Influence of Warming and Atmospheric Circulation Changes on Multidecadal European Flood Variability

Stefan Brönnimann,[1,2] Peter Stucki,[1,2] Jörg Franke,[1,2] Veronika Valler,[1,2] Yuri Brugnara,[1,2] Ralf Hand,[1,2] Laura C. Slivinski,[3,4] Gilbert P. Compo,[3,4] Prashant D. Sardeshmukh,[3,4] Michel Lang,[5] Bettina Schaefli[1,2]

[1] Oeschger Centre for Climate Change Research, University of Bern, Switzerland

[2] Institute of Geography, University of Bern, Switzerland

[3] University of Colorado, CIRES, Boulder, USA

[4] NOAA Physical Sciences Laboratory, Boulder, USA

[5] INRAE, Lyon-Villeurbanne, France

Supplementary Table S1

Supplementary Figures S1, S2, S3, S4 S5

Supplementary Tables

Supplementary Table S1: Streamflow series used in the paper with their hydrological characteristics, as well as the precipitation station used for comparison. The 14 long series shown in Fig. 1 are in highlighted bold

GRDC station number	river name	station name	Cluster #	country code (ISO 3166)	latitude, decimal degree	longitude, decimal degree	catchment size, km2	height of gauge zero, m above sea level	data available from year	data available until year	long-term average discharge, cubic kilometre per second	Precipitation station	latitude, decimal degree	longitude, decimal degree
6935300	Aare	Untersiggental/ Stilli		CH	47.5166	8.2348	17601	373.41	1904	2016	558.2	Bern	46.99	7.46
6337502	Aller	Celle		DE	52.622	10.063	4374	31.8	1890	2016	27.0	Clausthal	51.79	10.35
6731215	Bjerkreimselva	Bjerkreim		NO	58.58	6.08	633	55	1897	2015	50.9	Soyland	58.68	5.98
6142200	Danube	Achleiten		DE	48.5824	13.5044	76653	287.7	1900	2015	1421.1	Passau	48.58	13.42
6342800	Danube	Bratislava		SK	48.1396	17.1092	131331	128	1900	2017	2045.5	Vienna	48.23	16.35
6342900	Danube	Hofkirchen		DE	48.6766	13.1152	47496	299.6	1900	2016	636.9	Munich	48.17	11.5
6140700	Divoka Orlice	Nekor		CZ	50.0651	16.5404	182.4	431.19	1906	2018	3.7	Görlitz	51.16	14.95
6340120	Elbe	Barby		DE	51.9901	11.8826	94060	46	1899	2016	551.3	Jena	50.93	11.58
6340110	Elbe	Decin		CZ	50.7822	14.2096	51120.3	120.07	1887	2018	309.3	Prague	50.09	14.42
6140400	**Elbe**	**Dresden**		**DE**	**51.0597**	**13.7385**	**53096**	**102.73**	**1806**	**2016**	**332.2**	**Chemnitz**	50.79	12.87
6340140	**Elbe**	**Neu-Darchau**		**DE**	**53.2323**	**10.8888**	**131950**	**5.68**	**1874**	**2016**	**705.9**	**Marnitz**	53.32	11.93
6340150	Elbe	Wittenberge		DE	52.9908	11.7598	123532	17	1899	2016	677.2	Berlin	52.46	13.3
6338120	Ems	Greven		DE	52.094	7.603	2842	32.71	1900	2016	26.1	Münster	51.95	7.59
6731403	Glomma	Solbergfoss		NO	59.6373	11.1535	40540	101	1901	2013	690.6	Orje	59.48	11.65
6342200	Iller	Kempten		DE	47.7304	10.3169	954.6	656	1900	2016	46.4	Kempten	47.72	10.34
6342830	Ilz	Kalteneck		DE	48.6889	13.4519	762	327.97	1900	2016	16.1	Riedlhütte	48.89	13.43
6343100	Inn	Martinsbruck		CH	46.8858	10.4654	1945	1076.537	1904	2016	55.9	Bever	46.5	9.85
6943100	Inn	Wasserburg		DE	48.0593	12.2342	11983	420.45	1826	2016	354.2	Ebersberg	48.1	11.99
6607830	**Lea**	**Feildes Weir**		**GB**	**51.7642**	**0.0139**	**1036**	**27.7**	**1879**	**2018**	**4.4**	**Rothamsted**	51.81	0.36
6342513	Lech	Landsberg		DE	48.0415	10.8751	2295	584.41	1900	2016	82.4	Hohenpeissenberg	47.8	11.01
6335500	**Main**	**Schweinfurt**		**DE**	**50.0312**	**10.2208**	**12715**	**201.16**	**1844**	**2016**	**103.2**	**Bamberg**	49.88	10.92
6335301	**Main**	**Würzburg**		**DE**	**49.796**	**9.926**	**14031**	**164.55**	**1823**	**2016**	**108.9**	**Bamberg**	49.88	10.92
6336050	Moselle	Cochem		DE	50.1434	7.1683	27088	77	1900	2016	313.8	Karlsruhe	49.04	8.36

6731217	Ognaelvi	Helleland		NO	58.5336	6.1503	185	86	1896	2015	13.7	Soyland	58.68	5.98
6935310	Reuss	Mellingen		CH	47.421	8.2713	3382	392.631	1904	2016	139.2	Engelberg	46.8	8.4
not from GRDC	**Rhine**	**Basel/ Schifflände**		**CH**	**47.5599**	**7.5884**	**35905**	**292.887**	**1808**	**1995**	**1042.4**	**Basel**	47.53	7.58
6935051	Rhine	Domat/Ems		CH	46.8377	9.4561	3229	622.884	1899	2016	117.4	Bad Ragaz	47	9.5
6935052	Rhine	Düsseldorf		DE	51.2255	6.7702	147680	24.48	1900	2016	2126.9	Karlsruhe	49.04	8.36
6935145	**Rhine**	**Köln**		**DE**	**50.937**	**6.9633**	**144232**	**34.97**	**1816**	**2016**	**2085.4**	**Karlsruhe**	49.04	8.36
6335050	Rhine	Lobith		NL	51.84	6.11	160800	8.53	1901	2017	2214.1	Roermond	51.18	5.97
6435060	Rhine	Neuhausen		CH	47.6823	8.6259	11887	429.577	1904	2016	369.4	St. Gallen	47.4	9.4
6935054	**Rhine**	**Rees**		**DE**	**51.7569**	**6.3954**	**159300**	**8**	**1814**	**2016**	**2252.0**	**Roermond**	51.18	5.97
6935055	Rhine	Rekingen		CH	47.5704	8.33	14718	370.174	1904	2016	441.2	Zurich	47.38	8.57
not from GRDC	**Rhône**	**Beaucaire**		**FR**	**43.92**	**4.67**	**95590**	**3**	**1816**	**2017**	**1692.6**	**Montélimar**	44.58	4.73
6939200	Rhône	Chancy		CH	46.153	5.9707	10323	388.729	1904	2016	340.6	Geneva	46.2	6.15
6939050	Rhône	Porte-du-Scex		CH	46.3495	6.8886	5244	428.582	1905	2016	180.6	Sion	46.22	7.33
6343560	Saalach	Unterjettenberg		DE	47.6812	12.8228	927.3	494	1900	2016	38.2	Schneizlreuth	47.67	12.77
6343500	**Salzach**	**Burghausen**		**DE**	**48.1586**	**12.8343**	**6649**	**352**	**1826**	**2016**	**258.8**	**Kremsmünster**	48.06	14.13
6607651	**Thames**	**Kingston**		**GB**	**51.4154**	**-0.3077**	**9948**	**4.7**	**1883**	**2018**	**78.9**	**Oxford**	51.76	-1.26
6935400	Thur	Andelfingen		CH	47.5965	8.682	1696	402.751	1904	2016	46.9	Säntis	47.25	9.35
6731371	Tovdalselva	Flaksvatn		NO	58.3305	8.2031	1780.6	19	1899	2014	61.0	Mestad	58.22	7.89
6337100	**Weser**	**Bodenwerder**		**DE**	**51.973**	**9.516**	**15924**	**69.39**	**1839**	**2016**	**145.6**	**Göttingen**	51.56	9.85
6337400	**Weser**	**Hann. Münden**		**DE**	**51.426**	**9.641**	**12442**	**114.95**	**1831**	**2016**	**109.8**	**Creuzburg**	51.06	10.25
6337514	**Weser**	**Intschede**		**DE**	**52.964**	**9.125**	**37720**	**4.79**	**1857**	**2016**	**320.5**	**Rotenburg**	53.13	9.34
6337200	Weser	Vlotho		DE	52.176	8.862	17618	41.66	1820	2016	170.7	Göttingen	51.56	9.85

Supplementary Figures

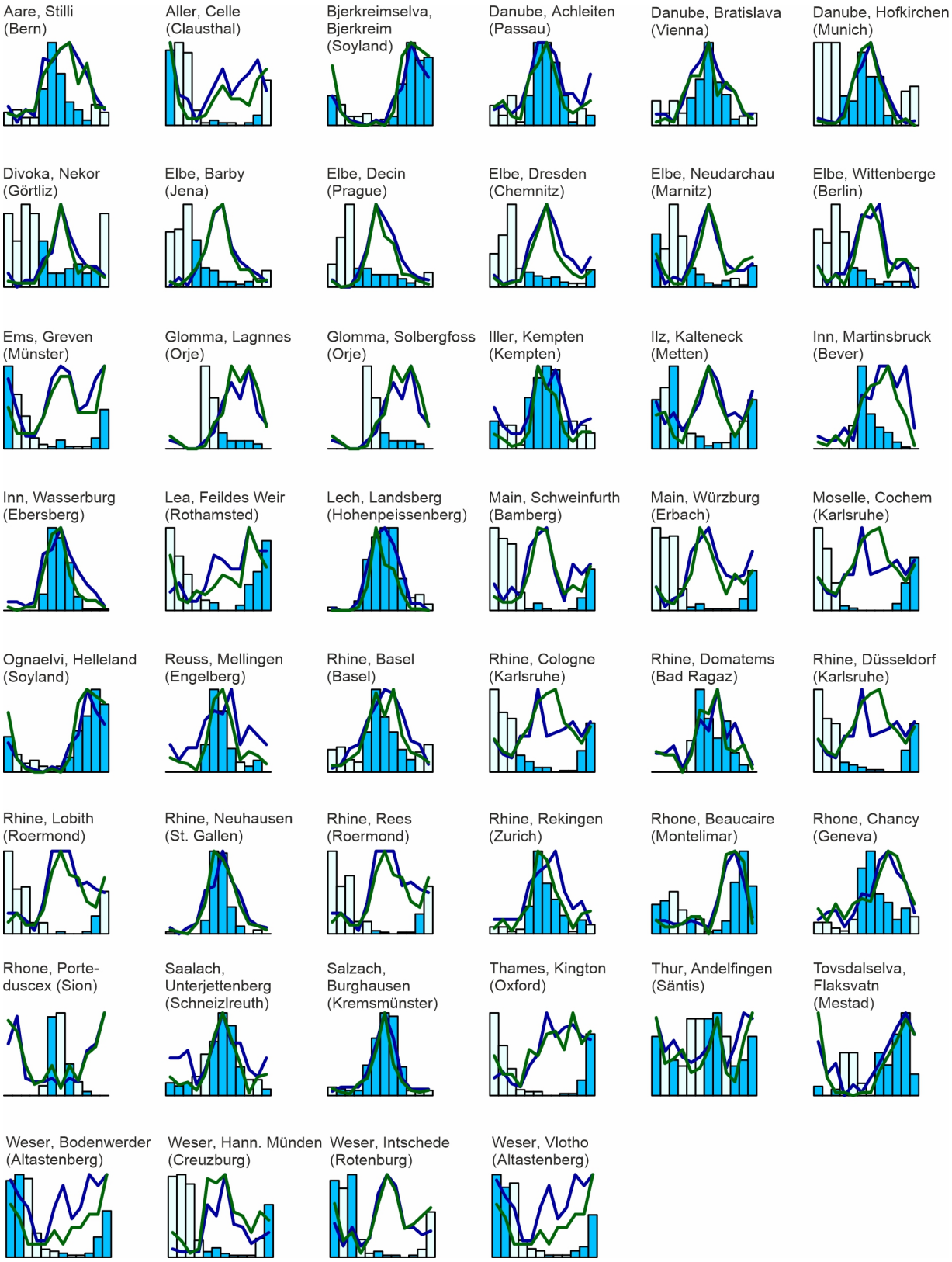

Fig. S1: Seasonality of annual peak streamflow (bars), Rx5d (blue) and Rx20day (green). The streamflow bars pertaining to the six months with highest Rx5day are marked in blue. Lines and bars are scaled between 0 and the maximum.

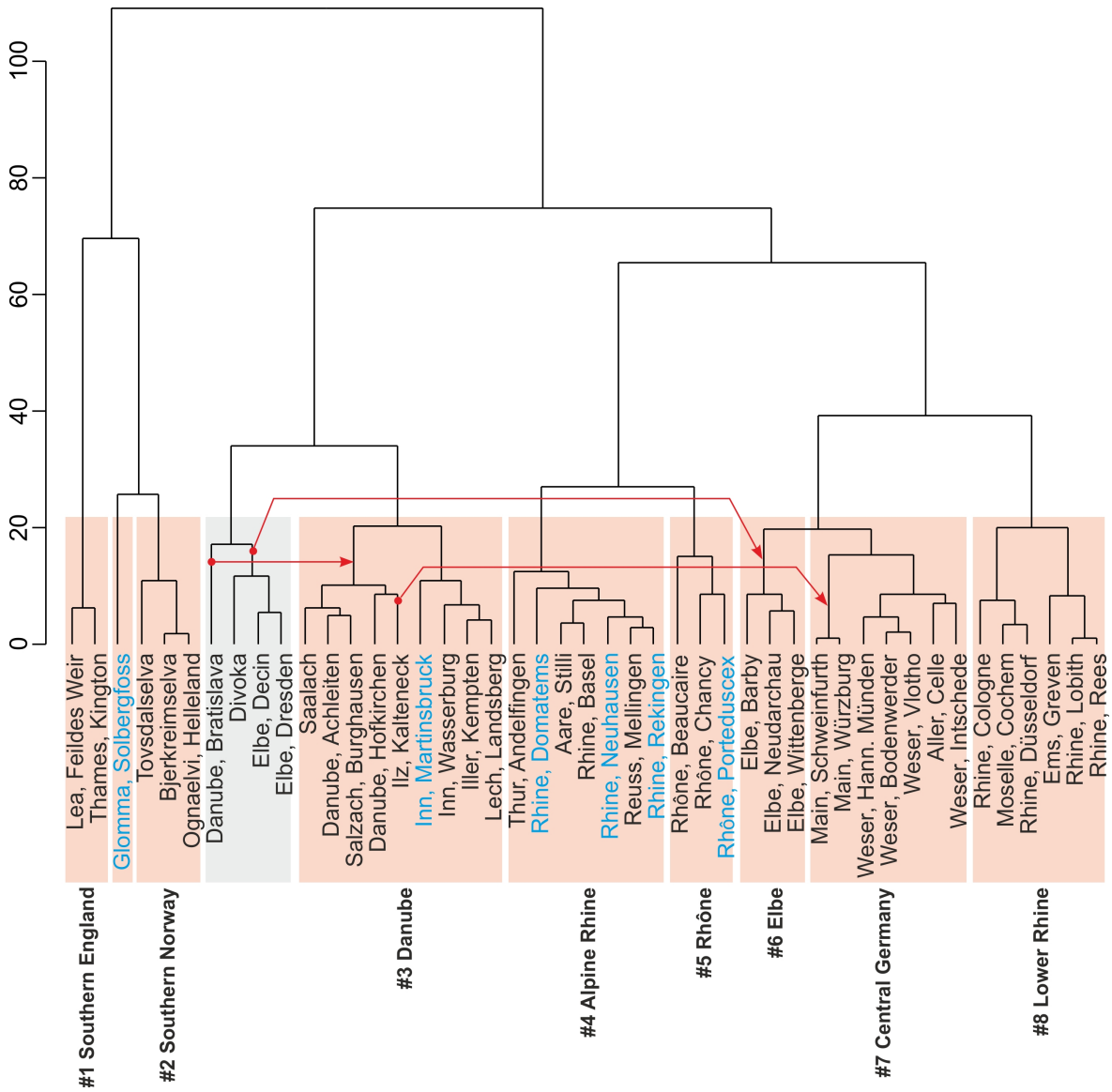

Fig. S2: Dendrogram of Ward cluster analysis and chosen regionalization (boxes – the grey cluster was split). Red points and arrows: Streamflow series that were assigned to another cluster (blue: series shown in Fig. 2).

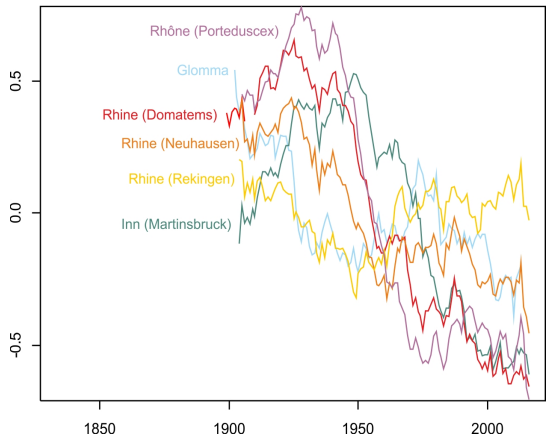

Fig. S3: Streamflow series (normalized, smoothed with a 30-yr moving average) that were excluded from the main analysis.

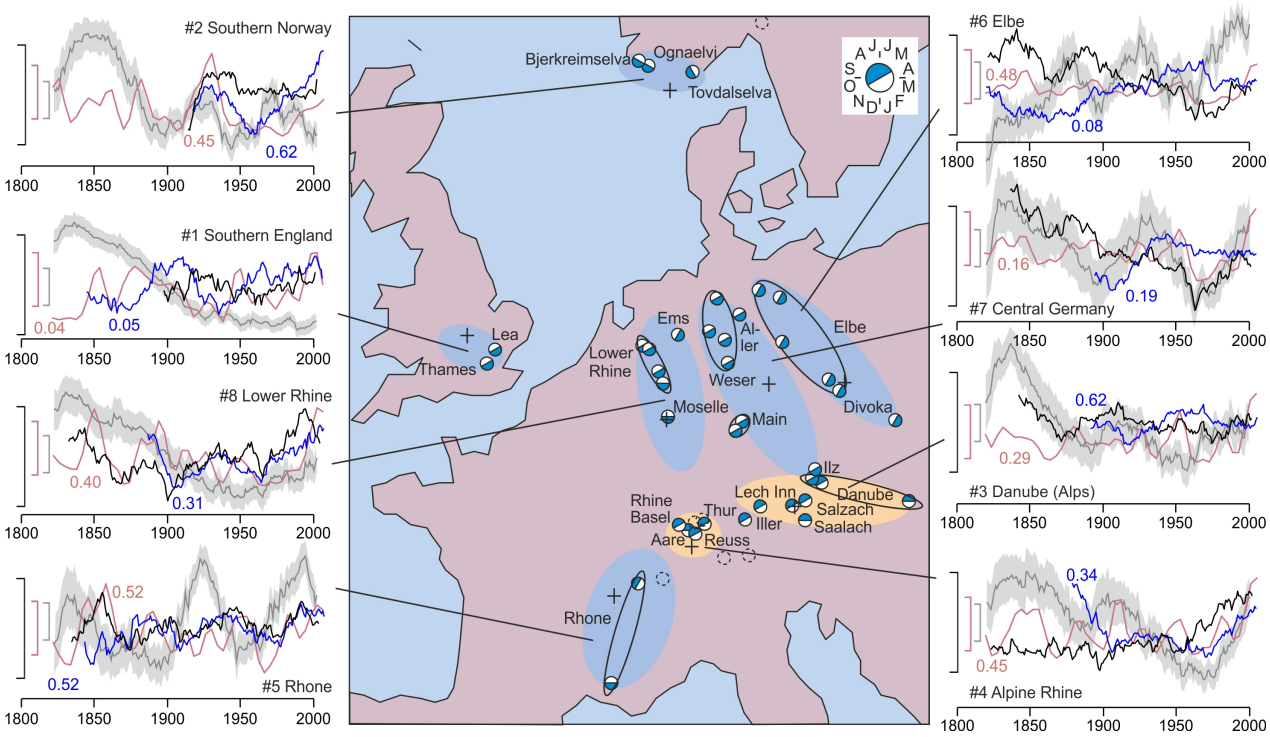

Figure S4. Regionally averaged (coloured ellipses; black ellipses indicate same river) series of normalized annual peak streamflow (black), precipitation (blue) and CONV5d from 20CRv3 at locations of crosses (grey, shading indicates the ensemble standard deviation), standardized and subsequently smoothed with a 30-yr moving average (black/grey scale bars, ranging from -0.5 to +0.5). Light red lines (scale bar from 1 to 1.5) show interpolated and smoothed flood intensity from Blöschl et al (2020) at the locations of the crosses (numbers: correlations with peak streamflow at 4-yr aggregation). Regions are colour-coded according to the predominance of cold (blue) or warm season floods (orange; the blue part of the white-blue circle for each river indicates the 6-month period with highest flood frequency). Dashed circles: Streamflow series excluded because of likely influence of snow melt on trends.

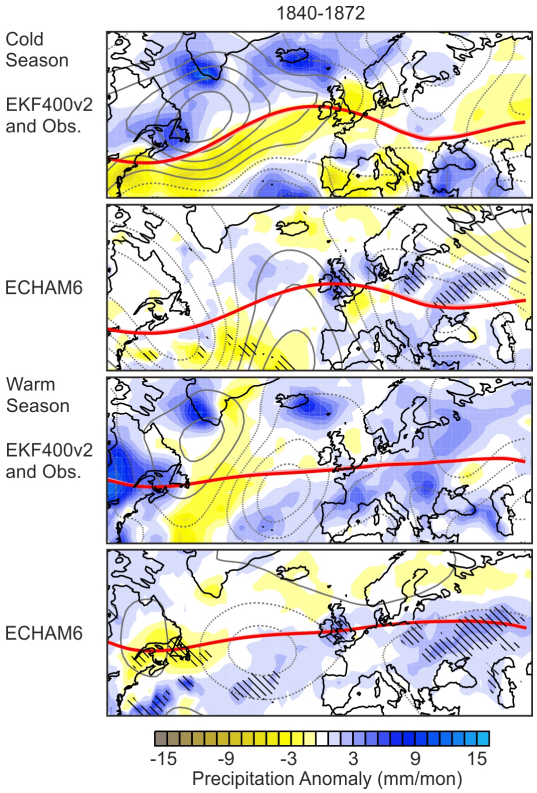

Fig. S5. Same as Fig. 8, but for the period 1840-1872. Note that ECHAM6 simulations start only in 1851.