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Scale-dependent biases in Alpine sub-daily areal precipitation extremes: added value of convection permitting models

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Supporting information

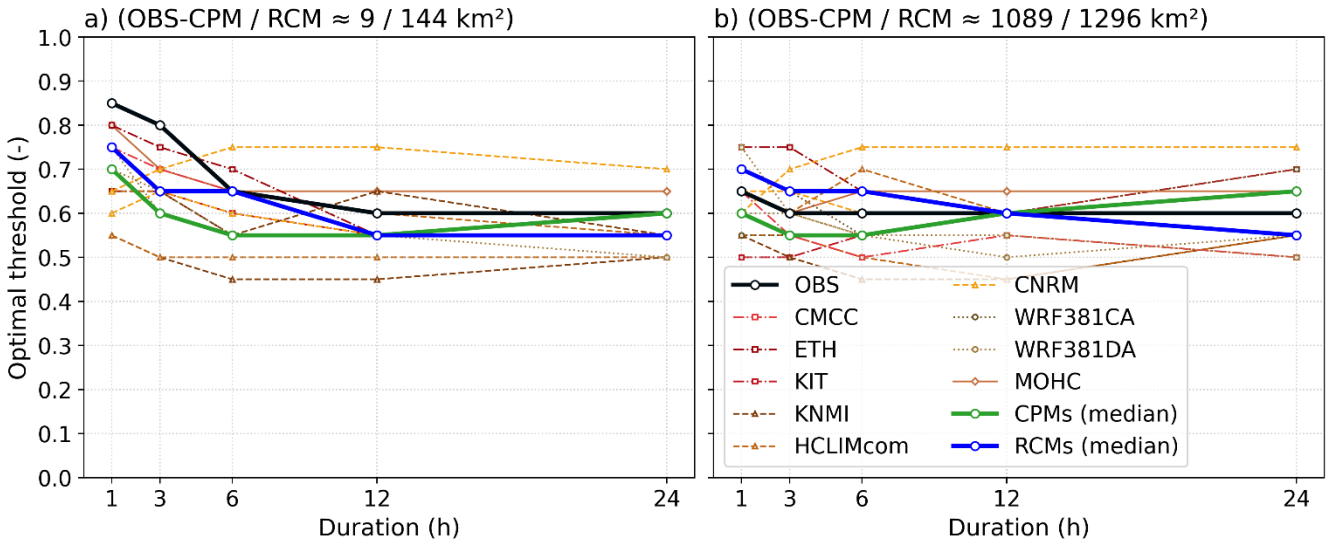

Figure S 1: Optimal left-censoring threshold for the Weibull tail of ordinary events, as a function of accumulation duration. Optimal thresholds were determined at each grid cell using the test of Marra et al. (2023), and are summarized here as the 80th percentile across the grid cells for each combination of dataset, duration, and spatial scale. Lines show results for CombiPrecip (OBS, black), individual CPM and RCM members (see legend), and the CPM and RCM ensemble medians (thick green and blue lines, respectively). (a) Smallest spatial scale: ≈9 km² for OBS and CPMs, ≈144 km² for RCMs. (b) Aggregated spatial scale: ≈1089 km² for OBS and CPMs (11×11 window), ≈1296 km² for RCMs (3×3 window). Finally, the 85th percentile is used as a uniform left-censoring threshold for all datasets, durations, and spatial scales in our SMEV application; this corresponds to the upper envelope of the optimal thresholds across the parameter space, ensuring that the chosen threshold lies at or above the optimum for every case considered.

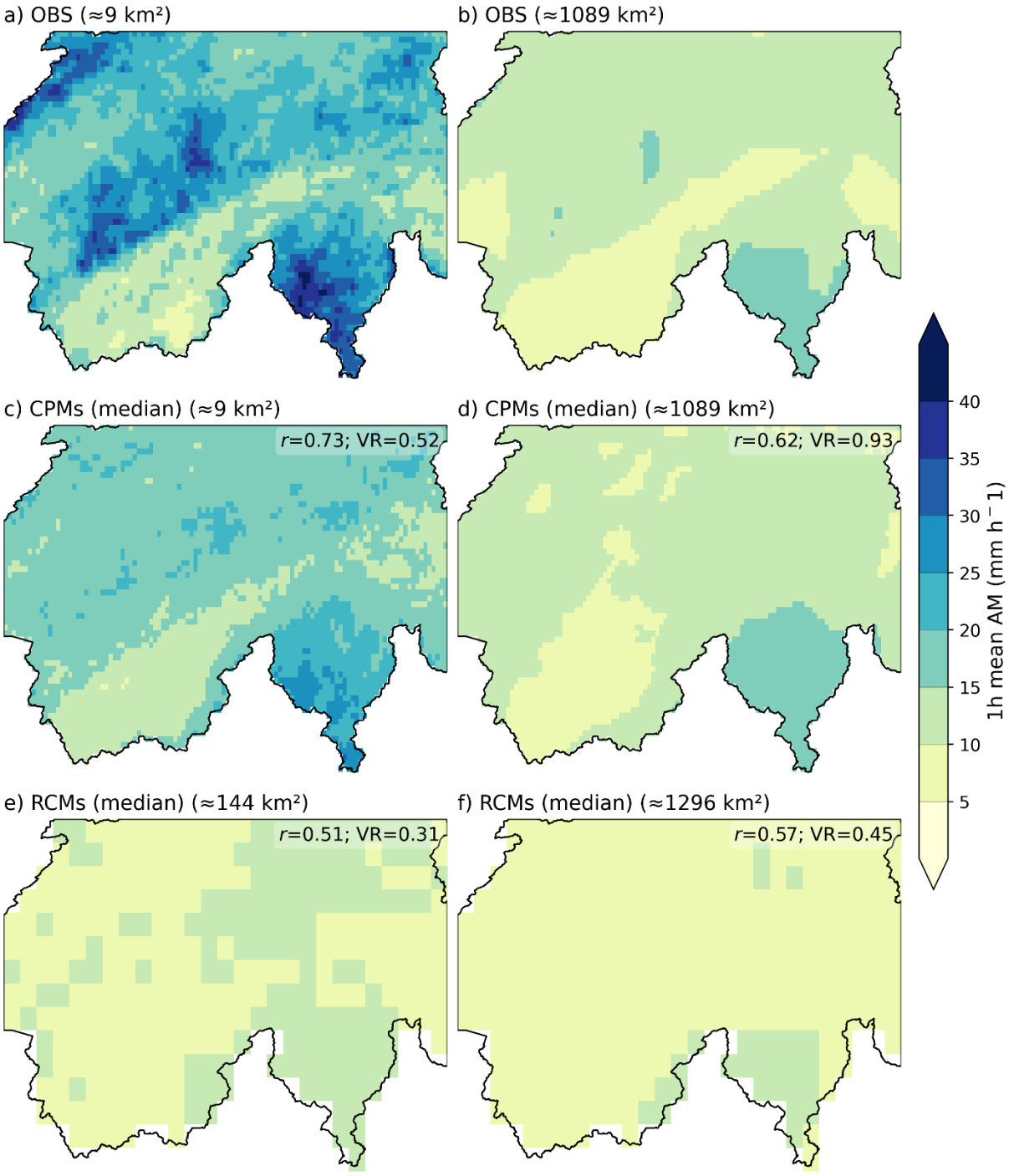

Figure S 2: Spatial distribution of 1h mean annual maximum precipitation (mean AM) over Switzerland for CombiPrecip (OBS) and model ensemble medians at smallest and aggregated spatial scales. (a-b) observational field at ≈9 and ≈1089 km². (c-d) CPM ensemble-median at ≈9 and ≈1089 km². (e-f) RCM ensemble-median at ≈144 and ≈1296 km². In each model panel, r denotes the spatial correlation with OBS and VR the variability ratio (model/OBS; ratio of spatial standard deviations).

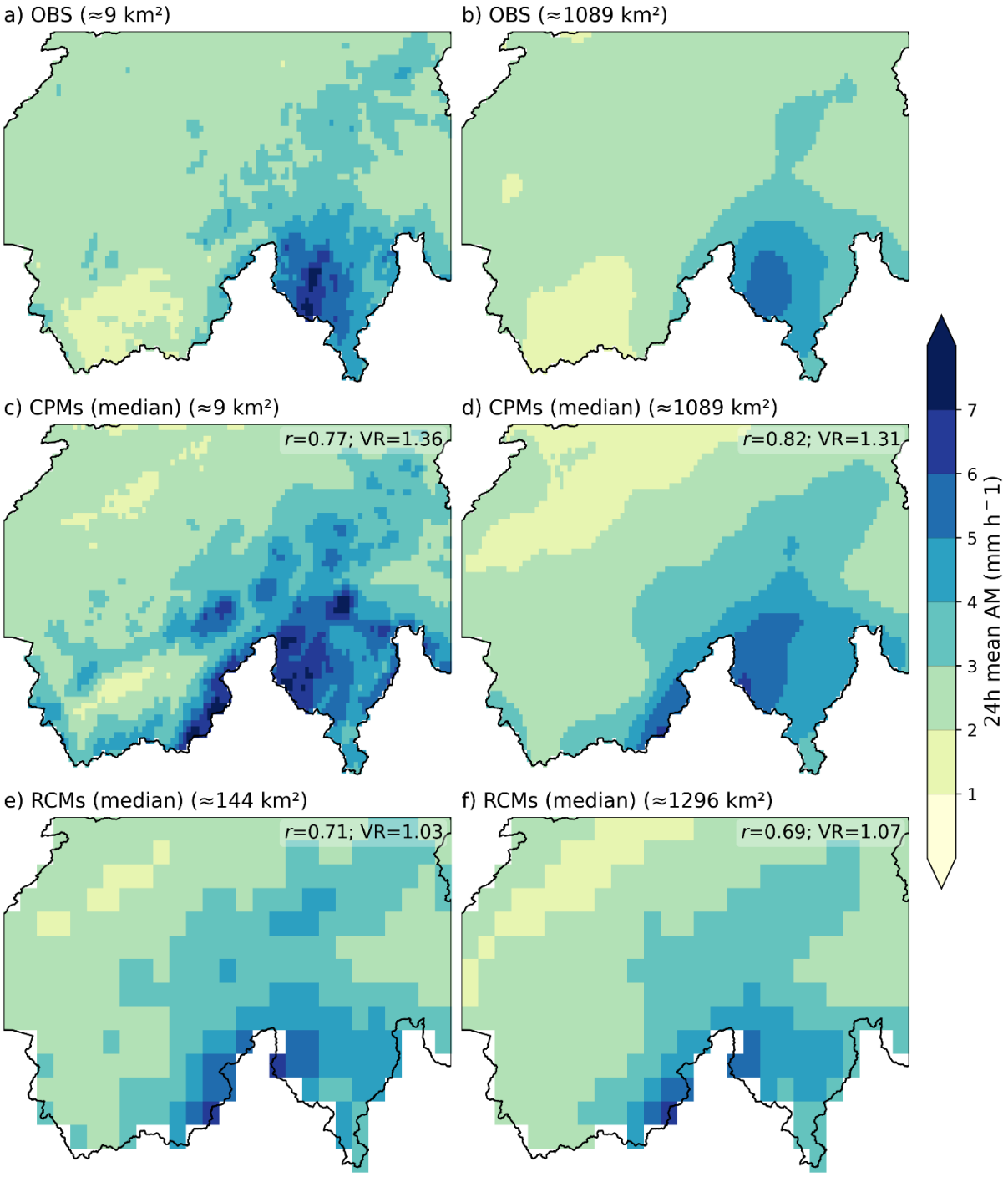

Figure S 3: Spatial distribution of 24h mean annual maximum precipitation (mean AM) over Switzerland for CombiPrecip (OBS) and model ensemble medians at smallest and aggregated spatial scales. (a-b) observational field at ≈9 and ≈1089 km². (c-d) CPM ensemble-median at ≈9 and ≈1089 km². (e-f) RCM ensemble-median at ≈144 and ≈1296 km². In each model panel, r denotes the spatial correlation with OBS and VR the variability ratio (model/OBS; ratio of spatial standard deviations).

Table S 1: Per-member spatial correlation (r), variability ratio (VR), and mean bias of CPM and RCM return levels relative to CombiPrecip (OBS), for (a) 1h-20y and (b) 24h-20y return levels. Statistics are reported at two spatial scales: smallest area (≈9 km² for CPMs and ≈144 km² for RCMs) and aggregated area (≈1089 km² for CPMs and ≈1296 km² for RCMs). For the return-level fields across the study domain, r is the Pearson spatial correlation between the model and OBS; VR is the ratio of model-to-OBS spatial standard deviations; mean bias is the model-to-OBS ratio of return levels averaged over the study domain. Em-dashes indicate cases where the driving RCM is not available (KIT and MOHC; see Table 1).

(a) 1h-20y return level

Model	CPM ≈ 9 km² – RCM ≈ 144 km²						CPM ≈ 1089 km² – RCM ≈ 1296 km²					
	r		*VR*		mean bias		*r*		*VR*		mean bias	
	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM
CMCC	0.66	0.57	0.49	0.85	0.81	0.97	0.61	0.79	0.73	1.04	0.90	1.01
ETH	0.53	0.63	0.76	0.99	1.08	1.08	0.58	0.65	1.66	1.57	1.37	1.27
KIT	0.46	—	0.65	—	1.01	—	0.44	—	1.18	—	1.17	—
KNMI	0.62	0.35	0.52	0.43	0.96	0.49	0.63	0.45	1.15	0.86	1.29	0.69
HCLIMcom	0.67	0.22	0.45	0.32	0.93	0.57	0.62	0.35	0.90	0.45	1.22	0.71
CNRM	0.48	0.08	0.57	0.38	0.81	0.66	0.41	0.03	1.25	0.44	1.09	0.86
MOHC	0.35	—	0.89	—	0.92	—	0.37	—	0.43	—	0.95	—
WRF381CA	0.60	0.46	0.49	0.27	0.69	0.54	0.65	0.47	0.72	0.48	0.88	0.74
WRF381DA	0.58	0.45	0.39	0.29	0.61	0.55	0.62	0.46	0.53	0.51	0.79	0.75

(b) 24h-20y return level

Model	CPM ≈ 9 km² – RCM ≈ 144 km²						CPM ≈ 1089 km² – RCM ≈ 1296 km²					
	r		*VR*		mean bias		*r*		*VR*		mean bias	
	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM	CPM	RCM
CMCC	0.78	0.69	1.14	0.88	1.07	1.20	0.83	0.77	1.10	0.78	1.06	1.20
ETH	0.83	0.81	1.55	1.17	1.31	1.25	0.86	0.79	1.42	1.21	1.32	1.28
KIT	0.68	—	1.64	—	1.42	—	0.71	—	1.47	—	1.40	—
KNMI	0.85	0.60	1.37	1.17	1.10	1.16	0.93	0.65	1.29	1.14	1.10	1.22
HCLIMcom	0.86	0.75	1.36	0.95	1.05	1.10	0.94	0.83	1.33	0.93	1.03	1.07
CNRM	0.80	0.53	1.81	0.96	1.22	1.22	0.87	0.62	1.73	0.87	1.21	1.24
MOHC	0.69	—	1.14	—	1.21	—	0.86	—	1.01	—	1.16	—
WRF381CA	0.69	0.62	1.27	0.99	1.07	1.03	0.76	0.63	1.13	1.01	1.06	1.07
WRF381DA	0.65	0.58	1.03	0.93	1.02	1.04	0.74	0.60	0.91	0.92	1.02	1.08

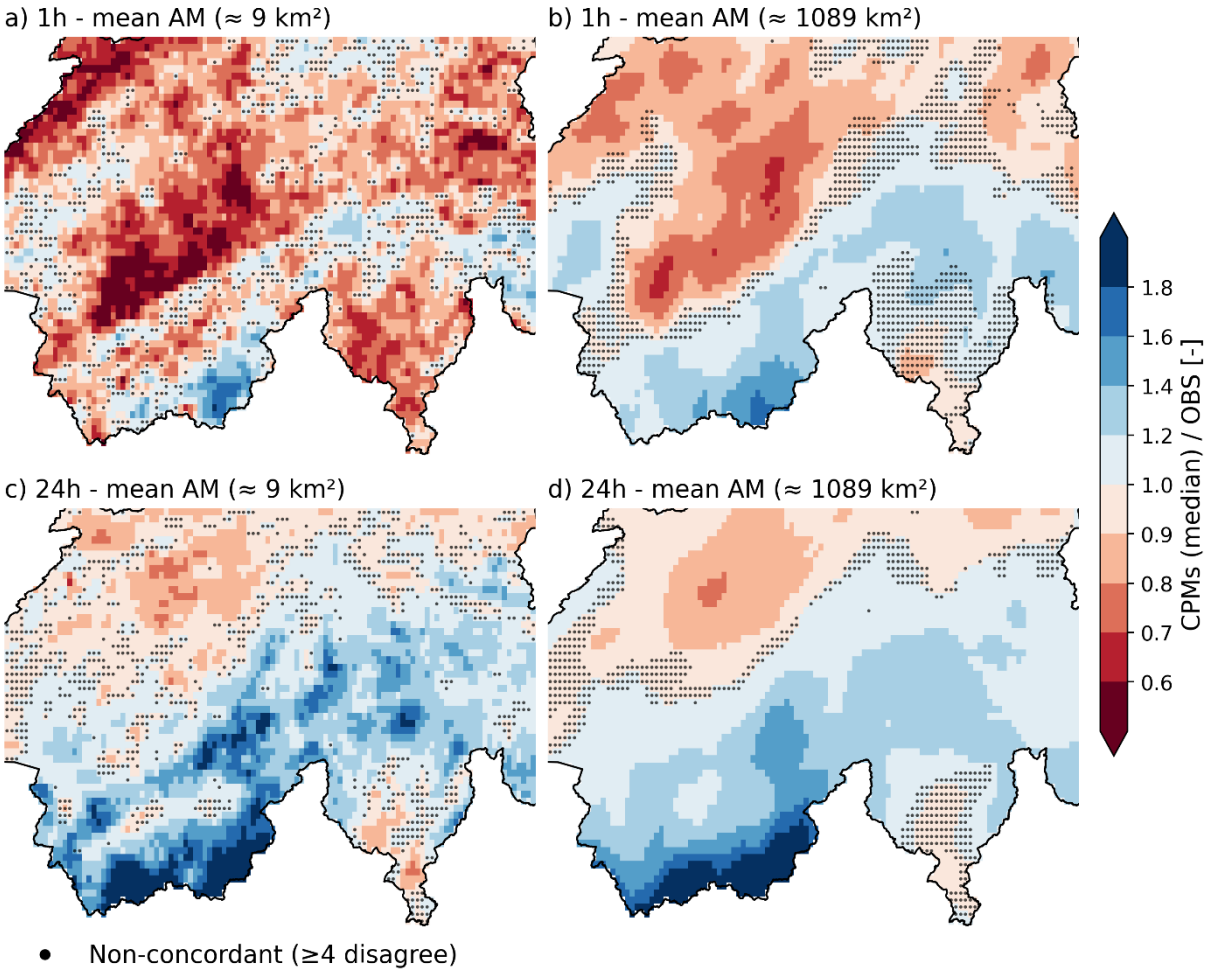

Figure S 4: Spatial patterns of bias of the CPM ensemble median relative to CombiPrecip (OBS) for mean annual maximum precipitation (mean AM) at 1-hour (a, b) and 24-hour (c, d) durations. Panels (a) and (c) show biases at the native CPM resolution (approximately 9 km²), while panels (b) and (d) present results after spatial aggregation to areas of about 1089 km² (11x11 grids). Bias is expressed as the ratio CPM/OBS, where values above 1 indicate overestimation. Black dots mark non-concordant grid cells, defined as locations where four or more CPM members disagree on the sign of the bias.

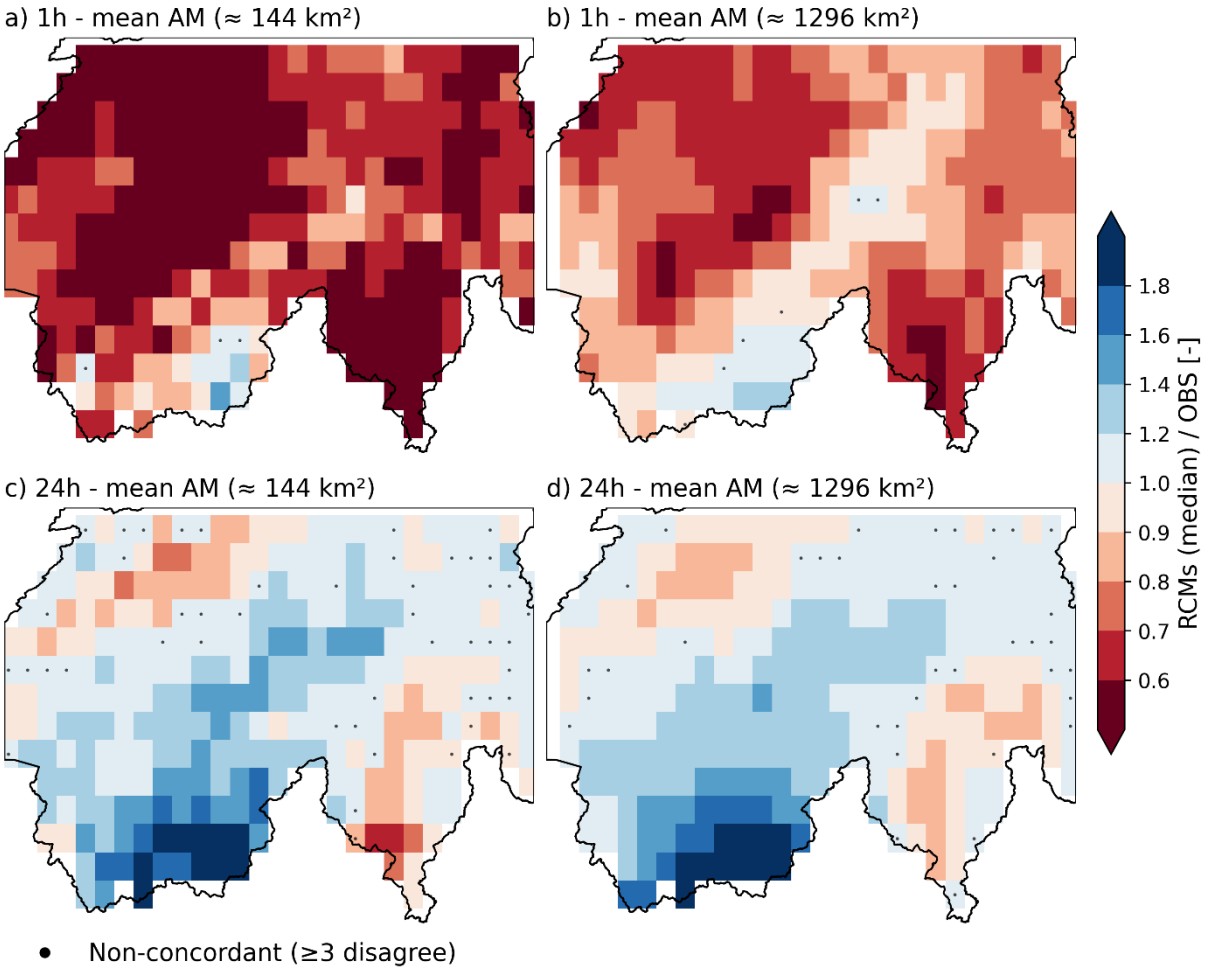

Figure S 5: Spatial patterns of bias of the RCM ensemble median relative to CombiPrecip (OBS) for mean annual maximum precipitation (mean AM) at 1-hour (a, b) and 24-hour (c, d) durations. Panels (a) and (c) show biases at the native RCM resolution (approximately 144 km²), while panels (b) and (d) present results after spatial aggregation to areas of about 1296 km² (3x3 grids). Bias is expressed as the ratio RCM/OBS, where values above 1 indicate overestimation. Black dots mark non-concordant grid cells, defined as locations where 3 or more RCM members disagree on the sign of the bias.

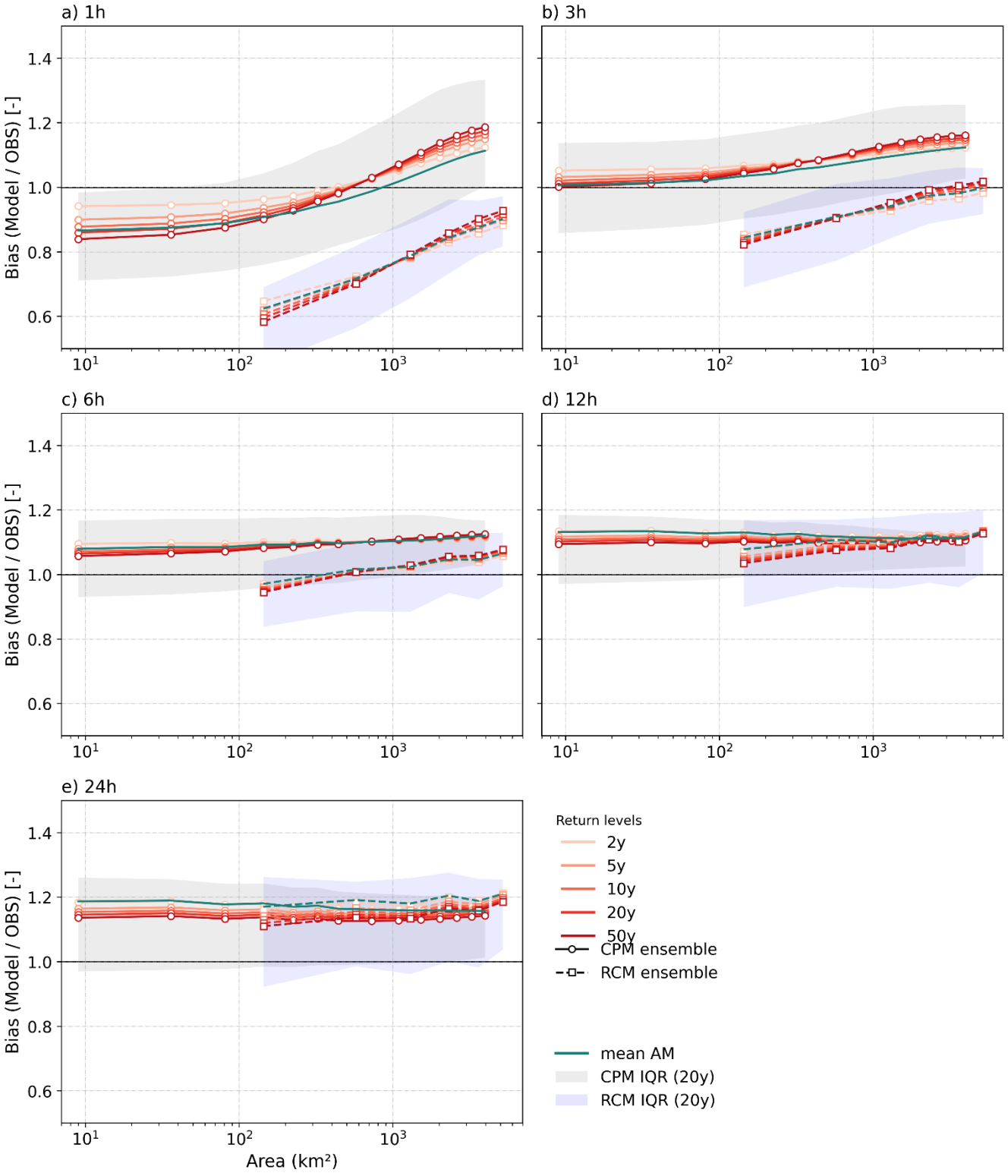
a) 1h
b) 3h
c) 6h
d) 12h
e) 24h
Bias (Model / OBS) [-]
1.4
1.2
1.0
0.8
0.6
10^1
10^2
10^3
Area (km²)
Return levels
2y
5y
10y
20y
50y
CPM ensemble
RCM ensemble
mean AM
CPM IQR (20y)
RCM IQR (20y)

Figure S 6: Scale dependence of CPM and RCM bias relative to CombiPrecip (OBS) shown for multiple event magnitude. Bias (Model/OBS) is plotted against areal extent for mean annual maxima (mean AM) and return levels of 2-, 5-, 10-, 20- and 50-years. Solid lines show ensemble-median biases from moving-window areal aggregation for the CPM and RCM ensembles. Shaded grey and blue bands indicate the corresponding 75th and 25th quartiles for return levels of 20-y return period respectively.

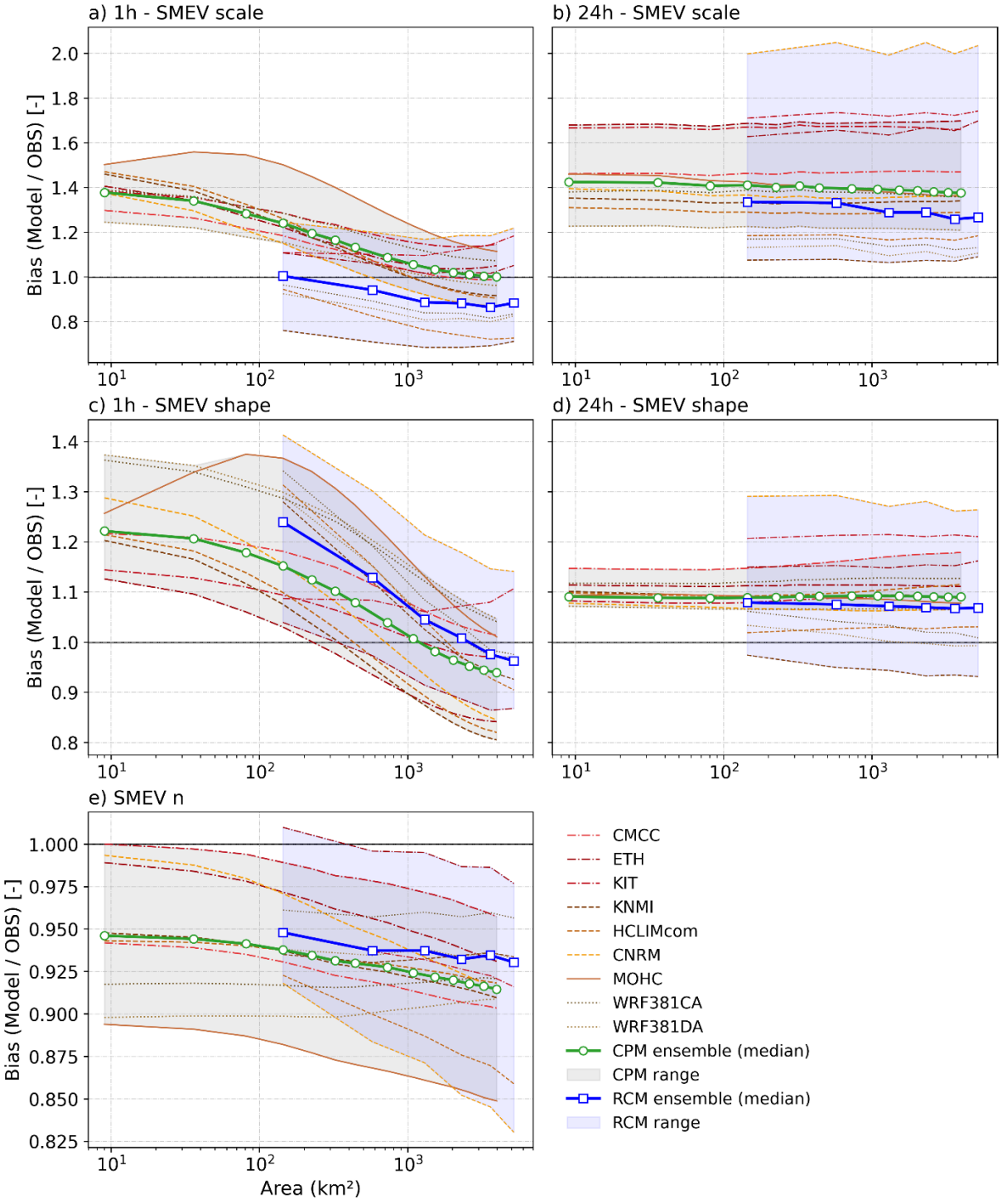

Figure S 7: Scale dependence of biases in SMEV parameters for the CPM and RCM ensembles relative to CombiPrecip (OBS). Panels show the bias (Model/OBS) of the Weibull scale parameter λ for 1 h (a) and 24 h (b), the Weibull shape parameter k for 1 h

(c) and 24 h (d), and the mean annual number of ordinary events n (e), all as a function of areal extent. Solid green and blue lines denote ensemble-median CPM and RCM biases, respectively; thin lines show individual model members, and shaded bands indicate the corresponding ensemble ranges. Values above (below) 1 indicate overestimation (underestimation) of the SMEV parameters relative to OBS.