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SUPPLEMENTARY INFORMATION

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Observed heavy precipitation increase confirms theory and early models

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The approach to illustrate observed changes in heavy precipitation has been repeated for gridded daily precipitation data for the US. Fig.S1a shows the same result as Fig.2b but for the contiguous US east of 100°W, specifically the region between 65° and 100°W and 25° and 49°N with data coverage (see domain in Fig.S5). Note that the period differs somewhat from Fig.2b since only data up to 2006 was available for the analysis. The changes are smaller than across Europe but consistent with the Clausius-Clapeyron scaling reflecting the weaker warming consistent with “warming hole” in the eastern US[1-3]. For the Clausius-Clapeyron scaling the observed daily precipitation data in the period 1951-1980 was scaled by 3.2% according to the observed temperature change signal between the two periods derived from ERA interim reanalysis. Fig.S1b shows the same analysis as Fig.2c but for the CMIP5 models over the same area as above. Again, the simulated changes are less pronounced than over Europe. Note however that no GCM shows a consistent decrease across all heavy rainfall bins but all GCMs show positive changes in one or the other heavy rainfall bin.

The analysis was also performed over the whole of the contiguous US (not shown). The results are consistent in sign but comparison is complicated since over many gridpoints in the western half of the US more than 90% of the days are dry days and thereby the percentiles analyzed here equal zero.

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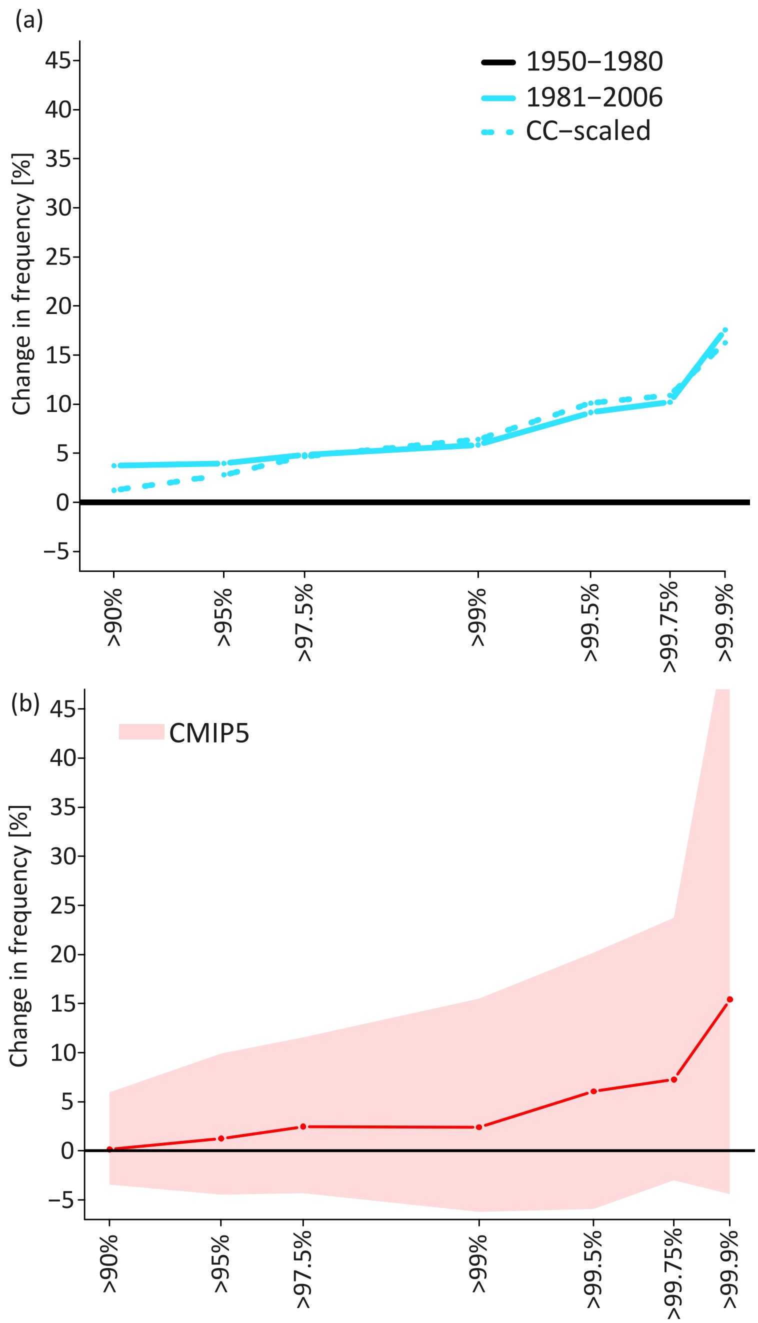

Figure S1: Change in heavy precipitation in the US east of 100°W: *Same as Fig.2b and 2c but for the contiguous US between 65° and 100°W and between 25° and 49°N (see Fig.S5) for the period 1981-2006 vs. 1950-1980. (a) Observations are from the daily gridded (0.25° by 0.25°) CPC Unified Gauge-Based Analysis of Daily Precipitation over the contiguous US* [4,5]*. Clausius-Clapeyron scaling is based on temperature difference derived from ERA interim.*

Quantitative model evaluation is beyond the scope of this manuscript and models and observations need to be compared with caution. In the main manuscript we argue that differences may arise from a combination of at least five reasons; due to (1) differences in warming between the two periods in models vs. observations, (2) internal variability in regional heavy rainfall, (3) a different forced heavy rainfall response to the warming, (4) due to statistical effects of different grid resolutions and (5) observational uncertainties such as inhomogeneities and changing station density.

In order to test the relevance of factor (1) and (2) we repeat the analysis shown in Fig.2c but compare the period 1961-90 with the 30-yr period in which the respective GCM simulates a 3°C global mean warming in an RCP8.5 experiment. Thereby we maximize the signal-to-noise ratio and reduce the role of internal variability (reason 2 above) and at the same time ensure that all models show the same level of warming (reason 1), while the regional warming over Europe may still differ across models. In case of the RCM simulations we choose the period in which the driving GCM shows a 30-yr mean global warming of 3°C with respect to 1961-90. The results shown in Figure S2 suggest that a substantial portion of the differences seen in Fig.2c can be accounted for by a different level of global warming and internal variability. In other words, if differences in warming are eliminated and variability is reduced as in Fig.S2 the models show more consistent changes.

Differences in Fig.2c and Fig.S2 may further relate to effects due to different grid resolution (reason 4). While differences in the absolute levels of heavy precipitation across models of different grid resolution are large, relative changes are generally found to be less sensitive to resolution. However, since we are analyzing land grid points only, the coverage along the coast may also change due to the gridding. We test the sensitivity by regridding the raw daily precipitation data of the RCMs by a conservative remapping to a 2 degree common grid and repeat the analysis for a 3°C warming. Fig.S3 shows that the frequency increase in RCMs after regridding to lower resolution is somewhat larger and thereby the changes are remarkably consistent so that no systematic difference between GCMs and RCMs is identified.

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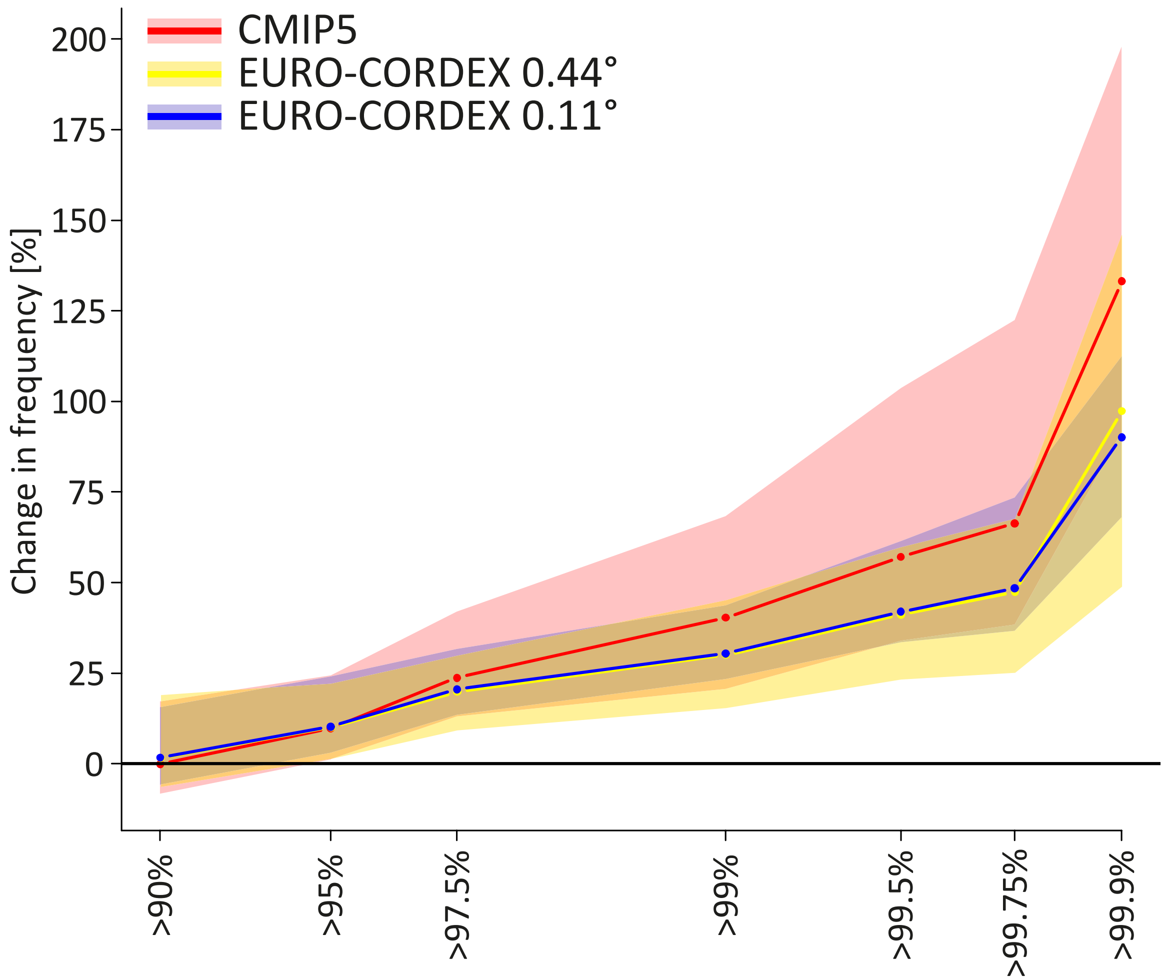

Figure S2: Better agreement for same level of warming: *Same as Fig.S1 but for a 30-yr period in which the respective GCM or the driving GCM of the RCMs shows a global mean warming of 3°C warming with respect to the period 1961-1990.*

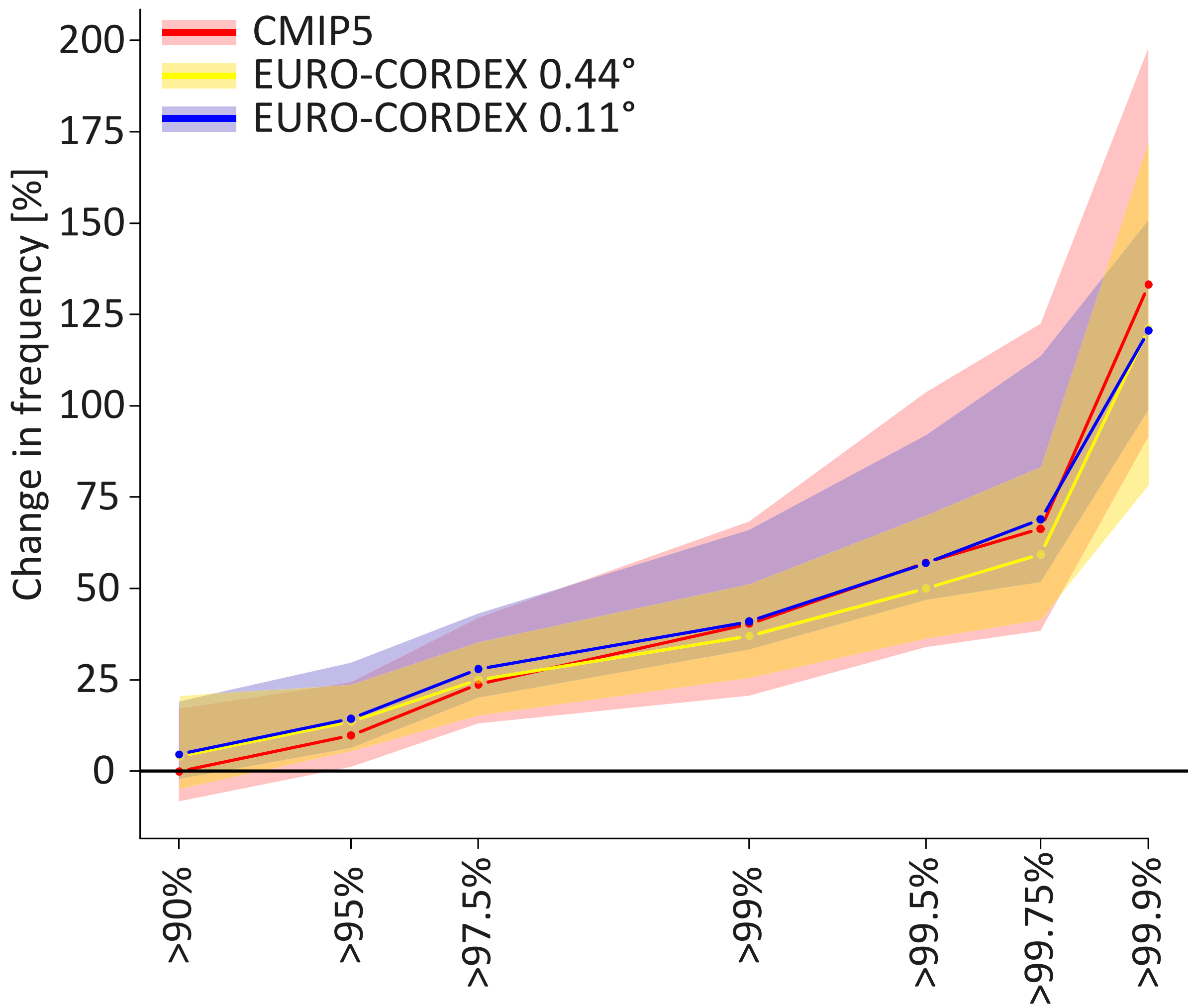

Figure S3: The effect of grid resolution: *Same as Fig.S2 but for the daily precipitation of all models regridded to the coarser common GCM grid.*

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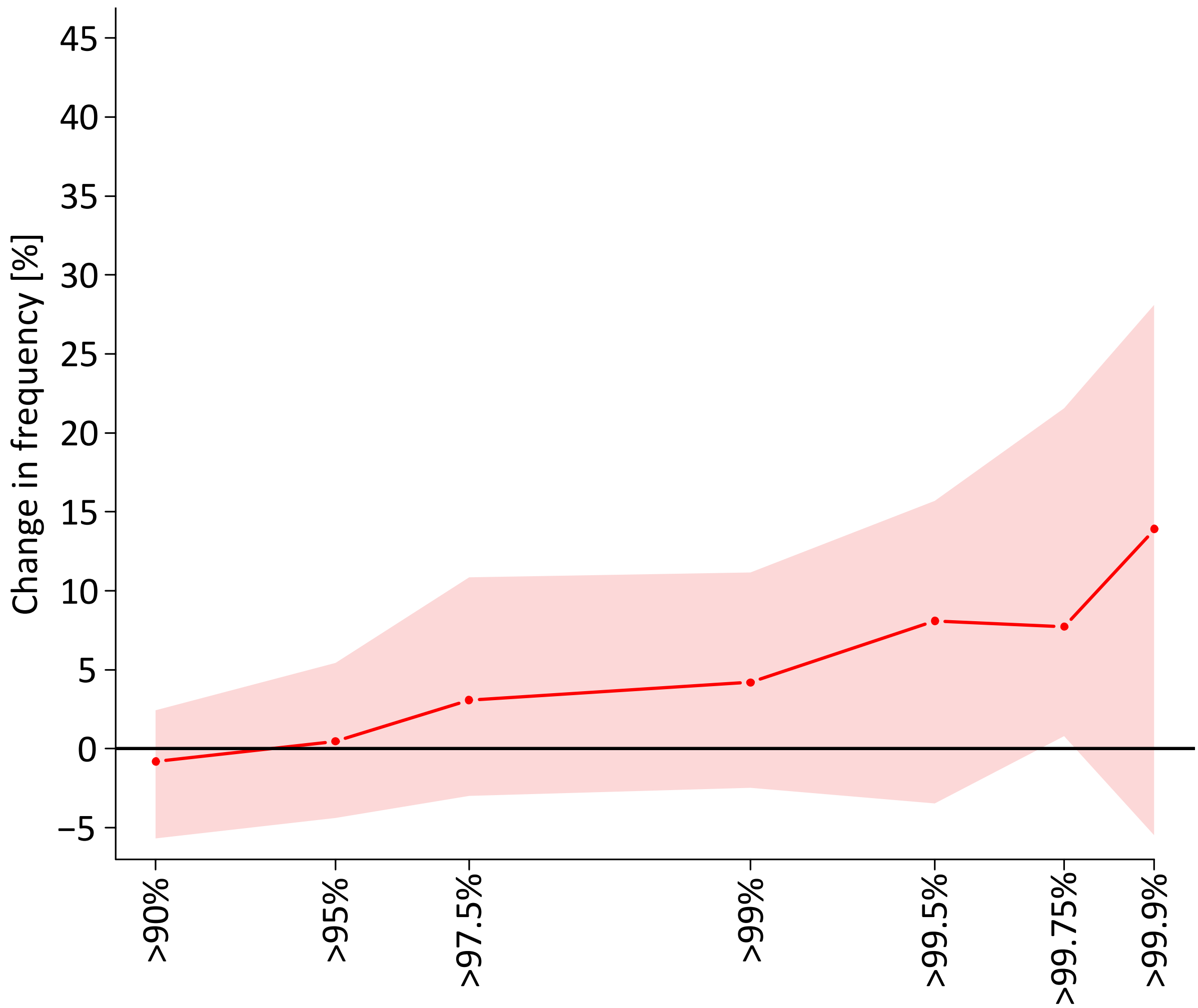

Figure S4: The role of internal variability *Same as Fig.2c but for a 21-member initial condition ensemble starting from different atmospheric initial conditions on 1 January 1950 performed with the fully coupled NCAR CESM (see ref. [6] for details). As in Fig.2c the figure illustrates changes between the period 1951-80 and 1981-2013.*

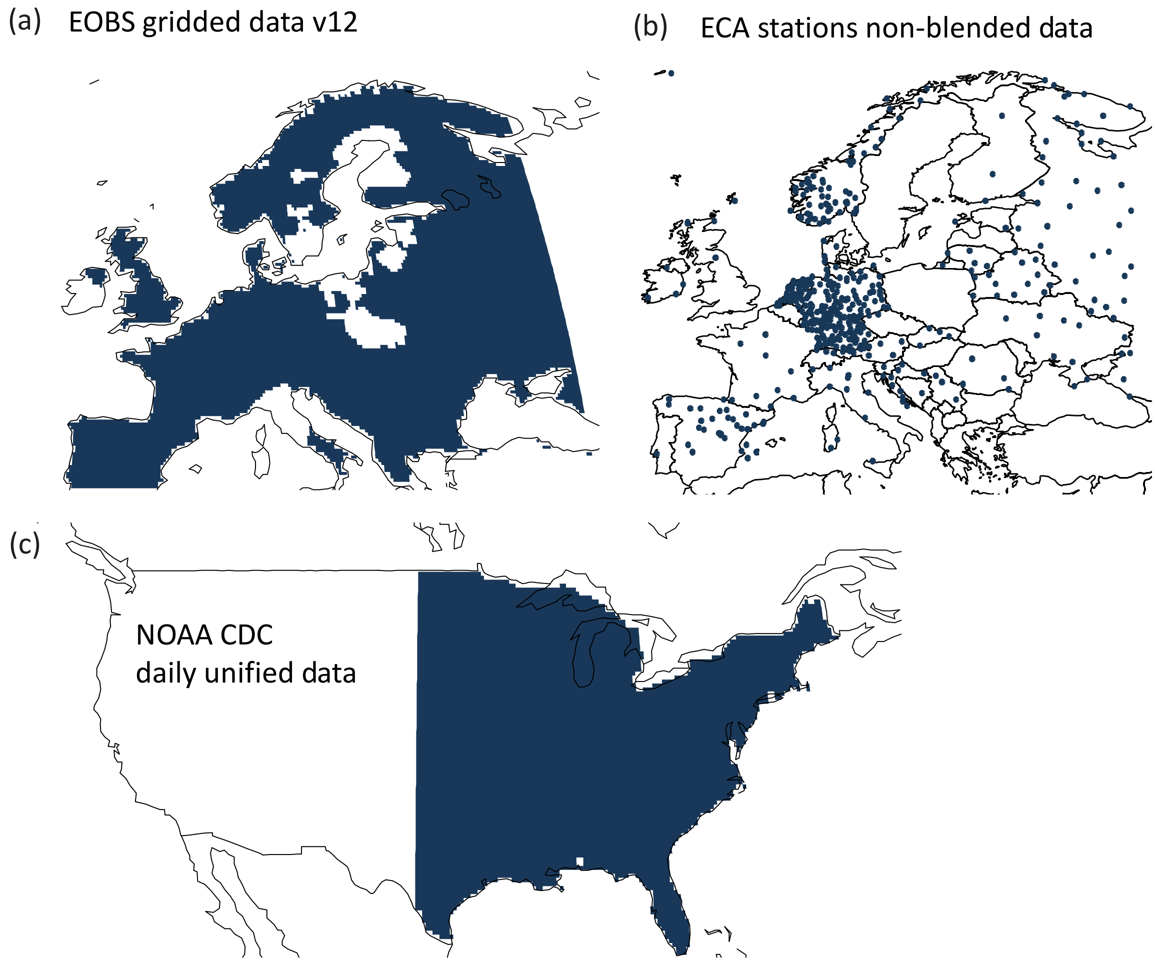

Figure S5: Area used for analysis on gridded and station data *(a) Gridpoints from EOBS data used to produce Fig.2a,b.* We use gridpoints in *the area 38°N to 72°N and 12°W to 40°E to minimize the number of gridpoints in which the 90th percentile of all-day precipitation is a dry day, and restrict the analysis to all land gridpoints for which the daily gridded EOBS data set (version 12 at 0.25° resolution) provides continuous data for each in day in both periods. (b) ECA stations used in Fig.2b. We use daily precipitation series from all the ECA stations (non-blended data) across the area 38°N to 72°N and 12°W to 40°E that provided data for more than 80% of the days of each of the periods 1951-80 and 1981-2013. (c) Gridpoints of NOAA CPC data set used in Fig.S1a.*

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Table S1 | Global climate models used in this study: *Table of 24 CMIP5 models analysed in this study. Daily output of precipitation are used for the historical runs (all forcings), and RCP8.5 simulations.*

CMIP5 models used	
ACCESS1-0	GFDL-ESM2M
ACCESS1-3	HadGEM2-CC
bcc-csm1-1	HadGEM2-ES
bcc-csm1-1-m	IPSL-CM5A-LR
CanESM2	IPSL-CM5A-MR
CESM1-BGC	MIROC5
CMCC-CM	MIROC-ESM
CMCC-CMS	MIROC-ESM-CHEM
CNRM-CM5	MPI-ESM-LR
CSIRO-Mk3-6-0	MPI-ESM-MR
EC-EARTH	MRI-CGCM3
GFDL-ESM2G	NorESM1-M

Table S2 | Regional climate models used in this study: *Table of 14 EURO-CORDEX regional climate models run at 0.44° and 8 EURO-CORDEX regional climate models run at 0.11° analyzed in this study. Daily output of precipitation are used for the historical runs (all forcings), and RCP8.5 simulations.*

EURO-CORDEX			
Driving GCM	**RCM 0.44°**	**Driving GCM**	**RCM 0.11°**
CanESM2	SMHI-RCA4	CNRM-CM5	CLMcom-CCLM4-8-17
CNRM-CM5	CNRM-ALADIN53	CNRM-CM5	CNRM-ALADIN53
CNRM-CM5	HMS-ALADIN52	EC-EARTH	CLMcom-CCLM4-8-17
CSIRO-Mk3-6-0	SMHI-RCA4	EC-EARTH	DMI-HIRHAM5
EC-EARTH	DMI-HIRHAM5	EC-EARTH	KNMI-RACMO22E
EC-EARTH	KNMI-RACMO22E	HadGEM2-ES	CLMcom-CCLM4-8-17
EC-EARTH	SMHI-RCA4	IPSL-CM5A-MR	IPSL-INERIS-WRF331F
IPSL-CM5A-MR	SMHI-RCA4	MPI-ESM-LR	CLMcom-CCLM4-8-17
GFDL-ESM2M	SMHI-RCA4		
HadGEM2-ES	ICTP-RegCM4-3		
HadGEM2-ES	SMHI-RCA4		
MIROC5	SMHI-RCA4		
MPI-ESM-LR	SMHI-RCA4		
NorESM1-M	SMHI-RCA4		

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