Title: Changing climate shifts timing of European floods

Authors:
Günter Blöschl1*, Julia Hall1, Juraj Parajka1, Rui A. P. Perdigão1, Bruno Merz2, Berit Arheimer3, Giuseppe T. Aronica4, Ardan Bilbashı5, Ognjen Bonacci6, Marco Borga7, Ivan Čanjevac8, Attilio Castellarin9, Giovanni B. Chirico10, Pierluigi Claps11, Károly Fiala12, Natalia Frolova13, Liudmyla Gorbachova14, Ali Gül15, Jamie Hannaford16, Shaun Harrigan16, Maria Kirīeva13, Andrea Kiss1, Thomas R. Kjeldsen17, Silvia Kohnová18, Jarkko J. Koskela19, Ondrej Ledvinka20, Neil Macdonald21, Maria Mavrova-Guirguinova22, Luis Mediero23, Ralf Merz24, Peter Molnar25, Alberto Montanari9, Conor Murphy26, Marzena Osuch27, Valeryia Ovchark28, Ivan Radevski29, Magdalena Rogger1, José L. Salinas1, Eric Sauquet30, Mojca Šraj31, Jan Szolgay32, Alberto Viglione1, Elena Volpi32, Donna Wilson33, Klodian Zaimi34, and Nenad Živković35

Affiliations:
1Institute of Hydraulic Engineering and Water Resources Management, Technische Universität Wien, Vienna, Austria.
2Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.
3Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.
4Department of Engineering, University of Messina, Messina, Italy.
6Faculty of Civil Engineering, Architecture and Geodesy, Split University, Split, Croatia.
7Department of Land, Environment, Agriculture and Forestry, University of Padova, Padua, Italy.
8University of Zagreb, Faculty of Science, Department of Geography, Zagreb, Croatia.
9Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Università di Bologna, Bologna, Italy.
10Department of Agricultural Sciences, University of Naples Federico II, Naples, Italy.
11Department Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Turin, Italy.
12Lower Tisza District Water Directorate, Szeged, Hungary.
13Department of Land Hydrology, Lomonosov Moscow State University, Moscow, Russia.
14Department of Hydrological Research, Ukrainian Hydrometeorological Institute, Kiev, Ukraine.
15Department of Civil Engineering, Dokuz Eylül University, Izmir, Turkey.
16Centre for Ecology & Hydrology, Wallingford, Oxfordshire, UK.
17Department of Architecture and Civil Engineering, University of Bath, Bath, UK.
18 Slovak University of Technology in Bratislava, Faculty of Civil Engineering, Department of Land and Water Resources Management, Radlinského 11, 810 05 Bratislava, Slovakia.
19 Finnish Environment Institute, Helsinki, Finland.
20 Czech Hydrometeorological Institute, Prague, Czechia.
21 Department of Geography and Planning & Institute of Risk and Uncertainty, University of Liverpool, Liverpool, UK.
22 University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria.
24 Department for Catchment Hydrology, Helmholtz Centre for Environmental Research – UFZ, Halle, Germany.
25 Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland.
26 Irish Climate Analysis and Research Units (ICARUS), Department of Geography, Maynooth University, Ireland.
27 Institute of Geophysics Polish Academy of Sciences, Department of Hydrology and Hydrodynamics, Warsaw, Poland.
28 Hydrometeorological Institute, Odessa State Environmental University, Odessa, Ukraine.
29 Institute of Geography, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje, Republic of Macedonia.
30 Irstea, UR HHLY, Hydrology-Hydraulics Research Unit, Lyon, France.
31 Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia.
32 Department of Engineering, University Roma Tre, Rome, Italy.
33 Norwegian Water Resources and Energy Directorate, Oslo, Norway.
34 Institute of Geo-Sciences, Energy, Water and Environment (IGEWE), Polytechnic University of Tirana, Tirana, Albania.
35 University of Belgrade, Faculty of Geography, Belgrade, Serbia.

*Corresponding author. Email: bloeschl@hydro.tuwien.ac.at
Abstract:
A warming climate is expected to impact river floods; however, no consistent large-scale climate change signal in observed flood magnitudes has been identified so far. We have analyzed the timing of river floods in Europe over the last five decades using a pan-European database from 4262 observational hydrometric stations, and find clear patterns of change in flood timing. Warmer temperatures have led to earlier spring snowmelt floods throughout North-Eastern Europe; delayed winter storms associated with polar warming have led to later winter floods around the North Sea and some sectors of the Mediterranean Coast; and earlier soil moisture maxima have led to earlier winter floods in Western Europe. Our results highlight the existence of a clear climate signal in flood observations at the continental scale.

One Sentence Summary:
The observed timing of floods has shifted consistently in many parts of Europe over the past 50 years as a result of a changing climate.
River flooding affects more people worldwide than any other natural hazard, with an estimated global annual average loss of US $104 billion (1). Damages are expected to increase due to economic growth and climate change (2, 3). The intensification of the water cycle due to a warming climate is projected to change the magnitude, frequency and timing of river floods (3). However, existing studies have been unable to identify a consistent climate change signal in flood magnitudes (4). Identification of a large-scale climate change signal in flood observations has been hampered by the existence of many processes controlling floods, including precipitation, soil moisture and snow, by non-climatic drivers of flood change such as land use change and river training, and by the inconsistency of data sets and their limited spatial extents (4, 5). It has been proposed that considering the seasonal timing of floods as a fingerprint of climate effects on floods may be a way to avoid some of those complications (6, 7). For example, in cold regions, earlier snowmelt due to warmer temperatures leads to earlier spring floods (6), and this climate-related signal may be less confounded by non-climatic drivers than flood magnitudes themselves because of the strong seasonality of climate. While the changing timing of floods has been studied at local scale in Nordic and Baltic countries (8–10), no consistent analysis exists at the European scale.

Here we analyze a large data set of flood observations in Europe to assess whether a changing climate has shifted the timing of river floods in the last five decades. Our analysis is based on river discharge or water level observations from 4262 hydrometric stations in European countries for the period 1960-2010 (Table S1). For each station, we use a series consisting of the dates of occurrence of the highest peak in any calendar year. We define the average timing of the floods by the average date on which floods have occurred during the
observation period. We then estimate the trend in the timing of the floods using the Theil-Sen slope estimator (11) for stations with at least 35 years of data and the long-term evolution using a 10-year moving average filter. Finally, we analyze the change signal of three potential drivers of flood changes in a similar fashion: the middle date of the maximum 7-day precipitation; the middle day of the month with the highest soil moisture; and the middle day of the first seven days in a year with air temperature above 0°C as a proxy for spring snowmelt and snowfall-to-rain transition. For more details on the data and the analysis see the Materials and Methods section in the Supplementary Material.

Our data show a clear shift in the timing of floods in Europe in the past 50 years (Fig. 1). The regionally interpolated trend patterns shown in Fig. 1, range from a −13 days per decade towards earlier floods to +9 days towards later floods, which translates into total shifts of −65 and +45 days, respectively, of linear trends over the entire 50 year period. The local, station specific, trends (Fig. S2) are larger, but reflect smaller scale rather than regional scale processes. The changes are most consistent in North-Eastern Europe (region 1 in Fig. 1) where 81% of the stations show a shift towards earlier floods (50% of the stations by more than −8 days / 50 yrs) (Fig. S2). The changes are largest in Western Europe along the North Atlantic Coast from Portugal to England (region 3) where 50% of the stations show a shift towards earlier floods by at least 15 days / 50 yrs (25% of the stations by more than 36 days / 50 yrs). Around the North Sea (region 2, South-Western Norway, the Netherlands, Denmark and Scotland) 50% of the stations show a shift towards later floods by more than 8 days / 50 yrs. In some parts of the Mediterranean Coast (region 4, North-Eastern Adriatic Coast, North-Eastern Spain), there is a shift towards later floods (50% of the stations by more than 5 days / 50 yrs). Apart from the
large-scale change patterns described for the four regions above, smaller-scale patterns of changes in flood timing can also be identified.

**Fig. 1. Observed trends of river flood timing in Europe (1960-2010).** Red indicates earlier floods, blue later floods (days per decade). 1-4 indicate regions with distinct drivers: [1] North-Eastern Europe: earlier snowmelt; [2] North Sea region: later winter storms; [3] Western Europe along the Atlantic Coast: earlier soil moisture maximum; [4] parts of the Mediterranean Coast: stronger Atlantic influence in winter.

In order to infer the causes of these changes in timing, we focused on six sub-regions or hotspots, where changes in flood timing are particularly clear (Fig. S2, Table S2). Since floods are the result of the seasonal interplay of precipitation, soil moisture and snow processes (12) we analyzed the temporal evolutions of these variables and compared them to those of the floods (Fig. 2A-2F). In Southern Sweden (Fig. 2A) and in the Baltics (Fig. 2B), floods are mainly due
to spring snowmelt (9, 10). The temporal evolution of flood timing therefore closely follows that of snowmelt, shifting from late March to February (green and orange lines in Fig. 2A, 2B).

Earlier snowmelt is known to be driven by both local temperature increases and a decreasing frequency of advection of arctic air masses (13). The Baltics are topographically less shielded from these air masses than Southern Sweden, which is reflected by larger variations in the timing of snowmelt in the 1990s. In South-Western Norway (Fig. 2C) precipitation maxima at the end of the year generate floods around the same time, since there is little subsurface water storage capacity there due to the prevalence of shallow soils. Changes in the North Atlantic Oscillation (NAO) since 1980 (14) may have resulted in a delayed arrival of heavy winter precipitation, with maxima shifting from October to December. These NAO anomalies have been less pronounced since the early 2000s. The floods follow closely the timing of extreme precipitation (Fig. 2C), which strongly suggests a causal link. The changes in the NAO may be related to Polar warming, among many other factors, although the role of anthropogenic effects is still uncertain (15, 16).

In Southern England (Fig. 2D), the subsurface water storage capacity tends to be much larger than in coastal Norway. The maximum rainfall, which occurs in autumn, therefore tends to get stored, and soil moisture and groundwater tables continuously increase until they reach a maximum in winter. Sustained winter rainfall on saturated soils then produces the largest floods in winter. As a result, the flood timing in Southern England is more closely associated with the timing of maximum soil moisture than with the timing of extreme precipitation (17). The variations in flood timing in North-Western Iberia (Fig. 2E) are similar to those of Southern England, although precipitation there occurs more in the winter, so extreme precipitation and maximum soil moisture (driven by sustained precipitation) are more closely aligned. Along the Northern Adriatic Coast (Fig. 2F), large-scale influences by the Atlantic Ocean condition
Adriatic meso-scale cyclonic activity, which produces heavy precipitation towards the end of the year (18). Meridional shifts in storm tracks have increased atmospheric flow from the Atlantic to the Mediterranean in winter (19), leading to later extreme precipitation and floods in the season (Fig. 2F).

Fig. 2. Long-term temporal evolution of timing of floods and their drivers for six hotspots in Europe. Southern Sweden (A), Baltics (B), South-Western Norway (C), Southern England (D), North-Western Iberia (E), Adriatic Coast (F). Timing of observed floods (green), 7-day maximum precipitation (purple), snowmelt indicator (orange), and timing of modeled maximum soil moisture (blue). Line shows median timing over the entire hotspot, bands indicate variability of timing within the year (± 0.5 circular standard deviation (Eq. 8)). All data were subject to a 10-year moving average filter. Vertical axes show month of the year (June to May).
To further assist in the interpretation of trends in flood timing across Europe, the spatial pattern of the average flood timing (1960-2010) is presented in Fig. 3. The average timing of the floods varies gradually from the West to the East due to increasing continentality (distance from the Atlantic), and from the South to the North due to the increasing influence of snow processes. The effect of snow storage and melt at high altitudes, e.g. in the Alps and the Carpathians (red arrows in Fig. 3), is superimposed on this pattern. The spatial patterns of the average timing of potential drivers, and their trends, are shown in Fig. S3, S4, S5.

Throughout North-Eastern Europe (region 1 in Fig. 1), spring occurrence of snowmelt and floods (yellow and green arrows in Fig. S4A and Fig. S3) combined with a warmer climate (Fig. S4A) has led to earlier floods. In the region around the North Sea (region 2 in Fig. 1), extreme precipitation and floods in the winter (blue arrows in Fig. S3A and Fig. 3) combined with a shift in the timing of extreme winter precipitation (Fig. S3B) has led to later floods. In Western Europe (region 3 in Fig. 1), winter occurrence of soil moisture maxima and floods (blue arrows in Fig. S5A and Fig. 3) combined with a shift in the timing of soil moisture maxima (Fig. S5B) has led to earlier floods. While region 3 shows a consistent behavior in flood timing changes, closely aligned with those of soil moisture, the effect of changing storm tracks on precipitation are different in Southern England and North-Western Iberia, due to the opposite effects of the NAO.
Fig. 3. Observed average timing of river floods in Europe (1960-2010). Each arrow represents one hydrometric station (n=4062). Color and arrow direction indicate the average timing of floods (light blue: winter floods (DJF), green to yellow: spring floods (MAM), orange to red summer floods (JJA) and purple to dark blue autumn floods (SON)). Lengths of the arrows indicate the concentration of floods within a year (R=0 evenly distributed, R=1 all floods occur on the same date).

If the trends in flood timing continue, considerable economic and environmental consequences may arise, as society and ecosystems have adapted to the average within-year timing of floods. Later winter floods in catchments around the North Sea, for example, may reduce agricultural productivity due to softer ground for spring farming operations, higher soil compaction, enhanced erosion and direct crop damage (20). Spring floods occurring earlier in the season in North-Eastern Europe may limit the replenishment of reservoirs if managers expect later floods that never arrive, with substantial reductions in water supply, irrigation and
hydropower generation (21). Perhaps more importantly, this study identifies a clear climate
change signal in flood observations at the continental scale using the timing of floods, which was
not possible using flood magnitudes to date (4, 5, 22).

References and Notes:


**Acknowledgments:**

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**Supplementary Materials:**

- Materials and Methods
- Supplementary Text
- Figures S1 to S5
- Tables S1 and S2
- References (23-41)
Supplementary Materials for

Changing climate shifts timing of European floods

Günter Blöschl, Julia Hall, Juraj Parajka, Rui A. P. Perdigão, Bruno Merz, Berit Arheimer, Giuseppe T. Aronica, Ardian Bilibashi, Ognjen Bonacci, Marco Borga, Ivan Čanjevac, Attilio Castellarin, Giovanni B. Chirico, Pierluigi Claps, Károly Fiala, Natalia Frolova, Liudmyla Gorbachova, Ali Gül, Jamie Hannaford, Shaun Harrigan, Maria Kireeva, Andrea Kiss, Thomas R. Kjeldsen, Silvia Kohnová, Jarkko J. Koskela, Ondrej Ledvinka, Neil Macdonald, Maria Mavrova-Guirguinova, Luis Mediero, Ralf Merz, Peter Molnar, Alberto Montanari, Conor Murphy, Marzena Osuch, Valeryia Ovcharuk, Ivan Radevski, Magdalena Rogger, José L. Salinas, Eric Sauquet, Mojca Šraj, Jan Szolgay, Alberto Viglione, Elena Volpi, Donna Wilson, Klodian Zaimi, and Nenad Živković

correspondence to: bloeschl@hydro.tuwien.ac.at

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Figures S1 to S5
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Materials and Methods

Data Sets

The hydrological data were obtained from a newly created European Flood Database (23) containing observations from 38 European countries for the period 1960 to 2010. The hydrological data used in this study consist of time series from 64 data holders/sources, which are listed in Table S1. The database of the flood dates can be downloaded from http://www.hydro.tuwien.ac.at/fileadmin/mediapool-hydro/Downloads/Data.zip.

The database contains the date of the largest peak discharge or highest water level in each calendar year of the observed record (daily mean or instantaneous discharge) for each station. The dates of the maximum annual floods rather than those of multiple floods within a year are analyzed for two reasons. First, the climatological average of the flood timing over a decade or a number of decades can be more meaningfully defined if only a single flood per year is considered. Second, due to data licensing issues, for some areas, only the annual maxima were available.

Analyzing the dates of the floods provides deeper insights into the processes driving change than analyzing flood magnitudes alone. In addition, the date can be identified equally well from discharge and water level data which increases the temporal and spatial coverage. Finally, for some stations only the dates were available.

Stations located within the region bounded by the latitudes 34° N - 71° N and the longitudes 22° W - 52° E, with catchment areas between 5 and 100,000 km² and with more than 10 years of data during the study period were considered here. Although the data could be stratified into smaller and larger catchments, we collectively examined catchments of all areas to maintain spatial coverage and sample size. Stratifying the stations by catchment area did not change the large-scale patterns obtained in the analysis. Catchments that were reported by the data providers to have experienced strong human modifications that could affect the timing of floods were excluded. A few stations may still be affected by human modifications, but will have little impact on the overall result since the focus is on large-scale patterns of change. To account for the uneven spatial distribution of the hydrometric stations included in the database, in areas with high station densities such as Austria, Germany, and Switzerland, only stations with at least 49 years of data in the analysis period were included. This screening resulted in a set of 4262 stations (Fig. S1A, circles) with a median catchment size of 403 km². The elevation map plotted in the background of Fig. S1 was obtained from: https://www.eea.europa.eu/data-and-maps/data/digital-elevation-model-of-europe/.

The data from these stations were used for estimating the average timing of the annual flood peaks (Fig. 3). For estimating the change in the flood timing (Fig. 1 and 2), stations with at least 35 years of data during the analysis period (70% completeness) were considered, which resulted in 3298 stations (Fig. 1B, full circles) with a median catchment size of 420 km².

For each hydrometric station, the contributing catchment boundary was derived from the CCM River and Catchment Database (24) (http://www.bafg.de/GRDC/EN/01_GRDC/13_dtbse/database_node.html). The river network shown in the Figures is also taken from this database. Daily gridded precipitation and mean surface temperature data from the E-OBS data set (Version 14.0) (25) for the
period 1960-2010 were used (http://www.ecad.eu/download/ensembles/ensembles.php). The data consist of interpolated ground-based observations from stations with spatial resolutions of 0.5° x 0.5° and 0.25° x 0.25°. Monthly gridded soil moisture data from the CPC Soil Moisture data set (26) for the period 1960-2010 was analyzed (http://www.esrl.noaa.gov/psd). The data are model-calculated monthly averaged soil moisture water height equivalents with a spatial resolution of 0.5°.

Analysis Method
As a first step, we calculated for each station the average day within a year on which floods have occurred during the observation period. To account for the fact that floods can occur throughout the year, all calculations were performed using circular statistics (17, 27). Only those stations for which the null hypothesis of circular uniformity (Kuiper's test (28)) was rejected (significance level, \( \alpha = 0.1 \)) were retained. This resulted in 4062 stations used in the analysis of the average timing, and 3184 stations for the trend analysis. Circular non-uniformity is considered necessary for a meaningful application of circular trend analysis.

The date of occurrence \( D_i \) of a flood in year \( i \) was converted into an angular value \( \theta_i \) by

\[
\theta_i = D_i \cdot \frac{2\pi}{m_i} \quad 0 \leq \theta_i \leq 2\pi
\]  

where \( D_i = 1 \) corresponds to January 1 and \( D_i = m_i \) to December 31, and where \( m_i \) is the number of days in that year. The average date of occurrence \( \bar{D} \) of a flood at a station is defined as (17, 27):

\[
\bar{D} = \left\{ \begin{array}{ll}
\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \cdot \frac{m}{2\pi} & \bar{x} > 0, \ \bar{y} \geq 0 \\
\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + \pi & \bar{x} = 0 \\
\tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) + 2\pi & \bar{x} > 0, \ \bar{y} < 0,
\end{array} \right.
\]

with

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} \cos(\theta_i)
\]

\[
\bar{y} = \frac{1}{n} \sum_{i=1}^{n} \sin(\theta_i)
\]

\[
\bar{m} = \frac{1}{n} \sum_{i=1}^{n} m_i
\]
where \( \bar{x} \) and \( \bar{y} \) are the cosine and sine components of the average date, respectively, \( \bar{m} \) is the average number of days per year (365.25), and \( n \) is the total number of flood peaks at that station. The concentration \( R \) of the date of occurrence around the average date is

\[
R = \sqrt{\bar{x}^2 + \bar{y}^2} \quad 0 \leq R \leq 1
\]

which ranges from \( R = 0 \) (no concentration, i.e. floods are widely dispersed throughout the year) to \( R = 1 \) (all floods at a station occur on the same day of the year).

As a second step, we estimated the trend in the timing by the adjusted Theil-Sen slope estimator (11, 29). This non-parametric estimator was chosen for its robustness and insensitivity to missing values and outliers. The trend estimator \( \beta \) is the median of the difference of dates over all possible pairs of years \((i, j)\) within the time series,

\[
\beta = \text{median} \left( \frac{D_j - D_i + k}{j - i} \right)
\]

with

\[
k = \begin{cases} 
-\bar{m} & \text{if } D_j - D_i > \bar{m}/2 \\
\bar{m} & \text{if } D_j - D_i < -\bar{m}/2 \\
0 & \text{otherwise}
\end{cases}
\]

where \( k \) makes the adjustment for the circular nature of the dates and \( \beta \) has units of days per year. The value of \( \beta \) is plotted at the respective station location in Fig. S2. To identify large-scale spatial patterns within Europe, \( \beta \) was spatially interpolated using the \textit{autoKrige} function (automatic kriging) within the R \textit{automap} package (30), which automatically fits a variogram to the spatial data. The derived trend patterns are plotted in Fig. 1 and in the background of Fig. S2.

Third, we estimated the long-term evolution in flood timing with a centered 10-year moving average filter using Equations 2-6 (with \( n=10 \)) to reduce the short-term year-to-year variability and sharpen the focus on long-term, decadal fluctuations. The periods 1960-1965 and 2005-2010 are shown in lighter colors in Fig. 2, as less than 10 years were available for calculating the average. We pooled these filtered series within sub-regions or hotspots that were selected based on their similarity, within a rectangular sub-region, of the average flood timing and its trends (Fig. S1). Names of the sub-regions are only indicative for a region and do not exactly correspond to any exactly defined geographic area. The series of flood timing within each hotspot were tested for evidence of a significant regionally consistent trend, using the Regional Mann-Kendall test (31). All regional trends were statistically significant at the \( \alpha=0.05 \) level (Table S2). For each hotspot, the median timing for each year was calculated based on the data from each station within the hotspot. A 10-year moving average filter was then applied to the annual median timing to obtain the longer-term evolution of the time series within each hotspot (solid lines in Fig. 2). Additionally, we estimated the long-term evolution of the circular standard deviation \( \sigma \),

\[
\sigma = \sqrt{-2 \ln(R)}
\]

\[
(8)
\]
as a measure of the spread of flood occurrence within the year across all stations in the hotspot, and plotted $\sigma$ as the widths of the bands in Fig. 2.

To investigate rain-induced effects on flood timing we identified for each grid point of the E-OBS dataset the 7-day period with the maximum precipitation in any calendar year (with at least 70% of the annual data available). We assigned the midpoint of the period as the date of the 7-day maximum precipitation, and repeated all timing and change analyses analogously to the floods described above (Fig. S3). Seven days are representative of flood generation in large catchments (32). In smaller catchments, shorter rainstorms (e.g. 1 or 3 days) may be more relevant. The average timing of the 1-day and 3-day maximum precipitation in Europe based on the E-OBS data set is very similar to the average timing of the 7-day maximum precipitation (Circular Pearson correlation coefficient $r=0.91$ and $r=0.95$, respectively), therefore we consider the 7-day maximum precipitation to be also representative for smaller catchments.

To understand the effect of snow processes on the flood timing we introduced a snowmelt-timing indicator as the first full seven days in a year when surface air temperatures exceeded 0° C. We only included those grid points at which such a date could be identified meaningfully in at least 70% of the years analyzed, i.e. where the 7-day temperatures were below 0° C before they started to rise in spring. The snowmelt-timing indicator is considered a proxy for both the snowmelt season and the transition from snowfall to rainfall. All timing and change analyses (Eq. 1 to Eq. 8) were repeated for maximum precipitation and the snowmelt indicator (Fig. S4).

When soil moisture is high, even small rainstorms may produce floods. To understand the effect of high soil moisture on floods, we identified for each grid point of the CPC Soil Moisture dataset the month of the highest soil moisture. We assigned the midpoint of the month as the date of maximum soil moisture and repeated all timing and change analyses (Eq. 1 to Eq. 8) (Fig. S5).

Only the data of grid points for which the null hypothesis of circular uniformity could be rejected ($\alpha=0.1$) were used. For clarity of the visual presentation, Fig. S3A to S5A show only every other grid point. In the hotspot analyses (Fig. 2), the maximum precipitation, snowmelt indicator and maximum soil moisture data series were first extracted based on their location within the catchment boundaries and then aggregated for each hotspot.

All the data analysis mentioned above was performed in R (33) using the supporting packages lattice (34), maptools (35), ncdf4(36), plyr (37), raster (38), RColorBrewer (39), rgdal (40) and rworldmap (41).
Supplementary Text

Author Contributions
G.B. and J.H. designed the study and wrote the first draft of the paper.
G.B. initiated the study.
J.H. collated the database with the help of most of the co-authors, and conducted the analyses.
J.P. compiled the catchment boundaries and assisted in drafting the paper.
R.P. and B.M interpreted the results in the context of underlying geophysical mechanisms.
B.A, P.M and E.S provided additional data to crosscheck the results of this study.
All authors interpreted results, and contributed to framing and revising the paper.
Fig. S1
Map of European study area, elevation, main rivers and lakes (A), and location of the hydrometric stations analyzed (B). Open and full circles indicate stations used for estimating the average flood timing $\geq 10$ years of data, $n=4262$), full circles indicate stations used for estimating the change in flood timing ($\geq 35$ years of data, $n=3298$).
Fig. S2
Observed trends in flood timing 1960-2010, at individual hydrometric stations (points, n=3184) and interpolated trends (background pattern). Rectangles show selected sub-regions that were subject to a detailed regional analysis (Fig. 2).
Fig. S3
7-day maximum precipitation (1960-2010). Average timing (color and direction of arrows) and concentration of timing within a year, R (length of arrows) (A), trend in timing; red indicates earlier precipitation, blue later precipitation (days per decade) (B).
Fig. S4
Snowmelt indicator (1960-2010), first 7-days of the year with air temperature above 0° C. Average timing (color and direction of arrows) and concentration of timing within a year, R (length of arrows) (A), trend in timing; red indicates earlier snowmelt indicator, blue later snowmelt indicator (days per decade) (B).
Fig. S5
Annual maximum monthly soil moisture (1960-2010). Average timing (color and direction of arrows) and concentration of timing within a year, R (length of arrows) (A), trend in timing; red indicates earlier soil moisture, blue later soil moisture (days per decade) (B).
### Table S1.
Data Sources contained in the European Flood Research Database

<table>
<thead>
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<th>Country/Project</th>
<th>Data Holder/Source/Project information</th>
</tr>
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<td>Austria</td>
<td>Ministry of Agriculture, Forestry, Environment and Water Management</td>
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<tr>
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<td>Bulgaria</td>
<td>Hydrological Yearbooks of the Rivers in Bulgaria, National Institute of Meteorology and Hydrology</td>
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<td>Croatia</td>
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<td>Denmark</td>
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<td>Hessian Agency for Nature Conservation, Environment and Geology (HLNUG)</td>
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<td>Lower Saxony Water Management, Coastal Defense and Nature Conservation Agency (NLWKN)</td>
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<td>State Office of Environment, Nature Protection and Geology of Mecklenburg-Vorpomern (LUNG)</td>
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<td>Schleswig-Holstein Agency for Coastal Defense, National Park and Marine Conservation (ACNM-SH)</td>
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<td>GRDC</td>
<td>The Global Runoff Data Centre, Koblenz, Germany</td>
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Greece
Hydroscope - Ministry for the Environment, Energy and Climate Change - Special Secretariat for Water

Hungary
General Directorate of Water Management, Hungary
Lower Tisza District Water Directorate

HYDRATE
HYDRATE Project database: Hydrometeorological Data Resources and Technology for Effective Flash Flood Forecasting

Ireland
Irish Environmental Protection Agency (EPA)
Office of Public Works (OPW)

Italy
Former National Hydrographic Service (SIMN)
The Italian National Institute for Environmental Protection and Research (ISPRA)
National Research Council (CNR)
Hydrological Services, Autonomous Province of Bozen/Bolzano - South Tyrol
Regional Agency for the Environmental Protection (ARPA), Emilia-Romagna
Italian National Agency for Electricity (ENEL)
Research Institute for Hydro-Geologic Protection (IRPI)
Regional Agency for the Environmental Protection (ARPA), Piedmont

Italy, Emilia-Romagna Region
Regional Agency for the Environmental Protection (ARPA), Emilia-Romagna

Italy, Lazio & Umbria

Italy, Piedmont Region
Regional Agency for the Environmental Protection (ARPA), Piedmont

Italy, Po Region
Basin Authority of the Po River

Italy, Sicily Region
Water Observatory - Sicily Region

Italy, Trentino Region
Civil Protection Department, Autonomous Province of Trento

Italy, Tuscany Region
Regional Functional Center of Meteo-Hydrological Monitoring, Tuscany

Italy, Veneto Region
Regional Agency for the Environmental Protection (ARPA), Veneto

Latvia
Latvian Environment, Geology and Meteorology Centre

Lithuania
Lithuanian Hydrometeorological Service under the Ministry of Environment

Netherlands
Dutch Ministry of Infrastructure and the Environment - Rijkswaterstaat

Norway
Database Hydra II; Norwegian Water Resources and Energy Directorate (NVE)

Poland
Institute of Meteorology and Water Management National Research Institute (IMGW-PIB)

Portugal
Portuguese Environmental Agency National Information System for Water Resources of Portugal (SNIRH)
National Hydrometeorological Service, Republic of Macedonia

Republic of Macedonia
National Hydrometeorological Service, Republic of Macedonia

Russia
Ministry of Natural Resources and Ecology of the Russian Federation
State Water Cadastre, State Hydrological Institute, Lomonosov Moscow State University
AIS GMVO, Russian Federal Agency for Water Resources

Serbia
Republic Hydrometeorological Service of Serbia (RHSS)

Slovakia
Slovak Hydrometeorological Institute, Bratislava (SHMI)

Slovenia
Slovenian Environment Agency (ARSO)
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<td>Spain</td>
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<td>UK National River Flow Archive (NRFA)</td>
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Table S2.
Changes in timing for selected hotspots. Trend slopes are in days per decade. Negative signs indicate earlier flood timing, positive values later flood timing. The significance level of the regional trends is given according to the Regional Mann-Kendall test with significance level alpha (α).

<table>
<thead>
<tr>
<th>Hotspot Name</th>
<th>No. of Stations</th>
<th>Maximum Slope</th>
<th>Minimum Slope</th>
<th>Regional Change slope</th>
<th>Regionally Significant</th>
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<tr>
<td>S Sweden</td>
<td>12</td>
<td>-1.58</td>
<td>-10.01</td>
<td>-4.84</td>
<td>α=0.01</td>
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<tr>
<td>Baltics</td>
<td>43</td>
<td>6.52</td>
<td>-7.46</td>
<td>-3.44</td>
<td>α=0.01</td>
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<tr>
<td>SW Norway</td>
<td>6</td>
<td>14.13</td>
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<td>7.91</td>
<td>α=0.01</td>
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<td>S England</td>
<td>49</td>
<td>12.34</td>
<td>-112.3</td>
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<td>α=0.01</td>
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<td>NW Iberia</td>
<td>25</td>
<td>2.90</td>
<td>-12.82</td>
<td>-6.67</td>
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<td>Adriatic Coast</td>
<td>19</td>
<td>9.92</td>
<td>-1.73</td>
<td>3.28</td>
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References:


