Supplementary Information

The benefits of increasing resolution in global and regional climate simulations for European climate extremes

Carley E. Iles, Robert Vautard, Jane Strachan, Sylvie Joussaume, Bernd R. Eggen and Chris D. Hewitt

Table S1: CMIP5 and CORDEX "historical" simulations used. CMIP5 models that drive EURO-CORDEX models are shown in the top part of the table, with the driving ensemble member(s) in bold, and their corresponding CORDEX simulations to the left. Crosses donate the available CORDEX simulations, with those forming part of the "common subset" in bold (blue for precipitation, orange for temperature and green for wind). Total numbers of models and simulations in each category are shown in the bottom three rows.

CMIP5 models	Atmospheric Resolution (lat x lon°)	Ensemble members used (bold indicates simulations used to drive CORDEX)			CORDEX 0.44°				CORDEX 0.11°		
		precipitation	temperature	wind		precip	temperature	wind	precip	temperature	wind
CanESM2	2.79 x 2.81	**r1,** r2, r3, r4, r5	**r1,** r2, r3, r4, r5	**r1**, r2, r3, r4, r5	CanESM2 r1 RCA	x	x	x			
					CanESM2 r1 WRF	x	x	x			
CNRM-CM5	1.40 x 1.41	**r1,** r2, r3, r4, r5, r6, r7, r8, r9, r10	**r1,** r2, r3, r4, r5, r6, r7, r8, r9, r10	**r1***	CNRM-CM5 r1 ALADIN52	x	x				
					CNRM-CM5 r1 ALADIN53	**x**	**x**		**x**	**x**	
					CNRM-CM5 r1 ALARO	**x**			**x**		
					CNRM-CM5 r1 CCLM4				x	x	x
					CNRM-CM5 r1 RCA	**x**	**x**	**x**	**x**	**x**	**x**
CSIRO-Mk3-6-0	1.87 x 1.875	**r1,** r2, r3, r4, r5, r6, r7, r8, r9, r10	**r1,** r2, r3, r4, r5, r6, r7, r8, r9, r10	**r1**, r7, r8, r9, r10	CSIRO-r1 RCA	x	x	x			
					EC-EARTH r12 CCLM4				x	x	
EC-EARTH	1.12 x 1.13	**r1, r2**$^{+}$, r7, r8, r9, r11, **r12**, r13	**r1, r2**, r5, r7, r8, **r12**, r13, r14		EC-EARTH r3 HIRHAM	**x**	**x**	x	**x**	**x**	x
					EC-EARTH r1 RACMO	**x**	**x**	x	**x**	**x**	x
					EC-EARTH r12 RACMO	**x**	**x**		**x**	**x**	x
					EC-EARTH r12 RCA	**x**	**x**	x	**x**	**x**	x
GFDL-ESM2M	2.02 x 2.5	**r1**	**r1**	**r1***	GFDL-ESM2M r1 RCA	x	x	x			
					HadGEM2-ES r1 CCLM4				x	x	
HadGEM2-ES	1.25 x 1.875	**r1,** r2, r3, r4, r5	**r1,** r2, r3, r4, r5	**r1**	HadGEM2-ES r1 RACMO	**x**	**x**	**x**	**x**	**x**	**x**
					HadGEM2-ES r1 RCA	**x**	**x**	**x**	**x**	**x**	**x**
IPSL-CM5A-MR	1.27 x 2.5	**r1, r2**	**r1**	**r1***, r2, r3	IPSL-CM5A-MR r1 RCA	**x**	**x**	**x**	**x**	**x**	**x**
					IPSL-CM5A-MR r1 WRF	**x**	**x**	**x**	**x**	**x**	**x**

MIROC5	1.40 x 1.41	**r1,** r2, r3, r4, r5	**r1,** r2, r3, r4, r5	**r1***, r4, r5	MIROC5 r1 RCA	x	x	x			
MPI-ESM-LR	1.87 x 1.875	**r1, r2,** r3	**r1, r2,** r3	**r1, r2**, r3	MPI-ESM-LR r1 CCLM4	x	x		x	x	
					MPI-ESM-LR r1 RCA	x	x	x	x	x	x
					MPI-ESM-LR r1 REMO	x	x		x	x	x
					MPI-ESM-LR r2 REMO	x	x		x	x	x
					NorESM-M r1 HIRHAM				x	x	x
NorESM1-M	1.89 x 2.5	**r1,** r2, r3	**r1,** r2, r3		NorESM-M r1 RCA	x	x	x			
					NorESM-M r1 WRF	x	x				
ACCESS1-0	1.25 x 1.875	r1, r2, r3	r1, r2, r3	r1*, r3							
ACCESS1.3	1.25 x 1.875	r2, r3	r1, r2, r3	r1*							
bcc-csm1-1	2.79 x 2.81	r1, r2, r3	r1, r2, r3								
bcc-csm1-1-m	2.79 x 2.81	r1, r2, r3	r1, r2, r3								
BNU-ESM	2.79 x 2.81	r1	r1	r1							
CCSM4	0.94 x 1.25	r1, r2, r3	r1, r2, r6								
CESM1-BGC	0.94 x 1.25	r1	r1								
CESM1-CAM5	0.94 x 1.25	r1	r1								
CESM1-FASTCHEM	0.94 x 1.25	r1, r2, r3	r1, r2, r3								
CMCC-CESM	3.44 x 3.75	r1	r1	r1							
CMCC-CM	0.75 x 0.75	r1	r1	r1*							
CMCC-CMS	3.71 x 3.75	r1	r1								
FGOALS_g2	2.79 x 2.81	r1, r2	r1, r2								
FGOALS-s2	1.66 x 2.81	r1									
GISS-E2-H	2 x 2.5	r6		r6*							
GISS-E2-R	2 x 2.5	r6	r6	r6*							
GFDL-CM3	2 x 2.5	r1, r2, r3, r4, r5	r1, r2, r3, r4, r5	r1*, r2, r3, r4, r5							
GFDL-ESM2G	2.02 x 2	r1	r1	r1*							
HadCM3	2.5 x 3.75	r1, r2, r3, r4, r5, r6, r7, r8, r9, r10	r1, r2, r3, r4, r5, r6, r7, r8, r9, r10								
HadGEM2-AO	1.25 x 1.875	r1	r1								
HadGEM2-CC	1.25 x 1.875	r1, r2, r3	r1	r1, r2, r3							
inmcm4	1.5 x 2	r1	r1	r1*							

IPSL-CM5A-LR	1.89 x 3.75	r1, r2, r3 ,r4, r5, r6	r1	r1*, r2, r3, r4, r5, r6							
IPSL-CM5B-LR	1.89 x 3.75	r1	r1	r1							
MIROC4h	0.56 x 0.56	r1, r2, r3	r1, r2, r3	r1, r2, r3							
MIROC-ESM	2.79 x 2.81	r1, r2, r3	r1, r2, r3	r1*, r2, r3							
MIROC-ESM-CHEM	2.79 x 2.81	r1	r1	r1*							
MPI-ESM-MR	1.87 x 1.875	r1, r2, r3	r1, r2, r3	r1, r2, r3							
MPI-ESM-P	1.87 x 1.875	r1, r2	r1, r2	r1, r2							
MRI-CGCM3	1.12 x 1.125	r1, r2, r3	r1, r2, r3	r1							
MRI-ESM1	1.12 x 1.125	r1	r1	r1*							
Total simulations		126	115	61	Total simulations	23	22	15	19	18	14
Total models		41	39	28							
Total models (simulations) in "common subset"		5 (15)	5 (14)	4 (6)	Total simulations in "common subset"	15	14	6	15	14	6

ᵼ r3 not available for EC-Earth, r2 substituted instead, * simulations used for the 3 hourly wind vs sfcWindmax comparison

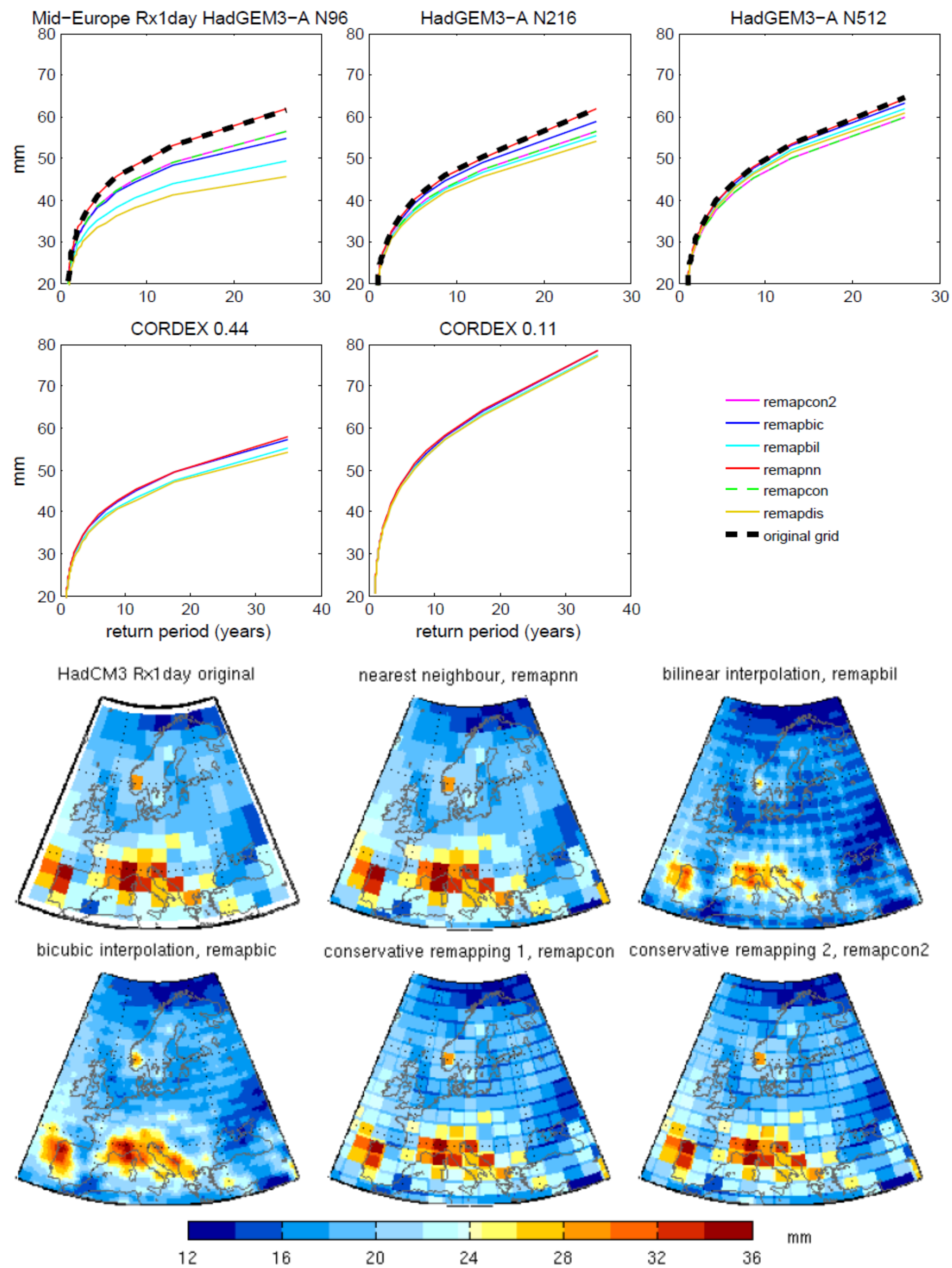
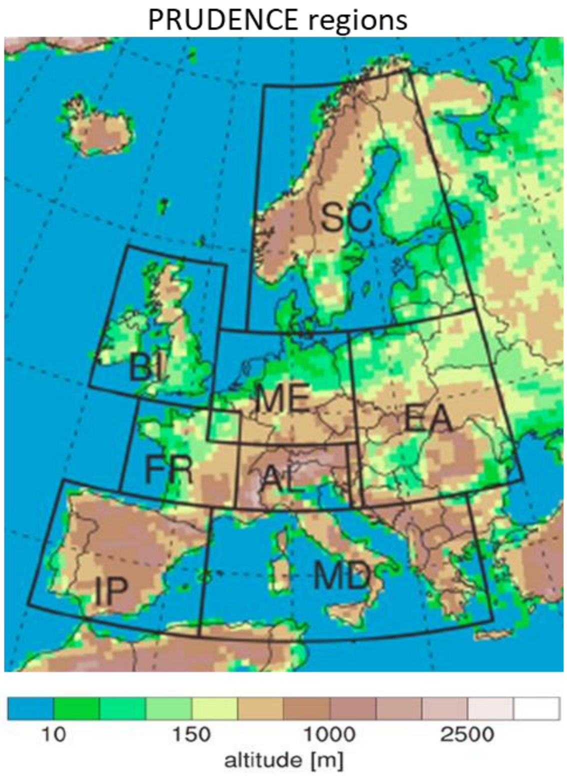


Figure S1: Sensitivity of results for extreme precipitation to regridding method for a range of models of different resolutions. Top panels – return period plots for Rx1day for Mid-Europe, for (top row) the UPSCALE simulations at N96 (130km - similar to CMIP5 resolutions), N216 (60 km) and N512 (25 km) resolution, and (second row) CORDEX at 0.44° (50 km) and 0.11° (12.5 km). Results using the original grid are shown by the black dashed line for UPSCALE. CDO operators are: remapbil - bilinear interpolation, remapbic - bicubic interpolation, remapcon - conservative remapping, remapcon2 – conservative remapping 2, remapnn - nearest neighbour and remapdis - distance weighted average. Results for lower resolution models are much more sensitive to regridding technique than higher resolution ones. Similar differences were found across all regions and were generally largest over the Alps. Bottom panels- sensitivity of spatial patterns of the climatological mean of Rx1day over Europe for the period 1950-2005 for a number of different regridding techniques for HadCM3- as an example of a coarse resolution model (c. 300 km). Higher resolution models did not show such obvious artefacts. Nearest neighbour was selected as the best performing method overall.



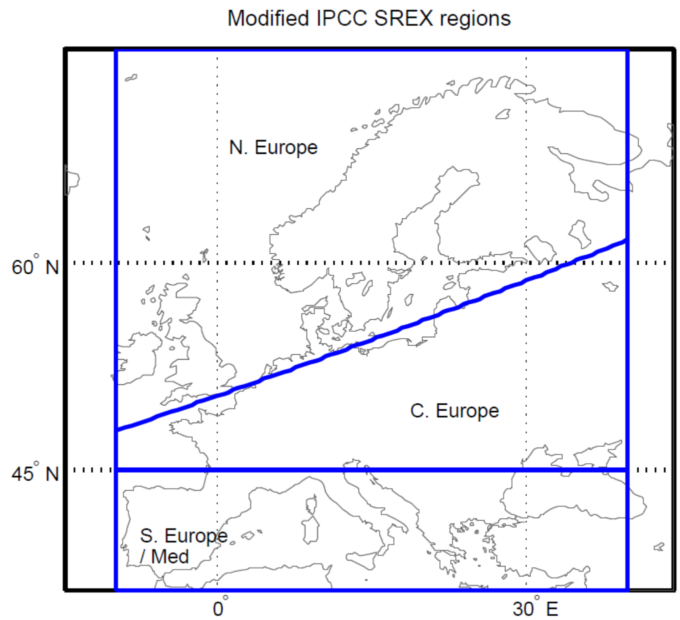


Figure S2: The regions used a) PRUDENCE regions, figure taken from (Weimer et al. 2016), b) modified SREX regions

Table S2: Regions used- based on the PRUDENCE regions (Christensen and Christensen, 2007) and the IPCC SREX regions (Seneviratne et al., 2012). We consider land areas only. Note that the IPCC regions used here are slightly modified from the original ones due to the constraints of a 0.5° grid and a domain size that spans 35°N to 72.5°N rather than 30°N to 75°N.

IPCC SREX regions	**Longitude**	**Latitude**
Northern Europe	-10° to 40°E	48° to 72.5°N at Western edge, 61.5° to 72.5°N at Eastern edge
Central Europe	-10° to 40°E	45° to 48°N at Western edge, 45° to 61.5°N at Eastern edge
South Europe/ Mediterranean (referred to here as Southern Europe)	-10° to 40°E	35 to 45°N
PRUDENCE regions		
BI: British Isles	-10° to 2°E	50 to 59°N
IP: Iberian Peninsula	-10° to 3°E	36 to 44°N
FR: France	-5° to 5°E	44 to 50°N
ME: Mid-Europe	2° to 16°E	48 to 55°N
SC: Scandinavia	5° to 30°E	55 to 70°N
AL: Alps	5° to 15°E	44 to 48°N
MD: Mediterranean	3° to 25°E	36 to 44°N
EA: Eastern Europe	16° to 30°E	44 to 55°N

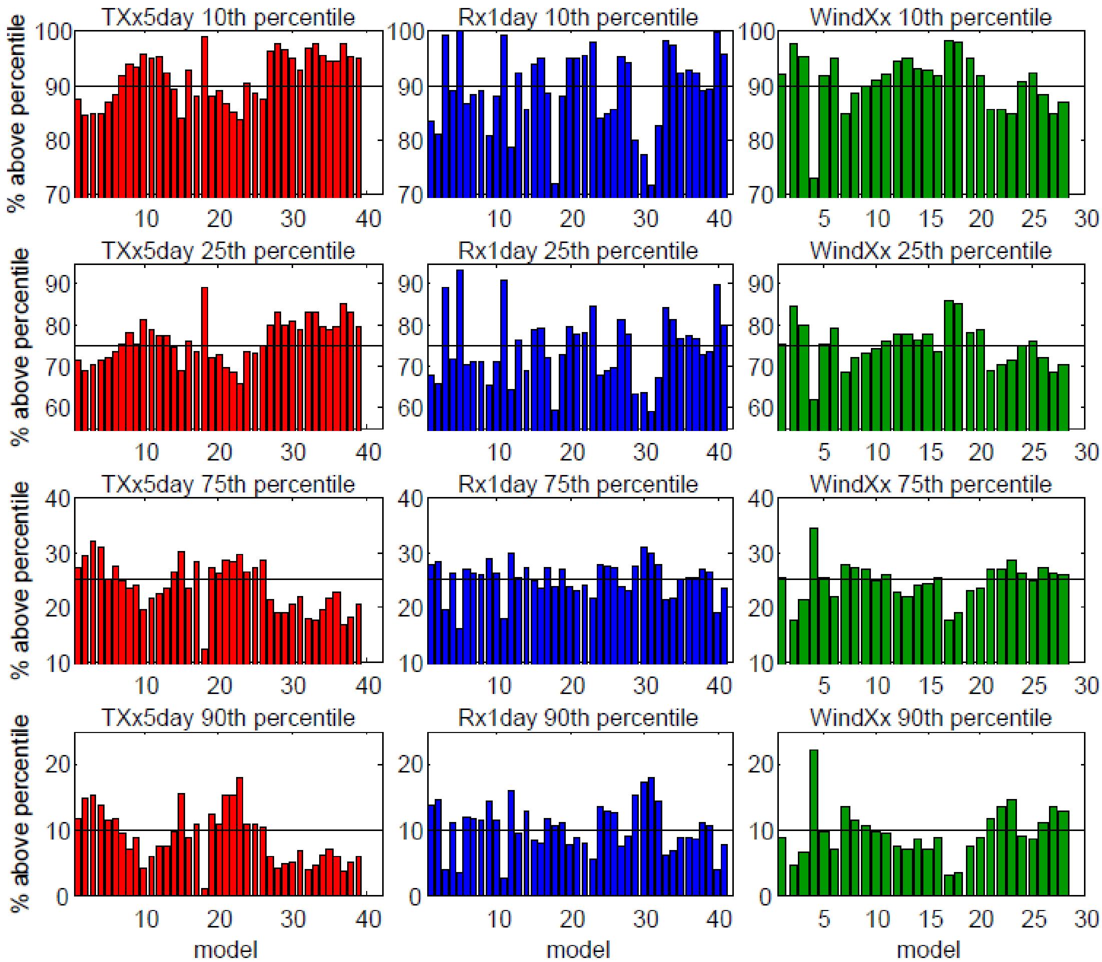


Figure S3: Distribution of models in the return period curves for Central Europe. Bars show for each model (numbered 1 to ~40) the percentage of values for that model that lie above the 10th (top row), 25th (second row), 75th (third row) and 90th (bottom row) percentile of values across all models. This is calculated for each grid cell, and then area averages are made. Horizontal lines indicate expected values if models were evenly spread throughout the distribution. Left column TXx5day, middle column Rx1day, right column WindXx. Results were similar for other regions.

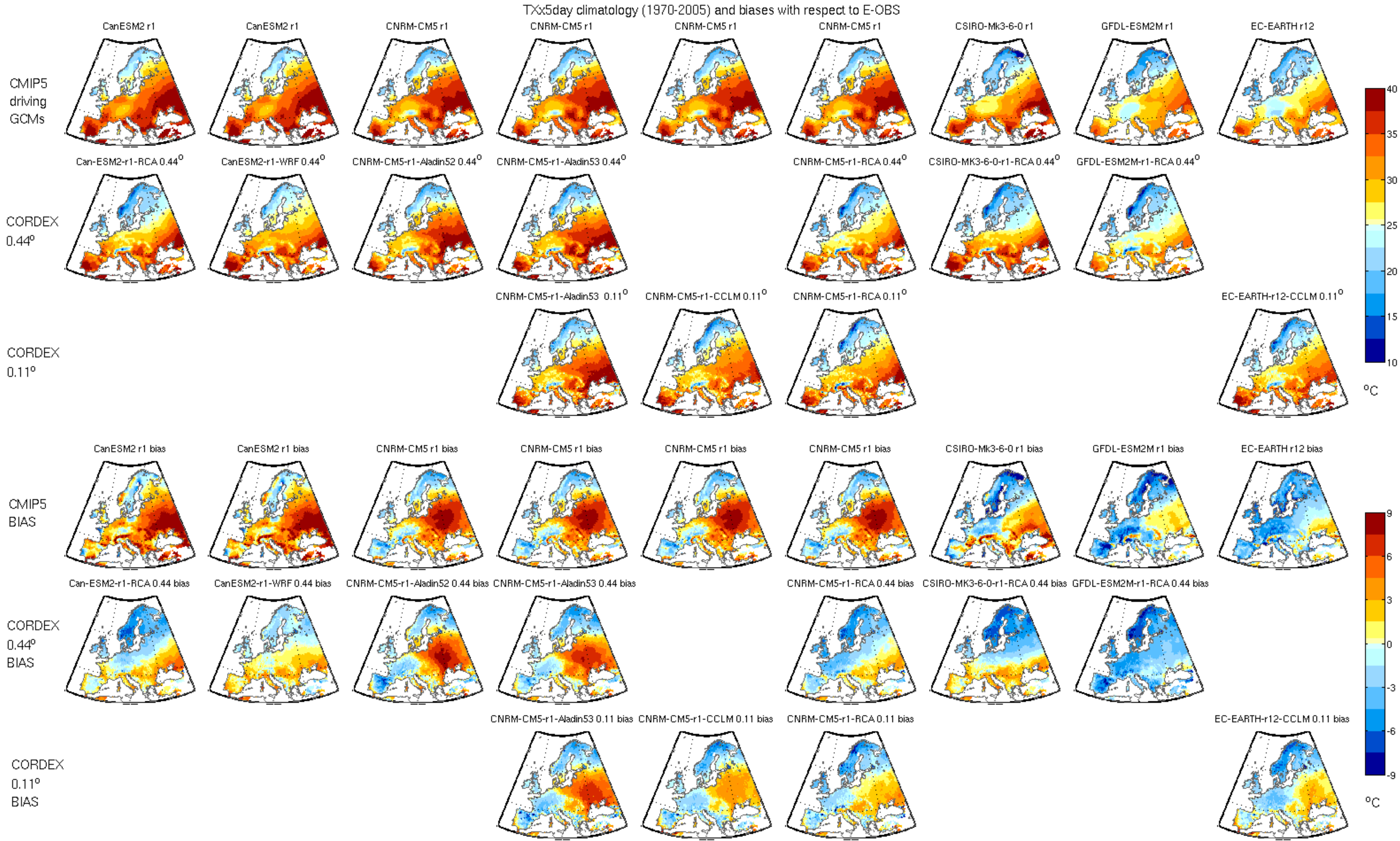


Figure S4: Climatological mean of TXx5day for individual CORDEX models and their driving CMIP5 GCMs for the period 1970-2005 and their biases with respect to E-OBS. Top row: CMIP5 driving GCMs, second row: CORDEX 0.44°, third row CORDEX 0.11°, fourth row CMIP5 biases, fifth row CORDEX 0.44° biases, sixth row CORDEX 0.11° biases. Each column represents a single GCM-RCM combination, with either one or two resolutions of the RCM. EOBS is shown at the bottom of page 3. Units °C.

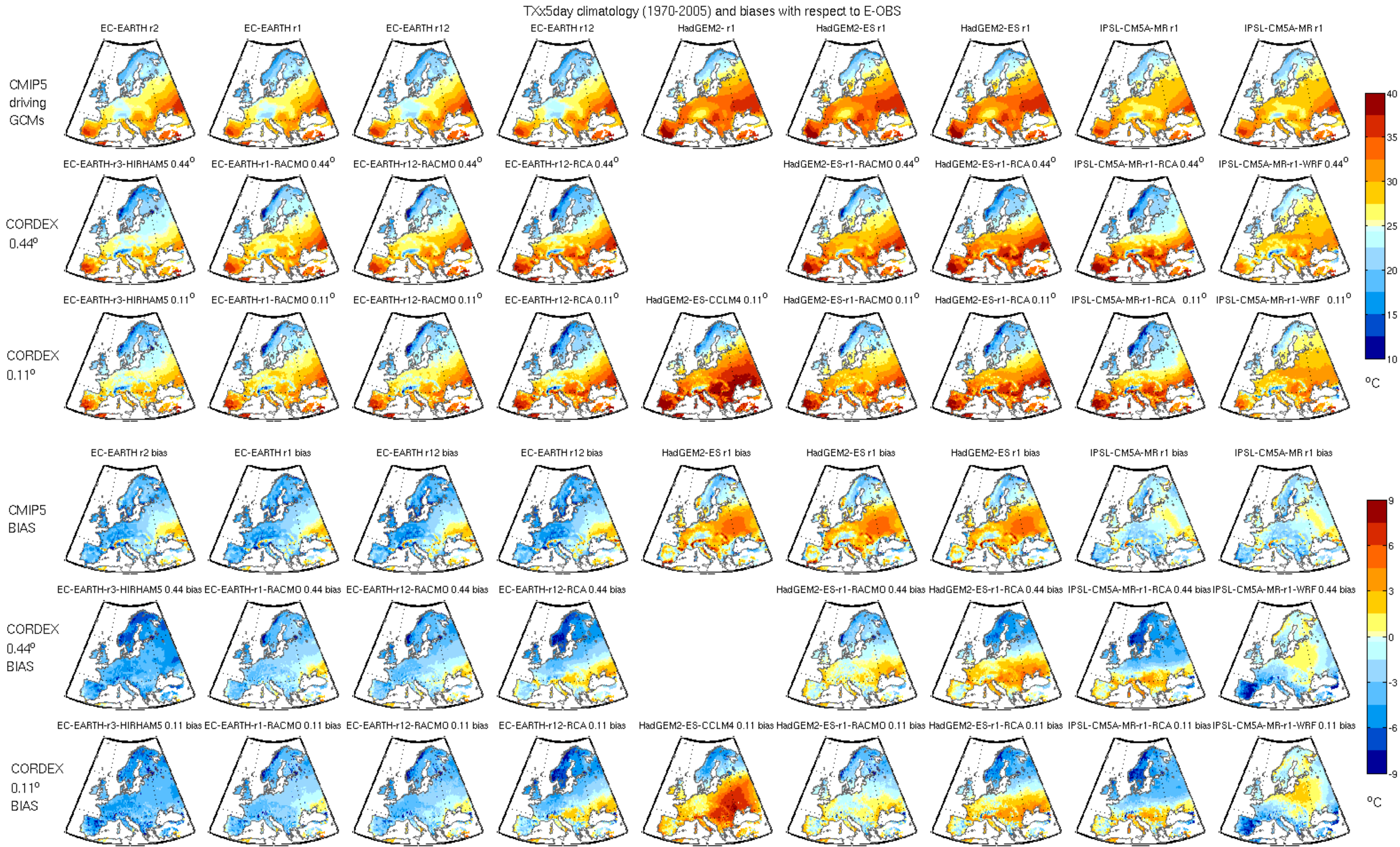


Figure S4 continued

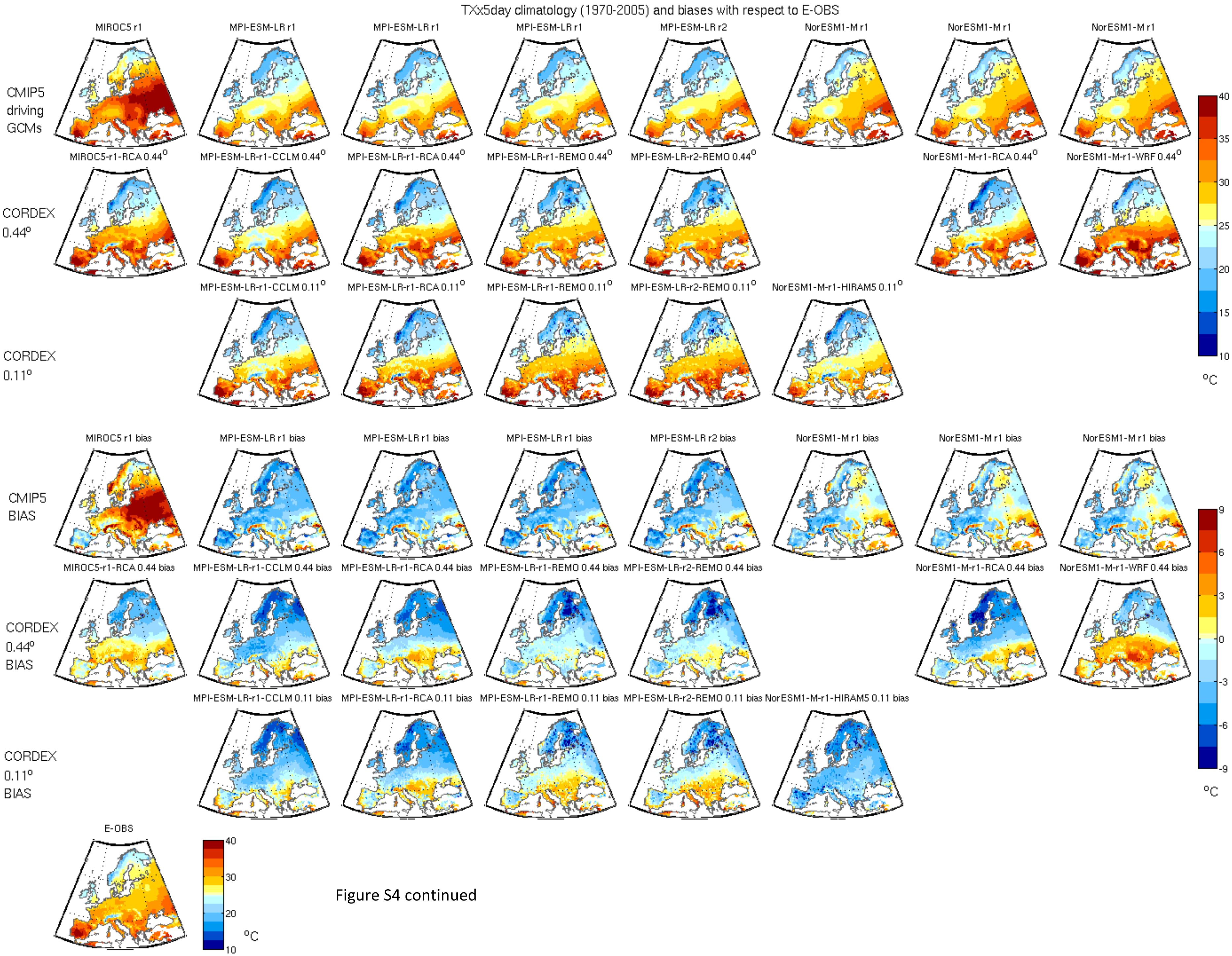


Figure S4 continued

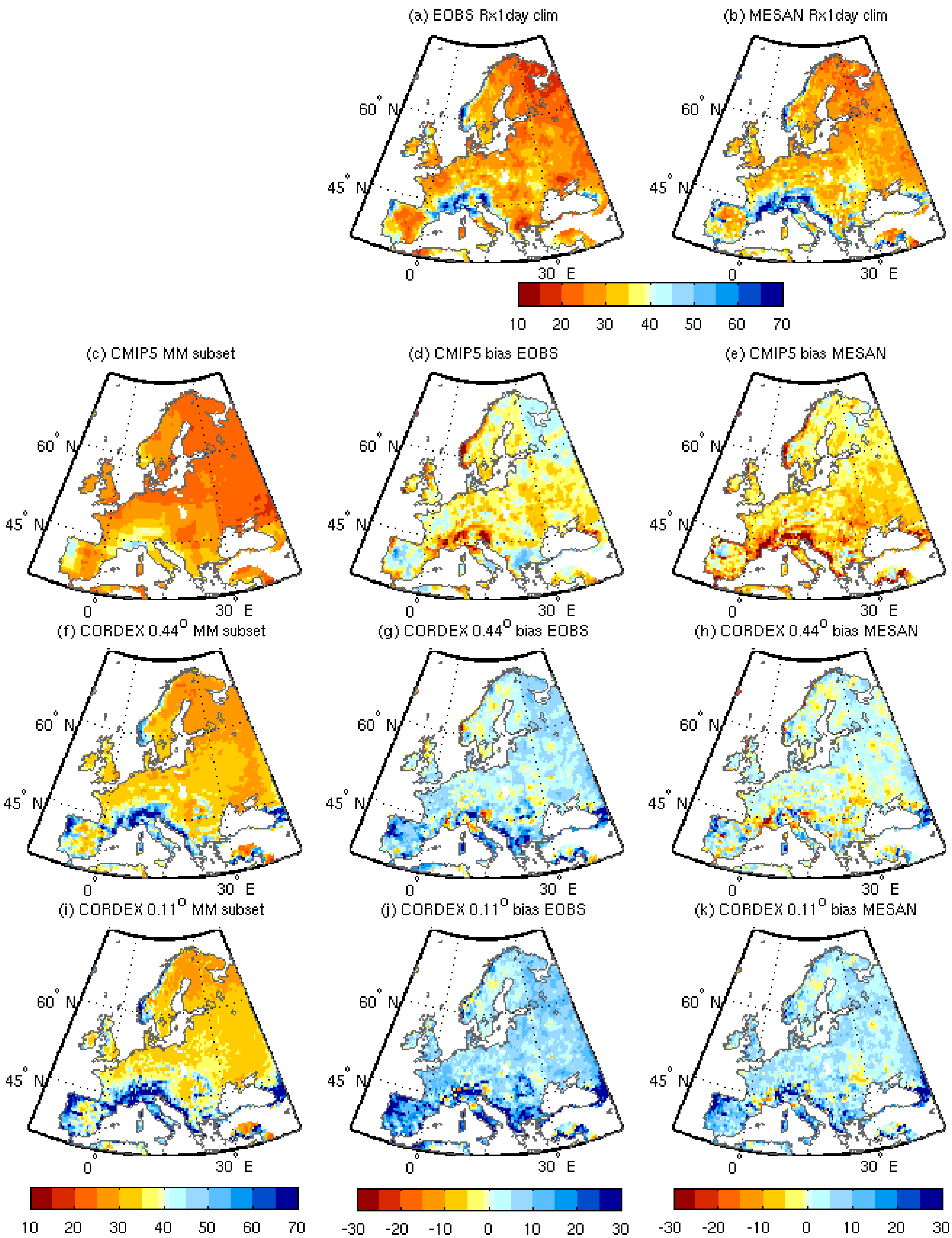


Figure S5: Climatological mean of Rx1day comparing E-OBS and MESAN for the period 1989-2005 for the "common subset" of models. (a) E-OBS, (b) MESAN, (c) CMIP5 multi model mean, (d) CMIP5 bias relative to E-OBS, (e) CMIP5 bias relative to MESAN, (f) CORDEX 0.44° multi model mean, (i) CORDEX 0.11° multi model mean, (g, j) CORDEX biases relative to E-OBS, (h, k) CORDEX biases relative to MESAN. Units mm.

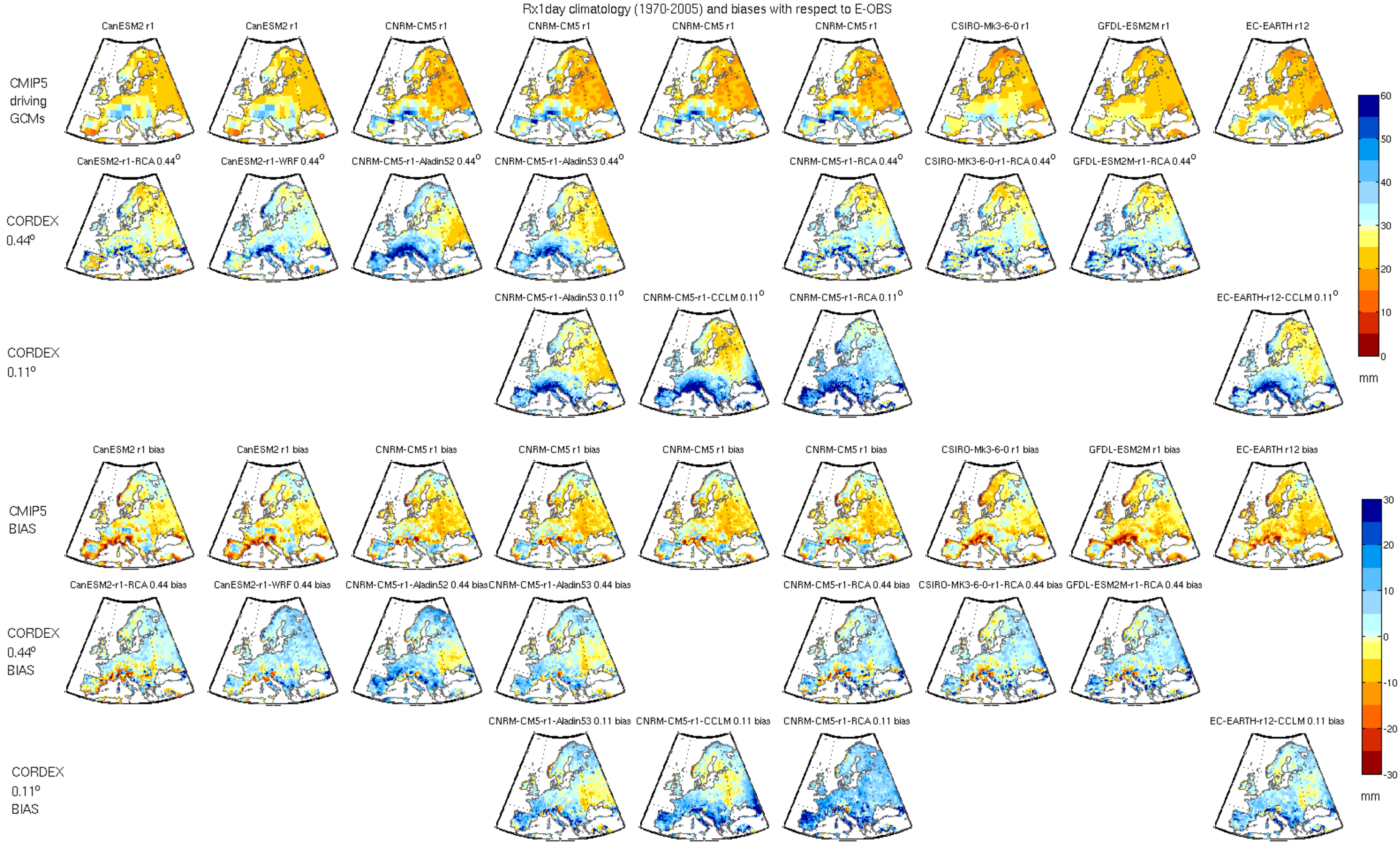


Figure S6: As for Figure S4 but for the climatological mean of Rx1day. Units mm.

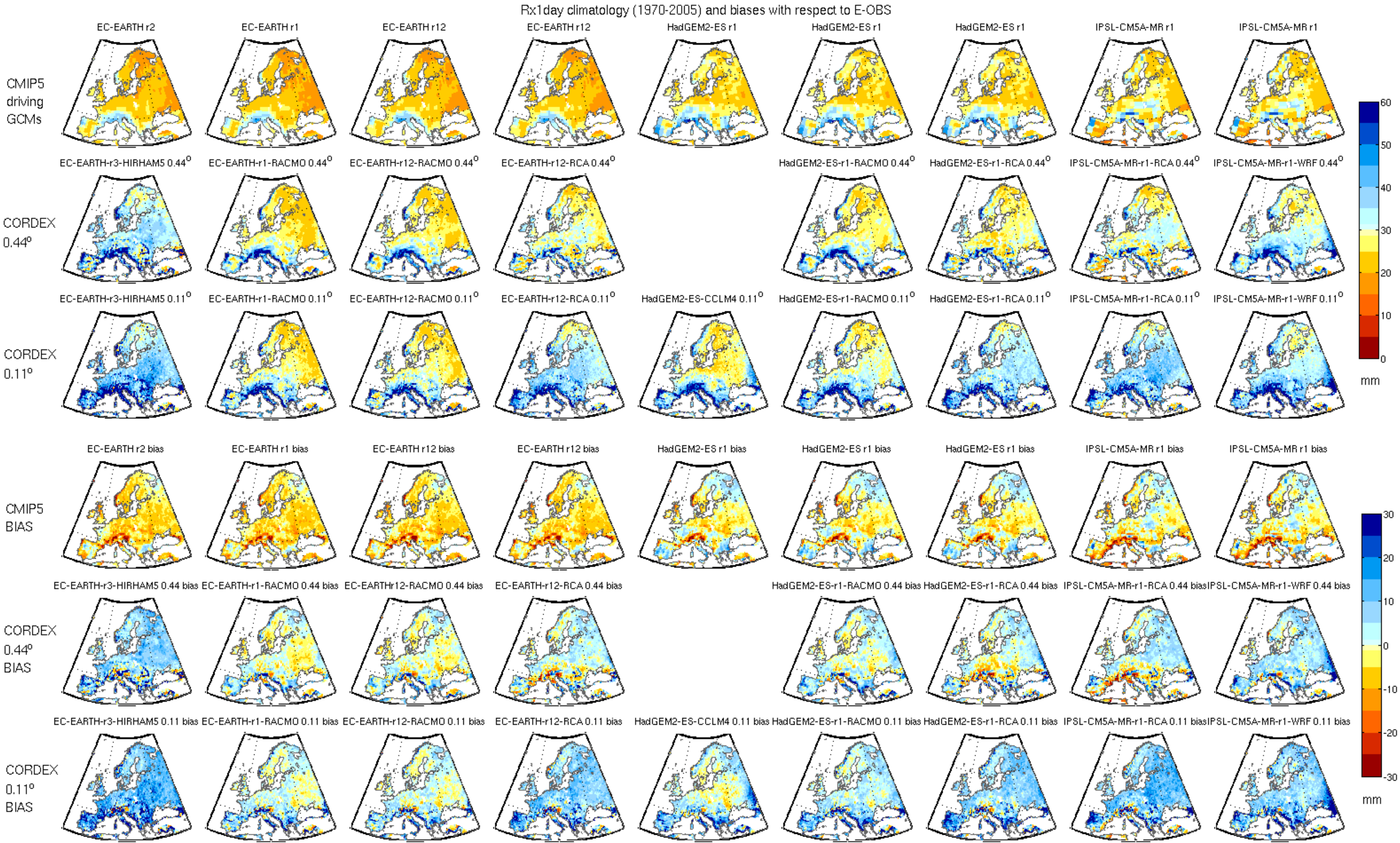


Figure S6 continued

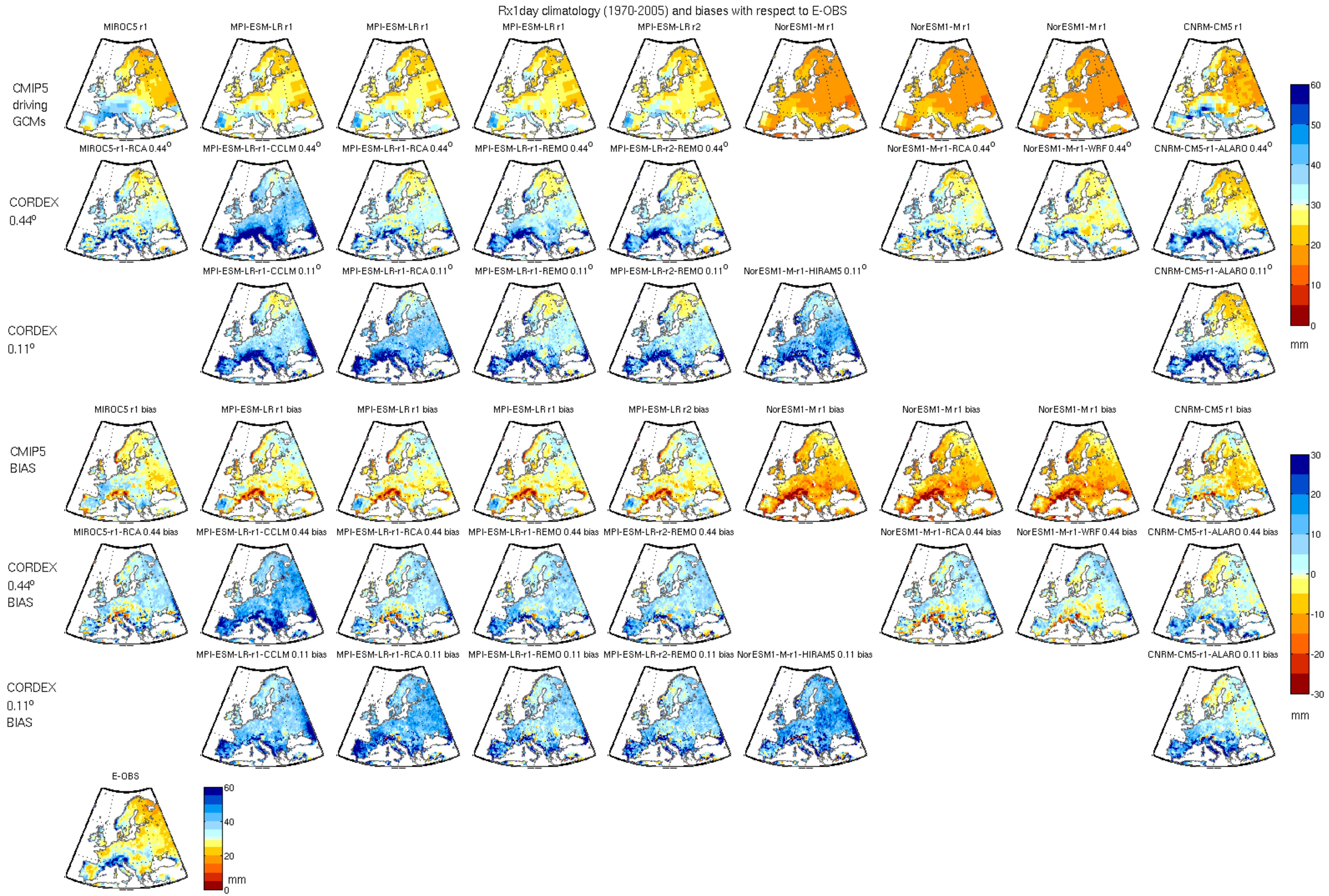


Figure S6 continued

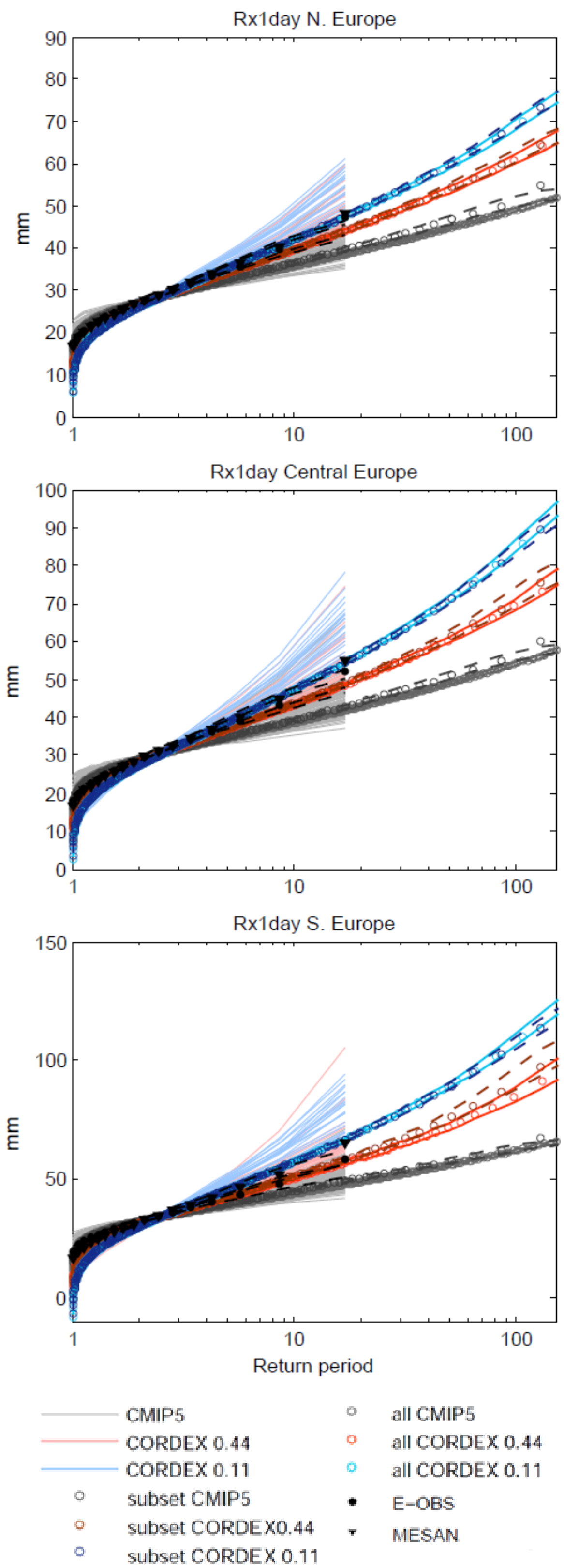


Figure S7: As for Figure 2 middle column, with the addition of the MESAN reanalysis (black triangles), and for the shorter common period 1989-2005. Units mm.

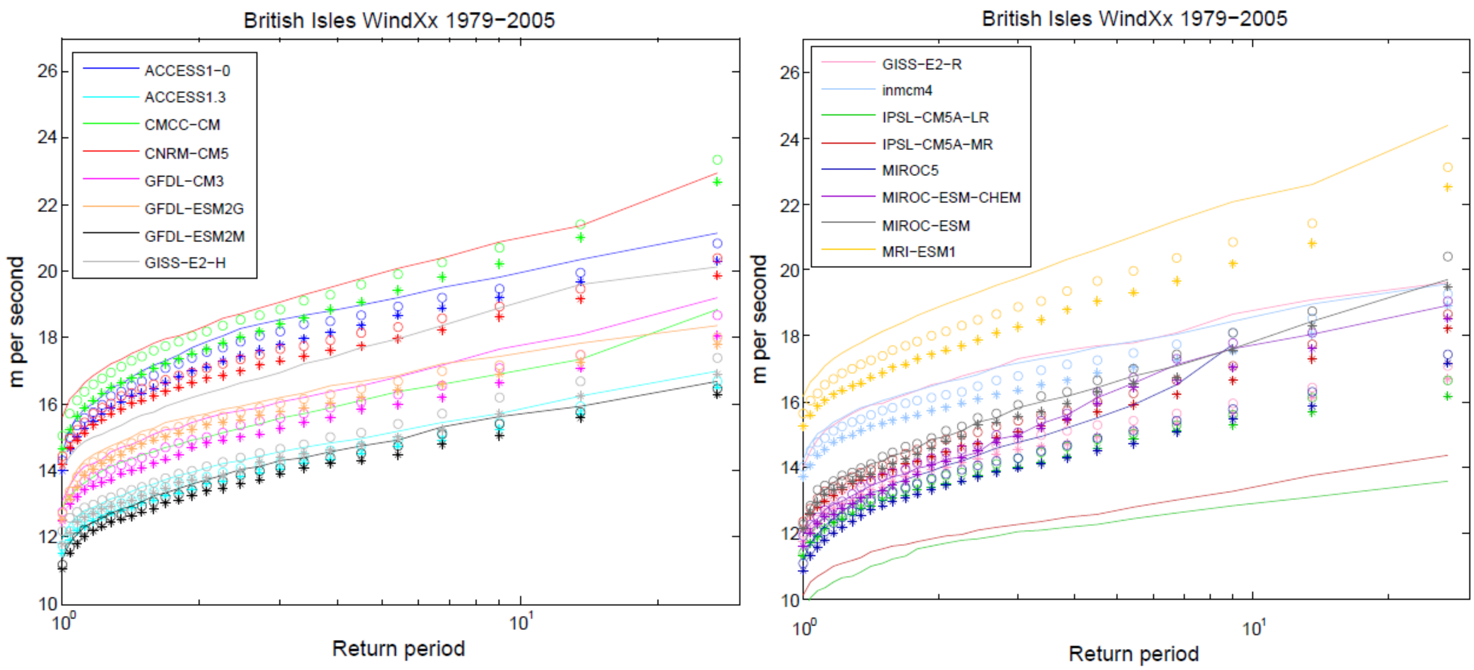


Figure S8: Difference in return period curves for annual maximum wind (WindXx) in CMIP5 models according to the temporal resolution of the underlying data for the example of the British Isles. Models with both the variable sfcWindmax (daily maximum wind) and 3 hourly data are plotted. sfcWindmax (solid lines), daily maximums of 3 hourly data (circles) and daily maximums of 6 hourly data (asterisks).

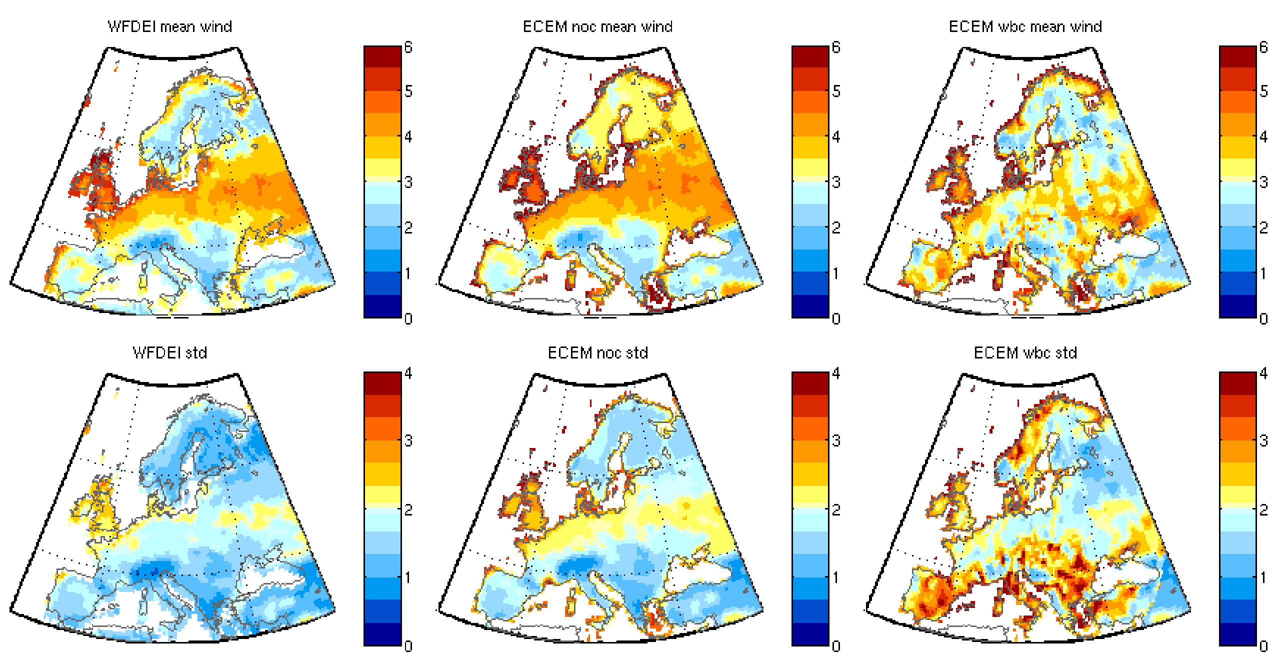


Figure S9: Mean (top row) and standard deviation (bottom row) of 6 hourly wind for the observational datasets WFDEI (left), ECEM noc (middle) and ECEM wbc (right) for the period 1979-2016. Units meters per second.

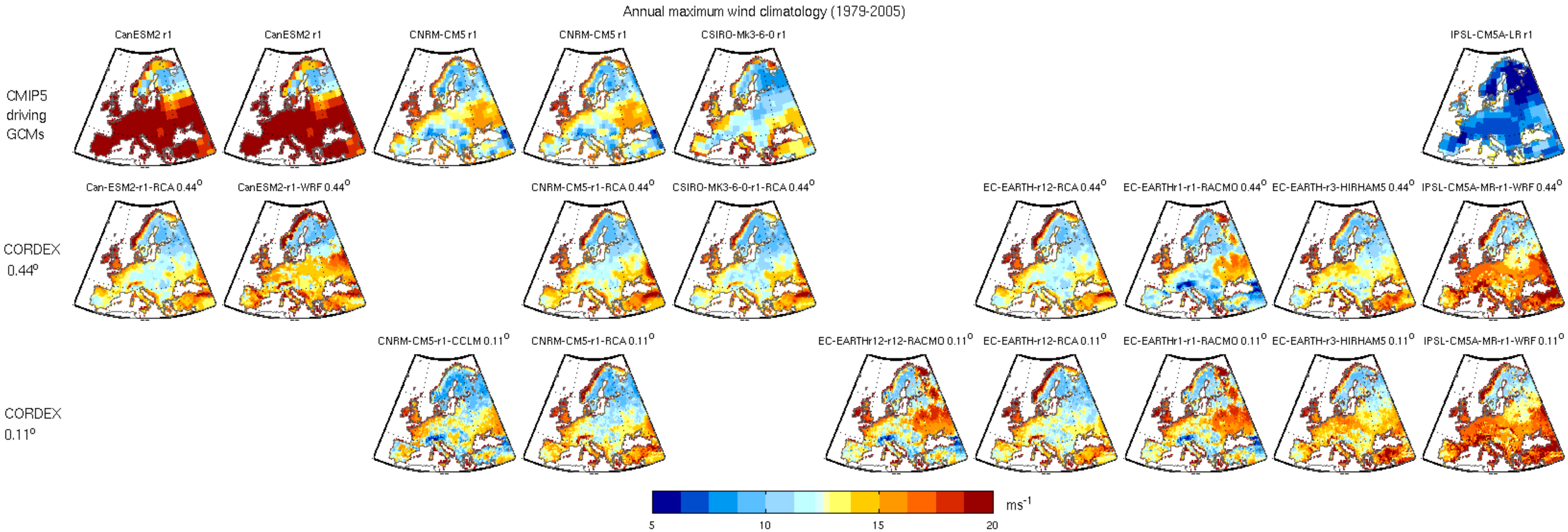


Figure S10: Climatological mean of annual maximum of daily maximum wind for the period 1979-2005 for individual CORDEX simulations and their driving GCMs. Top row: CMIP5 models, 2nd row CORDEX at 0.44°, 3rd row CORDEX at 0.11°. Columns correspond to a single GCM-RCM combination with either one or two resolutions of the RCM.

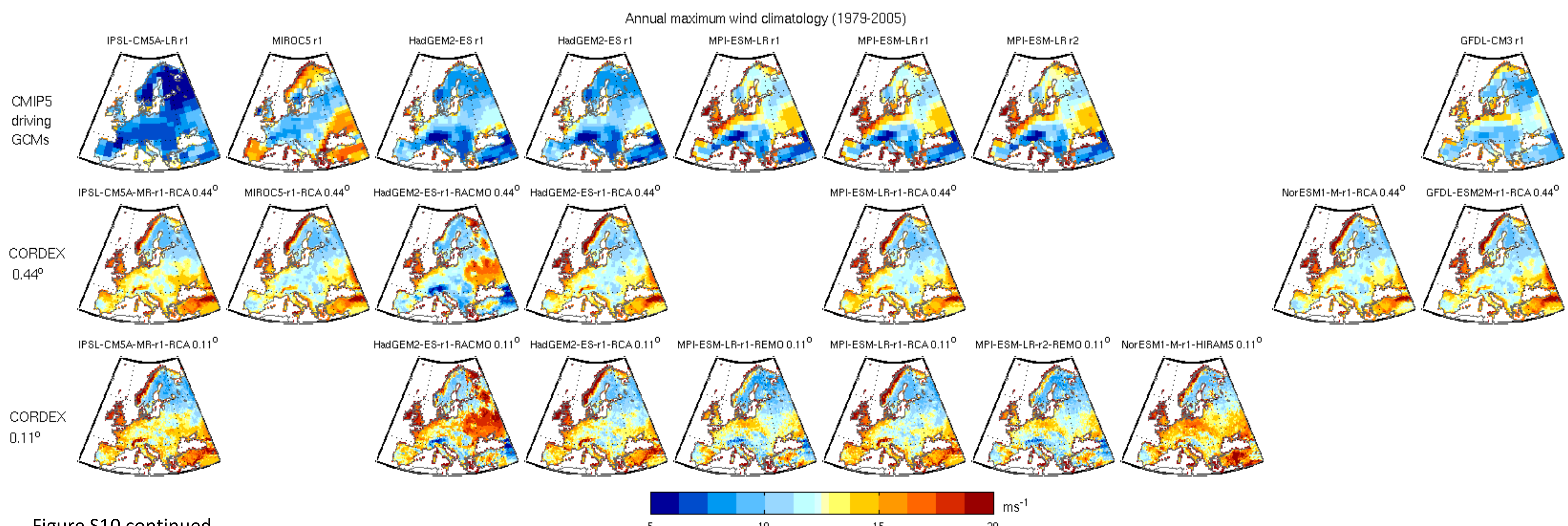


Figure S10 continued

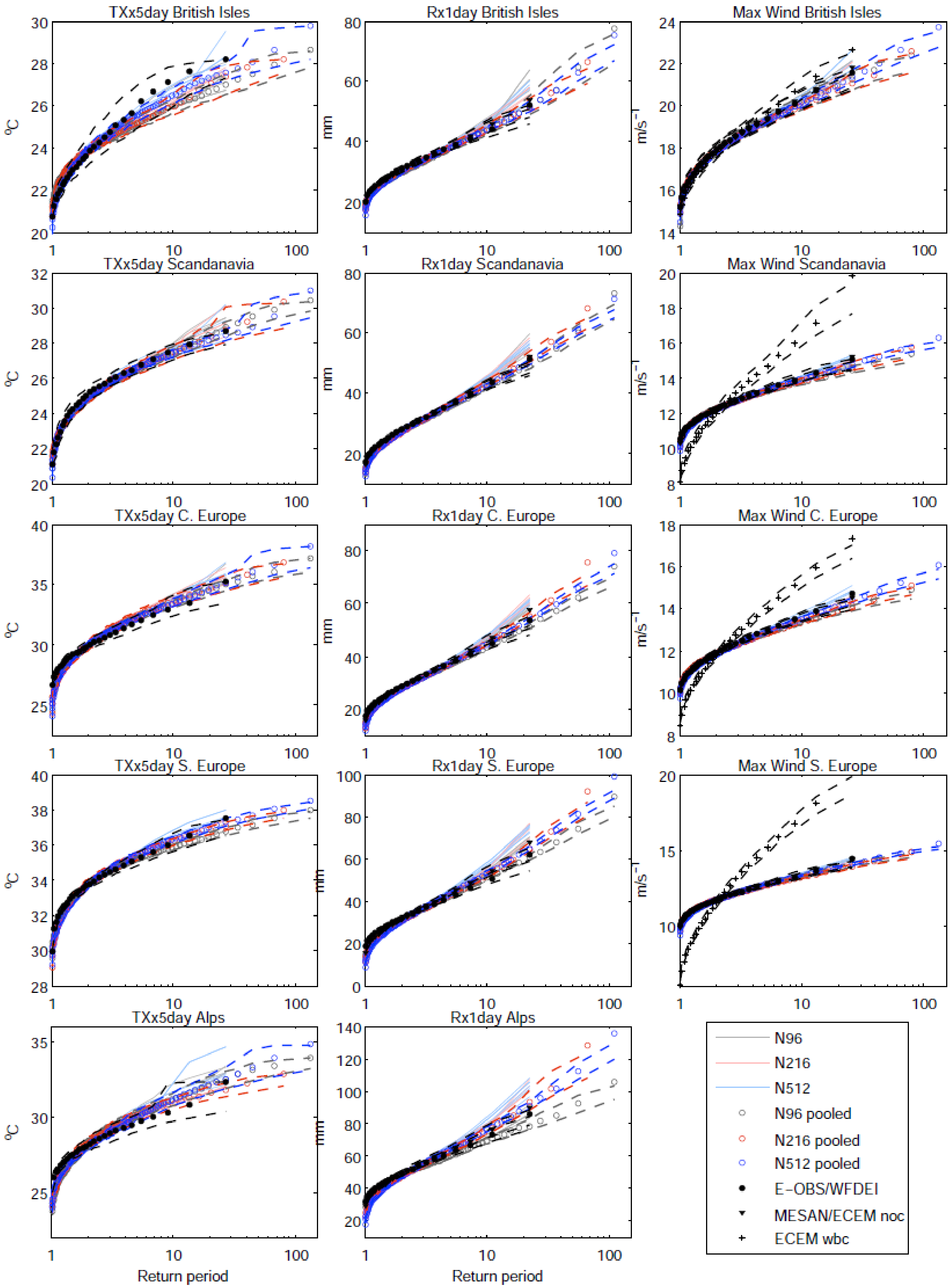


Figure S11: As figure 6 but with bias adjustment so that all models and observations have the same climatological mean

Additional References

Weimer, M., Mieruch, S., Schädler, G., and Kottmeier, C.: A new estimator of heat periods for decadal climate predictions – a complex network approach, Nonlin. Processes Geophys., 23, 307–317, https://doi.org/10.5194/npg-23-307-2016, 2016.