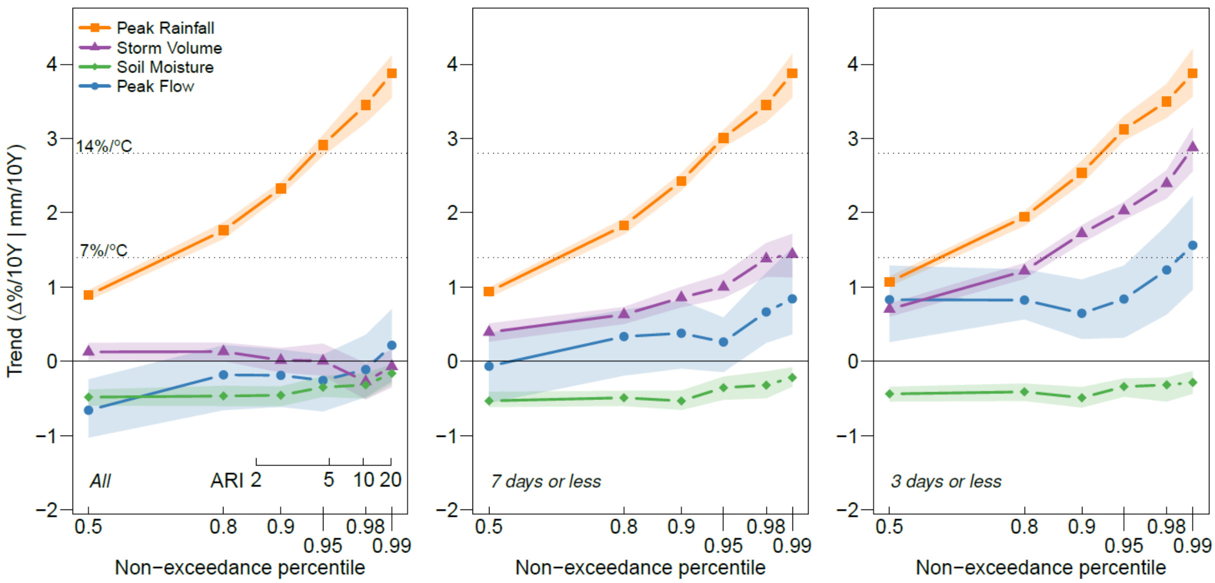

Figure 6. Trend in peak flow and its drivers with increasing event rarity stratified on storm event duration. Event durations are all events (left), events of duration seven days or less (middle), and events of duration three days or less (right). The median trend across all sites is presented with shading representing a 90% confidence interval around the median. Units for the x-axis are the non-exceedance percentile of the sampled events, with a notional average recurrence interval (ARI) in years is also shown. Units for the y-axis are % per decade (10Y) for peak rainfall, storm volume, and peak flow and mm per decade for soil moisture.

3.4 Influence of climate region on trends in flood peak, storm rainfall, and antecedent soil moisture

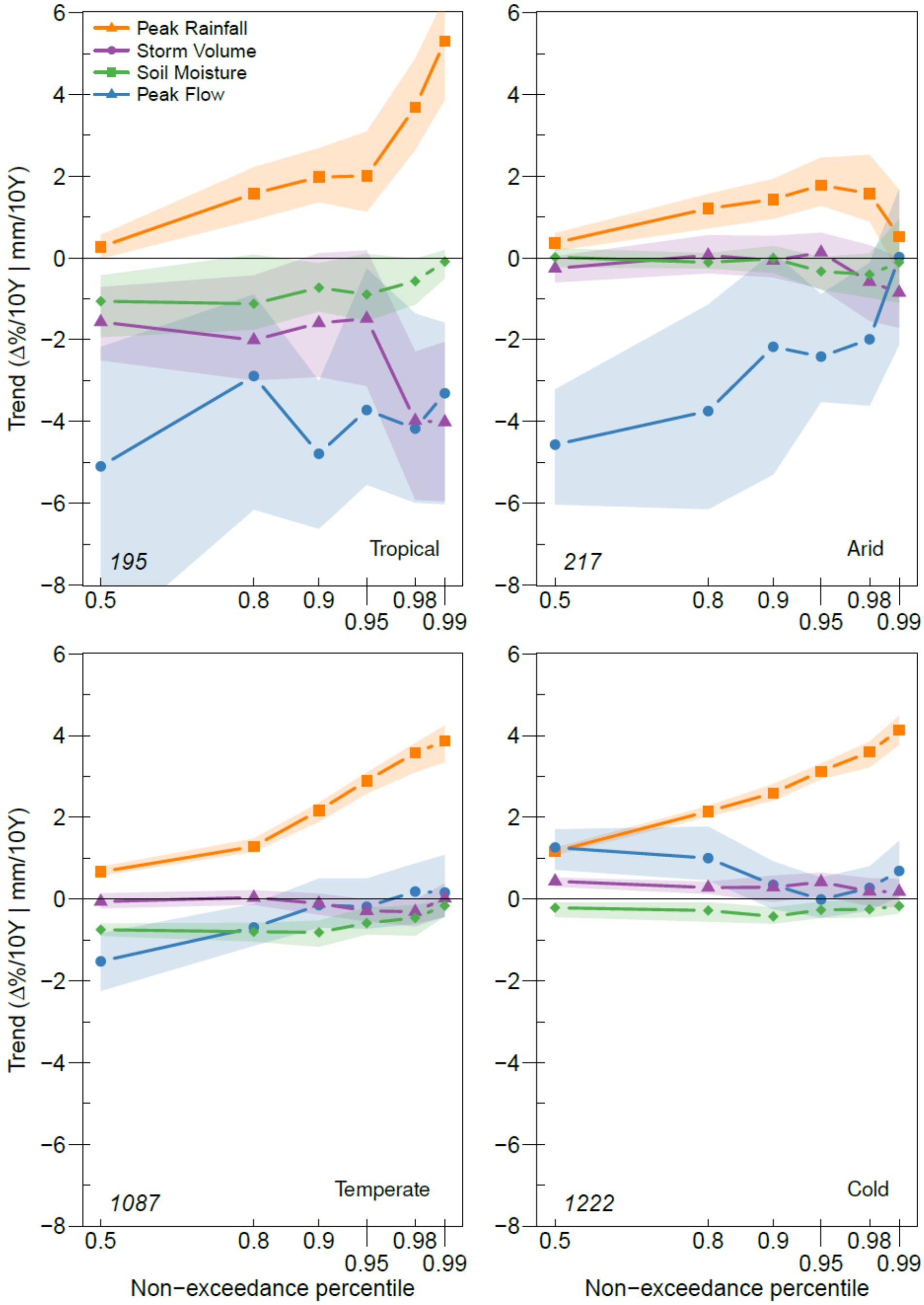

Figure 7. Median trend in peak flow and its drivers with increasing event rarity with climate zone. The climate zone is labelled in the bottom right corner of each panel. Shading represents 90% confidence intervals. Units for the x-axis are the non-exceedance percentile of the sampled events. Units for the y-axis are % per decade (10Y) for peak rainfall, storm volume, and peak flow and mm per decade for soil moisture. The number in the bottom left corner is the number of stations in each climate zone.

Recognising that flood trends vary with region (Figure 4) we follow Slater et al. (2021) and aggregate trends on Köppen climate zone (Beck et al., 2019). The trends with non-exceedance percentile for the main climate zones (tropical, arid, temperate, and cold), using all events, are presented in Figure 7. Consistent with the aggregated results (Figure 6) peak rainfall is increasing in each climate zone, with the magnitude of the increase greater with increasing event rarity. Sites located in the tropics exhibit increasing peak rainfall but decreasing storm volumes and antecedent soil moisture across all percentiles. Peak flows do not exhibit increases even for the most extreme events. Sites located in arid zones also exhibit increases in the peak rainfall, but this increase is smaller in magnitude than in tropical zones or the aggregated sample median (Figure 6). There is little positive or negative trend in the storm volume or antecedent soil moisture conditions and peak flows are decreasing for the common events. There is evidence of increasing peak flows only for the most extreme flows but there is large uncertainty due to the small sample size. The magnitude of the decrease in the peak flow for the more frequent non-exceedance percentiles is greater in tropical and arid zones than in the temperate and cold zones.

As most of the sites are in temperate and cold climate zones (Figure 7) the results for these regions look more similar to the results when the stations were aggregated (Figure 6). For both the temperate and cold zones peak rainfalls are increasing and the magnitude of the increases is greater the more extreme the event. For the temperate zone we see decreasing soil moisture and peak flows with increases only for approximately the 98^{th} percentile. This suggests the decrease in soil moisture has a strong influence on events that are more common than the 98^{th} percentile, and the increase in peak rainfall dominates above the 98^{th} percentile. In the cold zone the antecedent moisture on average is still decreasing but storm volumes are on average increasing as are the peak rainfalls. However, the magnitude of the storm volume increases does not increase with the event rarity as it does for peak rainfalls. The peak flow responds similarly to these increases and is increasing across percentiles, but due to the drier antecedent soil moisture conditions these increases still do not match the increase in the peak rainfall.

We further stratify these results restricting our sampling to storm durations less than or equal to three days (Figure S5). In tropical and arid regions, despite increases in storm volumes, there is still little evidence for increasing peak flows except for the rarest events. It is only in temperate and cold regions that increasing peak flows are found across all percentiles for these shorter storm durations. This suggests that the results in Figure 6, though showing a clear interaction between the antecedent soil moisture conditions and peak flows, are heavily weighted by temperate climate stations (particularly from Europe).

We can conclude that, irrespective of the storm duration, for colder regions of the world increases in flooding are more likely than for warmer regions.

Trends are also calculated for the subregions presented in Figure S1 and are presented in Figure S6. The two regions for Europe and one region for southern Africa are drawn directly from the International Panel on Climate Change (IPCC) reports (Gudmundsson et al., 2019; Seneviratne et al., 2012) while the remaining regions are aggregations of the IPCC regions. The subregion results (Figure S6) reflect the trends aggregated by climate zone (Figure 7). Sites in Brazil are largely tropical, and arid in the south-west of the US, and hence both regions exhibit the greatest decreases in peak flow; whereas the north-eastern US and northern Europe are largely cold and antecedent soil moisture and peak flows are increasing. In southern Europe increasing peak flows on average above the 95th percentile are commensurate with the fact that studies using annual maxima find decreases in flood magnitude (Blöschl et al., 2019; Gudmundsson et al., 2019; Mediero et al., 2014) but increases are projected for more extreme events (Arnell and Gosling, 2016; Dankers et al., 2014; Hirabayashi et al., 2013). Southern Africa shows little evidence of increasing trends in the peak flow for common events but for the rarest percentile studied increases in the peak flow start to follow the increases in the peak rainfall.

4. Discussion

4.1 Influence of larger-scale atmospheric changes

Here the focus remains on changes in the antecedent soil moisture and storm rainfall as these changes are the key drivers of changes in flooding (Ivancic and Shaw, 2015; Neri et al., 2019; Wasko et al., 2021a). Although changes in evapotranspiration are a secondary consideration due to the relatively short timescales of flooding, they will nevertheless impact on the antecedent soil moisture conditions. For example, increases in temperature can increase vapor pressure deficits (Denson et al., 2021) driving greater evapotranspiration (Massmann et al., 2019) resulting in drier soils due to greater water scarcity (Stephens et al., 2018). But higher terrestrial water storage resulting in wetter antecedent moisture conditions is also possible as higher carbon dioxide concentrations result in reduced stomatal conductance (Retallack and Conde, 2020; Swann et al., 2016).

Antecedent soil moisture conditions and storm rainfalls will also be affected by changes in large scale circulation patterns. For example, changes in storm tracks and moisture transport impact extreme rainfall events and antecedent soil moisture changing flood response (Shaw et al., 2016). The interannual frequency and intensity of atmospheric rivers across the U.S. is linked to flood occurrence and these atmospheric rivers are also non-stationary (Steinschneider and Lall, 2015). The changes in flood hazard in southern Africa have been tied to changes in the Namibia low-level jet (Tramblay et al., 2020). Across Australia, where shifts in flooding are tied to antecedent soil moisture these changes to antecedent moisture are highly correlated to changes in the mean rainfall due to Hadley Cell expanding poleward (Mathew and Kumar, 2019; Wasko et al., 2020b; Wasko and Nathan, 2019).

4.2 Changes in extreme rainfalls

It is generally expected with climate change there will be a shift to shorter more intense rainfall bursts occurring with less frequency and hence longer dry periods between events (Chang et al., 2016). It is worth observing that the decreasing trend in storm volume across the southern hemisphere is consistent with decreasing mean annual rainfalls outside of the tropics (Beck et al., 2019). In addition, in parts of the U.S. where the reverse is true, increases in the storm size and depth in response to higher temperatures have been observed in convective-permitting models (Prein et al., 2017). The greater increase to peak rainfalls than storm volumes is consistent with a shift to less uniform rainfall distributions as a result of higher temperatures (Wasko and Sharma, 2015) and a greater frequency of convective rainfall events (Berg et al., 2013; Molnar et al., 2015).

It is expected that the magnitude of extreme rainfall events will increase with higher temperatures due to the moisture holding capacity of the atmosphere increasing (Allan et al., 2020; Trenberth, 1999). This is generally approximated to a rate of increase of 6-7%/°C. The increases in peak rainfalls presented here for events similar in rarity to annual maxima are consistent with the increase expected due to increases in the moisture holding capacity of the atmosphere. It is expected that extremes that are greater than this may increase at an even greater rate due to latent heat releases which further invigorate the storm strength (Lenderink and van Meijgaard, 2008; Pendergrass, 2018) and will be coupled with the increase in the frequency of extreme rainfall events (Papalexiou and Montanari, 2019). The increases observed in rare quantile peak rainfalls here appear to be in line with the largest increases simulated in climate models (Pendergrass, 2018) and are similar to increases simulated in continuous simulation projections of rainfall to higher temperatures (Wasko and Sharma, 2017b).

4.3 Assumptions and limitations

To prevent confounding of trends due to a mixing of flood mechanisms snowmelt was omitted (Collins, 2019; Stein et al., 2020; Wasko et al., 2019). It is important to note that as rising temperatures are expected to cause precipitation to fall preferentially as rain (Trenberth, 2011) and cause flood processes to be more rainfall dominant (Chegwidden et al., 2020; Vormoor et al., 2016), it can be expected that the results presented here will only become more relevant as temperatures increase further. Even as snowpack decreases with increased temperatures, this will be offset by the increases in rainfall driven and rain-on-snow flood events (Davenport et al., 2020).

The results presented here assume that trends in point estimates of variables are representative of catchment averages and GLDAS is representative of gauged rainfall and soil moisture observations. Trends calculated using high-quality Australian streamflow data recommended for climate change studies matched to observed catchment average rainfall and modelled soil moisture (Wasko and Nathan, 2019) are similar to the trends using outlet data from GLDAS (Figure S7). The magnitude of the peak rainfall increases are almost identical. We cannot expect the peak flow trends to match exactly as the two studies use different station samples, but the close agreement between results suggest that trends in point estimates of variables from GLDAS are representative of observed catchment averages for small catchments. Although not shown here, repeating the analysis presented in Wasko and Nathan (2019) on the identical catchment sample (Zhang et al., 2016) using catchment outlet data from GLDAS found very similar correlations between trends in peak flow with both soil moisture and peak rainfall trends (albeit with different magnitudes) providing confidence in the adopted methodology.

Every effort was made to ensure the results presented here are able to be generalised across regions. Truly global reanalysis data sets are becoming available (Yang et al., 2021) as well as continental observations across regions such as northern and central Africa (Tramblay et al., 2021a) which were not well represented here. However, we note that the analysis performed here requires streamflow time series and many published data sets only publish flow indices (e.g. Do et al., 2018; Tramblay et al., 2021). To the best of the authors' knowledge no studies have been undertaken on the impact of changes in antecedent conditions on flooding outside the regions studied here. It is noted however that the seasonality of annual maxima flooding in Africa is more associated with soil moisture than rainfall (Tramblay et al., 2021b), and this is consistent with the finding here that frequent flood magnitude is modulated by soil moisture changes. Across the Eastern Monsoon Region of China floods with return periods greater than 10 years are generated by extreme rainfall (Yang et al., 2020). The fact that the dominant flood causing mechanism across the world is generally saturation excess for annual maxima (Stein et al., 2020) points to the modulating effect of soil moisture on these more frequent floods that occur on average once per year and those rarer floods, that occur less frequently than once every ten years, being rainfall driven (Wasko and Nathan, 2019).

Finally, it needs to be noted that percentage changes in flow do not have to match percentage changes in rainfalls as some of the storm rainfall is removed in the conversion to streamflow due to absorption to the soil and transmission losses. However, the fact that the percentage changes in flow are less than the percentage in rainfall does conclusively point to the influence of changes in soil moisture on the flood peak (Wasko, 2021). Although one should be careful about conflating temporal trends with temperature sensitivities, it is encouraging that the results presented here are consistent with peak flow temperature sensitivities, where, using catchment outlet data, it was found that although rainfall increased with increasing rarity, streamflow only had a positive association with temperature above the 99^{th} percentile (Wasko and Sharma, 2017a).

5. Conclusions

In this manuscript we investigated trends in flood magnitude in response to extreme rainfall, with a focus on the antecedent conditions driving the flood event. Where previous studies have focused on either mean changes in soil moisture (Albergel et al., 2013; Feng and Zhang, 2015) or antecedent precipitation (Woldemeskel and Sharma, 2016) this study presents an analysis of the soil moisture prior to the onset of flooding. We also used quantile regression to extrapolate past the commonly studied annual maxima. In engineering applications annual maxima are generally termed minor flooding and may be used for design of minor infrastructure such as domestic stormwater drainage, but most infrastructure is designed to withstand major flooding arising from events approaching, or exceeding, the 100-year recurrence interval. Here we find that the processes driving changes in flooding for rarer recurrence intervals are different to those driving change to frequent events. Hence, the trends presented in previous manuscripts studying annual maxima may not be materially relevant to engineering design. Moreover, factoring only peak rainfall intensities for estimating future flood risk may not be sufficient due to the influence of changing storm patterns and antecedent soil moisture conditions (Wasko et al., 2021c).

We found that, across many regions in the world, in the absence of snowmelt, changes in flood magnitude do not follow increases in peak rainfalls. Storm durations are decreasing, with more frequent extreme rainfalls increasing at a rate similar to increases in the moisture holding capacity of the atmosphere and rarer events exhibiting an even greater increase. In contrast, storm volumes show little consistent trend, varying with region and duration. For frequent events, soil moisture drying is often sufficient to outweigh increases in extreme rainfall resulting in decreased flood magnitude. However, the impact of soil moisture changes decreases with increasing event rarity, meaning for rarer events, flood magnitudes are increasing in response to increasing extreme rainfalls. These results suggest climate change is increasing major flooding, and hence increasing the risk of flood damage to infrastructure, while also decreasing the minor flooding responsible for filling water supplies, particularly in tropical and arid regions of the world.

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References

Albergel, C., Dorigo, W., Reichle, R.H., Balsamo, G., de Rosnay, P., Muñoz-Sabater, J., Isaksen, L., de Jeu, R., Wagner, W., 2013. Skill and Global Trend Analysis of Soil Moisture from Reanalyses and Microwave Remote Sensing. J. Hydrometeorol. 14, 1259–1277. https://doi.org/10.1175/JHM-D-12-0161.1

Allan, R.P., Barlow, M., Byrne, M.P., Cherchi, A., Douville, H., Fowler, H.J., Gan, T.Y., Pendergrass, A.G., Rosenfeld, D., Swann, A.L.S., Wilcox, L.J., Zolina, O., 2020. Advances in understanding large-scale responses of the water cycle to climate change. Ann. N. Y. Acad. Sci. 1472, 49–75. https://doi.org/10.1111/nyas.14337

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke Jr, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D., Wallace, J.M., 2003. Abrupt Climate Change. Science (80-.). 299, 2005–2010. https://doi.org/10.1126/science.1081056

Archfield, S.A., Hirsch, R.M., Viglione, A., Blöschl, G., 2016. Fragmented patterns of flood change across the United States. Geophys. Res. Lett. 43, 10,232-10,239. https://doi.org/10.1002/2016GL070590

Arent, D.J., Tol, R.S.J., Faust, E., Hella, J.P., Kumar, S., Strzepek, K.M., Tóth, F.L., Yan, D., 2014. Key economic sectors and services, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment

Report of the Intergovernmental Panel on Climate Change. pp. 659–708. https://doi.org/10.1017/CBO9781107415379.015

Arnell, N.W., Gosling, S.N., 2016. The impacts of climate change on river flood risk at the global scale. Clim. Change 134, 387–401. https://doi.org/10.1007/s10584-014-1084-5

Bao, J., Sherwood, S.C., Alexander, L. V., Evans, J.P., 2017. Future increases in extreme precipitation exceed observed scaling rates. Nat. Clim. Chang. 7, 128–132. https://doi.org/10.1038/nclimate3201

Beck, H.E., Wood, E.F., Pan, M., Fisher, C.K., Miralles, D.G., van Dijk, A.I.J.M., McVicar, T.R., Adler, R.F., 2019. MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment. Bull. Am. Meteorol. Soc. 100, 473–500. https://doi.org/10.1175/BAMS-D-17-0138.1

Bennett, B., Leonard, M., Deng, Y., Westra, S., 2018. An empirical investigation into the effect of antecedent precipitation on flood volume. J. Hydrol. 567, 435–445. https://doi.org/10.1016/j.jhydrol.2018.10.025

Berg, P., Moseley, C., Haerter, J.O., 2013. Strong increase in convective precipitation in response to higher temperatures. Nat. Geosci. 6, 181–185. https://doi.org/10.1038/ngeo1731

Bertola, M., Viglione, A., Vorogushyn, S., Lun, D., Merz, B., Blöschl, G., 2021. Do small and large floods have the same drivers of change? A regional attribution analysis in Europe. Hydrol. Earth Syst. Sci. 25, 1347–1364. https://doi.org/10.5194/hess-25-1347-2021

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Chang, W., Stein, M.L., Wang, J., Kotamarthi, V.R., Moyer, E.J., 2016. Changes in spatiotemporal precipitation patterns in changing climate conditions. J. Clim. 29, 8355–8376. https://doi.org/10.1175/JCLI-D-15-0844.1

Collins, M.J., 2019. River flood seasonality in the Northeast United States: Characterization and trends. Hydrol. Process. 33, 687–698. https://doi.org/10.1002/hyp.13355

Dankers, R., Arnell, N.W., Clark, D.B., Falloon, P.D., Fekete, B.M., Gosling, S.N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y., Wisser, D., 2014. First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. Proc. Natl. Acad. Sci. U. S. A. 111, 3257–61. https://doi.org/10.1073/pnas.1302078110

Davenport, F. V., Herrera-Estrada, J.E., Burke, M., Diffenbaugh, N.S., 2020. Flood Size Increases Nonlinearly Across the Western United States in Response to Lower Snow-Precipitation Ratios. Water Resour. Res. 56, e2019WR025571. https://doi.org/10.1029/2019WR025571

Denson, E., Wasko, C., Peel, M.C., 2021. Decreases in relative humidity across Australia. Environ. Res. Lett. 16, 074023. https://doi.org/10.1088/1748-9326/ac0aca

Do, H.X., Gudmundsson, L., Leonard, M., Westra, S., 2018. The Global Streamflow Indices and Metadata Archive (GSIM)-Part 1: The production of a daily streamflow archive and metadata. Earth Syst. Sci. Data 10, 765–785. https://doi.org/10.5194/essd-10-765-2018

Do, H.X., Mei, Y., Gronewold, A.D., 2020a. To What Extent Are Changes in Flood Magnitude Related to Changes in Precipitation Extremes? Geophys. Res. Lett. 47, e2020GL088684. https://doi.org/10.1029/2020GL088684

Do, H.X., Westra, S., Leonard, M., 2017. A global-scale investigation of trends in annual maximum streamflow. J. Hydrol. 552, 28–43. https://doi.org/10.1016/j.jhydrol.2017.06.015

Do, H.X., Zhao, F., Westra, S., Leonard, M., Gudmundsson, L., Boulange, J.E.S., Chang, J., Ciais, P., Gerten, D., Gosling, S.N., Müller Schmied, H., Stacke, T., Telteu, C.-E., Wada, Y., 2020b. Historical and future changes in global flood magnitude – evidence from a model–observation investigation. Hydrol. Earth Syst. Sci. 24, 1543–1564. https://doi.org/10.5194/hess-24-1543-2020

Donat, M.G., Lowry, A.L., Alexander, L. V., O'Gorman, P.A., Maher, N., 2016. More extreme precipitation in the world's dry and wet regions. Nat. Clim. Chang. 6, 508–513. https://doi.org/10.1038/nclimate2941

Fadhel, S., Rico-Ramirez, M.A., Han, D., 2018. Sensitivity of peak flow to the change of rainfall temporal pattern due to warmer climate. J. Hydrol. 560, 546–559.

https://doi.org/10.1016/j.jhydrol.2018.03.041

Feng, H., Zhang, M., 2015. Global land moisture trends: Drier in dry and wetter in wet over land. Sci. Rep. 5, 18018. https://doi.org/10.1038/srep18018

Fisher, N.I., 1993. Statistical analysis of circular data. Cambridge University Press, New York.

Fowler, H.J., Lenderink, G., Prein, A.F., Westra, S., Allan, R.P., Ban, N., Barbero, R., Berg, P., Blenkinsop, S., Do, H.X., Guerreiro, S., Haerter, J.O., Kendon, E.J., Lewis, E., Schaer, C., Sharma, A., Villarini, G., Wasko, C., Zhang, X., 2021. Anthropogenic intensification of short-duration rainfall extremes. Nat. Rev. Earth Environ. 2, 107–122. https://doi.org/10.1038/s43017-020-00128-6

GRDC, 2015. The Global Runoff Data Centre.

Gudmundsson, L., Leonard, M., Do, H.X., Westra, S., Seneviratne, S.I., 2019. Observed Trends in Global Indicators of Mean and Extreme Streamflow. Geophys. Res. Lett. 46, 756–766. https://doi.org/10.1029/2018GL079725

Guerreiro, S.B., Fowler, H.J., Barbero, R., Westra, S., Lenderink, G., Blenkinsop, S., Lewis, E., Li, X.-F., 2018. Detection of continental-scale intensification of hourly rainfall extremes. Nat. Clim. Chang. 8, 803–807. https://doi.org/10.1038/s41558-018-0245-3

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T.R., Kriaučiūnienė, J., Kundzewicz, Z.W., Lang, M., Llasat, M.C., Macdonald, N., McIntyre, N., Mediero, L., Merz, B., Merz, R., Molnar, P., Montanari, A., Neuhold, C., Parajka, J., Perdigão, R.A.P., Plavcová, L., Rogger, M., Salinas, J.L., Sauquet, E., Schär, C., Szolgay, J., Viglione, A., Blöschl, G., 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. Hydrol. Earth Syst. Sci. 18, 2735–2772. https://doi.org/10.5194/hess-18-2735-2014

Hao, L., Naiman, D.Q., 2007. Quantile Regression. SAGE Publications, Inc., 2455 Teller Road, Thousand Oaks California 91320 United States of America. https://doi.org/10.4135/9781412985550

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L. V., Broennimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M., Zhai, P.M., 2013. Observations: Atmosphere and Surface, in: Stocker, T., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 159–254.

Hettiarachchi, S., Wasko, C., Sharma, A., 2018. Increase in flood risk resulting from climate change in a developed urban watershed – the role of storm temporal patterns. Hydrol. Earth Syst. Sci. 22, 2041–2056. https://doi.org/10.5194/hess-22-2041-2018

Hill, P., Thomson, R., 2019. Chapter 3. Losses, Book 5: Flood Hydrograph Estimation:, in: Ball, J., Babister, M., Nathan, R., Weinmann, E., Retallick, M., Testoni, I. (Eds.), Australian Rainfall and Runoff - A Guide to Flood Estimation. Commonwealth of Australia.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Chang. 3, 816–821. https://doi.org/10.1038/nclimate1911

Ivancic, T.J., Shaw, S.B., 2015. Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge. Clim. Change 133, 681–693. https://doi.org/10.1007/s10584-015-1476-1

Jha, A.K., Bloch, R., Lamond, J., 2012. Cities and Flooding, Journal of Hydrologic Engineering. The World Bank. https://doi.org/10.1596/978-0-8213-8866-2

Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430–432. https://doi.org/10.1038/361430a0

Koenker, R., 2021. quantreg: Quantile Regression. R package version 5.85. [available at http://CRAN.R-project.org/package=quantreg].

Koenker, R., Bassett, G., 1978. Regression Quantiles. Econometrica 46, 33–50. https://doi.org/10.2307/1913643

Lee, D., Ward, P., Block, P., 2015. Defining high-flow seasons using temporal streamflow patterns from a global model. Hydrol. Earth Syst. Sci. 19, 4689–4705. https://doi.org/10.5194/hess-19-4689-2015

Lenderink, G., van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. Nat. Geosci. 1, 511–514. https://doi.org/10.1038/ngeo262

Mallakpour, I., Villarini, G., 2015. The changing nature of flooding across the central United States. Nat. Clim. Chang. 5, 250–254. https://doi.org/10.1038/nclimate2516

Massmann, A., Gentine, P., Lin, C., 2019. When Does Vapor Pressure Deficit Drive or Reduce Evapotranspiration? J. Adv. Model. Earth Syst. 11, 3305–3320. https://doi.org/10.1029/2019MS001790

Mathew, S.S., Kumar, K.K., 2019. Characterization of the long-term changes in moisture, clouds and precipitation in the ascending and descending branches of the Hadley Circulation. J. Hydrol. 570, 366–377. https://doi.org/10.1016/j.jhydrol.2018.12.047

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

Merz, B., Blöschl, G., Vorogushyn, S., Dottori, F., Aerts, J.C.J.H., Bates, P., Bertola, M., Kemter, M., Kreibich, H., Lall, U., Macdonald, E., 2021. Causes, impacts and patterns of disastrous river floods. Nat. Rev. Earth Environ. https://doi.org/10.1038/s43017-021-00195-3

Milly, P.C.D., Kam, J., Dunne, K.A., 2018. On the Sensitivity of Annual Streamflow to Air Temperature. Water Resour. Res. 54, 2624–2641. https://doi.org/10.1002/2017WR021970

Molnar, P., Fatichi, S., Gaál, L., Szolgay, J., Burlando, P., 2015. Storm type effects on super Clausius–Clapeyron scaling of intense rainstorm properties with air temperature. Hydrol. Earth Syst. Sci. 19, 1753–1766. https://doi.org/10.5194/hess-19-1753-2015

Nathan, R.J., McMahon, T.A., 1990. Evaluation of automated techniques for base flow and recession analyses. Water Resour. Res. 26, 1465–1473. https://doi.org/10.1029/WR026i007p01465

Neri, A., Villarini, G., Slater, L.J., Napolitano, F., 2019. On the statistical attribution of the frequency of flood events across the U.S. Midwest. Adv. Water Resour. 127, 225–236. https://doi.org/10.1016/j.advwatres.2019.03.019

Papalexiou, S.M., Montanari, A., 2019. Global and Regional Increase of Precipitation Extremes Under Global Warming. Water Resour. Res. 55, 4901–4914. https://doi.org/10.1029/2018WR024067

Paprotny, D., Sebastian, A., Morales-Nápoles, O., Jonkman, S.N., 2018. Trends in flood losses in Europe over the past 150 years. Nat. Commun. 9, 1985. https://doi.org/10.1038/s41467-018-04253-1

Pathiraja, S., Westra, S., Sharma, A., 2012. Why continuous simulation? The role of antecedent moisture in design flood estimation. Water Resour. Res. 48, W06534.

https://doi.org/10.1029/2011WR010997

Pendergrass, A.G., 2018. What precipitation is extreme? Science (80-.). 360, 1072–1073. https://doi.org/10.1126/science.aat1871

Pendergrass, A.G., Hartmann, D.L., 2014. Changes in the distribution of rain frequency and intensity in response to global warming. J. Clim. 27, 8372–8383. https://doi.org/10.1175/JCLI-D-14-00183.1

Prein, A.F., Liu, C., Ikeda, K., Trier, S.B., Rasmussen, R.M., Holland, G.J., Clark, M.P., 2017. Increased rainfall volume from future convective storms in the US. Nat. Clim. Chang. 7, 880–884. https://doi.org/10.1038/s41558-017-0007-7

Razavi, S., Gober, P., Maier, H.R., Brouwer, R., Wheater, H., 2020. Anthropocene flooding: Challenges for science and society. Hydrol. Process. 34, 1996–2000. https://doi.org/10.1002/hyp.13723

Retallack, G.J., Conde, G.D., 2020. Deep time perspective on rising atmospheric CO2. Glob. Planet. Change 189, 103177. https://doi.org/10.1016/j.gloplacha.2020.103177

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004. The Global Land Data Assimilation System. Bull. Am. Meteorol. Soc. 85, 381–394. https://doi.org/10.1175/BAMS-85-3-381

S Chegwidden, O., Rupp, D.E., Nijssen, B., 2020. Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States. Environ. Res. Lett. 15, 094048. https://doi.org/10.1088/1748-9326/ab986f

Sharma, A., Wasko, C., Lettenmaier, D.P., 2018. If Precipitation Extremes Are Increasing, Why Aren't Floods? Water Resour. Res. 54, 8545–8551. https://doi.org/10.1029/2018WR023749

Shaw, T.A., Baldwin, M., Barnes, E.A., Caballero, R., Garfinkel, C.I., Hwang, Y.T., Li, C., O'Gorman, P.A., Rivière, G., Simpson, I.R., Voigt, A., 2016. Storm track processes and the opposing influences of climate change. Nat. Geosci. 9, 656–664. https://doi.org/10.1038/ngeo2783

Sheffield, J., Goteti, G., Wood, E.F., 2006. Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling. J. Clim. 19, 3088–3111. https://doi.org/10.1175/JCLI3790.1

Slater, L., Villarini, G., Archfield, S., Faulkner, D., Lamb, R., Khouakhi, A., Yin, J., 2021. Global Changes in

20-Year, 50-Year, and 100-Year River Floods. Geophys. Res. Lett. 48, e2020GL091824. https://doi.org/10.1029/2020GL091824

Stedinger, J., Vogel, R., Foufoula-Georgiou, E., 1993. Frequency analysis of extreme events, in: Maidment, D. (Ed.), Handbook of Hydrology. McGraw-Hill.

Stein, L., Pianosi, F., Woods, R., 2020. Event-based classification for global study of river flood generating processes. Hydrol. Process. 34, 1514–1529. https://doi.org/10.1002/hyp.13678

Steinschneider, S., Lall, U., 2015. A hierarchical Bayesian regional model for nonstationary precipitation extremes in Northern California conditioned on tropical moisture exports. Water Resour. Res. 51, 1472–1492. https://doi.org/10.1002/2014WR016664

Stephens, C.M., McVicar, T.R., Johnson, F.M., Marshall, L.A., 2018. Revisiting Pan Evaporation Trends in Australia a Decade on. Geophys. Res. Lett. 45, 11,164-11,172. https://doi.org/10.1029/2018GL079332

Stephens, E., Day, J.J., Pappenberger, F., Cloke, H., 2015. Precipitation and floodiness. Geophys. Res. Lett. 42, 10,316-10,323. https://doi.org/10.1002/2015GL066779

Sun, Q., Zhang, X., Zwiers, F., Westra, S., Alexander, L. V., 2021. A Global, Continental, and Regional Analysis of Changes in Extreme Precipitation. J. Clim. 34, 243–258. https://doi.org/10.1175/JCLI-D-19-0892.1

Swann, A.L.S., Hoffman, F.M., Koven, C.D., Randerson, J.T., 2016. Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. Proc. Natl. Acad. Sci. U. S. A. 113, 10019–10024. https://doi.org/10.1073/pnas.1604581113

Tramblay, Y., Mimeau, L., Neppel, L., Vinet, F., Sauquet, E., 2019. Detection and attribution of flood trends in Mediterranean basins. Hydrol. Earth Syst. Sci. 23, 4419–4431. https://doi.org/10.5194/hess-23-4419-2019

Tramblay, Y., Rouché, N., Paturel, J.-E., Mahé, G., Boyer, J.-F., Amoussou, E., Bodian, A., Dacosta, H., Dakhlaoui, H., Dezetter, A., Hughes, D., Hanich, L., Peugeot, C., Tshimanga, R., Lachassagne, P., 2021a. ADHI: the African Database of Hydrometric Indices (1950–2018). Earth Syst. Sci. Data 13, 1547–1560. https://doi.org/10.5194/essd-13-1547-2021

Tramblay, Y., Villarini, G., Khalki, E.M., Gründemann, G., Hughes, D., 2021b. Evaluation of the Drivers

Responsible for Flooding in Africa. Water Resour. Res. 57, e2021WR029595. https://doi.org/10.1029/2021WR029595

Tramblay, Y., Villarini, G., Zhang, W., 2020. Observed changes in flood hazard in Africa. Environ. Res. Lett. 15, 1040b5. https://doi.org/10.1088/1748-9326/abb90b

Trenberth, K., 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. Clim. Change 42, 327–339.

Trenberth, K.E., 2011. Changes in precipitation with climate change. Clim. Res. 47, 123–138. https://doi.org/10.3354/cr00953

Vormoor, K., Lawrence, D., Schlichting, L., Wilson, D., Wong, W.K., 2016. Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. J. Hydrol. 538, 33–48. https://doi.org/10.1016/j.jhydrol.2016.03.066

Wasko, C., 2021. Review: Can temperature be used to inform changes to flood extremes with global warming? Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 379, 20190551. https://doi.org/10.1098/rsta.2019.0551

Wasko, C., Nathan, R., 2019. Influence of changes in rainfall and soil moisture on trends in flooding. J. Hydrol. 575, 432–441. https://doi.org/10.1016/j.jhydrol.2019.05.054

Wasko, C., Nathan, R., Peel, M.C., 2020a. Trends in Global Flood and Streamflow Timing Based on Local Water Year. Water Resour. Res. 56, e2020WR027233. https://doi.org/10.1029/2020WR027233

Wasko, C., Nathan, R., Peel, M.C., 2020b. Changes in Antecedent Soil Moisture Modulate Flood Seasonality in a Changing Climate. Water Resour. Res. 56, e2019WR026300. https://doi.org/10.1029/2019WR026300

Wasko, C., Shao, Y., Vogel, E., Wilson, L., Wang, Q.J., Frost, A., Donnelly, C., 2021a. Understanding trends in hydrologic extremes across Australia. J. Hydrol. 593, 125877. https://doi.org/10.1016/j.jhydrol.2020.125877

Wasko, C., Sharma, A., 2017a. Global assessment of flood and storm extremes with increased temperatures. Sci. Rep. 7, 7945. https://doi.org/10.1038/s41598-017-08481-1

Wasko, C., Sharma, A., 2017b. Continuous rainfall generation for a warmer climate using observed temperature sensitivities. J. Hydrol. 544, 575–590. https://doi.org/10.1016/j.jhydrol.2016.12.002

Wasko, C., Sharma, A., 2015. Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. Nat. Geosci. 8, 527–529. https://doi.org/10.1038/ngeo2456

Wasko, C., Sharma, A., Lettenmaier, D.P., 2019. Increases in temperature do not translate to increased flooding. Nat. Commun. 10, 5676. https://doi.org/10.1038/s41467-019-13612-5

Wasko, C., Sharma, A., Pui, A., 2021b. Linking temperature to catastrophe damages from hydrologic and meteorological extremes. J. Hydrol. 602, 126731. https://doi.org/10.1016/j.jhydrol.2021.126731

Wasko, C., Westra, S., Nathan, R., Orr, H.G., Villarini, G., Villalobos Herrera, R., Fowler, H.J., 2021c. Incorporating climate change in flood estimation guidance. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 379, 20190548. https://doi.org/10.1098/rsta.2019.0548

Westra, S., Alexander, L., Zwiers, F., 2013. Global increasing trends in annual maximum daily precipitation. J. Clim. 26, 3904–3918. https://doi.org/10.1175/JCLI-D-12-00502.1

Woldemeskel, F., Sharma, A., 2016. Should flood regimes change in a warming climate? The role of antecedent moisture conditions. Geophys. Res. Lett. 43, 7556–7563. https://doi.org/10.1002/2016GL069448

Yang, W., Yang, H., Yang, D., 2020. Classifying floods by quantifying driver contributions in the Eastern Monsoon Region of China. J. Hydrol. 585, 124767. https://doi.org/10.1016/j.jhydrol.2020.124767

Yang, Y., Pan, M., Lin, P., Beck, H.E., Zeng, Z., Yamazaki, D., David, C.H., Lu, H., Yang, K., Hong, Y., Wood, E.F., 2021. Global Reach-level 3-hourly River Flood Reanalysis (1980-2019). Bull. Am. Meteorol. Soc. 1–49. https://doi.org/10.1175/BAMS-D-20-0057.1

Zhang, X.S., Amirthanathan, G.E., Bari, M.A., Laugesen, R.M., Shin, D., Kent, D.M., MacDonald, A.M., Turner, M.E., Tuteja, N.K., 2016. How streamflow has changed across Australia since the 1950s: evidence from the network of hydrologic reference stations. Hydrol. Earth Syst. Sci. 20, 3947–3965. https://doi.org/10.5194/hess-20-3947-2016