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Title: Changing climate shifts timing of European floods

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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.

Main Text:

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 38 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.

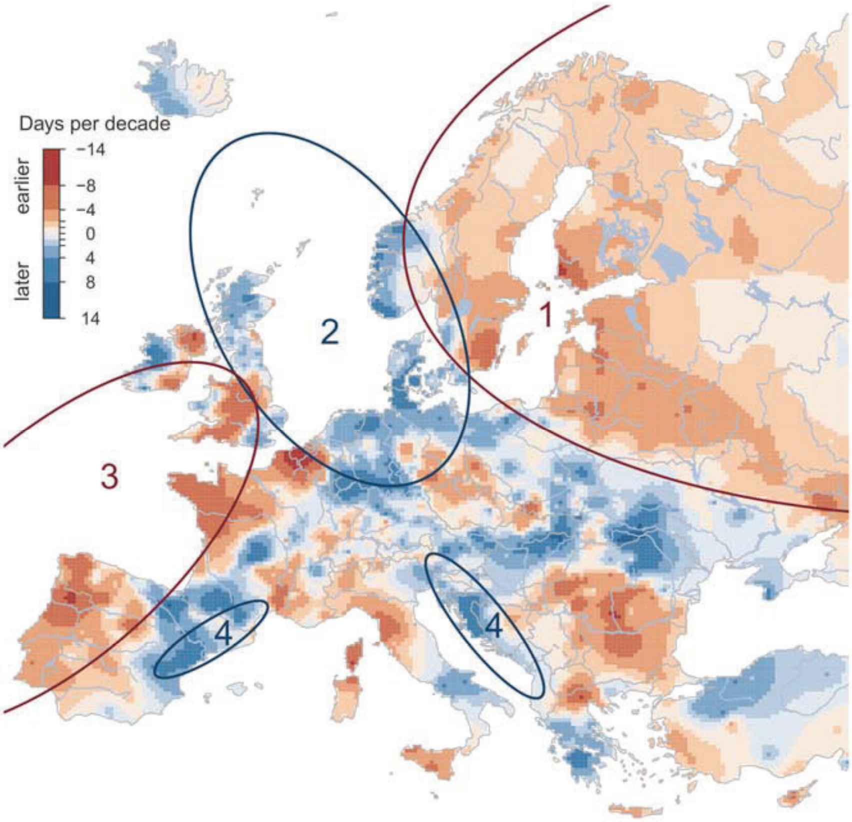

Fig. 1. Observed trends of river flood timing in Europe (1960-2010). Red indicates earlier floods, blue later floods (days per decade). 1-4 indicate regions with distinct drivers: [1] North-Eastern Europe: earlier snowmelt; [2] North Sea region: later winter storms; [3] Western Europe along the Atlantic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

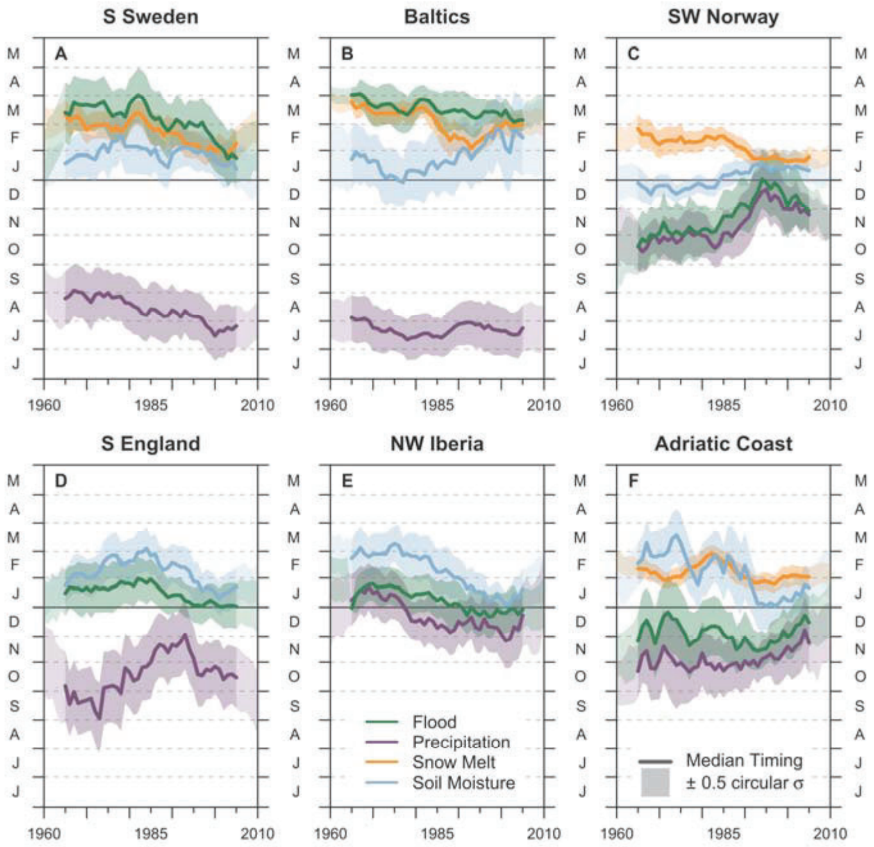

Fig. 2. Long-term temporal evolution of timing of floods and their drivers for six hotspots in Europe. Southern Sweden (**A**), Baltics (**B**), South-Western Norway (**C**), Southern England (**D**), North-Western Iberia (**E**), Adriatic Coast (**F**). Timing of observed floods (green), 7-day maximum 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.

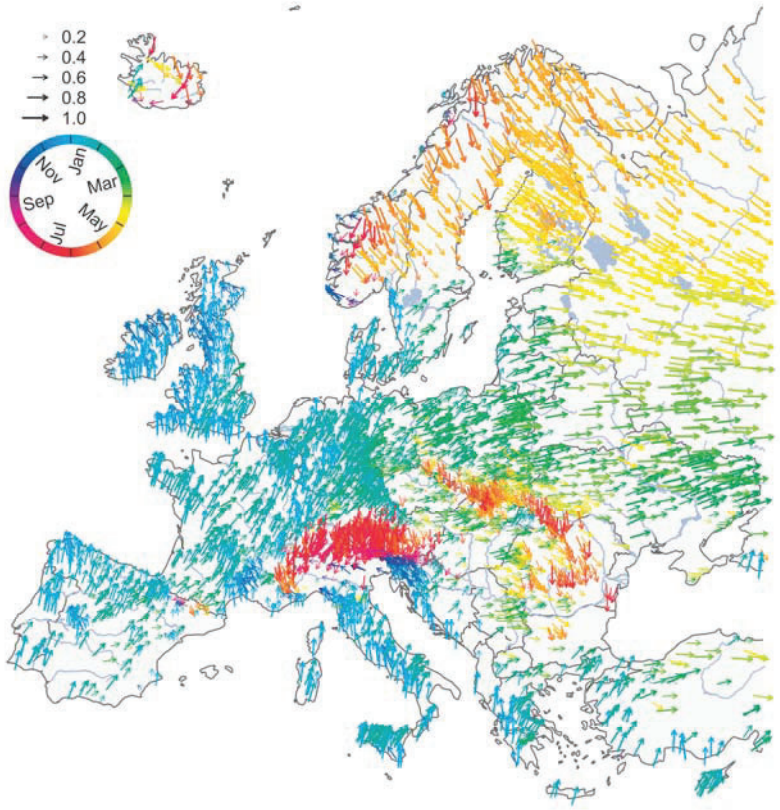

Fig. 3. Observed average timing of river floods in Europe (1960-2010). Each arrow represents one hydrometric station (n=4062). Color and arrow direction indicate the average timing of floods (light blue: winter floods (DJF), green to yellow: spring floods (MAM), orange to red summer floods (JJA) and 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).

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The flood date data used in this paper can be downloaded from http://www.hydro.tuwien.ac.at/fileadmin/mediapool-hydro/Downloads/Data.zip. The precipitation and temperature data can be downloaded from http://www.ecad.eu/download/ensembles/ensembles.php. The soil moisture data can be downloaded from http://www.esrl.noaa.gov/psd.

Supplementary Materials:

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