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

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Table S1: The CMIP5 and CORDEX "historical" simulations used in this analysis. 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 right. For other CMIP5 models the first ensemble member was used when available. CORDEX simulations forming part of the "common subset" are shown with colours (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 models	CORDEX 0.44°		CORDEX 0.11°		
		precip	temperature	wind		precip	temperature	precip	temperature	wind
CanESM2	2.79 x 2.81	**r1**	**r1**		CanESM2 RCA4	r1	r1			
					CanESM2 WRF341I	r1	r1			
CNRM-CM5	1.40 x 1.41	**r1**	**r1**	**r1**	CNRM-CM5 ALADIN52	r1	r1			
					CNRM-CM5 ALADIN53	**r1**	**r1**	**r1**	**r1**	**r1** (ALADIN63)
					CNRM-CM5 ALARO-0	**r1**		**r1**		
					CNRM-CM5 CCLM4			r1	r1	
					CNRM-CM5 RCA4	**r1**	**r1**	**r1**	**r1**	**r1**
					CNRM-CM5 HIRHAM5					**r1**
CSIRO-Mk3-6-0	1.87 x 1.875	**r1**	**r1**		CSIRO-Mk3-6-0 RCA4	r1	r1			
EC-EARTH	1.12 x 1.13	**r1, r2^{+}, r12**	**r1, r2^{+}, r12**,	**r1, r9^{+}, r12**	EC-EARTH CCLM4			r12	r12	
					EC-EARTH HIRHAM5	**r3**	**r3**	**r3**	**r3**	**r1, r3, r12**
					EC-EARTH RACMO22E	**r1, r12**	**r1, r12**	**r1, r12**	**r1, r12**	
					EC-EARTH RCA4	**r12**	**r12**	**r12**	**r12**	**r1, r3, r12**
					EC-EARTH COSMO-crCLIM					**r12**
					EC-EARTH HadREM3					**r12**
GFDL-ESM2M	2.02 x 2.5	**r1**	**r1**	r1	GFDL-ESM2M RCA4	r1	r1			
HadGEM2-ES	1.25 x 1.875	**r1**	**r1**	**r2***	HadGEM2-ES CCLM4			r1	r1	
					HadGEM2-ES RACMO22E	**r1**	**r1**	**r1**	**r1**	
					HadGEM2-ES RCA4	**r1**	**r1**	**r1**	**r1**	**r1**
					HadGEM2-ES COSMO-crCLIM					**r1**
					HadGEM2-ES HIRHAM5					**r1**

					HadGEM2-ES HadREM3					**r1**
IPSL-CM5A-MR	1.27 x 2.5	**r1**	**r1**	**r1**	IPSL-CM5A-MR RCA4	**r1**	**r1**	**r1**	**r1**	**r1**
					IPSL-CM5A-MR WRF331F	**r1**	**r1**	**r1**	**r1**	
MIROC5	1.40 x 1.41	**r1**	**r1**	r1	MIROC5 RCA4	r1	r1			
MPI-ESM-LR	1.87 x 1.875	**r1, r2**	**r1, r2**		MPI-ESM-LR CCLM4	**r1**	**r1**	**r1**	**r1**	
					MPI-ESM-LR RCA4	**r1**	**r1**	**r1**	**r1**	r1, r2, r3
					MPI-ESM-LR REMO2009	**r1, r2**	**r1, r2**	**r1, r2**	**r1, r2**	r3 (REMO2015)
					MPI-ESM-LR ALADIN63					r1
					MPI-ESM-LR COSMO-crCLIM					r1, r2, r3
					MPI-ESM-LR r1 HIRHAM5					r1
					MPI-ESM-LR r1 HadREM3					r1
					MPI-ESM-LR r1 RegCM4-6					r1
NorESM1-M	1.89 x 2.5	**r1**	**r1**		NorESM-M r1 HIRHAM5			r1	r1	r1
					NorESM-M r1 RCA4	r1	r1			r1
					NorESM-M r1 WRF331C	r1	r1			
					NorESM-M r1 COSMO-crCLIM					r1
					NorESM-M r1 REMO2009					r1 (REMO2015)
ACCESS1-0	1.25 x 1.875	r1	r1	r1						
ACCESS1.3	1.25 x 1.875	r2	r1	r1						
bcc-csm1-1	2.79 x 2.81	r1	r1							
bcc-csm1-1-m	2.79 x 2.81	r1	r1	r1						
BNU-ESM	2.79 x 2.81	r1	r1	r1						
CCSM4	0.94 x 1.25	r1	r1							
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	r1							
CMCC-CESM	3.44 x 3.75	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	r1							
FGOALS-s2	1.66 x 2.81	r1		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	r1	r1						
GFDL-ESM2G	2.02 x 2	r1	r1	r1						
HadCM3	2.5 x 3.75	r1	r1							
HadGEM2-AO	1.25 x 1.875	r1	r1							
HadGEM2-CC	1.25 x 1.875	r1	r1							
inmcm4	1.5 x 2	r1	r1	r1						
IPSL-CM5A-LR	1.89 x 3.75	r1	r1	r1						
IPSL-CM5B-LR	1.89 x 3.75	r1	r1							
MIROC4h	0.56 x 0.56	r1	r1	r1						
MIROC-ESM	2.79 x 2.81	r1	r1	r1						
MIROC-ESM-CHEM	2.79 x 2.81	r1	r1	r1						
MPI-ESM-MR	1.87 x 1.875	r1	r1							
MPI-ESM-P	1.87 x 1.875	r1	r1							
MRI-CGCM3	1.12 x 1.125	r1	r1	r1						
MRI-ESM1	1.12 x 1.125	r1	r1	r1						
Total simulations		44	42	25	Total simulations	23	22	19	18	31
Total models		41	39	23	Total models	20	19	17	16	23
Total models (simulations) in “common subset”		5 (15)	5 (14)	4 (15)	Total simulations in “common subset”	15	14	15	14	15

† r3 was not available for EC-Earth, r2 was substituted instead for precipitation and temperature, and r9 for wind. * r1 was not available for HadGEM2-ES wind, r2 was substituted instead.

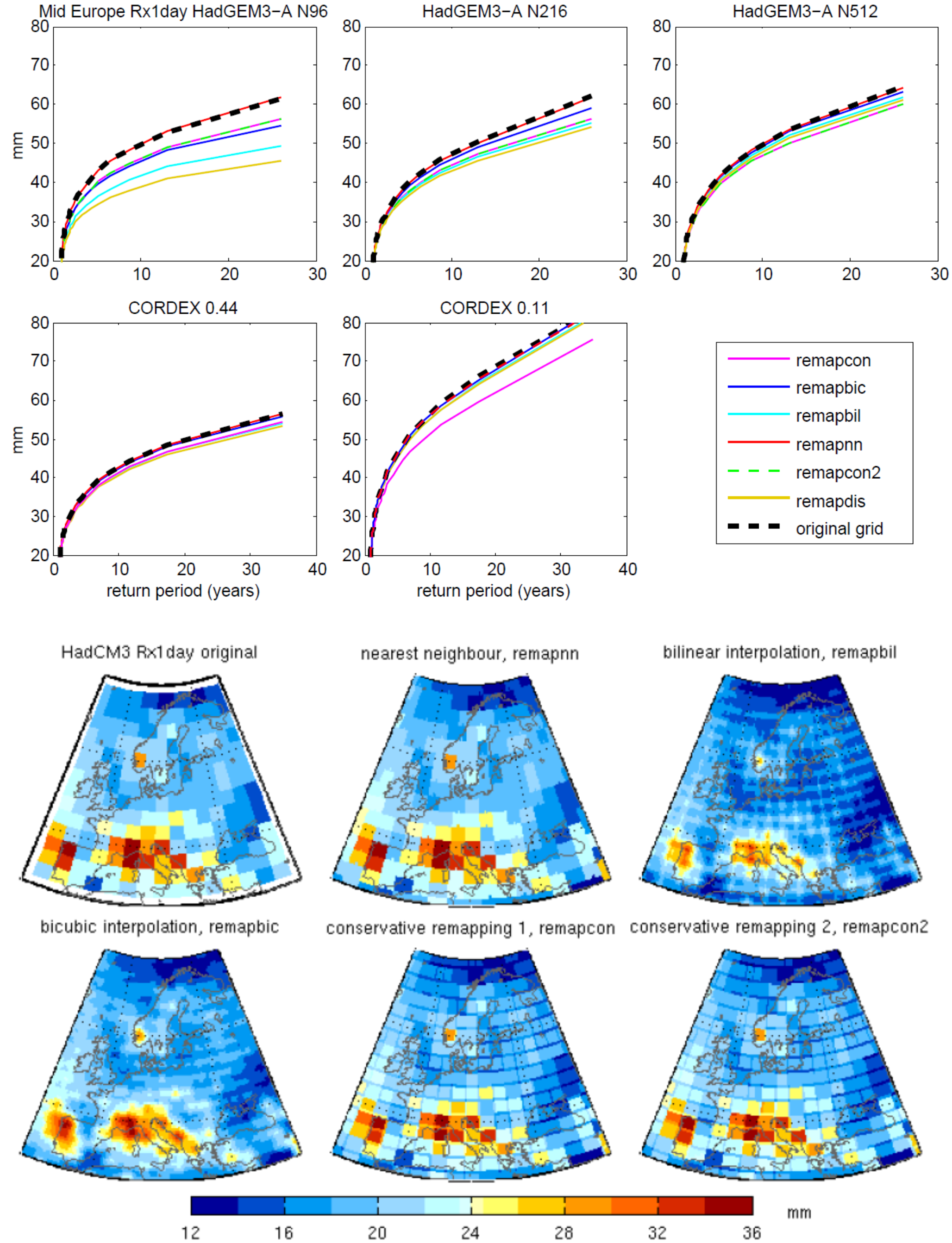
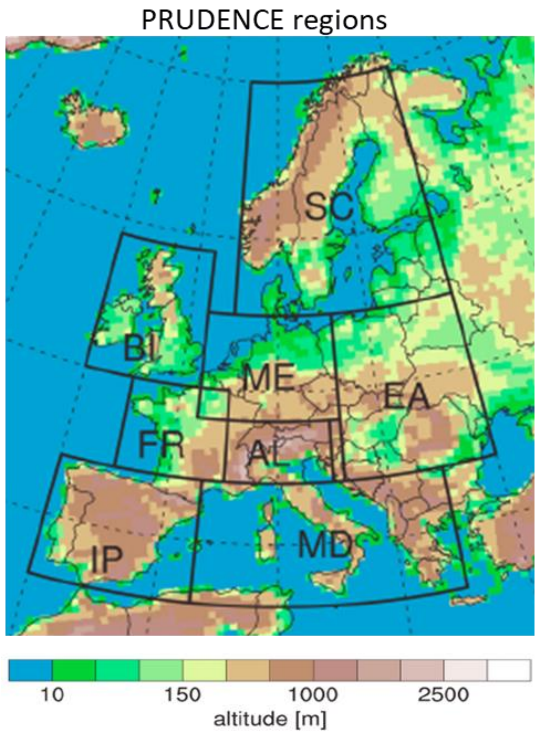


Figure S1: Sensitivity of results for extreme precipitation to regridding method for a range of models of different resolutions. Top panels – return period plots for Rx1day for Mid-Europe, for (top row) the UPSCALE simulations at N96 (130km - similar to CMIP5 resolutions), N216 (60 km) and N512 (25 km) 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. 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.



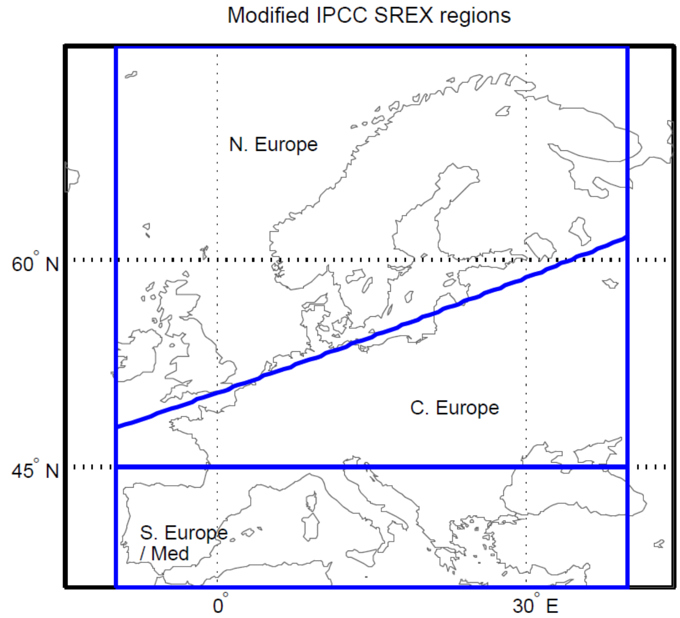


Figure S2: The regions used: a) PRUDENCE regions, figure taken from (Weimer et al. 2016), b) modified SREX regions.

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

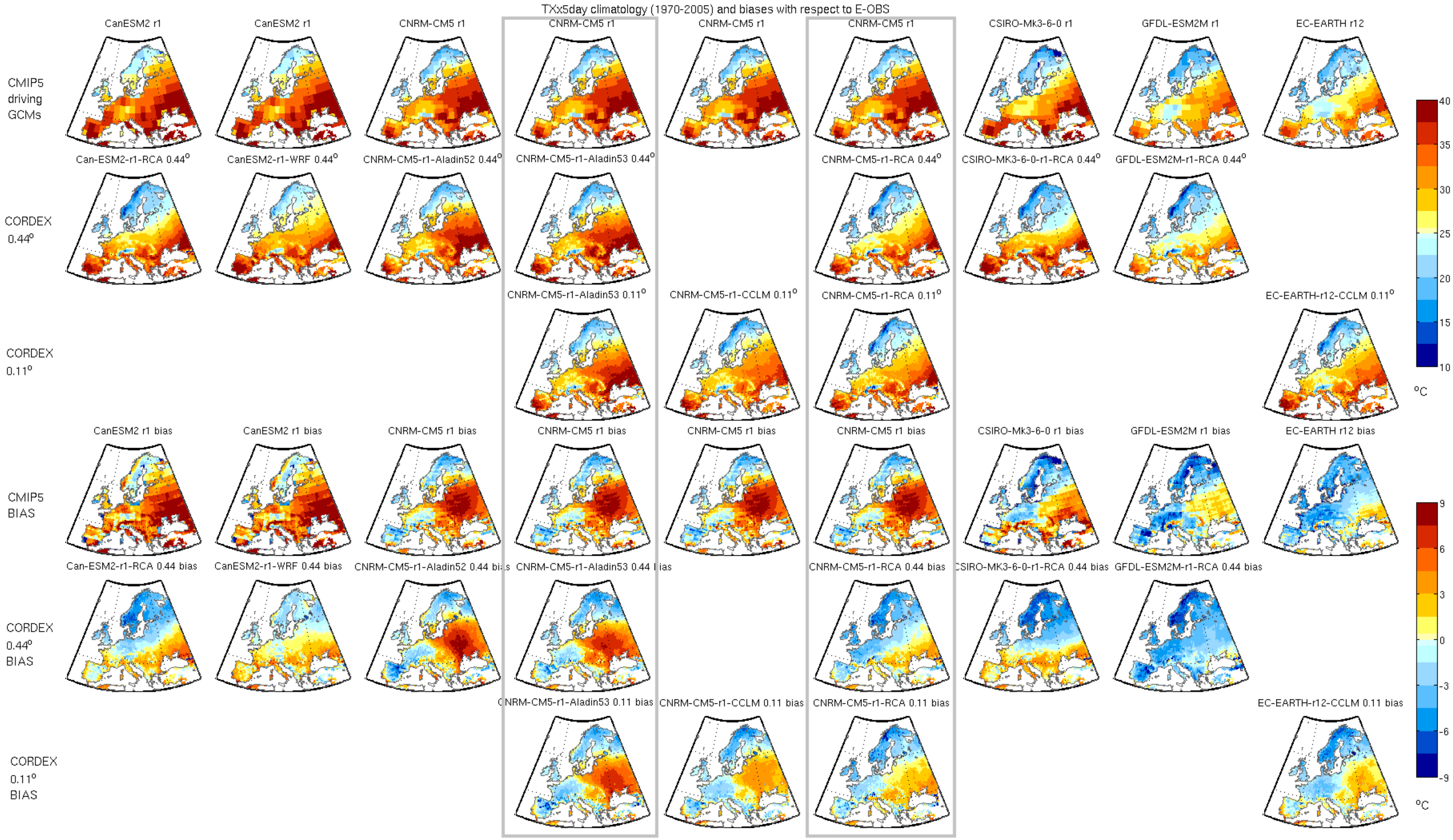


Figure S3: Climatological mean of TXx5day for individual CORDEX models and their driving CMIP5 GCMs for the period 1970-2005 and their biases with respect to E-OBS. Top row: CMIP5 driving GCMs, second row: CORDEX 0.44°, third row CORDEX 0.11°, fourth row CMIP5 biases, fifth row CORDEX 0.44° biases, sixth row CORDEX 0.11° biases. Each column represents a single GCM-RCM combination, with either one or two resolutions of the RCM. Models highlighted with grey rectangles are those used for the “common subset”. E-OBS is shown at the bottom of the third page. Units °C.

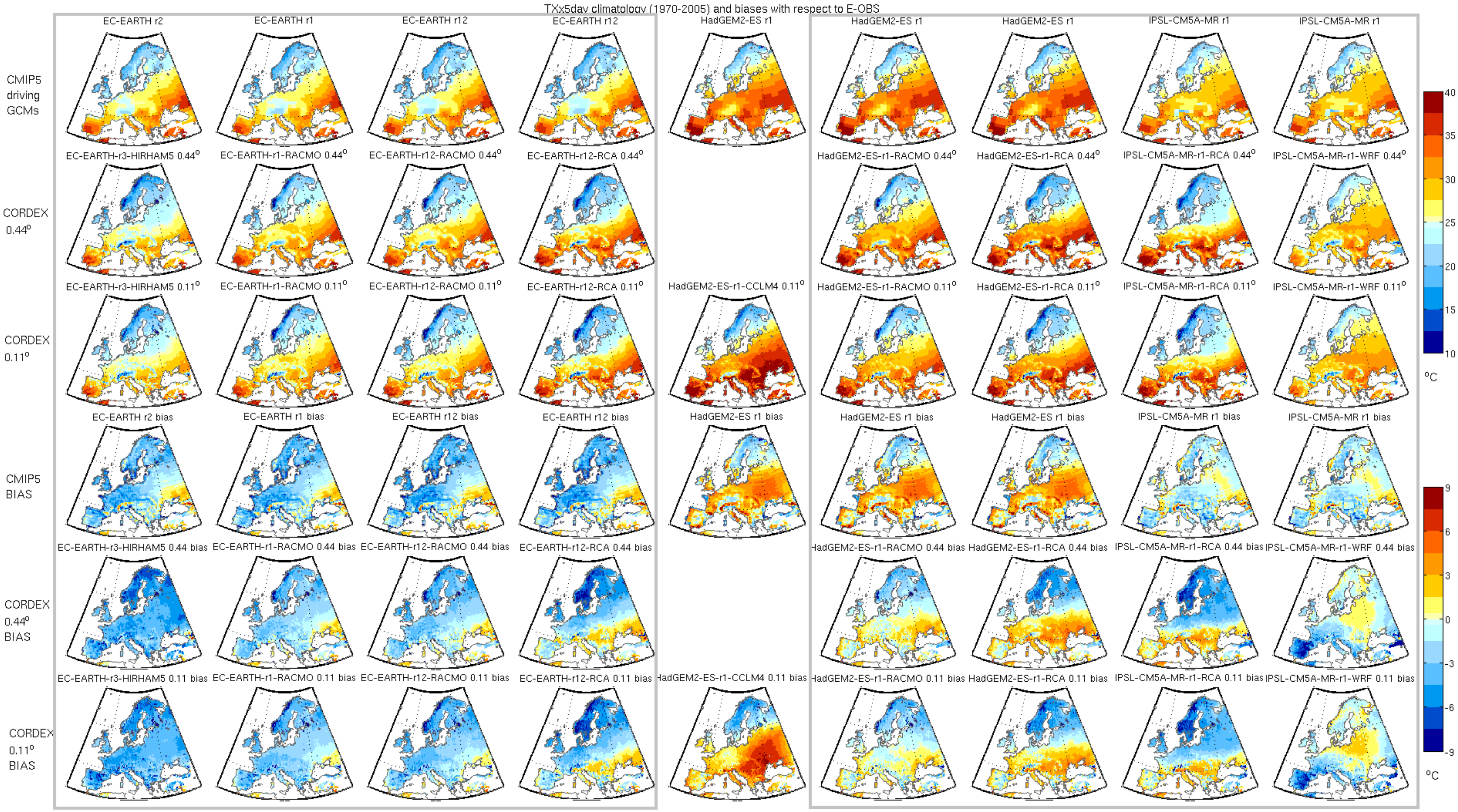


Figure S3 continued

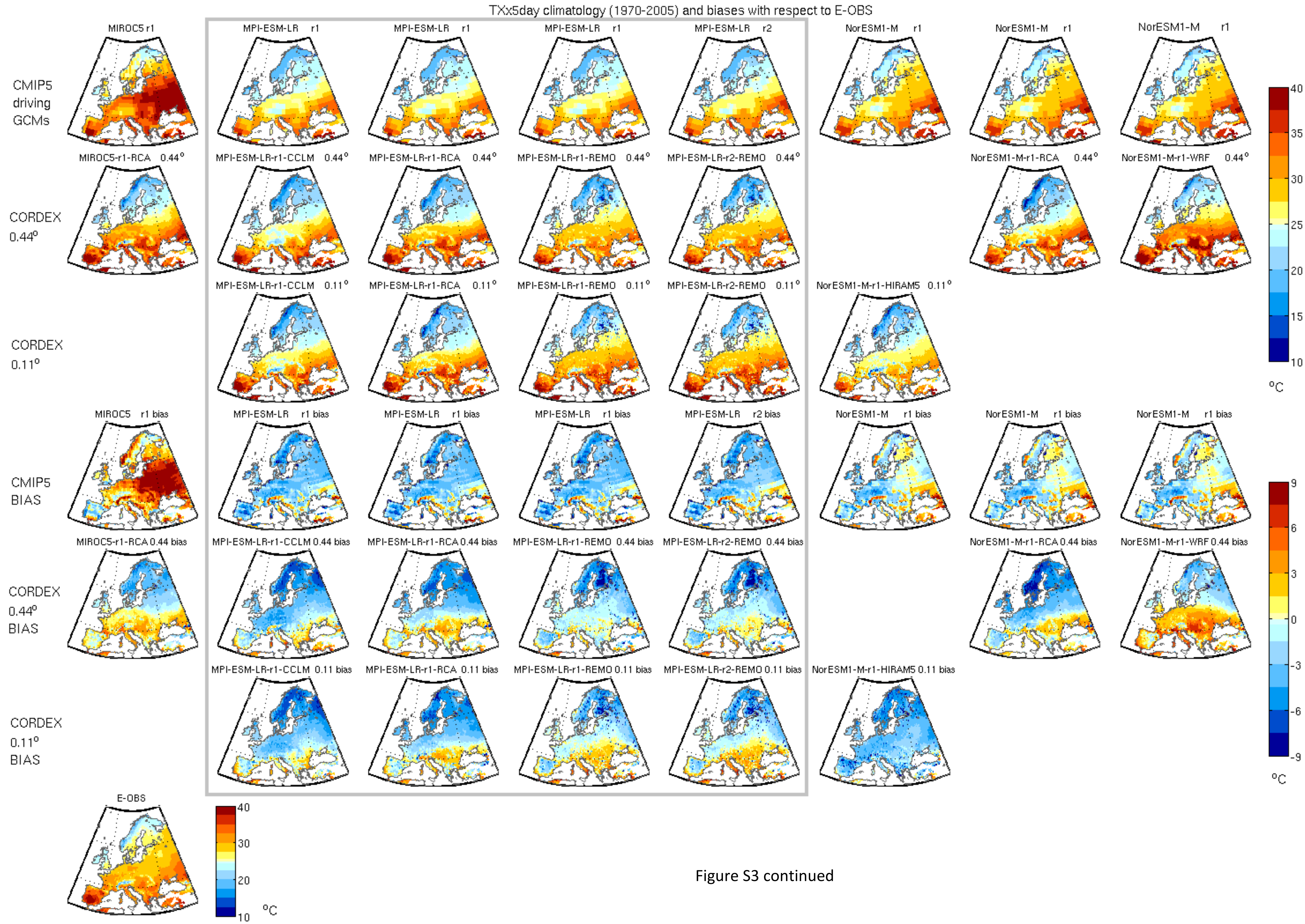


Figure S3 continued

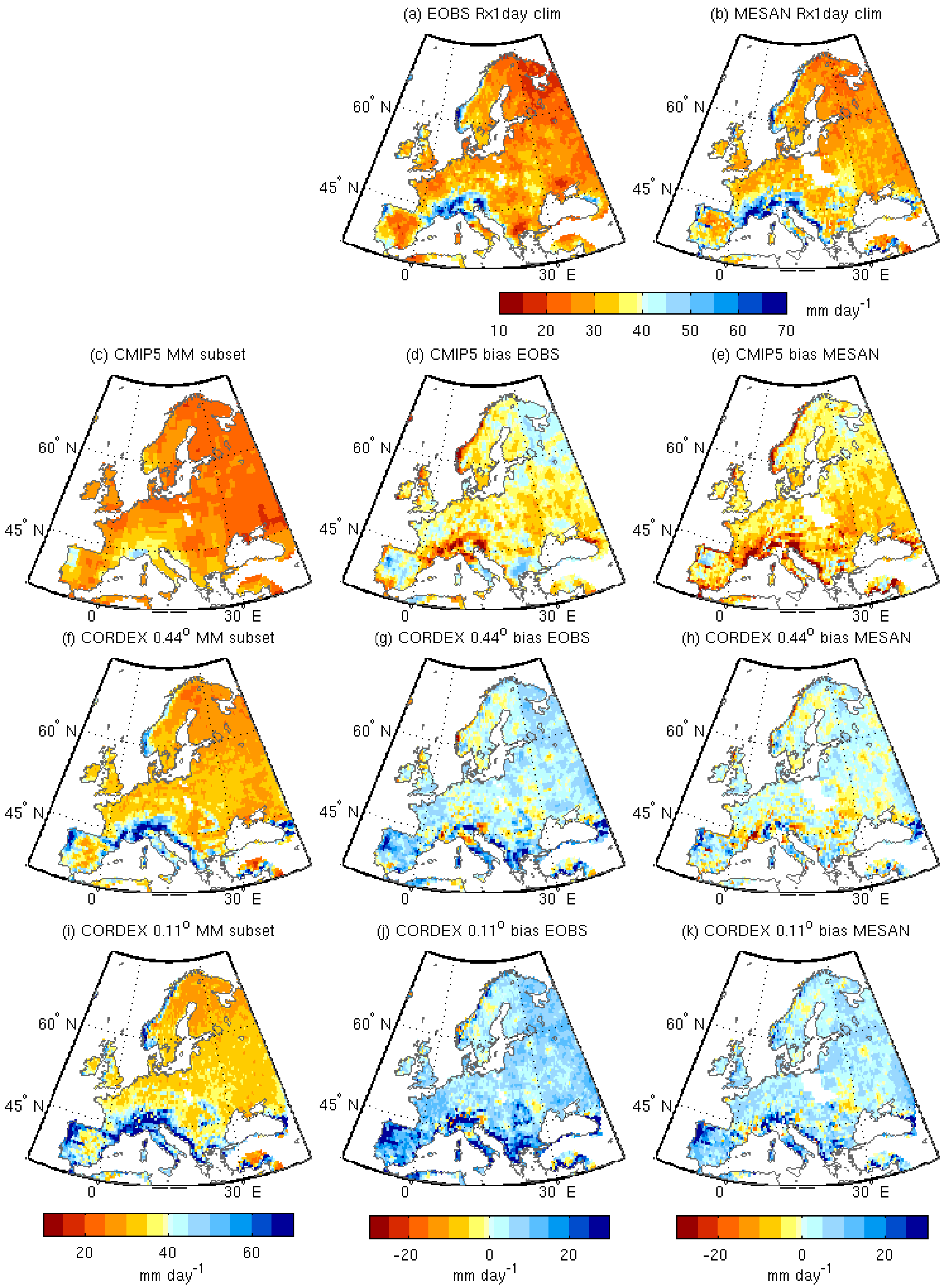


Figure S4: Climatological mean of Rx1day comparing results relative to E-OBS and MESAN for the period 1989-2005 for the "common subset" of models. (a) E-OBS, (b) MESAN, (c) CMIP5 multi model median, (d) CMIP5 bias relative to E-OBS, (e) CMIP5 bias relative to MESAN, (f) CORDEX 0.44° multi model median, (i) CORDEX 0.11° multi model median, (g, j) CORDEX biases relative to E-OBS, (h, k) CORDEX biases relative to MESAN. Units mm.

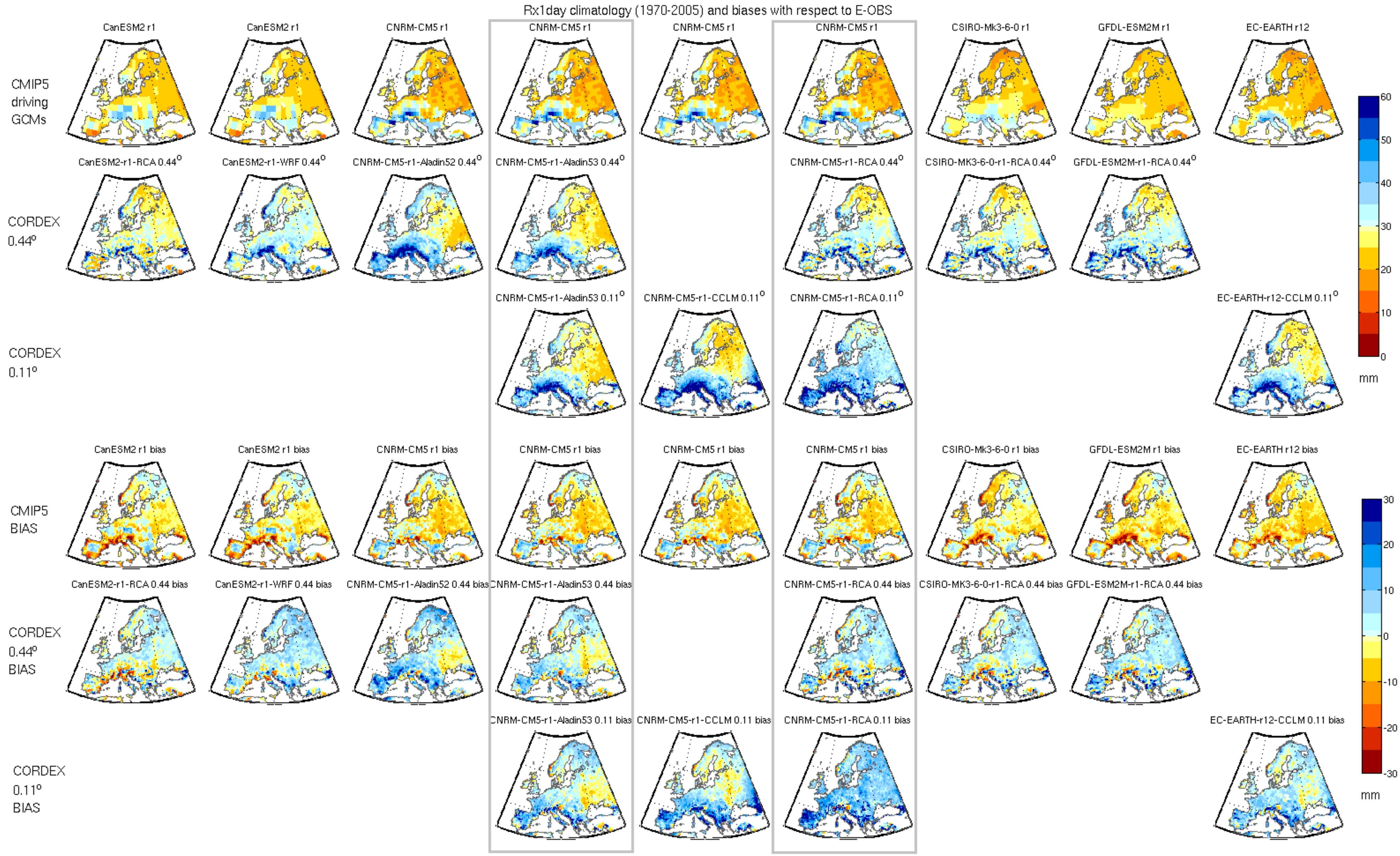


Figure S5: As for Figure S3 but for the climatological mean of Rx1day. Units mm.

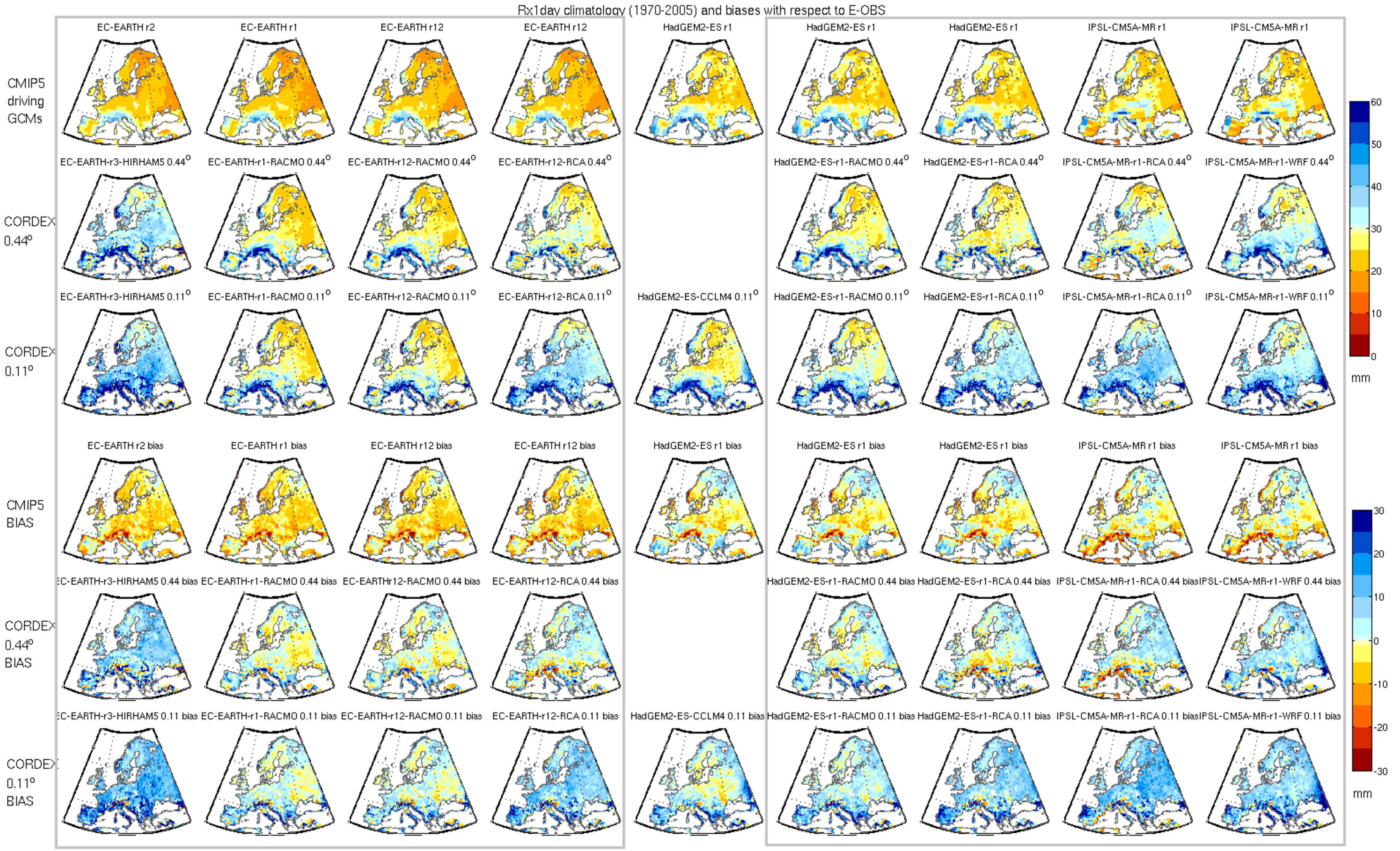


Figure S5 continued

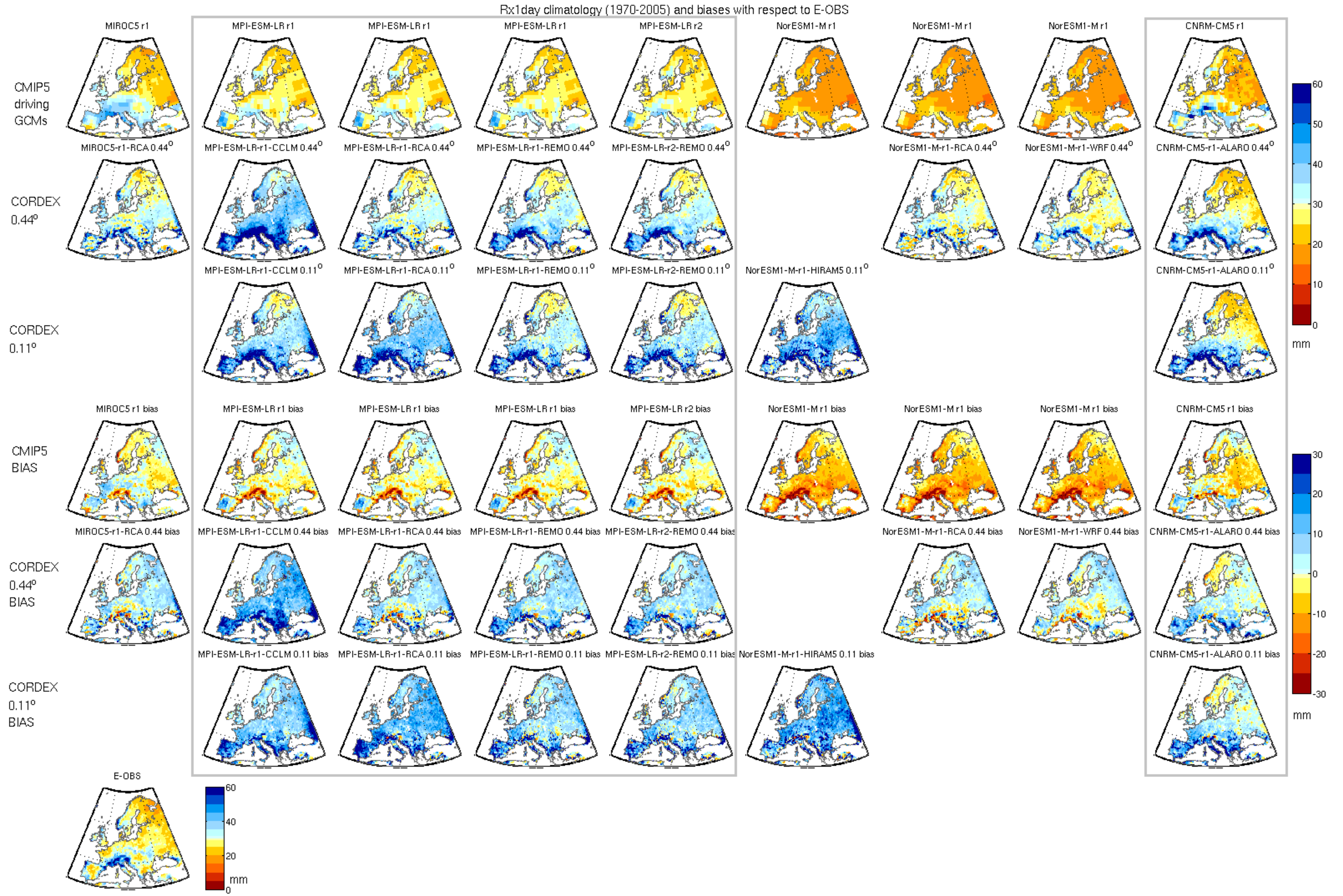


Figure S5 continued

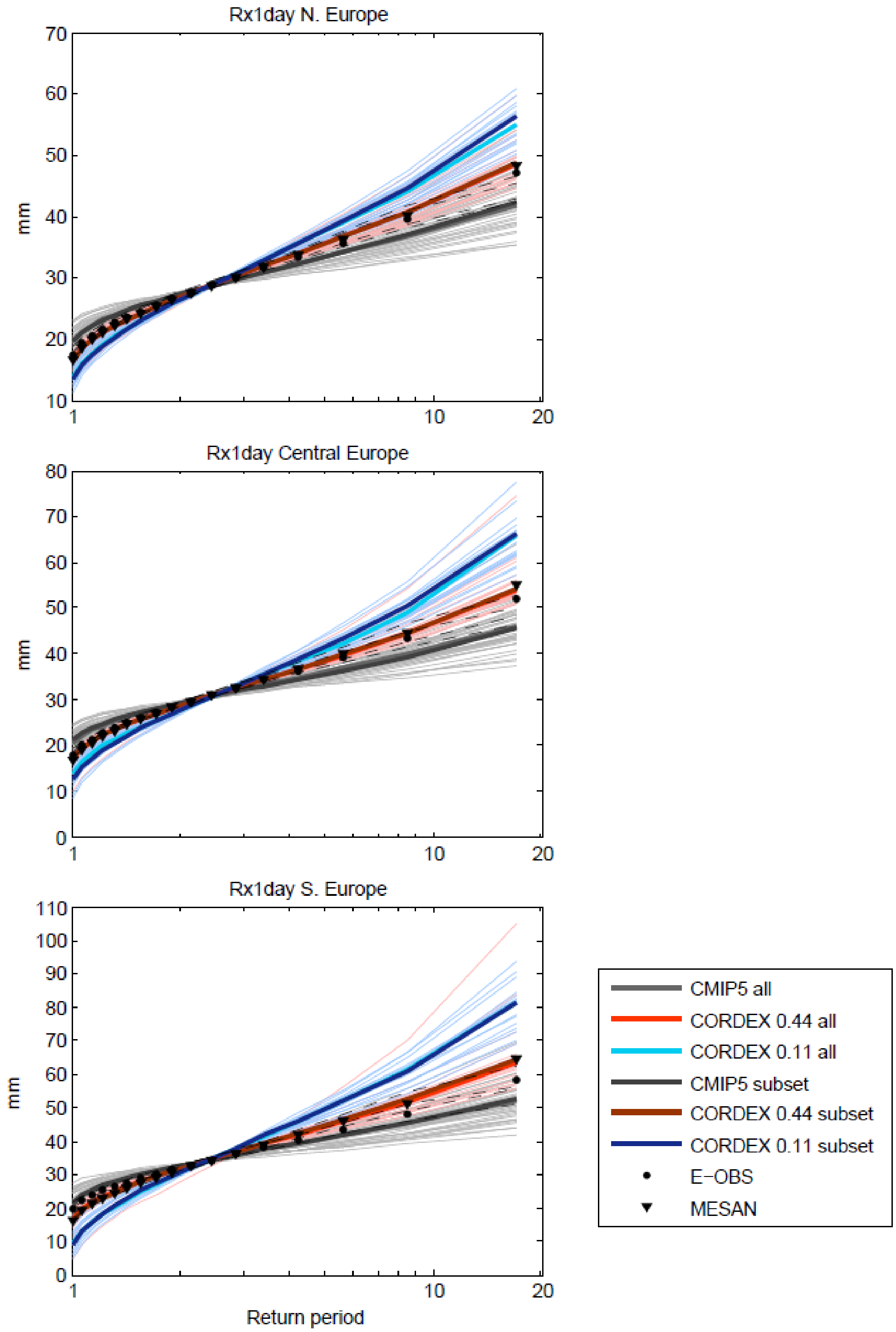


Figure S6: As for Figure 2 middle column, with the addition of the MESAN reanalysis (black triangles), and for the shorter common period 1989-2005. Units mm.

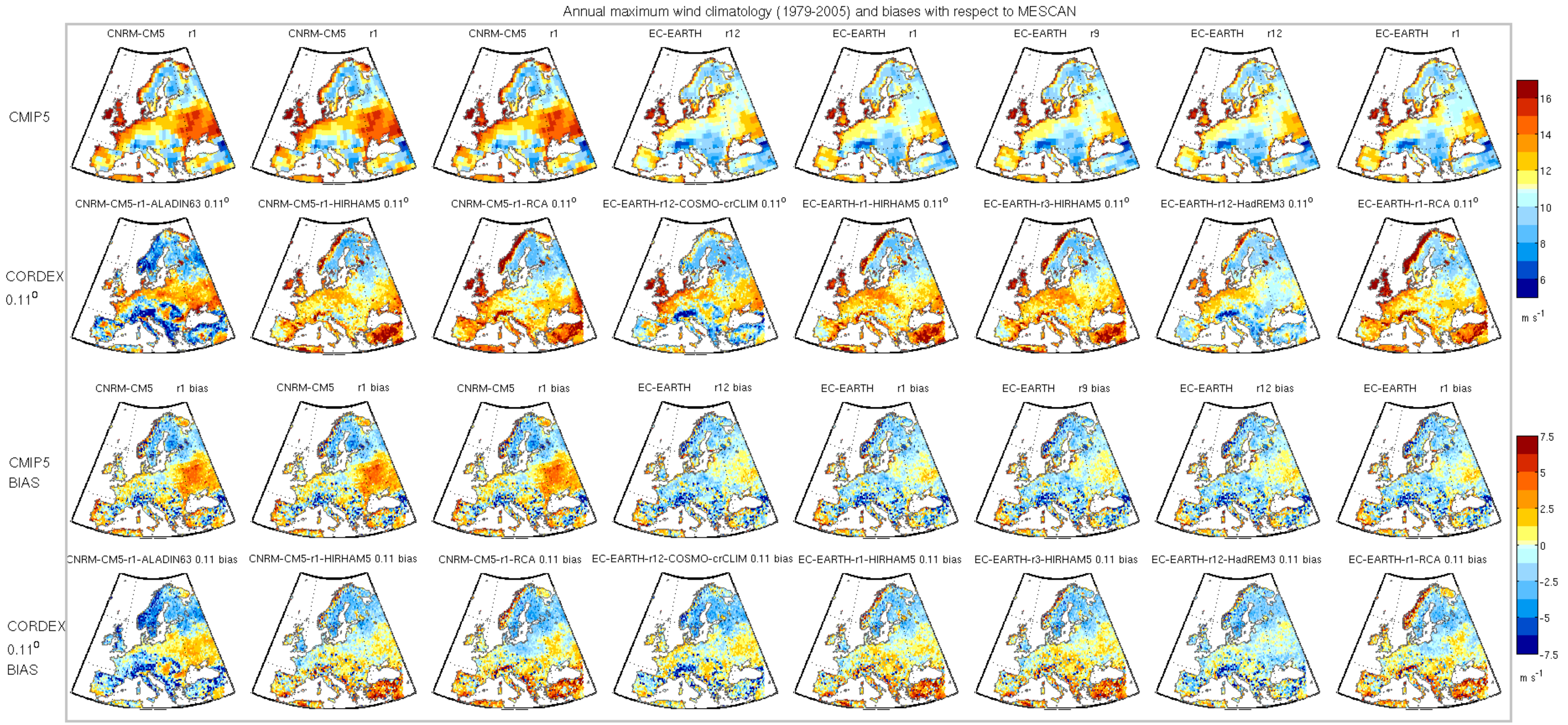


Figure S7: As for Figure S3 but for the climatological mean of annual maximum wind (WindXx) for the period 1979-2005. Note that CORDEX 0.44° is not included here as there was no overlap with the GCM-RCM combinations used for CORDEX 0.11°. Biases with respect to MESCAN are shown in the bottom half of the plot. MESCAN itself is shown at the end of the third page. Units meters per second.

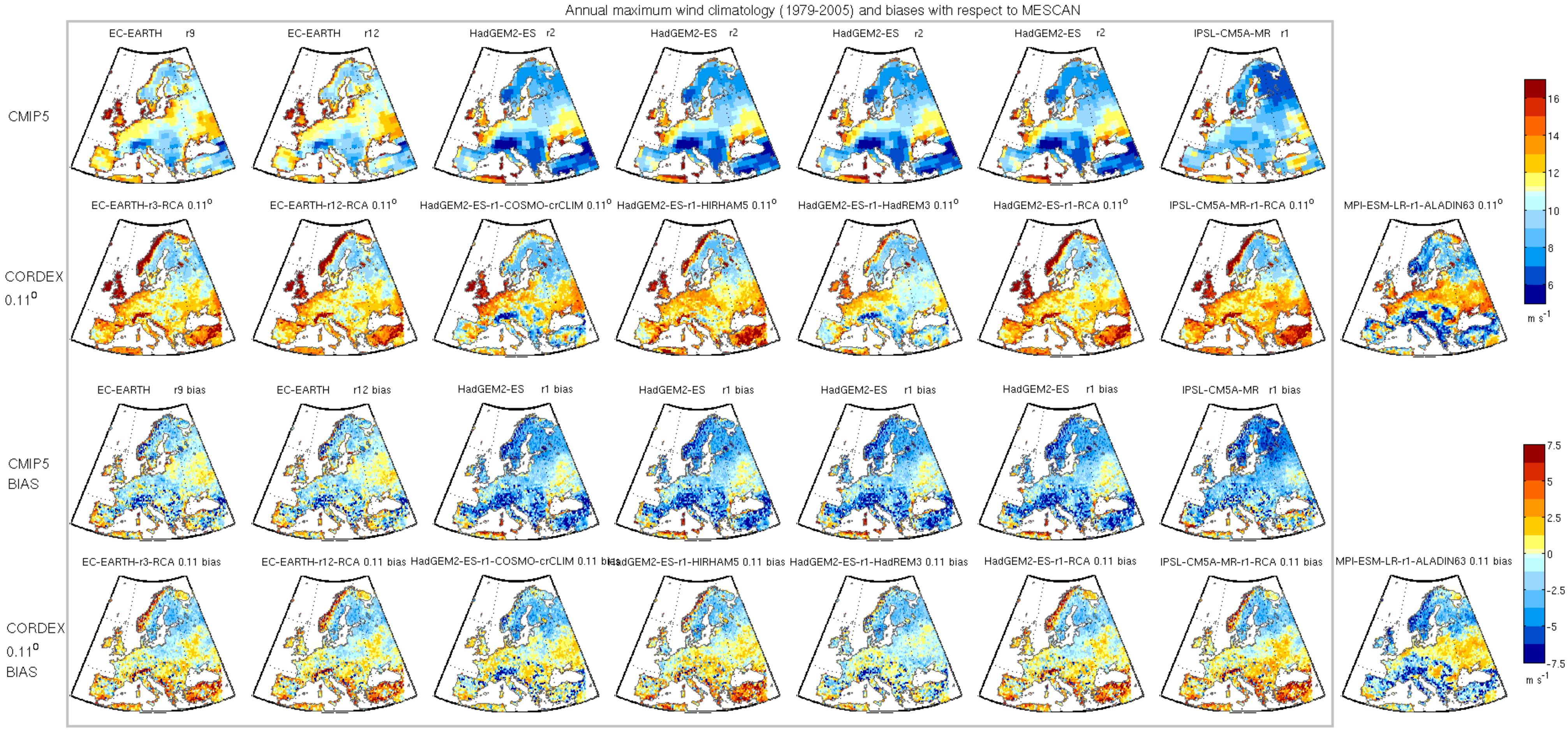


Figure S7 continued

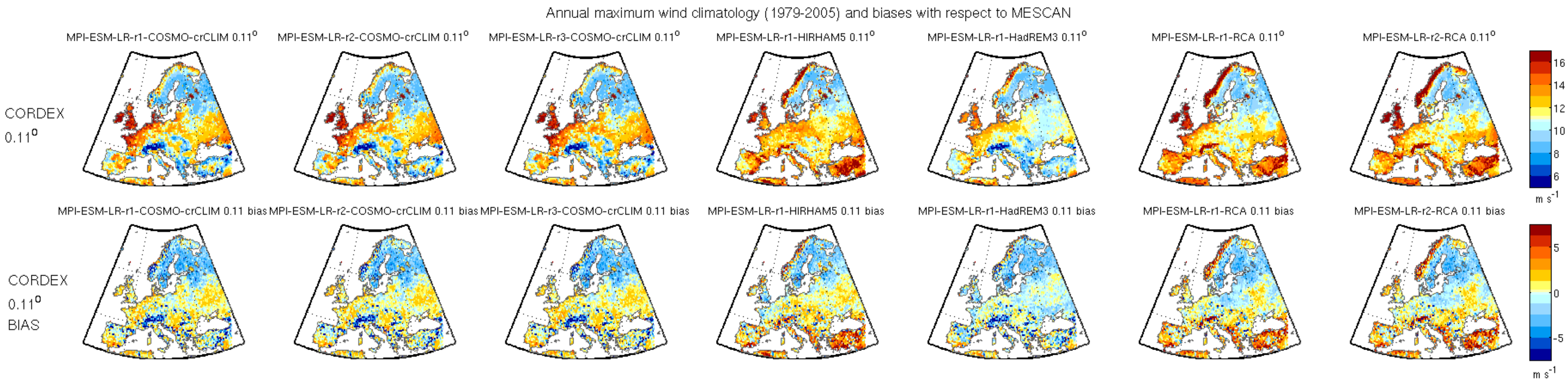


Figure S7 continued- note that the driving GCM is not shown for these simulations because wind data was not available.

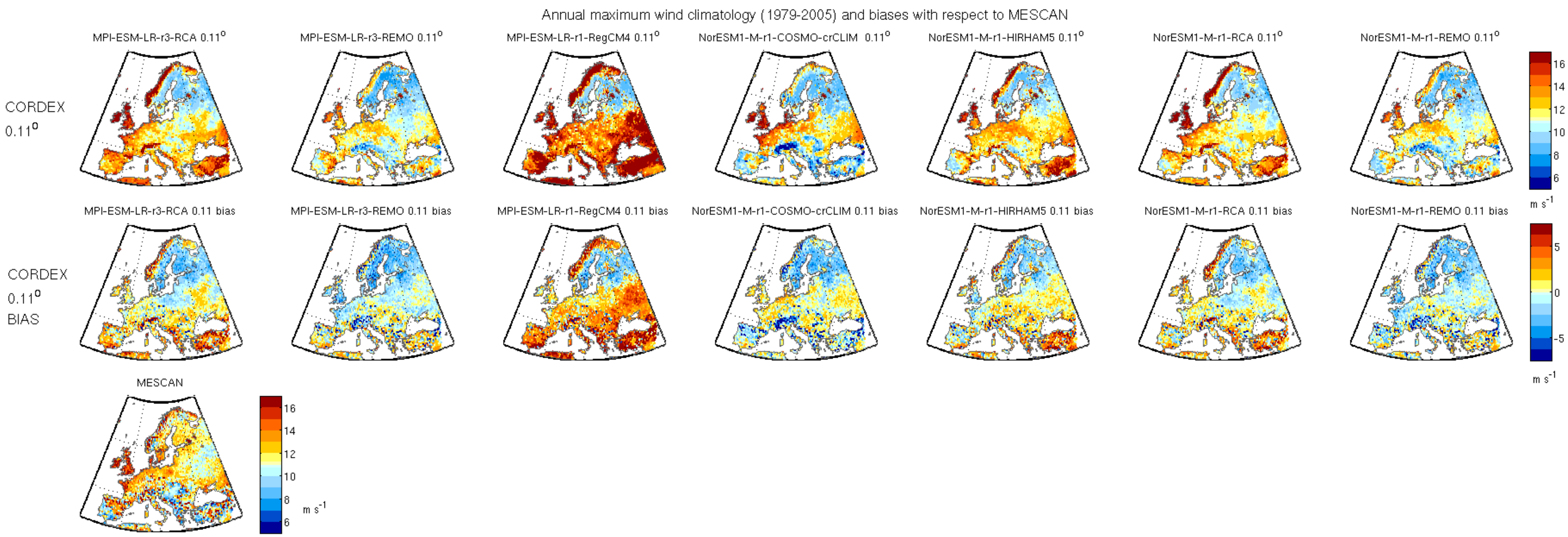


Figure S7 continued- note that the driving GCM is not shown for these simulations because wind data was not available.

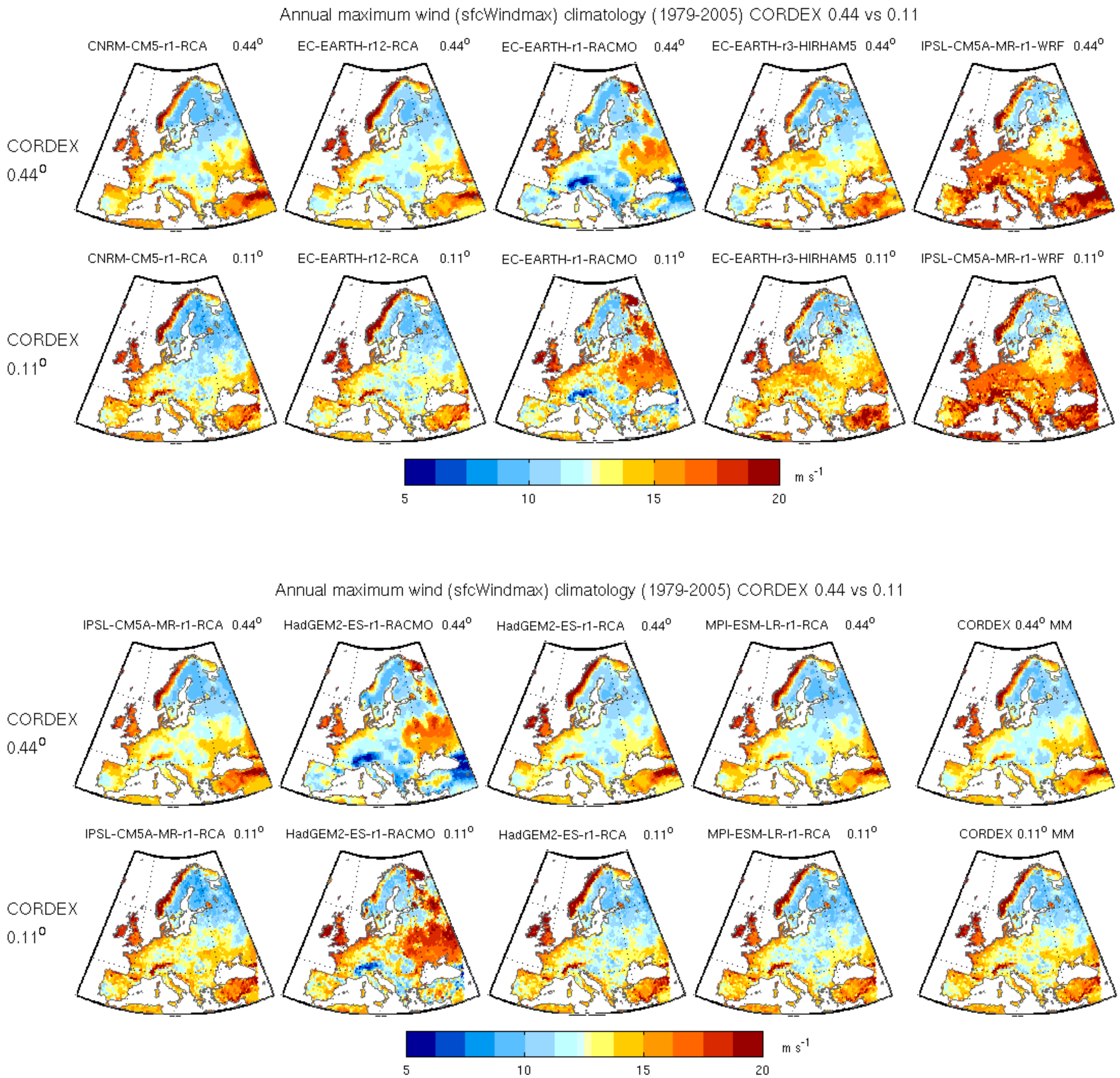


Figure S8: A comparison of climatological mean annual maximum wind (WindXx) using sfcWindmax for the CORDEX simulations that have data for both 0.44° (top row) and 0.11° (bottom row) resolutions. Last column shows the multi model median across these simulations.

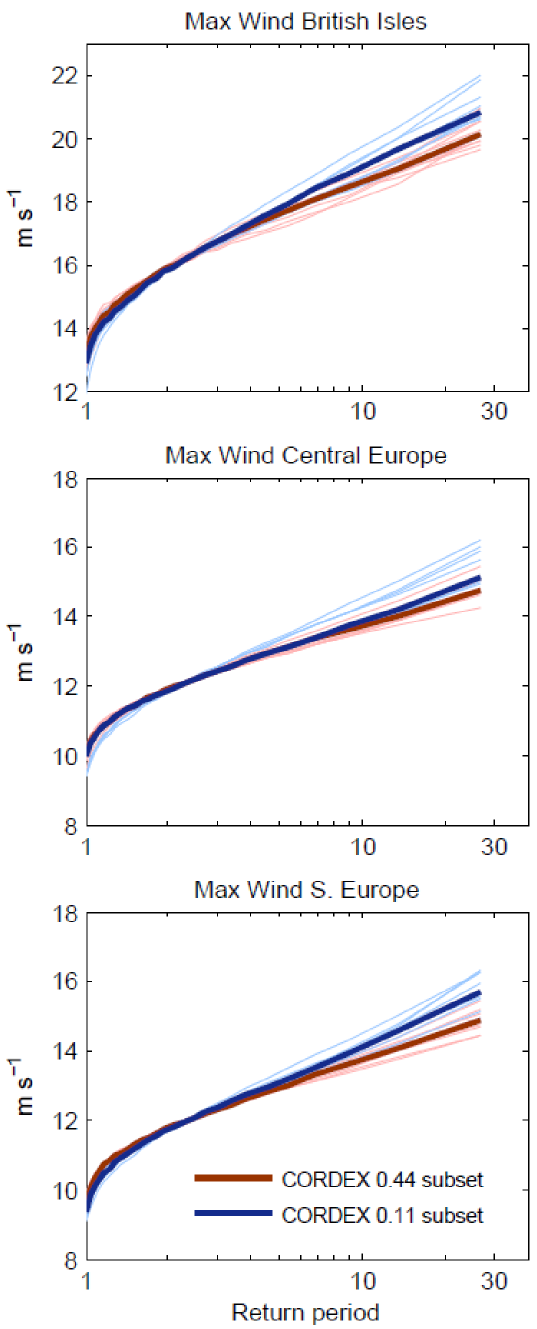


Figure S9-: As for Figure 2, right hand column, but using sfcWindmax for the CORDEX models for which data is available at both resolutions.

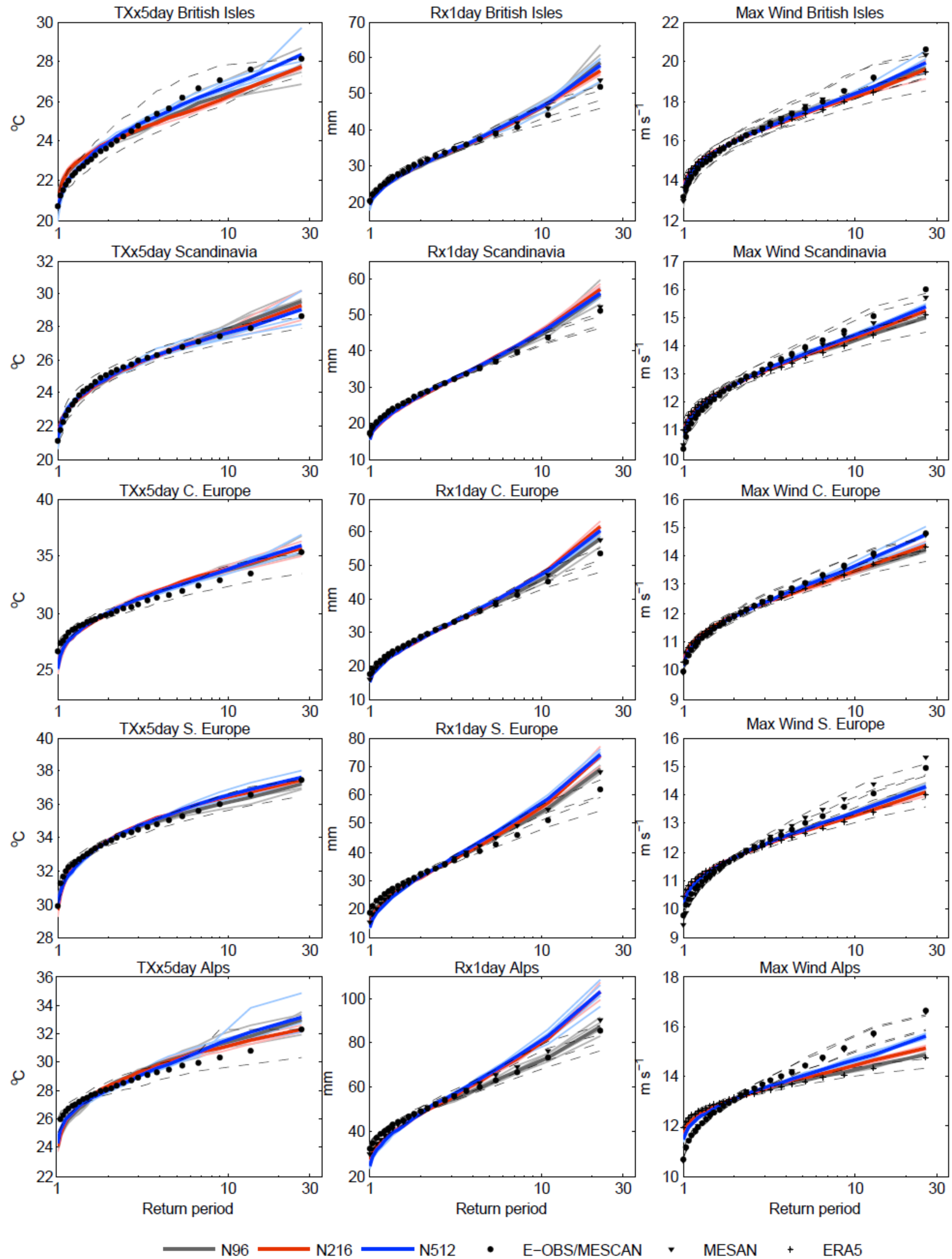


Figure S10: As Figure 6 but with adjustment so that all models and observations have the same climatological mean.

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.