Proactive Producer and Processor Networks for

Troodos Mountains Agriculture

3PRO-TROODOS

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Introduction

Climate projections for the Mediterranean region, based on a multi-scenario ensemble of Regional Climate Models at 50-km resolution, show a 2°C warming within two decades, whereas precipitation is expected to decrease between 10 and 40% by the end of the century (Zittis et al., 2019). These changes will have large implication for agriculture. However, the resolution of these models is too coarse to analyze the impact of climate change on the highly variable climate of Cyprus. Thus, there is need to downscale data of regional climate models to a higher spatial resolution. Previous downscaling for Cyprus to 1-km resolution have shown good results (Camera et al., 2017). However, the spatial weather generator used by Camera et al. (2017) does not capture large rainfall events very well, whereas larger rainfall events, which wet the subsoil layers are especially important for agriculture. Therefore, an improved climate downscaling approach is needed. The objectives of this study are (i) to select a regional climate model that fits the climatology of Cyprus; (ii) bias-correct and downscale the regional climate simulations to 1-km resolution over Cyprus.

Data and Methods for Model Selection

For the present analysis, we explored the high-resolution version of the most comprehensive sets of regional climate simulations, available at the time of writing. This is the European (EURO) initiative of the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Jacob et al., 2020). We considered all publicly available EURO-CORDEX simulations with a horizontal spatial resolution of 0.11° (~12 km) and a daily temporal resolution. From there, we took a subset of the EURO-CORDEX ensemble that includes historical experiments, as well as two future pathways. We analysed a "business-as-usual" representative concentration pathway (RCP), which is defined as RCP8.5 and a more optimistic scenario, RCP2.6, which is closer to the main targets of the Paris Agreement. Our final ensemble consists of 20 simulations (Table 1) and is based on a combination of six global earth-system models and eight regional climate models (RCMs). We have extracted data only for Cyprus.

For evaluation of the modelled data, we used a daily 1 × 1 km gridded dataset for precipitation and temperature (Camera et al., 2014), hereafter called CY-OBS. This high-resolution dataset covers the 1980-2010 period and it was derived from the statistical interpolation of a very dense network of weather stations. This dataset covers only the area of the island that is currently under the jurisdiction of the Republic of Cyprus.

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Table 1. List of EURO-CORDEX simulations

ID	GLOBAL MODEL	REGIONAL MODEL
R1	CNRM-CERFACS-CNRM-CM5 (r1i1p1)	CNRM-ALADIN63_v2
R2	CNRM-CERFACS-CNRM-CM5 (r1i1p1)	UGent-ALARO-0_v1
R3	CNRM-CERFACS-CNRM-CM5 (r1i1p1)	KNMI-RACMO22E_v2
R4	ICHEC-EC-EARTH (r12i1p1)	CLMcom-CCLM4-8-17_v1
R5	ICHEC-EC-EARTH (r12i1p1)	DMI-HIRHAM5_v1
R6	ICHEC-EC-EARTH (r12i1p1)	KNMI-RACMO22E_v1
R7	ICHEC-EC-EARTH (r12i1p1)	SMHI-RCA4_v1
R8	ICHEC-EC-EARTH (r12i1p1)	GERICS-REMO2015_v1
R9	MOHC-HadGEM2-ES (r1i1p1)	DMI-HIRHAM5_v1
R10	MOHC-HadGEM2-ES (r1i1p1)	KNMI-RACMO22E_v2
R11	MOHC-HadGEM2-ES (r1i1p1)	SMHI-RCA4_v1
R12	MOHC-HadGEM2-ES (r1i1p1)	ICTP-RegCM4-6_v1
R13	IPSL-IPSL-CM5A-LR (r1i1p1)	GERICS-REMO2015_v1
R14	MPI-M-MPI-ESM-LR (r1i1p1)	KNMI-RACMO22E_v1
R15	MPI-M-MPI-ESM-LR (r1i1p1)	SMHI-RCA4_v1
R16	MPI-M-MPI-ESM-LR (r1i1p1)	ICTP-RegCM4-6_v1
R17	MPI-M-MPI-ESM-LR (r1i1p1)	GERICS-REMO2015_v1
R18	NCC-NorESM1-M (r1i1p1)	KNMI-RACMO22E_v1
R19	NCC-NorESM1-M (r1i1p1)	SMHI-RCA4_v1
R20	NCC-NorESM1-M (r1i1p1)	GERICS-REMO2015_v1

The selection of the best-performing EURO-CORDEX experiments for Cyprus was based on a multi-step ranking:

Step 1: calculation of annual precipitation climatology, interannual variability as an indication of extreme dry and wet years (i.e. standard deviation) and multi-year trends (Sen's Slopes) for the 20 EURO-CORDEX experiments and the gridded observations.

Step 2: after observations were remapped in the EURO-CORDEX grids, biases of these three properties of precipitation were calculated on a grid cell level.

Step 3: the 20 experiments were ranked based on the median biases of each precipitation property (total annual amount, interannual variability, trend). Each of the three rankings received a weight. The total annual amount, interannual variability and the trend of precipitation were assigned a weight of 0.6, 0.2, 0.2, respectively, according to their importance for the 3PRO-Troodos applications.

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Step 4: the three weighted rankings were summed and this sum score provided the final ranking for precipitation.

Step 5: steps 1-4 were repeated for the five best-performing CORDEX experiments but this time for temperature to derive the final selection.

Results for Model Selection

Maps of observed and modelled precipitation climatology are presented in Figure 1. The re-gridded CY-OBS (Figure 1a) indicate a west-east gradient of precipitation and a peak over the Troodos mountains. This west-east gradient is captured well by most EURO-CORDEX experiments, however, differences in the precipitation amounts are evident for some cases, while the peaks are occasionally mislocated. A comparison of each EURO-CORDEX simulation against observations is presented in Figure 2. The biases of annual precipitation, standard deviation and Sen's Slope, representing the median values for Cyprus grid points are presented in Table 2. The five best-performing simulations are R3, R6, R13, R14 and R18. Four out of the five are simulations with KNMI-RACMO22E regional model and one with GERICS-REMO, driven by different global earth system models. The ranking process was repeated for annual temperature (Table 3), while a comparison with observed temperature is presented in Figure 3 and 4. Simulation with ID R14 (MPI-M-MPI-ESM-LR/ KNMI-RACMO22E) was found to overall perform better for both annual precipitation and temperature and will be used for further downscaling and bias correction, as presented in the following sections.

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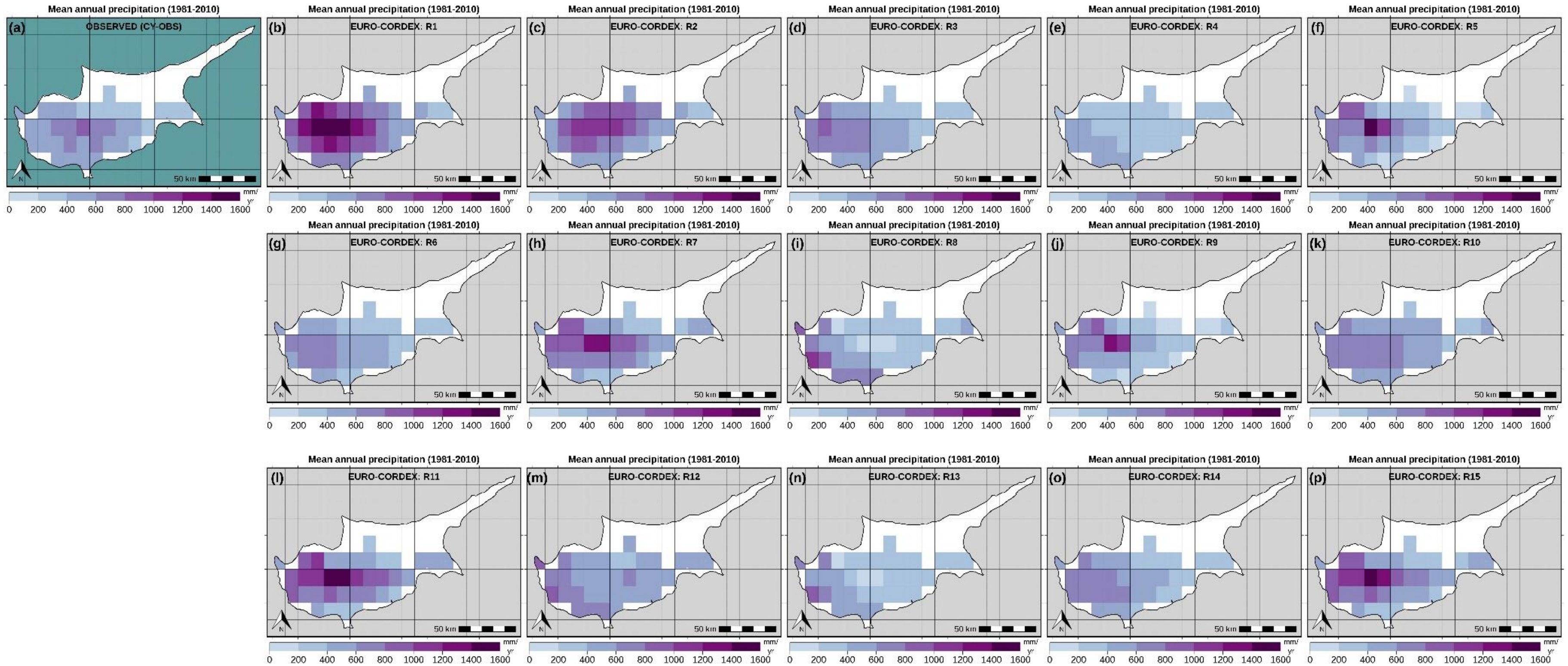
Table 2. Median bias values of annual precipitation (PR), standard deviation (SD) and Sen's Slope (SS) and overall ranking of the 20 EURO-CORDEX simulations. Best-performers are highlighted in blue.

ID	Annual PR bias (mm/yr)	Annual PR SD bias (mm)	PR SS bias (mm/decade)	Overall PR ranking
R1	364.1	47.2	58.2	20
R2	182.7	0.4	20.9	16
R3	**29.5**	**-14.2**	**49.2**	**4**
R4	-132.2	-35.5	-3.3	14
R5	-58.8	-35.6	33.9	9
R6	**-8.6**	**-45.4**	**4.5**	**2**
R7	93.6	-8.4	3.5	7
R8	-41.9	-76.1	67.9	11
R9	-102.7	-35.8	-4.9	15
R10	73	-13	-7.4	6
R11	169.3	25.2	4.7	18
R12	97.7	-48.5	30.1	18
R13	**-67**	**-30.9**	**2.9**	**5**
R14	**0.8**	**-13.6**	**-58**	**1**
R15	89.1	13.8	-70	12
R16	139.4	-20.6	-8.7	16
R17	-78.5	-24.1	-27.7	10
R18	**-27.3**	**-19.1**	**42**	**3**
R19	99.1	11.7	38.4	12
R20	-61.6	-31.8	19.5	8

Table 3. Same as Table 2 for temperature (T).

ID	Annual T bias (°C)	Annual T SD bias (°C)	T SS bias (°C/decade)	Overall T ranking
R3	-2.1	-0.1	-0.2	4
R6	-2.2	-0.1	-0.3	5
R13	-1.1	0	0	2
R14	**-0.4**	**0.1**	**0.1**	**1**
R18	-1.2	-0.1	-0.2	3


Mean annual precipitation (1981-2010)
(a) OBSERVED (CY-OBS)
(b) EURO-CORDEX: R1
(c) EURO-CORDEX: R2
(d) EURO-CORDEX: R3
(e) EURO-CORDEX: R4
(f) EURO-CORDEX: R5
(g) EURO-CORDEX: R6
(h) EURO-CORDEX: R7
(i) EURO-CORDEX: R8
(j) EURO-CORDEX: R9
(k) EURO-CORDEX: R10
(l) EURO-CORDEX: R11
(m) EURO-CORDEX: R12
(n) EURO-CORDEX: R13
(o) EURO-CORDEX: R14
(p) EURO-CORDEX: R15
50 km
N
mm/yr
0 200 400 600 800 1000 1200 1400 1600

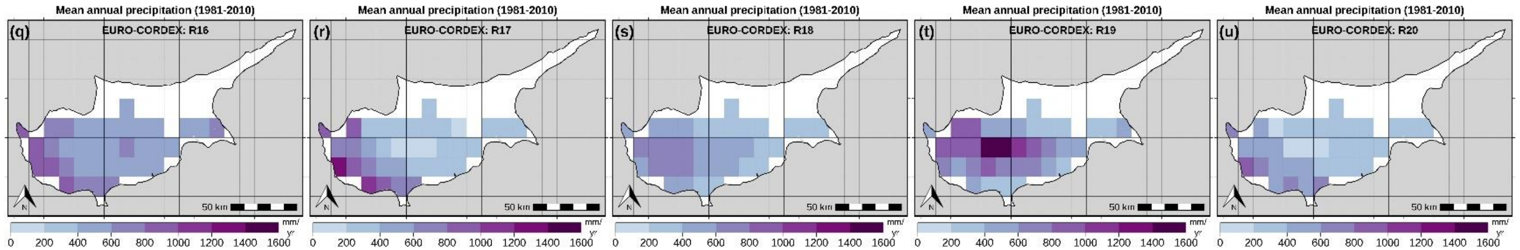


Figure. 1. Observed (a) and simulated (b-u) mean annual precipitation averaged for the period 1981-2010. Simulations are from the EURO-CORDEX 12-km ensemble, observations are CY-OBS remapped in the EURO-CORDEX 12-km grid. Modelled results (b-u) were masked according to the gridded observations.

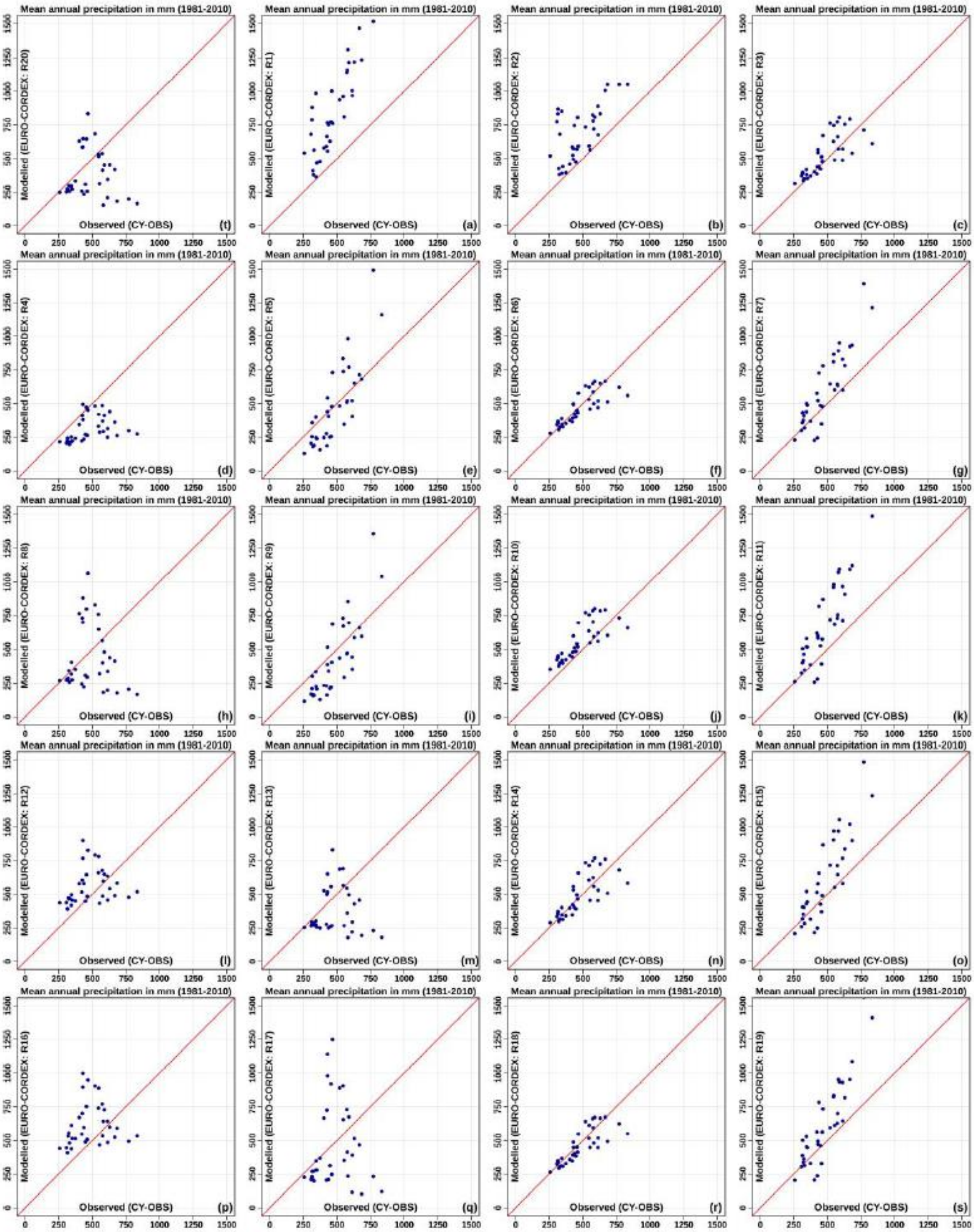


Figure 2. Observed (CY-OBS) vs. modelled (EURO-CORDEX) annual precipitation climatology (1981-2010). Each point represents a model grid-cell over Cyprus land.

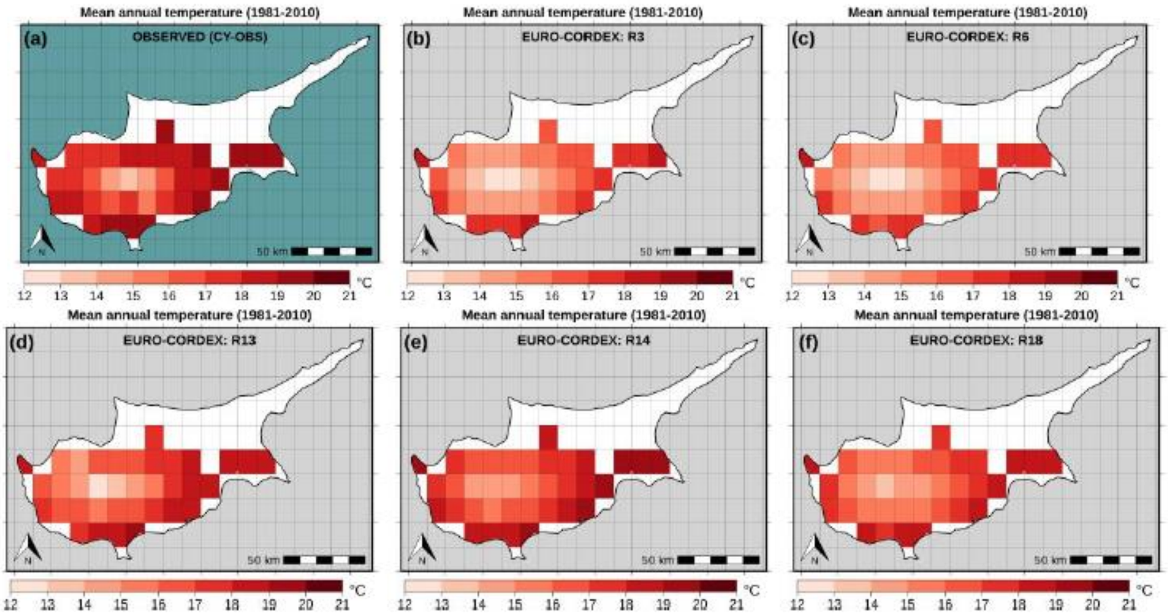


Figure 3. Observed (a) and simulated (b-f) mean annual temperature averaged for 1981-2010. Simulations are from the EURO-CORDEX 12-km ensemble, observations are CY-OBS remapped in the EURO-CORDEX 12-km grid. Modelled results (b-f) were masked according to the gridded observations.

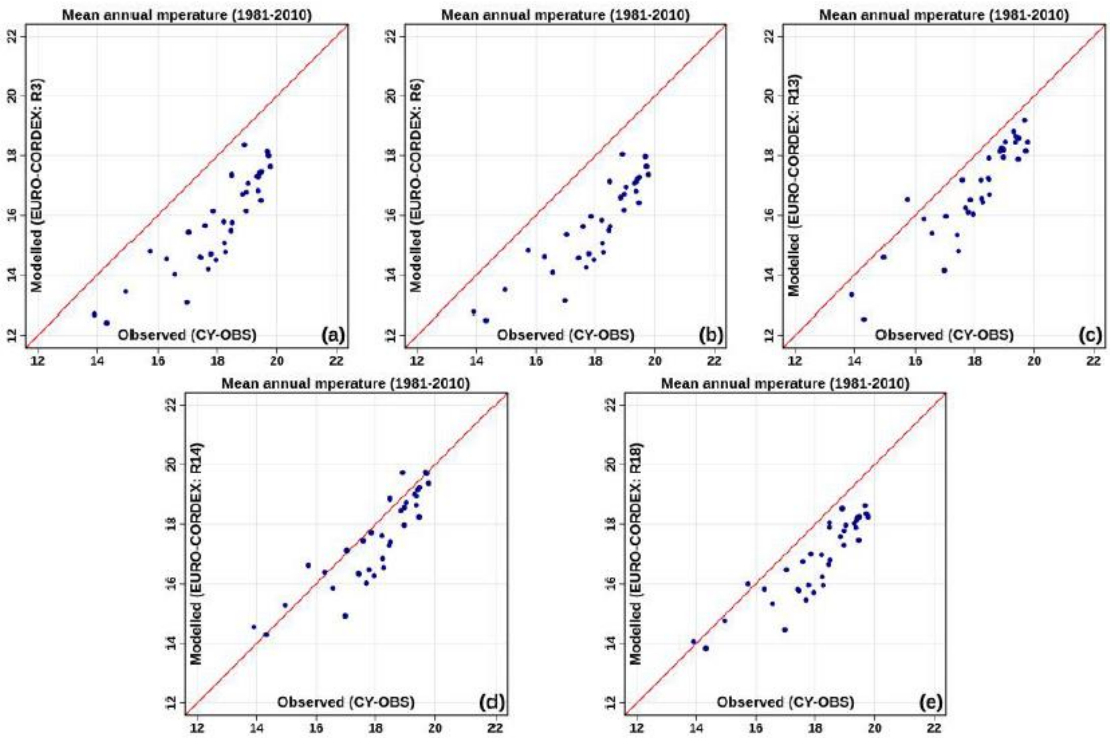


Figure 4. Observed (CY-OBS) vs. modelled (EURO-CORDEX) mean annual temperature climatology (1981-2010). Each point represents a model grid-cell over Cyprus land.

Methods and Data for Bias Correction and Downscaling

The observed data used for this study are the 1-km gridded daily precipitation data for Cyprus for 1981-2010 (Camera et al., 2014). The simulated data are obtained from the "KNMI-RACMO22E" model, as presented above. These data have a resolution of 12.5 x 12.5 km and 39 land grids for Cyprus (Fig. 5). We use the 1981-2010 period as reference period and the 2031-2060 period for the projections. We select the CY-OBS 1-km grid cells closest to the 12.5-km Model grid cells for the bias correction and downscaling.

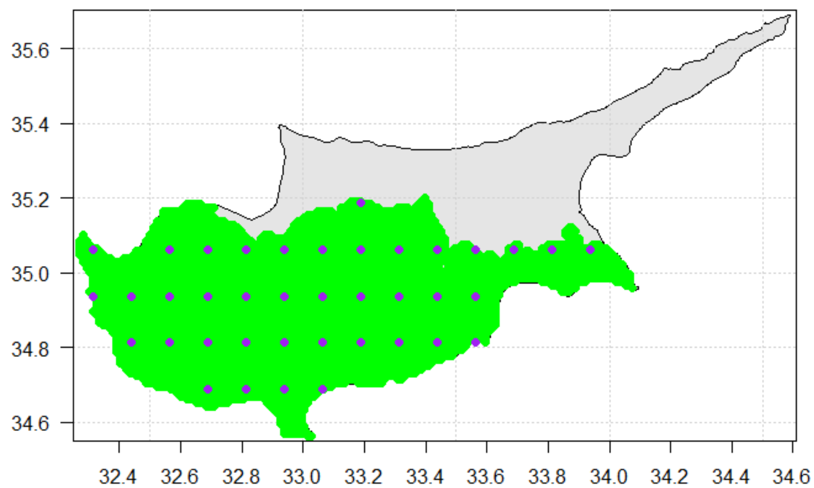


Figure 5. The 39 grid 12.5-km cells of the regional climate model, with the area covered by the 1-km gridded dataset in green.

The following steps describe the procedure for the bias correction:

1) We extract all wet days with precipitation amount greater than 0.1 mm.
2) We divide the data into two sub-periods: the wet period (November to March) and the dry period (April to October).
3) We split the data for these two periods into two subsets to better model the rainfall extremes. We use the 95th percentile of CY-OBS for each period to divide the data in non-extreme events and extreme events for each period (Figure 6). We refer those these four subsets as wet-under and wet-over and dry-under and dry-over.
4) We divide the data set in a calibration period (1981-2000) and a validation period (2001-2010).
5) We evaluate four distributions (gamma, Weibull, log-normal and Pareto) in order to select the most appropriate distribution for fitting the rainfall data of the four subsets for the calibration period.
6) Following the selection of the most appropriate marginal distributions for the CY-OBS and Model data (MOD), we produce random data sets fitting the selected marginals. The produced data sets

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are between [0,1]. Additionally, we produce several data sets with different length (2000, 1000, 500), in order to increase the accuracy of the next steps.

7) We select the best copula family (mathematical function) that describes with the highest accuracy the dependence of the produced data sets. We evaluate five copula families (Frank, Clayton, Joe, Survival Joe, Gambel).
8) We use the selected copula family, with the respective appropriate parameters, for the bias correction of the future simulated data set. The copula calculated bias corrected values are values between [0,1].
9) We transform the [0,1] values to the original values (mm), using the marginal distribution selected in step 5. We refer to these data sets as MOD-Cop
10) We compute the number of wet days for each subset of CY-OBS and MOD-Cop and the ratios between these two (see Table 4).
11) The model overestimates the number of wet days, therefore, we use the wet-day ratios to obtain a model data set with the same number as wet days as CY-OBS. We use bootstrap sampling to get the wet day ratio (fraction) of the MOD-Cop rain days for each individual subset. We sample until we find a rainfall data set with the same rainfall total as CY-OBS. We refer to this data set as MOD-CopB
12) We apply the Copula transformation from the calibration data set (1981-2000) to the validation data set (2001-2010).
13) We again compute the wet day ratios (step 10) and apply the bootstrap sampling to the MOD-Cop data of the calibration period (step 11).
14) We evaluate the calibration and validation results for acceptance.
15) We apply the Copula transformation and step 10 and 11 to bias correct the 2031-2060 data set.
16) We use fractions to apply the bias correction data to all 1-km grid cells, for each model cell: ModCopB_future(j) = MOD-CopB_future(i) x CY-OBS(j) / CY-OBS(i)

    where j is the center grid cell used in the previous step and the index j represents all other 1-km grid cells in the model grid cell.

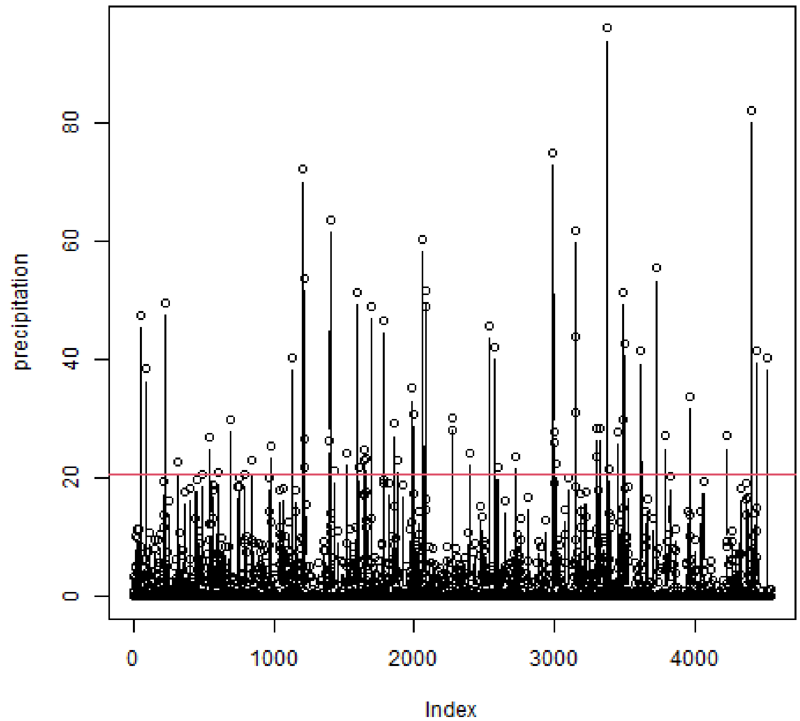

Figure 6. Days of the CY-OBS data set with daily precipitation (mm), showing the 95th percentile that separates the extreme rainfall events.

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Table 4. Number of wet days for CY-OBS and the model and the ratios for each grid cell for 1981-2010.

	CY-OBS				MODEL				RATIO			
GRID	wet_ under	wet_ over	dry_ under	dry_ over	wet_ under	wet_ over	dry_ under	dry_ over	wet_ under	wet_ over	dry_ under	dry_ over
1	1518	80	508	27	2125	112	1076	57	0.71	0.71	0.47	0.47
2	1570	83	528	28	2032	107	1028	55	0.77	0.78	0.51	0.51
3	1464	78	499	27	2020	107	1043	55	0.72	0.73	0.48	0.49
4	1411	75	437	23	1990	105	1023	54	0.71	0.71	0.43	0.43
5	1602	85	506	27	2367	125	1347	71	0.68	0.68	0.38	0.38
6	1584	84	546	29	2478	131	1595	84	0.64	0.64	0.34	0.35
7	1716	91	681	36	2536	134	1577	83	0.68	0.68	0.43	0.43
8	1648	87	726	39	2520	134	1507	80	0.65	0.65	0.48	0.49
9	1580	84	772	41	2529	134	1519	80	0.62	0.63	0.51	0.51
10	1668	88	843	45	2477	131	1464	78	0.67	0.67	0.58	0.58
11	1653	87	754	40	2316	122	1379	73	0.71	0.71	0.55	0.55
12	1445	77	582	31	2117	112	1269	67	0.68	0.69	0.46	0.46
13	1338	71	488	26	1925	102	1036	55	0.7	0.7	0.47	0.47
14	1363	73	502	27	1860	98	980	52	0.73	0.74	0.51	0.52
15	1589	84	501	27	2260	121	1183	63	0.7	0.69	0.42	0.43
16	1682	89	544	29	2578	136	1584	84	0.65	0.65	0.34	0.35
17	1688	89	667	36	2712	143	1778	94	0.62	0.62	0.38	0.38
18	1688	89	769	41	2755	146	1732	92	0.61	0.61	0.44	0.45
19	1811	96	899	48	2690	142	1650	87	0.67	0.68	0.54	0.55
20	1794	95	918	49	2642	140	1558	82	0.68	0.68	0.59	0.6
21	1669	88	849	45	2576	136	1492	79	0.65	0.65	0.57	0.57
22	1463	77	719	39	2447	129	1442	76	0.6	0.6	0.5	0.51
23	1371	73	665	36	2269	120	1343	71	0.6	0.61	0.5	0.51
24	1382	73	632	34	2056	109	1227	65	0.67	0.67	0.52	0.52
25	1334	71	568	30	1902	101	1159	62	0.7	0.7	0.49	0.48
26	1518	80	458	25	2238	118	1103	59	0.68	0.68	0.42	0.42
27	1679	92	647	35	2606	138	1528	81	0.64	0.67	0.42	0.43
28	1701	90	780	42	2625	139	1508	80	0.65	0.65	0.52	0.52
29	1713	91	799	43	2563	135	1448	77	0.67	0.67	0.55	0.56
30	1594	84	702	37	2495	132	1412	75	0.64	0.64	0.5	0.49
31	1526	81	672	36	2391	126	1368	73	0.64	0.64	0.49	0.49
32	1380	73	547	29	2270	120	1272	67	0.61	0.61	0.43	0.43
33	1233	65	544	29	2114	113	1137	60	0.58	0.58	0.48	0.48
34	1434	76	706	39	2000	106	1138	60	0.72	0.72	0.62	0.65
35	1293	70	561	30	1889	100	1115	59	0.68	0.7	0.5	0.51
36	1347	71	575	31	1833	97	1119	60	0.73	0.73	0.51	0.52
37	1252	66	493	26	1807	96	1098	58	0.69	0.69	0.45	0.45
38	1181	63	387	21	1847	98	1048	57	0.64	0.64	0.37	0.37
39	1349	71	523	28	2013	106	1020	54	0.67	0.67	0.51	0.52

Results for Bias Correction and Downscaling

Figure 7 shows the marginal distributions that gave the best fit for the wet day data series of the four subsets for all 39 model grid cells. The lognormal distribution is the most frequently selected distribution.

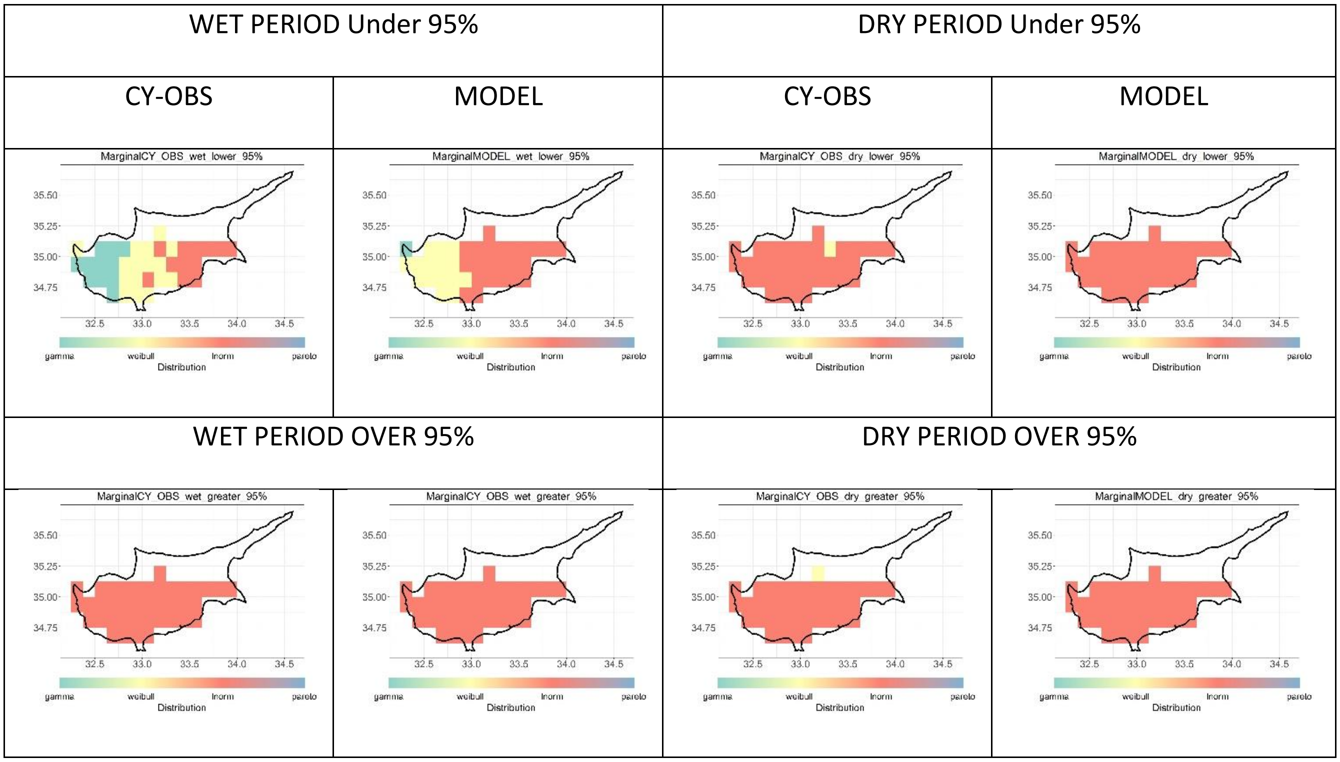

Figure 7. Marginal distributions that gave the best fit for the wet day data series of the four subsets.

The copula family that describes most appropriately the dependence between two random data sets, fitting the selected marginal distributions is the “Joe”. The Joe copula has the below presented characteristics (no symmetry, weak left tail dependence and strong right tail).

Copula	Dependence Structure Characteristics	Archimedean Generation Function $\psi(t)$	$\psi'(t)$	θ range and value for index	Kendall's τ and range	Spearman's ρ_S and range
Joe	Radially asymmetric, weak left tail dependence and very strong right tail dependence (stronger than Gumbel), left tail dependence goes to zero at left extreme	$\varphi(t) = -\ln[1-(1-t)^{\theta}]$	$\frac{-\theta(1-t)^{\theta-1}}{1-(1-t)^{\theta}}$	$1 \leq \theta < \infty$ $\theta = 1$ is independence	See Equation (27) $0 \leq \tau < 1$	No simple form $0 \leq \rho_S < 1$

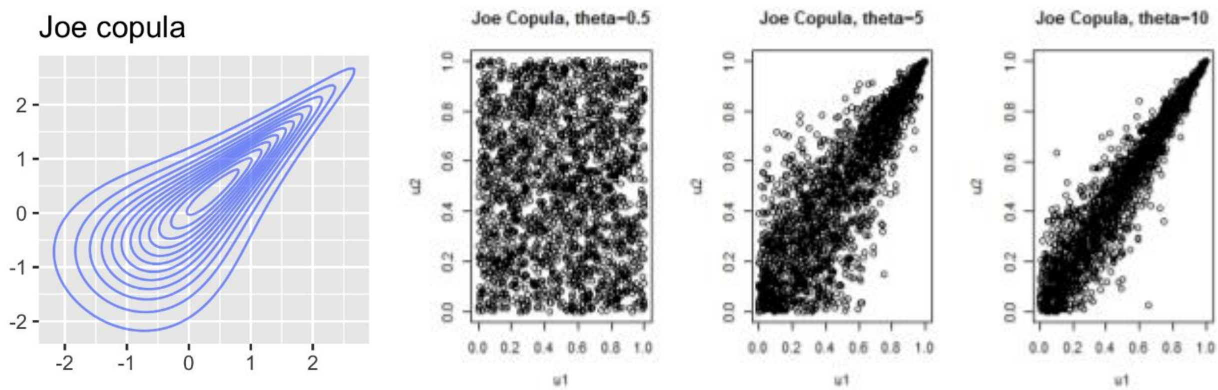

Figure 8. Description and illustration of the Joe Copula.

The rainfall results for the wet period are presented in Figure 9 for the normal data (under) and in Figure 10 for the extremes (over). It can be observed that the bias between the model and CY-OBS is can be very well corrected by the Copula transformation. The average total annual rainfall for 2031-2060 downscaled to 1-km is presented in Figure 11.

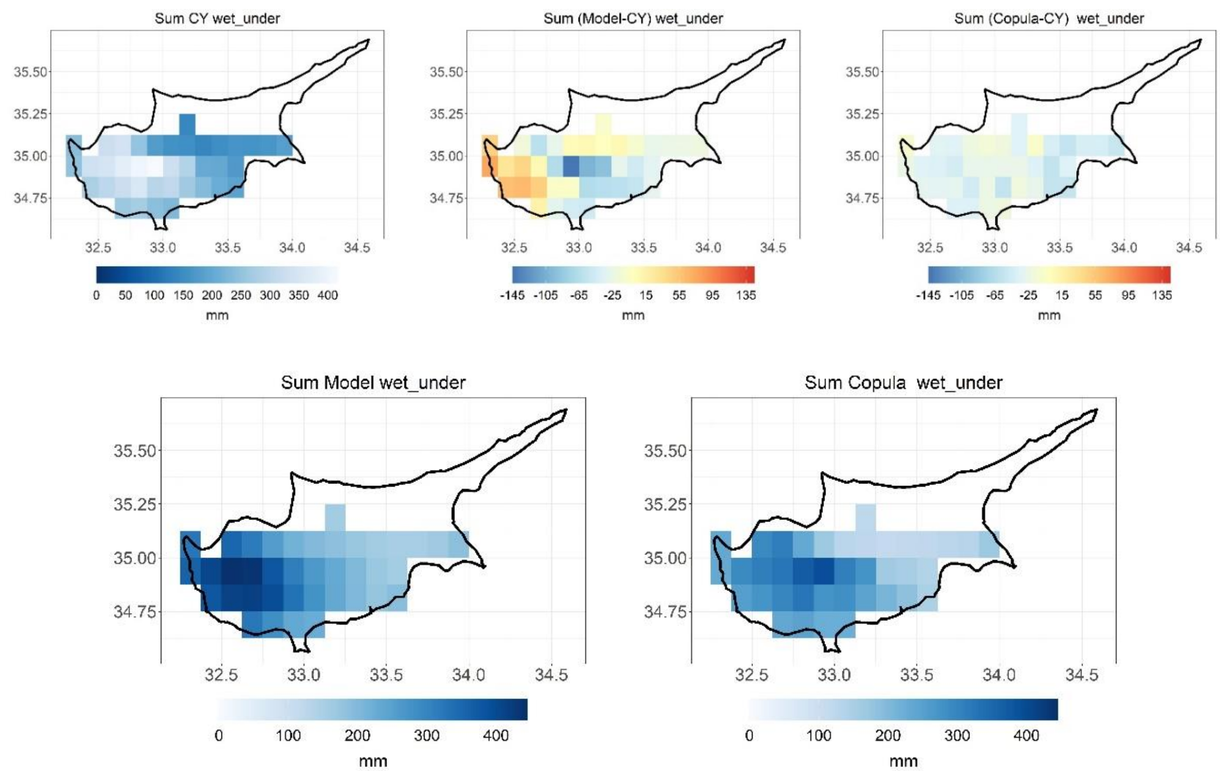

Figure 9. Observed average annual rainfall (top left) for the wet_under subset and the differences between the observations and the model (top middle) and between the observations and the bias corrected data (top right); the future rainfall for the model (bottom left) and the bias corrected data (bottom right) for 2031-2060.

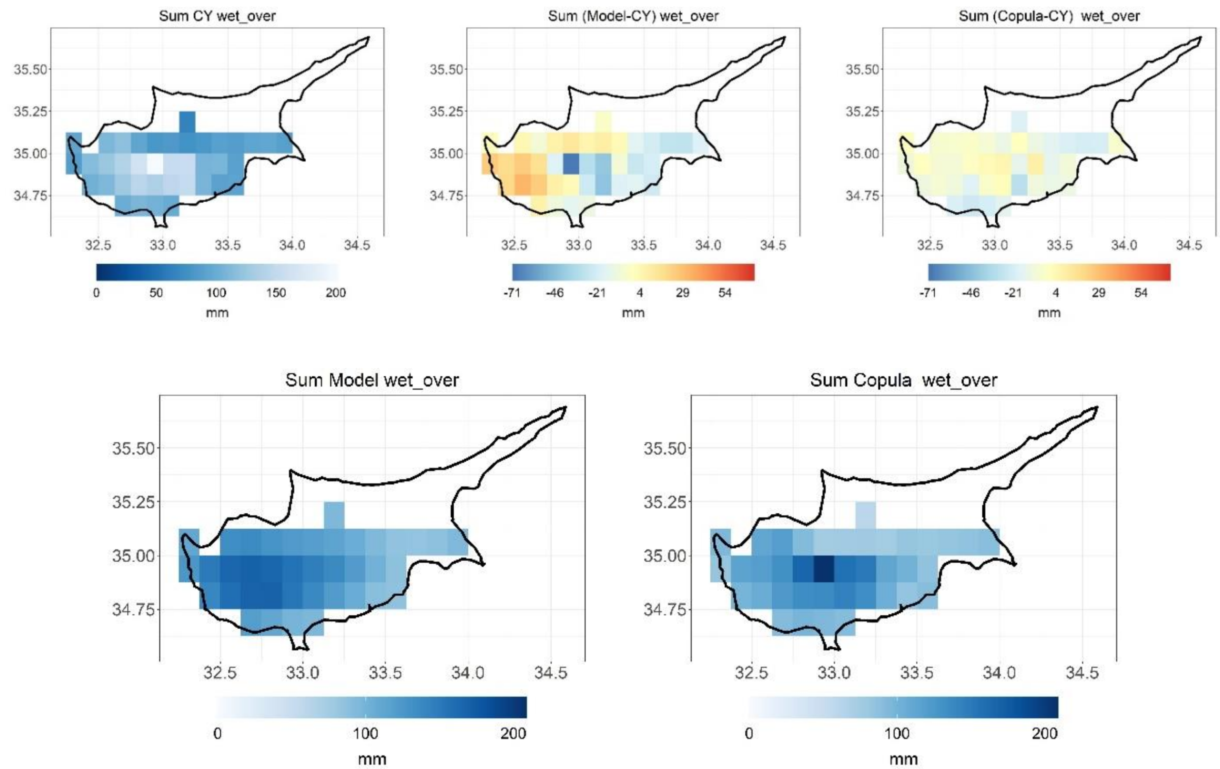

Figure 10. Observed average annual rainfall (top left) for the wet_over subset and the differences between the observations and the model (top middle) and between the observations and the bias corrected data (top right); the future rainfall for the model (bottom left) and the bias corrected data (bottom right) for 2031-2060.

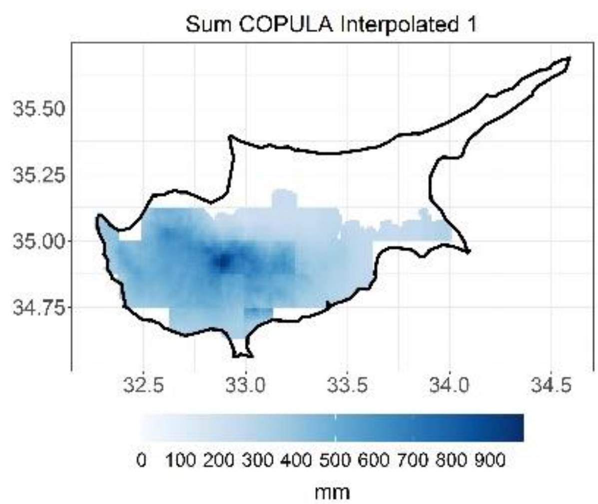

Figure 11. The bias-corrected total annual future rainfall (2031-2060) at 1-km

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