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European Climate Prediction system (EUCP)

Deliverable D3.3

Assessment of Multi-Model Based Ensemble of Convection Permitting Regional Climate Model (CPM) simulations for the historical and near future period

Deliverable Title	*Assessed multi-model based ensemble of simulations of high impact weather events for the historical and near future period*	
Brief Description	Report on the assessment of the ensemble of very high-resolution regional climate models (defined in D3.1 and evaluated in D3.2) for the simulation of high impact weather events in the historical and near future climate. The report presents a detailed analysis of the high-resolution simulations over seven domains covering Europe.	
WP number	3	
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Table of contents

List of Tables

List of Figures

1. Executive summary

The overarching objective of the European Climate Prediction (EUCP) system is to develop an innovative European regional ensemble climate prediction system based on a new generation of improved and higher-resolution climate models, covering timescales from seasons to decades, and designed to support taking practical and strategic climate adaptation and mitigation decisions on local, national and global scales. To accomplish these objectives, EUCP consists of several work packages. Here we present a deliverable of the Work Package 3: "Demonstrator of high impact weather in a changing climate on regional and local scales".

The main goal of WP3 is to produce a portfolio of high impact extreme meteorological events at the pan-European level using convection-permitting regional climate models (CPMs) running at horizontal grid spacings of 2.2-3 km for both historical and future periods up to a temporal horizon of 40 years or so. The produced data is not only to be analysed in WP3, but it is provided to WP4 for impact analysis. Additionally, where needed it is also available to WP2 for generating PDFs of climate changes in extreme events, and to WP5 for use in the seamless projection activities. In total, 10 modelling groups with seven regional climate models are participating in this WP.

The first deliverable of WP3 (D3.1) presented the simulation strategy for the experiments that were conducted in WP3, the second deliverable (D3.2) reported on the evaluation of CPM simulations driven by the ERA-Interim reanalysis, while this deliverable (D3.3) reports on the assessment of the historical and near-future simulations. This report analyses in parallel the whole modelling chain, from the parent global climate models (GCMs) via the intermediate regional climate models (RCMs) to the high-resolution CPMs, for each group and domain.

The analysis shows that CPMs have a more realistic representation of heavy precipitation than the coarser-resolution RCMs, especially during the summer season. CPMs to a large extent follow the change signal as obtained from their respective RCMs, including for heavy precipitation. The change signal until mid-century does not provide a completely clear conclusion, which can partly be attributed to a short time period for the change to occur, and the strong effect of internal variability that can dominate the forced change signal for some models.

The analysis presented here will be further enriched and drafted into a manuscript that will be submitted before the end of the project.

2. Project objectives

The deliverables 3.1-3 have contributed to the following EUCP objectives (Description of Action, Section 1.1):

No.	Objective	Yes	No
1	Develop an ensemble climate prediction system based on high-resolution climate models for the European region for the near-term (~1-40 years)	✔	
2	Use the climate prediction system to produce consistent, authoritative and actionable climate information	✔	
3	Demonstrate the value of this climate prediction system through high impact extreme weather events in the near past and near future	✔	
4	Develop, and publish, methodologies, good practice and guidance for producing and using EUCP's authoritative climate predictions for 1-40 year timescales	✔	

3. Detailed report

3.1 Introduction

The first two deliverables of WP3 covered the description of the simulation strategy (D3.1) and the evaluation of ERA-Interim driven simulations (D3.2). The main change compared to the original work plan was decided during the first project meeting, where all the groups agreed to perform continuous time-slice simulations for the historical and future periods instead of downscaling individual high-impact events. The obvious benefits of this approach came with several challenges. The length of the simulations and the related computational effort were considerably increased, the total data amount has increased to very large levels, and the very large increase in the time and effort required for post-processing, CMORizing, and sharing of the data (to be discussed in detail in D3.4) has required extending the deadline for the completion of this report. The latter should be regarded from the perspective that many groups finished their simulations more than a year ago, and still the data from some groups became available at the last minute for completing the report.

However, as a result of these efforts, we now have created the largest multi-model multi-domain CPM ensemble ever. The next subsections provide the basic assessment of the quality of simulations and the analysis of CPM characteristics in both the historical and near-future climate.

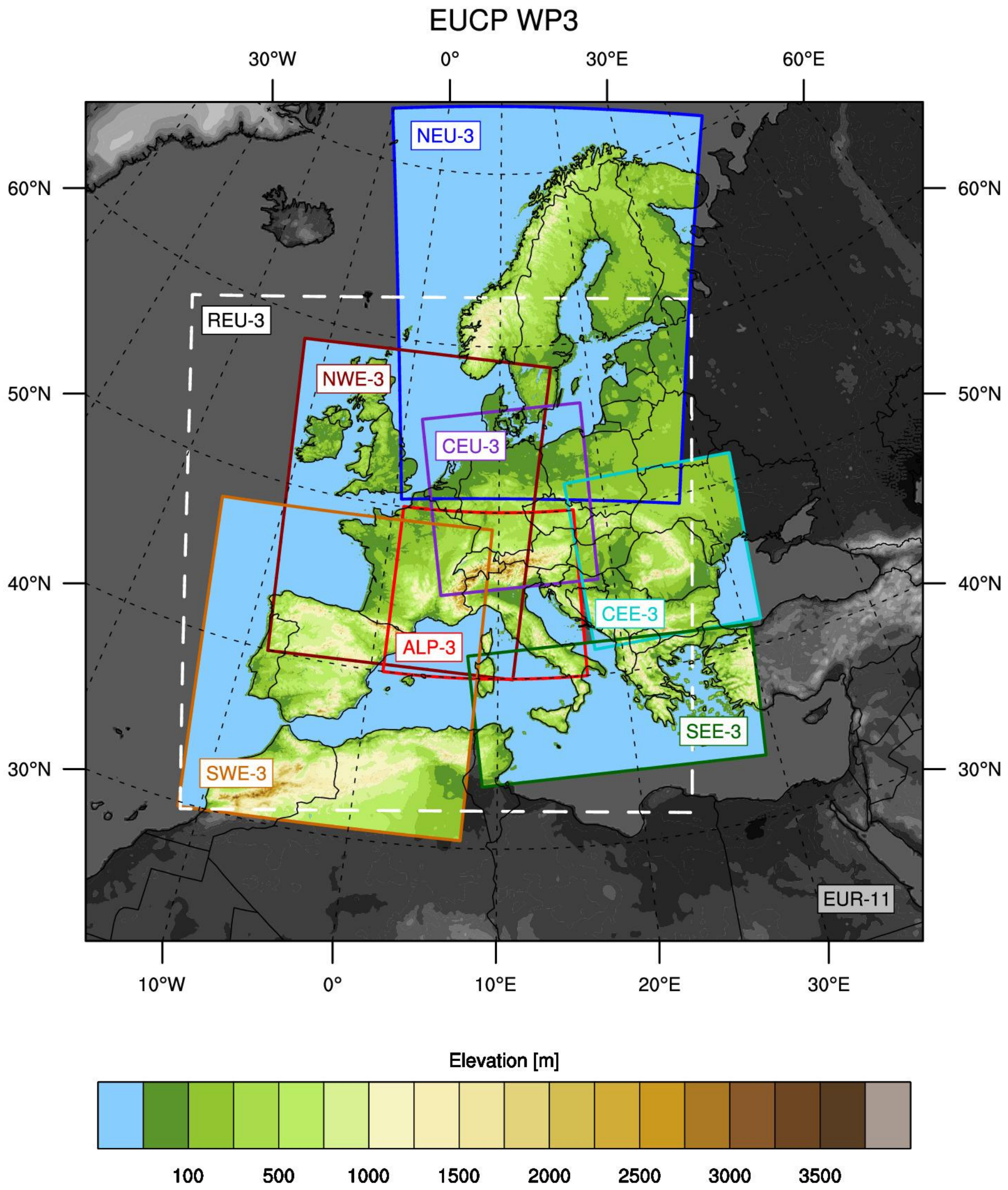

Figure 1: Set of domains used for CPM simulations. In addition to the sub-continental domains covered by the modelling groups, the dashed box indicates the Reduced Europe domain (REU-3) used by ETHZ and UKMO.

3.2 Description of the conducted experiments

The scenario simulations were performed over seven domains (Fig. 1) for two mandatory 10-yr periods: historical (1996-2005) and mid-century (2041-2050). Most of the groups additionally simulated the end of the century period (2090-2099), but we focus on mid-century changes in the report since this period is the focus of EUCP. All the simulations have been completed, post-processed to unify formatting (CMORized) and shared on appropriate servers. The evaluation simulations forced with ERA-Interim were thoroughly assessed in D3.2 and presented in Coppola et al. (2020) and Ban et al. (2021).

As shown in Table 1, most of the CPM simulations use an intermediate step, i.e., a lower resolution RCM (12-18 km RCM), for a smoother transition from the coarse GCM grid to the 2-3 km grid of a CPM. The only exception is UKMO, who used a high-resolution (about 25 km) GCM directly for CPM boundary data. Since the high-resolution GCM was atmosphere-only, it used SST data from a standard coarser CMIP5 GCM. We therefore regard the coarse CMIP5 GCM as the GCM and the high-resolution atmosphere-only GCM as the intermediate model ("RCM") in this case.

Many groups used a European domain for their RCM simulations, however the domains are not necessarily the same between different groups except for the CORDEX domains.

Table 1: Modelling systems used by the participating groups. ECS is the equilibrium climate sensitivity.

GROUP	**CPM**	**dx** (km)	**RCM**	**RCM domain**[a] **/ dx** (km)	**GCM**	**CMIPx**	**ECS**
CMCC	CCLM	3	CCLM	EC/12	EC-Earth r12	CMIP5	3.3
CNRM	AROME41t1	2.5	ALADIN63	EC/12	CNRM-CM5 r1	CMIP5	3.3
DMI/ SMHI	HCLIM38-AROME	3	HCLIM38-ALADIN	Europe/12	EC-Earth r12	CMIP5	3.3
KNMI	HCLIM38-AROME	2.5	RACMO	Europe/12	EC-Earth	No	3.3
ETHZ	CCLM-GPU	2.2	CCLM	Europe/12	MPI-ESM-LR r1	CMIP5	3.6
GERICS	REMO	3	REMO	Europe/12	MPI-ESM-LR r3	CMIP5	3.6
ICTP	RegCM4	3	RegCM4	Europe/12	HadGEM2-ES r1	CMIP5	4.6
IPSL	WRF, RegIPSL	3	WRF, RegIPSL	EC/15[b] MC/18[c]	IPSL-CM5-MR[b] IPSL-CM6[c]	CMIP5[b] CMIP6[c]	n.a. 4.6
UKMO	UM	2.2	HadGEM3-GC3.1-N512 (HiresMIP)	Global/25[d]	HadGEM2-ES r1	AMIP-CMIP5 SST	4.6

[a]EC denotes EURO-CORDEX and MC MED-CORDEX. Note that many groups are running a European domain as an intermediate step. However, this domain is not necessarily the same between the groups, except for the CORDEX domains.
[b]For ALP-3.
[c]For SWE-3.
[d]UKMO downscaled the high-resolution HadGEM3 AMIP GCM simulation without using an intermediate domain. However, since the HadGEM3 SST was taken from the lower-resolution HadGEM2-ES CMIP5 simulation, the latter is considered as the GCM forcing while the HadGEM3 AMIP simulation is considered as the intermediate ("global RCM") simulation.

Table 2 shows the number of groups and simulations per domain and provides the maximum ensemble size for each domain. The ensembles are rather small for each domain, especially when compared to traditional GCM and RCM ensembles. But obviously the ALP-3 domain has more than twice the number of members compared to the other domains and is currently the largest existing multi-model CPM ensemble. Note that the NEU-3 domain has only two ensemble members, but its southern part overlaps with the northern part of REU-3 (Fig. 1). In order to increase the ensemble size, an additional analysis domain S-NEU-3 is defined over the overlapping region.

Table 2: Distribution of modelling groups over the eight European simulation and analysis domains. No. MEMBERS indicates the sizes of CPM ensembles per domain.

DOMAIN[a]	FULL NAME	GROUPS	No. MEMBERS
ALP-3	Pan-Alpine	All	9
NWE-3	North-West Europe	CNRM, KNMI[b], ETHZ[c,d], UKMO[c]	4
SWE-3	South-West Europe	CMCC, IPSL, ETHZ, UKMO	4
SEE-3	South-East Europe	ICTP, ETHZ, UKMO	3
CEU-3	Central Europe	GERICS, ETHZ, UKMO	3
CEE-3	Central East Europe	ICTP, SMHI, ETHZ, UKMO	4
NEU-3	North Europe	GERICS, SMHI/DMI	2
S-NEU-3[e]	South NEU-3	GERICS, SMHI/DMI, ETHZ, UKMO	4

[a]Domain names consist of the geographical location indicator and the maximum allowed horizontal grid spacing. Note that some groups used smaller grid spacing, shown in Table 1.
[b]KNMI used the Pseudo-Global Warming (PGW) approach for NWE-3, where the future change is added on the ERA-Interim reanalysis fields.
[c]ETHZ and UKMO used the REU-3 simulation domain (cf Fig. 1), which includes large parts of the other seven analysis domains. For some analysis domains REU-3 covers only their parts. To address this issue and to maximise the number of members in each domain's ensemble, for SEE-3 and CEE-3 reduced analysis domains are used (marked with "R") which overlap with REU-3, while for NEU-3 an additional domain S-NEU-3 is created.
[d]ETHZ applied the PGW approach for REU-3, which is used for all the analysis domains except ALP-3. They used a traditional downscaling for a separate ALP-3 simulation.
[e]S-NEU-3 is not a separate domain, but a subdomain of NEU-3 that overlaps with REU-3 and is used only for analysis. It allows adding the two extra models in the otherwise smallest ensemble of only two members for NEU-3.

3.3 Analysis and Methods

Statistical Indices. This report presents the analysis for the indices listed in Table 3. The indices are calculated as a seasonal value where summer season includes months June-July-August, winter December-January-February, spring March-April-May, and autumn September-October-November gathered over the analysed 10-year long periods.

Table 3: Statistical indices analysed in the current report.

ABBREVIATION	DEFINITION	UNIT
Mean	Mean Precipitation	mm/d
Freq	Wet day/hour[a] frequency	[fraction]
Int	Wet day/ hour[a] intensity	[mm/d] / [mm/h]
pXX	XX percentile[b] of daily/hourly precipitation	[mm/d] / [mm/h]

[a] A wet day (hour) is defined as a day (hour) with precipitation ≥ 1 *mm* (0.1 *mm*)
[b] Percentiles are calculated using all events (wet and dry) following Schär et al., 2016

Observations. For the assessment of the historical simulations we use the E-OBS version 20.0-e daily data (Cornes et al., 2018). The issues with E-OBS underestimating precipitation are well known, especially in complex topography (e.g. Vautard et al., 2021). The dataset is used because it is readily available for all the domains and also the full evaluation of the modelling systems was performed in D3.2 using higher-resolution datasets and hence does not need to be repeated here. This is why E-OBS is used here only as a common climatological reference for all the domains and the deviations from it cannot be interpreted as indicators of the model performance.

Methods. Given that the ensembles are rather small, even for the largest ALP-3, we show all the members separately. The analysis was performed using RCAT (Regional Climate Analysis Tool, https://regional-climate-analysis-tool.readthedocs.io/), the parallelized python tool for climate model analysis developed at SMHI within EUCP. In order to keep consistency between the presentation of different domains, we show in detail only one season (JJA), even though for some domains the peak convective activity is later in the year (Mediterranean).

We use the Analyzing Scales of Precipitation (ASoP) method (Klingaman et al 2017, Berthou et al 2018). ASoP gives a distribution of the contributions of each precipitation intensity bin to the mean precipitation rate. The distributions are calculated for each model grid point, and then averaged over desired regions. In the first step, the method defines the precipitation intensity bins such that all bins have a similar number of events, except for the largest bins due to the small number of events there. We used the same number of bins (80) for all ASoP analysis where the bin edges were defined according to Eq. 1 in Klingaman et al 2017. In the second step, the frequency of events in each bin is multiplied by the mean precipitation rate of the bin to obtain the actual contribution of the bin to the mean precipitation rate. Note that the sum of all actual contributions gives the mean precipitation rate. Furthermore, dividing the actual contributions by the mean precipitation rate gives the fractional contributions to the mean precipitation. The sum of all fractional contributions equals one, so the information provided by fractional contributions is predominantly about the shape of the distribution.

Throughout the analysis all model data are kept on their original grids in order to account for the detailed representation in the high-resolution models and potential added value in temporal and/or spatial climate change responses. The exception is in the assessment of the control experiments when model biases are calculated with respect to E-OBS observations, where analyzed model data is interpolated to the E-OBS grid (including coarser resolution GCMs). The model results were not bias adjusted.

3.4 Results

Given the total of seven modelling domains and 10 participating groups, and a sparse matrix of connections between groups and domains (each group simulated between 2 and 3 domains), the presentation of the results is challenging. In order to summarize the results as much as possible, this section is organised in subsections based on performed analyses, rather than on domains or modelling groups. A basic assessment of the historical simulations is presented first. Note that the main evaluation of the WP3 CPMs (i.e. the evaluation simulations forced with ERA-Interim) was performed and reported in D3.2. This is followed by presenting the differences between RCMs and CPMs for a number of variables and indices, which could be regarded as a potential added value of CPMs (potential because no observations are present). The change from the historical period to the mid-century (end of century for ALP-3 ETHZ, as the mid-century data was not available at the time this report was written) is then analysed, with a particular emphasis on the differences between RCMs and CPMs, i.e. the potential added value for the change signal.

3.4.1 Basic assessment of the historical simulations

The historical period simulations allow for a comparison with observations. However, the major influence on the RCM and CPM results comes from the parent GCM forcing, which generally differs from observations for many reasons. The main evaluation of the participating RCMs and CPMs was presented in the previous deliverable (D3.2) using simulations forced with ERA-Interim (see also Ban et al., 2021). Here we present an assessment against observations of the entire modelling chain, from GCM via RCM to CPM, with a focus on mean daily precipitation.

It is important to stress that given the 10-yr time slice, the effects of internal variability are large. On such time scales the internal variability alone may easily exceed several tens of percent of the difference. This, combined with the inadequacy of E-OBS for high-resolution precipitation in complex terrain, clearly indicates that the basic assessment presented here is not a rigorous evaluation of the modelling systems. Nevertheless, comparing against the same reference climate allows one to compare the differences occurring in the entire GCM-RCM-CPM modelling chain, and over the different domains. For the ETHZ and KNMI simulations, the bias analysis is more useful since their CPM runs were driven by ERA-Interim. The terms such as “underestimate” or “overestimate” are used below for convenience only - they do not necessarily imply an issue with the model performance.

For the largest-ensemble domain ALP-3 (Fig. 2), the GCM biases are frequently surpassed by the CPM biases (see e.g. CNRM, IPSL and ICTP). For some groups there is a connection between the GCM and RCM/CPM signals (e.g. CNRM, UKMO, KNMI), but this is not necessarily strong nor valid for all the groups implying that RCMs/CPMs can change the forcing signal considerably. On the other hand, for most of the groups there is a strong connection between their RCM and CPM, a notable exception being ICTP and to a certain extent HCLIM. For most of the groups, albeit not all, the RCM and CPM share most of the code and differ only in that the deep convection parameterization is switched off for the CPM. This could explain the general similarity in the mean results within each RCM-CPM pair. On the other hand, the GCMs generally do not have a similar code to the nested RCMs/CPMs, which can explain the noted differences between the parent GCM and the nested RCM/CPM.

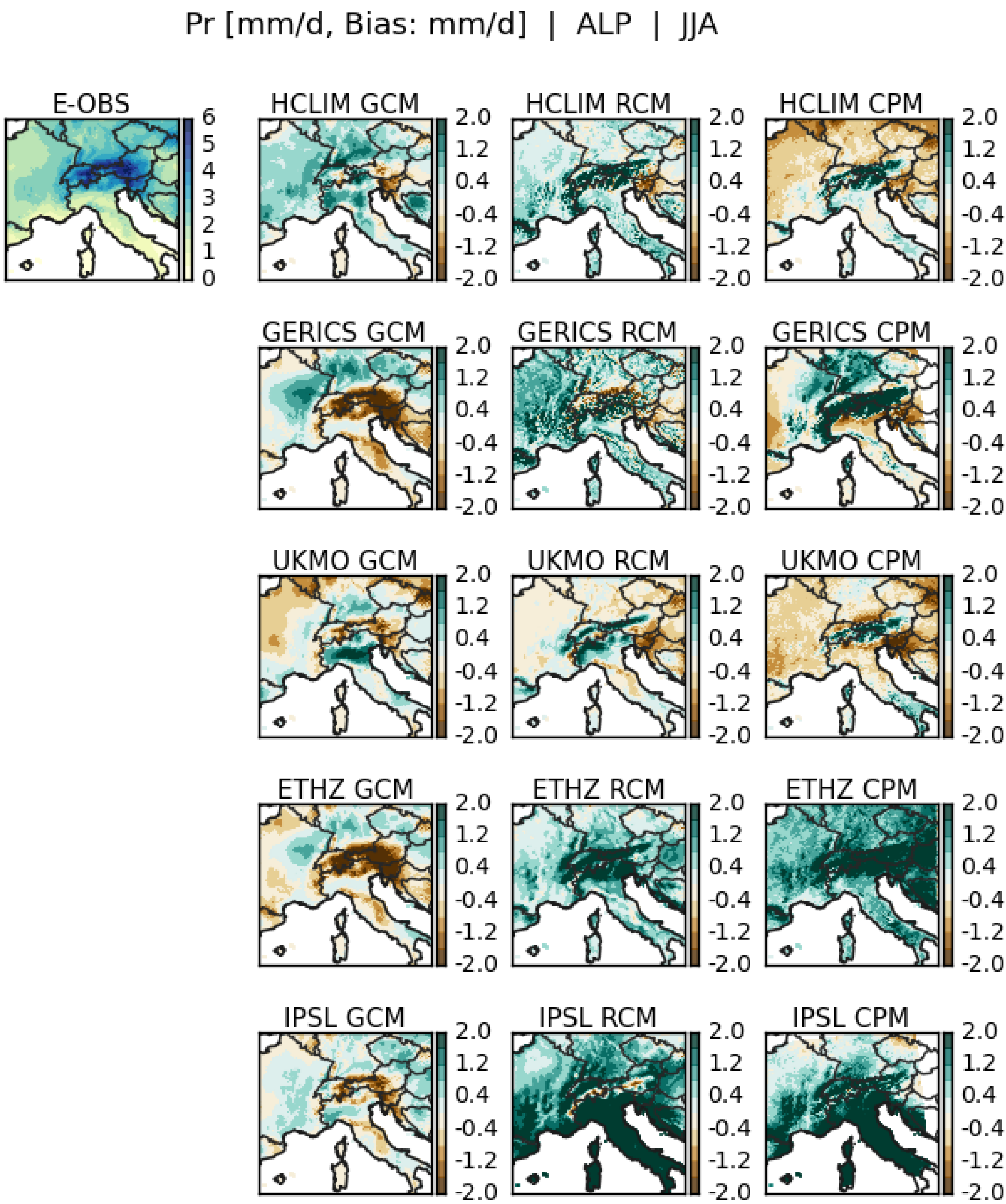

Figure 2: Observed mean daily JJA precipitation for ALP-3 for the historical period (E-OBS, leftmost column), and biases for GCM, RCM and CPM for each participating modelling group, given in panel titles. See Table 1 for the details of models used by each group. Since ETHZ and KNMI use the PGW approach, ERA-Interim is shown as the corresponding GCM (the difference between ETHZ and KNMI is because of the different simulation periods). Note that SMHI and DMI shared the resources in performing some of the simulations (see Table 2), and therefore HCLIM is used as the "institute" name.

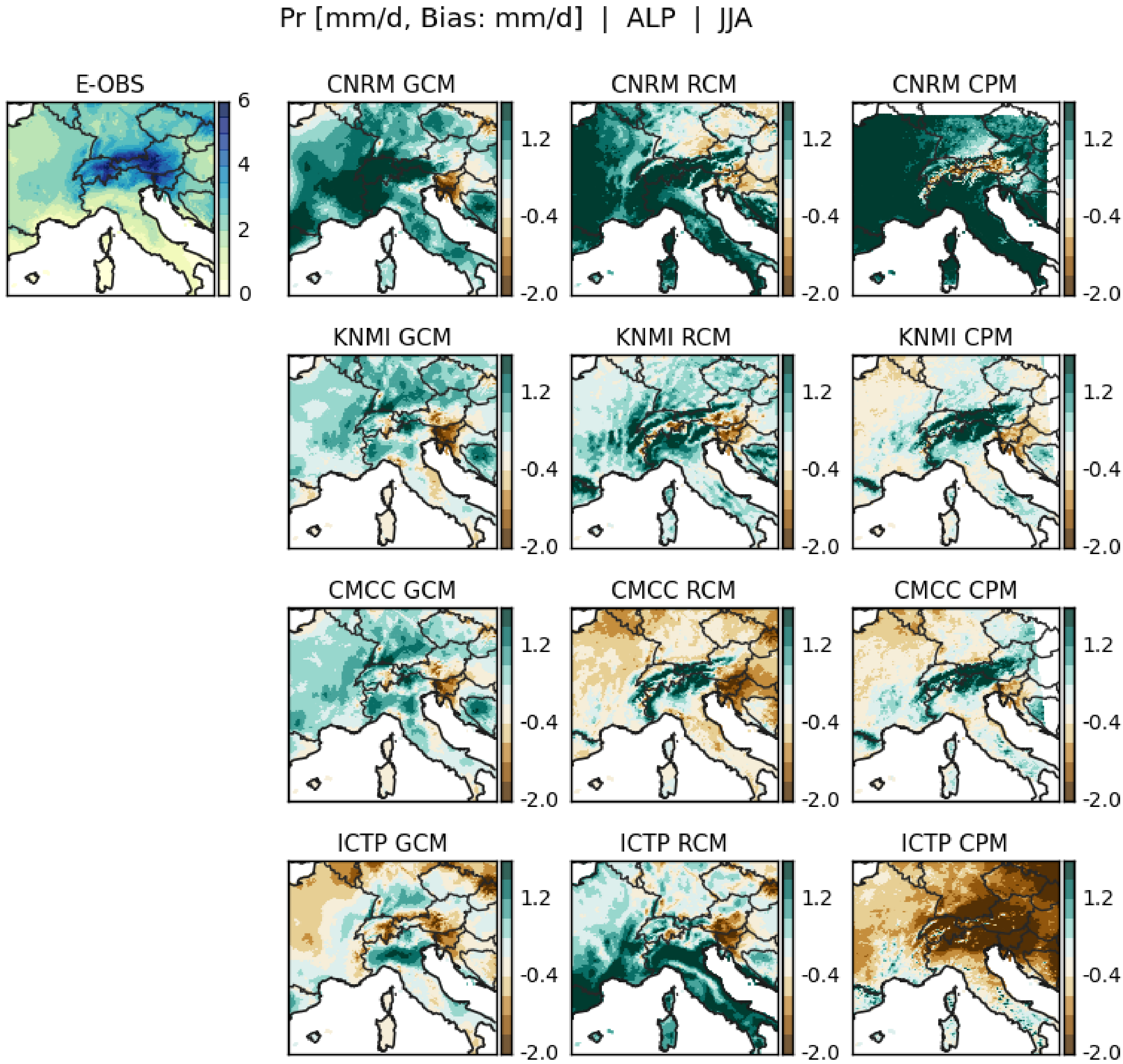

Figure 2: cont.

For NWE-3 (Fig. 3), the connection between GCM and RCM/CPM is strong for all the participating groups. Since all the groups participated in ALP-3, the other six domains offer a possibility to examine the performance and consistency of the same modelling system over different domains. The CNRM modelling chain has a very consistent performance over the two domains (NWE-3 and ALP-3): the GCM predominantly overestimates the precipitation to start with, and the RCM and CPM amplify the overestimation signal from their respective parent domain, which results in the largest overestimation being present in the CPM. UKMO also has a similar signature across the domains, but with the opposite sign: the CPM reduces the precipitation compared to its forcing model ("RCM", see Table 1) and results in a larger underestimation. For KNMI for both domains, the RCM tends to increase the precipitation compared to the forcing, while the CPM decreases the precipitation even more so that it ends up being lower than the GCM forcing. Note that for KNMI the "GCM" for NWE-3 is ERA-Interim because of the PGW approach. For ETHZ, both the RCM and CPM are close to the

“GCM” forcing, which is also ERA-Interim because of PGW. The CPM tends to somewhat increase the precipitation compared to RCM, both for ALP-3 and NWE-3.

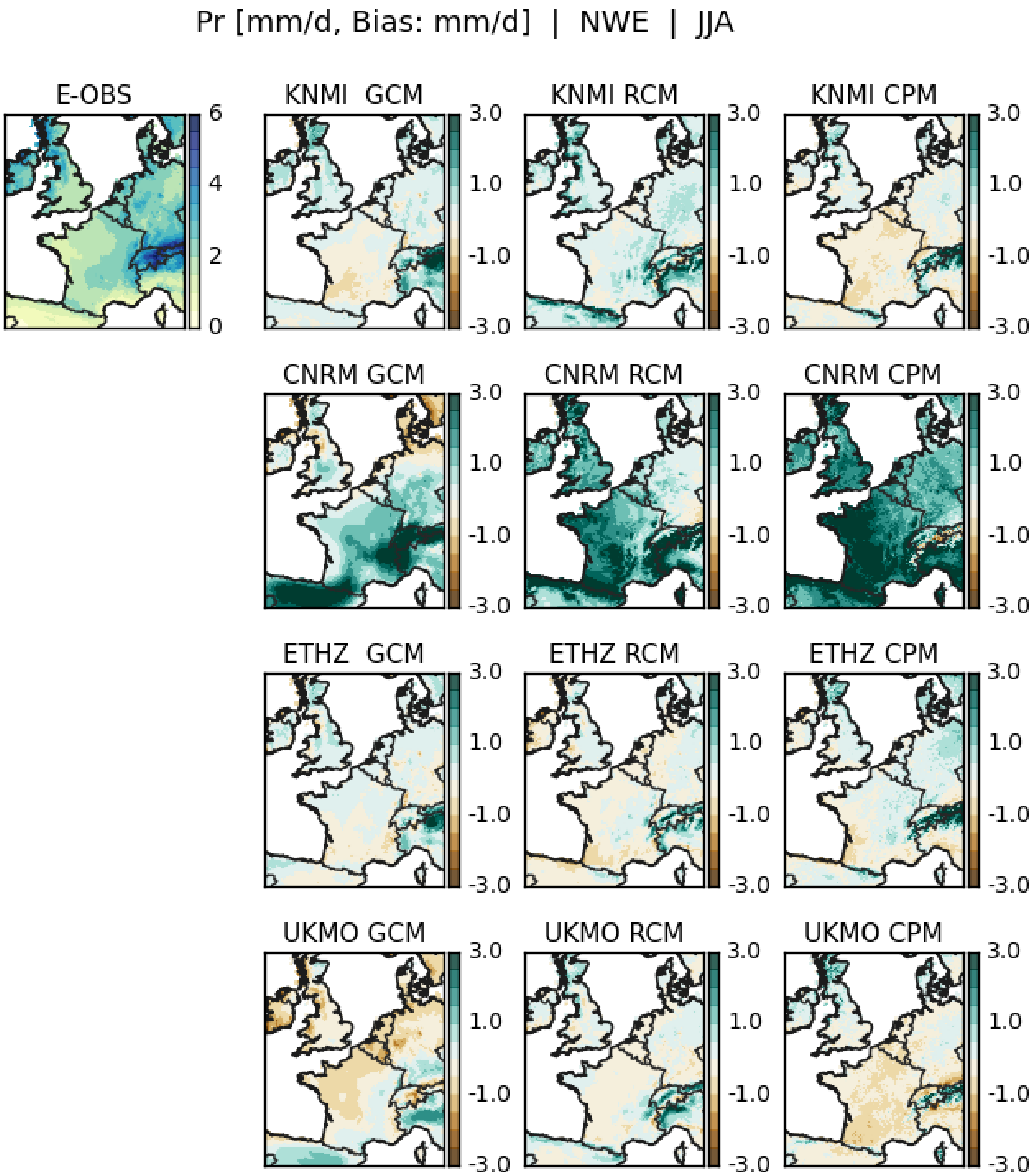

Figure 3: As Fig. 2, except for NWE-3.

Figure 4 shows the results for the SWE-3 domain. CMCC shows a similar pattern for both SWE-3 and ALP-3: the RCM changes the GCM overestimation signal into a predominant underestimation, while the CPM removes some of the underestimation. All components of IPSL overestimate precipitation, and the CPM somewhat increases the precipitation compared to RCM. The latter is different from ALP-3, where IPSL CPM does not change precipitation much compared to the RCM, albeit both overestimate precipitation. The reason for the difference is because two different modelling systems were used for the two domains by IPSL. For UKMO and ETHZ similar conclusions are valid as before, in that the UKMO CPM decreases and ETHZ CPM increases the precipitation relative to their parent RCMs.

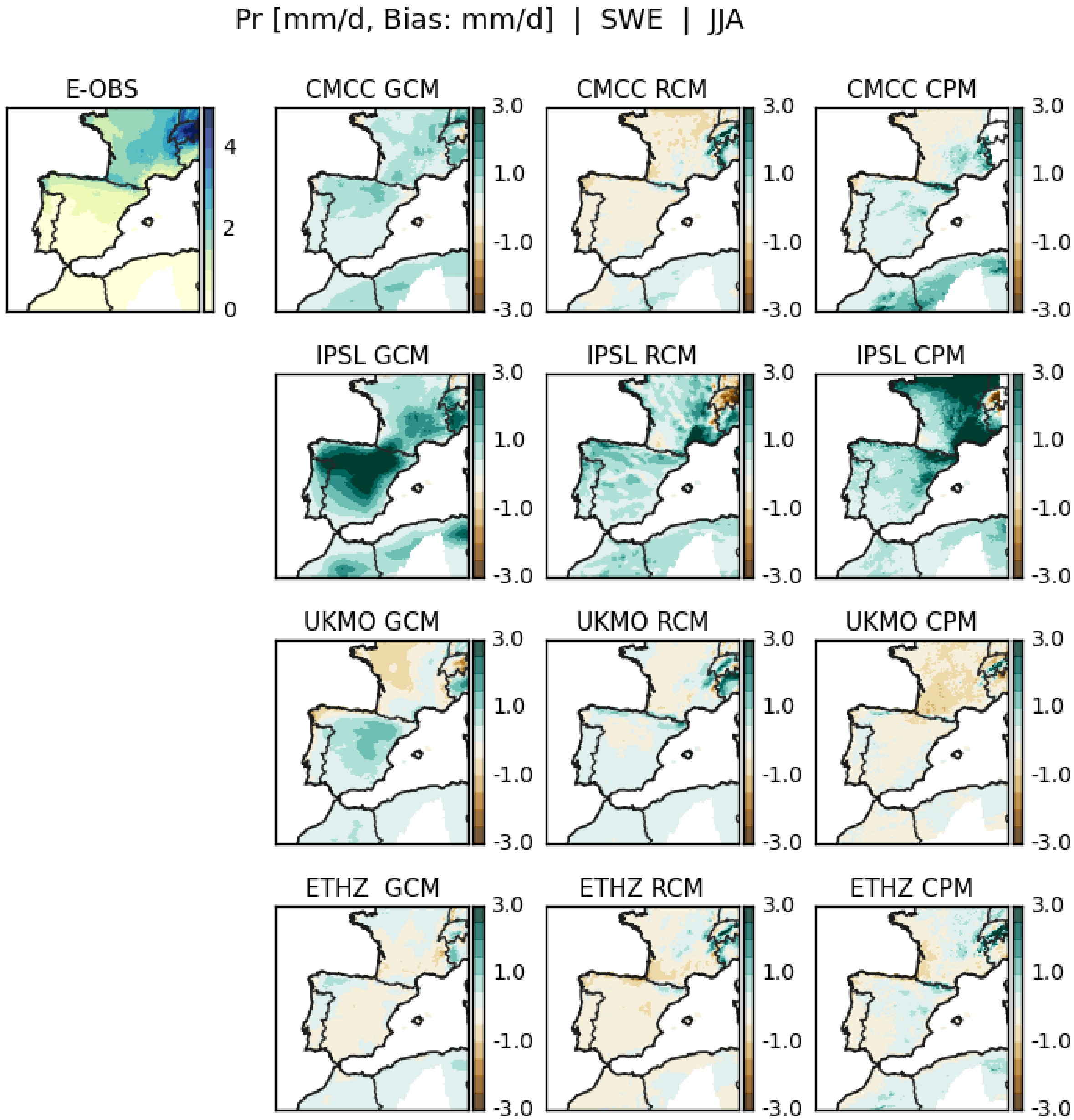

Figure 4: As Fig. 2, except for SWE-3.

Figure 5 shows the three modelling groups for the SEE-3 domain. For ICTP, the modelling system exhibits the same pattern as for the ALP-3 domain: the RCM increases while the CPM decreases the precipitation. And as also noted for ALP-3, the differences between the RCM and CPM are large. UKMO and ETHZ do not cover the entire domain, and the available outputs are close to their boundaries. ETHZ has the consistent behaviour of the CPM increasing precipitation, while here the same happens for UKMO which is different to all other domains.

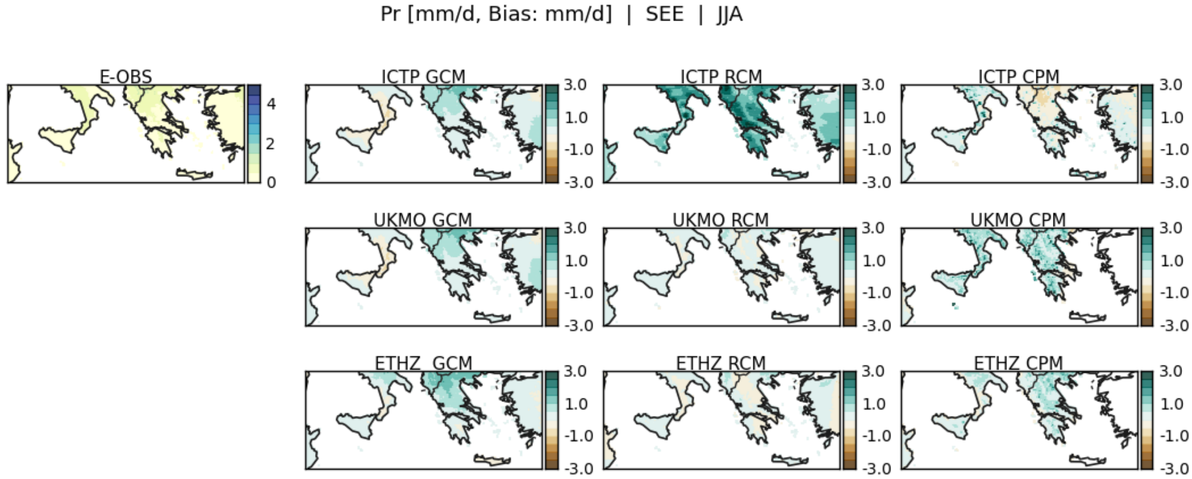

Figure 5: As Fig. 2, except for SEE-3.

For CEU-3 (Fig. 6), GERICS RCM tends to increase precipitation, while the CPM tends to decrease precipitation except over the mountainous regions. This is in accordance with GERICS ALP-3 results, where similar conclusions can be drawn. ETHZ and UKMO follow their known patterns: the CPM increases precipitation for ETHZ and decreases precipitation for UKMO.

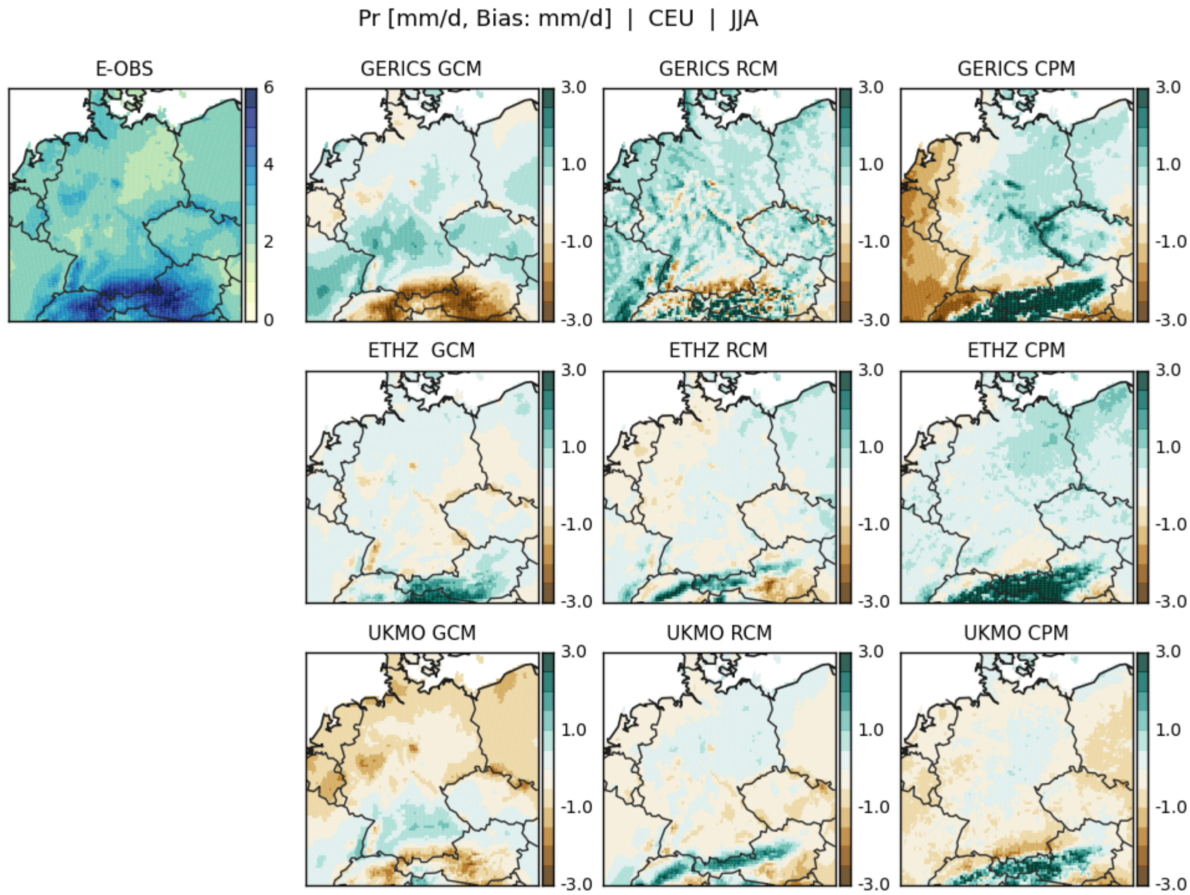

Figure 6: As Fig. 2, except for CEU-3.

For CEE-3 (Fig. 7), ICTP exhibits the same pattern as for the other domains, particularly for the CPM: there is a large negative precipitation bias in the CPM, which is not stemming from its forcing domains. It therefore appears to be a persistent feature of the CPM. HCLIM (SMHI) RCM slightly increases precipitation compared to the GCM, while the CPM reduces precipitation, in accordance with ALP-3. The ETHZ and UKMO patterns are consistent with the other domains.

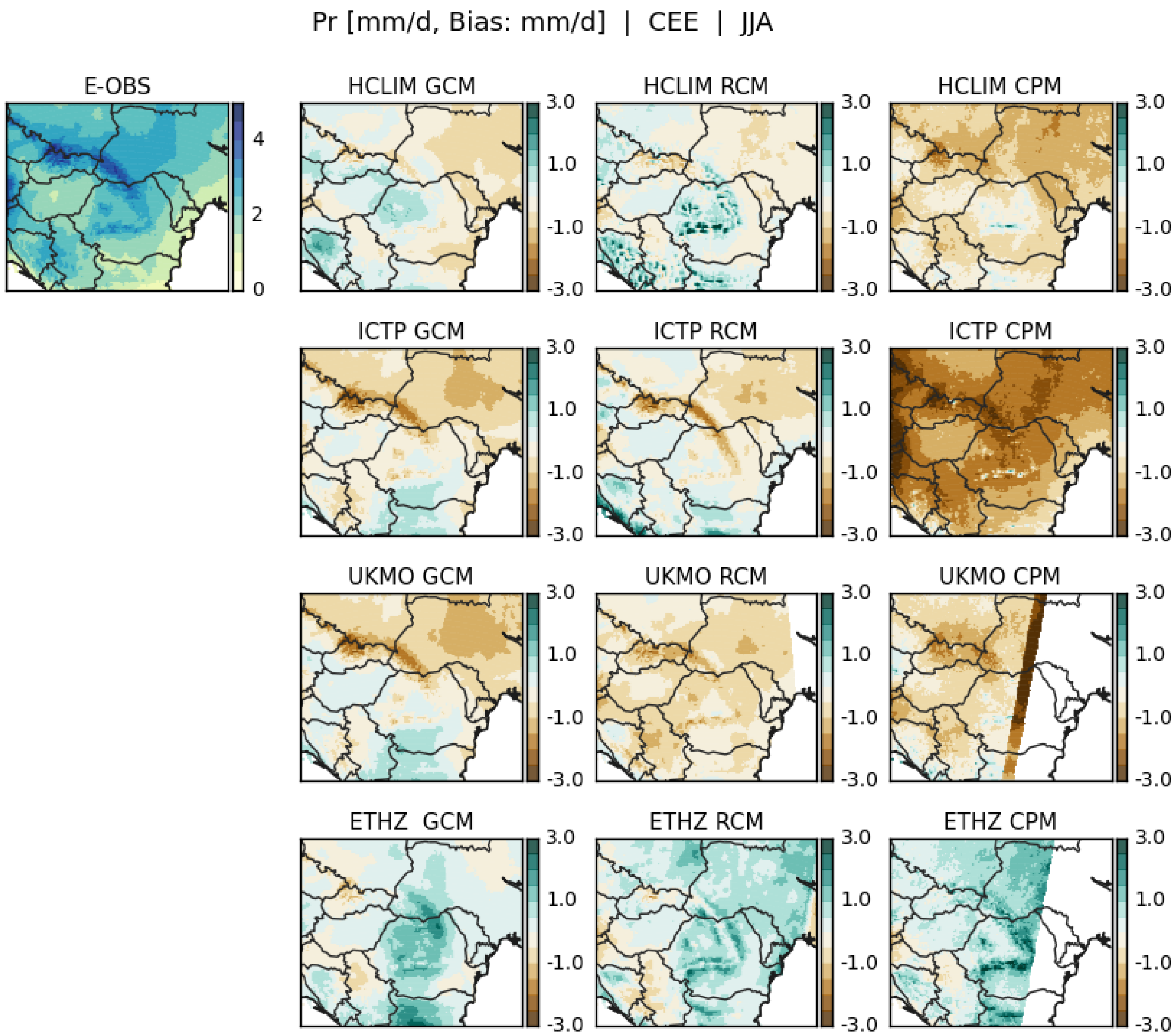

Figure 7: As Fig. 2, except for CEE-3.

Finally, for NEU-3 (Fig. 8), HCLIM shows the similar pattern as for other domains, in that the RCM increases and the CPM decreases precipitation. Since HCLIM (DMI/SMHI) and KNMI use the same CPM, these conclusions can be stretched over more domains and are still consistent. For GERICS, the RCM is consistent with the other domains, implying precipitation increase. However, unlike for the other domains the CPM increases precipitation by a large amount and results in a large positive bias.

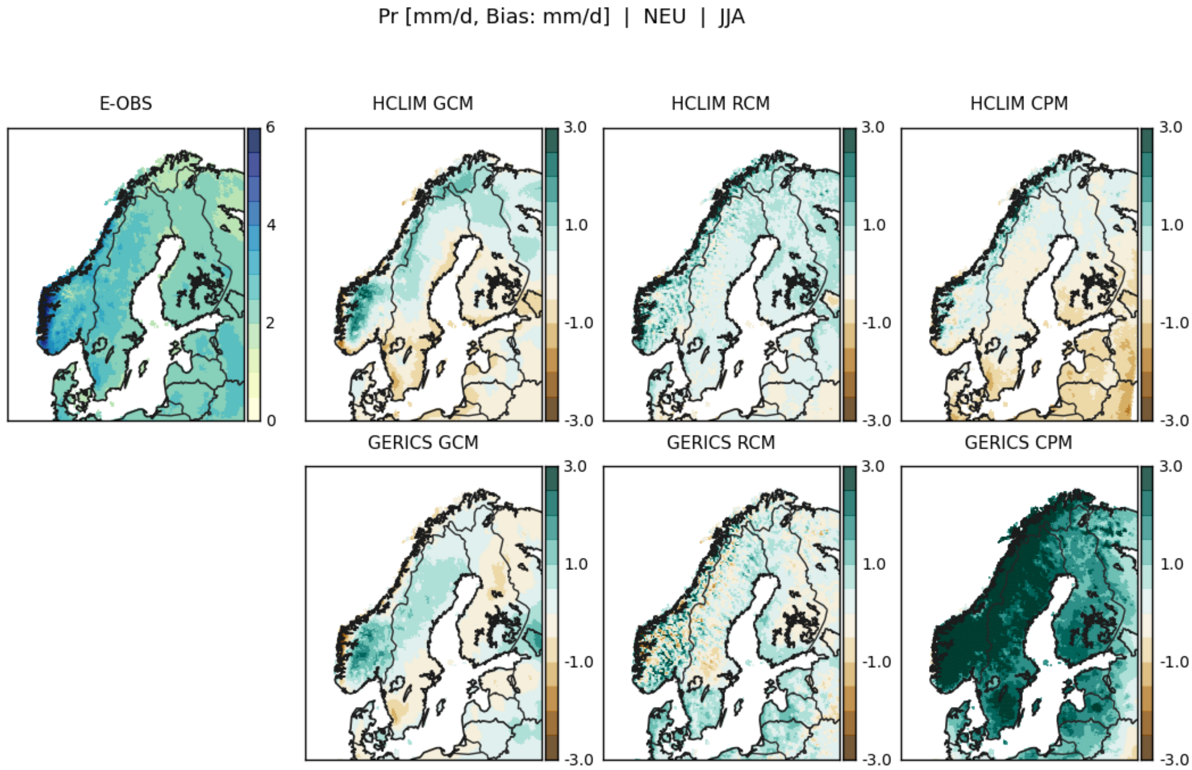

Figure 8: As Fig. 2, except for NEU-3.

Summary of the assessment

- CPMs seem not to generally improve the mean precipitation. However, it is important to stress that the large biases found for the GCM-driven historical runs are in part a simple consequence of the fact that there is large natural variability on a 10-year time scale. Also, the adequacy of the observational dataset E-OBS is questionable, especially for precipitation in complex terrain. Nevertheless, some CPMs show an excessively large precipitation underestimation or overestimation, and this seems not always related to their parent domain forcing. Such issues could be a result of some of the CPMs being at an early stage of development or usage. Additionally, it is generally not expected nor observed that CPMs improve the seasonal mean daily precipitation but their benefits become evident on subdaily scales, particularly for heavy precipitation.
- The internal consistency of modelling systems between the different domains is very high, with just a few exceptions, and can be summarized as follows:
    - The CPMs that decrease precipitation compared to their parent domains are: UKMO, HCLIM (SMHI/DMI), KNMI, and ICTP. UKMO decreases precipitation in six out of seven domains. SMHI/DMI and KNMI use the same CPM.
    - The CPMs that increase precipitation compared to their parent domains are: ETHZ, CMCC, and CNRM. ETHZ and CMCC use the same RCM/CPM.
    - The IPSL system overestimates precipitation for both their domains, but the CPM increases precipitation only for SWE-3. GERICS CPM decreases precipitation for two domains, but increases by a large amount for NEU-3.

3.4.2 CPM potential added value in the historical period

Wet-day frequency and intensity

Figure 9 shows the wet day frequency versus wet day intensity, calculated per grid point and then averaged over the domains (including land and sea points). Despite the considerable spread, it is apparent that CPMs tend to group together, as do RCMs with RCMs and GCMs with GCMs. The general tendency, with some exceptions, within a single modelling system is that the higher the resolution, the smaller the wet-day frequency and the larger the wet-day intensity. This is in accordance with the results from previous single-domain studies (Kendon et al. 2012, Prein et al. 2013, Ban et al. 2014, Lind et al., 2020, Kumar-Shahi et al., under review), now confirmed to generally hold for all domains and seasons (the corresponding figures for the other seasons are shown in Appendix: Figs. A1-A3).

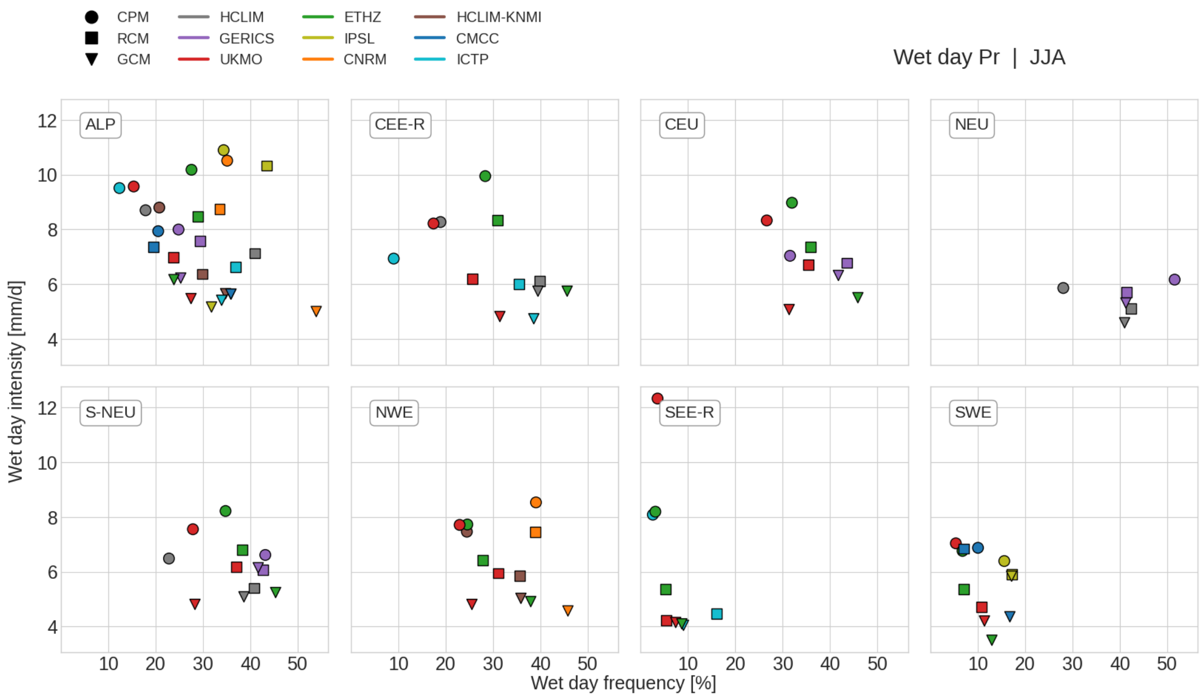

Figure 9: JJA wet-day intensity vs frequency in the historical period for the eight domains and the entire modelling chain (GCM-RCM-CPM) of each group.

ASoP analysis

Figs. 10 and 11 depict the fractional contributions to total hourly JJA precipitation for RCMs and CPMs. While Fig. 10 is shown to illustrate the shape of the original distributions, we focus on Fig. 11 which shows the differences between CPMs and RCMs (CPM minus RCM). Almost all the curves have negative lobes for lower intensities, peaking at about 1 mm/h and implying a larger contribution of lower intensities to RCM precipitation compared to CPMs. The opposite holds for higher intensities, with the positive peak at or close to 10 mm/h, indicating the much larger contribution of higher intensities to CPM precipitation compared to RCMs. This agrees well with previous CPM studies (Prein et al., 2015, Belušić et al., 2020, Berthou et al., 2020, Fumière et al., 2020, Lind et al., 2020), and is clearly evident here for all the domains and almost all the modelling systems. An exception is GERICS, which shows the opposite behaviour for all of its domains: a larger contribution of low intensities to CPM precipitation and of high intensities to RCM precipitation. Since this behaviour is inconsistent with all the other models and also the previous studies, we conclude that it is likely a result of issues with the modelling system. However, an interesting conclusion can be drawn. It is frequently regarded that ensemble mean is the optimal measure when addressing ensembles (Ban et al., 2021; Pichelli et al., 2021). In this case, the ensemble mean of ALP-3 would not be affected a lot by the opposite behaviour of one model, due to the ensemble having nine members. For S-NEU-3 and CEU-3 the outcome would be quite different, given that there are only four and three members, respectively. Finally, for the whole NEU-3 where there are only two members, using the ensemble mean would completely change the outcome because the CPM benefits would cancel out between the two modelling systems. Since the community will be confined to mostly small CPM ensemble sizes in the years to come, it is important to perform a thorough evaluation of each CPM before using it in analyses or climate services.

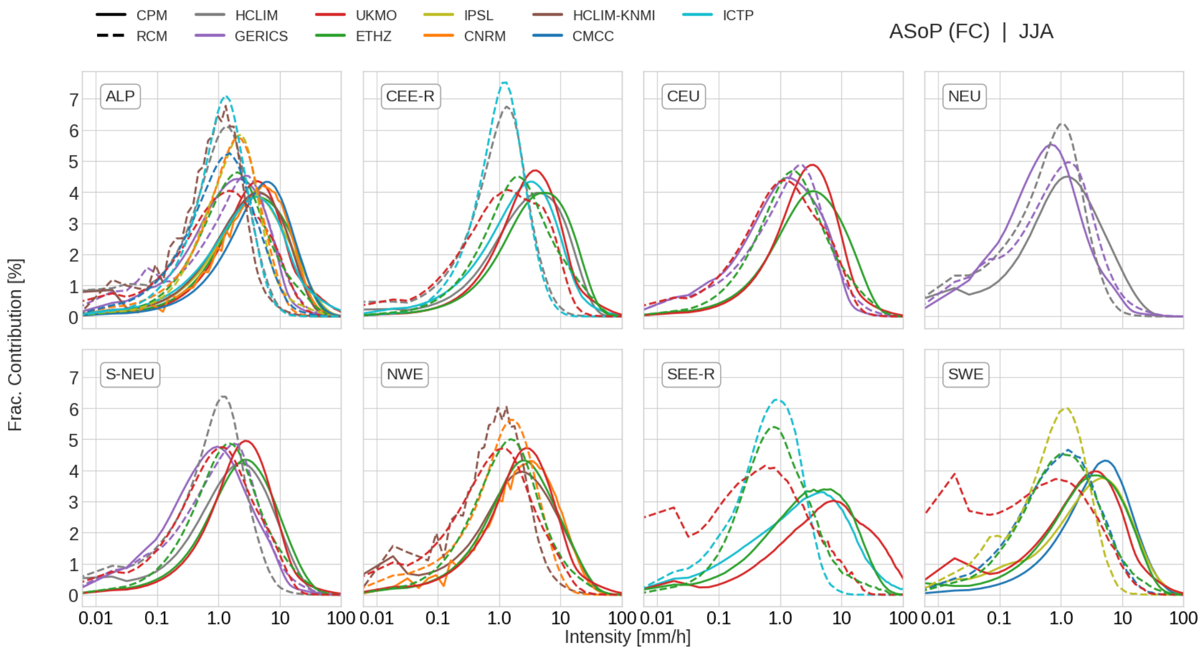

Figure 10: ASoP fractional contribution to total JJA precipitation, for the eight analysis domains (see Table 2). Dashed curves represent RCMs and full curves CPMs. "R" in CEE-3 and SEE-3 stands for "reduced domain", where they overlap with REU-3 (see Table 2).

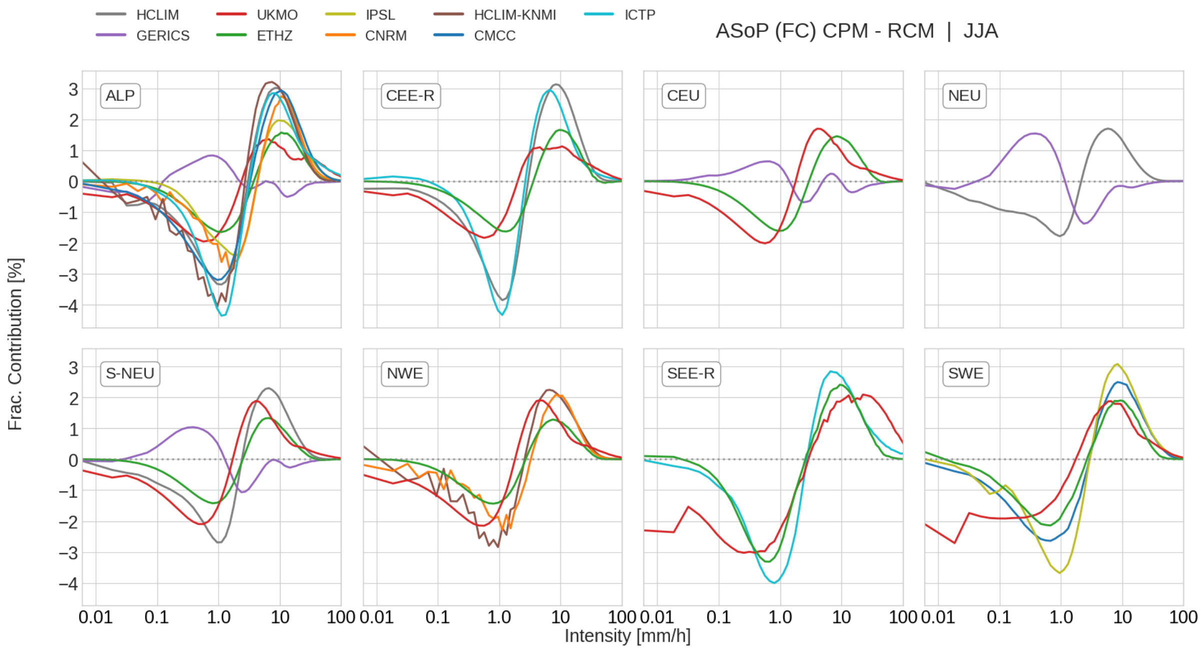

Figure 11: As Fig. 10, except showing CPM-RCM differences (CPM minus RCM).

Percentiles

The upper percentiles corroborate the ASoP findings (Fig. 12). We also see that the differences between CPMs and RCMs generally grow with increasing percentiles, except for ETHZ which for some domains tends to keep the same magnitude of the difference or even decrease with increasing percentiles (e.g. for CEE-3, CEU-3, S-NEU-3).

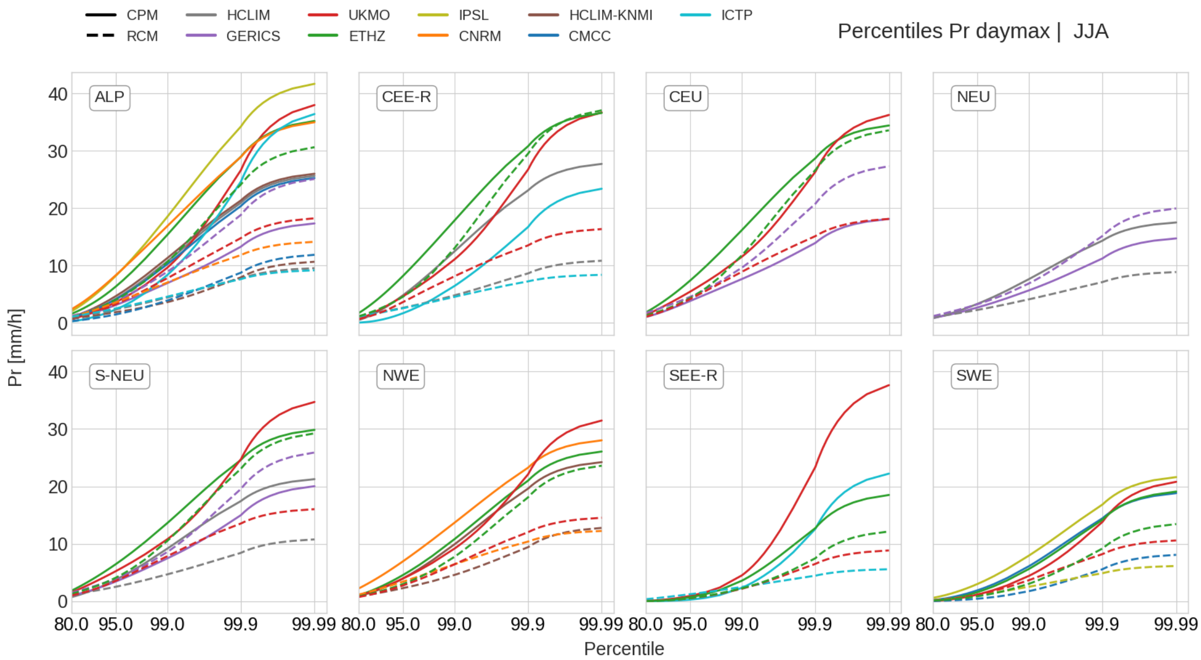

Figure 12: Upper percentiles of maximum hourly precipitation in a day, for the eight analysis domains.

Diurnal cycle

The precipitation diurnal cycle agrees with the previous studies on added value of CPMs (Fig. 13). Generally, the peak afternoon precipitation activity is about 2-3 h later in CPMs compared to RCMs, except for SEE-3. The two model exceptions are IPSL for SWE-3 and GERICS for all domains, which peak starting from 20 UTC to later than 00 UTC, depending on the domain. It is not considered realistic that the JJA precipitation peaks so late (e.g. Ban et al., 2021).

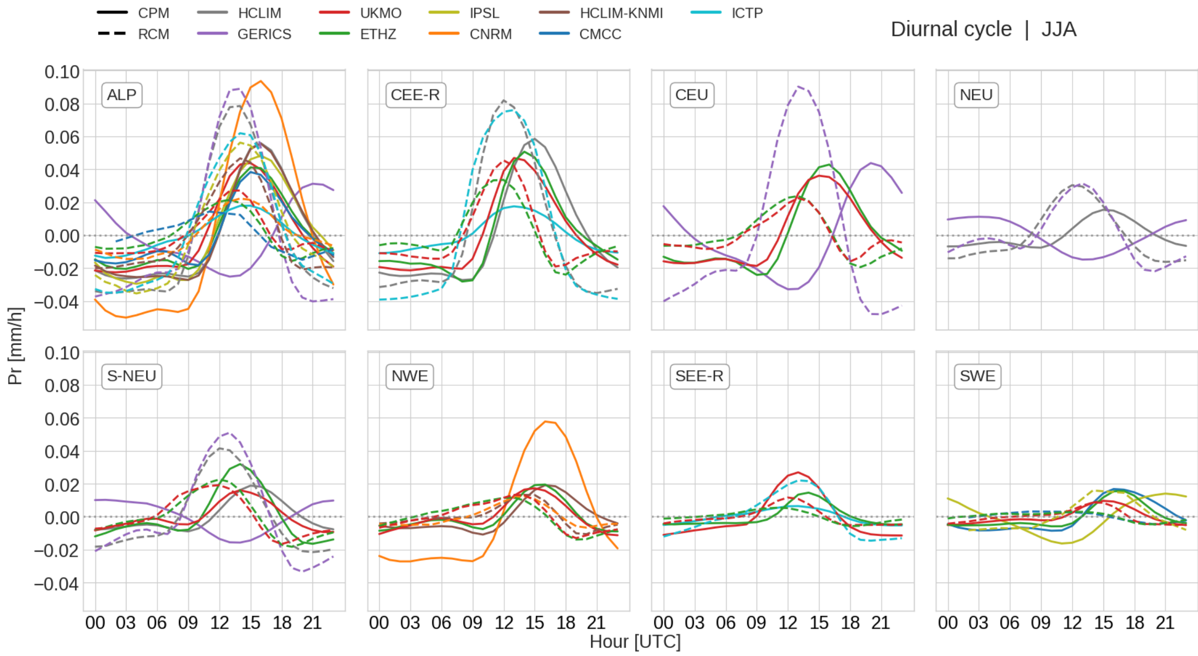

Figure 13: Diurnal cycle of JJA precipitation for the eight analysis domains. The mean precipitation is removed, so shown are the anomalies.

Summary of the potential added value in the historical period

CPMs show clear differences to RCMs in a number of indices and hence have large potential added value. The results are consistent with previous studies using individual models or small ensembles, and typically analysed over a smaller area where high-resolution observations confirmed that the added value was realistic. Hence we extrapolate those conclusions and argue that the differences between CPMs and RCMs listed above most likely point to the added value of CPMs.

3.4.3 Changes to mid-century

Spatial structure

Changes in mean daily JJA precipitation, shown only for ALP-3, seem to be predominantly governed by GCMs (Fig. 14). Most if not all of the groups show a very similar spatial change structure for the entire modelling chain (GCM-RCM-CPM). The results are similar for other domains and are hence not shown. An interesting conclusion appears: the changes in mean precipitation seem to be the least sensitive to the nested model (RCM/CPM) formulation, including the potential errors. This is evident if we compare the current result to the modelling chain performance in a specific period such as the historical period (Fig. 2), where the performance appears more sensitive to the RCM/CPM formulation.

Figure 14 also shows that there are substantial differences between the models, with some showing consistent drying and others a wetting trend. Note that these differences are derived from two 10-year periods, so the natural variability in these trends is still relatively high (e.g. Aalbers et al, 2018). In addition, the time difference between the periods is also not very large, further reducing the signal to noise ratio.

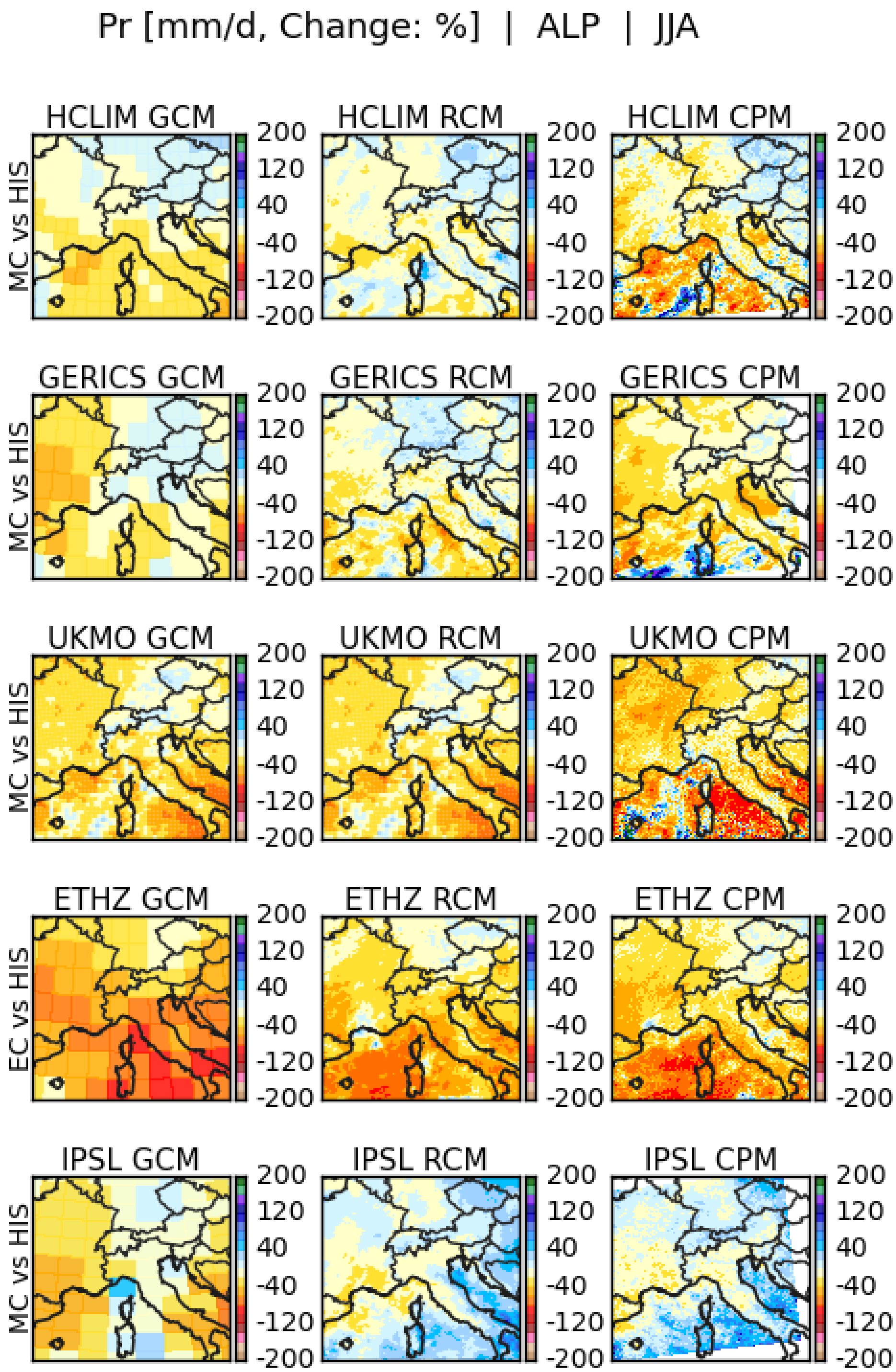

Figure 14: Changes in mean daily JJA precipitation for ALP-3.

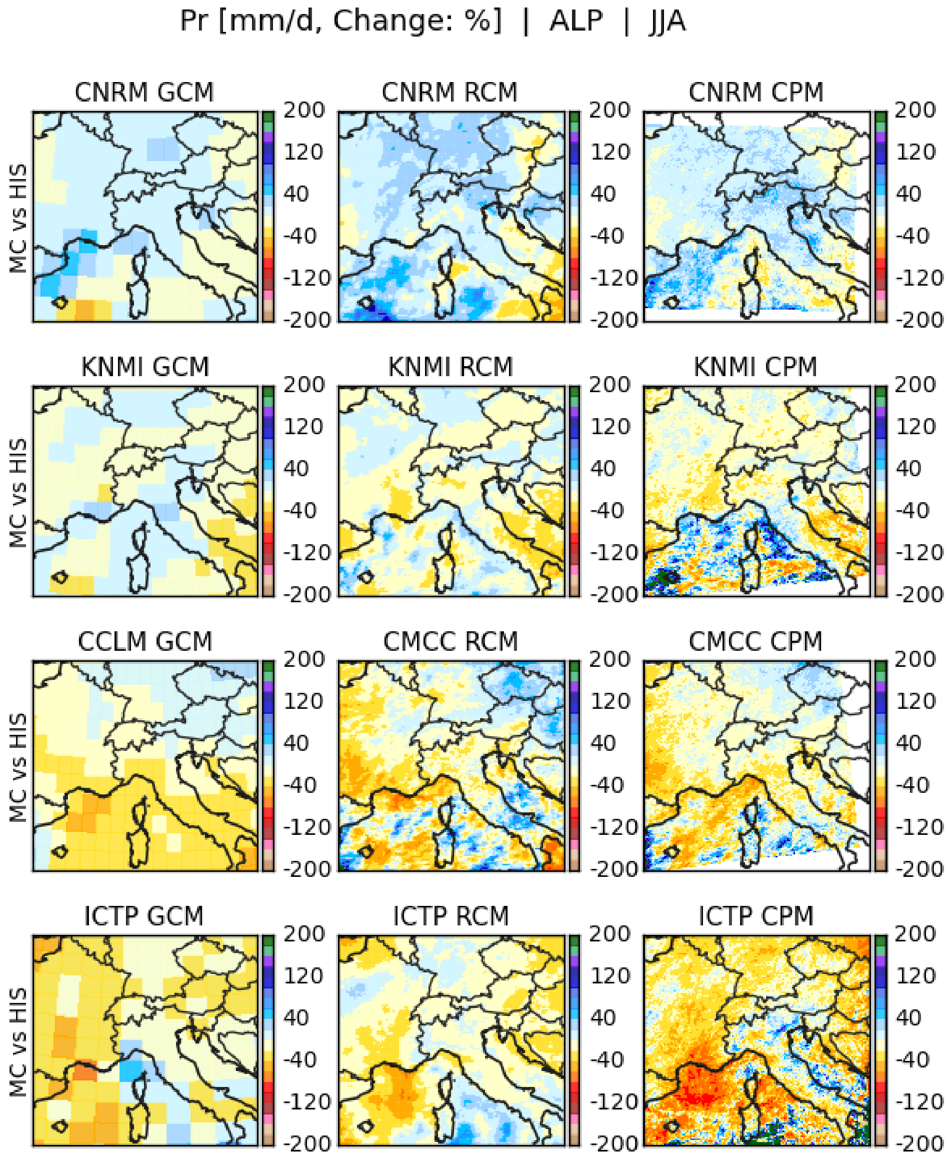

Figure 14: cont.

Wet-day frequency and intensity

Unlike for the reference historical period, where the wet-day frequency and intensity group around the type of model (e.g. CPMs with CPMs), for the change signal the grouping tends to predominantly be within the same modelling system (Fig. 15). This is evident despite the noise and is consistent with the above results for the spatial structure and indicates a strong effect of GCM forcing. However, even with this grouping and some exceptions, there seems to be a tendency for the CPMs to have stronger decreases in wet-day frequency than the corresponding RCMs. The results are similar for the other seasons and hence are not shown.

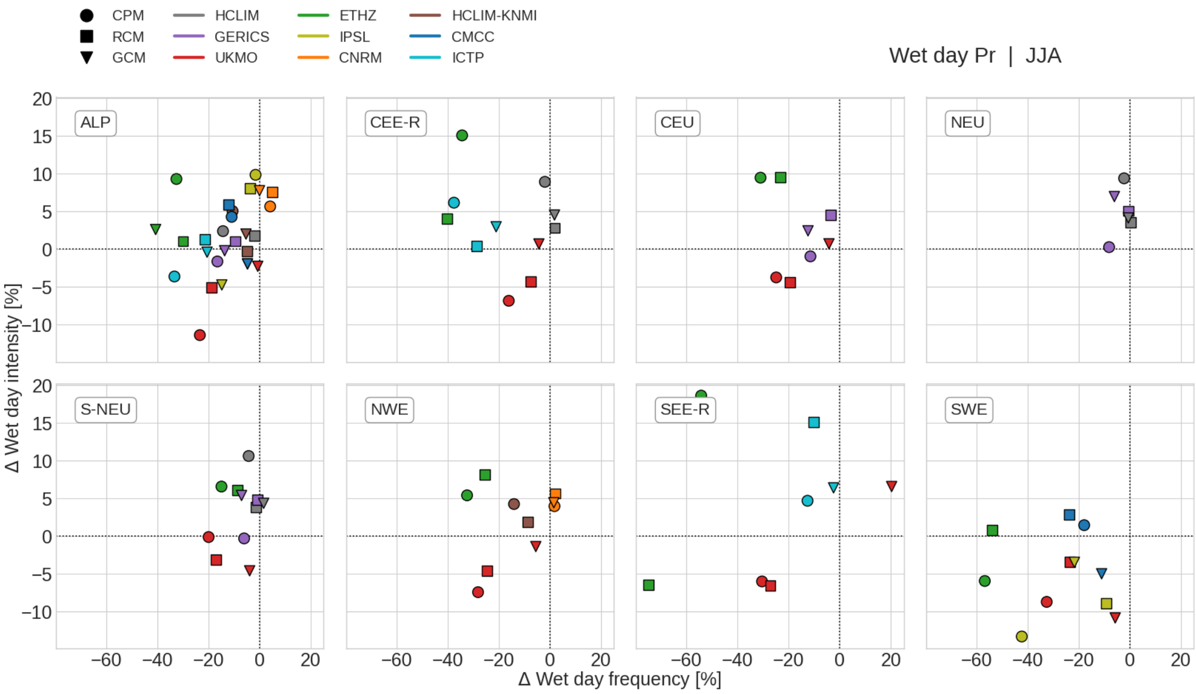

Figure 15: The change to mid-century of JJA wet-day intensity vs frequency for the eight domains and the entire modelling chain (GCM-RCM-CPM) of each group.

Daily precipitation vs temperature

Similar to the above, the JJA daily precipitation vs temperature changes are grouped around the same modelling system (Fig. 16). An interesting feature for ALP-3 is the nearly-linear decrease of precipitation change with increasing temperature change. Again we see GCM-RCM-CPM often being close by on the Figure.

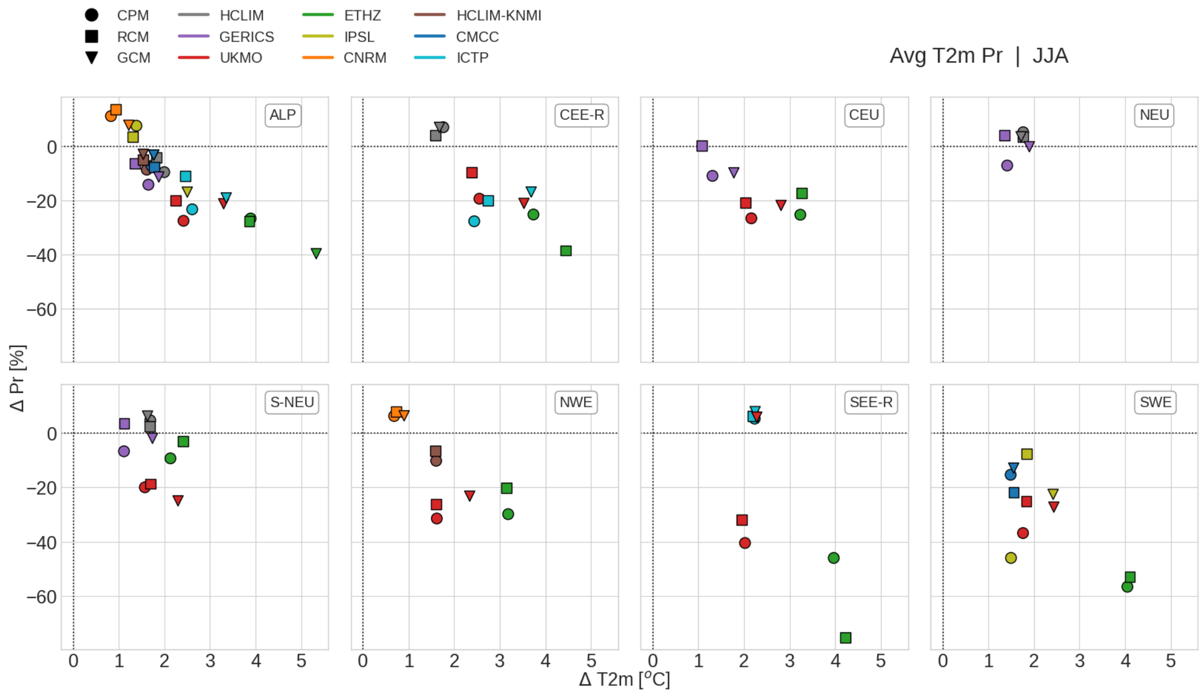

Figure 16: The change to mid-century of JJA daily precipitation vs temperature for the eight domains and the entire modelling chain (GCM-RCM-CPM) of each group.

ASoP

The ASoP analysis (Fig. 17) shows the rather general result that the CPMs have a larger relative future increase of high-intensity precipitation compared to the RCMs. Largest exceptions are for SWE-3, where only CMCC out of four modelling groups shows such behaviour, and for UKMO whose CPM for most of the domains increases lower-intensity precipitation and reduces higher intensities. Furthermore, the GERICS CPM appears not to be consistent with the other groups, but this is much less expressed compared to the differences in the historical climate. These different signs of responses, as well as more noise compared to the historical period, are in general accordance with Pichelli et al. (2021). They report on a reduction in uncertainty by CPMs compared to RCMs in the historical climate for ALP-3, but not for JJA future changes (although they looked at the end of the century change).

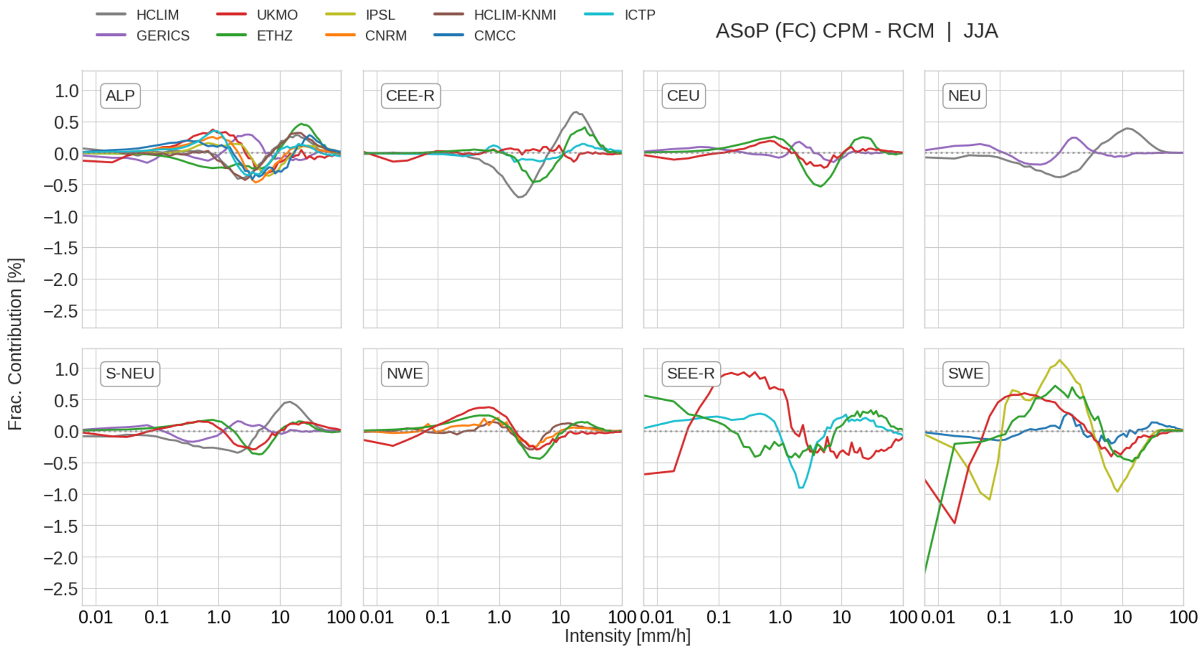

Figure 17: The ASoP fractional contributions of hourly JJA precipitation change to mid-century, shown as the difference in the change between CPM and RCM (CPM minus RCM).

Diurnal cycle

The change in the diurnal cycle of mean hourly precipitation (Fig. 18) does not show a clear difference between CPMs and RCMs, nor a clear preference for the sign of change. The ensemble mean response shows a decrease in the early afternoon hours, which seems to be determined by one or two models per domain that have a strong such signal. Similar results are obtained for the 99.9th percentile of hourly precipitation and also if only land points are considered (not shown).

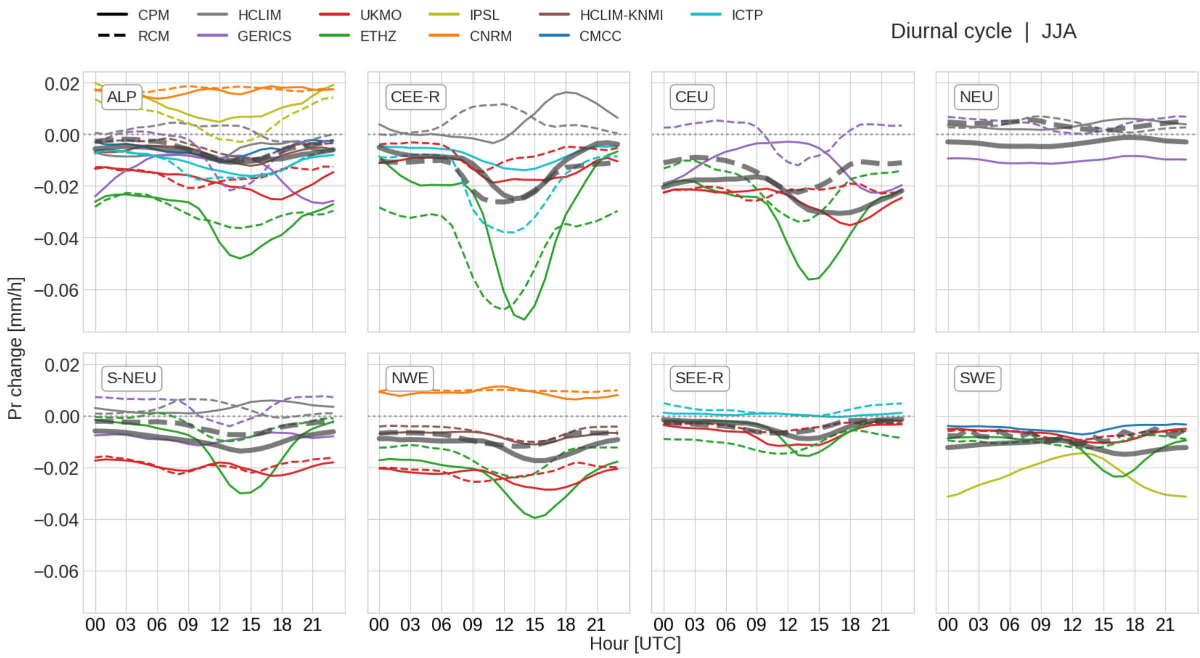

Figure 18: The diurnal cycle of hourly JJA precipitation change to mid-century. Grey bold lines denote ensemble mean for each domain.

Daily maximum precipitation percentile change

Here we show in a series of seven figures (one per domain) the changes in the 99th percentile of JJA daily maximum of hourly precipitation (Figs. 19-25). The results could not be easily condensed, because the spatial variability of the signal within a domain is large and using a single value per domain does not give clear results. For example, note the opposite sign of change for ICTP in ALP-3 over the SE part compared to the rest of the domain (Fig. 19) or ETHZ for the southern part of NWE-3 compared to the northern part (Fig. 20). A smart choice of subdomains is needed (e.g. Pichelli et al., 2021), but in the context of this work, which is already having seven to eight different domains, this has shown to be too cumbersome. It will however be further explored for the accompanying paper. Note that since the Mediterranean region has the peak convective activity in Autumn, we show the SON figures for ALP-3, SWE-3 and SEE-3 in Appendix (Figs. A4-A6).

Unlike previous studies that showed an increase of heavy precipitation until the end of the century (e.g. Kendon et al., 2017, Ban et al., 2015, Pichelli et al., 2021), here we do not get a consistent signal. A general conclusion for all the domains and modelling groups is that there is a considerably strong relationship between the CPM and RCM percentile changes, implying the large effects of the parent forcing models on the final CPM results, even for heavy precipitation events. CPMs do not seem to show a larger change of heavy precipitation until mid-century compared to RCMs: even if a larger change appears for some models and parts of domains, it is usually the opposite in the other parts of the domain or for other domains. An exception is a very consistent larger change in the HCLIM CPM compared to the RCM for NEU-3 (Fig. 25).

Other studies have found that the increase in heavy precipitation tends to be larger in CPMs (e.g. Kendon et al., 2017, Pichelli et al., 2021). The reason for this discrepancy could be because the previous studies addressed the end of the century changes in the high-emission (high-forcing) scenario RCP8.5, while we focus on the mid-century changes where the effects of internal climate variability could dominate over the forced change signal. Furthermore, focusing on a smaller set of modelling systems and a specific subregion or a group of subregions with similar characteristics, as frequently done in other studies, would provide more consistent results. More research is needed to detect and quantify potential common responses of CPMs to different strengths of large-scale forcing. The results of such analyses will be assessed in subsequent publications.

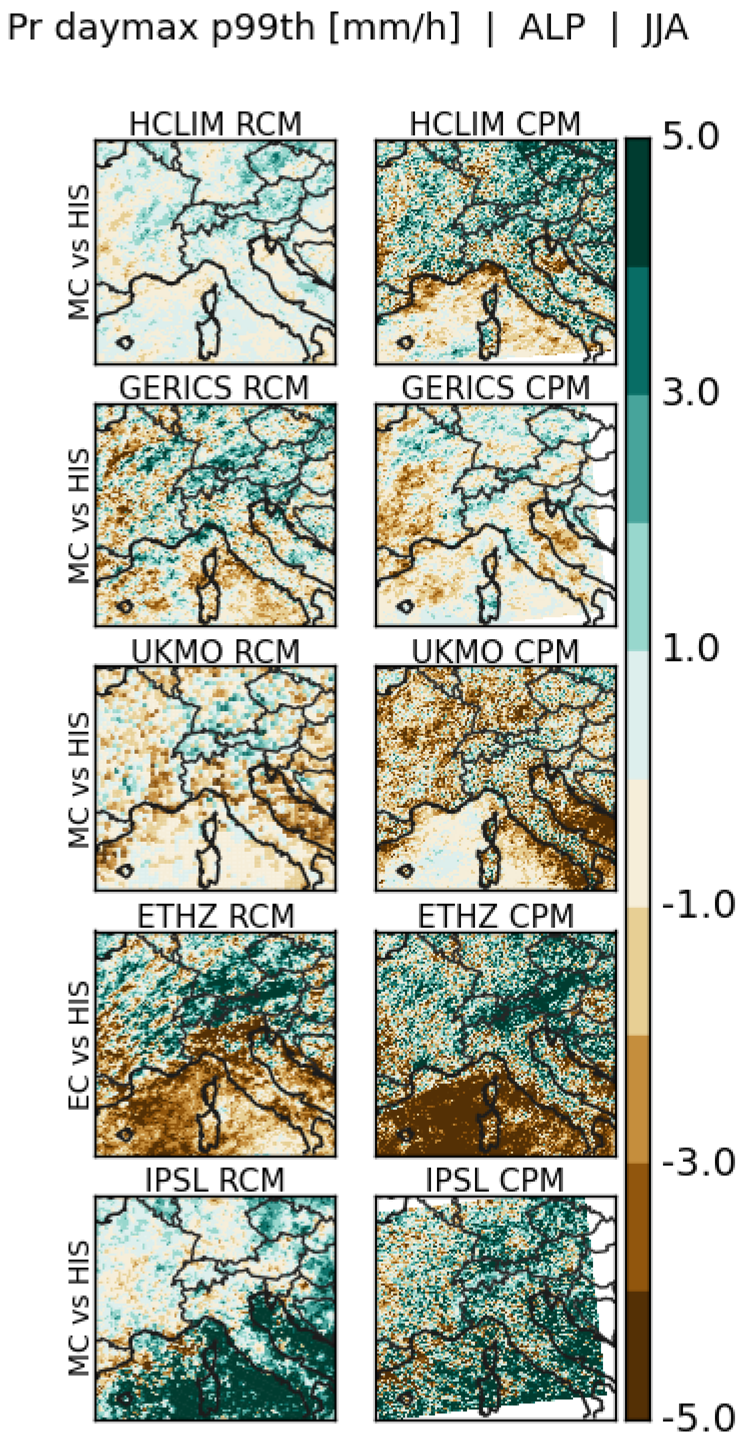

Figure 19: The change to mid-century of the JJA 99th percentile of the daily maximum of hourly precipitation for RCMs (left) and CPMs (right) for ALP-3.

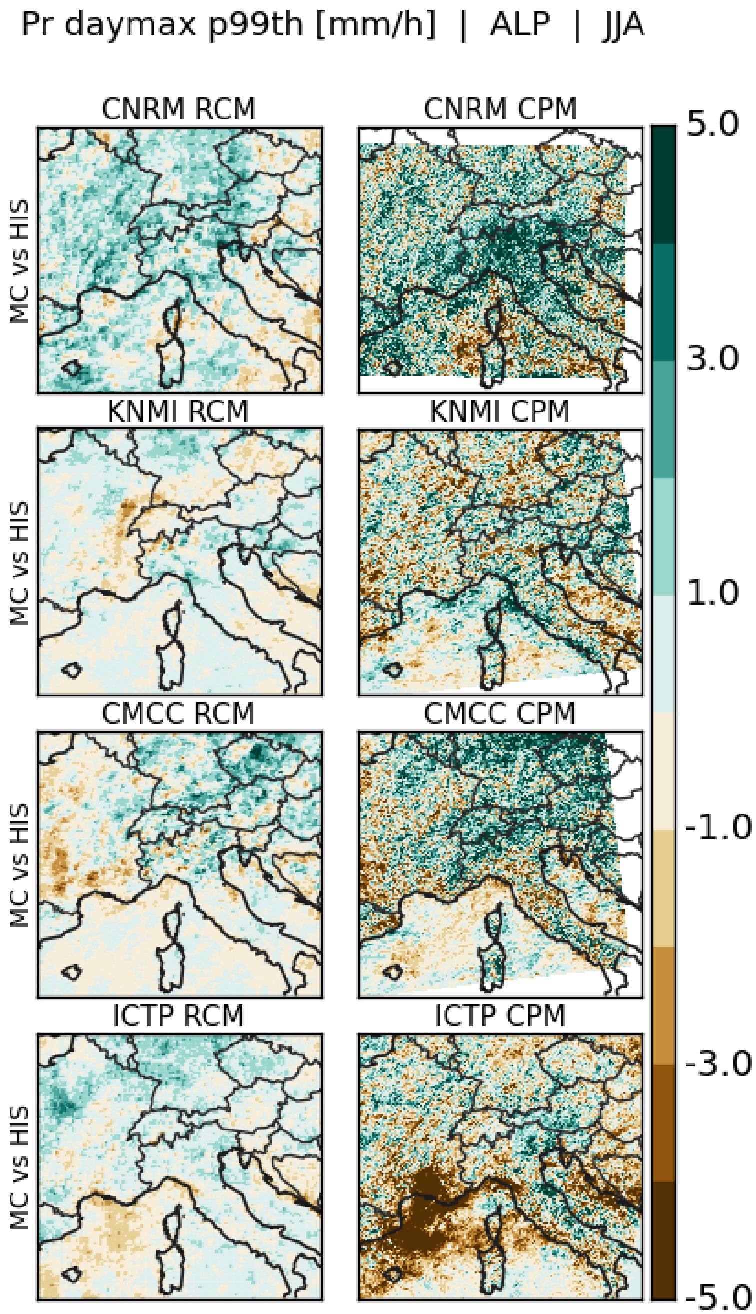

Figure 19: cont.

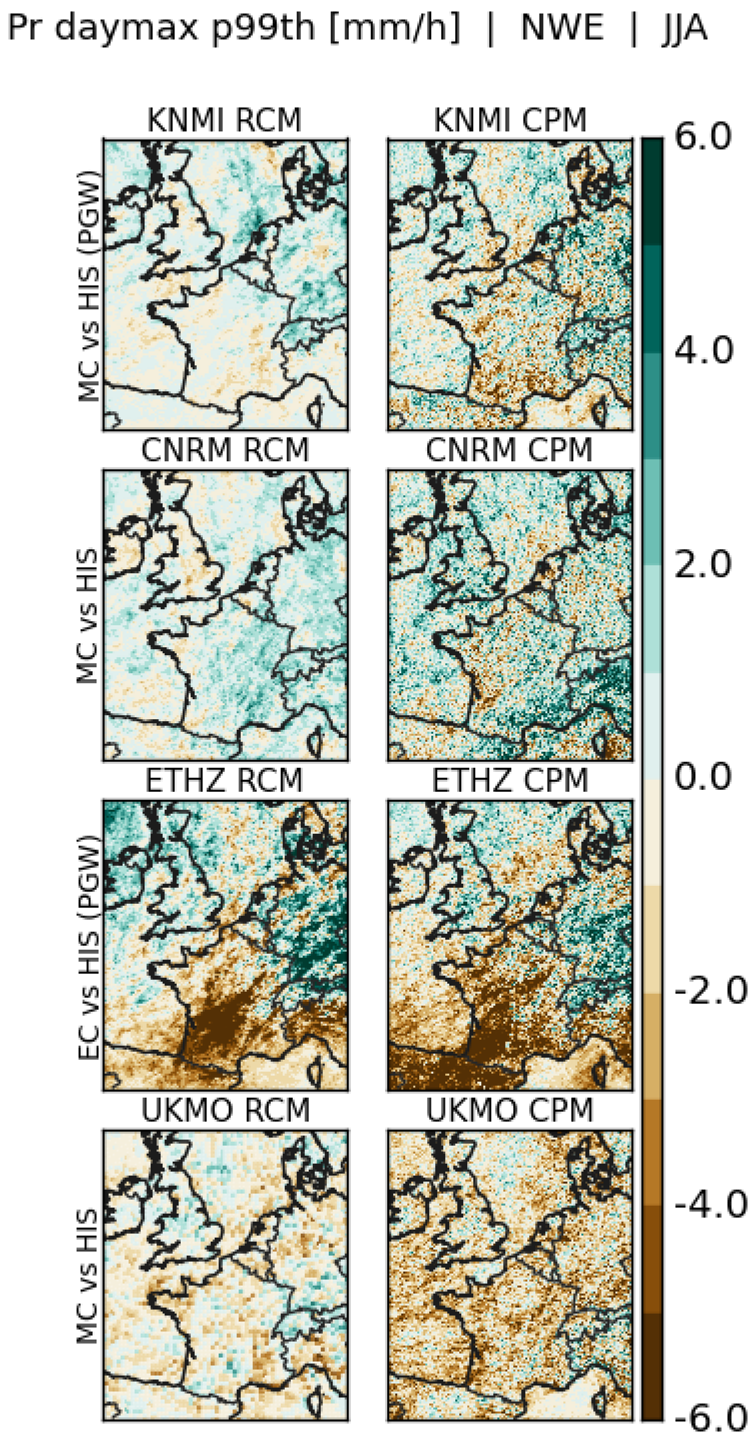

Figure 20: As Fig. 19, except for NWE-3.

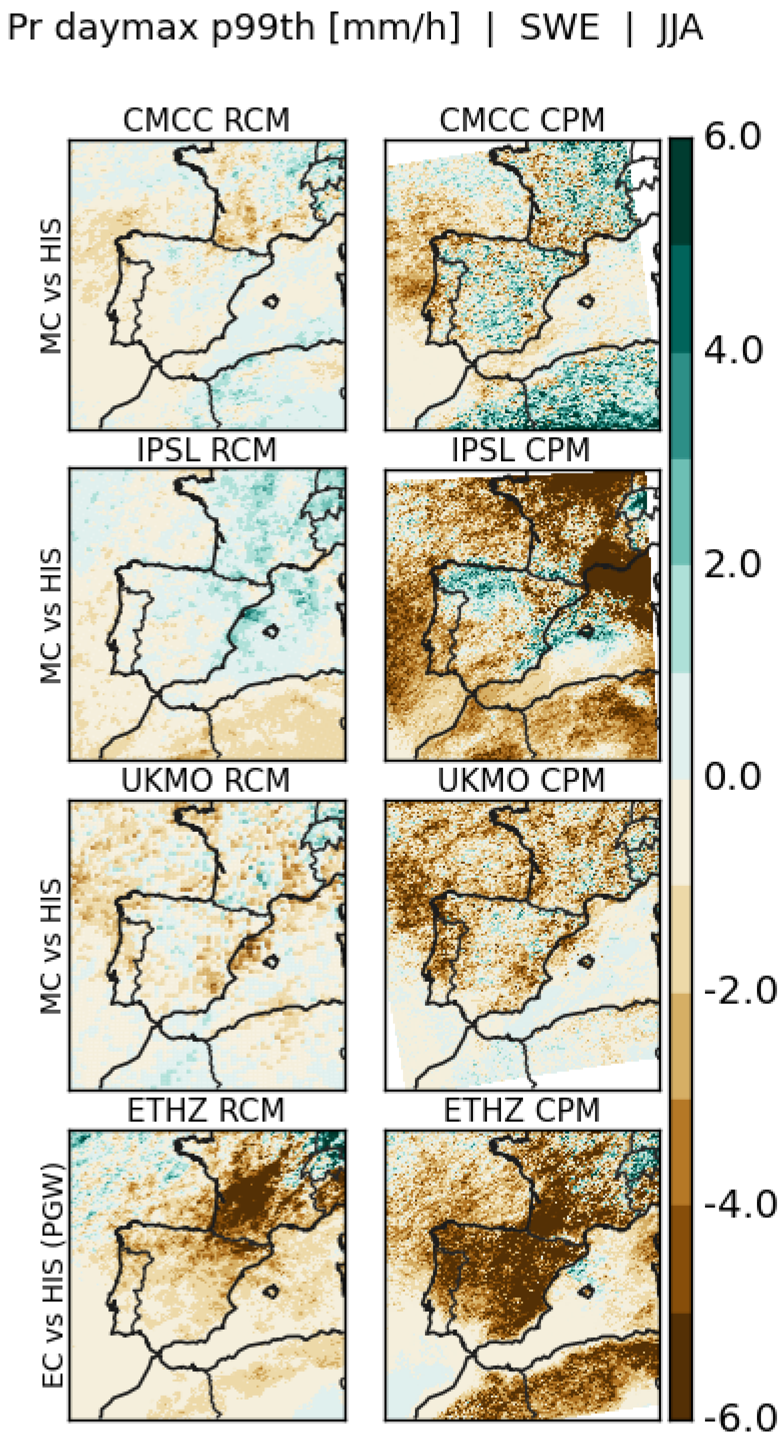

Figure 21: As Fig. 19, except for SWE-3.

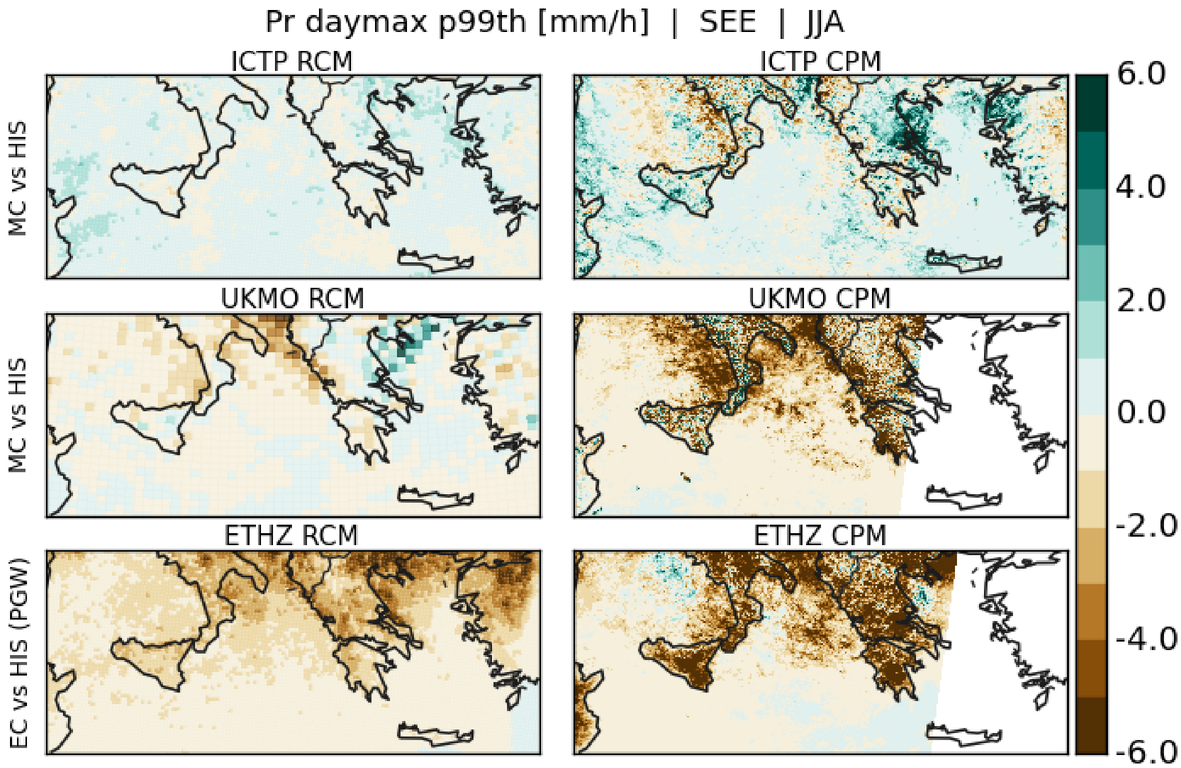

Figure 22: As Fig. 19, except for SEE-3.

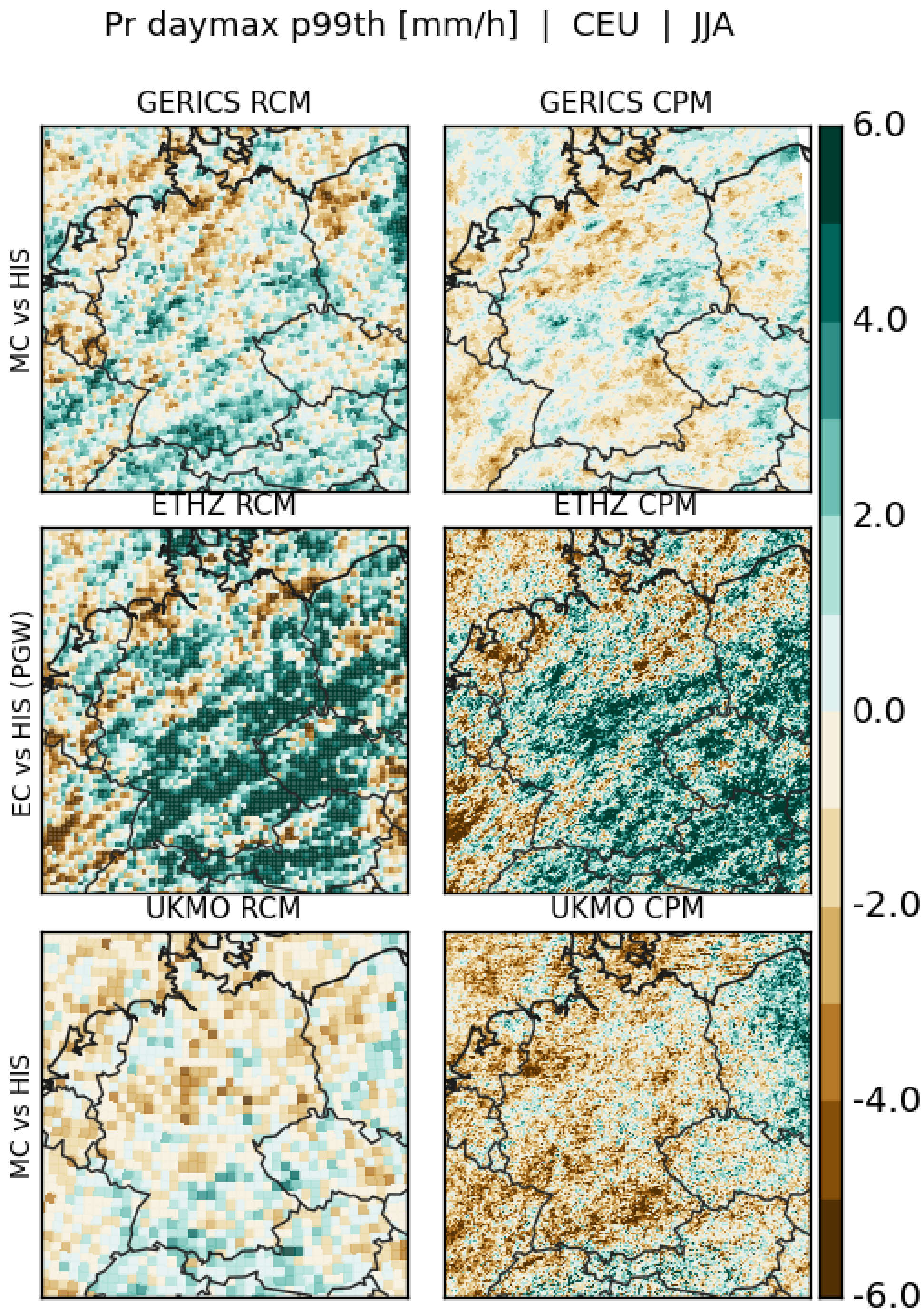

Figure 23: As Fig. 19, except for CEU-3.

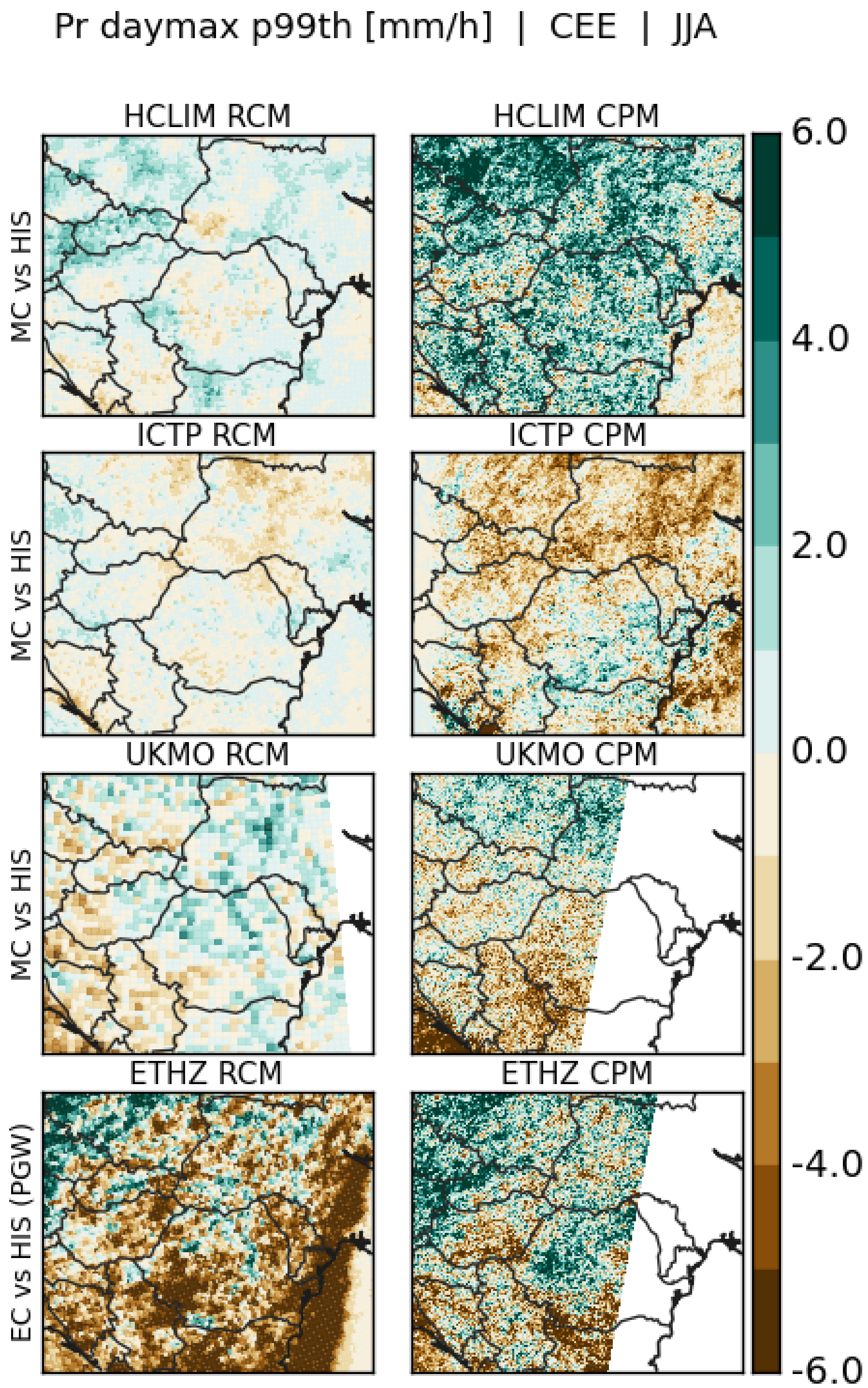

Figure 24: As Fig. 19, except for CEE-3.

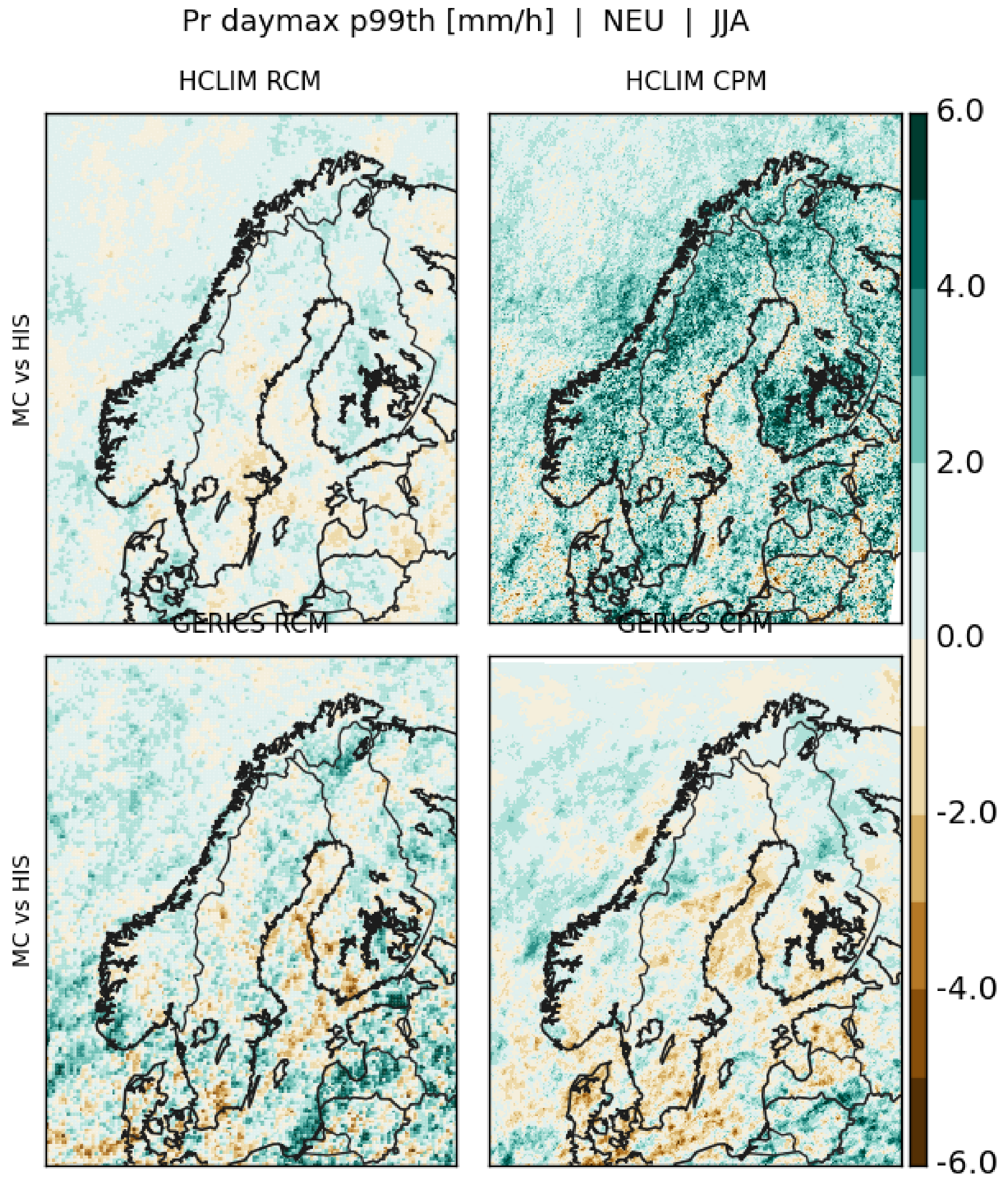

Figure 25: As Fig. 19, except for NEU-3.

Summary of the changes to mid-century

While CPMs show a large and common added value compared to RCMs and GCMs in a certain period such as the historical period, it is not straightforward to find a similarly strong added value for the changes to mid-century that is consistent among the participating models and the seven European domains. It appears that the future change signal in the nested models is considerably constrained by the forcing parent models. However, a few aspects need to be considered. First of all, three factors combine to decrease the signal to noise ratio in the present analysis: the large internal variability given the rather short 10-yr simulation periods, the relatively small forced change to mid-century, and the seemingly rather strong connection of nested models to their parent models. The latter locks CPMs within their modelling chain and despite some clear indications of CPMs' systematically different performance compared to RCMs and GCMs, such as the stronger future decrease in wet-day frequency and the larger future increase in heavy precipitation, the noise from internal variability and weak forcing obscures the CPM signal. Additionally, the present analysis is rather bulk, using entire domains, calculating a limited number of indices and focusing predominantly on a single season. The subsequent analyses will also address the change to the end of the century and its effect on the signal to noise ratio, and additionally distinguish between different underlying surfaces and orography, large-scale circulation, past model performance, types of experiments (PGW or GCM downscaling), etc.

3.5 Outlook

The analysis presented here will be drafted into a manuscript, which is planned to be submitted by the end of the project. This will be the first multi-domain multi-model CPM ensemble analysis. The analysis here was focused on the mid-century changes as mandated by the project, where the change signal is more difficult to extract compared to the end of the century. Therefore, for the manuscript we plan on analysing the changes to the end of the century too.

The data is planned to be published on ESGF, in coordination with the procedures from the CORDEX-FPS on Convection initiative (www.hymex.org/cordexfps-convection/).

4. Lessons Learnt and links Built

The change in simulation strategy from event-based to time slices has been a major shift in the workflow. The benefits are many, including the more appropriate initialisation/spin-up procedures, simpler analysis, and availability of a wider set of high-impact events. At the same time, this created a considerably larger demand for computational resources to perform the time-slice simulations, which naturally took longer time than originally planned. However, the largest unplanned time and effort sink was post-processing, CMORization of output files and storage. The size of the output is in hundreds of TB and together with the need to create new CMORizing procedures for the specificities of CPMs, CMORizing took an unexpectedly long time. This has caused long delays in having access to the data, issues with formatting and corrupted files, and each of the errors required considerable time to solve. Furthermore, the download and upload speed and the space available at different servers were also limiting factors, delaying the work by many months. This could not have been planned in advance because the simulation strategy was changed after the project started.

However, all these challenges were addressed and the data has been successfully shared within WP3 and with other project participants. The CMORization was essential for data sharing with WP2, WP4, WP5, WP6 and other project participants, as it allows for a uniform and straightforward application of the WP3 outputs. It should be noted that the work has co-benefiting from the strong links with the CORDEX FPS on Convection (Coppola et al., 2020), including the scientific and technical aspects. The details of the post-processing procedures, results and challenges will be reported in D3.4.

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6. Appendix

Here we show a number of figures completing the presentation in the main body of the report.

Wet-day frequency and intensity:

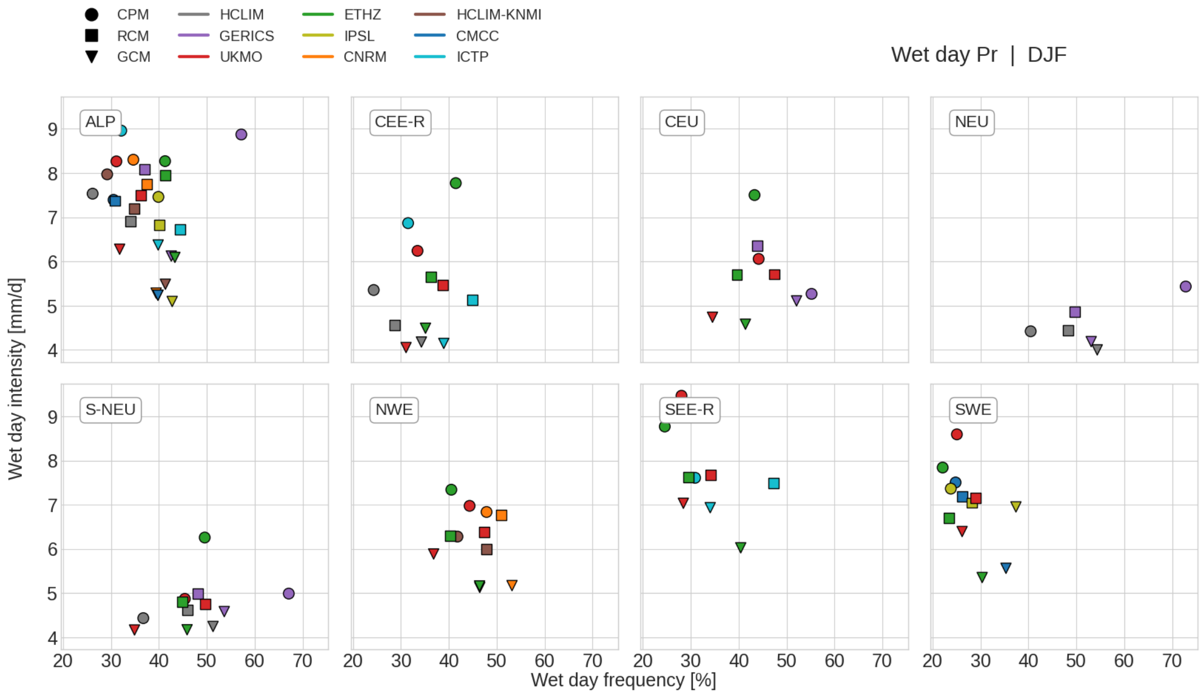

Figure A1: As Fig. 9, except for DJF.

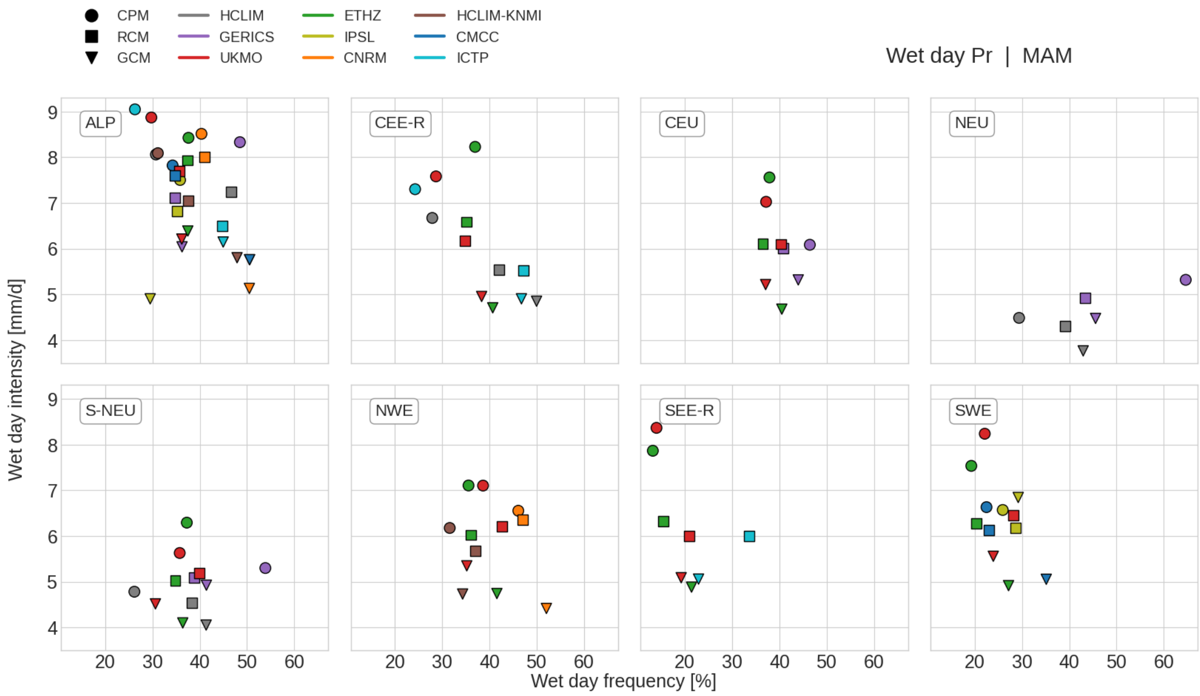

Figure A2: As Fig. 9, except for MAM.

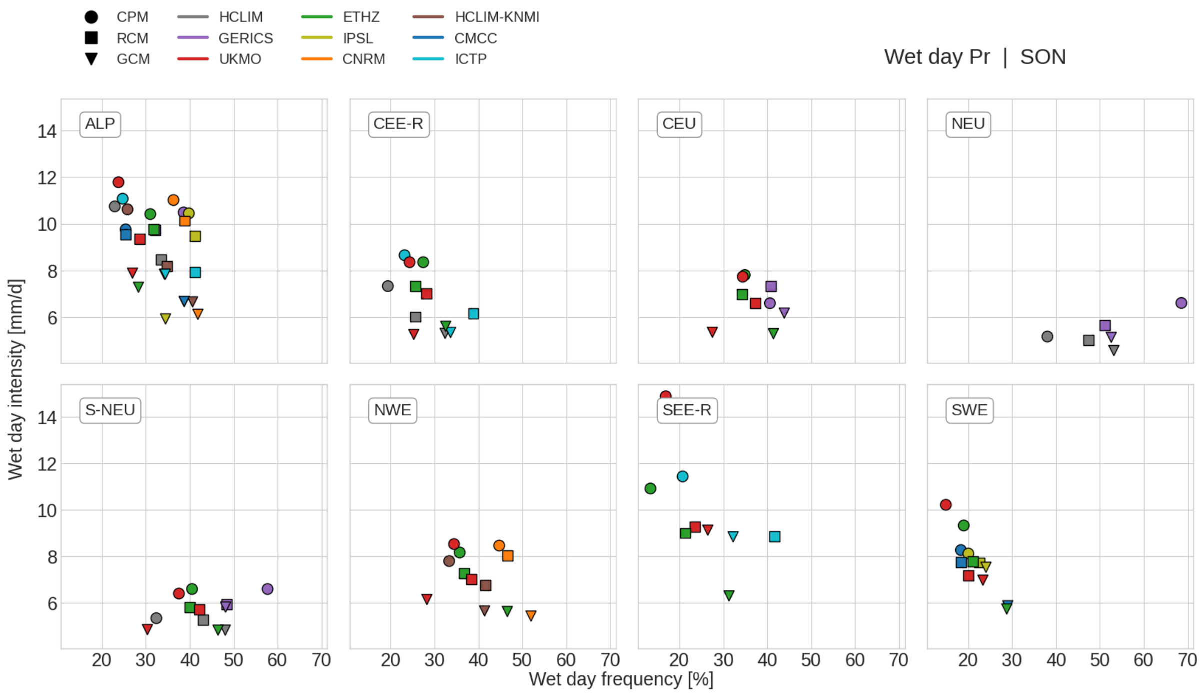

Figure A3: As Fig. 9, except for SON.

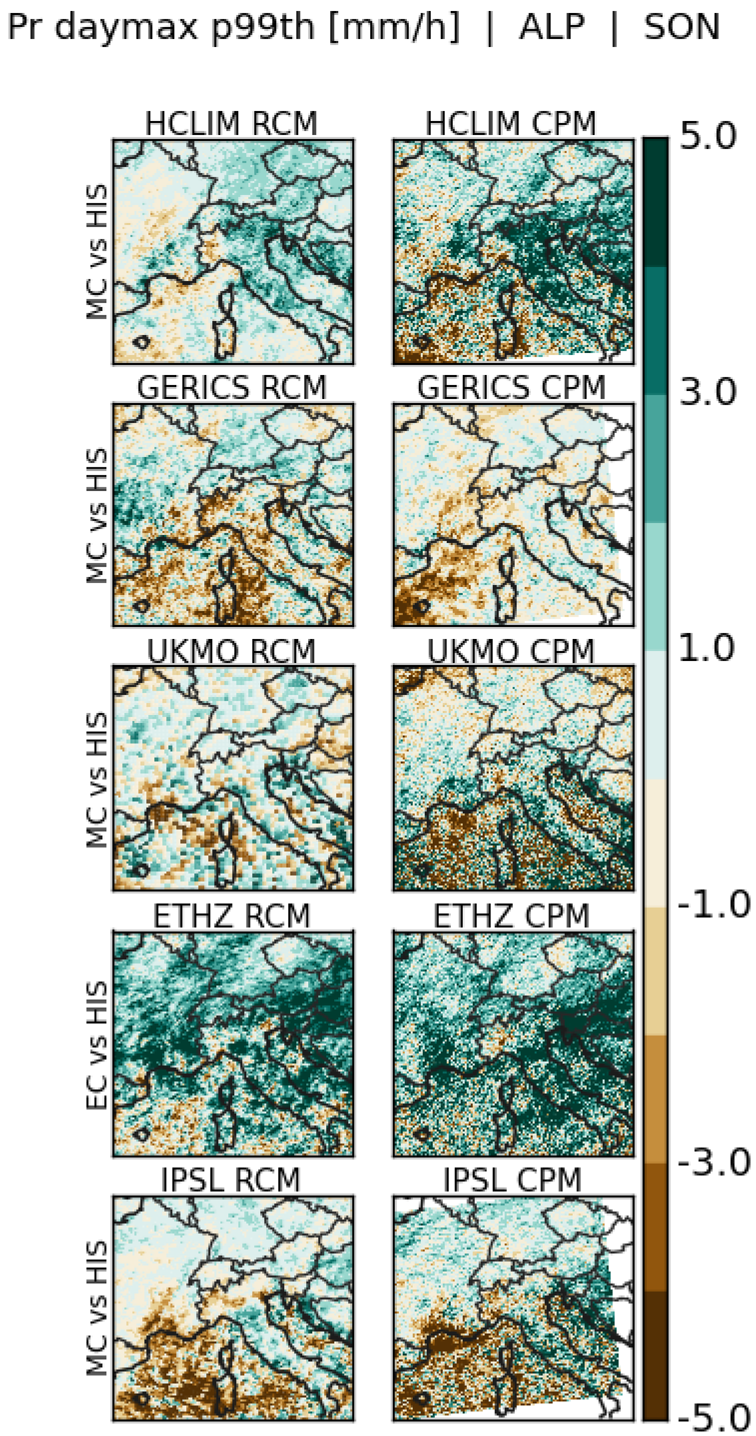

Figure A4: As Fig. 19, except for SON.

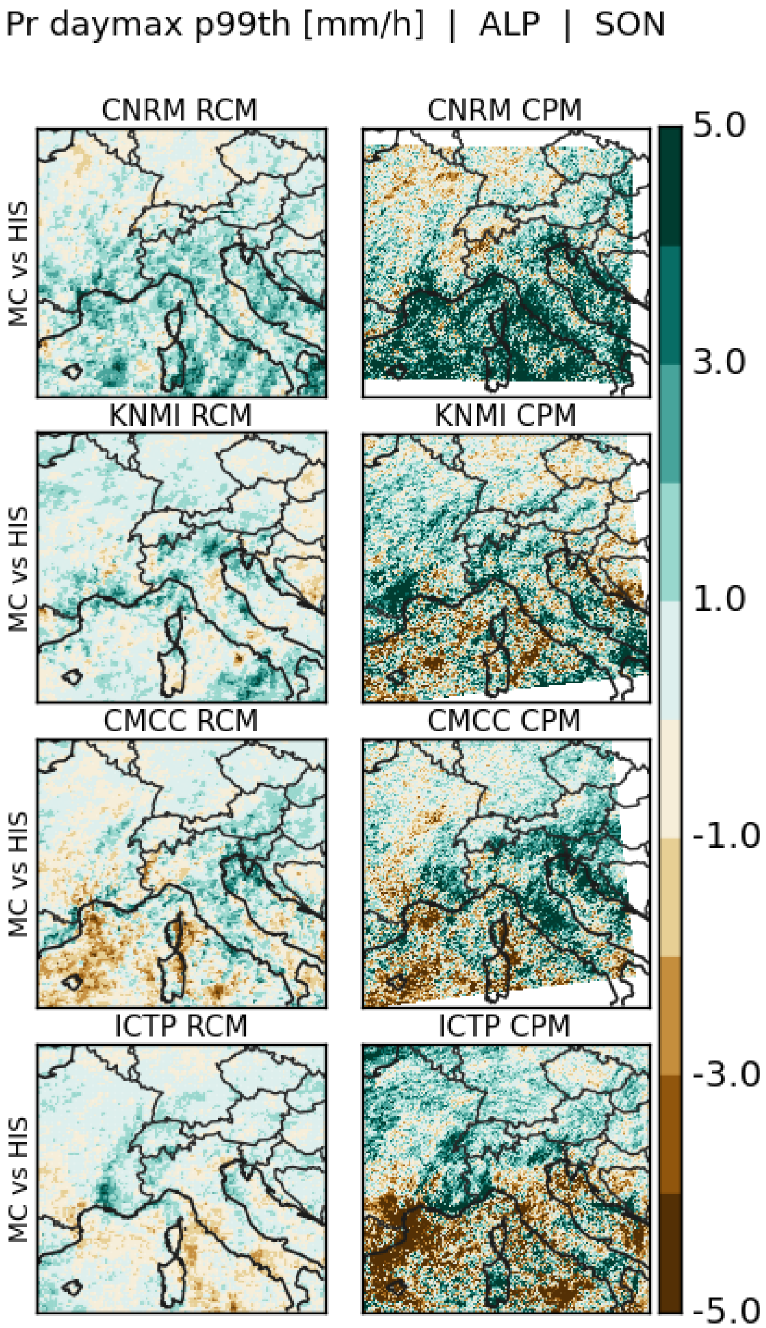

Figure A4: cont.

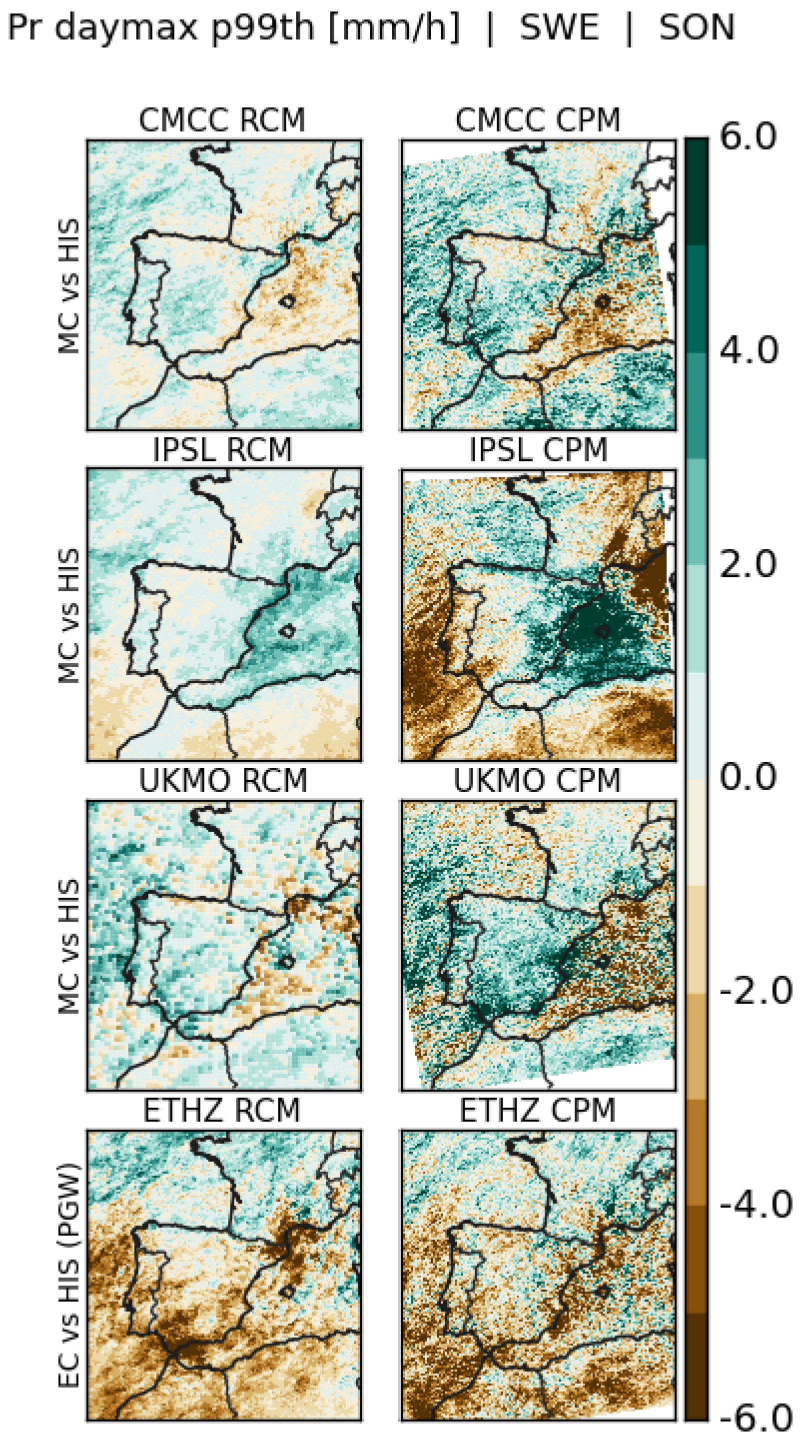

Figure A5: As Fig. 21, except for SON.

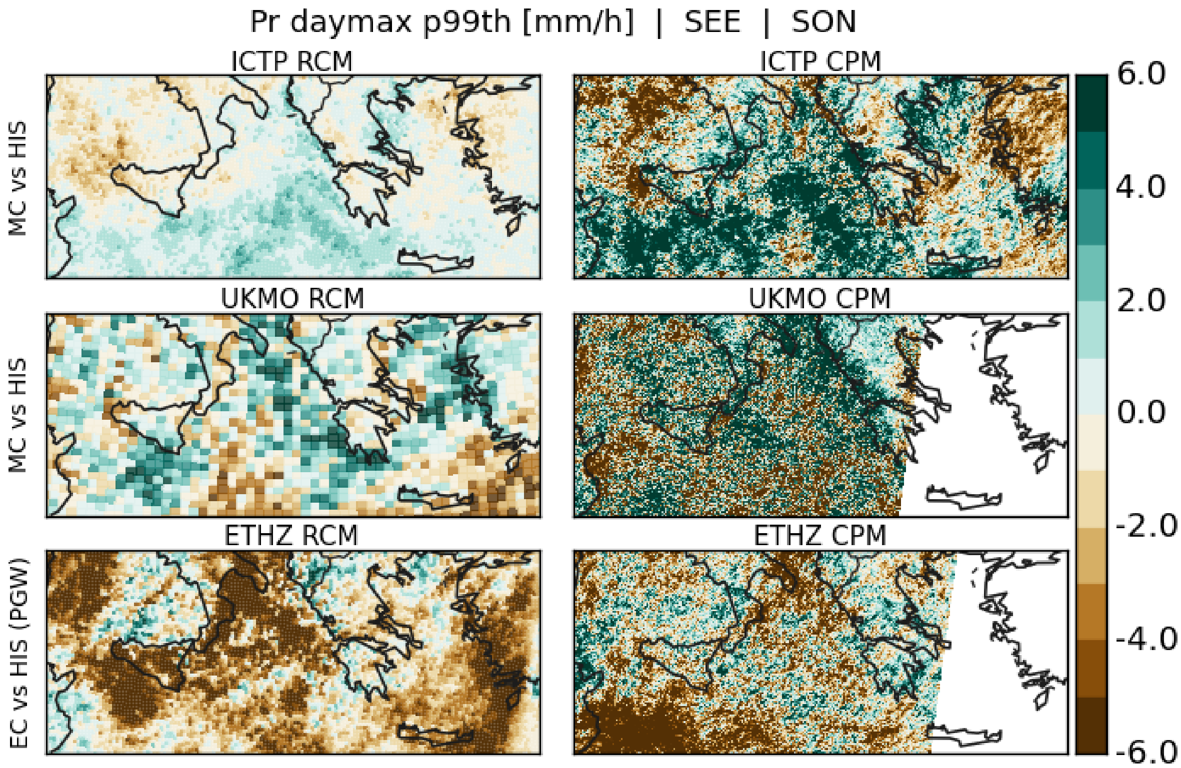

Figure A6: As Fig. 22, except for SON.