

## Title: Changing climate shifts timing of European floods

### Authors:

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

### Affiliations:

<sup>1</sup>Institute of Hydraulic Engineering and Water Resources Management, Technische Universität Wien, Vienna, Austria.

<sup>2</sup>Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.

<sup>3</sup>Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

<sup>4</sup>Department of Engineering, University of Messina, Messina, Italy.

<sup>5</sup>CSE – Control Systems Engineer, Renewable Energy Systems & Technology, Tirana, Albania.

<sup>6</sup>Faculty of Civil Engineering, Architecture and Geodesy, Split University, Split, Croatia.

<sup>7</sup>Department of Land, Environment, Agriculture and Forestry, University of Padova, Padua, Italy.

<sup>8</sup>University of Zagreb, Faculty of Science, Department of Geography, Zagreb, Croatia.

<sup>9</sup>Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Università di Bologna, Bologna, Italy.

<sup>10</sup>Department of Agricultural Sciences, University of Naples Federico II, Naples, Italy.

<sup>11</sup>Department Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Turin, Italy.

<sup>12</sup>Lower Tisza District Water Directorate, Szeged, Hungary.

<sup>13</sup>Department of Land Hydrology, Lomonosov Moscow State University, Moscow, Russia.

<sup>14</sup>Department of Hydrological Research, Ukrainian Hydrometeorological Institute, Kiev, Ukraine.

<sup>15</sup>Department of Civil Engineering, Dokuz Eylul University, Izmir, Turkey.

<sup>16</sup>Centre for Ecology & Hydrology, Wallingford, Oxfordshire, UK.

<sup>17</sup>Department of Architecture and Civil Engineering, University of Bath, Bath, UK.

<sup>18</sup>Slovak University of Technology in Bratislava, Faculty of Civil Engineering, Department of Land and Water Resources Management, Radlinského 11, 810 05 Bratislava, Slovakia.

<sup>19</sup>Finnish Environment Institute, Helsinki, Finland.

<sup>20</sup>Czech Hydrometeorological Institute, Prague, Czechia.

<sup>21</sup>Department of Geography and Planning & Institute of Risk and Uncertainty, University of Liverpool, Liverpool, UK.

<sup>22</sup>University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria.

<sup>23</sup>Department of Civil Engineering: Hydraulic, Energy and Environment, Technical University of Madrid, Madrid, Spain.

<sup>24</sup>Department for Catchment Hydrology, Helmholtz Centre for Environmental Research – UFZ, Halle, Germany.

<sup>25</sup>Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland.

<sup>26</sup>Irish Climate Analysis and Research Units (ICARUS), Department of Geography, Maynooth University, Ireland.

<sup>27</sup>Institute of Geophysics Polish Academy of Sciences, Department of Hydrology and Hydrodynamics, Warsaw, Poland.

<sup>28</sup>Hydrometeorological Institute, Odessa State Environmental University, Odessa, Ukraine.

<sup>29</sup>Institute of Geography, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje, Republic of Macedonia.

<sup>30</sup>Irstea, UR HHLY, Hydrology-Hydraulics Research Unit, Lyon, France.

<sup>31</sup>Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia.

<sup>32</sup>Department of Engineering, University Roma Tre, Rome, Italy.

<sup>33</sup>Norwegian Water Resources and Energy Directorate, Oslo, Norway.

<sup>34</sup>Institute of Geo-Sciences, Energy, Water and Environment (IGEWE), Polytechnic University of Tirana, Tirana, Albania.

<sup>35</sup>University of Belgrade, Faculty of Geography, Belgrade, Serbia.

\*Corresponding author. Email: bloeschl@hydro.tuwien.ac.at

1 **Abstract:**

2 A warming climate is expected to impact river floods; however, no consistent climate change  
3 signal in observed flood magnitudes has been identified so far. We have analyzed the timing of  
4 river floods in Europe over the last five decades using a pan-European database from 4729  
5 observational hydrometric stations, and find clear patterns of change in flood timing. Warmer  
6 temperatures have led to earlier spring snowmelt floods throughout North-Eastern Europe;  
7 delayed winter storms associated with polar warming have led to later winter floods around the  
8 North Sea; and some sectors of the Mediterranean Coast and earlier soil moisture maxima have  
9 led to earlier winter floods in Western Europe. Our results highlight the existence of a clear  
10 climate signal in flood observations at the continental scale.

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14 **One Sentence Summary:**

15 We find that the observed timing of floods has shifted consistently in many parts of Europe over  
16 the past 50 years as a result of a changing climate.

17

18 **Main Text:**

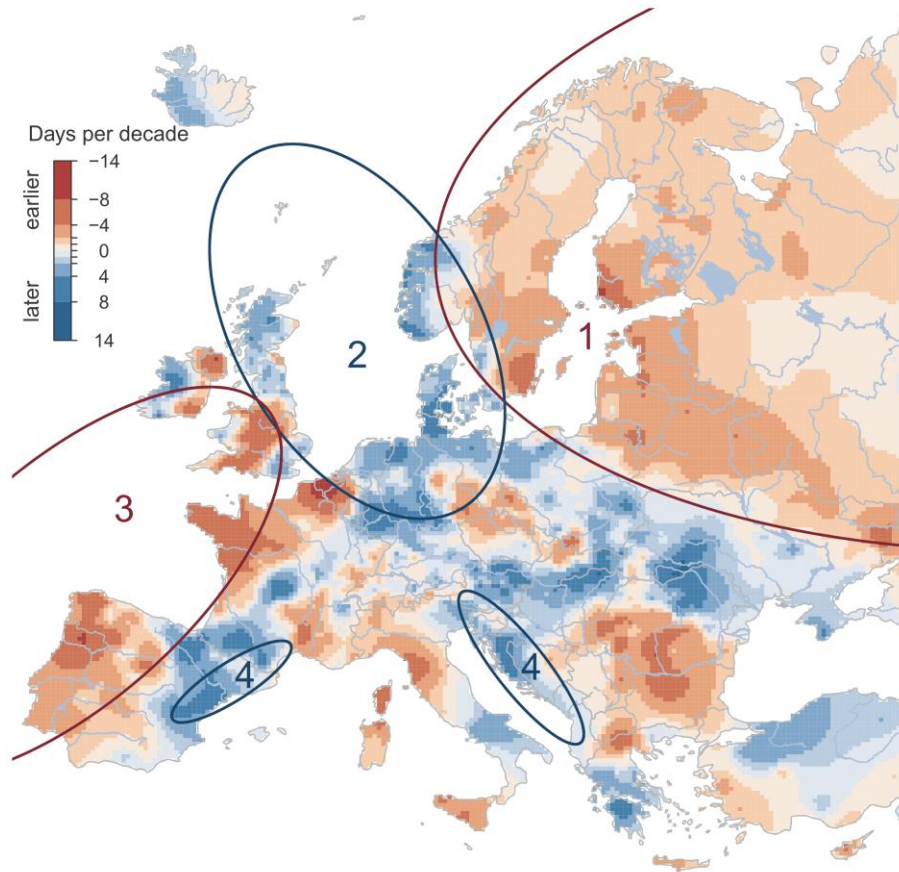
19 River flooding affects more people worldwide than any other natural hazard, with an estimated  
20 global annual average loss of US \$104 billion (1). Damages are expected to increase due to  
21 economic growth and climate change (2, 3). The intensification of the water cycle due to a  
22 warming climate is projected to change the magnitude, frequency and timing of river floods (3).  
23 However, existing studies have been unable to identify a consistent climate change signal in  
24 flood magnitudes (4). Identification of a large-scale climate change signal in flood observations  
25 has been hampered by the existence of many processes controlling floods, including  
26 precipitation, soil moisture and snow, by non-climatic drivers of flood change such as land use  
27 change and river training, and by the inconsistency of data sets and their limited spatial extents  
28 (4, 5). It has been proposed that considering the seasonal timing of floods as a fingerprint of  
29 climate effects on floods may be a way to avoid some of those complications (6, 7). For example,  
30 in cold regions, earlier snowmelt due to warmer temperatures leads to earlier spring floods (6),  
31 and this climate-related signal may be less confounded by non-climatic drivers than flood  
32 magnitudes themselves because of the strong seasonality of climate. While the changing timing  
33 of floods has been studied at local scale in Nordic and Baltic countries (8–10), no consistent  
34 analysis exists at the European scale.

35 Here we analyze a large data set of flood observations in Europe to assess whether a  
36 changing climate has shifted the timing of river floods in the last five decades. Our analysis is  
37 based on river discharge or water level observations from 4729 hydrometric stations in 38  
38 European countries for the period 1960-2010. For each station, we use a series consisting of the  
39 dates of occurrence of the highest peak in any calendar year. We define the average timing of the  
40 floods by the average date on which floods have occurred during the observation period. We then  
41 estimate the trend in the timing of the floods using the Theil-Sen slope estimator (11) and the

42 long-term evolution using a 10-year moving average filter. Finally, we analyze the change signal  
43 of three potential drivers of flood changes in a similar fashion: the middle date of the maximum  
44 7-day precipitation; the middle day of the month with the highest soil moisture; and the middle  
45 day of the first seven days in a year with air temperature above 0° C as a proxy for spring  
46 snowmelt and snowfall-to-rain transition.

47 Our data show a clear shift in the timing of floods in Europe in the past 50 years (Fig. 1).  
48 The regionally interpolated trend patterns shown in Fig.1s range from a -13 days per decade  
49 towards earlier floods to +9 days towards later floods, which translates into total shifts of -65  
50 and +45 days, respectively, of linear trends over the entire 50 year period. The local, station  
51 specific, trends (Fig. S2) are larger, but reflect smaller scale rather than regional scale processes.  
52 The changes are most consistent in North-Eastern Europe (region 1 in Fig. 1) where 81% of the  
53 stations show a shift towards earlier floods (50% of the stations by more than -8 days / 50 yrs).  
54 The changes are largest in Western Europe along the North Atlantic Coast from Portugal to  
55 England (region 3) where 50% of the stations show a shift towards earlier floods by at least 16  
56 days (25% of the stations by more than 36 days). Around the North Sea (region 2, South-Western  
57 Norway, the Netherlands, Denmark and Scotland) 50% of the stations show a shift towards later  
58 floods by more than 7 days. In some parts of the Mediterranean Coast (region 4, North-Eastern  
59 Adriatic Coast, North-Eastern Spain), there is a shift towards later floods (50% of the stations by  
60 more than 6 days). Apart from the large-scale change patterns described for the four regions  
61 above, smaller-scale patterns of changes in flood timing can be identified..

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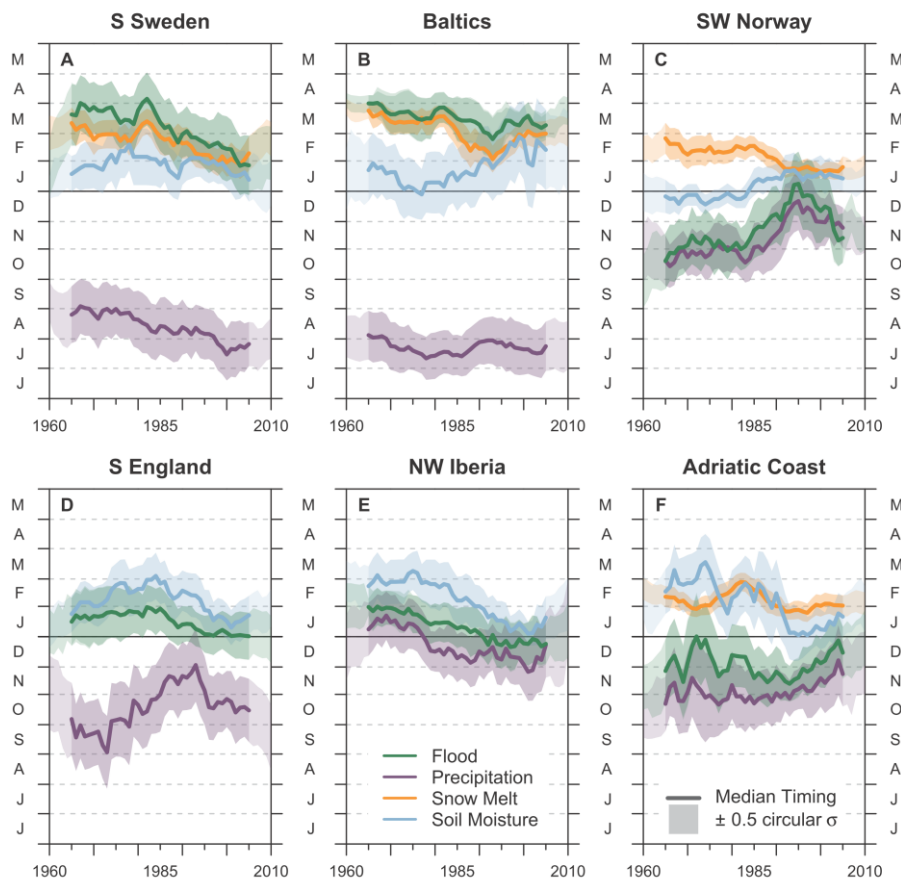


63  
 64 **Fig. 1. Observed trends of river flood timing in Europe (1960-2010).** Red indicates earlier floods, blue  
 65 later floods (days per decade). 1-4 indicate regions with distinct drivers. [1] North-Eastern Europe: earlier  
 66 snowmelt. [2] North Sea region: later winter storms. [3] Western Europe along the Atlantic Coast: earlier  
 67 soil moisture maximum. [4] parts of the Mediterranean Coast: stronger Atlantic influence in winter.

68  
 69 In order to infer the causes of these changes in timing, we focused on six sub-regions or  
 70 hotspots, where changes in flood timing are particularly clear (Fig. S2, Table S2). Since floods  
 71 are the result of the seasonal interplay of precipitation, soil moisture and snow processes (12) we  
 72 analyzed the temporal evolutions of these variables and compared them to those of the floods  
 73 (Fig. 2A-2F). In Southern Sweden (Fig. 2A) and in the Baltics (Fig. 2B), floods are mainly due  
 74 to spring snowmelt (9, 10). The temporal evolution of flood timing therefore closely follows that  
 75 of snowmelt, shifting from late March to February (green and orange lines in Fig. 2A, 2B).

76 Earlier snowmelt is known to be driven by both local temperature increases and a decreasing  
77 frequency of advection of arctic air masses (13). The Baltics are topographically less shielded  
78 from these air masses than Southern Sweden, which is reflected by larger variations in the timing  
79 of snowmelt in the 1990s. In South-Western Norway (Fig. 2C) precipitation maxima at the end  
80 of the year generate floods around the same time, since there is little subsurface water storage  
81 capacity there due to the prevalence of shallow soils. Changes in the North Atlantic Oscillation  
82 (NAO) since 1980 (14) may have resulted in a delayed arrival of heavy winter precipitation, with  
83 maxima shifting from October to December. These NAO anomalies have been less pronounced  
84 since the early 2000s and which may have resulted in a slight reduction of the shift in flood and  
85 precipitation timing to November. The floods follow closely the timing of extreme precipitation  
86 (Fig. 2C), which strongly suggests a causal link. The changes in the NAO may be related to Polar  
87 warming, among many other factors, although the role of anthropogenic effects still is uncertain  
88 (15, 16). In Southern England (Fig. 2D), the subsurface water storage capacity tends to be much  
89 larger than in coastal Norway. The maximum rainfall, which occurs in autumn, therefore tends to  
90 get stored, and soil moisture and groundwater tables continuously increase until they reach a  
91 maximum in winter. Sustained winter rainfall on saturated soils then produces the largest floods  
92 in winter. Therefore, the flood timing in Southern England is more closely associated with the  
93 timing of maximum soil moisture than with the timing of extreme precipitation (17). The  
94 variations in flood timing in North-Western Iberia (Fig. 2E) are similar to those of Southern  
95 England, although precipitation there occurs more in the winter, so extreme precipitation and  
96 maximum soil moisture (driven by sustained precipitation) are more closely aligned. Along the  
97 Northern Adriatic Coast (Fig. 2F), large-scale influences by the Atlantic Ocean condition  
98 Adriatic meso-scale cyclonic activity, which produces heavy precipitation towards the end of the

99 year (18). Meridional shifts in storm tracks have increased atmospheric flow from the Atlantic to  
 100 the Mediterranean in winter (19), leading to extreme precipitation and floods to peak later in the  
 101 season (Fig. 2F).



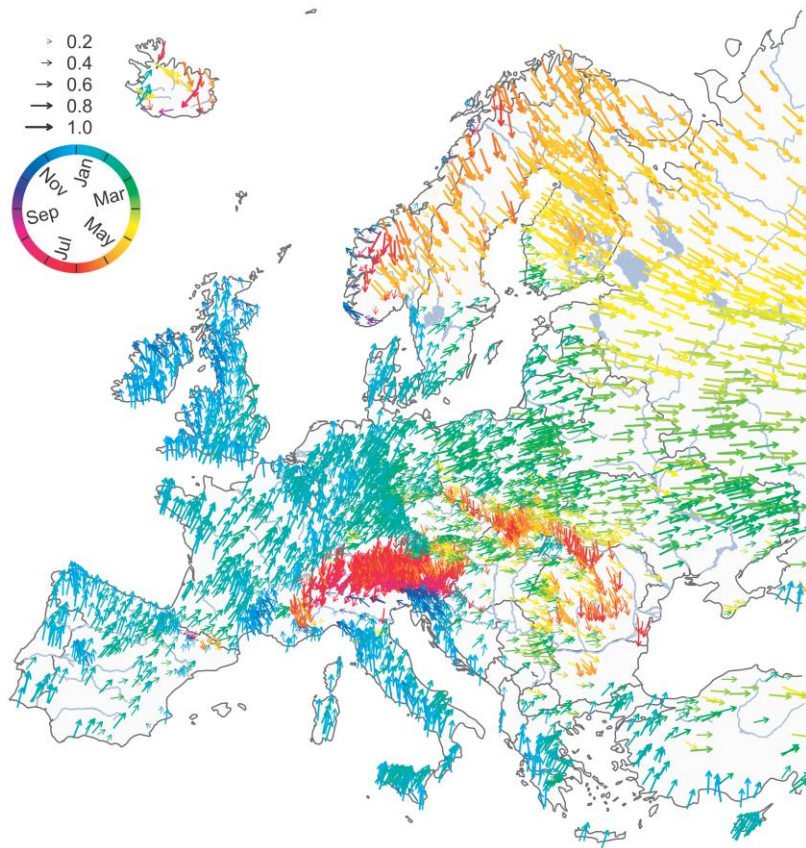
102  
 103 **Fig. 2. Long-term temporal evolution of timing of floods and their drivers for six hotspots in**  
 104 **Europe.** Southern Sweden (A), Baltics (B), South-Western Norway (C), Southern England (D), North-  
 105 Western Iberia (E), Adriatic Coast (F). Timing of observed floods (green), 7-day maximum precipitation  
 106 (purple), snowmelt indicator (orange), and timing of modeled maximum soil moisture (blue). Line shows  
 107 median timing over the entire hotspot, bands indicate variability of timing within the year ( $\pm 0.5$  circular  
 108 standard deviation (Eq. 8). All data were subject to a 10-year moving average filter. Vertical axes show  
 109 month of the year (June to May).

110  
 111 To further assist in the interpretation of trends in flood timing across Europe of Fig. 1, the  
 112 spatial pattern of the average flood timing (1960-2010) is presented in Fig. 3. The average timing



113 of the floods varies gradually from the West to the East due to increasing continentality, and  
114 from the South to the North due to the increasing influence of snow processes. The effect of  
115 snow storage and melt at high altitudes, e.g. in the Alps and the Carpathians (reddish arrows in  
116 Fig. 3), is superimposed on this pattern. The spatial patterns of the average timing of potential  
117 drivers, and their trends, are shown in Fig. S3, S4, S5.

118 Throughout North-Eastern Europe (region 1 in Fig. 1), spring occurrence of snowmelt and  
119 floods (yellow and green arrows in Fig. S4A and Fig. S3) combined with a warmer climate (Fig.  
120 S4A) has led to earlier floods. In the region around the North Sea (region 2 in Fig. 1), extreme  
121 precipitation and floods in the winter (blue arrows in Fig. S3A and Fig. 3) combined with a shift  
122 in the timing of extreme winter precipitation (Fig. S3B) has led to later floods. In Western  
123 Europe (region 3 in Fig. 1), winter occurrence of soil moisture maxima and floods (blue arrows  
124 in Fig. S5A and Fig. 3) combined with a shift in the timing of soil moisture maxima (Fig. S5B)  
125 has led to earlier floods. While region 3 shows a consistent behavior in flood timing changes,  
126 closely aligned with those of soil moisture, the effect of changing storm tracks on precipitation  
127 are different in Southern England and North-Western Iberia, due to the opposite effects of the  
128 NAO.



129  
 130 **Fig. 3. Observed average timing of river floods in Europe (1960-2010).** Each arrow represents one  
 131 hydrometric station (n=4421). Color and arrow direction indicate the average timing of floods (light blue:  
 132 winter floods (DJF), green to yellow: spring floods (MAM), orange to red summer floods (JJA) and  
 133 purple to dark blue autumn floods (SON)). Lengths of the arrows indicate the concentration of floods  
 134 within a year (R=0 evenly distributed, R=1 all floods occur on the same date).

135

136 If the trends in flood timing continue, considerable economic and environmental  
 137 consequences may arise, as society and ecosystems have adapted to the average within-year  
 138 timing of floods. Later winter floods in catchments around the North Sea, for example, may  
 139 reduce agricultural productivity due to softer ground for spring farming operations, higher soil  
 140 compaction, enhanced erosion and direct crop damage (20). Spring floods occurring earlier in the  
 141 season in North-Eastern Europe may limit the replenishment of reservoirs if managers expect  
 142 later floods that never arrive, with substantial reductions in water supply availability, irrigation

143 and hydropower generation (21). Perhaps more importantly, this study identifies a clear climate  
144 change signal in flood observations at the continental scale using the timing of floods, which was  
145 not possible using flood magnitudes (4, 5, 22).

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293 The hydrological data used in this paper can be obtained at  
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296 found at <http://www.esrl.noaa.gov/psd>.

297

### 298 **Supplementary Materials:**

299 Materials and Methods

300 Supplementary Text

301 Figures S1 to S5

302 Tables S1 and S2

303 References (23-41)