Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR024841

**Key Points:**
- We estimate the importance of extreme precipitation, soil moisture excess, and snowmelt as flood drivers, using dates of annual flow peaks
- In Europe, most annual floods are caused by subextreme precipitation with high antecedent soil moisture, not by annual peak rainfall
- The relative importance of these flood-generating mechanisms has not changed substantially from 1960 to 2010

**Supporting Information:**
- Supporting Information S1

**Correspondence to:**
W. R. Berghuijs,
bwouter@ethz.ch

**Citation:**
Berghuijs, W. R., Harrigan, S., Molnar, P., Slater, L. J., & Kirchner, J. W. (2019). The relative importance of different flood-generating mechanisms across Europe. *Water Resources Research*, *55*, 4582–4593. https://doi.org/10.1029/2019WR024841

Received 24 JAN 2019
Accepted 8 MAY 2019
Accepted article online 14 MAY 2019
Published online 5 JUN 2019



# The Relative Importance of Different Flood-Generating Mechanisms Across Europe

**Wouter R. Berghuijs[1], Shaun Harrigan[2], Peter Molnar[3], Louise J. Slater[4,5], and James W. Kirchner[1,6,7]**

[1]Department of Environmental Systems Science, ETH Zurich, Zürich, Switzerland, [2]European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK, [3]Institute of Environmental Engineering, ETH Zurich, Zürich, Switzerland, [4]School of Geography and the Environment, University of Oxford, Oxford, UK, [5]School of Social Sciences: Geography and Environment, Loughborough University, Loughborough, UK, [6]Swiss Federal Research Institute WSL, Birmensdorf, Switzerland, [7]Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

**Abstract** Inferring the mechanisms causing river flooding is key to understanding past, present, and future flood risk. However, a quantitative spatially distributed overview of the mechanisms that drive flooding across Europe is currently unavailable. In addition, studies that classify catchments according to their flood-driving mechanisms often identify a single mechanism per location, although multiple mechanisms typically contribute to flood risk. We introduce a new method that uses seasonality statistics to estimate the relative importance of extreme precipitation, soil moisture excess, and snowmelt as flood drivers. Applying this method to a European data set of maximum annual flow dates in several thousand catchments reveals that from 1960 to 2010 relatively few annual floods were caused by annual rainfall peaks. Instead, most European floods were caused by snowmelt and by the concurrence of heavy precipitation with high antecedent soil moisture. For most catchments, the relative importance of these mechanisms has not substantially changed during the past five decades. Exposing the regional mechanisms underlying Europe's most costly natural hazard is a key first step in identifying the processes that require most attention in future flood research.

## 1. Introduction

Flooding is one of the most damaging natural hazards worldwide (Field, 2012; Kundzewicz et al., 2014; Paprotny et al., 2018), and future settlement patterns and climate change are expected to increase flood risk globally (Arnell & Gosling, 2016; Hirabayashi et al., 2013; Milly et al., 2002; Winsemius et al., 2015). For Europe, annual flood damages during the period 2000-2012 have been estimated at €4.9 billion, and future damages are expected to grow substantially (Alfieri et al., 2015; Jongman et al., 2014). These facts highlight the need to understand flood risk trends.

Trends in river flooding can be inferred from long-term data on the timing, magnitude, and frequency of river flows and inundations (e.g., Archfield et al., 2016; Berghuijs et al., 2017; Blöschl et al., 2017; Do et al., 2017; Hall et al., 2014; Hirsch & Ryberg, 2012; Hodgkins et al., 2017; Mudelsee et al., 2003; Slater & Villarini, 2016). For example, the timing of European floods has shifted in recent decades (Blöschl et al., 2017), but trends in flood magnitudes are less clear (e.g., Berghuijs et al., 2017; Hall et al., 2014; Hodgkins et al., 2017). Understanding such trends requires identifying the hydrological processes that trigger floods (Blöschl et al., 2015; Ivancic & Shaw, 2015; Sharma et al., 2018; Slater & Wilby, 2017). The limited understanding of regional variations in flood-generating mechanisms is one reason why the causes of historical flood trends are often unclear (Blöschl et al., 2015) and why projections of future flooding under climate change remain uncertain (Kundzewicz et al., 2014).

Causes of flooding are well documented in studies that investigate a small number of flood events or river basins (e.g., Blöschl et al., 2013; Keller et al., 2018; Nied et al., 2013), but it is impractical to conduct such detailed site-specific investigations in hundreds or thousands of catchments across entire continents. In addition, studies that infer flood-generating mechanisms across many sites generally identify only a single dominant mechanism driving river flooding at each site (e.g., Berghuijs et al., 2016; Hirschboeck, 1991; Parajka et al., 2010; but see Merz & Blöschl, 2003, for an exception). However, this approach overlooks the fact that even at a single site, individual floods can arise through different mechanisms (e.g., Blöschl et al., 2013; Keller et al., 2018; Merz and Blöschl, 2003; Sikorska et al., 2015).

Classifications of flood-generating mechanisms across many catchments are available for parts of Europe, such as Austria and the Alpine-Carpathian range (Merz and Blöschl, 2003; Parajka et al., 2010), and other regions such as the continental United States (Berghuijs et al., 2016). Continental-scale assessments of European river flooding use the seasonal timing of floods as a basis to qualitatively discuss the regional differences in flood-generating mechanisms (e.g., Blöschl et al., 2017; Hall et al., 2014; Hall & Blöschl, 2018; Mediero et al., 2015), without employing any formal attribution methods. Thus, for most of Europe, there is no reproducible quantitative mapping of the importance of different flood-generating mechanisms.

The importance of different flood-generating mechanisms may shift over time, particularly under climate change. For example, increased temperatures affect the snow dynamics of cold regions, thereby potentially altering the magnitude of snowmelt floods (e.g., Hall et al., 2014; Musselman et al., 2018; Regonda et al., 2005; Vormoor et al., 2016). Warmer temperatures also tend to increase precipitation extremes, potentially increasing the risk of extreme rainfall floods (e.g., Kendon et al., 2014; Trenberth et al., 2003; Westra et al., 2013). Thus, the relative importance of flood drivers may shift over time, but to date there has been no systematic effort to detect whether such changes are taking place across Europe.

Here we introduce a new method that estimates the relative importance of different flood-generating mechanisms, extending previously developed approaches based on seasonality statistics. We apply this new method to a large data set of observed annual flood dates in several thousand catchments across Europe. We describe regional patterns in the relative importance of extreme precipitation, soil moisture excess, and snowmelt as flood drivers across Europe over the period 1960-2010 and assess how the relative importance of different flood-generating mechanisms has changed during these five decades.

## 2. Methods

### 2.1. Data

The flood data we analyze are obtained from the European Flood Database (Hall et al., 2015) and consist of the dates of annual maximum streamflows or water levels (daily or instantaneous values) for each calendar year from 1960 to 2010, for 4,062 catchments (Blöschl et al., 2017; Hall et al., 2015). Catchment station elevations range from just below sea level to almost 2 km, and catchments range in size from ~10 to ~100,000 km$^2$ (Hall & Blöschl, 2018). We only use the 4,037 catchments east of 12°W longitude (thus excluding Iceland). We obtained daily 0.25° gridded precipitation and mean surface temperature data for the same time period from the E-OBS data set (version 15.0; Haylock et al., 2008). We calculate Hamon potential evapotranspiration based on these temperature data and grid-cell locations following Federer et al. (1996). Data are openly available and are described in detail in the cited references.

### 2.2. Relative Importance of Flood-Generating Mechanisms

Because the available flood data are limited to the dates of annual maximum flow each year, we infer the relative importance of different flood-generating mechanisms by comparing these dates of annual maximum flow with the timing of each candidate mechanism. Our approach can be summarized in three steps. First, we define the mechanisms that can cause flooding (section 2.2.1). Next, we calculate the seasonality statistics of flooding and these driving mechanisms for each site (section 2.2.2). Finally, we estimate the relative importance of each mechanism at each site by comparing the seasonality statistics of annual floods with those of the potential driving mechanisms (section 2.2.3).

#### 2.2.1. Definition of Flood-Generating Mechanisms

In this study, we focus on processes that drive flooding (e.g., rainfall), rather than catchment properties (e.g., land cover) that modify how water is partitioned but do not drive flooding themselves. Three major mechanisms that may lead to flooding have been classified by Berghuijs et al. (2016):

*Extreme precipitation*: In extreme precipitation floods, the maximum annual flow results from (and thus occurs during the same time of the year as) the largest precipitation event of that year. In this study, we use daily precipitation amounts. Changing this to multiple-day maximum precipitation did not change the later results substantially, because the seasonality statistics of these two properties are nearly identical across Europe.

*Soil moisture excess*: In soil moisture excess floods, the maximum annual flow is caused by (and thus occurs during the same time of the year as) the largest daily soil moisture excess event. Soil moisture excess is defined as the daily precipitation amount minus the available soil moisture storage capacity. Soil moisture storage dynamics are controlled by the interplay between precipitation, evapotranspiration, and runoff and are simulated using a very simple water balance model,

$$\frac{\mathrm{d}S_u}{\mathrm{d}t} = P - E - \max(Q, 0), \tag{1}$$

where $S_u$ is storage amount in the unsaturated zone (millimeter), $P$ is precipitation (millimeter per day), $Q$ is soil moisture excess (millimeter per day), and $E$ is evaporation (millimeter per day), which is calculated by

$$E = \min\left(0.75 \cdot E_p, S_u\right), \tag{2}$$

Potential evapotranspiration, $E_p$ (millimeter per day), is scaled to 75% of its daily value because not all $E_p$ tends to be used for evapotranspiration. $\Delta t$ is the time step of calculation, here set at 1 day. Soil moisture excess, $Q$ (millimeter per day), now equals

$$Q = P - \left(S_{u,\max} - S_u\right). \tag{3}$$

$S_{u,max}$ is the soil moisture storage capacity fixed at 125 mm. Changing this to 75 mm did not substantially affect the results. We use maximum soil moisture excess, rather than maximum soil moisture, because high soil moisture by itself does not drive flooding; additional rainfall is needed to trigger floods.

*Snowmelt*: In snowmelt floods, the maximum annual flow is caused by (and thus occurs during the same time of the year as) the largest daily snowmelt or rain-on-snow event of the year. Snowmelt or rain-on-snow events are defined as the sum of daily liquid precipitation and snowmelt during melting days. Snowmelt dynamics are estimated using a degree-day model,

$$\frac{\mathrm{d}S_s}{\mathrm{d}t} = P_s - M, \tag{4}$$

where $S_s$ is the snow storage (millimeter); $P_s$ is snowfall (millimeter per day), assuming all $P$ is snow when the daily average temperature $T$ is below the temperature threshold $T_{crit}$, set at 1 (°C); and snowmelt $M$ (millimeter per day) is

$$M = \min(f_{dd} \cdot \max(T - T_{crit}, 0), S_s), \tag{5}$$

where $f_{dd}$ is the melt rate constant set at 2.0 (millimeter per day per degree Celsius). The daily snowmelt or rain-on-snow event is now quantified by the sum of liquid precipitation and snowmelt, which is set to zero for days with no snowmelt.

We stress that the mechanisms outlined above are not intended as predictive models for flooding. Instead, our aim is to use simple process descriptions to characterize the seasonality of regional flood drivers, in order to decipher the main causes of flooding across many sites using the flood data (i.e., the timing of annual maximum floods) and the gridded climate data that are available across the entire European continent.

#### 2.2.2. Seasonality Characteristics

The seasonality of flooding and flood-generating mechanisms is characterized by circular statistics (e.g., Bayliss & Jones, 1993; Black & Werritty, 1997; Blöschl et al., 2017; Parajka et al., 2010). We quantify the *mean date of occurrence*, $\overline{D}_i$ (day of year) of all these processes:

$$\overline{D}_i = \begin{cases} \tan^{-1}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)\cdot\frac{\overline{m}}{2\pi} & \overline{x}_i>0, \quad \overline{y}_i\geq 0 \\ \left(\tan^{-1}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)+\pi\right)\cdot\frac{\overline{m}}{2\pi} & \overline{x}_i\leq 0 \\ \left(\tan^{-1}\left(\frac{\overline{y}_i}{\overline{x}_i}\right)+2\pi\right)\cdot\frac{\overline{m}}{2\pi} & \overline{x}_i>0, \overline{y}_i<0 \end{cases} \quad (6)$$

with

$$\overline{x}_i = \frac{1}{n}\sum_{k=1}^{n}\cos(\theta_{i,k}), \quad (7)$$

$$\overline{y}_i = \frac{1}{n}\sum_{k=1}^{n}\sin(\theta_{i,k}), \quad (8)$$

$$\theta_{i,k} = D_{i,k}\cdot\frac{2\pi}{\overline{m}} 0\leq\theta_k\leq 2\pi, \quad (9)$$

where $\overline{x}_i$ and $\overline{y}_i$ are the mean cosine and sine components of the seasonality for each process $i$, $D_{i,k}$ is the date of occurrence of process $i$ in each individual year $k$, $\overline{m}$ is the average number of days per year, and $n$ is the number of years of data used at that location. The cosine and sine components of the seasonality can be used to calculate the *concentration*, $R_i$ (dimensionless):

$$R_i = \sqrt{\overline{x}_i^{\,2} + \overline{y}_i^{\,2}}, \quad (10)$$

which expresses the consistency in timing around the *mean date of occurrence*, $\overline{D}_i$. An $R_i$ value of 1 indicates that process $i$ always occurs at the same time of the year, whereas an $R_i$ value of 0 indicates process $i$ is equally likely to occur at any time of the year. Figure 1 provides an example of these indices for a catchment in Switzerland (Figure 1).

### 2.2.3. Calculation of the Relative Importance of Flood Drivers

When floods are caused by the three mechanisms outlined in section 2.2.1, the summed cosine and sine components of the seasonality of the three processes ($\overline{x}_i$ and $\overline{y}_i$), each weighted by their importance as flood drivers, should approximate the cosine and sine components of the seasonality of flooding. Thus, we estimate the relative importance of each flood driver by solving the following set of linear equations:

$$\alpha_p\overline{x}_p + \alpha_m\overline{x}_m + \alpha_s\overline{x}_s = \overline{x}_f, \quad (11)$$

$$\alpha_p\overline{y}_p + \alpha_m\overline{y}_m + \alpha_s\overline{y}_s = \overline{y}_f, \quad (12)$$

$$\alpha_p + \alpha_m + \alpha_s = 1, \quad (13)$$

where $\alpha_i$ indicates the relative importance of each flood driver (with $[0 \leq \alpha_i \leq 1]$), $\overline{x}_i$ and $\overline{y}_i$ are the average cosine and sine components of the dates of occurrence of floods or drivers (equations (7) and (8)), and the subscript indicates the process of interest ($f$ = flood, $p$ = extreme precipitation, $m$ = soil moisture excess, and $s$ = snowmelt). For drivers, we use the cosine and sine components of the dates of occurrence for the grid cell where the streamflow gauging station is located. An $\alpha_i$ value of 0 indicates no flooding is caused by the mechanism, whereas an $\alpha_i$ value of 1 indicates all flooding is caused by that mechanism. The example in Figure 1 yields $\alpha_p = 0.77$, $\alpha_m = 0.03$, and $\alpha_s = 0.20$, indicating that flooding in this catchment is largely driven by extreme precipitation events.

Solving equations (11)–(13) is straightforward when the cosine and sine components of flood seasonality fall within the triangular area spanned by the cosine and sine components of the flood-generating mechanisms (Figure 1, indicated in gray). When the cosine and sine components of flood seasonality fall outside the triangular area spanned by the three mechanisms, we estimate the relative importance of the mechanisms from the point on the triangle that is closest to the point describing the flood seasonality. To avoid considering snowmelt as a flood driver at sites with little snow, we set $\alpha_s$ to 0 wherever the mean fraction of

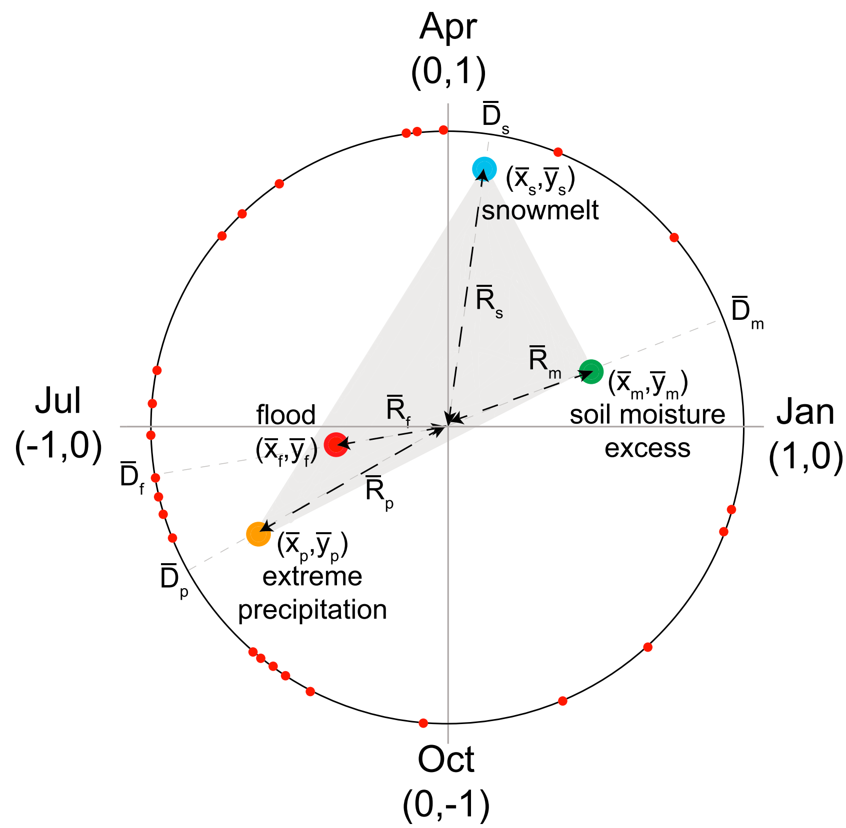


**Figure 1.** The seasonality characteristics of floods and flood-generating mechanisms characterized by circular statistics for the Reuss river (Switzerland, 46°38′34.8″N 8°35′24.0″E). The *dates of occurrence* of each year, $D_{i,k}$ (day of year), fall on the unit circle (here only shown for floods). These dates are used to derive the mean cosine and sine components, $\bar{x}_i$ and $\bar{y}_i$, and thus to estimate the mean date of flooding. The *concentration*, $R_i$ (dimensionless), expresses how tightly occurrences are clustered around the mean date, and the subscripts indicate the process of interest ($f$ = flood, $p$ = precipitation, $m$ = soil moisture excess, and $s$ = snowmelt). The cosine and sine components of the flood generating mechanisms are used to infer their relative importance as flood drivers by comparing their seasonality statistics (equations (11)–(13)), which yields $\alpha_p = 0.77$, $\alpha_m = 0.03$, and $\alpha_s = 0.20$ in this example. Thus, in this catchment, the majority of flooding is driven by extreme precipitation events.

precipitation falling as snow (estimated using a temperature threshold of 1 °C; Hock, 2003) does not exceed 5%; changing this threshold to 10% does not affect the results substantially.

We apply the method outlined above to 3,777 European catchments that have a minimum of 20 years of data on the timing of flood peaks. In addition, to assess how flood drivers have changed over the past five decades, we use equations (11)–(13) to estimate the relative importance of the mechanisms separately for the periods 1960-1984 and 1985-2010 for the 2,784 catchments that have at least 40 years of data between 1960 and 2010 (thus guaranteeing at least 15 years of coverage in both the 1960-1984 and 1985-2010 intervals).

## 3. Results and Discussion

### 3.1. Seasonality of Floods and Their Driving Mechanisms

The *mean date of occurrence* of floods and the *concentration* of floods around their mean date exhibit distinct regional differences across Europe (Figures 2a and 2b). Annual floods typically occur in winter across large parts of western Europe and the Mediterranean. In northeastern Europe, floods often occur in spring, whereas floods tend to occur during summer around the Alps. These patterns have been described in detail by earlier studies (Blöschl et al., 2017; Hall & Blöschl, 2018), and thus, we will not elaborate on them further here.

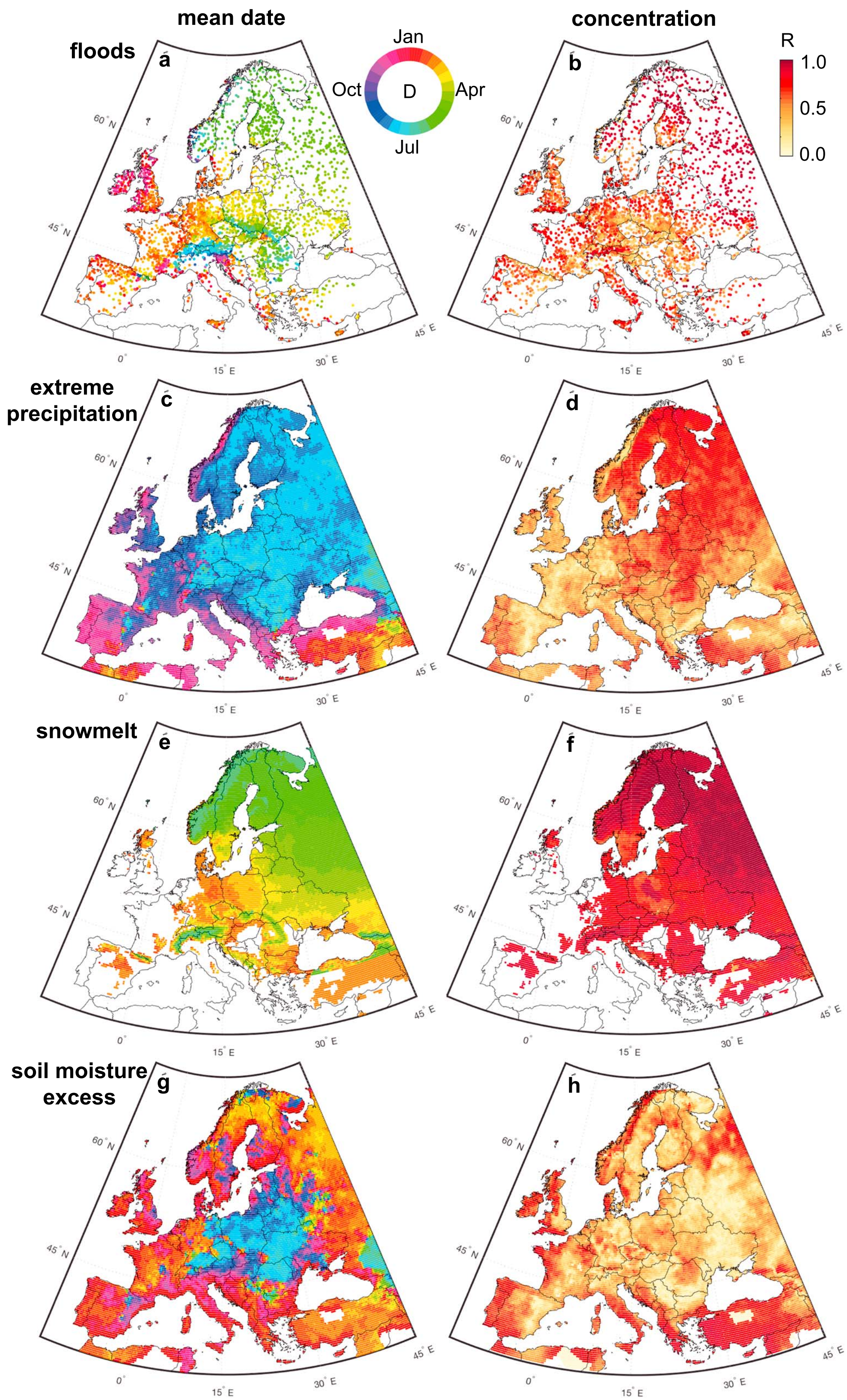


**Figure 2.** The spatial pattern of the timing of maximum annual flows and the flood-driving mechanisms (panels a, c, e, and g) and their concentration around their mean date of occurrence (panels b, d, f, and h) over the period 1960-2010.

The mean date of occurrence of maximum daily precipitation and its concentration also exhibits distinct regional differences (Figures 2c and 2d), but these regional patterns differ from the seasonality characteristics of floods. Broadly speaking, maximum daily precipitation tends to occur in summer in most of central and (north) eastern Europe, and these regions often have a low interannual variability of precipitation timing, as indicated by concentrations $R$ close to one. However, most floods in this region occur months earlier (again, with relatively low interannual variability), effectively excluding annual maximum precipitation as a major driver of annual maximum streamflow. Conversely, in the Carpathians and the Alps, annual maximum precipitation coincides seasonally with annual maximum flooding and thus is a plausible driver.

Unsurprisingly, annual maxima of snowmelt and rain on snow are strongly concentrated in late spring across much of (north) eastern Europe (Figures 2e and 2f). In most of this region, these maxima roughly coincide with the seasonality of flooding, making them a plausible flood driver. Snowmelt occurs earlier in the year in regions with milder winters and lower fractions of precipitation falling as snowfall (e.g., Denmark and Germany), where it does not coincide strongly with the seasonality of flooding.

Soil moisture excess (the difference between daily precipitation and available soil moisture storage capacity) peaks in winter across much of Europe (Figures 2g and 2h) owing to lower evaporation rates (and thus greater soil moisture) during the winter months. The timing of peak soil moisture excess coincides with the seasonality of peak flooding across large parts of Germany, France, Spain, and Britain. In contrast, across much of Poland, Belarus, Ukraine, Czech Republic, and northern Romania, soil moisture excess peaks in the summer because the summer maxima in precipitation outweigh the winter maxima in soil moisture. In much of this region, peak soil moisture excess does not coincide with the seasonality of annual flooding.

### 3.2. The Relative Importance of Flood-Generating Mechanisms

As we have seen above, the seasonality characteristics presented in Figure 2 facilitate a qualitative assessment of extreme precipitation, snowmelt, and soil moisture excess as flood drivers across Europe. By solving equations (11)–(13), we quantify the relative importance of the three flood-generating mechanisms for each catchment (Figure 3).

Across Europe as a whole, maximum annual precipitation is the least important flood driver (mean $\alpha_p = 0.23$; Figure 3a). However, in 22% of the catchments, extreme precipitation is more important than snowmelt and soil-moisture excess combined (i.e., $\alpha_p > 0.5$). These precipitation-flood-dominated catchments are primarily located in and near the Alps and the Carpathians. The dominant role of precipitation extremes for flood generation in these regions is consistent with more detailed national studies in Austria and Switzerland (Froidevaux et al., 2015; Merz and Blöschl, 2003). In contrast, however, maximum annual precipitation is not an important flood driver in nearly half of our 3,777 European catchments ($\alpha_p < 0.1$ for 46% of the catchments).

Across Europe, snowmelt or rain-on-snow are somewhat more important than peak precipitation as a flood driver (mean $\alpha_s = 0.29$). Snowmelt floods exceed the combined influence of the other driving mechanisms ($\alpha_s > 0.5$) in 31% of the studied catchments (Figure 3b). Snowmelt and rain on snow are dominant flood drivers across Scandinavia and northeastern Europe, and in some mountainous catchments, but are progressively less important as one moves toward western Europe. For the majority of our study catchments, snowmelt is not an important cause of flooding ($\alpha_s < 0.1$ for 61% of the catchments).

Across Europe as a whole, soil moisture excess is the most important flood driver (mean $\alpha_m = 0.49$). Soil moisture excess exceeds the combined influence of other processes ($\alpha_s > 0.5$) in 43% of the studied catchments. Floods are almost exclusively driven by soil moisture excess in a broad arc stretching across much of Europe, including large parts of Portugal, Spain, France, UK, Ireland, Belgium, the Netherlands, Germany, Poland, Italy, and majority of countries in southeast Europe. Elsewhere, such as in the Alps, North-Eastern Europe, and Scandinavia, soil moisture excess flooding is not important ($\alpha_m < 0.1$ for 43% of our study catchments).

The disconnect between precipitation extremes and flooding helps to contextualize flood trends. For example, observations indicate that annual maximum daily precipitation is increasing (Westra et al., 2013), but such a persistent increase is not found in observed annual maximum floods in Europe (Hall et al., 2014). Similarly, model simulations of European river floods at 1.5, 2, and 3 °C global warming indicate a very

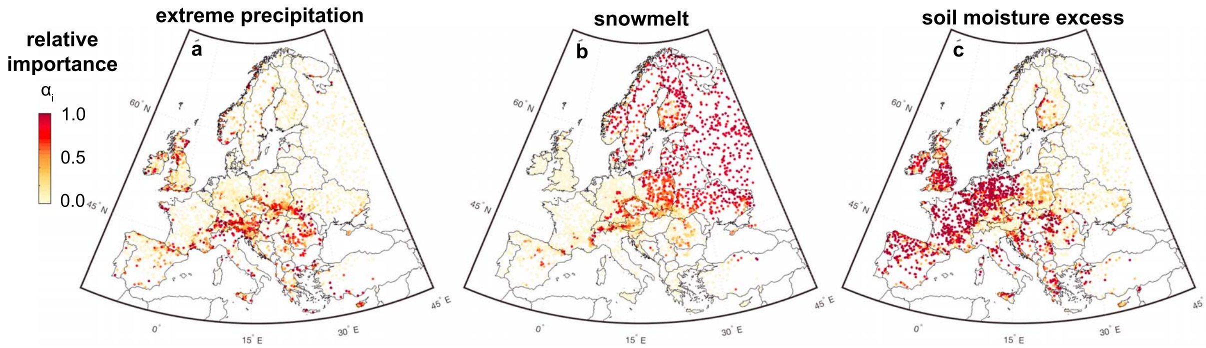


**Figure 3.** The spatial pattern of the relative importance of precipitation floods (panel a), snowmelt floods (panel b), and soil moisture excess (panel c) over the period 1960-2010 for the 3,777 catchments that have at least 20 years of data.

weak correlation between changes in precipitation extremes and changes in flood magnitudes (Thober et al., 2018). These observations are not very surprising when we consider that most annual peak floods are in fact not caused by annual peak precipitation. Our results point to the processes (snowmelt and soil moisture excess) that likely better explain flood trends in Europe (Blöschl et al., 2017).

Exposing the flood-generating mechanisms also helps to contextualize regional differences in *flood synchrony scales* (i.e., the maximum radius around an individual river gauge within which at least half of the other river gauges also record flooding almost simultaneously; Berghuijs et al., 2019). Regions with more mixed flood-generating mechanisms (i.e., northern Spain toward the Alps, into central Europe, and the Carpathians) have more localized flooding compared to regions with more homogeneous flood-generating mechanisms (i.e., western and northeastern Europe) where floods are usually correlated over large distances (Berghuijs et al., 2019).

### 3.3. Changes in the Importance of Flood-Generating Mechanisms

To assess whether the relative importance of the three flood drivers has changed over the period 1960-2010, we use equations (11)–(13) to estimate the relative importance of the mechanisms separately for the periods 1960-1984 and 1985-2010 and compare their differences ($\Delta\alpha = \alpha_{post1985}$ - $\alpha_{pre1985}$, Figure 4) in each catchment. The average importance of each flood driver has not changed substantially (mean $\Delta\alpha_p$, $\Delta\alpha_s$, and $\Delta\alpha_m$ are 0.01, 0.00, and 0.00, respectively, with standard deviations ranging from 0.14 to 0.16). For most regions in Europe, there are no discernible changes in the relative importance of these mechanisms. Regions with the strongest changes in individual catchments are those with multiple flood generating mechanisms (e.g., central Europe); these changes are not unidirectional and may represent year-to-year variability. Elsewhere, such as Ukraine, the pattern of change appears more unidirectional, with fewer snowmelt floods in the later period. Overall, the temporal changes are much smaller than the spatial differences in the relative importance of flood-generating mechanisms across Europe.

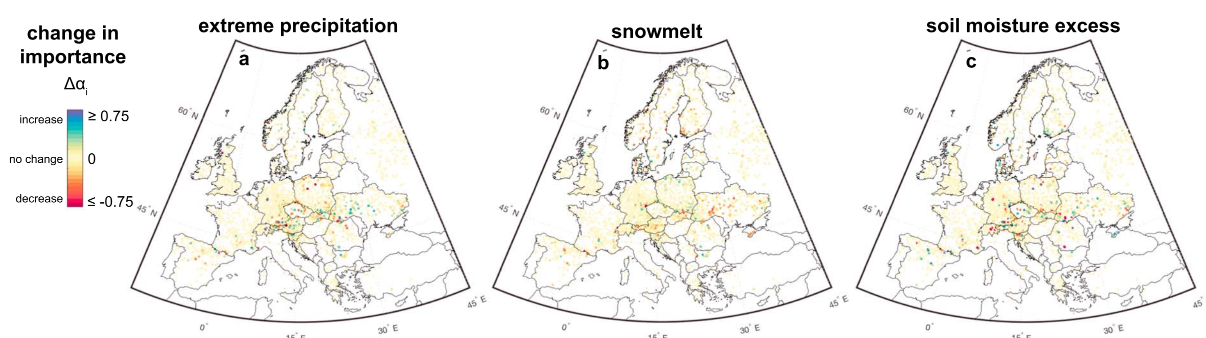


**Figure 4.** The spatial pattern of changes in the relative importance of precipitation floods (panel a), snowmelt floods (panel b), and soil moisture excess floods (panel c) between the periods 1960-1984 and 1985-2010, where $\Delta\alpha = \alpha_{post1985}$ - $\alpha_{pre1985}$.

10.1029/2019WR024841

### 3.4. Limitations in Inferring Flood Drivers

Our method is designed to infer causes of flooding when data (per site) are scarce and many catchments are studied. Because our flood data are limited to the dates of annual floods for each calendar year (i.e., the actual streamflow rate is not provided), drivers can only be inferred by comparing these dates with the timing of candidate mechanisms. Such inferences can be made by comparing the average timing of many events (e.g., seasonality statistics as used here), or by comparing the timing of individual events. Both approaches have their particular strengths and weaknesses.

At the scale of the European continent, 0.25° gridded data provide a rough approximation of the occurring precipitation (Hofstra et al., 2009), as the grid cells average over considerable spatial heterogeneity. As a result, individual rainstorms recorded in the data set will not always reflect local catchment conditions, challenging an accurate attribution of flood drivers on an event-by-event basis. In addition, the simulated snowmelt and soil moisture dynamics are obviously highly simplified representations of water cycling, which will not always accurately represent the event-scale catchment conditions. While more complex state-of-the-art models can be used to infer the importance of flood drivers, these models still come with substantial uncertainties (Zaherpour et al., 2018). Seasonality statistics characterize the mean timing of a process, and such means are (when enough years of data are used; Cunderlik et al., 2004) less impacted by inaccurate representations at the event scale. For example, the timing of simulated peak snowmelt in large-scale hydrological models often mismatches observations (e.g., Zaherpour et al., 2018), but the seasonality statistics of simulated snowmelt are expected to remain representative under such conditions (i.e., they will not shift to a completely different season).

Previous works that quantitatively (e.g., Berghuijs et al., 2016) or qualitatively infer (e.g., Hall & Blöschl, 2018) dominant flood drivers based on seasonality characteristics primarily base this on the mean date of flooding. Here we also use the concentration of floods to estimate the importance of flood drivers. This allows distinguishing between cases where floods (or their drivers) occur systematically during a particular time of the year, or when processes are more variable in their timing. Despite using information on the consistency in timing around the mean date of occurrence, and acknowledging that multiple mechanisms typically contribute to flood risk, limitations remain that can result in an inaccurate estimate of the importance of flood drivers. For example, our method does not discriminate between potential drivers that occur before or after flood events, potentially biasing attributions.

Floods may be driven by other mechanisms than the three tested drivers. A mechanism that may cause flooding, but that is not included is glacial flood outburst. Such floods occur frequently in Iceland (Björnsson, 2003), but we excluded catchments in Iceland from the data set provided by Blöschl et al. (2017). A more common flood-generating mechanism across Europe may be rainfall that occurs over several days, instead of a single day. Seasonality statistics of maximum multiple-day precipitation are near-identical to the seasonality characteristics of maximum daily precipitation amounts (Blöschl et al., 2017). In practice this means that our approach identifies whether rainfall maxima are driving flooding but it does not distinguish whether these are single-day or multiple-day rainfall events. In addition, the mechanisms that typically cause events may shift with the severity of the event (e.g., Bennett et al., 2018; Pendergrass, 2018), but because our flood data are limited to the dates of annual floods we cannot infer those differences.

Seasonality statistics most robustly quantify the importance of drivers when floods occur during very different times of the year, but with little year-to-year variation in these timings. The seasonality characteristics of the flood drivers are distinctly different across almost all of Europe (Figure 2), even though precipitation is an important factor for all three. Yet, in some regions, flooding and flood drivers both have strong interannual variability, which results in more uncertain estimated importances. However, a benchmark test indicates that, for the number of years of data and the seasonalities of the flood drivers in our data set, using seasonality statistics tends to accurately estimate the relative importance of different flood-generating mechanisms (Figure S1).

Our analysis can be strengthened by focusing on a smaller sample of catchments where more data are available. For example, incorporating information on the magnitude of flood events or expert knowledge may help improve the assessment of local flood generating mechanisms. An obvious future step will also be the inclusion of flow magnitudes, rather than just their timing. Unfortunately, at present, data licensing issues inhibit flow magnitudes to be made available for the thousands of sites across Europe (Blöschl et al., 2017).

## 4. Summary and Conclusions

This work provides a continental-scale overview of flood-generating mechanisms and their relative importance for Europe. We developed a new method for inferring the relative importance of different flood-generating mechanisms from the dates of maximum annual flows (section 2). We applied our method to a large European-wide data set of flood observations to generate a continental-scale, quantitative overview of the seasonality statistics of extreme precipitation, snowmelt, and soil moisture excess across Europe (Figure 2). There are distinct differences in the seasonality of these three mechanisms and flooding across Europe, allowing us to generate a continental-scale overview of the relative importance of each for generating flooding (Figure 3).

This continental-scale overview indicates that annual maximum precipitation was the least important driver of annual maximum flooding (mean $\alpha_p = 0.23$; Figure 3a), except in the Alps Carpathians, and Pyrenees. Snowmelt was more important (mean $\alpha_s = 0.29$; Figure 3b), particularly in northeastern Europe and Scandinavia. However, the dominant driver of flooding across much of Europe is soil moisture excess (mean $\alpha_m = 0.49$; Figure 3c). For most of our study catchments, the relative importance of these mechanisms has not changed substantially over the past five decades (Figure 4).

These findings further call into question the widespread assumption that changes in extreme precipitation will be reflected in changes in floods (Ivancic & Shaw, 2015; Sharma et al., 2018). Our results show that the combined effects of high soil moisture and precipitation are a more widespread driver of flooding than extreme rainfall alone. The exposed relative importance of the flood-generating mechanisms reveals regional patterns in the causes of Europe's most damaging natural hazard and points to the processes that require more attention in future flood research.

**Acknowledgments**
The maximum annual flow data are part of the European Flood Database and were downloaded from the Ingenieurhydrologie und Wassermengenwirtschaft website (www.hydro.tuwien.ac.at/fileadmin/mediapoolhydro/Downloads/Data.zip). We acknowledge the E-OBS data set from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). Precipitation and temperature data sets are generated in the European Climate Assessment & Dataset project and can be downloaded at the Home European Climate Assessment & Dataset website (www.ecad.eu/download/ensembles/ensembles.php).

## References

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

Archfield, S. A., Hirsch, R. M., Viglione, A., & Blöschl, G. (2016). Fragmented patterns of flood change across the United States. *Geophysical Research Letters*, *43*, 10,232–10,239. https://doi.org/10.1002/2016GL070590

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Bayliss, A.C., & Jones, R. C. (1993). Peaks-over-threshold flood database: Summary statistics and seasonality. IH Report No. 121, Institute of Hydrology, Wallingford, UK.

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

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

Berghuijs, W. R., Allen, S. T., Harrigan, S., & Kirchner, J. W. (2019). Growing spatial scales of synchronous river flooding in Europe. *Geophysical Research Letters*, *46*(3), 1423–1428. https://doi.org/10.1029/2018GL081883

Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2016). Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, *43*, 4382–4390. https://doi.org/10.1002/2016GL068070

Björnsson, H. (2003). Subglacial lakes and jökulhlaups in Iceland. *Global and Planetary Change*, *35*(3-4), 255–271. https://doi.org/10.1016/S0921-8181(02)00130-3

Black, A. R., & Werritty, A. (1997). Seasonality of flooding: A case study of North Britain. *Journal of Hydrology*, *195*(1-4), 1–25. https://doi.org/10.1016/S0022-1694(96)03264-7

Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., et al. (2015). Increasing river floods: fiction or reality? *Wiley Interdisciplinary Reviews: Water*, *2*(4), 329–344. https://doi.org/10.1002/wat2.1079

Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A., Merz, B., Arheimer, B., et al. (2017). Changing climate shifts timing of European floods. *Science*, *357*(6351), 588–590. https://doi.org/10.1126/science.aan2506

Blöschl, G., Nester, T., Komma, J., Parajka, J., & Perdigão, R. A. P. (2013). The June 2013 flood in the Upper Danube Basin, and comparisons with the 2002, 1954 and 1899 floods. *Hydrology and Earth System Sciences*, *17*(12), 5197–5212. https://doi.org/10.5194/hess-17-5197-2013

Cunderlik, J. M., Ouarda, T. B. M. J., & Bobée, B. (2004). On the objective identification of flood seasons. *Water Resources Research*, *40*, W01520. https://doi.org/10.1029/2003WR002295

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

Federer, C. A., Vörösmarty, C., & Fekete, B. (1996). Intercomparison of methods for calculating potential evaporation in regional and global water balance models. *Water Resources Research*, *32*(7), 2315–2321. https://doi.org/10.1029/96WR00801

Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., & Midgley, P. M. (Eds.) (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report*

*of the intergovernmental panel on climate change* (p. 582). Cambridge, UK, and New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139177245
Froidevaux, P., Schwanbeck, J., Weingartner, R., Chevalier, C., & Martius, O. (2015). Flood triggering in Switzerland: The role of daily to monthly preceding precipitation. *Hydrology and Earth System Sciences*, *19*(9), 3903–3924. https://doi.org/10.5194/hess-19-3903-2015
Hall, J., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., et al. (2015). A European Flood Database: facilitating comprehensive flood research beyond administrative boundaries. *Proceedings of the International Association of Hydrological Sciences*, *370*, 89–95. https://doi.org/10.5194/piahs-370-89-2015
Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., et al. (2014). Understanding flood regime changes in Europe: A state of the art assessment. *Hydrology and Earth System Sciences*, *18*(7), 2735–2772. https://doi.org/10.5194/hess-18-2735-2014
Hall, J., & Blöschl, G. (2018). Spatial patterns and characteristics of flood seasonality in Europe. *Hydrology and Earth System Sciences*, *22*(7), 3883–3901. https://doi.org/10.5194/hess-22-3883-2018
Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., & New, M. (2008). A European daily high resolution gridded data set of surface temperature and precipitation for 1950–2006. *Journal of Geophysical Research*, *113*(D20), D20119. https://doi.org/10.1029/2008JD010201
Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., et al. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816–821. https://doi.org/10.1038/nclimate1911
Hirsch, R. M., & Ryberg, K. R. (2012). Has the magnitude of floods across the USA changed with global CO2 levels? *Hydrological Sciences Journal*, *57*(1), 1–9. https://doi.org/10.1080/02626667.2011.621895
Hirschboeck, K. K. (1991). Climate and floods. In R. W. Paulson, E. B. Chase, & D. W. Moody (Eds.), *National Water Summary 1988 – 89, Floods and Droughts*, *Water-Supply, Pap.* (p. 67–88). Washington, DC: US Geol. Surv.
Hock, R. (2003). Temperature index melt modelling in mountain areas. *Journal of Hydrology*, *282*(1-4), 104–115. https://doi.org/10.1016/S0022-1694(03)00257-9
Hodgkins, G. A., Whitfield, P. H., Burn, D. H., Hannaford, J., Renard, B., Stahl, K., et al. (2017). Climate-driven variability in the occurrence of major floods across North America and Europe. *Journal of Hydrology*, *552*, 704–717. https://doi.org/10.1016/j.jhydrol.2017.07.027
Hofstra, N., Haylock, M., New, M., & Jones, P. D. (2009). Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature. *Journal of Geophysical Research*, *114*(D21), D21101. https://doi.org/10.1029/2009JD011799
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. *Climatic Change*, *133*(4), 681–693. https://doi.org/10.1007/s10584-015-1476-1
Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C., Mechler, R., Botzen, W. W., et al. (2014). Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, *4*(4), 264–268. https://doi.org/10.1038/nclimate2124
Keller, L., Rössler, O., Martius, O., & Weingartner, R. (2018). Delineation of flood generating processes and their hydrological response. *Hydrological Processes*, *32*(2), 228–240. https://doi.org/10.1002/hyp.11407
Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C., & Senior, C. A. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, *4*(7), 570–576. https://doi.org/10.1038/nclimate2258
Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., et al. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, *59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411
Mediero, L., Kjeldsen, T. R., Macdonald, N., Kohnova, S., Merz, B., Vorogushyn, S., et al. (2015). Identification of coherent flood regions across Europe by using the longest streamflow records. *Journal of Hydrology*, *528*, 341–360. https://doi.org/10.1016/j.jhydrol.2015.06.016
Merz, R., & Blöschl, G. (2003). A process typology of regional floods. *Water Resources Research*, *39*(12), 1340. https://doi.org/10.1029/2002WR001952
Milly, P. C. D., Wetherald, R., Dunne, K. A., & Delworth, T. L. (2002). Increasing risk of great floods in a changing climate. *Nature*, *415*(6871), 514–517. https://doi.org/10.1038/415514a
Mudelsee, M., Börngen, M., Tetzlaff, G., & Grünewald, U. (2003). No upward trends in the occurrence of extreme floods in central Europe. *Nature*, *425*(6954), 166–169. https://doi.org/10.1038/nature01928
Musselman, K. N., Lehner, F., Ikeda, K., Clark, M. P., Prein, A. F., Liu, C., et al. (2018). Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, *8*(9), 808–812. https://doi.org/10.1038/s41558-018-0236-4
Nied, M., Hundecha, Y., & Merz, B. (2013). Flood-initiating catchment conditions: A spatio-temporal analysis of large-scale soil moisture patterns in the Elbe River basin. *Hydrology and Earth System Sciences*, *17*(4), 1401–1414. https://doi.org/10.5194/hess-17-1401-2013
Paprotny, D., Sebastian, A., Morales-Nápoles, O., & Jonkman, S. N. (2018). Trends in flood losses in Europe over the past 150 years. *Nature Communications*, *9*(1), 1985. https://doi.org/10.1038/s41467-018-04253-1
Parajka, J. P., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., et al. (2010). Seasonal characteristics of flood regimes across the Alpine-Carpathian range. *Journal of Hydrology*, *394*(1-2), 78–89. https://doi.org/10.1016/j.jhydrol.2010.05.015
Pendergrass, A. G. (2018). What precipitation is extreme? *Science*, *360*(6393), 1072–1073. https://doi.org/10.1126/science.aat1871
Regonda, S. K., Rajagopalan, B., Clark, M., & Pitlick, J. (2005). Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate*, *18*(2), 372–384. https://doi.org/10.1175/JCLI-3272.1
Sharma, A., Wasko, C., & Lettenmaier, D. P. (2018). If precipitation extremes are increasing, why aren't floods? *Water Resources Research*, *54*(11), 8545–8551. https://doi.org/10.1029/2018WR023749
Sikorska, A. E., Viviroli, D., & Seibert, J. (2015). Flood-type classification in mountainous catchments using crisp and fuzzy decision trees. *Water Resources Research*, *51*, 7959–7976. https://doi.org/10.1002/2015WR017326
Slater, L. J., & Villarini, G. (2016). Recent trends in U.S. flood risk. *Geophysical Research Letters*, *43*, 428–436.
Slater, L. J., & Wilby, R. L. (2017). Measuring the changing pulse of rivers. *Science*, *357*(6351), 552–552. https://doi.org/10.1126/science.aao2441
Thober, S., Kumar, R., Wanders, N., Marx, A., Pan, M., Rakovec, O., et al. (2018). Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming. *Environmental Research Letters*, *13*(1), 014003. https://doi.org/10.1088/1748-9326/aa9e35
Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The changing character of precipitation. *Bulletin of the American Meteorological Society*, *84*(9), 1205–1218. https://doi.org/10.1175/BAMS-84-9-1205
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. *Journal of Hydrology*, *538*, 33–48. https://doi.org/10.1016/j.jhydrol.2016.03.066
Westra, S., Alexander, L. V., & Zwiers, F. W. (2013). Global increasing trends in annual maximum daily precipitation. *Journal of Climate*, *26*(11), 3904–3918. https://doi.org/10.1175/JCLI-D-12-00502.1

Winsemius, H. C., Aerts, J. C. J. H., van Beek, L. P., Bierkens, M. F., Bouwman, A., Jongman, B., et al. (2015). Global drivers of future river flood risk. *Nature Climate Change*, *6*(4), 381–385. https://doi.org/10.1038/NCLIMATE2893

Zaherpour, J., Gosling, S. N., Mount, N., Schmied, H. M., Veldkamp, T. I., et al. (2018). Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. *Environmental Research Letters*, *13*(6), 065015. https://doi.org/10.1088/1748-9326/aac547