

A ~700 years perspective on the 21st century drying in the eastern part of Europe based on $\delta^{18}\text{O}$ in tree ring cellulose

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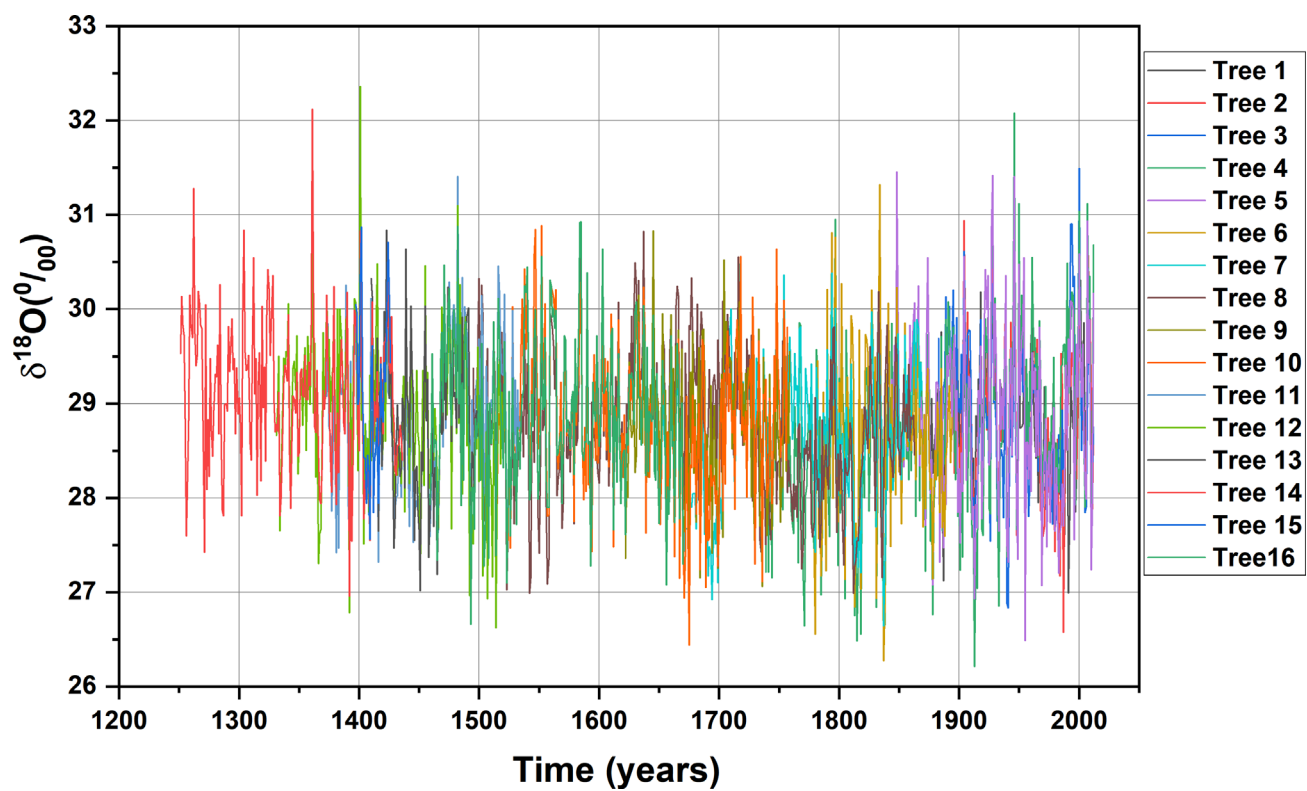
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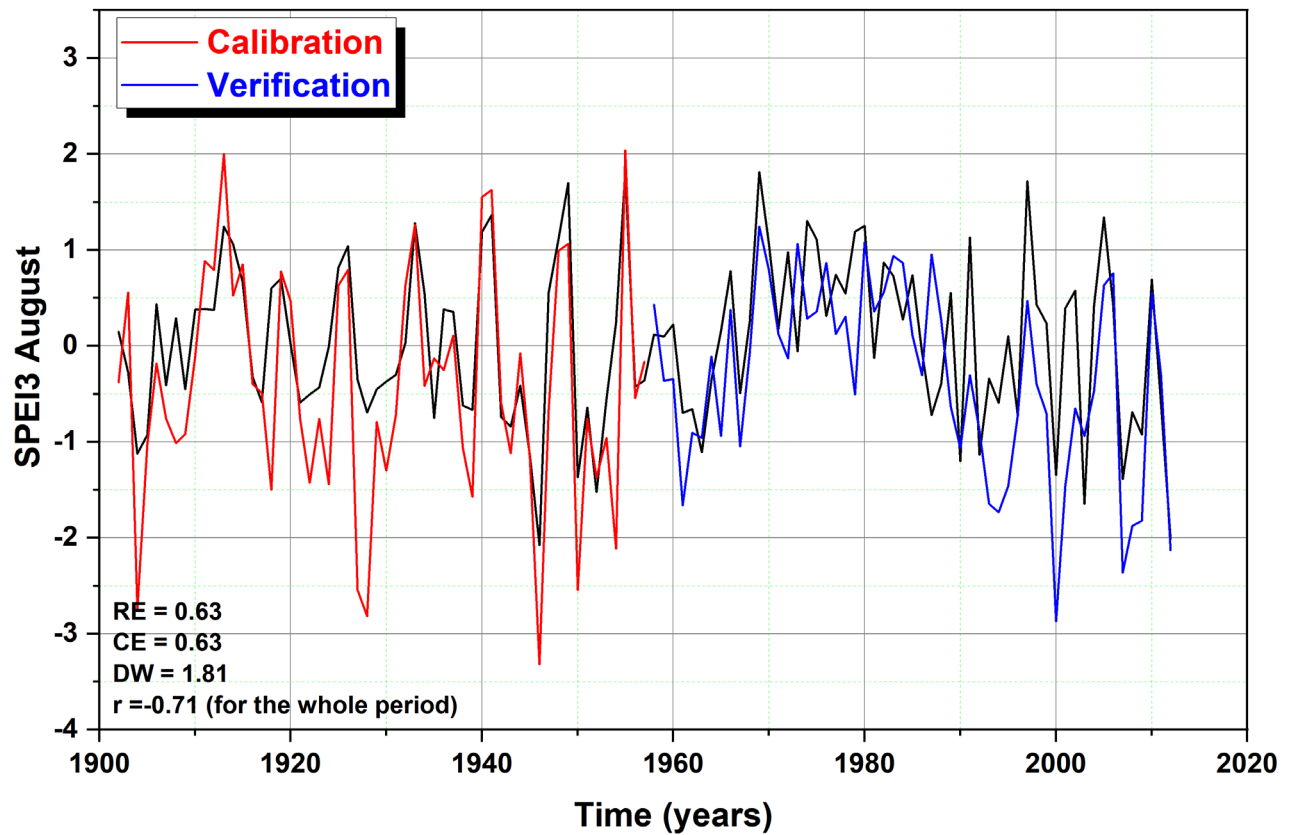
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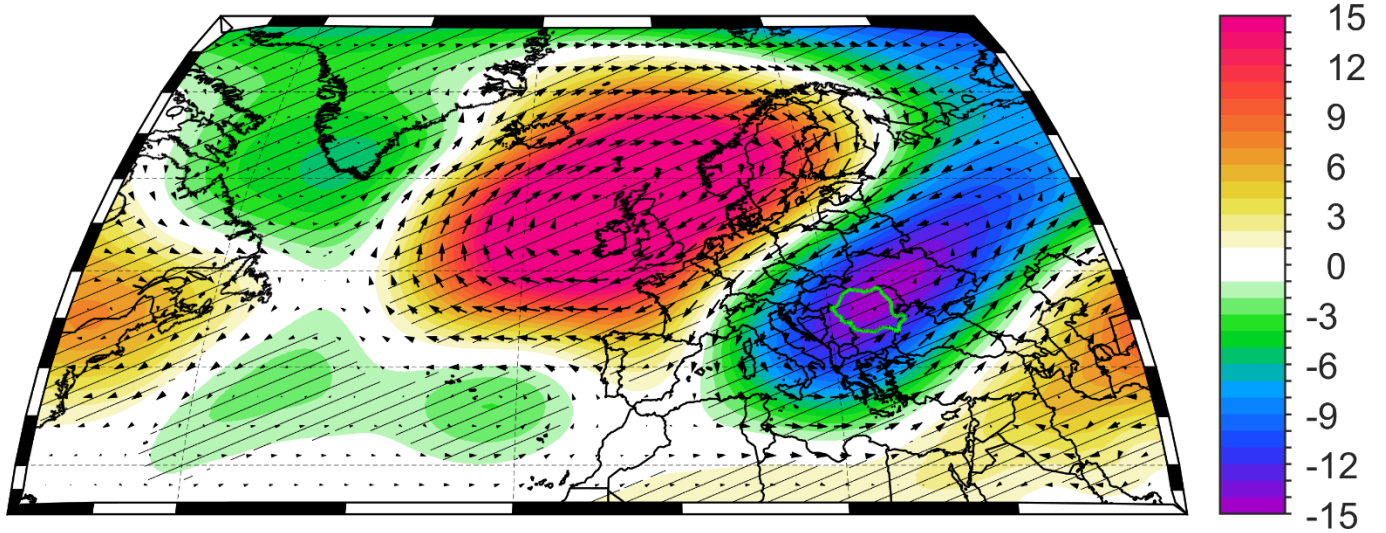
Supplementary Figure 1. The raw $\delta^{18}\text{O}$ values for each chronology used in this study, measured in the *Pinus cembra* L. from Călimani Mountains.



Supplementary Figure 2. The calibration – verification reconstructed model for August SPEI3, the black line indicates the observed data, the red line indicates the reconstructed SPEI3 for the calibration period and the blue line indicates the reconstructed SPEI3 for the verification period. RE – reduction of error, CE – coefficient of efficiency, DW – Durbin-Watson test, and r – correlation coefficient.

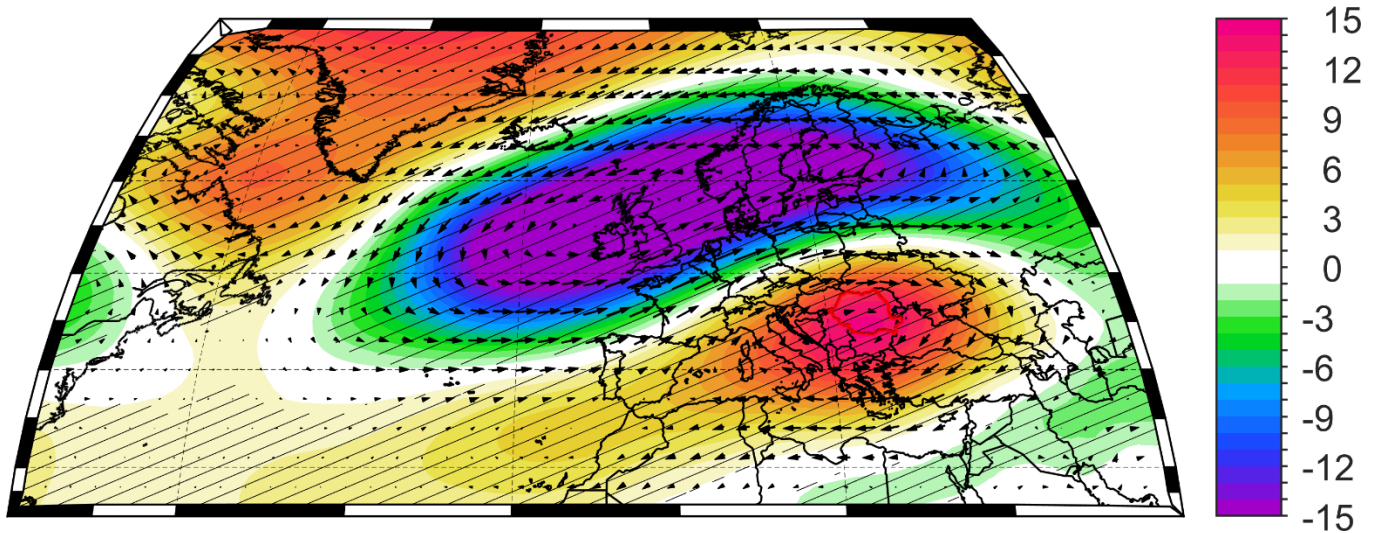
a)

HIGH Composite Map: Z500 and 500mb JJA

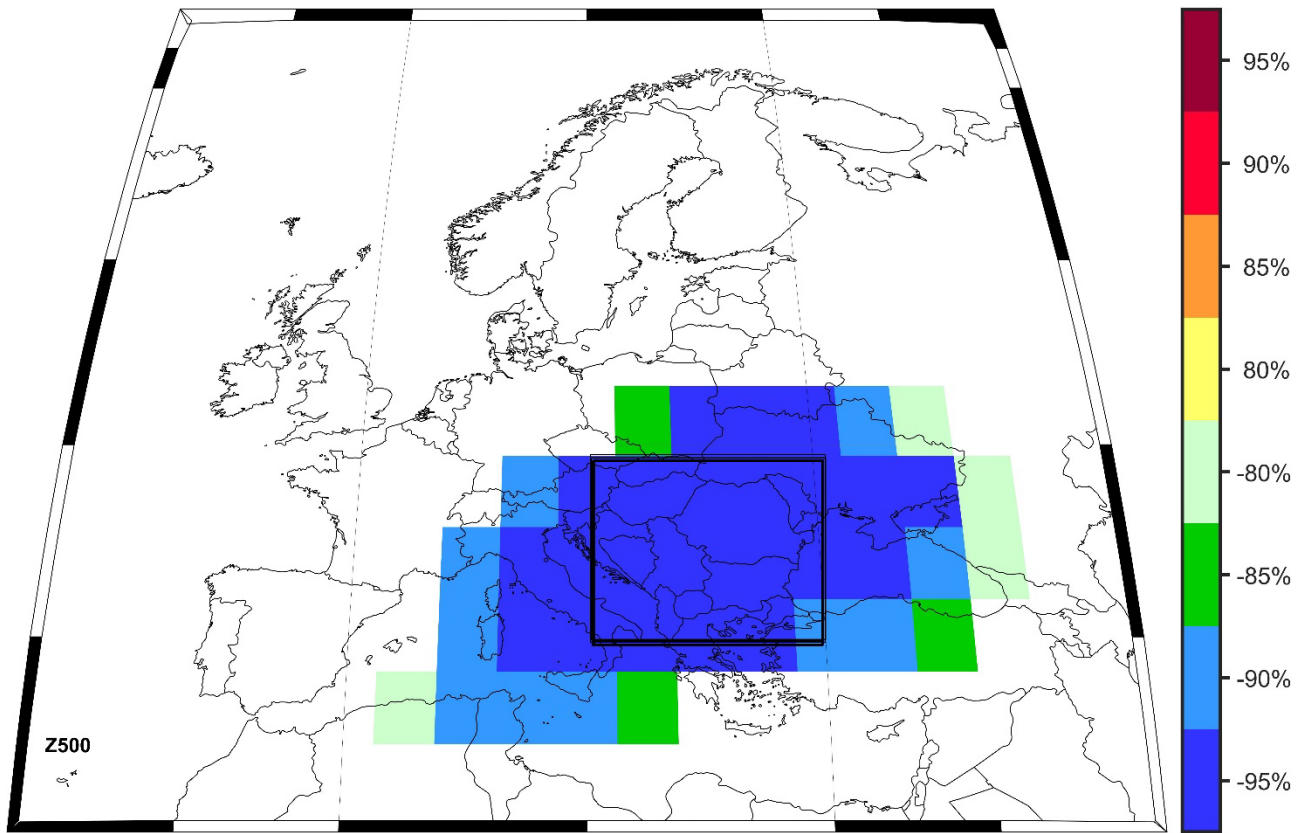


b)

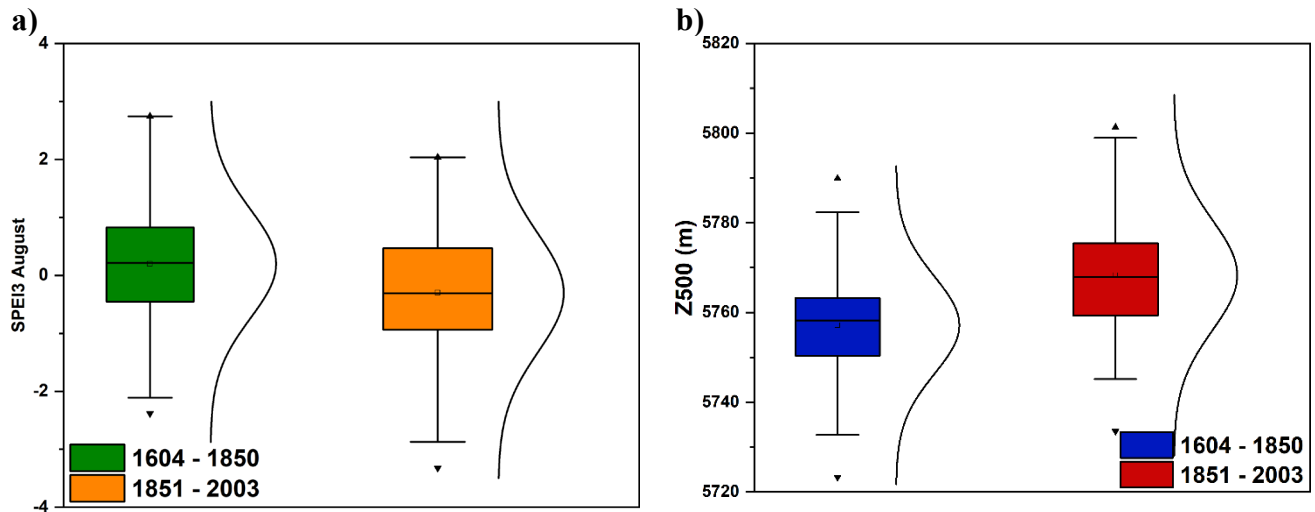
LOW Composite Map: Z500 and 500mb JJA



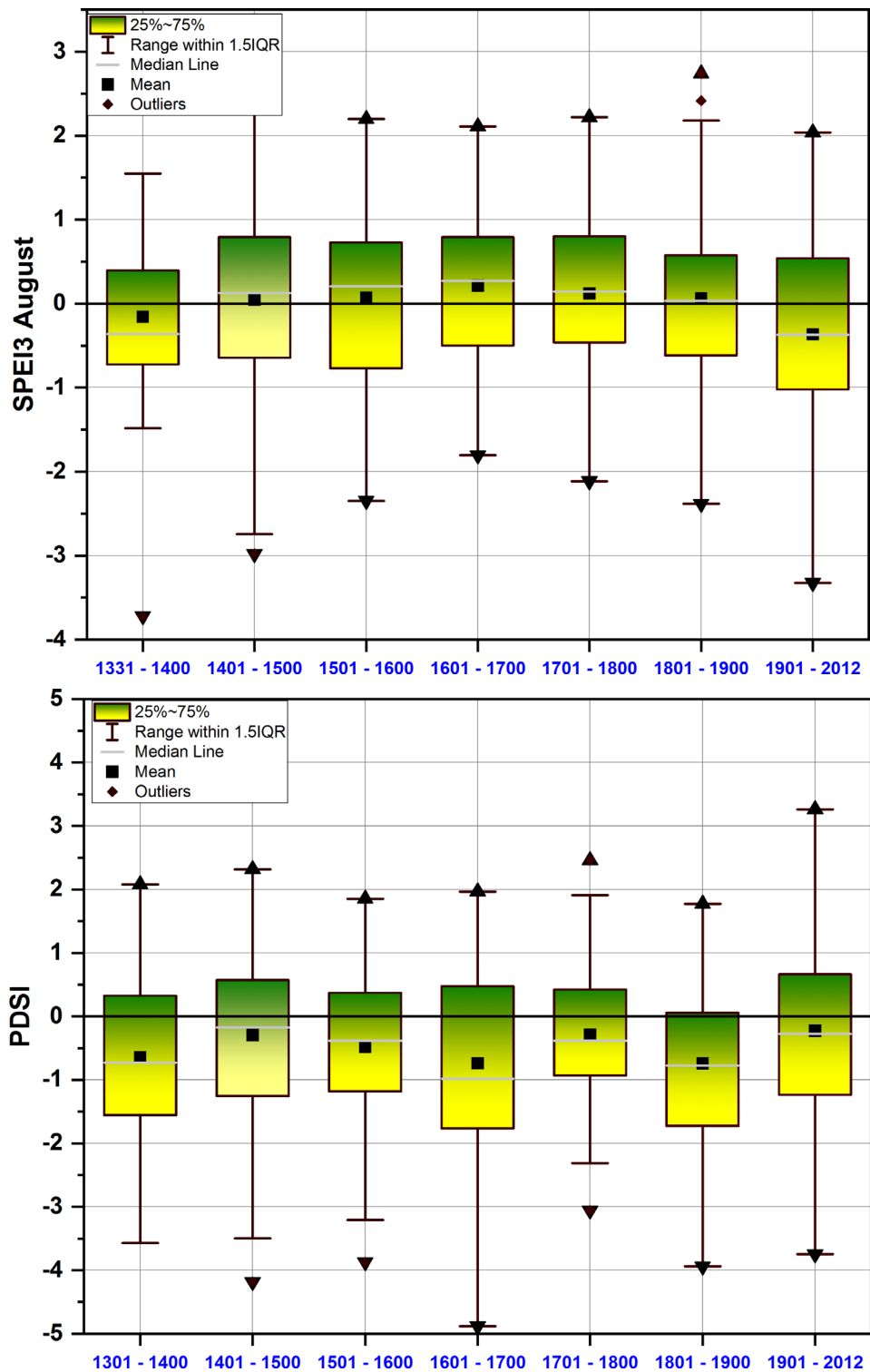
Supplementary Figure 3. a) The composite map between High SPEI3 (< -1 std. dev.) and summer Geopotential Height at 500mb and summer 500mb wind vectors (arrows) and b) the composite map between Low SPEI3 (> 1 std. dev.) and summer geopotential height at 500mb and summer 500mb wind vectors (arrows). Units: Z500 (m) and wind vectors (m/s). Analyzed period: 1836 – 2012CE ¹.



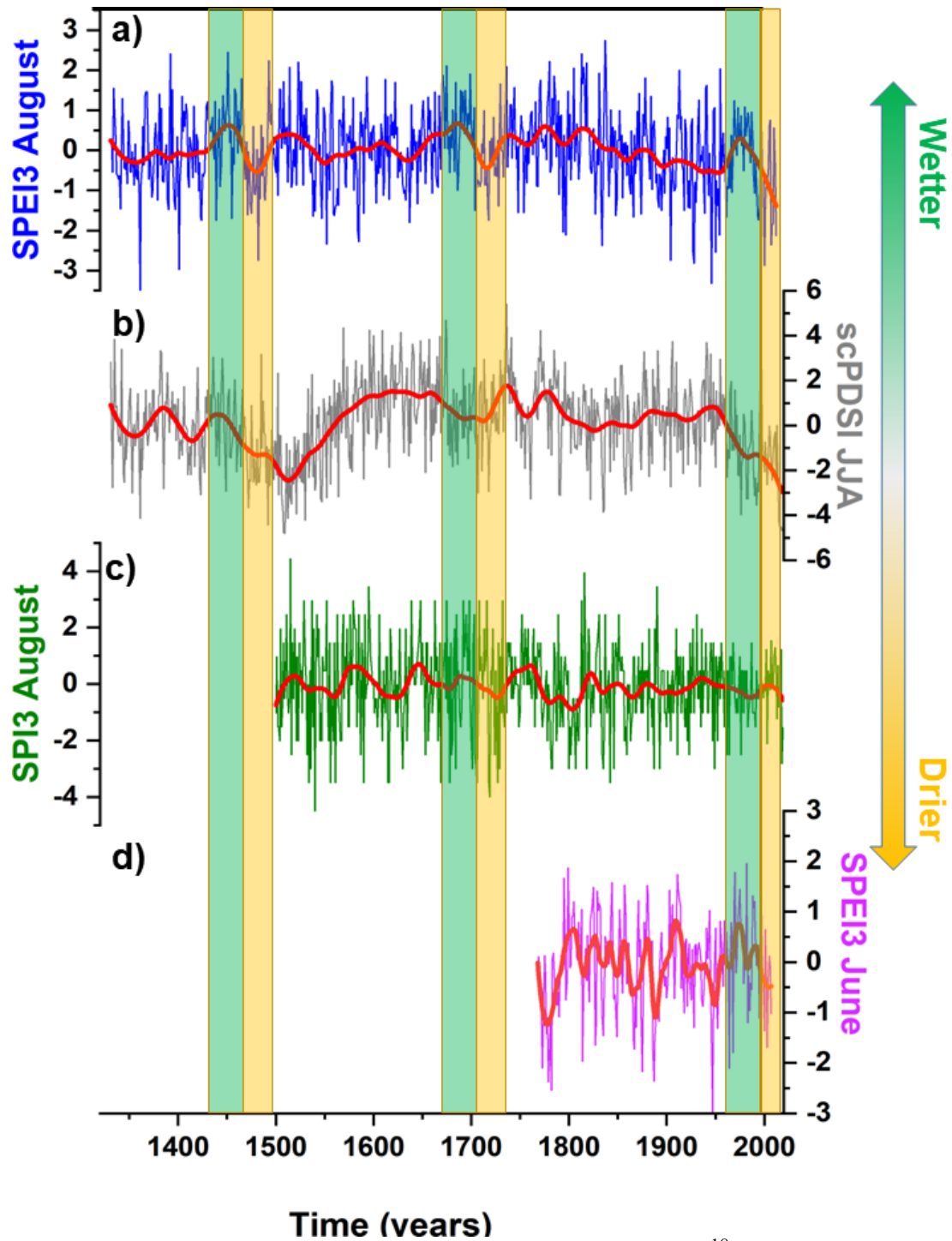
Supplementary Figure 4. Stability map of the correlation between reconstructed August SPEI3 and summer (JJA) Z500 over the period 1604 – 2003CE. Regions, where the correlation is stable, positive and significant for at least 80% of the 51-year moving window correlations, are shaded with dark red (95 %), red (90 %), orange (85 %) and yellow (80 %). The corresponding regions where the correlation is stable, but negative, are shaded with dark blue (95 %), blue (90 %), green (85 %) and light green (80 %). The black square in Figure S4 represent the area for which was defined a Z500 index.



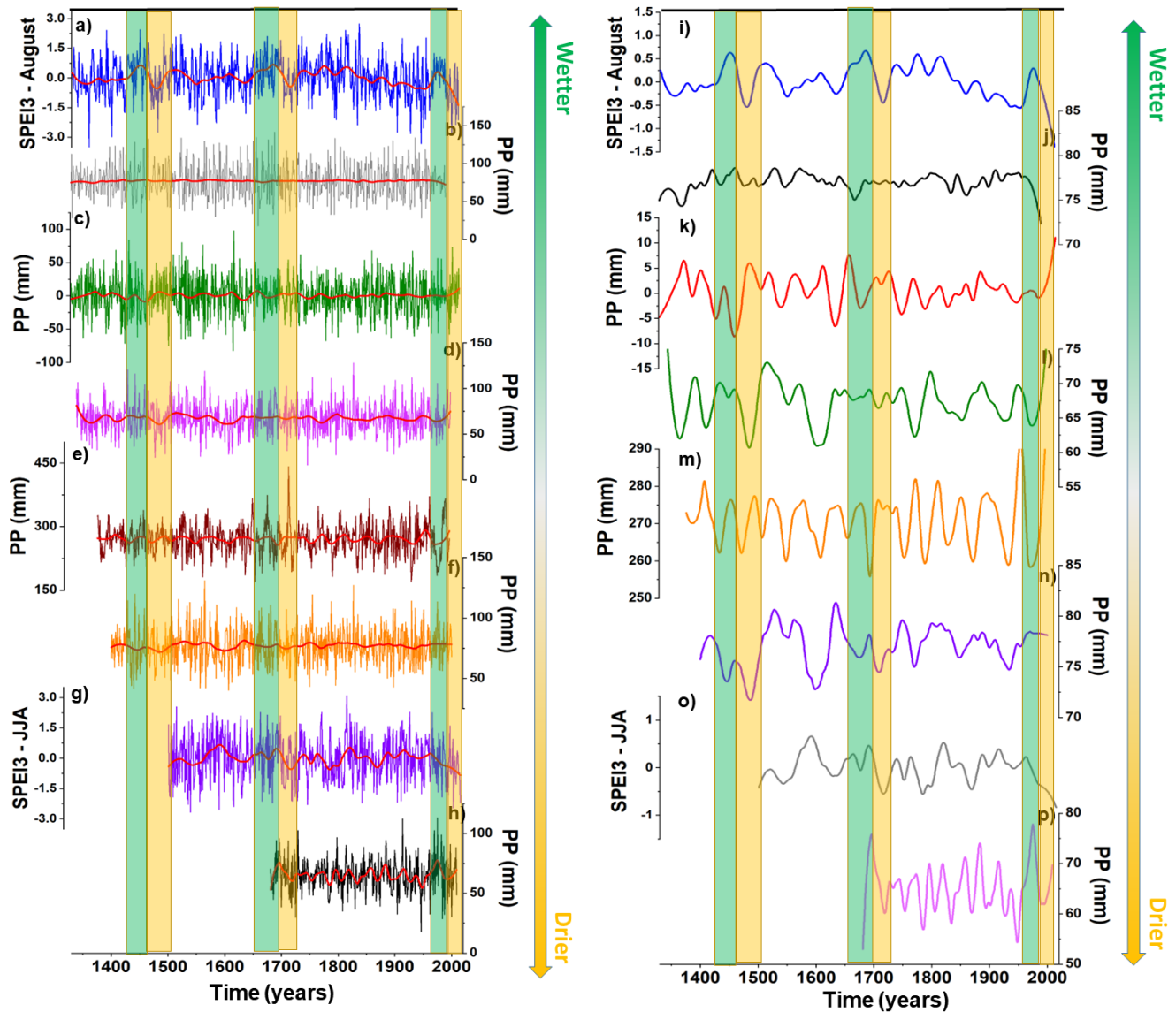
Supplementary Figure 5. a) Box plot and Gaussian situation of the reconstructed August SPEI3 index for two distinct periods: 1604 – 1850CE and 1851 – 2003CE and b) same as in a) but for summer Z500 index. The box plot and the Gaussian distribution indicates that there is a significant difference ($p \ll 0.001$, Kolmogorov-Smirnov) in the distribution of the August SPEI3 index and summer z500 index for the two periods.



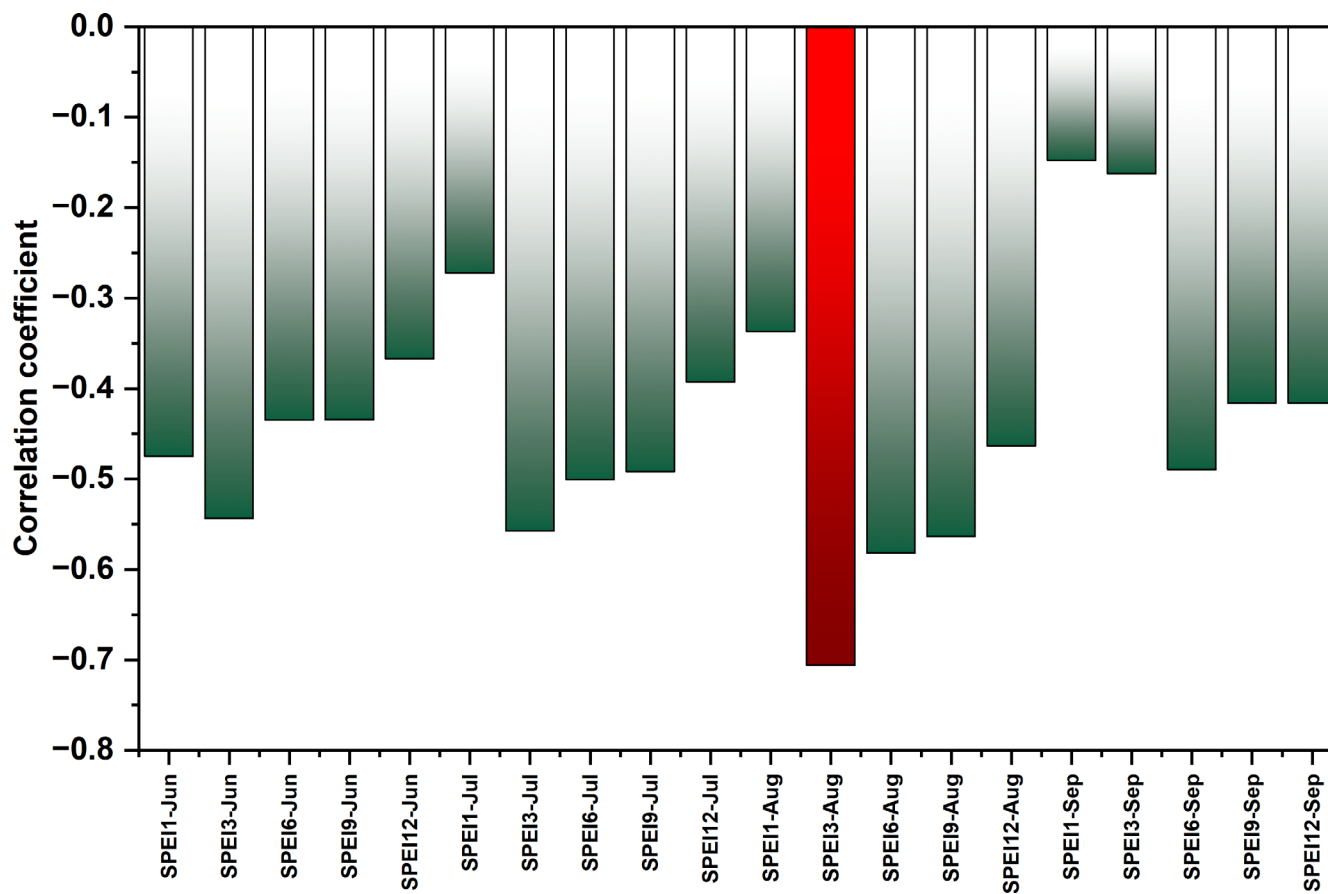
Supplementary Figure 6. Box plots of the reconstructed August SPEI3 (upper figure) and PDSI index averaged over the region 25°E - 28°E, 46°N - 48°N from Old World Drought Atlas² (lower panel) for different centuries over the period 1331 (1301) – 2012CE.



Supplementary Figure 7. a) Reconstructed August SPEI3 based on the $\delta^{18}\text{O}$ in tree ring cellulose from Călimani Mts. from 1331 – 2012CE period (blue line); b) Summer (JJA) scPDSI reconstruction over Czech Republic and Southern Germany³ (grey line) and c) August SPI3 reconstruction over Germany⁴ (green line); d) June SPEI3 reconstruction over Romania⁵ (magenta line). The bold red lines in a) – d) represents the 31 years running mean for each time series;



Supplementary Figure 8. a) Reconstructed August SPEI3 based on the $\delta^{18}\text{O}$ in tree ring cellulose from Călimani Mts. for 1331 – 2012CE period b) Reconstruction of May-June Precipitation over the North Aegean for 1331 – 1989CE period⁶; c) Reconstruction of May-July precipitation for Bohemia (Czech Republic) for 1331 – 2013CE period⁷ d) Reconstructions of spring precipitation in southwestern Turkey for 1339 – 1998CE period⁸; e) Reconstruction of March-July precipitation in southern Moravia (Czech Republic), for 1376 – 1996CE period⁹; f) Reconstruction of Spring/Summer Precipitation for Eastern Mediterranean for 1400 -2000CE period¹⁰; g) Reconstruction of the JJA SPEI3 drought index the Czech Lands for 1501 -2014CE period¹¹; h) Reconstruction of the July Precipitation for south-eastern part of Romania for 1615 – 2010CE period¹²; i) as in a) but with 31 running mean; j) as in b) but with 31 running mean; k) as in c) but with 31 running mean; l) as in d) but with 31 running mean; m) as in e) but with 31 running mean; n) as in f) but with 31 running mean; o) as in g) but with 31 running mean; p) as in h) but with 31 running mean.



Supplementary Figure 9. The correlation coefficients between $\delta^{18}\text{O}$ chronology and SPEI index, from June to September, for different periods of accumulation from one month to 12 months

Supplementary Table 1. The occurrence of the extreme dry events (years when the SPEI3 index is lower than -1.5 standard deviation) from our August SPEI3 reconstruction in different historical/documentary sources. The most extreme 5 years are with bold.

Year CE	Aug SPEI3	Historical evidence of the extremely dry years from the 1331-2012 period
1361	-3.72	Winter without snow, Extreme drought, bad harvest, famine¹³; Dry spells, droughts in Poland¹⁴; Hot summer, bad harvest¹⁵; Summer drought, lack of precipitation in the Carpathian Basin, very bad grain harvest in Austria, in the Czech Lands and also in Hungary¹⁶;
1401	-2.98	Dry spells¹⁴;
1423	-1.66	Extreme drought, famine, plague ¹³ ;
1424	-1.75	Drought, famine, plague ¹³ ; Drought, plague ¹⁷ ; Extreme drought, 3 months without precipitation ¹⁵ ;
1439	-1.75	Very harsh winter ¹³ ; Very dry (spring-)summer in South-Hungary ¹⁶ ;
1455	-1.70	Dry spells, droughts in Poland ¹⁴ ; Warm and dry summer in Czech, low Danube level ¹⁶ ;
1471	-1.61	Abnormally dry, not a drop of rain had fallen during the summer, from the month of May to the month of September, the land was dry and the heat of the sun had dried up all the swamps ¹⁸ ;
1475	-1.57	Droughty summer and so hot that woods took fire in Hungary, England and France ¹⁸ ;
1482	-2.74	Very heavy snow ¹⁷ ; Hot summer ¹⁵ ; Dry weather and droughts in Czech Lands ¹⁴ ; Very dry summer in large parts of Transylvania ¹⁶ ;
1538	-1.64	Drought ¹³ ; Heat waves ¹⁹ ; Extreme drought, dry summer, locusts, bad harvest ¹⁷ ;
1540	-1.52	Drought in spring, famine ¹³ ; Heat waves ¹⁹ ; Hot summer, drought ²⁰ ; Extreme drought, dry summer, locusts, bad harvest ¹⁷ ;;
1547	-1.70	Lack of precipitation in spring and summer, extreme drought ¹³ ; Very dry and hot in Franconia ¹⁵ ; Extremely thin tree-rings (dry patterns) ⁹ ;
1552	-2.35	Drought ¹³ ; Dry and hot spring, lack of precipitation in summer ¹⁵ ;
1559	-1.59	Drought ¹³ ; Warm winter in Europe ¹⁷ ;
1560	-1.63	Winter without snow, dry spring ¹³ ; Heat waves ¹⁹ ; Hot summer, drought in summer ²⁰ ;
1584	-2.02	Heat waves, drought ²⁰ ; Drought, famine ¹⁹ ; Hot and dry ¹⁵ ;
1585	-2.28	Drought in spring and summer, famine, extreme drought ¹³ , Drought ²¹ ; Very hot and dry summer ²⁰ ; Extreme drought ¹⁹ ;
1590	-1.57	Severe drought, bad harvest, famine ¹³ ; Drought in late summer ²⁰ ;
1637	-1.81	Famine ¹³ ; Bad harvest ¹⁹ ; Very hot and dry summer ²⁰ ; Hot and dry May ²² ; Dry spring and very dry summer ⁹ ;
1718	-1.75	Extreme drought ¹⁹ ; winter without snow, drought in spring in Transylvania and Europe, bad harvest, very low streamflow, forest fires ²⁰ ; Summer without rain, drought, bad harvest, famine ²¹ ; Dry summer ¹⁷ ;
1748	-1.55	In Ukraine, Moldova and Valahia locusts and famine ¹³ ; Heat waves ¹⁹ ; Drought in Transylvania ²⁰ ;
1754	-1.55	Very dry summer ¹³ ; drought in summer ²⁰ ; heat waves and drought in summer ¹⁷ ;
1794	-2.04	From Mai to September an extreme drought ¹³ ; Extreme drought ¹⁹ ; Drought in spring and summer in Transylvania ²⁰ ; spring and summer extreme dry, bad harvest ²¹ ; Dry and hot summer ¹⁷ ;
1797	-2.11	Hot and dry summer ²¹ ; Very hot and dry summer ²⁰ ; Long term drought ¹⁹ ; Extraordinarily warm and dry summer ¹⁷ ; Dry February and March ⁹ ;
1827	-1.59	Extreme drought summer, hot and dry, forest fires ²⁰ ;
1834	-2.38	Drought in Moldova ²¹ ; Drought in Ardeal ²⁰ ; Drought ¹⁷ ; Drought in Czech Lands ²³ ;

1848	-1.63	Very warm February, drought in May in Odesa, hot summer in Basarabia ¹³ ; Dry and hot summer ¹⁷ ;
1866	-1.66	In July and September drought ²⁰ , Dry summer ²¹ ;
1874	-1.59	Prolong drought in Bessarabia, locust in Danube Delta ¹³ ; Dry summer ²⁰ , Dry summer ²¹ ;
1904	-2.74	Drought in Moldova ¹³ Very extreme drought ²¹ ; Dry year ¹⁷ ; Drought in Czech Lands ²³ ;
1927	-2.55	Drought in June ^{17,21} ;
1928	-2.82	Drought in Moldova, dust storm ¹³; Drought in July ²¹;
1939	-1.57	Warm winter ¹³ ; Warm summer ²¹ ; Hot summer ¹⁷ ;
1946	-3.32	Dust storm ^{13,17}, Hot and very dry weather ²¹; Very hot and dry weather with maximum temperatures +40°C ²⁰; Drought in Czech Lands ²³; Extreme dry summer ¹²;
1950	-2.55	Hot and very dry weather ^{13,17} ;
1954	-2.11	Dust storm ¹³ ; Hot summer ²¹ ;
1961	-1.66	Extreme drought, lack of precipitations ¹⁷ ;
1993	-1.64	Drought ¹⁷ ; Severe drought ²⁴ ;
1994	-1.73	Hot summer, drought from January to July ¹⁷ ; Moderate drought ²⁴ ;
2000	-2.87	Very hot year, tropical heat waves ¹⁷; Extreme drought ²⁴; Drought in Czech Lands ²⁵; Extreme dry summer ¹²;
2007	-2.37	Severe drought ²⁴ ; Drought in Czech Lands ^{23,25} ;
2008	-1.88	Moderate drought ²⁴ ;
2009	-1.82	Moderate drought ²⁴ ; Drought in Czech Lands ²⁵ ;
2012	-2.13	Severe drought ²⁴

Supplementary Table 2. The occurrence of the extreme wet events (years when the SPEI3 index is higher than +1.5 standard deviation) from our August SPEI3 reconstruction in different historical/documentary sources. The most extreme 5 years are with bold

Year CE	Aug SPEI3	Historical evidence of the extreme wet years from the 1331-2012 period
1334	1.55	Harsh winter with snow in spring ¹³
1392	2.42	Harsh winter¹³; Cold spring, storms¹⁵; Flood on Vltava and Elbe rivers²⁶;
1394	1.51	Cold year, storms ¹⁵ ;
1451	2.45	Storms, floods, destroyed bridges and houses¹⁵; Floods in Poland²⁶; Very wet and very snowy winter¹⁸;
1458	1.53	Rainy summer ¹³ ; Harsh winter ¹⁷ ;
1465	1.78	Harsh winter, cold and wet weather ¹⁵ ;
1493	2.24	Year with heavy snowfall¹⁵; Great flood (Pozsony/Bratislava), floods in Poland caused by rainy summer, Flood on Danube²⁶;
1504	1.53	Very rainy summer, floods, high river streamflow ¹³ ; Rainy summer ²⁰ ; Rainy summer ¹⁷ ;
1505	1.51	Floods ¹⁹ ;
1508	1.71	Very wet summer (from middle of May to end of August), floods in Hungary Ardeal and Moldova ²¹ ; Floods ¹⁹ ; Big floods in Transylvania with huge damages ¹⁷ ; Storms ¹⁴ ; Danube extraordinary flood ²⁶ ;
1514	2.07	Year with heavy snowfall ¹⁷ ; Wet summer in Czech ¹⁵ ;
1523	2.20	Wet summer ¹³ ;
1526	1.71	Rainy August, catastrophic floods ²¹ ; Rainy and floods ¹⁹ ; Rainy summer and floods ²⁰ ; Cold rain and floods ¹⁷ ; Cool weather ²² ;
1542	1.51	Bad harvest ¹⁹ ; Excessive rains, floods ²⁰ ;
1557	1.73	Summer with excess of rainfall, wet spring and summer ¹³ ; Excessive rainfall ¹⁹ ; Summer with many rainfalls ¹⁷ ;
1558	1.60	Heavy and prolonged winters ¹⁹ ; Floods in August ¹⁵ ; Wet summer ²² ;
1593	1.84	Rainy summer and spring ¹³ ; Floods and continuous rains ²¹ ; Excessive rainfall ²⁰ ; Rainy summer ¹⁷ ; Wet summer ¹⁵ ;
1612	1.77	Locust invasions ¹⁹ ; Rainy summer ¹⁵ ;
1622	1.69	Floods throughout Transylvania ²⁰ ; Wet spring, floods, famine, plague ¹⁹ ; Extreme wet year ¹⁷ ;
1670	1.68	Huge floods in southwestern Russia ¹³ ; Heavy rains in Romania destroying the harvest ²¹ ; Wet and rainy summer ²⁰ ; Excessive rainfall, floods ¹⁹ ; Floods in Moldova ¹⁷ ; Floods ⁹ ;
1671	1.88	Wet summer with heavy rainfalls ²¹ ; Rainy summer ²⁰ ; Floods ¹⁹ ; Wet summer with many heavy rainfalls ¹⁷ ;
1675	2.11	Year with heavy snowfall ¹³ ; Heavy rainfalls and floods ²¹ ; Rainy summer, floods in Transylvania ²⁰ ; Heavy rainfalls ¹⁹ ; Wet weather and floods ¹⁵ ; Wet summer, floods ⁹ ;
1684	1.69	Floods in Ukraine ¹³ ; Floods ¹⁹ ;
1699	1.91	Heavy rainfalls and floods in July ²⁰ ; Floods ¹⁷ ; Cold summer ¹⁵ ;
1730	1.66	Rainy Autumn ¹³ ; Floods ¹⁹ ; Wet spring and summer, floods on Crisul Repere River ²⁰ ; Wet spring and summer ¹⁷ ;
1736	2.09	Year with heavy snowfall ¹³ ; Heavy rainfalls, cloudburst ¹⁹ ; Continues rainfalls in many regions of Central Europe ¹⁵ ;
1744	1.57	Storms ¹³ ; Extreme rains, floods ¹⁹ ;
1770	1.59	Heavy rainfall ¹⁹ ; Heavy snowfall In April ²² ; Extreme wet summer ¹² ;
1771	1.75	Wet year ²⁰ ; Heavy rainfall, floods ¹⁹ ; Floods, ¹⁵ ;
1780	2.22	Heavy rainfall in summer²⁰; Heavy rainfall¹⁹;
1785	1.86	Floods ¹⁹ ;

1805	2.06	Heavy rains lead to floods ²¹ ; Wet summer in Transylvania ²⁰ ; Heavy rains and floods ¹⁷ ; Cold and wet in July ²² ;
1813	2.42	Wet summer ^{17,20,21}; Cold and wet in July ²²;
1814	1.66	Plague ¹⁹ ; Cold and wet summer ²² ;
1815	2.07	Mount Tambora explosion ²⁷ ; Extremely wet summer ²⁸ ; Cold and wet summer ²² ;
1816	1.78	Heavy rains and floods ²⁰ ; Wet year ¹⁷ ; Year Without a Summer ²⁷⁻²⁹ ;
1818	2.18	End of summer very wet ^{17,20,21} ; Cold and wet summer ²² ;
1831	1.93	Maximum temperatures in July ~15°C ¹³ ; From May to September many cold rains ^{20,21} ; Cold and wet summer ²² ;
1837	2.74	Heavy rainfalls in Moldova ¹³; Cold and wet summer, heavy rainfalls ²¹; Cold and wet summer ²⁰; Many heavy rainfalls in summer ¹⁷;
1838	2.07	Heavy rainfalls ¹³ ; rainy summer without harvest ¹⁷ ;
1878	1.80	Rainy summer ²¹
1913	2.00	Very rainy August ¹⁷ ;
1940	1.55	July and August very rainy ²¹ ; Cyclonic circulation over the Eastern Europe, wet and cold ²² ;
1941	1.62	Cold and rainy summer, storms, heavy rains ¹⁷ ; Wet summer, storms ²¹ ;
1955	2.04	Summer with many heavy rainfalls and floods ¹³ ; Heavy rainfalls in July and August ²¹ ; Rainy summer ²² ;

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