Supplementary Material

Detecting the human fingerprint in the summer 2022 West-Central European soil drought

Dominik L. Schumacher[1], Mariam Zachariah[2], Friederike Otto[2], Clair Barnes[2], Sjoukje Philip[3], Sarah Kew[3], Maja Vahlberg[4], Roop Singh[4], Dorothy Heinrich[4], Julie Arrighi[4,5,6], Maarten van Aalst[4,6,7], Mathias Hauser[1], Martin Hirschi[1], Verena Bessenbacher[1], Lukas Gudmundsson[1], Hiroko K. Beaudoing[8,9], Matthew Rodell[8], Sihan Li[10], Wenchang Yang[11], Gabriel A. Vecchi[11,12], Luke J. Harrington[13], Flavio Lehner[14,15], Gianpaolo Balsamo[16], and Sonia I. Seneviratne[1]

[1] Institute for Atmospheric and Climate Science, ETH Zurich, 8092, Switzerland
[2] Grantham Institute, Imperial College, London, SW7 2BU, UK
[3] Royal Netherlands Meteorological Institute (KNMI), De Bilt, 3731, The Netherlands
[4] Red Cross Red Crescent Climate Centre, The Hague, 2593, Netherlands
[5] Global Disaster Preparedness Center, Washington DC, 20006, USA
[6] University of Twente, Enschede, 7500, Netherlands
[7] International Research Institute for Climate and Society, Columbia University, New York, NY 10964-1000, US
[8] Earth Sciences Division, NASA GSFC, Greenbelt, MD 20771, USA
[9] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA
[10] Department of Geography, University of Sheffield, S10 2TN, UK
[11] Department of Geosciences, Princeton University, Princeton, NJ 08544, USA
[12] High Meadows Environmental Institute, Princeton University, Princeton, NJ 08544, USA
[13] Te Aka Mātuatua School of Science, University of Waikato, Hillcrest, Hamilton 3214, New Zealand
[14] Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853-1504, USA,
[15] Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO 80301, USA
[16] European Centre for Medium-range Weather Forecasts, ECMWF, Reading, RG2 9AX, UK

Supplementary text

Surface soil moisture event return period and trend analysis

For West-Central Europe, the return periods of the surface soil moisture in the 2022 climate are 13, 14 and 17 years, from the ERA5-Land, ERA5 and GLDAS-CLSM datasets, respectively (**Suppl. Fig. 17**). Analysing the three observational datasets individually, they each show significant changes towards drought conditions for surface soil moisture between the past and present climates (**Suppl. Fig. 17**; **Suppl. Table 11**), with probability ratios of at least 7 for ERA5, at least 3 for ERA5-Land, and higher orders of magnitude for GLDAS-CLSM. Soil moisture decreased during this period by around 10% for ERA5, 8% for ERA-Land and 14% for GLDAS-CLSM.

For the NHET region, **Fig. S18** shows the trend fitting results for June–August average surface soil moisture. The return periods for the 2022 event are found to be consistent across the datasets, ranging from 16 to 20 years. The changes are clearly towards more frequent drought, with ERA5 and ERA5-Land giving a probability ratio of around 170 (18–6000), and GLDAS-CLSM a much larger ratio. The corresponding changes in intensity show that surface soil moisture has decreased by around 2.7% (1.4% to 3.8%) for ERA5, 2.6% (1.5% to 3.6%) according to ERA5-Land, and has decreased by around 4.4% (3.7% to 5%) according to GLDAS-CLSM (S**uppl. Table 12**). The estimates from the ERA-based products and the GLDAS do not overlap in their confidence intervals, indicating that the magnitude of the observed trend is difficult to quantify and is sensitive to the dataset used, however both datasets indicate a clear tendency towards drought conditions. In the synthesis, the uncertainty related to the large difference between their estimates is included for each of these datasets in addition to the standard sampling uncertainty.

Supplementary figures

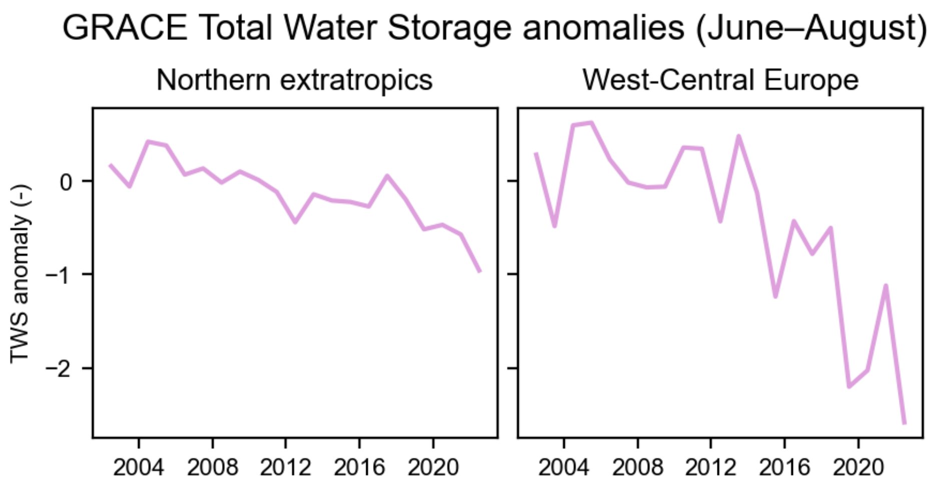


Fig. S1: Summer total water storage anomalies from the Gravity Recovery and Climate Experiment for the northern extratropics and West-Central Europe, available since 2002.

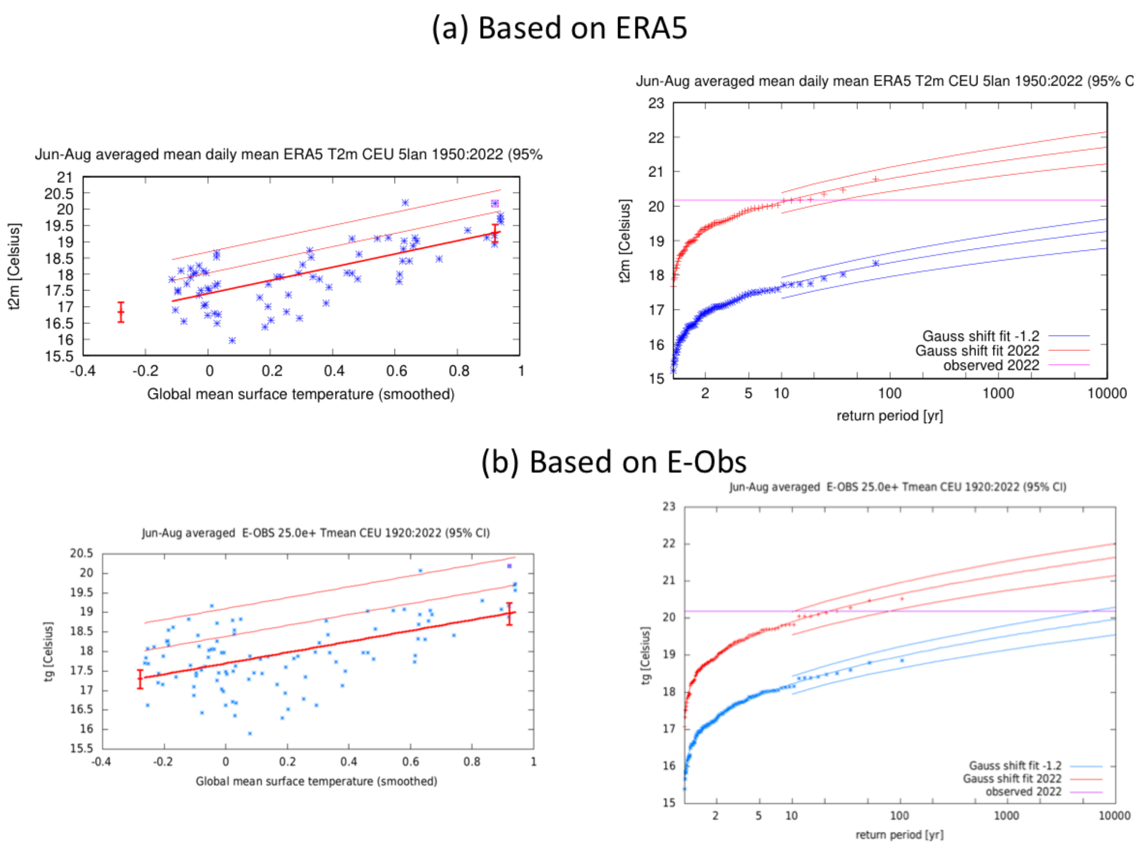
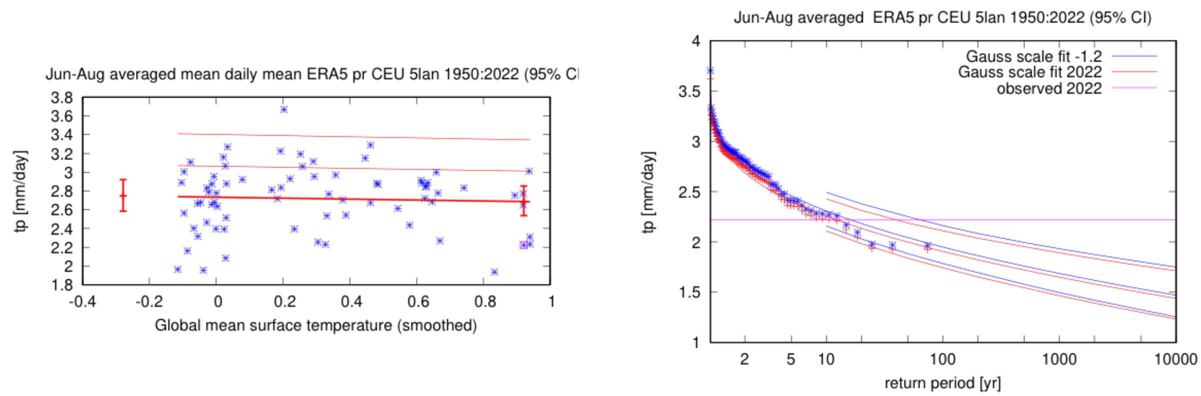


Fig. S2: Gaussian fit of WCE mean summer temperature with constant dispersion parameter, and the location parameter shifting proportional to GMST of the index series, based on two gridded datasets: (a) ERA5, and (b)

E-OBS. The 2022 event is included in the fit. **Left**: Observed temperature as a function of the smoothed GMST. The thick red line denotes the time-varying location parameter. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2022 climate and a 1.2 ºC cooler climate. The 2022 observation is highlighted with the magenta box. **Right**: Return time plots for the climate of 2022 (red) and a climate with GMST 1.2 ºC cooler (blue). The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. The markers show the data and the lines show the fits and uncertainty from the bootstrap. The magenta line shows the magnitude of the 2022 event analysed here.

(a) Based on ERA5



(b) Based on E-Obs

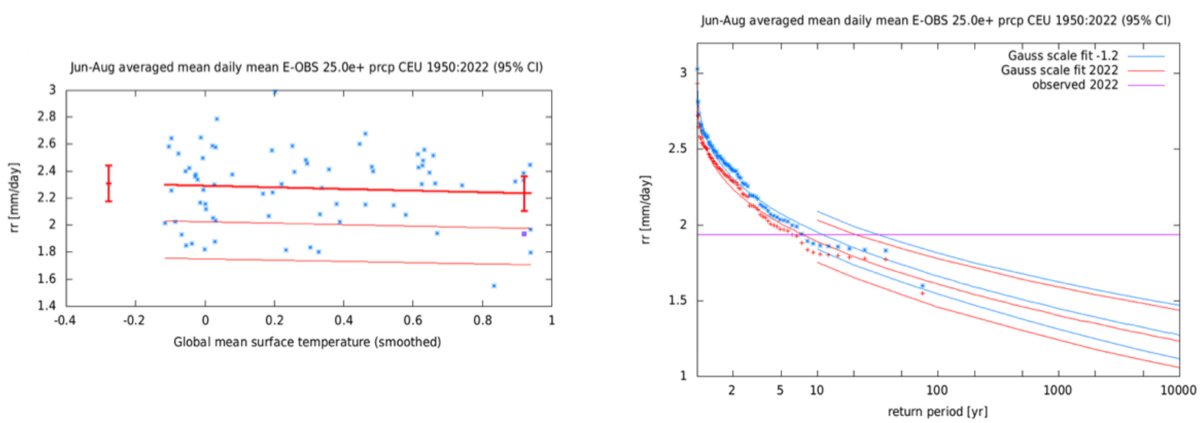


Fig. S3: Gaussian fit of WCE summer mean precipitation with constant dispersion parameter, and the location parameter scaling proportional to GMST of the index series, for the WCE region based on two gridded datasets: (a) ERA5, and (b) E-OBS. The 2022 event is included in the fit. **Left**: Observed precipitation as a function of the smoothed GMST. The thick red line denotes the time-varying location parameter. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2022 climate and a 1.2ºC cooler climate. The 2022 observation is highlighted with the magenta box. **Right**: Return time plots for the climate of 2022 (red) and a climate with GMST 1.2 ºC cooler (blue). The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. The markers show the data and the lines show the fits and uncertainty from the bootstrap. The magenta line shows the magnitude of the 2022 event analysed here.

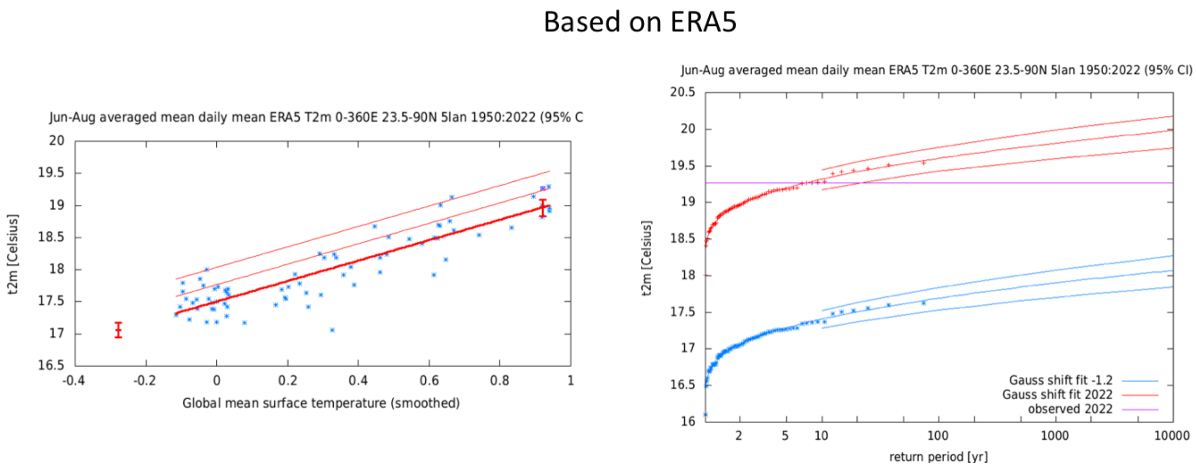


Fig. S4: same as Fig. S2, based on the ERA5 dataset for the NHET region.

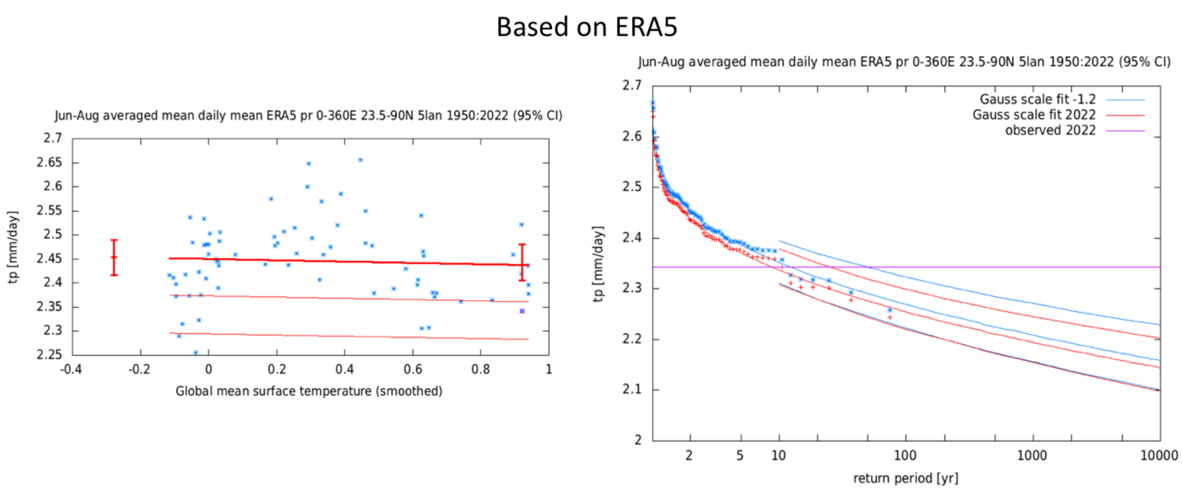


Fig. S5: same as Fig. S3, based on the ERA5 dataset for the NHET region.

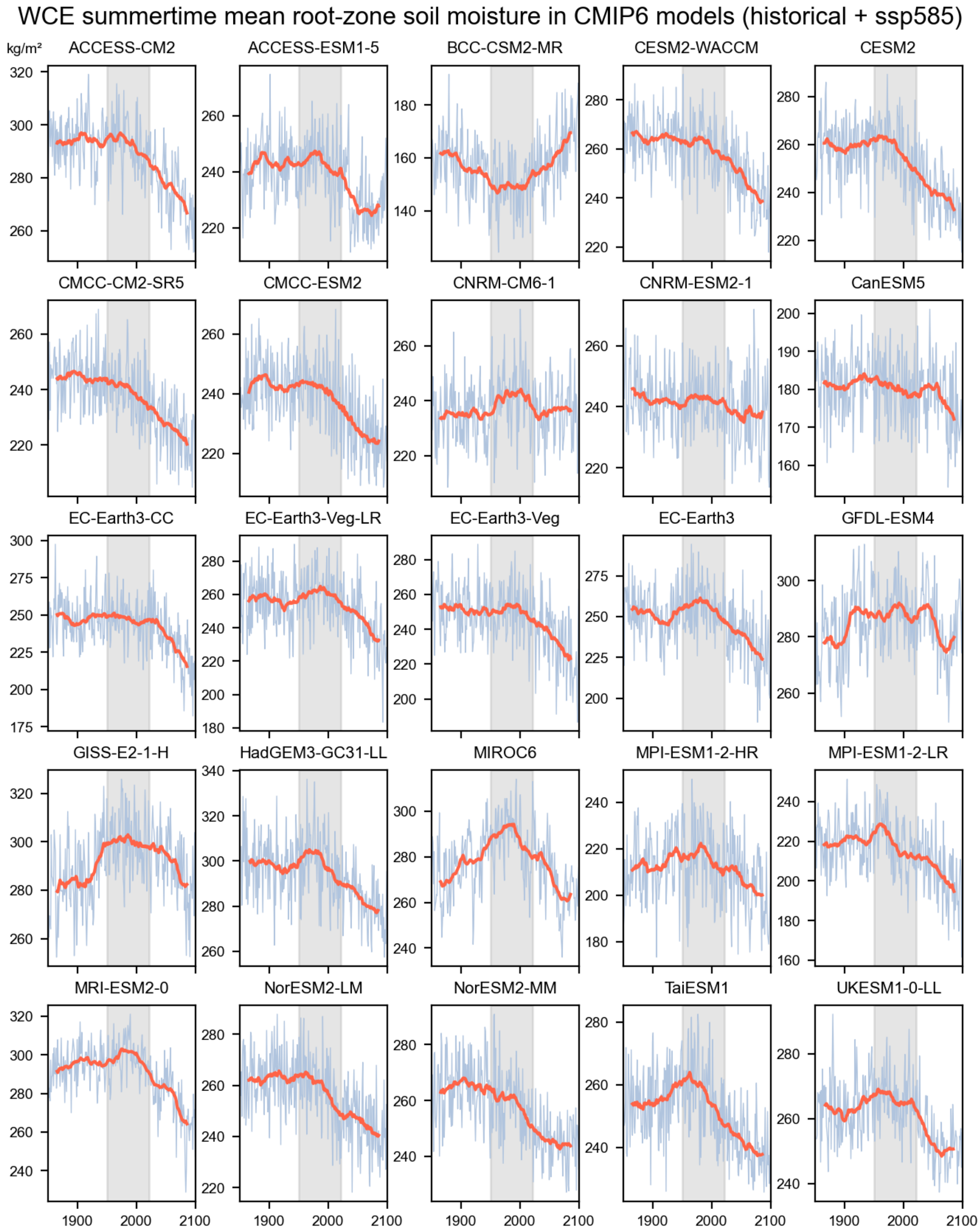


Fig. S6: Mean summer root-zone soil moisture in CMIP6 models across West-Central Europe. Data are shown for the time period of 1850–2100 for each model, combining historical and SSP585 simulations. The observational analysis period of 1950–2022 is highlighted (grey shading), and a 31-year centred moving average is added to visualise the long-term evolution of root-zone soil moisture (red line). Note that KACE-1-0-G, which did not pass the validation and is hence not used for analysis, portrays considerably lower root-zone soil moisture values compared to all other available CMIP6 models, and is hence excluded from this figure.

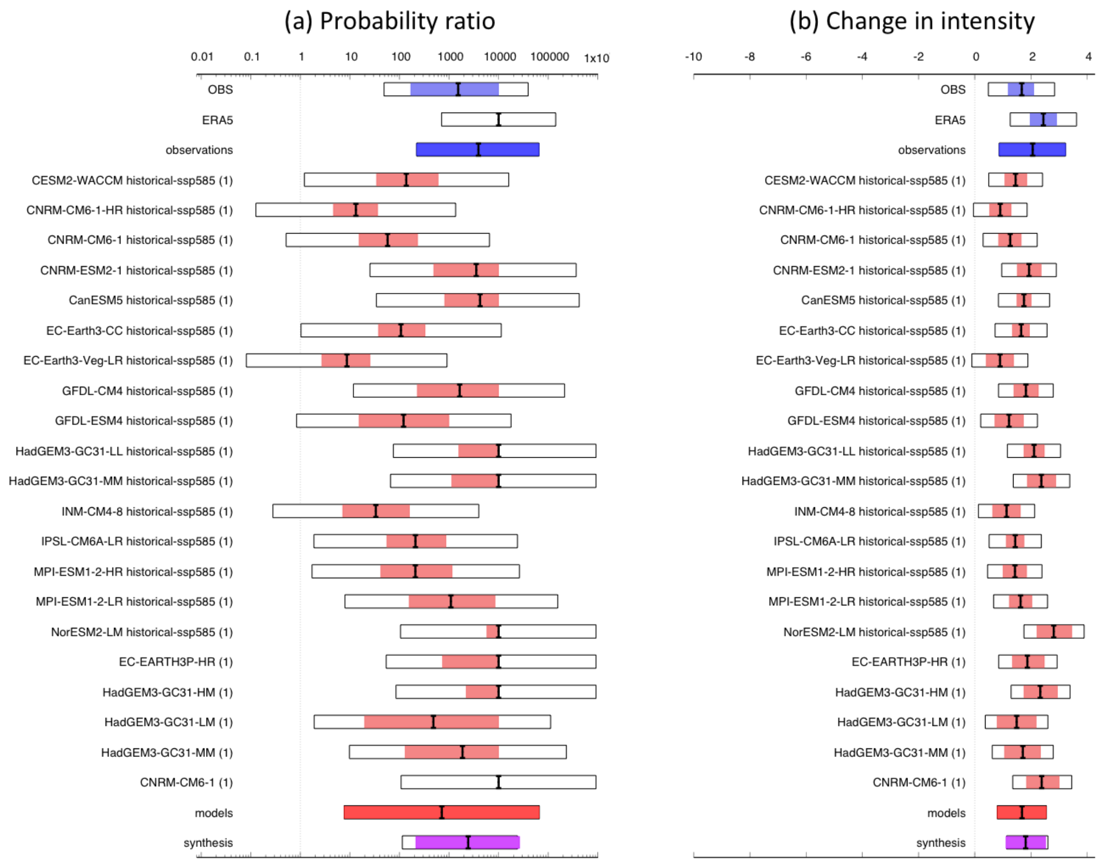


Fig. S7: Synthesis of (a) probability ratios and (b) intensity changes when comparing the return period and magnitudes of the **2022 summer temperature for the WCE region** in the current climate and a 1.2 ºC cooler climate. Note that ‘OBS’ refers to the ‘E-OBS’ dataset.

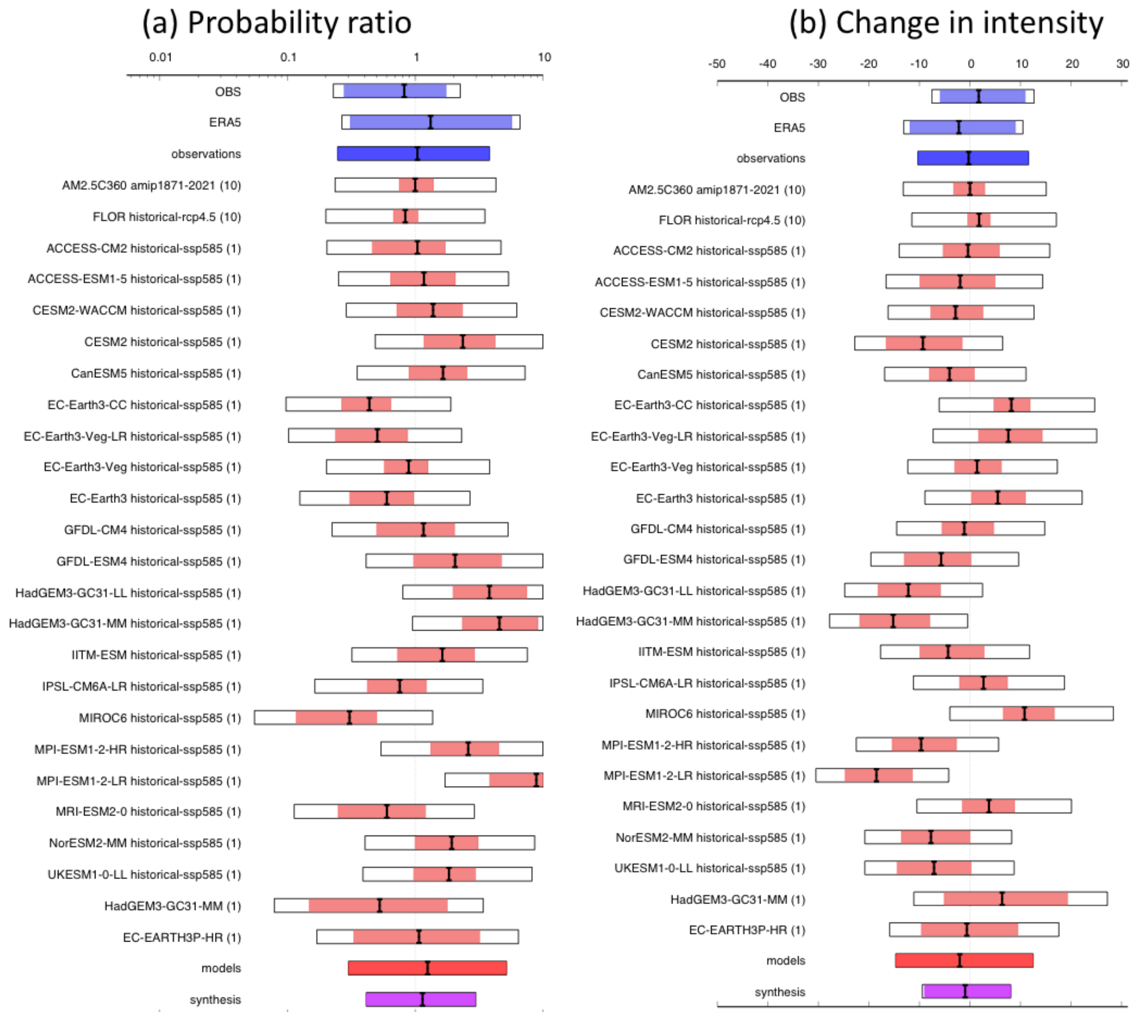


Fig. S8: Synthesis of (a) probability ratios and (b) intensity changes when comparing the return period and magnitudes of the **2022 summer precipitation for the WCE region** in the current and a 1.2 ºC cooler climate. Note that 'OBS' refers to the 'E-OBS' dataset.

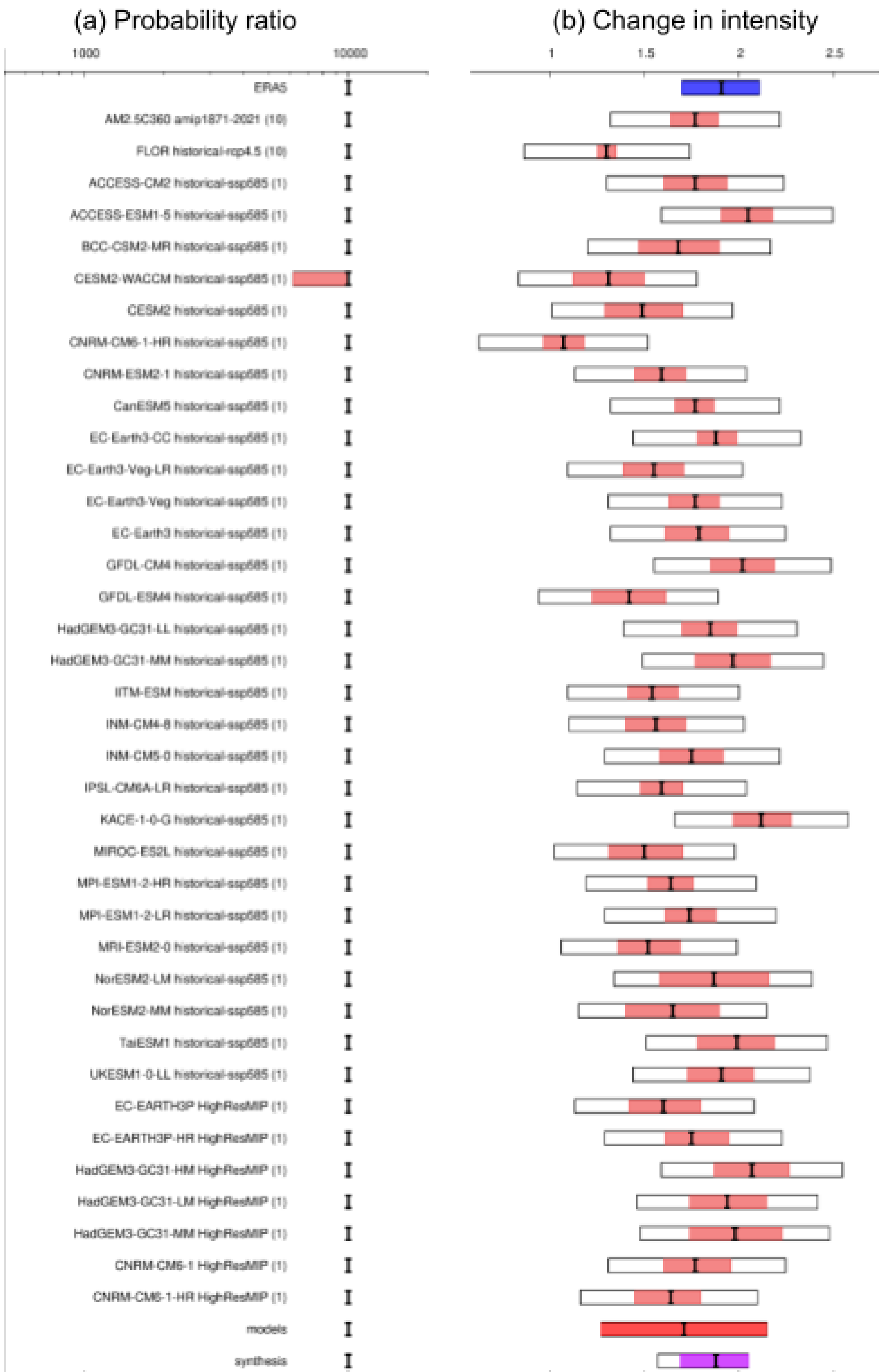


Fig. S9: Synthesis of (a) probability ratios and (b) intensity changes when comparing the return period and magnitudes of the **2022 summer temperature for the NHET region** in the current and a 1.2 ºC cooler climate.

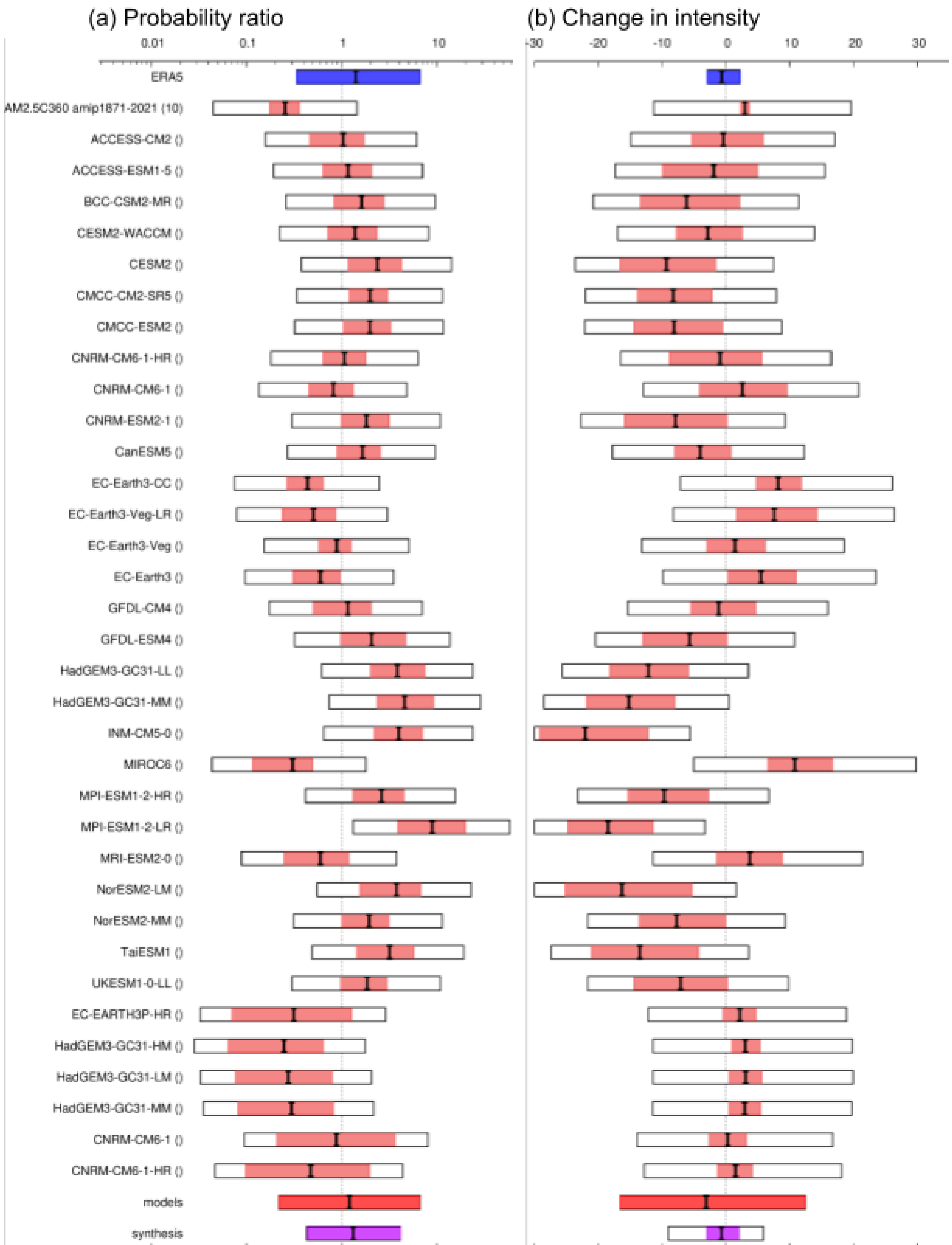


Fig. S10: Synthesis of (a) probability ratios and (b) intensity changes when comparing the return period and magnitudes of the **2022 summer precipitation for the NHET region** in the current and a 1.2 ºC cooler climate.

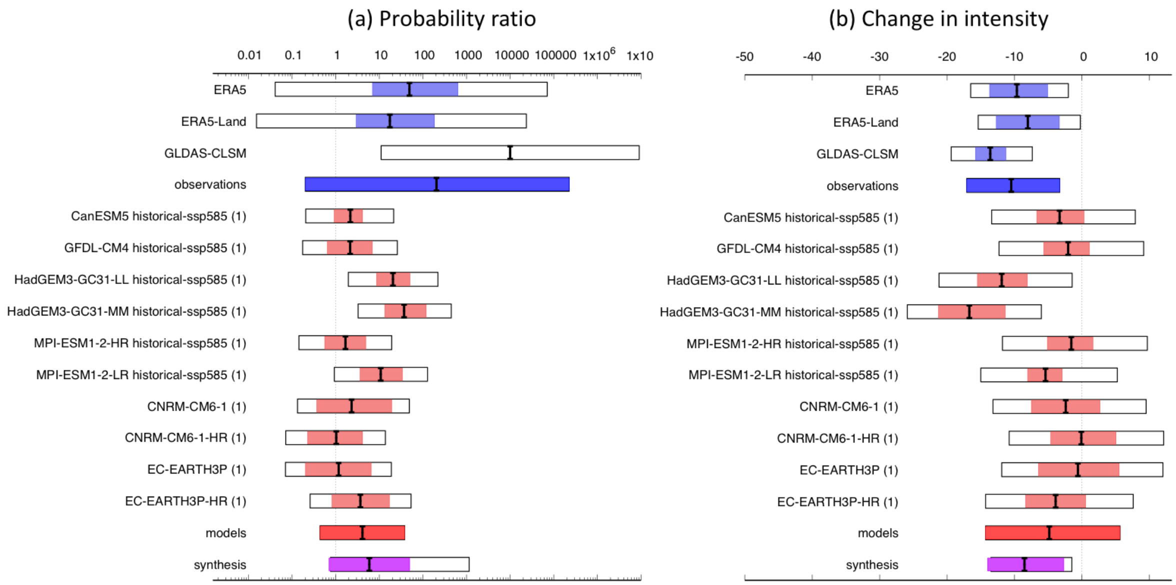


Fig. S11: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer surface soil moisture for the WCE region** in the current climate and a 1.2ºC cooler climate.

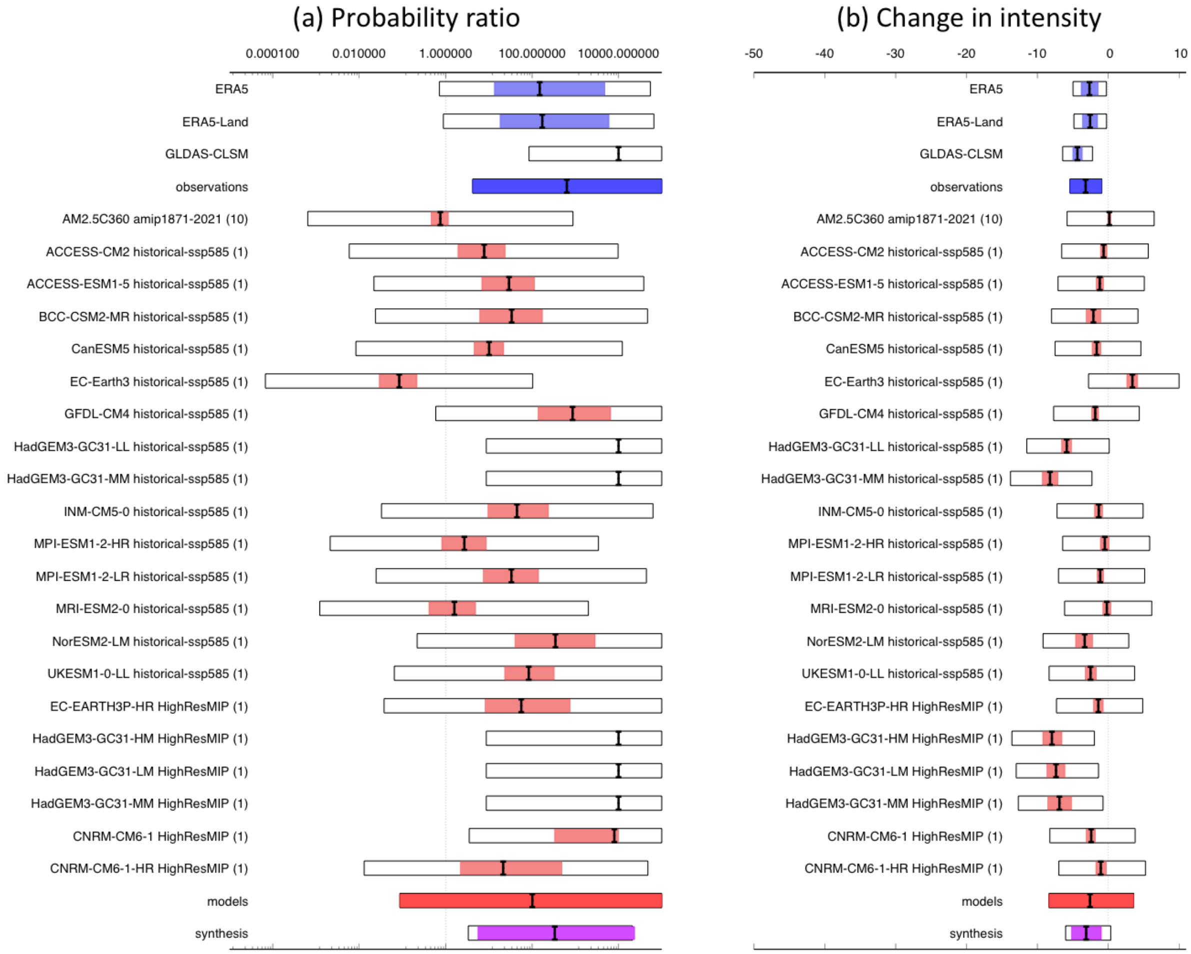


Fig. S12: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer surface soil moisture for the NHET** region in the current climate and a 1.2ºC cooler climate.

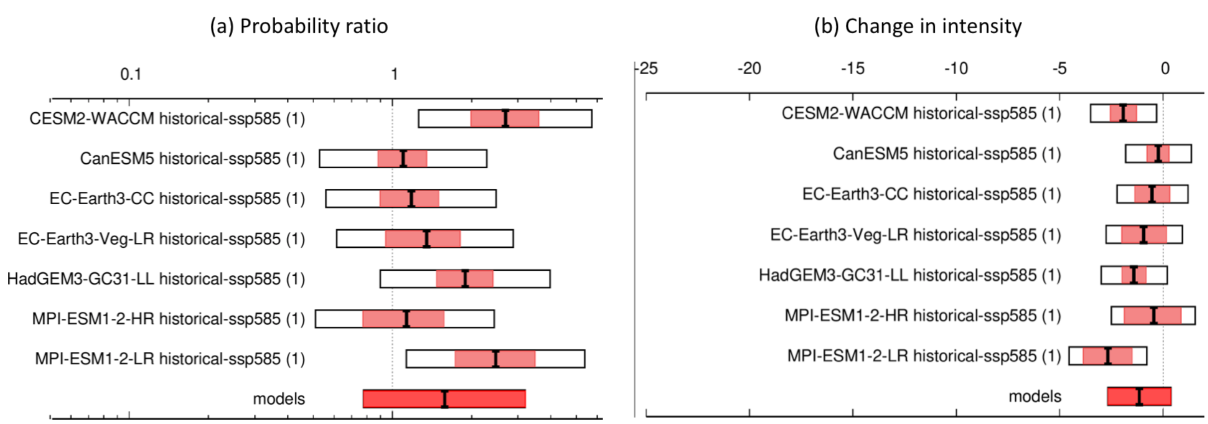


Fig. S13: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer root zone soil moisture for the WCE region** in the current and a **0.8 ºC warmer** climate.

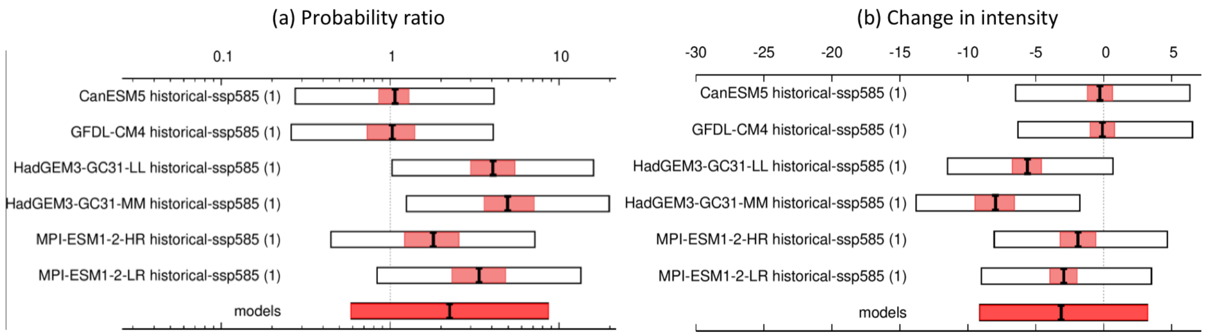


Fig. S14: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer surface soil moisture for the WCE region** in the current climate and a **0.8 ºC warmer** climate.

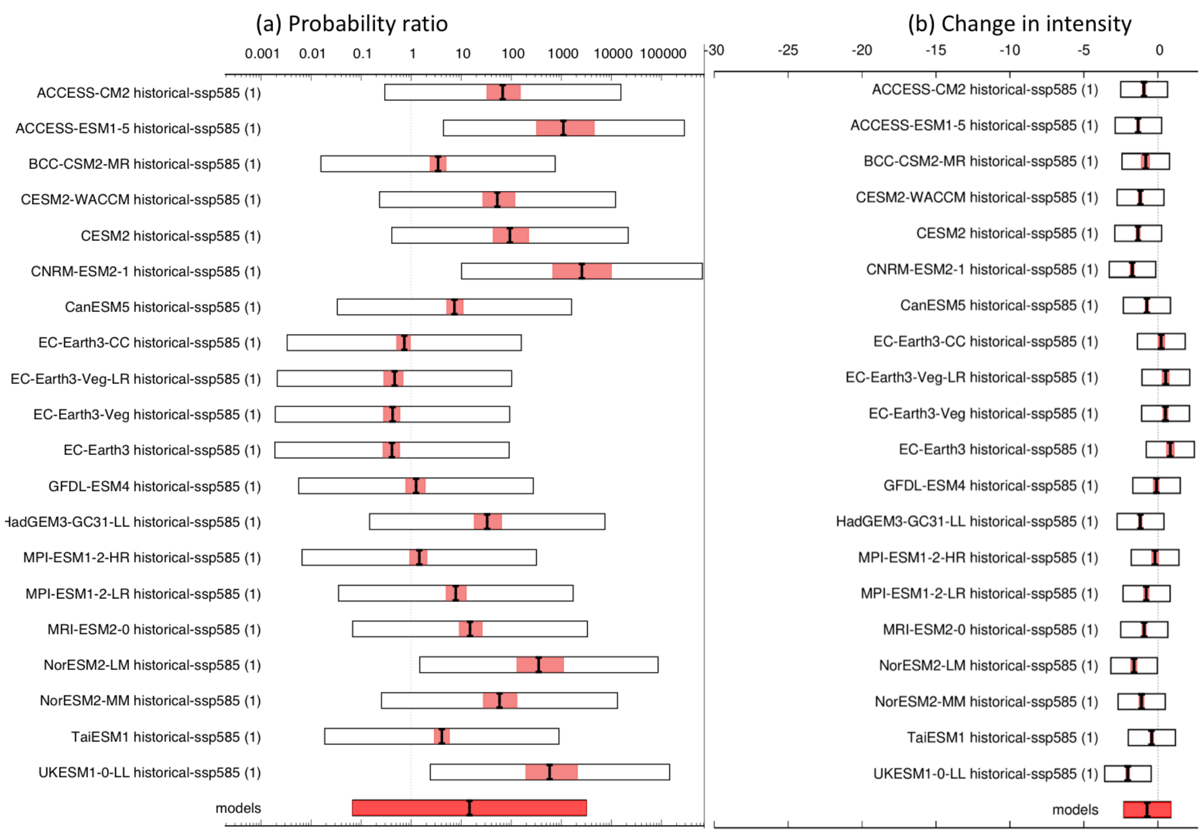


Fig. S15: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer root zone soil moisture for the NHET region** in the current climate and a **0.8 ºC warmer** climate.

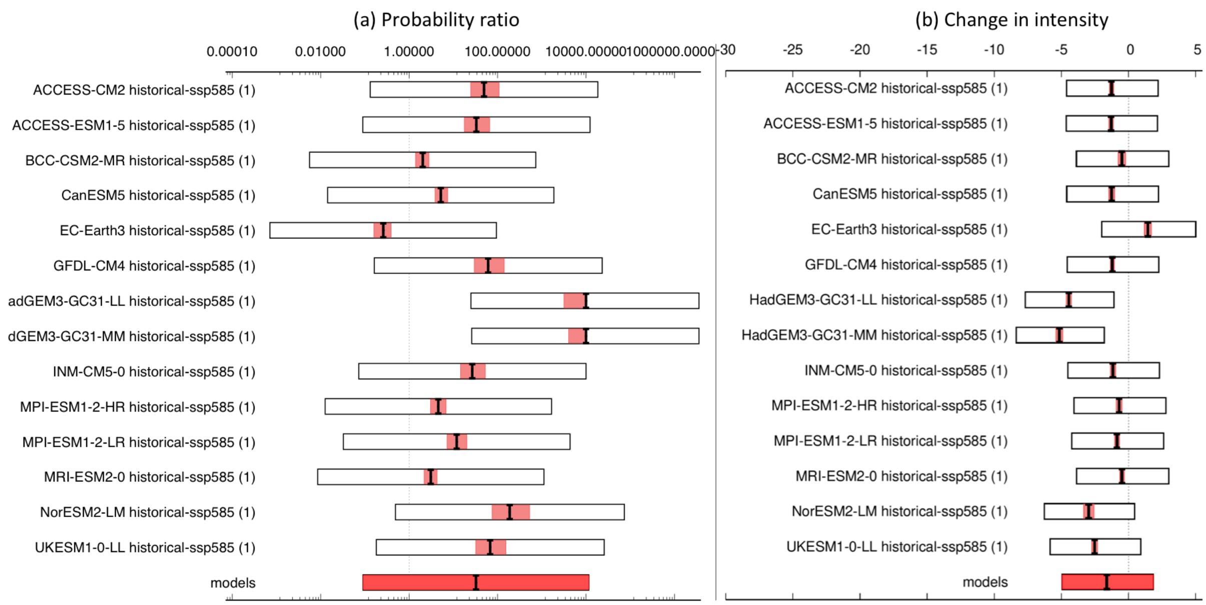


Fig. S16: Synthesis of (a) probability ratios and (b) intensity changes (%) when comparing the return period and magnitudes of the **2022 summer surface soil moisture for the NHET region** in the current climate and a **0.8 ºC warmer** climate.

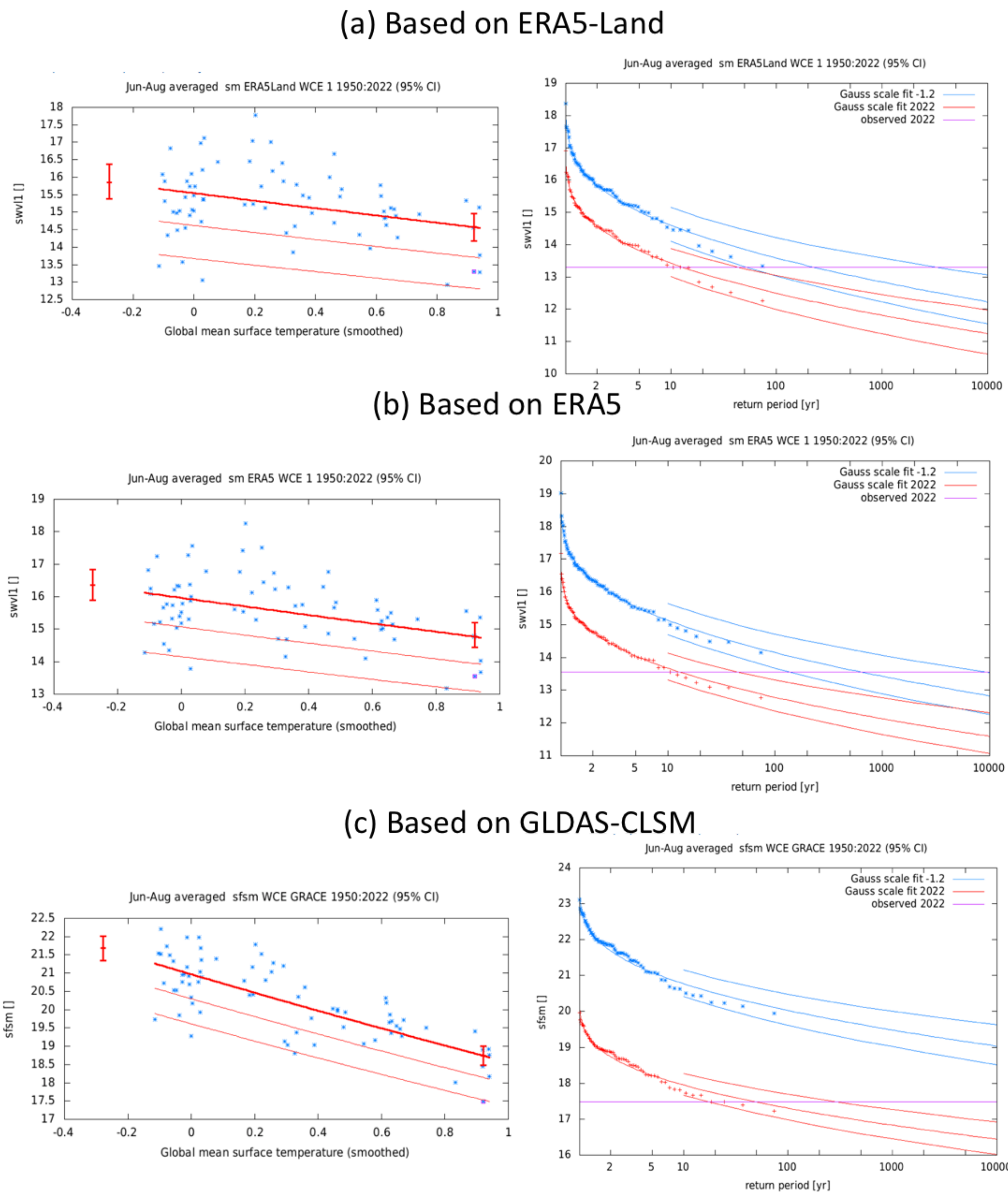


Fig. S17: Summer surface soil moisture in West-Central Europe. Gaussian fit with constant dispersion parameter, and the location parameter scaling proportional to GMST of the index series, for the WCE region based on three gridded datasets; (a) ERA5-Land, (b) ERA5, and (c) GLDAS-CLSM. The 2022 event is included in the fit (1950–2022). **Left**: Observed summer mean surface soil moisture as a function of the smoothed GMST. The thick red line denotes the time-varying location parameter. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2022 climate and a 1.2ºC cooler climate. The 2022 observation is highlighted with the magenta box. **Right**: Return time plots for the climate of 2022 (red) and a climate with GMST 1.2 ºC cooler (blue). The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. The markers show the data and the lines show the fits and uncertainty from the bootstrap. The magenta line shows the magnitude of the 2022 event analysed here.

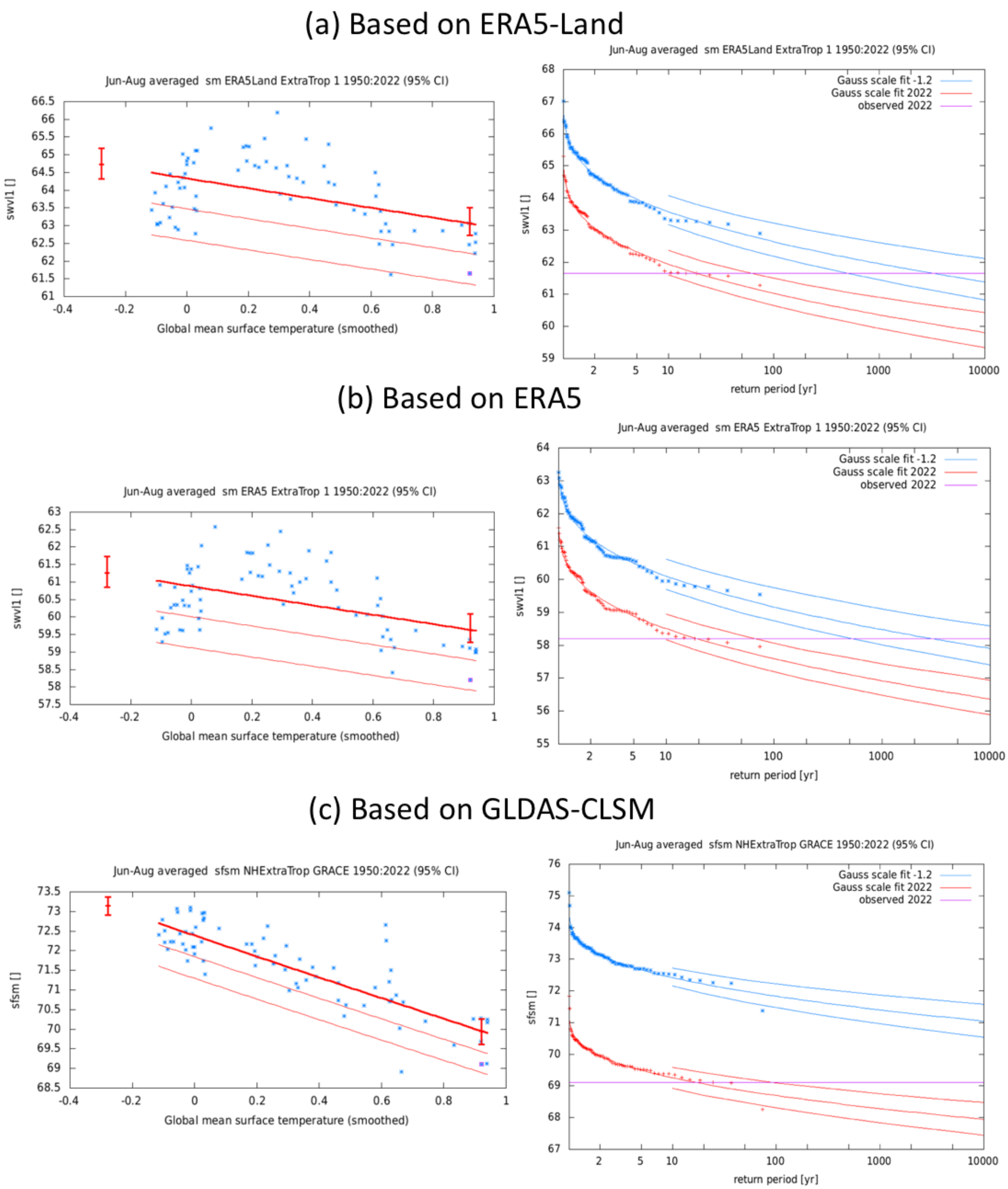


Fig. S18. *same as* Fig. S17, but for the **NHET region**.

Supplementary horizontal tables

Table S1. Evaluation results for the climate models considered for the attribution analysis of summer **root-zone soil moisture for WCE**. The table contains qualitative assessments of seasonal cycle and spatial pattern of precipitation and temperature from the models (good, reasonable, bad) along with estimates for dispersion parameter, shape parameter and event magnitude. The corresponding estimates for observations are shown in blue. The seasonal cycles and spatial patterns for soil moisture are also evaluated, whenever available. Based on overall suitability, the models are classified as good, reasonable and bad, shown by green, yellow and red highlights, respectively.

	Temperature			Precipitation			Root zone soil moisture	
Observations			Sigma			Sigma		
E-OBS			0.656 (0.557 ... 0.746)			0.121 (0.101 ... 0.138)		
ERA5			0.654 (0.549 ... 0.739)			0.125 (0.102 ... 0.144)		
Models	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern
AM2.5C360 amip1871-2021 (10)	reasonable	good	0.838 (0.792 ... 0.880)	reasonable	good	0.142 (0.135 ... 0.149)	<not evaluated>	<not evaluated>
FLOR historical-rcp4.5 (10)	reasonable	good	0.901 (0.851 ... 0.946)	reasonable	good	0.140 (0.132 ... 0.147)	<not evaluated>	<not evaluated>
ACCESS-CM2 historical-ssp585 (1)	reasonable	good	0.917 (0.779 ... 1.09)	reasonable	good	0.131 (0.112 ... 0.154)	reasonable	reasonable
ACCESS-ESM1-5 historical-ssp585 (1)	reasonable	good	0.963 (0.823 ... 1.14)	reasonable	good	0.164 (0.141 ... 0.196)	reasonable	reasonable
BCC-CSM2-MR historical-ssp585 (1)	reasonable	good	1.19 (1.02 ... 1.43)	reasonable	reasonable	0.181 (0.153 ... 0.215)	good	reasonable

CESM2-WACCM historical-ssp585 (1)	reasonable	good	0.858 (0.738 ... 1.03)	reasonable	reasonable	0.147 (0.125 ... 0.178)	good	reasonable
CESM2 historical-ssp585 (1)	reasonable	good	0.955 (0.816 ... 1.13)	reasonable	reasonable	0.162 (0.138 ... 0.194)	good	reasonable
CMCC-CM2-SR5 historical-ssp585 (1)	reasonable	reasonabl e	1.09 (0.934 ... 1.31)	reasonable	reasonable	0.174 (0.147 ... 0.207)	reasonable	reasonable
CMCC-ESM2 historical-ssp585 (1)	reasonable	good	1.12 (0.951 ... 1.34)	reasonable	reasonable	0.188 (0.162 ... 0.227)	reasonable	reasonable
CNRM-CM6-1 historical-ssp585 (1)	good	good	0.803 (0.686 ... 0.956)	reasonable	reasonable	0.178 (0.150 ... 0.214)	reasonable	reasonable
CNRM-ESM2-1 historical-ssp585 (1)	good	good	0.835 (0.711 ... 1.00)	reasonable	reasonable	0.190 (0.162 ... 0.228)	reasonable	reasonable
CanESM5 historical-ssp585 (1)	reasonable	good	0.751 (0.642 ... 0.893)	good	good	0.135 (0.116 ... 0.163)	reasonable	reasonable
EC-Earth3-CC historical-ssp585 (1)	good	good	0.865 (0.738 ... 1.03)	reasonable	good	0.145 (0.122 ... 0.175)	good	good
EC-Earth3-Veg-LR historical-ssp585 (1)	good	good	0.778 (0.661 ... 0.928)	reasonable	good	0.123 (0.107 ... 0.147)	reasonable	good
EC-Earth3-Veg historical-ssp585 (1)	good	good	0.874 (0.748 ... 1.04)	reasonable	good	0.154 (0.133 ... 0.187)	reasonable	good
EC-Earth3 historical-ssp585 (1)	reasonable	good	0.930 (0.795 ... 1.10)	reasonable	good	0.133 (0.113 ... 0.159)	reasonable	good
GFDL-CM4 historical-ssp585 (1)	good	good	0.746 (0.640 ... 0.887)	good	good	0.101 (0.0870 ... 0.120)	reasonable	bad
HadGEM3-GC31-LL historical-ssp585 (1)	reasonable	good	0.756 (0.640 ... 0.898)	reasonable	good	0.138 (0.118 ... 0.167)	reasonable	good
KACE-1-0-G historical-ssp585 (1)	reasonable	bad	1.06 (0.906 ... 1.27)	bad	bad	0.264 (0.223 ... 0.319)	bad	bad
MIROC6 historical-ssp585 (1)	reasonable	bad	0.681 (0.578 ... 0.818)	reasonable	reasonable	0.119 (0.101 ... 0.141)	reasonable	reasonable

MPI-ESM1-2-HR historical-ssp585 (1)	good	good	0.746 (0.637 ... 0.895)	reasonable	good	0.161 (0.138 ... 0.195)	good	good
MPI-ESM1-2-LR historical-ssp585 (1)	good	good	0.756 (0.646 ... 0.898)	reasonable	good	0.133 (0.113 ... 0.158)	good	good
MRI-ESM2-0 historical-ssp585 (1)	good	good	0.634 (0.540 ... 0.747)	good	good	0.106 (0.0900 ... 0.126)	reasonable	bad
NorESM2-LM historical-ssp585 (1)	reasonable	good	0.838 (0.721 ... 0.997)	reasonable	reasonable	0.183 (0.155 ... 0.222)	good	reasonable
NorESM2-MM historical-ssp585 (1)	reasonable	good	1.05 (0.900 ... 1.25)	reasonable	reasonable	0.165 (0.138 ... 0.197)	reasonable	reasonable
TaiESM1 historical-ssp585 (1)	reasonable	good	0.969 (0.829 ... 1.16)	reasonable	reasonable	0.180 (0.155 ... 0.214)	bad	reasonable
UKESM1-0-LL historical-ssp585 (1)	good	good	0.916 (0.779 ... 1.09)	reasonable	good	0.149 (0.127 ... 0.180)	reasonable	reasonable

Table S2. Evaluation results for the climate models considered for the attribution analysis of summer **root zone soil moisture for NHET**. The table contains qualitative assessments of seasonal cycle and spatial pattern of precipitation and temperature from the models (good, reasonable, bad) along with estimates for dispersion parameter, shape parameter and event magnitude. The corresponding estimates for observations are shown in blue. The seasonal cycles and spatial patterns for soil moisture are also evaluated, whenever available. Based on overall suitability, the models are classified as good, reasonable and bad, shown by green, yellow and red highlights, respectively.

	Temperature			Precipitation			Root zone soil moisture	
Observations			Sigma			Sigma		
E-OBS			0.656 (0.557 ... 0.746)			0.121 (0.101 ... 0.138)		
ERA5			0.654 (0.549 ... 0.739)			0.125 (0.102 ... 0.144)		
Models	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern
AM2.5C360 amip1871-2021 (10)	reasonable	good	0.838 (0.792 ... 0.880)	good	good	0.0290 (0.0280 ... 0.0310)	<not evaluated>	<not evaluated>
FLOR historical-rcp45 (10)	reasonable	good	0.901 (0.851 ... 0.946)	good	good	0.0240 (0.0230 ... 0.0250)	<not evaluated>	<not evaluated>
ACCESS-CM2 historical-ssp585 (1)	reasonable	good	0.917 (0.779 ... 1.09)	good	good	0.0340 (0.0290 ... 0.0410)	reasonable	good

ACCESS-ESM1-5 historical-ssp585 (1)	reasonable	good	0.963 (0.823 ... 1.14)	good	reasonable	0.0240 (0.0210 ... 0.0290)	reasonable	reasonable
BCC-CSM2-MR historical-ssp585 (1)	reasonable	good	1.19 (1.02 ... 1.43)	good	reasonable	0.0290 (0.0240 ... 0.0340)	reasonable	reasonable
CESM2-WACCM historical-ssp585 (1)	reasonable	good	0.858 (0.738 ... 1.03)	good	good	0.0310 (0.0260 ... 0.0370)	reasonable	reasonable
CESM2 historical-ssp585 (1)	reasonable	good	0.955 (0.816 ... 1.13)	good	good	0.0320 (0.0270 ... 0.0380)	reasonable	good
CMCC-CM2-SR5 historical-ssp585 (1)	reasonable	reasonabl e	1.09 (0.934 ... 1.31)	good	good	0.0250 (0.0210 ... 0.0290)	reasonable	good
CMCC-ESM2 historical-ssp585 (1)	reasonable	good	1.12 (0.951 ... 1.34)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	good
CNRM-CM6-1 historical-ssp585 (1)	good	good	0.835 (0.711 ... 1.00)	good	good	0.0220 (0.0180 ... 0.0260)	reasonable	good
CNRM-ESM2-1 historical-ssp585 (1)	good	reasonabl e	0.687 (0.591 ... 0.818)	good	good	0.0260 (0.0220 ... 0.0310)	reasonable	reasonable
CanESM5 historical-ssp585 (1)	reasonable	good	0.751 (0.642 ... 0.893)	good	good	0.0290 (0.0250 ... 0.0340)	good	good
EC-Earth3-CC historical-ssp585 (1)	good	good	0.865 (0.738 ... 1.03)	good	good	0.0230 (0.0190 ... 0.0270)	good	good
EC-Earth3-Veg-LR historical-ssp585 (1)	good	good	0.778 (0.661 ... 0.928)	good	good	0.0260 (0.0220 ... 0.0300)	good	good
EC-Earth3-Veg historical-ssp585 (1)	good	good	0.874 (0.748 ... 1.04)	good	good	0.0220 (0.0190 ... 0.0270)	good	good
EC-Earth3 historical-ssp585 (1)	reasonable	good	0.930 (0.795 ... 1.10)	good	good	0.0210 (0.0180 ... 0.0260)	good	good
GFDL-ESM4 historical-ssp585 (1)	good	good	0.625 (0.538 ... 0.746)	good	good	0.0240 (0.0210 ... 0.0290)	reasonable	reasonable
HadGEM3-GC31-LL historical-ssp585 (1)	reasonable	good	0.756 (0.640 ... 0.898)	good	good	0.0280 (0.0240 ... 0.0330)	bad	bad

KACE-1-0-G historical-ssp585 (1)	reasonable	bad	1.06 (0.906 ... 1.27)	bad	reasonable	0.0380 (0.0320 ... 0.0440)	reasonable	reasonable
MIROC6 historical-ssp585 (1)	reasonable	bad	0.681 (0.578 ... 0.818)	good	good	0.0220 (0.0190 ... 0.0260)	reasonable	reasonable
MPI-ESM1-2-LR historical-ssp585 (1)	good	good	0.756 (0.646 ... 0.898)	reasonabl e	good	0.0230 (0.0200 ... 0.0280)	reasonable	reasonable
MRI-ESM2-0 historical-ssp585 (1)	good	good	0.634 (0.540 ... 0.747)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	good
NorESM2-LM historical-ssp585 (1)	reasonable	good	0.838 (0.721 ... 0.997)	good	good	0.0300 (0.0260 ... 0.0360)	reasonable	reasonable
NorESM2-MM historical-ssp585 (1)	reasonable	good	1.05 (0.900 ... 1.25)	good	good	0.0310 (0.0260 ... 0.0370)	reasonable	reasonable
TaiESM1 historical-ssp585 (1)	reasonable	good	0.969 (0.829 ... 1.16)	good	good	0.0250 (0.0210 ... 0.0300)	reasonable	good
UKESM1-0-LL historical-ssp585 (1)	good	good	0.916 (0.779 ... 1.09)	good	good	0.0340 (0.0290 ... 0.0400)	reasonable	reasonable

Table S3 Evaluation results for the climate models considered for the attribution analysis of summer **surface soil moisture for WCE**. The table contains qualitative assessments of seasonal cycle and spatial pattern of precipitation and temperature from the models (good, reasonable, bad) along with estimates for dispersion parameter, shape parameter and event magnitude. The corresponding estimates for observations are shown in blue. The seasonal cycles and spatial patterns for soil moisture are also evaluated, whenever available. Based on overall suitability, the models are classified as good, reasonable and bad, shown by green, yellow and red highlights, respectively.

	Temperature			Precipitation			Surface soil moisture	
Observations			Sigma			Sigma		
E-OBS			0.656 (0.557 ... 0.746)			0.121 (0.101 ... 0.138)		
ERA5			0.654 (0.549 ... 0.739)			0.125 (0.102 ... 0.144)		
Models	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern
AM2.5C360 amip1871-2021 (10)	reasonable	good	0.838 (0.792 ... 0.880)	reasonabl e	good	0.142 (0.135 ... 0.149)	<not evaluated>	<not evaluated>
FLOR historical-rcp4.5 (10)	reasonable	good	0.901 (0.851 ... 0.946)	reasonabl e	good	0.140 (0.132 ... 0.147)	<not evaluated>	<not evaluated>
ACCESS-CM2 historical-ssp585 (1)	reasonable	good	0.917 (0.779 ... 1.09)	reasonabl e	good	0.131 (0.112 ... 0.154)	reasonable	reasonable
ACCESS-ESM1-5 historical-ssp585 (1)	reasonable	good	0.963 (0.823 ... 1.14)	reasonabl e	good	0.164 (0.141 ... 0.196)	reasonable	bad
BCC-CSM2-MR historical-ssp585 (1)	reasonable	good	1.19 (1.02 ... 1.43)	reasonabl e	reasonable	0.181 (0.153 ... 0.215)	reasonable	reasonable

CMCC-CM2-SR5 historical-ssp585 (1)	reasonable	reasonabl e	1.09 (0.934 ... 1.31)	reasonabl e	reasonable	0.174 (0.147 ... 0.207)	reasonable	reasonable
CMCC-ESM2 historical-ssp585 (1)	reasonable	good	1.12 (0.951 ... 1.34)	reasonabl e	reasonable	0.188 (0.162 ... 0.227)	reasonable	reasonable
CanESM5 historical-ssp585 (1)	reasonable	good	0.751 (0.642 ... 0.893)	good	good	0.135 (0.116 ... 0.163)	reasonable	reasonable
EC-Earth3 historical-ssp585 (1)	reasonable	good	0.930 (0.795 ... 1.10)	reasonabl e	good	0.133 (0.113 ... 0.159)	reasonable	good
GFDL-CM4 historical-ssp585 (1)	good	good	0.746 (0.640 ... 0.887)	good	good	0.101 (0.0870 ... 0.120)	reasonable	reasonable
HadGEM3-GC31-LL historical-ssp585 (1)	reasonable	good	0.756 (0.640 ... 0.898)	reasonabl e	good	0.138 (0.118 ... 0.167)	reasonable	good
HadGEM3-GC31-MM historical-ssp585 (1)	reasonable	good	0.813 (0.695 ... 0.978)	reasonabl e	good	0.146 (0.125 ... 0.174)	reasonable	good
IITM-ESM historical-ssp585 (1)	good	reasonabl e	0.870 (0.749 ... 1.03)	reasonabl e	good	0.138 (0.117 ... 0.164)	reasonable	bad
INM-CM4-8 historical-ssp585 (1)	reasonable	bad	0.799 (0.684 ... 0.953)	bad	reasonable	0.228 (0.194 ... 0.277)	reasonable	bad
INM-CM5-0 historical-ssp585 (1)	good	reasonabl e	0.895 (0.768 ... 1.07)	bad	reasonable	0.209 (0.178 ... 0.251)	reasonable	bad
IPSL-CM6A-LR historical-ssp585 (1)	good	good	0.706 (0.602 ... 0.842)	reasonabl e	good	0.126 (0.108 ... 0.150)	reasonable	bad (very patchy)
KACE-1-0-G historical-ssp585 (1)	reasonable	bad	1.06 (0.906 ... 1.27)	bad	bad	0.264 (0.223 ... 0.319)	bad	bad
MIROC6 historical-ssp585 (1)	reasonable	bad	0.681 (0.578 ... 0.818)	reasonabl e	reasonable	0.119 (0.101 ... 0.141)	reasonable	reasonable
MIROC-ES2L historical-ssp585 (1)	reasonable	bad	0.634 (0.542 ... 0.759)	reasonabl e	bad	0.104 (0.0890 ... 0.124)	reasonable	reasonable
MPI-ESM1-2-HR historical-ssp585 (1)	good	good	0.746 (0.637 ... 0.895)	reasonabl e	good	0.161 (0.138 ... 0.195)	reasonable	good

MPI-ESM1-2-LR historical-ssp585 (1)	good	good	0.756 (0.646 ... 0.898)	reasonable	good	0.133 (0.113 ... 0.158)	reasonable	good
NorESM2-LM historical-ssp585 (1)	reasonable	good	0.838 (0.721 ... 0.997)	reasonable	reasonable	0.183 (0.155 ... 0.222)	reasonable	bad
TaiESM1 historical-ssp585 (1)	reasonable	good	0.969 (0.829 ... 1.16)	reasonable	reasonable	0.180 (0.155 ... 0.214)	reasonable	reasonable
UKESM1-0-LL historical-ssp585 (1)	good	good	0.916 (0.779 ... 1.09)	reasonable	good	0.149 (0.127 ... 0.180)	reasonable	reasonable
EC-EARTH3P (1)	good	good	0.771 (0.644 ... 0.863)	reasonable	good	0.0710 (0.0590 ... 0.0790)	reasonable	<not evaluated>
EC-EARTH3P-HR (1)	good	good	0.659 (0.560 ... 0.748)	good	good	0.128 (0.0180 ... 0.144)	reasonable	<not evaluated>
HadGEM3-GC31-HM (1)	good	good	0.734 (0.616 ... 0.826)	good	good	0.149 (0.123 ... 0.171)	good	<not evaluated>
HadGEM3-GC31-MM (1)	good	good	0.712 (0.614 ... 0.786)	good	good	0.131 (0.110 ... 0.147)	good	<not evaluated>
CNRM-CM6-1-HR (1)	good	good	0.769 (0.650 ... 0.873)	good	good	0.185 (0.153 ... 0.212)	good	<not evaluated>

Table S4. Evaluation results for the climate models considered for the attribution analysis of summer **surface soil moisture for NHET region**. The table contains qualitative assessments of seasonal cycle and spatial pattern of precipitation and temperature from the models (good, reasonable, bad) along with estimates for dispersion parameter, shape parameter and event magnitude. The corresponding estimates for observations are shown in blue. The seasonal cycles and spatial patterns for soil moisture are also evaluated, whenever available. Based on overall suitability, the models are classified as good, reasonable and bad, shown by green, yellow and red highlights, respectively.

	Temperature			Precipitation			Root zone soil moisture	
Observations			Sigma			Sigma		

E-OBS			0.656 (0.557 ... 0.746)			0.121 (0.101 ... 0.138)		
ERA5			0.654 (0.549 ... 0.739)			0.125 (0.102 ... 0.144)		
Models	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern	Sigma	Seasonal cycle	Spatial pattern
AM2.5C360 amip1871-2021 (10)	reasonable	good	0.838 (0.792 ... 0.880)	good	good	0.0290 (0.0280 ... 0.0310)	<not evaluated>	<not evaluated>
FLOR historical-rcp45 (10)	reasonable	good	0.901 (0.851 ... 0.946)	good	good	0.0240 (0.0230 ... 0.0250)	<not evaluated>	<not evaluated>
ACCESS-CM2 historical-ssp585 (1)	reasonable	good	0.917 (0.779 ... 1.09)	good	good	0.0340 (0.0290 ... 0.0410)	reasonable	good
ACCESS-ESM1-5 historical-ssp585 (1)	reasonable	good	0.963 (0.823 ... 1.14)	good	reasonable	0.0240 (0.0210 ... 0.0290)	reasonable	reasonable
BCC-CSM2-MR historical-ssp585 (1)	reasonable	good	1.19 (1.02 ... 1.43)	good	reasonable	0.0290 (0.0240 ... 0.0340)	good	reasonable
CMCC-CM2-SR5 historical-ssp585 (1)	reasonable	reasonabl e	1.09 (0.934 ... 1.31)	good	good	0.0250 (0.0210 ... 0.0290)	reasonable	reasonable
CMCC-ESM2 historical-ssp585 (1)	reasonable	good	1.12 (0.951 ... 1.34)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	reasonable
CanESM5 historical-ssp585 (1)	reasonable	good	0.751 (0.642 ... 0.893)	good	good	0.0290 (0.0250 ... 0.0340)	good	reasonable
EC-Earth3 historical-ssp585 (1)	reasonable	good	0.930 (0.795 ... 1.10)	good	good	0.0210 (0.0180 ... 0.0260)	reasonable	good
GFDL-CM4 historical-ssp585 (1)	good	good	0.746 (0.640 ... 0.887)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	reasonable
HadGEM3-GC31-LL historical-ssp585 (1)	reasonable	good	0.756 (0.640 ... 0.898)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	good
HadGEM3-GC31-MM historical-ssp585 (1)	reasonable	good	0.813 (0.695 ... 0.978)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	good

INM-CM4-8 historical-ssp585 (1)	reasonable	bad	0.799 (0.684 ... 0.953)	reasonable	good	0.0210 (0.0180 ... 0.0250)	reasonable	reasonable
INM-CM5-0 historical-ssp585 (1)	good	reasonable	0.895 (0.768 ... 1.07)	reasonable	good	0.0230 (0.0200 ... 0.0270)	reasonable	reasonable
IPSL-CM6A-LR historical-ssp585 (1)	good	good	0.706 (0.602 ... 0.842)	good	good	0.0190 (0.0160 ... 0.0230)	reasonable	bad
KACE-1-0-G historical-ssp585 (1)	reasonable	bad	1.06 (0.906 ... 1.27)	bad	reasonable	0.0380 (0.0320 ... 0.0440)	reasonable	bad
MIROC6 historical-ssp585 (1)	reasonable	bad	0.681 (0.578 ... 0.818)	good	good	0.0220 (0.0190 ... 0.0260)	reasonable	reasonable
MIROC-ES2L historical-ssp585 (1)	reasonable	bad	0.634 (0.542 ... 0.759)	good	reasonable	0.0200 (0.0170 ... 0.0240)	reasonable	reasonable
MPI-ESM1-2-HR historical-ssp585 (1)	good	good	0.746 (0.637 ... 0.895)	good	good	0.0280 (0.0230 ... 0.0320)	reasonable	good
MPI-ESM1-2-LR historical-ssp585 (1)	good	good	0.756 (0.646 ... 0.898)	reasonable	good	0.0230 (0.0200 ... 0.0280)	reasonable	good
MRI-ESM2-0 historical-ssp585 (1)	good	good	0.634 (0.540 ... 0.747)	good	good	0.0280 (0.0240 ... 0.0330)	reasonable	good
NorESM2-LM historical-ssp585 (1)	reasonable	good	0.838 (0.721 ... 0.997)	good	good	0.0300 (0.0260 ... 0.0360)	reasonable	reasonable
NorESM2-MM historical-ssp585 (1)	reasonable	good	1.05 (0.900 ... 1.25)	good	good	0.0310 (0.0260 ... 0.0370)	reasonable	good
UKESM1-0-LL historical-ssp585 (1)	good	good	0.916 (0.779 ... 1.09)	good	good	0.0340 (0.0290 ... 0.0400)	reasonable	good
EC-EARTH3P (1)	good	good	0.771 (0.644 ... 0.863)	good	good	0.0250 (0.0210 ... 0.0280)	good	<not evaluated>
EC-EARTH3P-HR (1)	good	good	0.659 (0.560 ... 0.748)	good	good	0.0270 (0.0210 ... 0.0310)	good	<not evaluated>
HadGEM3-GC31-HM (1)	good	good	0.734 (0.616 ... 0.826)	good	good	0.0280 (0.0230 ... 0.0330)	good	<not evaluated>

HadGEM3-GC31-LM (1)	good	good	0.720 (0.593 ... 0.828)	good	good	0.0320 (0.0270 ... 0.0360)	good	<not evaluated>
HadGEM3-GC31-MM (1)	good	good	0.712 (0.614 ... 0.786)	good	good	0.0330 (0.0270 ... 0.0380)	good	<not evaluated>
CNRM-CM6-1 (1)	good	good	0.640 (0.525 ... 0.733)	good	good	0.0370 (0.0280 ... 0.0450)	good	<not evaluated>
CNRM-CM6-1-HR (1)	good	good	0.769 (0.650 ... 0.873)	good	good	0.0300 (0.0250 ... 0.0340)	good	<not evaluated>

Supplementary tables

The tables presented below list all probability ratios and intensity changes calculated from observation-based estimates and validated models for summer root-zone and surface soil moisture of West-Central Europe and the northern extratropics. The results compare present conditions to a 1.2 ºC cooler climate, corresponding to the late 19th century, and hence convey the impact of anthropogenic climate change on soil moisture.

Table S5. Probability Ratio (PR) and change in intensity (ΔI) of the 2022 mean summer **root zone soil moisture in the WCE region** between the current climate and the pre-industrial climate, from the observation-based datasets and the models that passed validation. This event is defined as a 1-in-20 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
ERA5-Land	30 (4.3 ... 451)	-8.6 (-12.9 ... -3.9)
GLDAS-CLSM	8.1e+6 (9.1e+4 ... 2.9e+10)	-13.7 (-16.0 ... -11.5)
CESM2-WACCM historical-ssp585 (1)	4.8 (1.7 ... 11.6)	-2.9 (-4.8 ... -0.9)
CanESM5 historical-ssp585 (1)	2.3 (1.2 ... 4.4)	-1.9 (-3.5 ... -0.3)
EC-Earth3-CC historical-ssp585 (1)	1.1 (0.6 ... 1.9)	-0.4 (-2.2 ... 1.4)
EC-Earth3-Veg-LR historical-ssp585 (1)	0.7 (0.2 ... 1.5)	1.1 (-1.3 ... 4.3)
HadGEM3-GC31-LL historical-ssp585 (1)	5.5 (2.0 ... 12.7)	-3.6 (-5.7 ... -1.4)
MPI-ESM1-2-HR historical-ssp585 (1)	0.8 (0.3 ... 2.1)	0.9 (-2.9 ... 4.4)
MPI-ESM1-2-LR historical-ssp585 (1)	7.6 (2.9 ... 21.3)	-5.7 (-9.0 ... -2.9)

Table S6. Probability Ratio (PR) and change in intensity of the 2022 summer mean **temperature in the WCE region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-20 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
E-OBS	1.5e+3 (1.7e+2 ... 3.3e+4)	1.7 (1.2 ... 2.1)
ERA5	5.2e+5 (2.2e+4 ... 1.8e+8)	2.4 (2.0 ... 2.9)
CESM2-WACCM historical-ssp585 (1)	1.4e+2 (34 ... 6.0e+2)	1.4 (1.1 ... 1.9)
CNRM-CM6-1-HR historical-ssp585 (1)	13 (4.6 ... 36)	0.91 (0.53 ... 1.3)
CNRM-CM6-1 historical-ssp585 (1)	58 (15 ... 2.3e+2)	1.3 (0.85 ... 1.6)
CNRM-ESM2-1 historical-ssp585 (1)	3.5e+3 (4.9e+2 ... 2.9e+4)	1.9 (1.5 ... 2.4)
CanESM5 historical-ssp585 (1)	4.2e+3 (8.2e+2 ... 2.9e+4)	1.7 (1.5 ... 2.0)
EC-Earth3-CC historical-ssp585 (1)	1.1e+2 (38 ... 3.3e+2)	1.6 (1.3 ... 1.9)
EC-Earth3-Veg-LR historical-ssp585 (1)	8.7 (2.7 ... 25)	0.90 (0.41 ... 1.4)
GFDL-CM4 historical-ssp585 (1)	1.6e+3 (2.3e+2 ... 1.4e+4)	1.8 (1.4 ... 2.3)

GFDL-ESM4 historical-ssp585 (1)	1.2e+2 (15 ... 9.9e+2)	1.2 (0.71 ... 1.7)
HadGEM3-GC31-LL historical-ssp585 (1)	1.1e+4 (1.6e+3 ... 1.1e+5)	2.1 (1.7 ... 2.5)
HadGEM3-GC31-MM historical-ssp585 (1)	1.1e+4 (1.1e+3 ... 1.2e+5)	2.4 (1.9 ... 2.9)
INM-CM4-8 historical-ssp585 (1)	33 (7.2 ... 1.6e+2)	1.1 (0.64 ... 1.6)
IPSL-CM6A-LR historical-ssp585 (1)	2.1e+2 (56 ... 8.7e+2)	1.4 (1.1 ... 1.7)
MPI-ESM1-2-HR historical-ssp585 (1)	2.1e+2 (42 ... 1.1e+3)	1.4 (1.0 ... 1.8)
MPI-ESM1-2-LR historical-ssp585 (1)	1.1e+3 (1.6e+2 ... 8.5e+3)	1.6 (1.2 ... 2.0)
NorESM2-LM historical-ssp585 (1)	1.1e+5 (5.8e+3 ... 2.8e+6)	2.8 (2.2 ... 3.4)
EC-EARTH3P-HR (1)	1.4e+4 (7.4e+2 ... 1.4e+6)	1.9 (1.3 ... 2.5)
HadGEM3-GC31-HM (1)	6.9e+4 (2.2e+3 ... 4.4e+7)	2.3 (1.8 ... 2.9)
HadGEM3-GC31-LM (1)	4.8e+2 (20 ... 9.4e+4)	1.5 (0.80 ... 2.2)
HadGEM3-GC31-MM (1)	1.9e+3 (1.3e+2 ... 1.1e+5)	1.7 (1.1 ... 2.3)
CNRM-CM6-1 (1)	1.2e+6 (2.3e+4 ... 9.2e+8)	2.4 (1.8 ... 3.0)

Table S7. Probability Ratio (PR) and change in intensity of the 2022 summer mean **precipitation in the WCE region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-10 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
E-OBS	0.82 (0.28 ... 2.0)	1.7 (-5.9 ... 11)
ERA5	1.3 (0.31 ... 5.7)	-2.2 (-12 ... 9.0)
AM2.5C360 amip1871-2021 (10)	1.0 (0.75 ... 1.4)	0.0010 (-3.2 ... 2.9)
FLOR historical-rcp4.5 (10)	0.84 (0.68 ... 1.0)	1.8 (-0.45 ... 4.0)
ACCESS-CM2 historical-ssp585 (1)	1.0 (0.46 ... 1.7)	-0.39 (-5.3 ... 5.8)
ACCESS-ESM1-5 historical-ssp585 (1)	1.2 (0.64 ... 2.1)	-1.9 (-9.9 ... 5.0)
CESM2-WACCM historical-ssp585 (1)	1.4 (0.72 ... 2.3)	-2.8 (-7.8 ... 2.6)
CESM2 historical-ssp585 (1)	2.4 (1.2 ... 4.2)	-9.3 (-17 ... -1.6)
CanESM5 historical-ssp585 (1)	1.6 (0.89 ... 2.5)	-4.0 (-8.0 ... 0.86)
EC-Earth3-CC historical-ssp585 (1)	0.44 (0.27 ... 0.65)	8.2 (4.7 ... 12)
EC-Earth3-Veg-LR historical-ssp585 (1)	0.51 (0.24 ... 0.87)	7.6 (1.7 ... 14)
EC-Earth3-Veg historical-ssp585 (1)	0.89 (0.57 ... 1.3)	1.4 (-3.0 ... 6.2)
EC-Earth3 historical-ssp585 (1)	0.60 (0.31 ... 0.98)	5.5 (0.30 ... 11)
GFDL-CM4 historical-ssp585 (1)	1.2 (0.50 ... 2.0)	-1.1 (-5.5 ... 4.7)
GFDL-ESM4 historical-ssp585 (1)	2.0 (0.97 ... 4.7)	-5.7 (-13 ... 0.19)
HadGEM3-GC31-LL historical-ssp585 (1)	3.8 (2.0 ... 7.5)	-12 (-18 ... -5.8)

HadGEM3-GC31-MM historical-ssp585 (1)	4.6 (2.3 ... 9.1)	-15 (-22 ... -8.0)
IITM-ESM historical-ssp585 (1)	1.6 (0.73 ... 2.9)	-4.3 (-9.9 ... 2.8)
IPSL-CM6A-LR historical-ssp585 (1)	0.76 (0.42 ... 1.2)	2.7 (-2.1 ... 7.4)
MIROC6 historical-ssp585 (1)	0.31 (0.12 ... 0.50)	11 (6.6 ... 17)
MPI-ESM1-2-HR historical-ssp585 (1)	2.6 (1.3 ... 4.5)	-9.7 (-15 ... -2.7)
MPI-ESM1-2-LR historical-ssp585 (1)	8.9 (3.8 ... 20)	-18 (-25 ... -11)
MRI-ESM2-0 historical-ssp585 (1)	0.60 (0.25 ... 1.2)	3.8 (-1.5 ... 8.9)
NorESM2-MM historical-ssp585 (1)	1.9 (1.0 ... 3.1)	-7.7 (-14 ... 0.022)
UKESM1-0-LL historical-ssp585 (1)	1.8 (0.98 ... 3.0)	-7.1 (-14 ... 0.23)
HadGEM3-GC31-MM (1)	0.53 (0.15 ... 1.8)	6.4 (-5.1 ... 19)
EC-EARTH3P-HR (1)	1.1 (0.33 ... 3.2)	-0.62 (-9.6 ... 9.5)

Table S8. Probability Ratio (PR) and change in intensity (ΔI) of the 2022 summer mean root zone soil moisture in the NHET region between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-20 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
ERA5-Land	691 (48 ... 6.7e+4)	-2.4 (-3.2 ... 1.4)
GLDAS-CLSM	5.9e+9 (1.3e+7 ... 7.0e+15)	-3.1 (-3.6 ... -2.7)
AM2.5C360 amip1871-2021 (10)	0.051 (0.036 ... 0.070)	3.4 (3.2 ... 3.6)
ACCESS-CM2 historical-ssp585 (1)	11 (3.2 ... 37)	-0.52 (-0.83 ... -0.23)
ACCESS-ESM1-5 historical-ssp585 (1)	3.1e+4 (2.9e+3 ... 4.6e+5)	-1.7 (-2.1 ... -1.4)
BCC-CSM2-MR historical-ssp585 (1)	1.1e+4 (1.2e+3 ... 1.2e+5)	-4.0 (-4.9 ... -3.2)
CESM2-WACCM historical-ssp585 (1)	56 (17 ... 1.9e+2)	-1.1 (-1.5 ... -0.77)
CESM2 historical-ssp585 (1)	1.1e+2 (27 ... 4.7e+2)	-1.4 (-1.8 ... -0.94)
CNRM-ESM2-1 historical-ssp585 (1)	2.8e+5 (1.6e+4 ... 6.1e+6)	-2.4 (-2.8 ... -2.0)
CanESM5 historical-ssp585 (1)	48 (17 ... 1.3e+2)	-1.2 (-1.6 ... -0.91)
EC-Earth3-CC historical-ssp585 (1)	0.66 (0.33 ... 1.2)	0.31 (-0.12 ... 0.76)
EC-Earth3-Veg-LR historical-ssp585 (1)	0.42 (0.14 ... 1.0)	0.61 (-0.027 ... 1.3)
EC-Earth3-Veg historical-ssp585 (1)	0.39 (0.17 ... 0.79)	0.56 (0.16 ... 0.95)
EC-Earth3 historical-ssp585 (1)	0.16 (0.056 ... 0.40)	2.1 (1.3 ... 2.9)
GFDL-ESM4 historical-ssp585 (1)	0.39 (0.088 ... 1.4)	0.41 (-0.15 ... 0.98)
HadGEM3-GC31-LL historical-ssp585 (1)	8.8e+2 (1.9e+2 ... 4.6e+3)	-1.9 (-2.4 ... -1.5)
MPI-ESM1-2-HR historical-ssp585 (1)	0.58 (0.17 ... 1.5)	0.31 (-0.26 ... 0.91)

MPI-ESM1-2-LR historical-ssp585 (1)	32 (8.6 ... 1.4e+2)	-1.2 (-1.7 ... -0.73)
MRI-ESM2-0 historical-ssp585 (1)	18 (4.4 ... 67)	-0.96 (-1.5 ... -0.47)
NorESM2-LM historical-ssp585 (1)	4.9e+2 (69 ... 4.9e+3)	-1.7 (-2.3 ... -1.2)
NorESM2-MM historical-ssp585 (1)	74 (11 ... 5.4e+2)	-1.2 (-1.6 ... -0.66)
TaiESM1 historical-ssp585 (1)	30 (6.1 ... 1.3e+2)	-0.90 (-1.3 ... -0.46)
UKESM1-0-LL historical-ssp585 (1)	1.3e+3 (2.7e+2 ... 7.6e+3)	-2.2 (-2.7 ... -1.7)

Table S9. Probability Ratio (PR) and change in intensity of the 2022 summer mean **temperature in the NHET region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-10 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
ERA5	5.2e+14 (4.9e+10 ... ∞)	1.9 (1.7 ... 2.1)
AM2.5C360 amip1871-2021 (10)	3.9e+13 (2.8e+11 ... 1.5e+16)	1.8 (1.6 ... 1.9)
FLOR historical-rcp4.5 (10)	9.5e+7 (1.4e+7 ... 9.7e+8)	1.3 (1.2 ... 1.4)
ACCESS-CM2 historical-ssp585 (1)	1.1e+11 (8.0e+8 ... 3.8e+13)	1.8 (1.6 ... 1.9)
ACCESS-ESM1-5 historical-ssp585 (1)	8.6e+19 (1.3e+16 ... 4.6e+24)	2.0 (1.9 ... 2.2)
BCC-CSM2-MR historical-ssp585 (1)	3.5e+8 (6.3e+6 ... 3.9e+10)	1.7 (1.5 ... 1.9)
CESM2-WACCM historical-ssp585 (1)	5.7e+4 (6.2e+3 ... 6.8e+5)	1.3 (1.1 ... 1.5)
CESM2 historical-ssp585 (1)	3.3e+5 (2.4e+4 ... 5.2e+6)	1.5 (1.3 ... 1.7)
CNRM-CM6-1-HR historical-ssp585 (1)	6.7e+6 (3.0e+5 ... 2.1e+8)	1.1 (0.96 ... 1.2)
CNRM-ESM2-1 historical-ssp585 (1)	9.5e+13 (1.7e+11 ... 1.3e+17)	1.6 (1.4 ... 1.7)
CanESM5 historical-ssp585 (1)	3.2e+12 (1.3e+10 ... 1.6e+15)	1.8 (1.7 ... 1.9)
EC-Earth3-CC historical-ssp585 (1)	3.2e+11 (2.1e+9 ... 1.2e+14)	1.9 (1.8 ... 2.0)
EC-Earth3-Veg-LR historical-ssp585 (1)	1.2e+8 (3.3e+6 ... 7.2e+9)	1.6 (1.4 ... 1.7)
EC-Earth3-Veg historical-ssp585 (1)	1.2e+8 (3.4e+6 ... 6.9e+9)	1.8 (1.6 ... 1.9)
EC-Earth3 historical-ssp585 (1)	4.0e+7 (1.1e+6 ... 2.1e+9)	1.8 (1.6 ... 2.0)
GFDL-CM4 historical-ssp585 (1)	1.4e+15 (1.2e+12 ... 3.1e+18)	2.0 (1.8 ... 2.2)
GFDL-ESM4 historical-ssp585 (1)	1.4e+9 (1.2e+7 ... 2.7e+11)	1.4 (1.2 ... 1.6)
HadGEM3-GC31-LL historical-ssp585 (1)	4.8e+11 (3.1e+9 ... 2.3e+14)	1.9 (1.7 ... 2.0)
HadGEM3-GC31-MM historical-ssp585 (1)	2.2e+11 (1.5e+9 ... 8.7e+13)	2.0 (1.8 ... 2.2)
IITM-ESM historical-ssp585 (1)	4.0e+12 (1.3e+10 ... 2.5e+15)	1.5 (1.4 ... 1.7)
INM-CM4-8 historical-ssp585 (1)	1.1e+10 (9.1e+7 ... 2.8e+12)	1.6 (1.4 ... 1.7)
INM-CM5-0 historical-ssp585 (1)	3.0e+13 (6.4e+10 ... 4.2e+16)	1.8 (1.6 ... 1.9)
IPSL-CM6A-LR historical-ssp585 (1)	1.9e+11 (1.4e+9 ... 8.8e+13)	1.6 (1.5 ... 1.7)
KACE-1-0-G historical-ssp585 (1)	1.2e+10 (1.3e+8 ... 2.0e+12)	2.1 (2.0 ... 2.3)
MIROC-ES2L historical-ssp585 (1)	3.7e+10 (2.0e+8 ... 1.2e+13)	1.5 (1.3 ... 1.7)
MPI-ESM1-2-HR historical-ssp585 (1)	1.1e+16 (1.1e+13 ... 4.7e+19)	1.6 (1.5 ... 1.8)
MPI-ESM1-2-LR historical-ssp585 (1)	1275174008127252 (1.4e+12 ... 3.4e+18)	1.7 (1.6 ... 1.9)
MRI-ESM2-0 historical-ssp585 (1)	3.2e+10 (3.1e+8 ... 6.8e+12)	1.5 (1.4 ... 1.7)

NorESM2-LM historical-ssp585 (1)	4.3e+7 (1.1e+6 ... 4.8e+9)	1.9 (1.6 ... 2.2)
NorESM2-MM historical-ssp585 (1)	2.6e+7 (4.9e+5 ... 2.3e+9)	1.7 (1.4 ... 1.9)
TaiESM1 historical-ssp585 (1)	7.3e+11 (2.0e+9 ... 3.8e+14)	2.0 (1.8 ... 2.2)
UKESM1-0-LL historical-ssp585 (1)	1.8e+10 (2.2e+8 ... 3.4e+12)	1.9 (1.7 ... 2.1)
EC-EARTH3P HighResMIP (1)	2.5e+14 (1.5e+11 ... ∞)	1.6 (1.4 ... 1.8)
EC-EARTH3P-HR HighResMIP (1)	∞ (1.1e+15 ... ∞)	1.8 (1.6 ... 2.0)
HadGEM3-GC31-HM HighResMIP (1)	2.3e+14 (1.0e+11 ... ∞)	2.1 (1.9 ... 2.3)
HadGEM3-GC31-LM HighResMIP (1)	7.2e+13 (3.1e+10 ... ∞)	1.9 (1.7 ... 2.2)
HadGEM3-GC31-MM HighResMIP (1)	2.7e+15 (9.0e+11 ... ∞)	2.0 (1.7 ... 2.2)
CNRM-CM6-1 HighResMIP (1)	2.6e+14 (7.7e+10 ... ∞)	1.8 (1.6 ... 2.0)
CNRM-CM6-1-HR HighResMIP (1)	2.8e+14 (8.9e+10 ... ∞)	1.6 (1.4 ... 1.8)

Table S10. Probability Ratio (PR) and change in intensity of the 2022 summer mean **precipitation in the NHET region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-10 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
ERA5	1.4 (0.34 ... 6.6)	-0.65 (-2.9 ... 2.2)
AM2.5C360 amip1871-2021 (10)	0.26 (0.18 ... 0.36)	3.0 (2.3 ... 3.7)
ACCESS-CM2 (1)	1.0 (0.46 ... 1.7)	-0.39 (-5.3 ... 5.8)
ACCESS-ESM1-5 (1)	1.2 (0.64 ... 2.1)	-1.9 (-9.9 ... 5.0)
BCC-CSM2-MR (1)	1.6 (0.82 ... 2.8)	-6.2 (-13 ... 2.2)
CESM2-WACCM (1)	1.4 (0.72 ... 2.3)	-2.8 (-7.8 ... 2.6)
CESM2 (1)	2.4 (1.2 ... 4.2)	-9.3 (-17 ... -1.6)
CMCC-CM2-SR5 (1)	2.0 (1.2 ... 3.0)	-8.3 (-14 ... -2.1)
CMCC-ESM2 (1)	2.0 (1.0 ... 3.3)	-8.1 (-14 ... -0.53)
CNRM-CM6-1-HR (1)	1.1 (0.64 ... 1.8)	-0.91 (-8.9 ... 5.6)
CNRM-CM6-1 (1)	0.82 (0.45 ... 1.3)	2.6 (-4.2 ... 9.6)
CNRM-ESM2-1 (1)	1.8 (0.99 ... 3.1)	-7.9 (-16 ... 0.17)
CanESM5 (1)	1.6 (0.89 ... 2.5)	-4.0 (-8.0 ... 0.86)
EC-Earth3-CC (1)	0.44 (0.27 ... 0.65)	8.2 (4.7 ... 12)
EC-Earth3-Veg-LR (1)	0.51 (0.24 ... 0.87)	7.6 (1.7 ... 14)
EC-Earth3-Veg (1)	0.89 (0.57 ... 1.3)	1.4 (-3.0 ... 6.2)
EC-Earth3 (1)	0.60 (0.31 ... 0.98)	5.5 (0.30 ... 11)
GFDL-CM4 (1)	1.2 (0.50 ... 2.0)	-1.1 (-5.5 ... 4.7)
GFDL-ESM4 (1)	2.0 (0.97 ... 4.7)	-5.7 (-13 ... 0.19)
HadGEM3-GC31-LL (1)	3.8 (2.0 ... 7.5)	-12 (-18 ... -5.8)
HadGEM3-GC31-MM (1)	4.6 (2.3 ... 9.1)	-15 (-22 ... -8.0)
INM-CM5-0 (1)	4.0 (2.2 ... 7.0)	-22 (-29 ... -12)
MIROC6 (1)	0.31 (0.12 ... 0.50)	11 (6.6 ... 17)

MPI-ESM1-2-HR (1)	2.6 (1.3 ... 4.5)	-9.7 (-15 ... -2.7)
MPI-ESM1-2-LR (1)	8.9 (3.8 ... 20)	-18 (-25 ... -11)
MRI-ESM2-0 (1)	0.60 (0.25 ... 1.2)	3.8 (-1.5 ... 8.9)
NorESM2-LM (1)	3.8 (1.5 ... 6.7)	-16 (-25 ... -5.3)
NorESM2-MM (1)	1.9 (1.0 ... 3.1)	-7.7 (-14 ... 0.022)
TaiESM1 (1)	3.2 (1.4 ... 5.7)	-13 (-21 ... -4.3)
UKESM1-0-LL (1)	1.8 (0.98 ... 3.0)	-7.1 (-14 ... 0.23)
EC-EARTH3P-HR (1)	0.32 (0.070 ... 1.3)	2.2 (-0.51 ... 4.7)
HadGEM3-GC31-HM (1)	0.25 (0.064 ... 0.65)	3.1 (0.90 ... 5.4)
HadGEM3-GC31-LM (1)	0.27 (0.077 ... 0.80)	3.1 (0.53 ... 5.6)
HadGEM3-GC31-MM (1)	0.30 (0.081 ... 0.83)	2.9 (0.49 ... 5.5)
CNRM-CM6-1 (1)	0.88 (0.21 ... 3.7)	0.28 (-2.7 ... 3.2)
CNRM-CM6-1-HR (1)	0.47 (0.098 ... 1.9)	1.5 (-1.3 ... 4.2)

Table S11. Probability Ratio (PR) and change in intensity (ΔI) of the 2022 summer mean **surface soil moisture in the WCE region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-20 year event based on observations.

Model / Observations	**Probability ratio PR**	**Change in intensity ΔI [%]**
ERA5	49 (7.0 ... 6.3e+2)	-9.6 (-14 ... -5.1)
ERA5-Land	17 (3.0 ... 1.8e+2)	-8.0 (-13 ... -3.4)
GLDAS-CLSM	1.0e+7 (1.1e+5 ... 3.1e+10)	-14 (-16 ... -11)
CanESM5 historical-ssp585 (1)	2.2 (0.93 ... 4.1)	-3.3 (-6.7 ... 0.29)
GFDL-CM4 historical-ssp585 (1)	2.1 (0.64 ... 6.9)	-2.1 (-5.7 ... 1.1)
HadGEM3-GC31-LL historical-ssp585 (1)	21 (8.7 ... 50)	-12 (-16 ... -8.1)
HadGEM3-GC31-MM historical-ssp585 (1)	37 (13 ... 1.2e+2)	-17 (-21 ... -11)
MPI-ESM1-2-HR historical-ssp585 (1)	1.7 (0.56 ... 4.9)	-1.6 (-5.1 ... 1.6)
MPI-ESM1-2-LR historical-ssp585 (1)	11 (3.6 ... 34)	-5.4 (-8.1 ... -2.9)
CNRM-CM6-1 (1)	2.3 (0.37 ... 19)	-2.4 (-7.5 ... 2.7)
CNRM-CM6-1-HR (1)	1.0 (0.23 ... 4.1)	-0.10 (-4.6 ... 5.0)
EC-EARTH3P (1)	1.2 (0.20 ... 6.5)	-0.60 (-6.5 ... 5.5)
EC-EARTH3P-HR (1)	3.7 (0.83 ... 17)	-3.9 (-8.4 ... 0.55)

Table S12. Probability Ratio (PR) and change in intensity (ΔI) of the 2022 summer mean **surface soil moisture in the NHET region** between the current climate and the pre-industrial climate, from the observed datasets and the models that passed validation. This event is defined as a 1-in-20 year event based on observations.

Model / Observations	**Probability ratio PR [-]**	**Change in intensity ΔI [%]**
ERA5	1.5e+2 (13 ... 4.8e+3)	-2.7 (-3.8 ... -1.4)
ERA5-Land	1.7e+2 (18 ... 6.0e+3)	-2.6 (-3.6 ... -1.5)
GLDAS-CLSM	1.4e+11 (2.2e+7 ... ∞)	-4.4 (-5.0 ... -3.7)

AM2.5C360 amip1871-2021 (10)	0.75 (0.46 ... 1.2)	0.14 (-0.068 ... 0.36)
ACCESS-CM2 historical-ssp585 (1)	7.8 (1.9 ... 24)	-0.66 (-1.1 ... -0.19)
ACCESS-ESM1-5 historical-ssp585 (1)	29 (6.8 ... 1.1e+2)	-1.2 (-1.7 ... -0.69)
BCC-CSM2-MR historical-ssp585 (1)	34 (6.1 ... 1.7e+2)	-2.1 (-3.1 ... -1.1)
CanESM5 historical-ssp585 (1)	10 (4.5 ... 22)	-1.6 (-2.3 ... -1.0)
EC-Earth3 historical-ssp585 (1)	0.084 (0.029 ... 0.22)	3.4 (2.6 ... 4.1)
GFDL-CM4 historical-ssp585 (1)	8.6e+2 (1.4e+2 ... 6.5e+3)	-1.9 (-2.4 ... -1.4)
HadGEM3-GC31-LL historical-ssp585 (1)	4.6e+6 (2.3e+5 ... 1.6e+8)	-5.9 (-6.6 ... -5.2)
HadGEM3-GC31-MM historical-ssp585 (1)	1.3e+8 (3.2e+6 ... 1.1e+10)	-8.2 (-9.3 ... -7.1)
INM-CM5-0 historical-ssp585 (1)	45 (9.5 ... 2.4e+2)	-1.3 (-2.0 ... -0.81)
MPI-ESM1-2-HR historical-ssp585 (1)	2.7 (0.81 ... 8.7)	-0.49 (-1.1 ... 0.098)
MPI-ESM1-2-LR historical-ssp585 (1)	33 (7.4 ... 1.4e+2)	-1.1 (-1.6 ... -0.66)
MRI-ESM2-0 historical-ssp585 (1)	1.6 (0.41 ... 4.9)	-0.21 (-0.77 ... 0.36)
NorESM2-LM historical-ssp585 (1)	3.5e+2 (40 ... 2.9e+3)	-3.3 (-4.6 ... -2.2)
UKESM1-0-LL historical-ssp585 (1)	84 (23 ... 3.2e+2)	-2.5 (-3.2 ... -1.7)
EC-EARTH3P-HR HighResMIP (1)	56 (8.1 ... 7.6e+2)	-1.4 (-2.1 ... -0.72)
HadGEM3-GC31-HM HighResMIP (1)	1.1e+7 (3.0e+5 ... 1.4e+10)	-8.0 (-9.2 ... -6.6)
HadGEM3-GC31-LM HighResMIP (1)	3.3e+6 (7.7e+4 ... 7.2e+9)	-7.4 (-8.7 ... -6.1)
HadGEM3-GC31-MM HighResMIP (1)	3.7e+5 (9.9e+3 ... 3.5e+8)	-6.9 (-8.6 ... -5.2)
CNRM-CM6-1 HighResMIP (1)	8.0e+3 (3.3e+2 ... 7.4e+6)	-2.4 (-3.1 ... -1.8)
CNRM-CM6-1-HR HighResMIP (1)	21 (2.2 ... 4.9e+2)	-1.1 (-1.8 ... -0.27)