Citation for published version:
Bloschl, G, Hall, J, Parajka, J, Perdigao, RAP, Merz, B, Arheimer, B & Kjeldsen, T 2017, 'Changing climate shifts timing of European floods', Science, vol. 357, no. 6351, pp. 588-590. https://doi.org/10.1126/science.aan2506

DOI:
10.1126/science.aan2506

Publication date:
2017

Document Version
Peer reviewed version

This is the author’s version of the work. It is posted here by permission of the AAAS for personal use, not for redistribution. The definitive version was published in Sciencev.357 on 11/8/17 DOI:10.1126/science.aan2506.

Title: Changing climate shifts timing of European floods

Authors:

Günter Blöschl[1*], Julia Hall[1], Juraj Parajka[1], Rui A. P. Perdigão[1], Bruno Merz[2], Berit Arheimer[3], Giuseppe T. Aronica[4], Ardian Bilibashi[5], Ognjen Bonacci[6], Marco Borga[7], Ivan Čanjevac[8], Attilio Castellarin[9], Giovanni B. Chirico[10], Pierluigi Claps[11], Károly Fiala[12], Natalia Frolova[13], Liudmyla Gorbachova[14], Ali Gül[15], Jamie Hannaford[16], Shaun Harrigan[16], Maria Kireeva[13], Andrea Kiss[1], Thomas R. Kjeldsen[17], Silvia Kohnová[18], Jarkko J. Koskela[19], Ondrej Ledvinka[20], Neil Macdonald[21], Maria Mavrova-Guirguinova[22], Luis Mediero[23], Ralf Merz[24], Peter Molnar[25], Alberto Montanari[9], Conor Murphy[26], Marzena Osuch[27], Valeryia Ovcharuk[28], Ivan Radevski[29], Magdalena Rogger[1], José L. Salinas[1], Eric Sauquet[30], Mojca Šraj[31], Jan Szolgay[18], Alberto Viglione[1], Elena Volpi[32], Donna Wilson[33], Klodian Zaimi[34], and Nenad Živković[35]

Affiliations:

[1]Institute of Hydraulic Engineering and Water Resources Management, Technische Universität Wien, Vienna, Austria.

[2]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.
[3]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

[4]Department of Engineering, University of Messina, Messina, Italy.

[5]CSE – Control Systems Engineer, Renewable Energy Systems & Technology, Tirana, Albania.

[6]Faculty of Civil Engineering, Architecture and Geodesy, Split University, Split, Croatia.

[7]Department of Land, Environment, Agriculture and Forestry, University of Padova, Padua, Italy.

[8]University of Zagreb, Faculty of Science, Department of Geography, Zagreb, Croatia.

[9]Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Università di Bologna, Bologna, Italy.

[10]Department of Agricultural Sciences, University of Naples Federico II, Naples, Italy.

[11]Department Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Turin, Italy.

[12]Lower Tisza District Water Directorate, Szeged, Hungary.

[13]Department of Land Hydrology, Lomonosov Moscow State University, Moscow, Russia.

[14]Department of Hydrological Research, Ukrainian Hydrometeorological Institute, Kiev, Ukraine.

[15]Department of Civil Engineering, Dokuz Eylul University, Izmir, Turkey.

[16]Centre for Ecology & Hydrology, Wallingford, Oxfordshire, UK.

[17]Department 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.

[23]Department of Civil Engineering: Hydraulic, Energy and Environment, Technical University of Madrid, Madrid, Spain.

[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 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 4729 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:

We find that 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 4729 hydrometric stations in 38 European countries for the period 1960-2010. 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) 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.

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.1s 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 lager, 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). 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 16 days (25% of the stations by more than 36 days). 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 7 days. 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 6 days). Apart from the large-scale change patterns described for the four regions above, smaller-scale patterns of changes in flood timing can be identified..

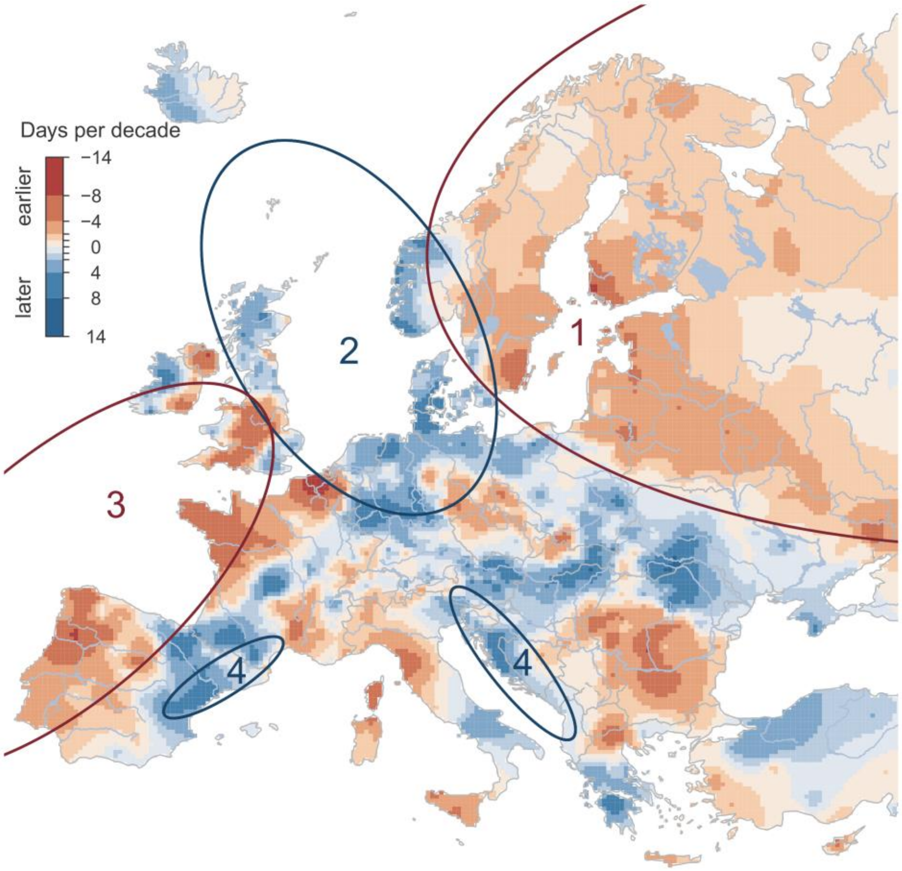

Fig. 1. Observed trends of river flood timing in Europe (1960-2010). Red indicates earlier floods, blue later floods (days per decade). 1-4 indicate regions with distinct drivers. [1] North-Eastern Europe: earlier snowmelt. [2] North Sea region: later winter storms. [3] Western Europe along the Atlantic 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 and which may have resulted in a slight reduction of the shift in flood and precipitation timing to November. 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 still is 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. Therefore, 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 extreme precipitation and floods to peak later in the season (Fig. 2F).

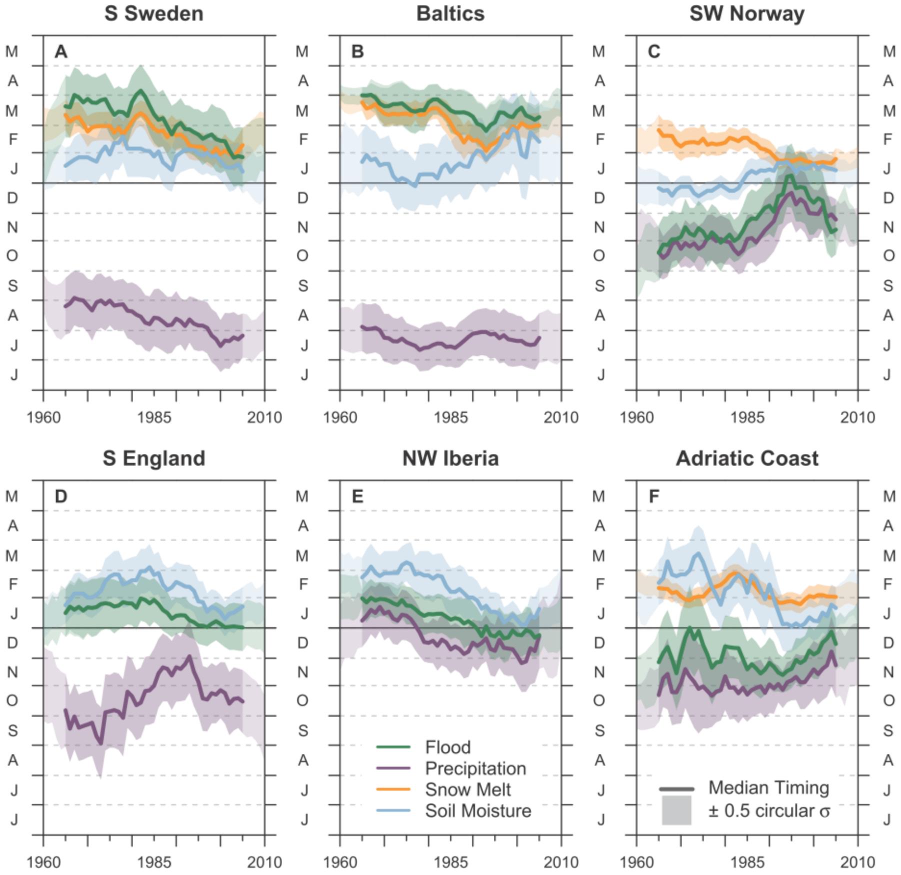

Fig. 2. Long-term temporal evolution of timing of floods and their drivers for six hotspots in Europe. Southern Sweden (**A**), Baltics (**B**), South-Western Norway (**C**), Southern England (**D**), North-Western Iberia (**E**), Adriatic Coast (**F**). Timing of observed floods (green), 7-day maximum 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 of Fig. 1, 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, 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 (reddish 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.

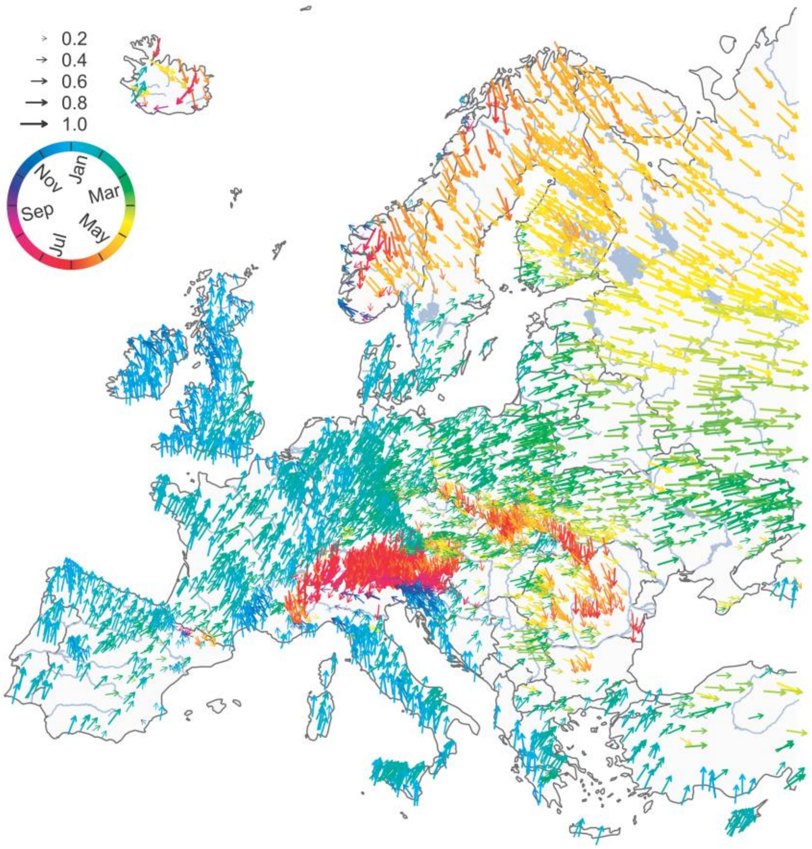

Fig. 3. Observed average timing of river floods in Europe (1960-2010). Each arrow represents one hydrometric station (n=4421). Color and arrow direction indicate the average timing of floods (light blue: winter floods (DJF), green to yellow: spring floods (MAM), orange to red summer floods (JJA) and 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 availability, 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 (4, 5, 22).

References and Notes:

1. UNISDR, “Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction” (Geneva, Switzerland: United Nations International Strategy for Disaster Reduction (UNISDR), 2015).

2. H. C. Winsemius *et al.*, Global drivers of future river flood risk. *Nat. Clim. Chang.* **6**, 381–385 (2016).

3. IPCC, *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2012).

4. J. Hall *et al.*, Understanding flood regime changes in Europe: a state of the art assessment. *Hydrol. Earth Syst. Sc.* **18**, 2735–2772 (2014).

5. Z. Kundzewicz, *Changes in flood risk in Europe* (IAHS Press Wallingford, 2012).

6. J. Parajka *et al.*, Seasonal characteristics of flood regimes across the Alpine-Carpathian range. *J. Hydrol.* **394**, 78–89 (2010).

7. R. Merz, G. Blöschl, A process typology of regional floods. *Water Resour. Res.* **39**, 1340 (2003).

8. D. Wilson, H. Hisdal, D. Lawrence, Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. *J. Hydrol.* **394**, 334–346 (2010).

9. B. Arheimer, G. Lindström, Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). *Hydrol. Earth Syst. Sc.* **19**, 771–784 (2015).

10. D. Sarauskiene, J. Kriauciuniene, A. Reihan, M. Klavins, Flood pattern changes in the rivers of the Baltic countries. *J. Environ. Eng. Landsc.* **23**, 28–38 (2015).

11. P. K. Sen, Estimates of the Regression Coefficient Based on Kendall’s Tau. *J. Am. Stat. Assoc.* **63**, 1379–1389 (1968).

12. M. Sivapalan, G. Blöschl, R. Merz, D. Gutknecht, Linking flood frequency to long-term water balance: Incorporating effects of seasonality. *Water Resour. Res.* **41**, W06012 (2005).

13. A. Draveniece, Detecting changes in winter seasons in Latvia: the role of arctic air masses. *Boreal. Environ. Res.* **14**, 89–99 (2009).

14. J. W. Hurrell, H. Van Loon, Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Chang.* **36**, 301–326 (1997).

15. N. P. Gillett *et al.*, Attribution of polar warming to human influence. *Nat. Geosci.* **1**, 750–754 (2008).

16. E. Hanna, T. E. Cropper, P. D. Jones, A. A. Scaife, R. Allan, Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. *Int. J. Climatol.* **35**, 2540–2554 (2015).

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

18. B. Ivančan-Picek, K. Horvath, N. Mahović, M. Gajić-Čapka, Forcing mechanisms of a heavy precipitation event in the southeastern Adriatic area. *Nat. Hazards*. **72**, 1231–1252 (2014).

19. E. Xoplaki, J. F. Gonzalez-Rouco, J. Luterbacher, H. Wanner, Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. *Clim. Dynam.* **23**, 63–78 (2004).

20. S. Klaus, H. Kreibich, B. Merz, B. Kuhlmann, K. Schröter, Large-scale, seasonal flood risk analysis for agricultural crops in Germany. *Environ. Earth Sci.* **75**, 1–13 (2016).

21. T. P. Barnett, J. C. Adam, D. P. Lettenmaier, Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*. **438**, 303–309 (2005).

22. M. Mudelsee, M. Boerngen, G. Tetzlaff, U. Gruenewald, No upward trends in the occurrence of extreme floods in central Europe. *Nature*. **425** (2003).

23. J. Hall *et al.*, A European Flood Database: facilitating comprehensive flood research beyond administrative boundaries. *Proc. Int. Assoc. Hydrol. Sci.* **370**, 89–95 (2015).

24. J. Vogt *et al.*, “A pan-European River and Catchment Database” (2007).

25. M. Haylock *et al.*, A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. *J. Geophys. Res.* **113** (2008), doi:10.1029/2008JD010201.

26. H. van den Dool, J. Huang, Y. Fan, Performance and analysis of the constructed analogue method applied to US soil moisture over 1981-2001. *J. Geophys. Res.* **108** (2003), doi:10.1029/2002JD003114.

27. K. V. Mardia, *Statistics of directional data* (Academic Press Inc. London, 1972).

28. K. V. Mardia, P. E. Jupp, in *Directional Statistics* (John Wiley & Sons, Inc., 2008; http://dx.doi.org/10.1002/9780470316979.ch6), pp. 93–118.

29. H. Theil, A Rank-invariant Method of Linear and Polynomial Regression Analysis, Part 1. *Proc. R. Neth. Acad. Sci.* **53**, 386–392 (1950).

30. P. H. Hiemstra, E. J. Pebesma, C. J. Twenhöfel, G. B. Heuvelink, Real-time automatic interpolation of ambient gamma dose rates from the Dutch radioactivity monitoring network. *Comput. Geosci.* **35**, 1711–1721 (2009).

31. D. R. Helsel, L. M. Frans, Regional Kendall Test for Trend. *Environ. Sci. Technol.* **40**, 4066–4073 (2006).

32. G. Blöschl, T. Nester, J. Komma, J. Parajka, R. Perdigão, The June 2013 flood in the Upper Danube basin, and comparisons with the 2002, 1954 and 1899 floods. *Hydrol. Earth Syst. Sc.* **17**, 5197–5212 (2013).

33. R Core Team*: A Language and Environment for Statistical Computing* (2016; https://www.R-project.org).

34. D. Sarkar*, Lattice: Multivariate Data Visualization with R* (Springer, New York, 2008; http://lmdvr.r-forge.r-project.org).

35. R. Bivand, N. Lewin-Koh, *maptools: Tools for Reading and Handling Spatial Objects* (2016; https://CRAN.R-project.org/package=maptools).

36. D. Pierce, *ncdf4: Interface to Unidata netCDF (Version 4 or Earlier) Format Data Files* (2015; https://CRAN.R-project.org/package=ncdf4).

37. H. Wickham, The split-apply-combine strategy for data analysis. *J. Stat. Softw.* **40**, 1–29 (2011).

38. R. J. Hijmans, *raster: Geographic Data Analysis and Modeling* (2016; https://CRAN.R-project.org/package=raster).

39. E. Neuwirth, *RColorBrewer: ColorBrewer Palettes* (2014; https://CRAN.R-project.org/package=RColorBrewer).

40. R. Bivand, T. Keitt, B. Rowlingson, *rgdal: Bindings for the Geospatial Data Abstraction Library* (2016; https://CRAN.R-project.org/package=rgdal).

41. A. South, rworldmap: a new R package for mapping global data. *The R Journal*. **3**, 35–43 (2011).

Acknowledgments:

We would like to acknowledge the support of the ERC Advanced Grant "FloodChange", Project No. 291152, the Austrian Science Funds FWF as part of the Doctoral Programme on Water Resource Systems (W1219-N22), the EU FP7 project SWITCH-ON (Grant No 603587) and the Russian Science Foundation (Project No. 14-17-00155). The authors also acknowledge the involvement in the data screening process of C. Álvaro Díaz, I. Borzì (Sicily, Italy), E. Diamantini, K. Jeneiová, M. Kupfersberger, and S. Mallucci during their stays at the Vienna University of Technology. We also thank L. Gaál and D. Rosbjerg for contacting Finish and Danish data holders respectively and A. Christofides for pointing us to the Greek data source, B. Renard (France), T. Kiss (Hungary), W. Rigott (South Tyrol, Italy), G. Lindström (Sweden) and P. Burlando (Switzerland) for assistance in preparing and/or providing data or metadata from their respective regions, and B. Lüthi and Y. Hundecha for preparing supporting data to cross-check the results that are not part of the paper.

The hydrological data used in this paper can be obtained at http://www.hydro.tuwien.ac.at/downloads/xxx. Precipitation and temperature data is available from http://www.ecad.eu/download/ensembles/ensembles.php. The soil moisture data can be found at http://www.esrl.noaa.gov/psd.

Supplementary Materials:

Materials and Methods

Supplementary Text

Figures S1 to S5

Tables S1 and S2

References (*23-41*)