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Downscaling of climate change scenarios for a high-resolution, site-specific assessment of drought stress risk for two viticultural regions with heterogeneous landscapes

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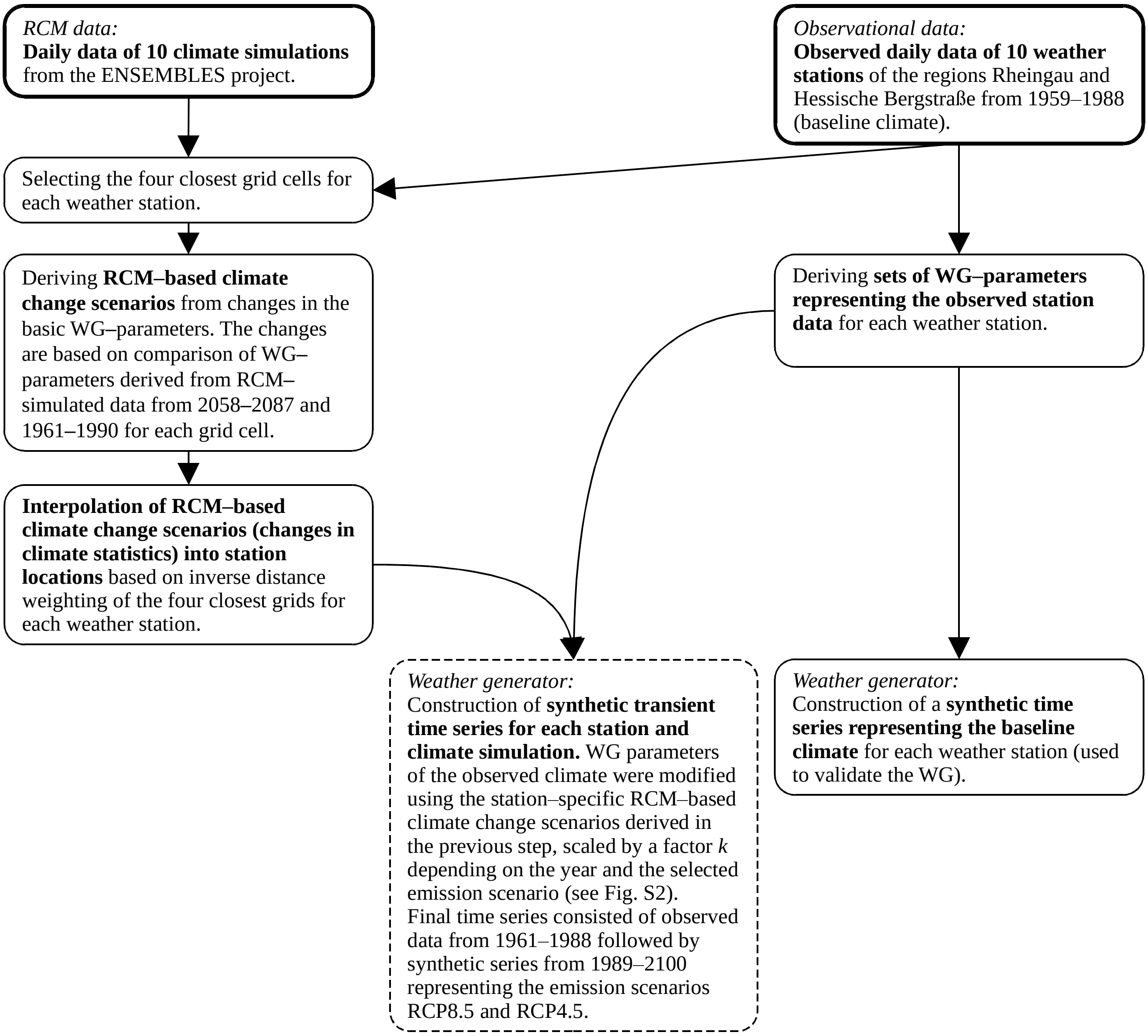


Figure S1: Flow diagram describing the steps of downscaling RCMs to station (point) data using a weather generator (WG). Input data are marked in boxes with bold border, calculation steps are marked in boxes with normal border. The dashed box marks the time series used for the subsequent water balance calculations (see Fig. S3).

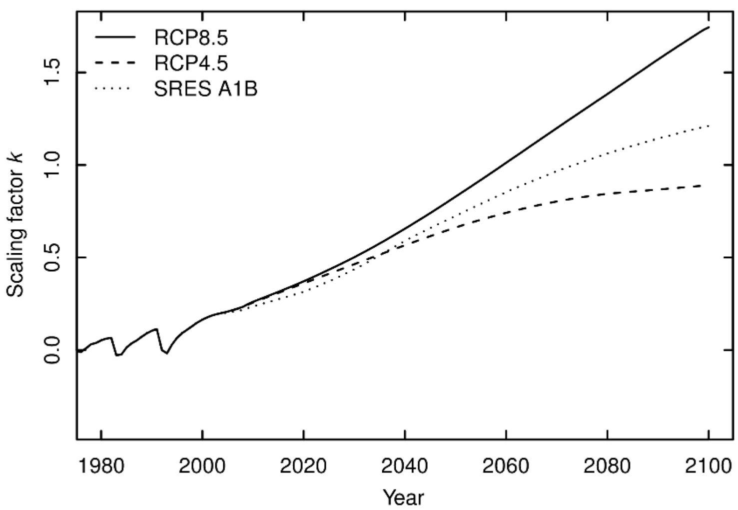


Figure S2: The scaling factor *k* according to Eq. (1) used by the weather generator to construct synthetic transient time series for different emission scenarios. RCP8.5 and RCP4.5 were used in the study.

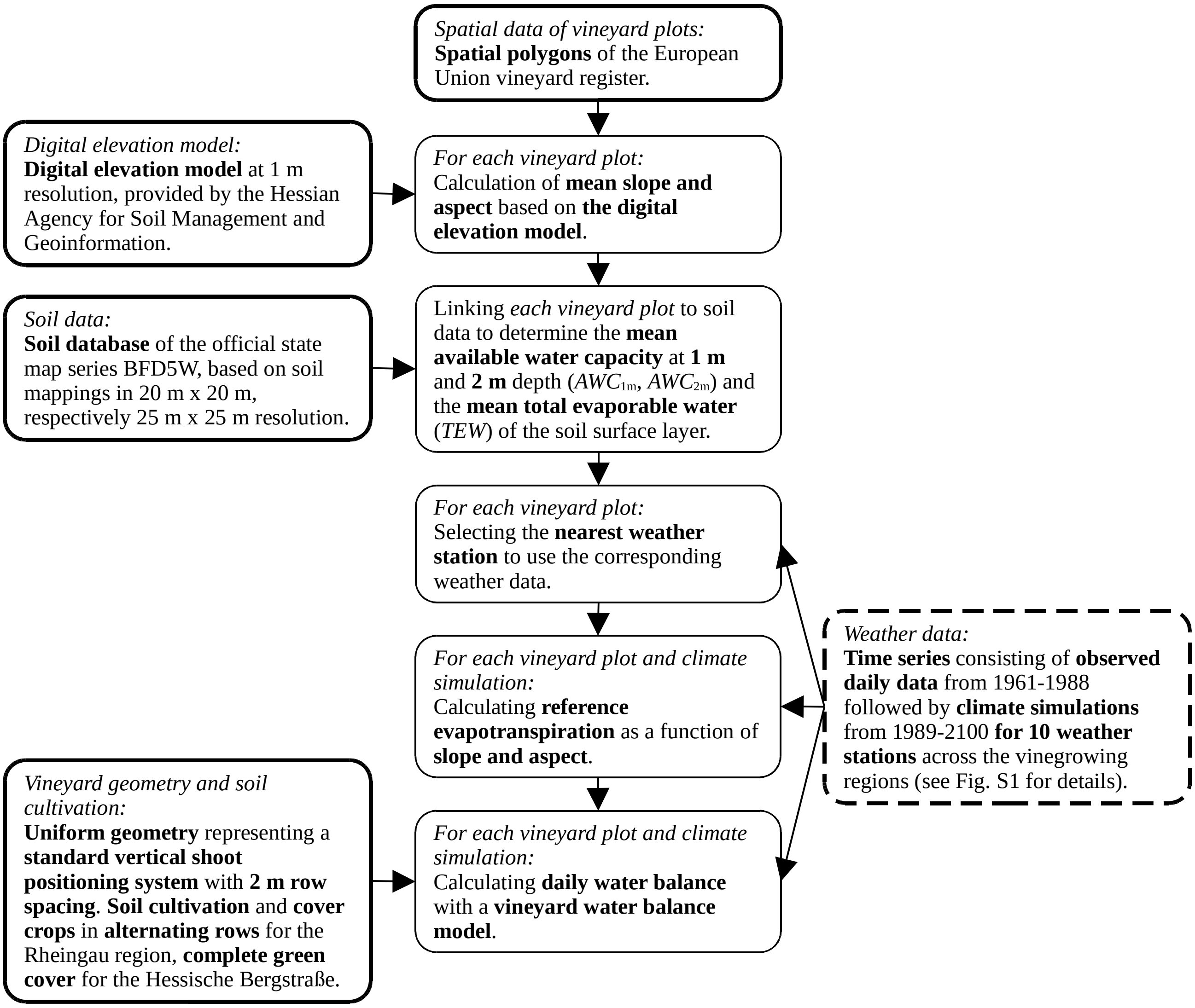


Figure S3: Flow diagram describing the steps involved in calculating water balance at the spatial resolution of individual plots for two winegrowing regions. Input data are marked in boxes with bold border, calculation steps are marked in boxes with normal border. The dashed box marks the climate simulation data produced in a previous step (Fig. S1).

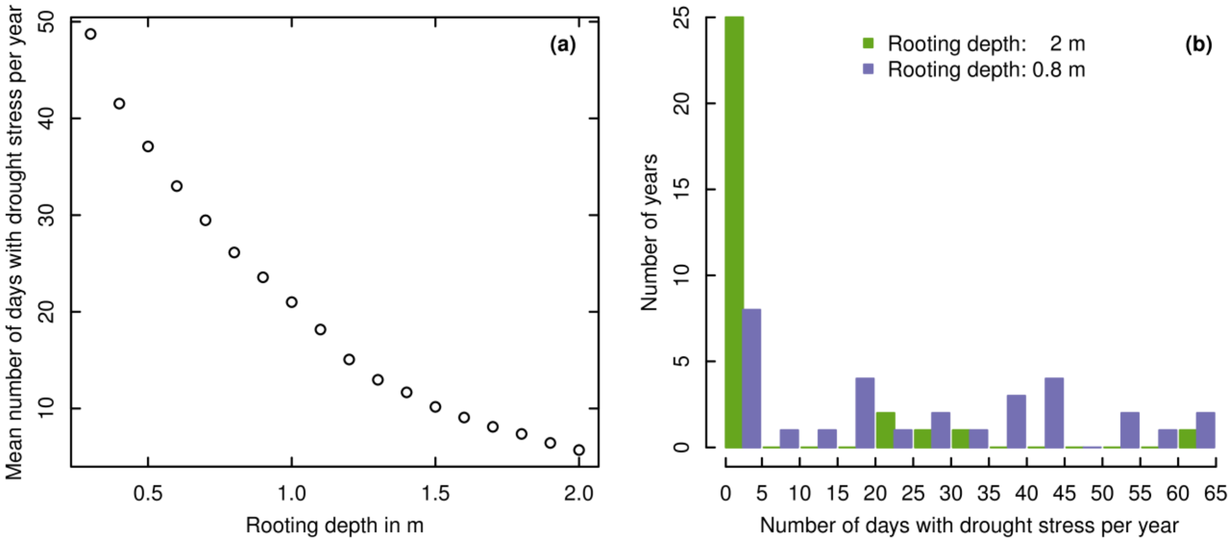


Figure S4: Simulated impact of rooting depth on drought stress occurrence during vegetation period for a vineyard plot with an available water capacity (*AWC*) of 180 mm (2 m depth; typical for soil type loamy sand). It was assumed that a shallower rooting depth would proportionally reduce *AWC*. Simulations were performed with a vineyard water balance model and a time series recorded from 1959-1988 (30 years) at Geisenheim (Rheingau), Germany. (a) Mean number of drought stress days per annual vegetation period (1 May–30 Sep) for the 30–year period. (b) Histogram of the annual number of drought stress days of the 30 years for rooting depths of 2 m and a rooting depth of 0.8 m.

Note to Figure S4:

Limited rooting depths apply to situations of shallow soils and young vineyards (especially in the first three years) which do not have an established root system. The available water capacity is reduced. The risk of drought is substantially increased for soils with limited depths lower than approximately 1.30 m.

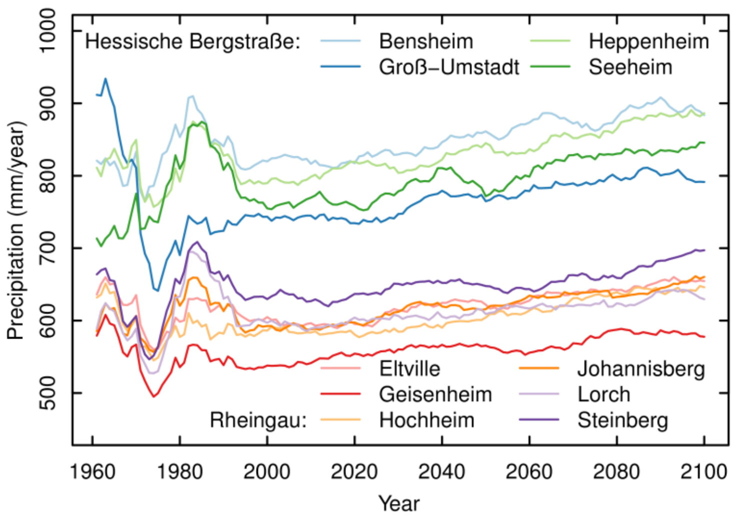


Figure S5: Annual precipitation rates (11–year running means) of 10 weather stations located in the winegrowing regions Hessische Bergstraße and Rheingau (Germany). Times series consist of observed values from 1961–1988 followed by the multi-model ensemble mean of 10 climate models from 1989–2100 for RCP8.5.

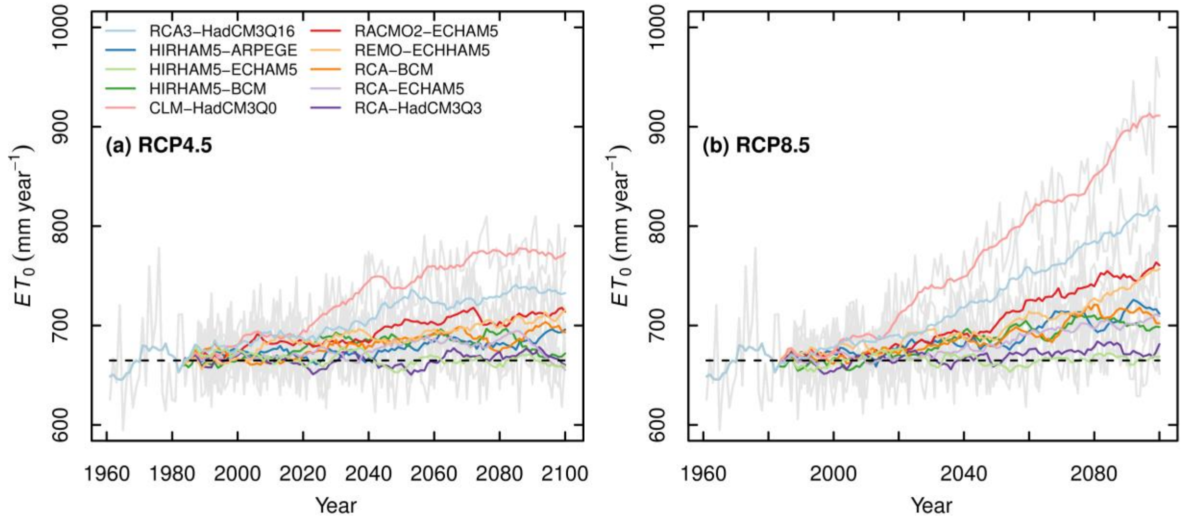


Figure S6: Annual reference evapotranspiration (ET_0) of 10 climate simulations for the weather station Geisenheim (Rheingau, Germany). Grey lines show the range of annual values of all models, coloured lines 11–year running means for individual model runs. The period from 1961–1988 shows observed data. (a) for RCP4.5, (b) for RCP8.5.

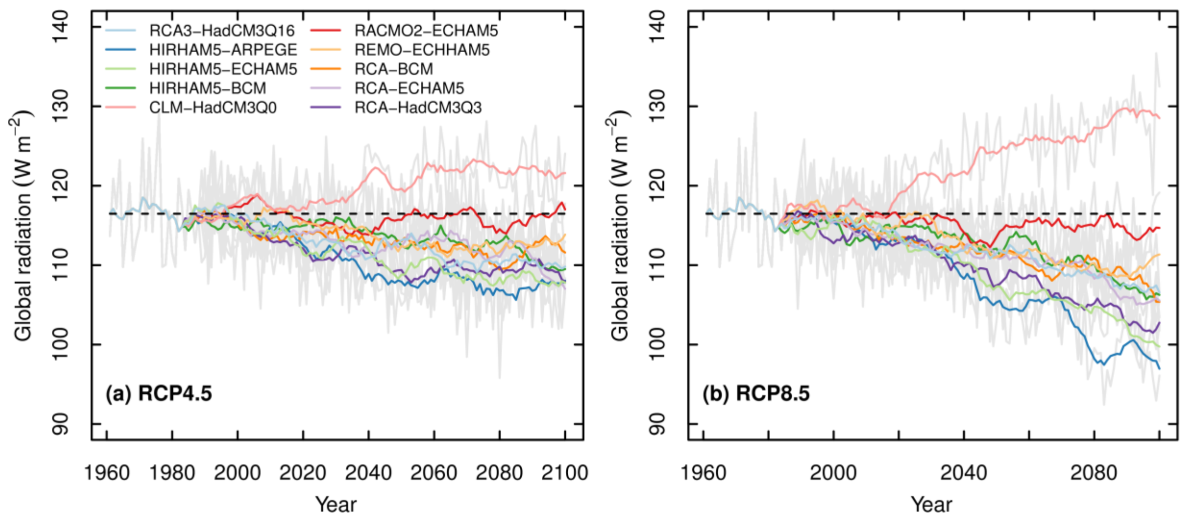


Figure S7: As Fig. S6, here for global radiation.

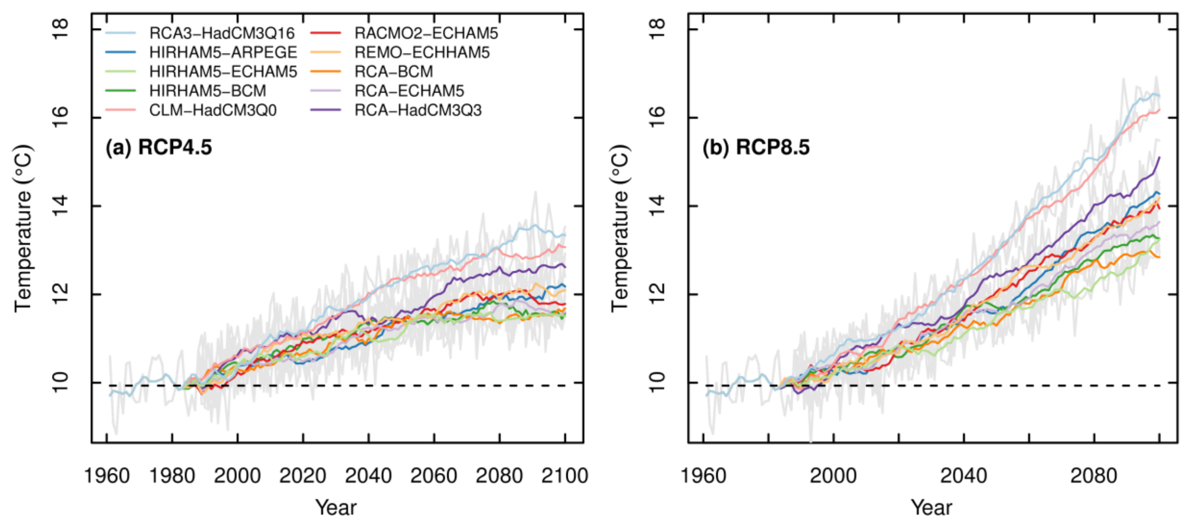


Figure S8: As Fig. S6, here for annual mean temperature.

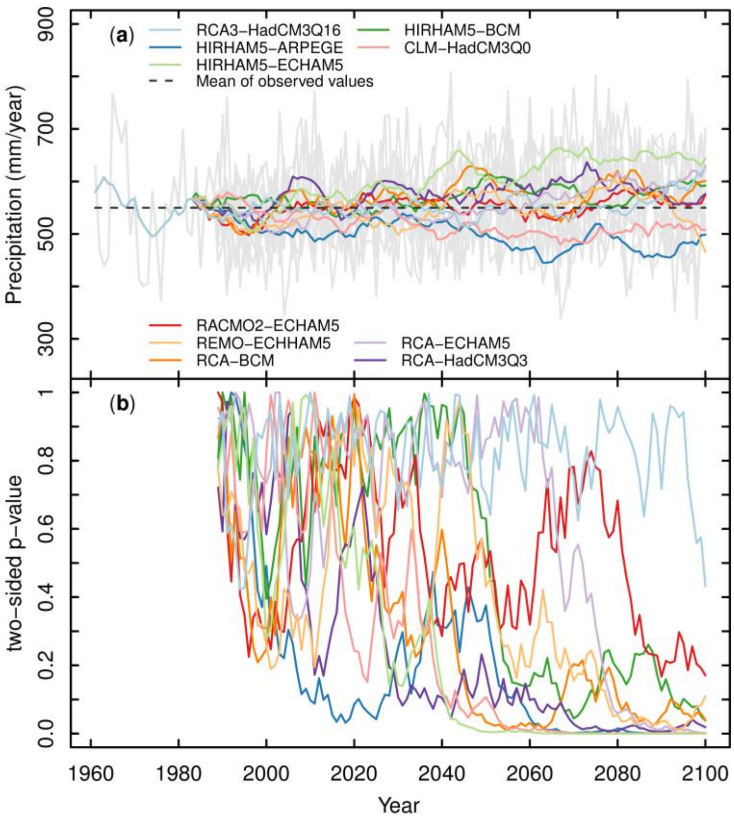


Figure S9: (a)Annual precipitation rates of 10 climate simulations with different models for the station Geisenheim (Rheingau), Germany, (b) p–values calculated with Mann–Kendall trend test for time series of annual precipitation rates shown in (a) starting in 1961; as in Fig. 6, but for RCP4.5.

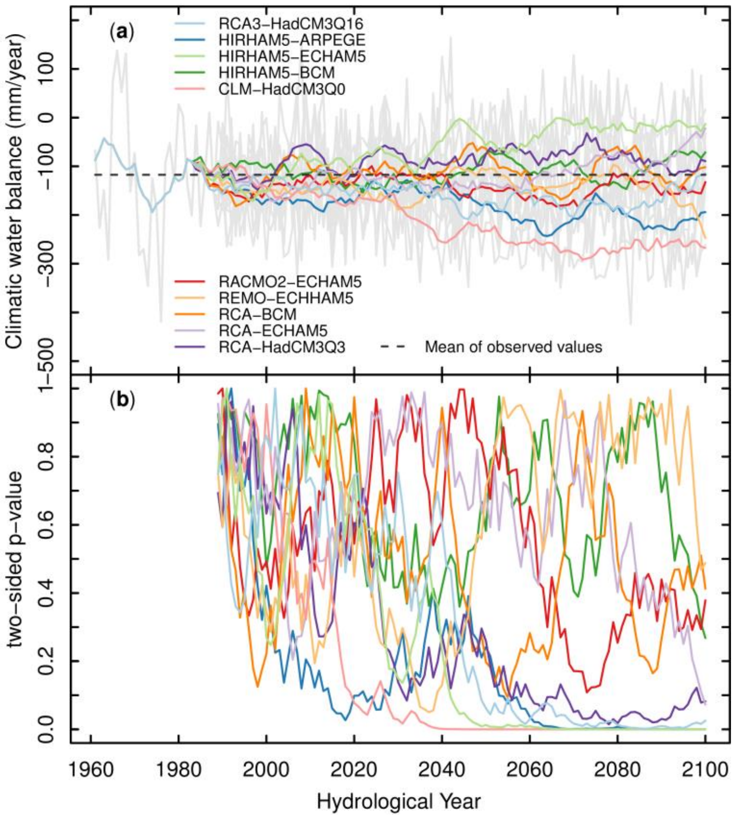


Figure S10: (a) Climatic water balance of 10 climate simulations of different models for the station Geisenheim (Rheingau), Germany, (b) p–values calculated with Mann–Kendall trend test for time series shown in (a) starting in 1961; as in Fig. 7, but for RCP4.5.

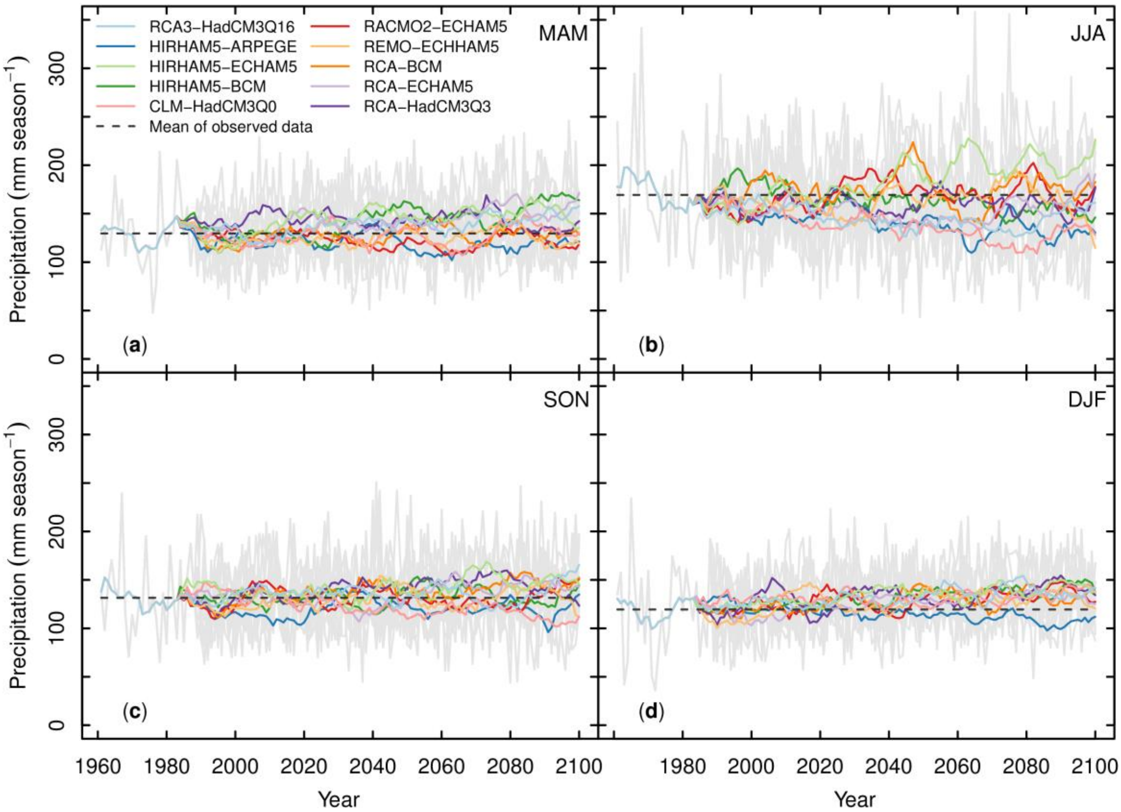


Figure S11: Seasonal precipitation simulated with 10 climate models for the station Geisenheim (Rheingau), Germany, as in Fig. 8 but for RCP4.5.

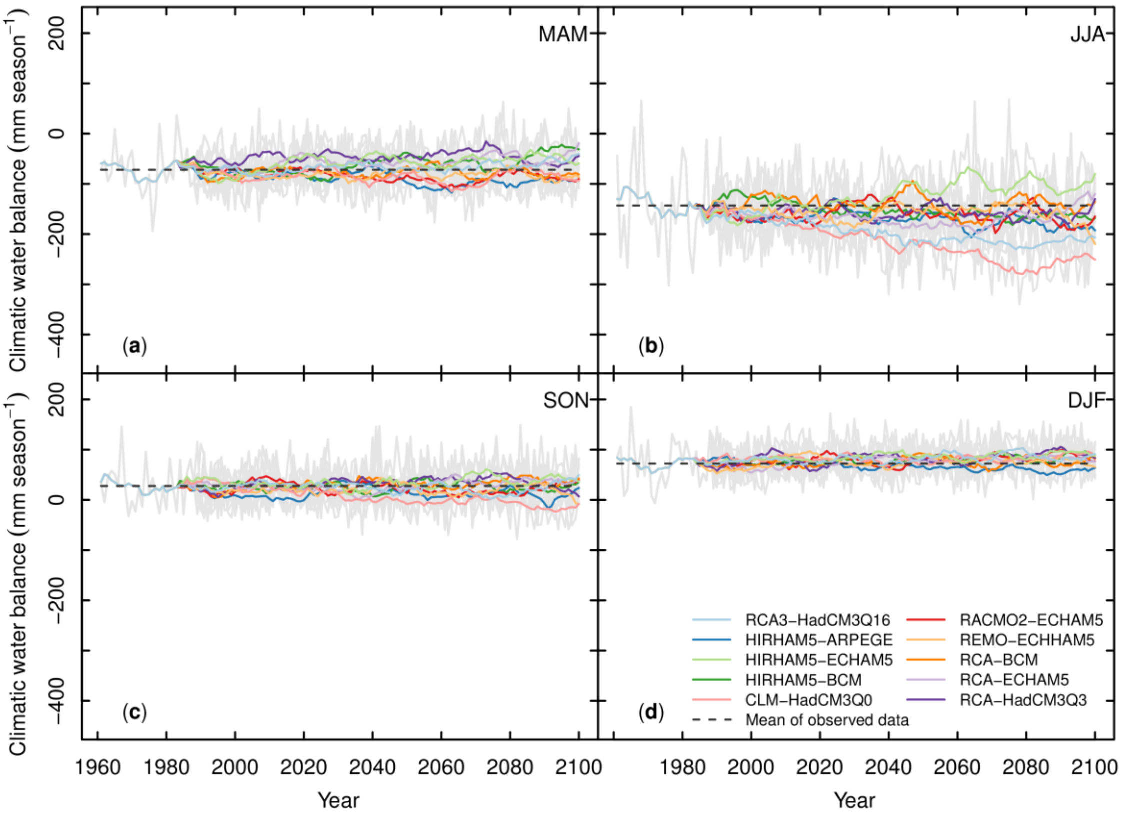


Figure S12: Seasonal climatic water balance simulated with 10 climate models for the station Geisenheim (Rheingau), Germany, as in Fig. 9 but for RCP4.5.

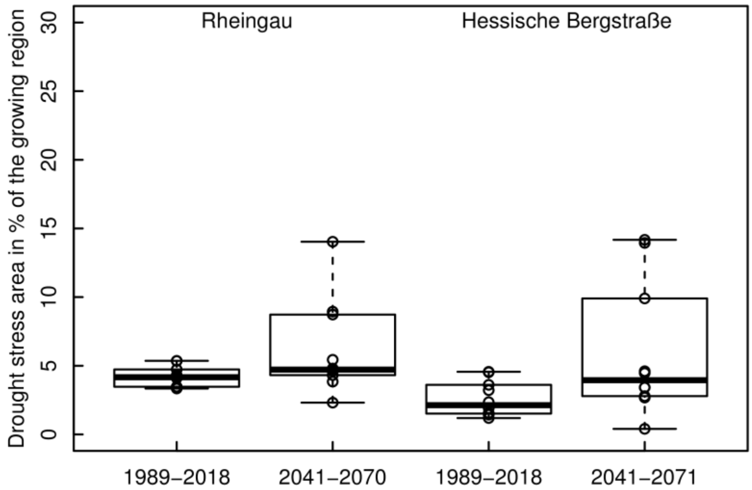
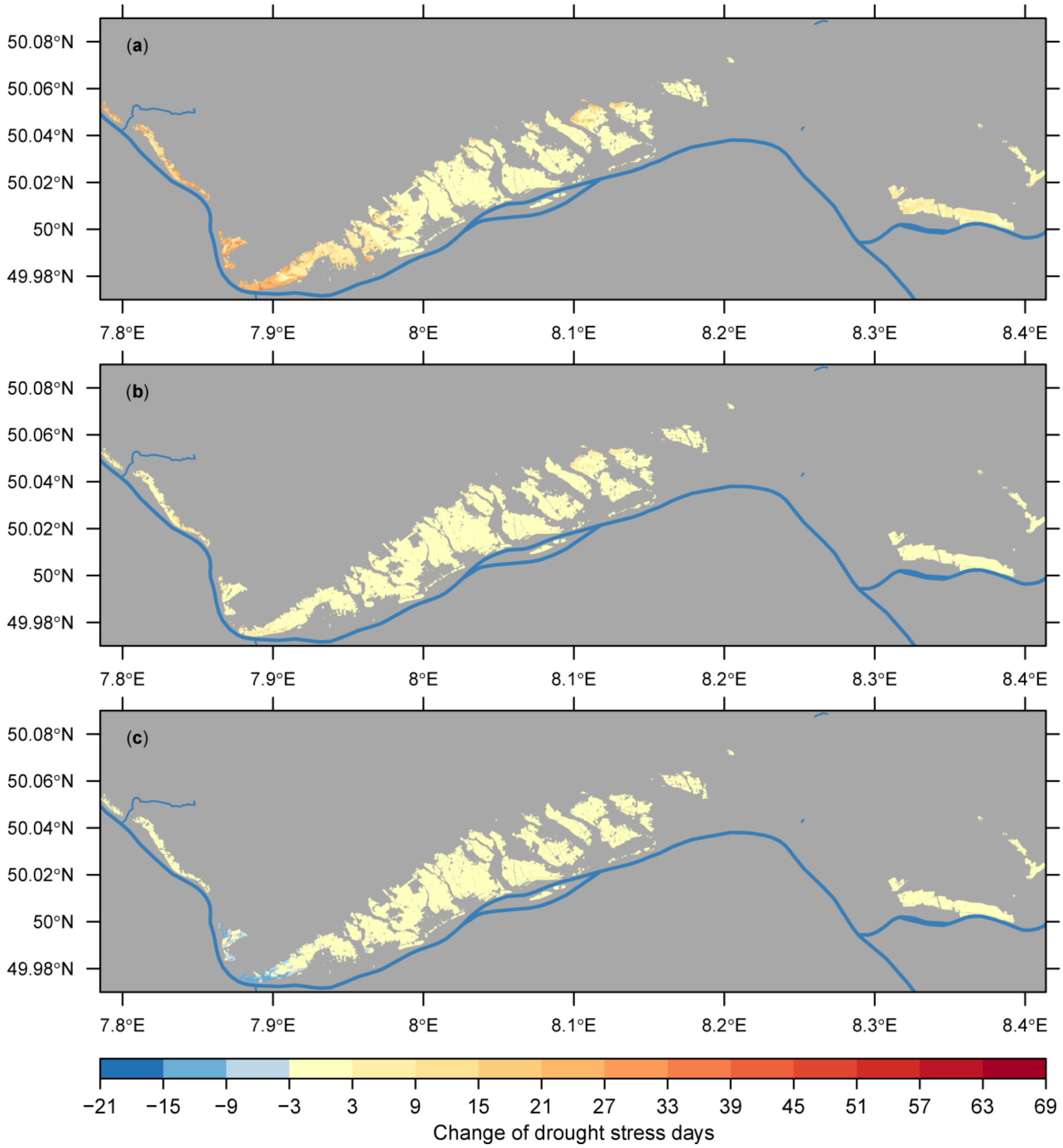


Figure S13: Potential drought stress area of two winegrowing regions (Rheingau and Hessische Bergstraße) in Germany, as in Fig. 10 but for RCP4.5.



65 **Figure S14: Projected change of the occurrence of drought stress days for the growing region Rheingau (Germany), as in Fig. 11 but for RCP4.5.**

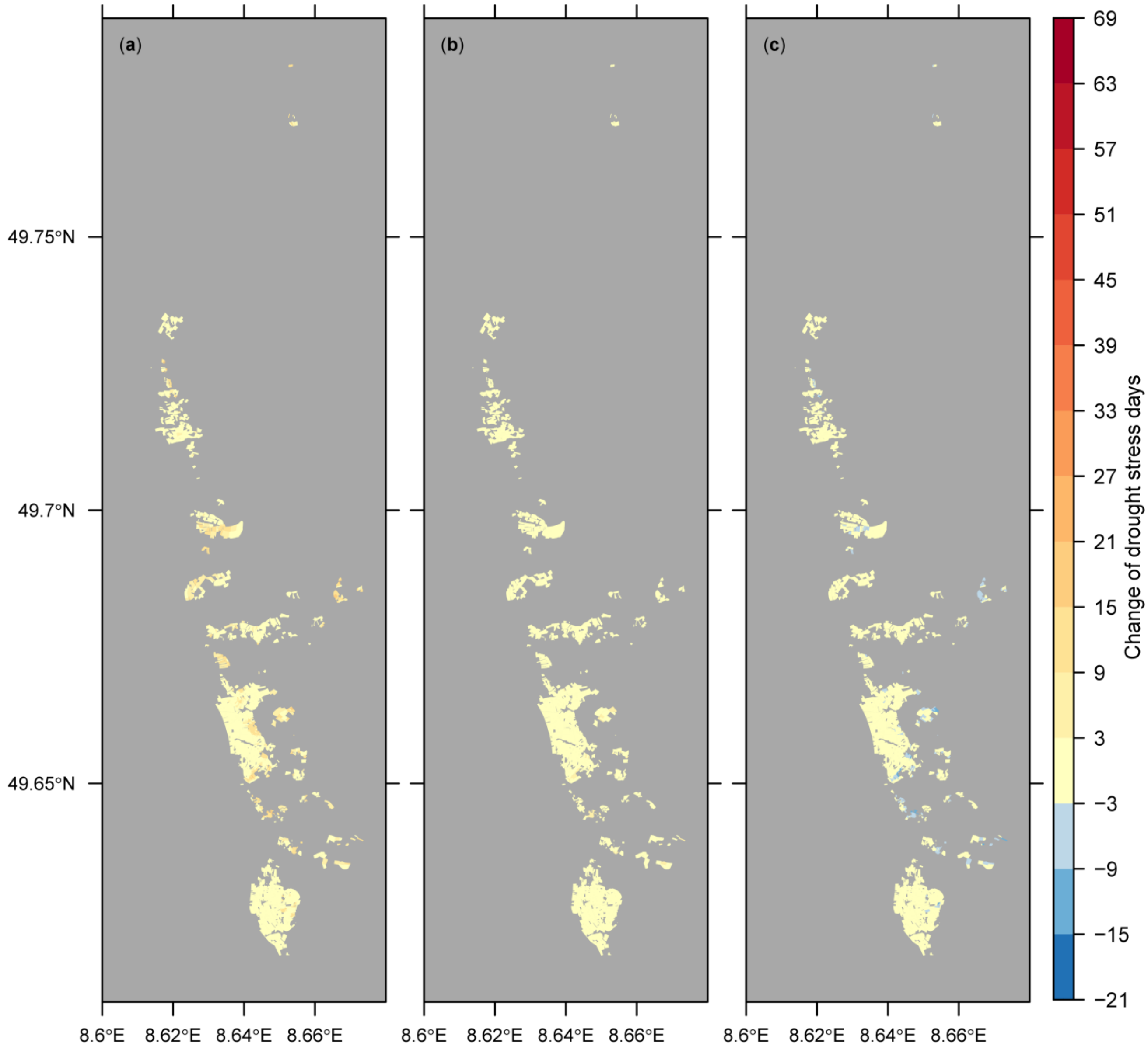


Figure S15: Projected change of the occurrence of drought stress days for the growing region Hessische Bergstraße (Germany), as in Fig. 12 but for RCP4.5.

Table S1: Monthly means of the weather variables daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), relative humidity (Rh), vapour pressure deficit (VPD), solar radiation (R_s), wind speed (u_2, at 2 m above ground) based on recordings of the weather station in Geisenheim (Rheingau, Germany) for the periods 1961–1990 and 1991–2020. Reference evapotranspiration (ET_0) was calculated from the monthly values according to FAO56 guidelines (Allen et al., 1998). The last line shows the annual values.

	1961–1990							1991–2020						
Month	T_{max} (°C)	T_{min} (°C)	Rh (%)	VPD (kPa)	R_s (Wm^{-2})	u_2 (ms^{-1})	ET_0 (mm)	T_{max} (°C)	T_{min} (°C)	Rh (%)	VPD (kPa)	R_s (Wm^{-2})	u_2 (ms^{-1})	ET_0 (mm)
Jan	3.4	-1.2	82	0.12	30	1.8	13	5.1	-0.1	81	0.14	36	1.9	13
Feb	5.3	-0.6	77	0.17	58	1.8	18	6.7	0.1	77	0.18	66	1.9	20
Mar	9.7	1.9	72	0.27	99	2.0	38	11.4	2.7	71	0.31	115	2.1	43
Apr	14.2	4.8	67	0.42	154	2.0	63	16.3	5.8	64	0.50	179	2.0	74
May	18.9	8.7	66	0.57	195	1.9	92	20.3	9.7	65	0.63	215	2.0	103
Jun	22.0	11.9	67	0.67	207	1.8	103	23.7	12.8	65	0.78	233	1.9	118
Jul	23.9	13.4	67	0.73	208	1.7	112	25.9	14.8	65	0.89	230	1.8	128
Aug	23.6	13.2	70	0.66	179	1.6	96	25.5	14.3	67	0.81	200	1.7	111
Sep	20.1	10.3	76	0.43	127	1.5	61	20.8	10.8	74	0.49	140	1.6	68
Oct	14.3	6.6	82	0.24	70	1.4	33	14.9	7.1	81	0.26	77	1.6	35
Nov	7.8	2.5	82	0.16	36	1.6	18	9.0	3.6	84	0.16	39	1.6	17
Dec	4.5	-0.1	83	0.12	25	1.7	14	5.7	0.9	84	0.13	29	1.8	13
Annual	14.0	6.0	74	0.38	116	1.7	661	15.5	7.0	73	0.44	130	1.8	743

Table S2: Change in mean values over the period 1961–1990 to 1991–2020 of weather variables used to calculate reference evapotranspiration (ET_0) according to FAO56 guidelines (Allen et al., 1998). The weather variables are based on recordings of the weather station in Geisenheim (Rheingau, Germany). The impact of the change of one weather variable on ET_0 (ΔET_0) was assessed by calculating ET_0 with monthly values from 1961–1990 (see Table S1) and replacing the single weather variable with values from the period 1991–2020.

Weather variable	1991–2020 minus 1961–1990	ΔET_0
Daily maximum temperature (ΔT_{max})	+1.5 °C	+22 mm
Daily minimum temperature (ΔT_{min})	+1.0 °C	+8 mm
Relative humidity (ΔRh) Vapor pressure deficit (ΔVPD)	-1 % +0.06 kPa	+12 mm
Solar radiation (ΔR_s)	+14 Wm^{-2}	+31 mm
Wind speed (Δu_2)	+0.1 ms^{-1}	+6 mm

Table S3: Change in mean values over the period 1989–2018 to 2041–2070 of the weather variables daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), relative humidity (*Rh*), vapour pressure deficit (*VPD*), global radiation (R_s), and wind speed (u_2) used to calculate reference evapotranspiration (ET_0) according to FAO56 guidelines (Allen et al., 1998). The weather data were produced by a weather generator by scaling the statistics of an observed climate at the Geisenheim weather station (Rheingau, Germany) from 1959–1988 with different climate change scenarios from different models for RCP4.5 and RCP8.5. The impact of the change of one weather variable on ET_0 (ΔET_0) was assessed by calculating ET_0 with monthly values from 1989–2018 (not explicitly shown) and replacing the single weather variable with values from the period 2041–2070.

RCP4.5	**CLM-HadCM3Q0**		**RCA3-HadCM3Q16**		**RACMO2-ECHAM5**		**REMO-ECHHAM5**		**RCA-BCM**	
Weather variable	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**
ΔT_{max} (°C)	+1.8	+26	+1.9	+27	+1.2	+18	+1.1	+14	+1.0	+12
ΔT_{min} (°C)	+1.7	+14	+1.9	+16	+1.2	+11	+1.1	+11	+1.1	+9
ΔRh (%)	-1	+12	+1	-2	0	-1	-1	+3	0	0
ΔVPD (kPa)	+0.08		+0.06		+0.03		+0.03		+0.02	
ΔR_s (Wm^{-2})	+4	+17	-5	-1	-1	0	-4	-13	-3	-2
Δu_2 (ms^{-1})	0.0	-1	-0.1	-3	0.0	-2	0.0	+1	0.0	0

RCP4.5	**HIRHAM5-BCM**		**RCA-ECHAM5**		**HIRHAM5-ARP.**		**RCA-HadCM3Q3**		**HIRHAM5-ECH.5**	
Weather variable	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**
ΔT_{max} (°C)	+0.9	+11	+1.0	+14	+1.0	+16	+1.0	+10	+0.8	+7
ΔT_{min} (°C)	+1.0	+8	+1.0	+9	+1.1	+10	+1.3	+9	+1.0	+7
ΔRh (%)	0	-3	0	-2	0	-1	+1.0	-10	+1.0	-8
ΔVPD (kPa)	+0.02		+0.02		+0.03		+0.01		-0.00	
ΔR_s (Wm^{-2})	-2	+1	-2	-1	-7	-16	-5.0	-10	-6.0	-13
Δu_2 (ms^{-1})	0.0	+2	0.0	-2	0.0	-1	0.0	0	0.0	1

RCP8.5	**CLM-HadCM3Q0**		**RCA3-HadCM3Q16**		**RACMO2-ECHAM5**		**REMO-ECHHAM5**		**RCA-BCM**	
Weather variable	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**
ΔTmax (°C)	+3.0	+44	+2.8	+39	+1.9	+25	+1.9	+25	+1.2	15
ΔTmin (°C)	+2.6	+22	+2.6	+23	+2.0	+17	+2.0	+17	+1.3	11
ΔRh (%)	-2	+21	0	+2	0	0	0	-2	0	1
ΔVPD (kPa)	+0.14		+0.09		+0.05		+0.05		+0.03	
ΔRs (Wm-2)	+8	+30	-4	+6	-2	0	-4	-9	-5	-8
Δu2 (ms-1)	0.0	-2	0.0	-1	0.0	-1	-0.1	-4	0.0	0

RCP8.5	**HIRHAM5-BCM**		**RCA-ECHAM5**		**HIRHAM5-ARP.**		**RCA-HadCM3Q3**		**HIRHAM5-ECH.5**	
Weather variable	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**	**2041–2070 minus 1989–2018**	**ΔET_0 (mm)**
ΔT_{max} (°C)	+1.4	+19	+1.4	+20	+1.7	+26	+2.0	+23	+1.2	+13
ΔT_{min} (°C)	+1.5	+13	+1.5	+13	+1.7	+16	+2.3	+17	+1.4	+10
ΔRh (%)	0	-1	0	-4	0	+3	+2	-17	+1	-10
ΔVPD (kPa)	+0.03		+0.03		+0.05		+0.02		+0.01	
ΔR_s (Wm^{-2})	-2	0	-4	-7	-9	-20	-6	-9	-8	-17
Δu_2 (ms^{-1})	0.0	+1	0.0	-1	0.0	-1	-0.1	-3	0.0	+1

Note to Table S3:

Following the calculation procedure of the FAO56 guidelines, the vapour pressure deficit was calculated from monthly means of temperature and relative humidity data. Regarding the calculation of ET_0 the variables relative humidity and vapour pressure deficit are interchangeable and lead to the same results. The changes in the annual means of the weather variables shown in the table do not take into account seasonal shifts, which are, however, included in the changes in reference evapotranspiration calculated with monthly means. Therefore the data are useful for assessing the impact of changes in weather variables on ET_0 for each model but less appropriate to compare different models.

Table S4: Range of change signals of 10 climate simulations with different models for the station Geisenheim (Rheingau), Germany, as in Table 3, but for RCP4.5.

	Ensemble change signals (2071–2100 minus 1961–1988)		
Season	P (mm)	ET_0 (mm)	CWB (mm)
Spring (MAM)	-11 to +28	-12 to +14	-22 to +28
Summer (JJA)	-43 to +30	-8 to +72	-116 to +38
Autumn (SON)	-17 to +20	+4 to +19	-36 to +14
Winter (DJF)	-10 to +24	+2 to +9	-12 to +20
Year	-45 to +118	0 to +108	-150 to +93