AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2015JD024727

Key Points:

- Investigated models underestimate the observed mean temperature in the area of the European Alps
- Investigated models overestimate the observed mean precipitation in the area of the European Alps
- Increase of winter precipitation in the future

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Citation:
Smiatek, G., H. Kunstmann, and A. Senatore (2016), EURO-CORDEX regional climate model analysis for the Greater Alpine Region: Performance and expected future change, *J. Geophys. Res. Atmos.*, *121*, 7710–7728, doi:10.1002/2015JD024727.

Received 28 DEC 2015
Accepted 12 JUN 2016
Accepted article online 18 JUN 2016
Published online 9 JUL 2016

EURO-CORDEX regional climate model analysis for the Greater Alpine Region: Performance and expected future change

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Abstract Simulations from 13 highly resolved regional climate models run within the Coordinated Downscaling Experiment initiative at 0.11° resolution with boundary forcings from five different Coupled Model Intercomparison Project Phase 5 global models are employed to derive future climate change signal for the Greater Alpine Region (GAR) and four smaller investigation areas. Evaluation statistics include mean temperature and precipitation, frequency of days with precipitation over 1 mm and over 15 mm, 90% quantile of the frequency distribution, and maximum number of consecutive dry days. The evaluation for the period from 1971 to 2000 indicates that the models reproduce spatial seasonal precipitation patterns. In general, the simulations underestimate the seasonal mean temperature and overestimate the mean precipitation values. In GAR the ensemble seasonal mean temperature bias ranges from −0.8 to −1.9°C. The bias in precipitation varies between +14.8% in summer and +41.6% in the winter season. Larger errors are found for other statistics and in the investigated regions. In general, no significant gains in the quality of reproduction of the observed precipitation and temperature statistics compared to previous experiments can be identified. The temperature calculations for 2071–2100 related to the period from 1971 to 2000 in the GAR area show ensemble mean increases in the seasonal mean 2 m temperature of 2.5°C in fall and winter, 2.4°C in summer, and 1.9°C in spring. In the same area, precipitation is simulated to increase up to 12.3% in winter and 5.7% in spring. Only minor changes of the ensemble mean are predicted with +2.3% in fall and −1.7% in summer.

1. Introduction

In the last century the mean temperature in the European Alps has increased by 1.1°C [*Böhm et al.*, 2001] that is almost twice the global average of 0.6°C [*Jones et al.*, 1999]. Future climate change projections indicate here adverse effects on almost all natural and socioeconomic sectors. Therefore, the Alpine area is subject of an extensive research investigating observed present and expected future climate change.

With its large topographic variability and strong climatic gradients, the Alps represent a demanding area to regional climate models (RCM) used for projections of expected future climate change. Data from several dynamical downscaling experiments, such as PRUDENCE [*Christensen and Christensen*, 2007], ENSEMBLES [*van der Linden and Mitchell*, 2009], and CORDEX (Coordinated Regional Downscaling Experiment) [*Giorgi et al.*, 2009], have been used to assess the model performance and projected future changes. In their review article, *Gobiet et al.* [2014] conclude that the state-of-the-art RCM models are able to reproduce the main characteristics of the Alpine climate, but there are still important biases present in the simulations. In the evaluation of the ERA-Interim driven EURO-CORDEX (European domain of the CORDEX intitative) model ensemble *Kotlarski et al.* [2014] identified substantial deficiencies with typical area mean biases of ±1.5°C in temperature and ±40% in precipitation together with systematic wet, cold, and dry biases in various parts of Europe. The biases mostly corresponded to results obtained from ENSEMBLES simulations.

Concerning future trends, *Jacob et al.* [2014] derived from the EURO-CORDEX data for the Alpine space a likely increase of the annual mean temperature for 2071–2100 compared to the 1971–2000 mean in the range between 1.9°C and 3.4°C. In the same period the annual mean precipitation is likely to increase from 4 to 8%. The total precipitation at days with daily rain amount over the 99th percentile is expected to increase from

Table 1. EURO-CORDEX Input Data Applied in the Present Study[a]

Run Acronym	Insti-tution	RCM	Driving Model	RCP Scenario	Period
cclm1_c			MPI-ESM-LR	-	1961–2005
cclm1_s				RCP4.5	2006–2100
cclm2_c			CNRM-CM5	-	1950–2005
cclm2_s	CCLMCOM	CCLM 4.8_17		RCP4.5	2006–2100
cclm3_c			EC-EARTH (2)	-	1949–2005
cclm3_s				RCP4.5	2006–2100
cclm4_c			HadGEM2-ES	-	1949–2005
cclm4_s				RCP4.5	2006–2099
knmi1_c			EC-EARTH (1)	-	1961–2005
knmi1_s	KNMI	RACMO22E		RCP4.5	2006–2100
knmi2_c			HadGEM2-ES	-	1949–2005
knmi2_s				RCP4.5	2006–2099
smhi1_c			CNRM-CM5	-	1970–2005
smhi1_s				RCP4.5	2006–2100
smhi2_c			EC-EARTH (2)	-	1970–2005
smhi2_s				RCP4.5	2006–2100
smhi3_c	SMHI	RCA4	IPSL-CM5A-MR	-	1970–2005
smhi3_s				RCP4.5	2006–2100
smhi4_c			HadGEM2-ES	-	1970–2005
smhi4_s				RCP4.5	2006–2099
smhi5_c			MPI-ESM-LR	-	1970–2005
smhi5_s				RCP4.5	2006–2099
ipsl_c	IPSL	WRF331F	IPSL-CM5A-MR	-	1971–2005
ipsl_s		WRF331F	IPSL-CM5A-MR	RCP4.5	2006–2100
dmi_c	DMI	HIRHAM5	EC-EARTH (3)	-	1961–2005
dmi_s			EC-EARTH	RCP4.5	2006–2100

[a]The HadGEM2-ES driven simulations apply 360 day calendar. Numbers in parentheses denote different realizations of the same driving model.

25 to 60%. Again, the results strengthened the outcome obtained in ENSEMBLES, but the authors pointed out the need for further investigations.

This study intends to contribute to such investigation for the Greater Alpine Area (GAR). It revisits an analysis of the projected climate change derived from several dynamical downscaling experiments as presented by *Smiatek et al.* [2009] within the ClimChAlp (Climate change, impacts, and adaptation strategies in the Alpine Space) project. In the present article this investigation is referred to as ClimChAlp. It employs newly available high-resolution climate change data from the European domain of the EURO-CORDEX experiments in context of the results which were obtained from data of the PRUDENCE and ENSEMBLES projects. In addition to the GAR region, it investigates also the model performance and the projected future changes in selected smaller investigation areas. This is an important aspect, as planning of measures aiming at adaptation and resilience increasing often require sound information at specific regional scales.

The outline of the article is as follows: the available regional climate data, the investigation areas, and the applied statistics are presented in section 2. In section 3, the evaluation for the present-day climate and the discussion of the simulated future climate change are given. Finally, conclusions are drawn in section 4.

2. Material and Methods

2.1. Applied Data

Climate change data applied in the present study originate from the EURO-CORDEX initiative (www.euro-cordex.net). The dynamic regional downscaling experiments were run with the CMIP5 (Coupled Model

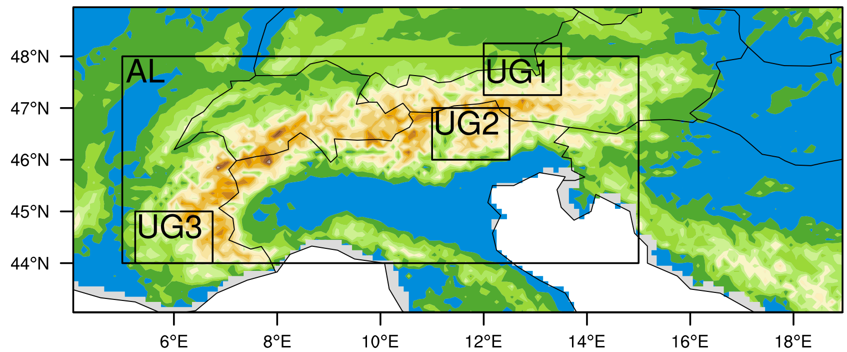

Figure 1. Investigation areas GAR, AL, UG1, UG2, and UG3. Shading represents topographic height according to the GTOPO30 [*USGS*, 1996] elevation model.

Intercomparison Project Phase 5) global climate projections [*Taylor et al.*, 2012] and representative concentration pathways (RCPs) scenarios [*Moss et al.*, 2010]. The present work employs data from five published models which provide highly resolved data at 0.11° resolution (EUR11) based on the RCP4.5 scenario. Table 1 shows details of the applied RCM/global climate model (GCM). A detailed description of the EURO-CORDEX initiative is given by *Jacob et al.* [2014]. The authors conclude a substantial larger change of the temperature-based indices in the experiments under the RCP8.5 scenario compared to the RCP4.5 scenario. This difference was less obvious in precipitation indices. *Kotlarski et al.* [2014] provide a joint standard evaluation of the EURO-CORDEX RCM ensemble.

2.2. Investigation Areas and Investigated Statistics

As in the ClimChAlp experiment, assessment of the future climate change is performed in the Greater Alpine area (GAR) (4°W–19°W and 43°N–49°N) and three smaller investigation areas which allow for accessing regional effects in various parts of the Alpine region. These investigation areas are UG-1 (north of the main Alpine ridge), UG-2 (south of the main Alpine ridge), and UG-3 (southwestern part) all of 1.5° by 1° in size.

GAR is larger than the standard Alpine investigation area applied in numerous regional studies [*Christensen and Christensen*, 2007; *Boberg et al.*, 2010]. Therefore, this area (5°W–15°W and 44°N–48°N), named AL, has been added to the present investigation allowing comparison with the above mentioned studies. Figure 1 shows the location of the investigation areas.

Evaluations for the present climate (1971–2000) are performed against the European daily high-resolution gridded data set E-OBS Version 10.0 [*Haylock et al.*, 2008; *van den Besselaar et al.*, 2011]. For that purpose the RCM data has been bilinerarly remapped to 0.25° resolution of the E-OBS data set and the temperature corrected for differences in the grid cell elevation between E-OBS and the RCMs assuming a constant lapse rate of 0.6°C per 100 m. As in ClimChAlp, applied climatological statistics include seasonal mean temperature and precipitation, the frequency of wet days with precipitation above 1 mm and strong precipitation frequency with precipitation above 15 mm/d, 90% quantile of the precipitation distribution on wet days, and the maximum number of consecutive dry days. Acronyms and applied statistics are presented in Table 2. All statistics consider land points only, and investigated periods include the historical period from 1971 to 2000 and the future period from 2071 to 2100.

Table 2. Precipitation and Temperature Statistics Used in This Study

Acronym	Definition	Unit
MEA-P	Mean climatological precipitation	mm/d
MEA-T	Mean climatological temperature	°C
FRE-1	Frequency (ratio) of days with precipitation ≥ 1 mm (wet day)	Fraction
FRE-15	Frequency (ratio) of days with precipitation ≥ 15 mm	Fraction
Q90	90% quantile of distribution function on wet days	mm/d
XCDD	Maximum number of consecutive dry days	d

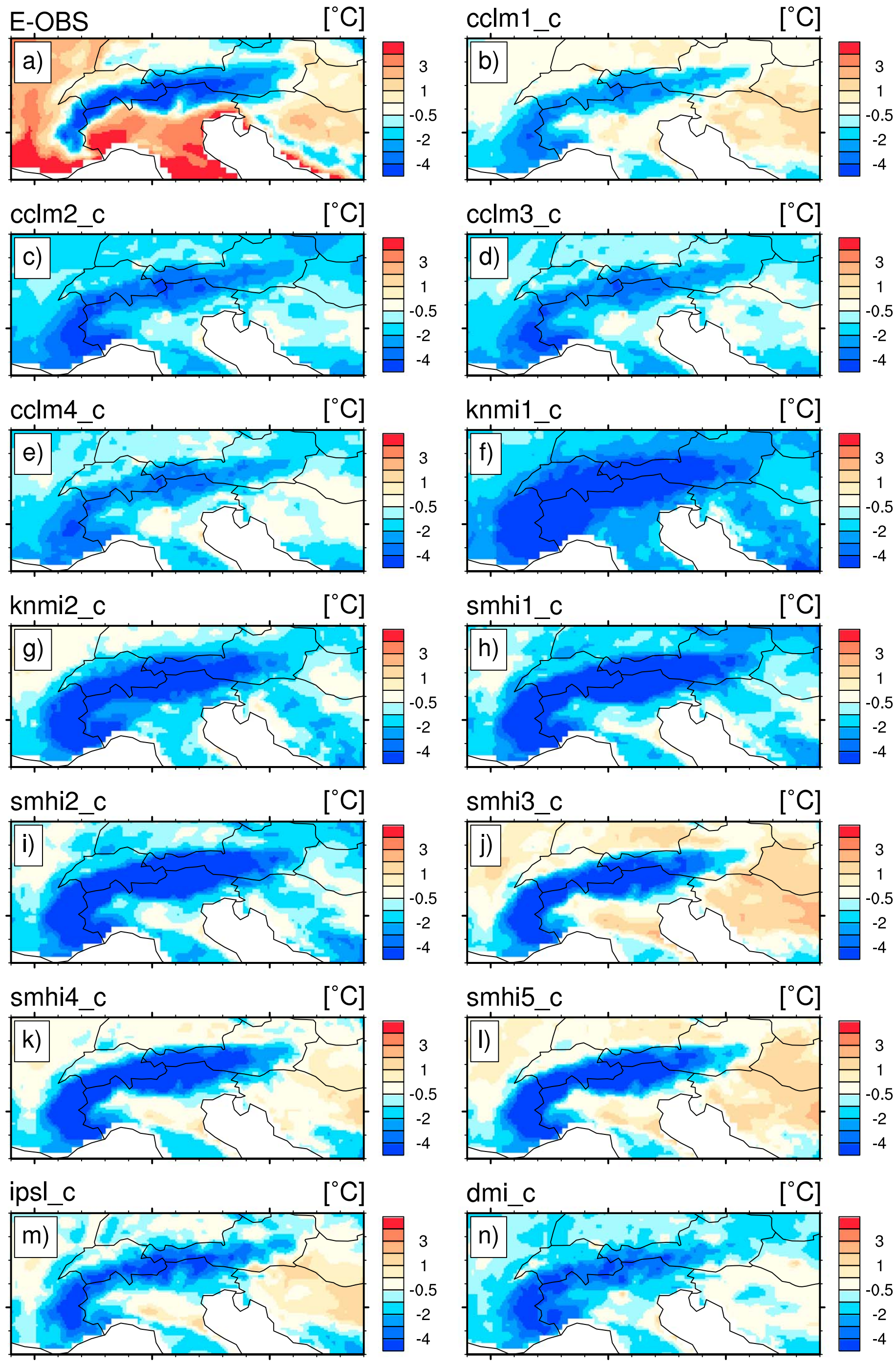

Figure 2. Observed (a) mean seasonal temperature and (b–n) mean seasonal temperature bias for the winter season (December–February (DJF)) 1971–2000. For explanation of the RCM run acronyms see Table 1.

3. Results

3.1. Present Climate

Figures 2–5 show spatial distributions of the mean winter and summer model biases for temperature and precipitation in the GAR area compared to the E-OBS reference. The considered period is from 1971 to 2000. With exception of the simulation cclm4_c all investigated models underestimate the observed temperatures in large areas of GAR in both seasons with largest differences along the Alpine ridge. The mean bias ranges from −3.0°C to −0.4°C in winter and −3.3°C to +2.1°C in summer. In order to exclude outliers which might result

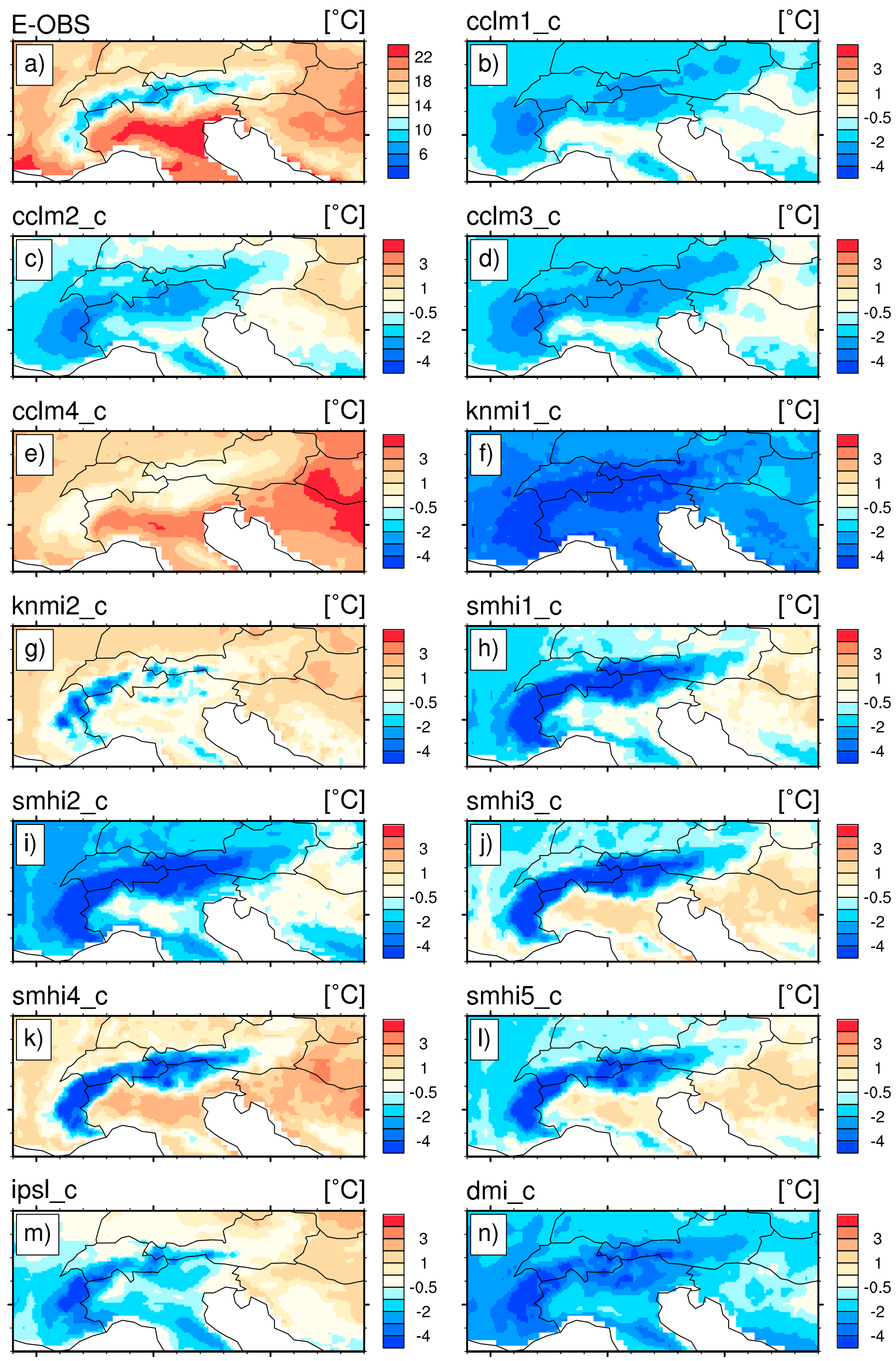

Figure 3. As Figure 2 but for the summer season (June–August (JJA)).

from data interpolation, we consider the lower 5% and upper 95th percentile values in the analysis of the bias ranges present in the RCM simulations. In winter the 5 ptile values range from −2.9°C in simulation cclm1_c to −8.2°C in smhi2_c and the 95 ptile values from −0.85°C in knmi1_c to +1.9°C in smhi3_c. In summer the ranges between the 5 ptile and 95 ptile values are generally smaller. The 5 ptile values range here from −6°C in smhi2_c to +0.3°C in cclm4_c, and the 95 ptile values range from −1.9°C in knmi1_c to +4.1°C in cclm4_c. cclm4_c is the only simulation revealing a warm bias in the entire area. *Kotlarski et al.* [2014] investigated a set of seven EURO-CORDEX models driven at 0.11° resolution with ERA-Interim boundary forcings stating an underestimation of the observed seasonal temperature in large parts of the European modeling domain.

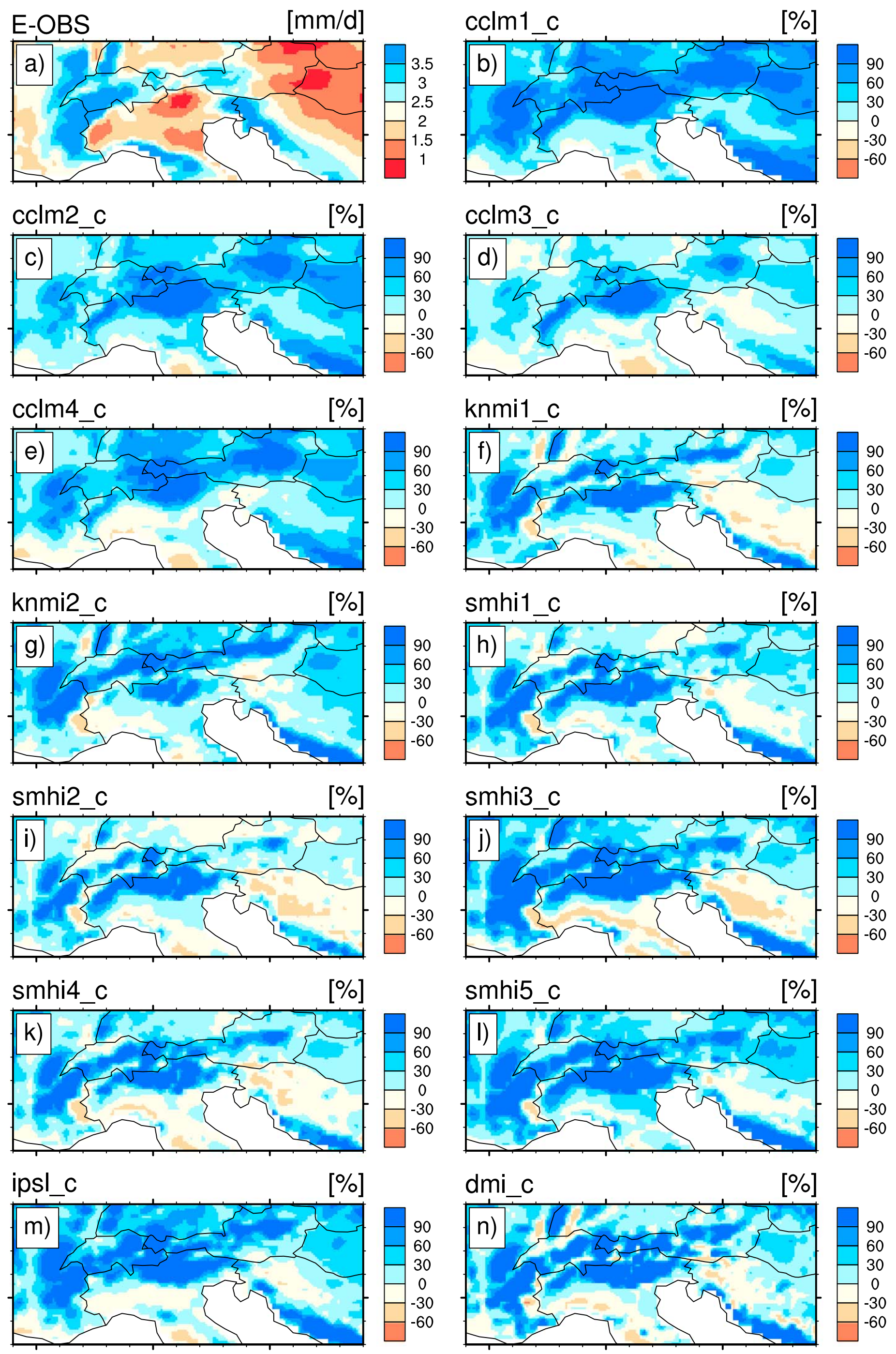

Figure 4. Observed (a) mean seasonal precipitation and (b–n) mean seasonal precipitation bias for the winter season (DJF) 1971–2000. For explanation of the RCM run acronyms see Table 1.

In general, for the mean temperature, all RCMs show a high spatial correlation with the E-OBS reference (Figure 6a) of around 0.90 in winter and 0.95 in summer. This applies even for the models with larger cold bias indicating systematic errors.

Reproduction of the observed precipitation patterns is presented in Figures 4 and 5. All models overestimate winter precipitation in large parts of the GAR area with mean values ranging from +32% to +67% and 95 ptile values up to +211%. In summer, the mean bias ranges from −37% to +99% with 95 ptile values up to +311%, and a general overestimation is prevailing. Only knmi2_c, smhi4_c, and especially cclm4_c reveal a dry bias

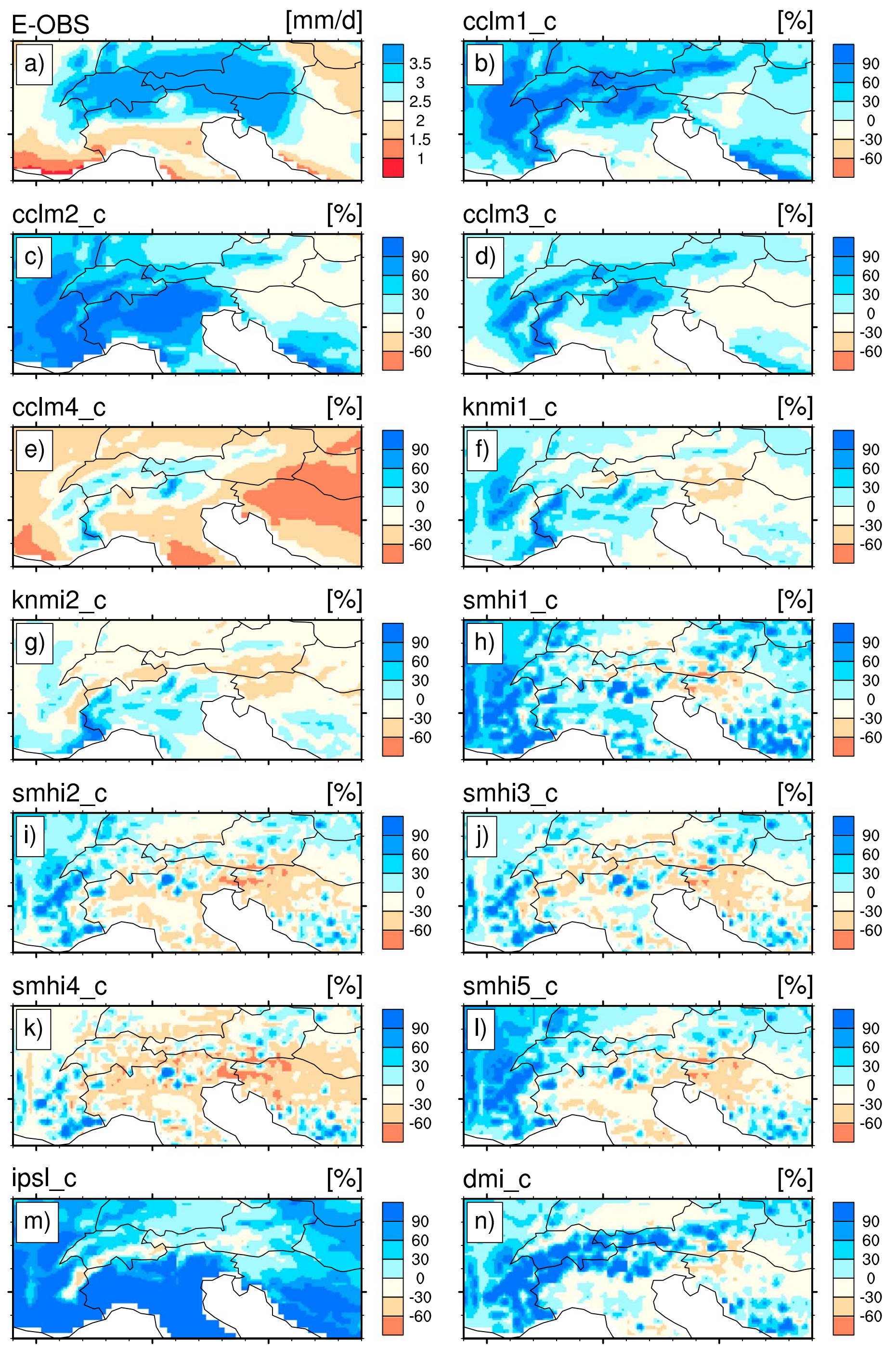

Figure 5. As Figure 4 but for the summer season (JJA).

where the 5 ptile value is −68%. Spatial correlation with E-OBS is in both seasons lower than 0.85, reaching with the dmi_c simulation the value of 0.55 in summer (Figure 6b). Simulation cclm_c3 performs best in winter. In summer the best performing simulations are knmi2_c and knmi1_c. The spatial correlations with the E-OBS reference are well in the range of the evaluation of the CORDEX runs with ERA-Interim reanalysis [*Kotlarski et al.*, 2014].

Figure 7 shows observed and simulated seasonal area mean temperatures in the investigation areas AL and UG1 to UG3, revealing substantial cold biases of up to 5°C in all investigation areas and in both investigated seasons. The ensemble mean bias in the AL area ranges from −2.4°C in spring to −1.5°C in summer

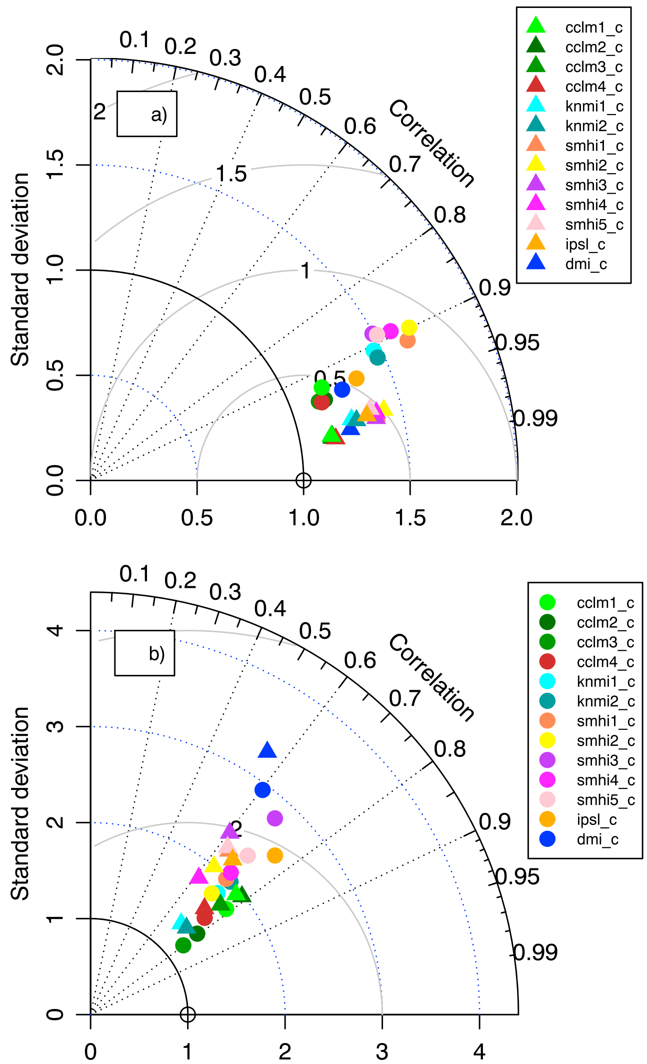

Figure 6. Spatial Taylor diagrams of simulated seasonal mean (a) temperature and (b) precipitation 1971–2000 in relation to E-OBS observational reference for the GAR area. Dots refer to winter season and triangles to summer season.

(see Table 3). The biases are larger than biases found in the PRUDENCE [*Jacob et al.*, 2007] experiments that were performed at approximately 50 km resolution and for which biases up to +2°C in relation to the Climatic Research Unit (CRU) climatology were found in the AL area. The biases are, however, in the same range as in CORDEX experiments with ERA-Interim boundary data [*Kotlarski et al.*, 2014]. This indicates that the shortcoming is rather in the area of the RCMs than in the area of the driving GCMs. Clear limitations can be suspected for example in parameterizations which were developed for coarser model resolutions but applied at much higher resolution. *Kotlarski et al.* [2014] point out that some models tend to increase the cold bias when run at higher spatial resolutions.

The bias ranges in the smaller investigation areas UG1, UG2, and UG3 are also larger than biases found in the ClimChAlp investigation where RCM models runs with comparable resolutions where investigated. The seasonal ensemble mean maximum bias is −4.4°C (Table 3). It should be noted here that the temperatures were corrected for differences in the grid cell elevation between E-OBS and the RCMs.

Figure 8 displays observed and simulated seasonal area mean precipitation in the investigation areas AL, UG1, UG2, and UG3 for 1971–2000. In the AL area all models overestimate the observed winter precipitation. The bias range is between +24% and +76%. In summer the range is from a small underestimation of −20% to an overestimation up to +70%. In their evaluation of EURO-CORDEX simulations with ERA-Interim, *Kotlarski et al.* [2014] found an overestimation of up to 60% in the winter season. The investigated models reproduced the summer mean precipitation within a range from −40% to +50%. Again, the biases are higher as found in the PRUDENCE experiment where the intermodel winter bias range was from −19% to + 26% and summer bias range was from −29% to +12%, both compared to CRU (Climatic Research Unit) climatology values. The biases in the smaller investigation areas reach values up to 157% especially in the summer season with a large number of convective rain events. Taking into account, the assumed rain gauge undercatch in the order of 50% at high elevations [*Frei et al.*, 2003]; these results are still in a reasonable range. *Prein and Gobiet* [2016] concluded that in high latitudes and in mountainous regions undercatch errors of up to 80% are present in European gridded observational data and that the undercatch is not corrected in the E-OBS data set used in present study. Thus, the wet bias shown by the majority of the models might in reality be smaller, especially in the smaller investigation areas. A better reproduction of convective precipitation is expected from convection permitting models which, however, have to be run at much higher spatial resolution.

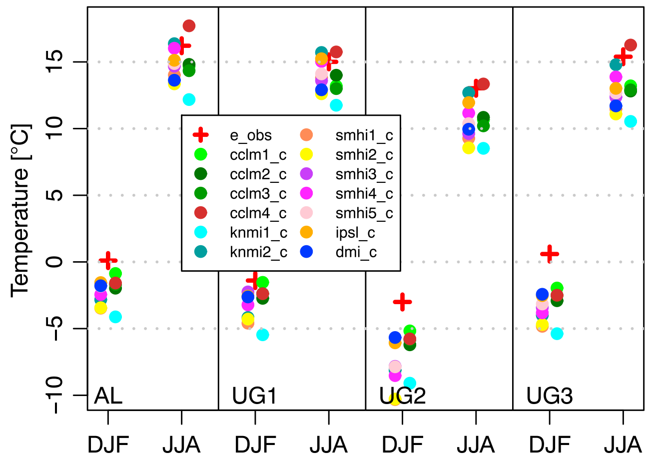

Figure 7. Observed and simulated area mean winter (DJF) and summer (JJA) temperature MEA-T in the investigation areas AL, UG1, UG2, and UG3 for 1971–2000.

Figure 9 shows wet day frequency FRE-1 and strong precipitation frequency FRE-15. In the winter season the models overestimate both the frequency statistics. Only simulation cclm3_c reveals a small underestimation in the areas UG1 and UG3 for FRE-15. The spread between the models is comparatively small. In the summer season the picture is less clear, and the spread between the investigated simulations is much larger. The largest discrepancy between the investigated simulations can be found in the investigation area UG1. Ensemble mean biases are positive in all seasons with one exception in UG1 area (Table 3).

Table 3. Ensemble Mean Biases to E-OBS Observations 1971–2000

Area	Indicator	Unit	DJF	MAM	JJA	SON
GAR	MEA-T	°C	−1.5	−1.9	−0.8	−1.2
	MEA-P	%	41.5	36.7	14.8	17.6
	FRE-1	%	25.9	19.4	10.7	15.7
	FRE-15	%	48.5	56.3	16.1	13.3
	Q90	%	10.0	11.8	−1.3	0.8
	XCDD	%	−31.8	−21.7	−1.3	−17.6
AL	MEA-T	°C	−2.3	−2.4	−1.5	−1.8
	MEA-P	%	50.8	42.7	19.9	24.0
	FRE-1	%	32.3	23.3	16.2	22.8
	FRE-15	%	54.6	58.6	18.9	18.3
	Q90	%	13.1	12.7	−2.0	−0.2
	XCDD	%	−34.6	−25.0	−2.7	−19.7
UG1	MEA-T	°C	−1.7	−2.6	−1.1	−1.4
	MEA-P	%	39.7	30.9	1.2	22.1
	FRE-1	%	25.9	17.2	5.7	18.8
	FRE-15	%	62.2	50.0	−6.9	17.8
	Q90	%	9.7	8.0	−7.0	−0.1
	XCDD	%	−36.9	−20.8	−8.1	−15.3
UG2	MEA-T	°C	−4.4	−3.8	−2.5	−2.9
	MEA-P	%	107.0	76.3	18.3	49.1
	FRE-1	%	52.1	31.3	9.5	29.9
	FRE-15	%	153.8	133.8	23.6	48.5
	Q90	%	54.6	38.8	1.7	16.6
	XCDD	%	−40.9	−32.6	38.0	−33.3
UG3	MEA-T	°C	−4.0	−3.5	−2.6	−3.0
	MEA-P	%	53.8	45.5	50.0	22.9
	FRE-1	%	55.2	45.0	51.1	34.4
	FRE-15	%	45.4	35.1	43.3	11.6
	Q90	%	−2.1	−4.9	−7.0	−9.5
	XCDD	%	−38.0	−55.7	−25.4	−24.1

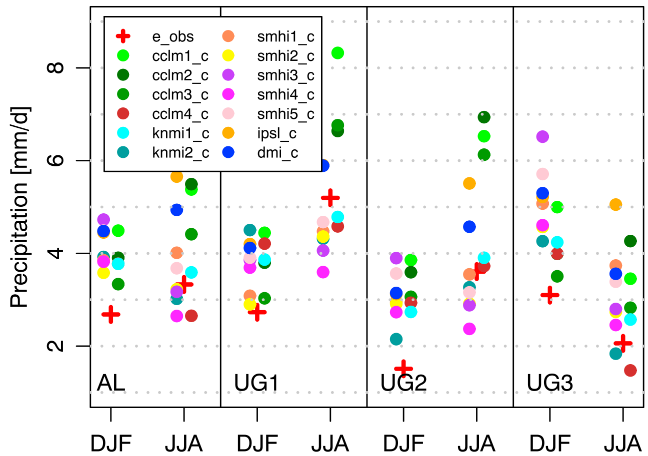

Figure 8. Observed and simulated area mean winter (DJF) and summer (JJA) precipitation MEA-P in the investigation areas AL, UG1, UG2, and UG3 for 1971–2000.

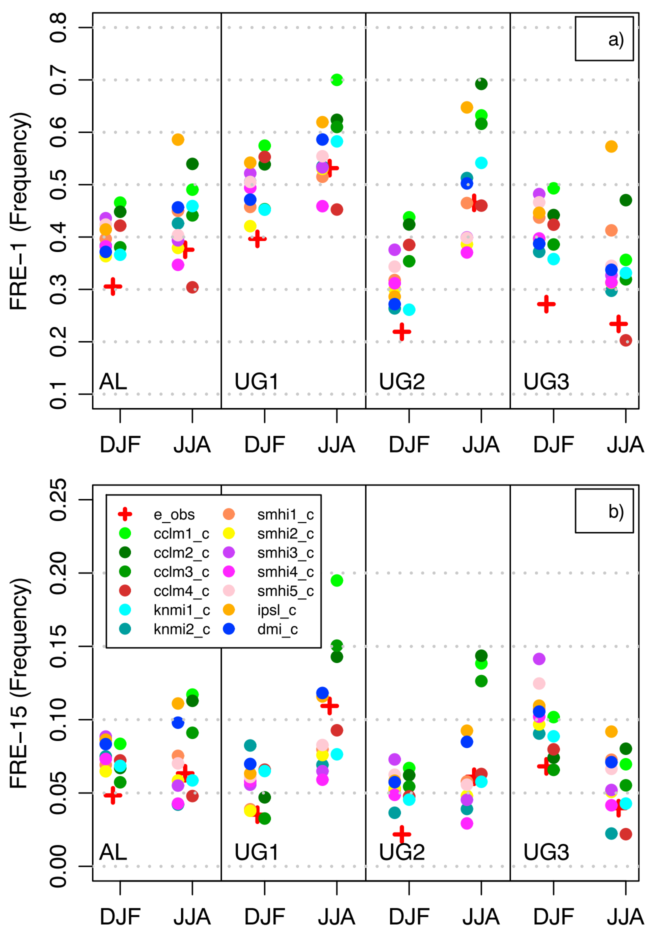

Figure 9. Observed and simulated area mean winter (DJF) and summer (JJA) frequency of days with precipitation of at least 1 mm (a) (FRE-1) and frequency of days with precipitation over 15 mm (b) (FRE-15) for 1971–2000 in the investigation areas AL, UG1, UG2, and UG3.

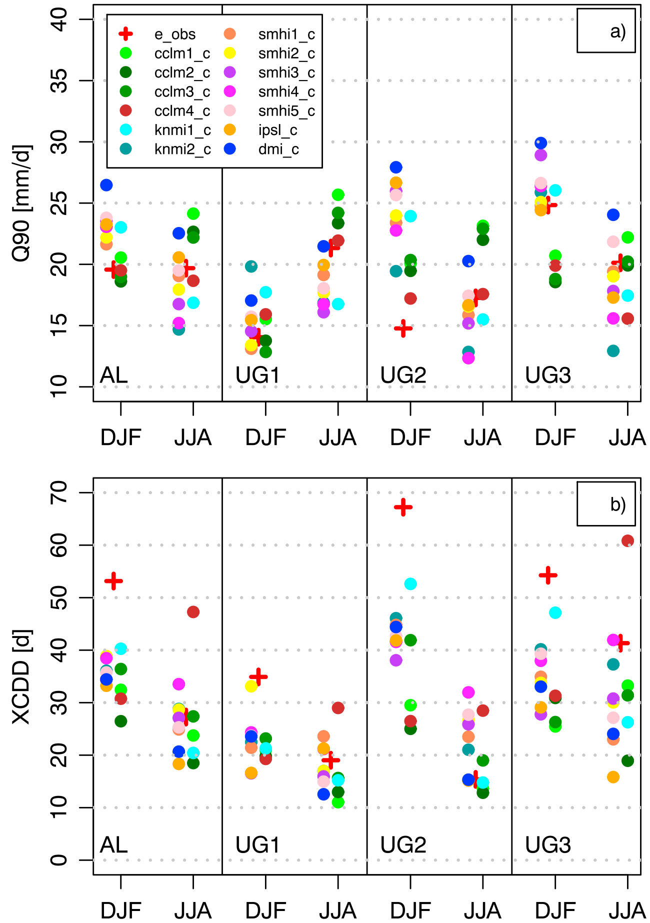

Figure 10. Observed and simulated area mean winter (DJF) and summer (JJA) 90% quantile (Q90) on wet days (a) and maximum number of consecutive dry days (XCDD) (b) for 1971–2000 in the investigation areas AL, UG1, UG2 and UG3.

Present results show the same general notion to overestimation of the number of rainy days as well as the number of strong precipitation events with slightly larger intermodel ranges as found in the ClimChAlp investigation. The overestimation of the wet day frequency in the Alpine area in winter was also present in the PRUDENCE [*Frei et al.*, 2006] and ENSEMBLES [*Rajczak et al.*, 2013] simulations. In summer, these simulations showed rather an underestimation.

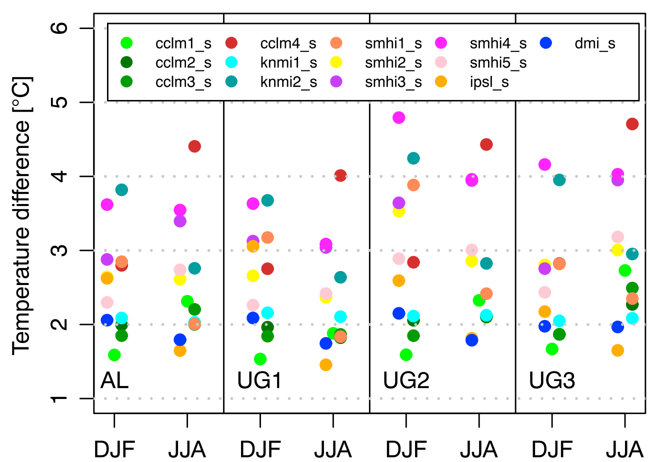

Figure 11. Changes in the area mean winter (DJF) and summer (JJA) temperature MEA-T as difference 2071–2100 to 1971–2000 in the investigation areas AL, UG1, UG2, and UG3.

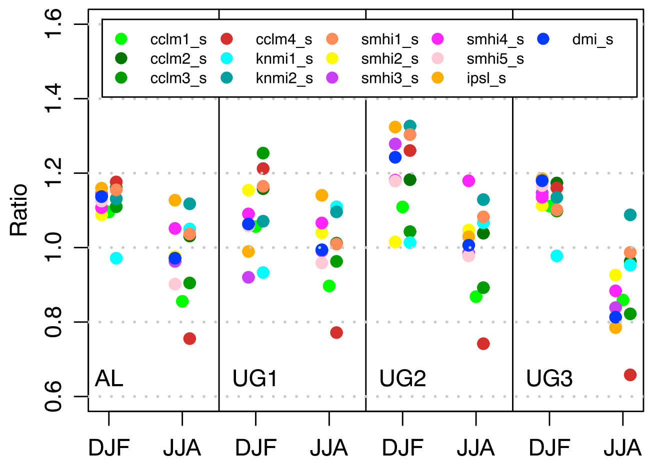

Figure 12. Changes in the area mean winter (DJF) and summer (JJA) precipitation MEA-P as ratio 2071–2100 to 1971–2000 in the investigation areas AL, UG1, UG2, and UG3.

Table 4. Ensemble Mean Statistics of Projected Changes in the Investigated Areas as Difference 2071–2100 to 1971–2000 in °C for MEA-T and Ratio 2071–2100 to 1971–2000 in % for All Other Statistics

		DJF			MAM			JJA			SON		
Area	Indicator	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum
GAR	MEA-T	1.5	2.5	3.7	1.2	1.9	2.7	1.7	2.4	4.1	1.7	2.5	3.8
	MEA-P	1.1	12.3	17.1	0.9	5.7	14.4	−20.5	−1.7	14.5	−7.8	2.3	8.4
	FRE-1	−2.0	3.1	7.8	−4.7	−1.1	3.6	−28.8	−6.8	3.9	−18.4	−5.3	−1.0
	FRE-15	−14.9	0.3	24.3	−15.5	1.0	22.6	−12.9	10.9	35.3	−10.7	10.2	35.0
	Q90	2.8	11.4	17.7	4.3	8.2	10.6	−0.1	5.6	15.2	5.8	9.9	13.1
	XCDD	−14.9	0.3	24.3	−15.5	1.0	22.6	−12.9	10.9	35.3	−10.7	10.2	35.0
AL	MEA-T	1.6	2.5	3.8	1.2	2.0	3.0	1.6	2.6	4.4	1.7	2.6	3.9
	MEA-P	−2.8	12.0	17.6	−1.1	4.7	12.6	−24.4	−2.0	12.7	−11.1	−0.3	6.3
	FRE-1	−2.3	3.2	7.4	−6.1	−1.6	3.4	−29.9	−6.2	4.2	−18.9	−6.4	−1.3
	FRE-15	−17.2	−0.9	30.2	−18.6	2.6	21.2	−17.7	11.1	48.9	−12.5	9.4	40.5
	Q90	0.0	10.3	17.9	4.0	7.0	8.9	−1.4	4.1	16.8	3.2	8.0	12.2
	XCDD	−17.2	−0.9	30.2	−18.6	2.6	21.2	−17.7	11.1	48.9	−12.5	9.4	40.5
UG1	MEA-T	1.5	2.6	3.7	1.2	2.1	3.2	1.5	2.3	4.0	1.5	2.5	3.8
	MEA-P	−8.0	8.7	25.4	−0.7	11.1	28.8	−22.8	0.4	14.0	−6.0	4.7	15.5
	FRE-1	−3.9	1.4	10.2	−0.3	3.8	12.7	−27.1	−4.0	5.3	−15.3	−2.2	7.5
	FRE-15	−13.1	19.6	64.3	−1.1	15.8	36.7	−25.8	3.0	23.8	−5.9	8.8	23.3
	Q90	−4.0	7.9	18.7	−0.5	5.6	12.9	−7.2	4.9	12.4	0.0	7.7	14.7
	XCDD	−23.6	8.8	46.2	−35.5	−15.3	16.1	−24.4	4.8	34.3	−18.3	12.8	68.0
UG2	MEA-T	1.6	2.9	4.8	1.3	2.3	3.7	1.8	2.7	4.4	1.7	2.6	3.9
	MEA-P	1.3	18.9	32.7	−0.3	7.2	23.6	−25.8	0.3	17.9	−13.2	−1.8	8.9
	FRE-1	−1.5	5.9	14.3	−6.6	−0.7	5.7	−28.4	−3.6	6.7	−20.1	−7.1	1.6
	FRE-15	−0.3	26.0	39.9	−2.1	10.7	33.1	−31.1	2.4	42.3	−21.5	−4.4	7.4
	Q90	−2.7	13.6	28.7	1.0	9.3	18.3	−5.5	3.7	22.5	−5.8	7.1	16.7
	XCDD	−30.0	−1.8	37.3	−28.6	−2.2	29.1	−12.1	10.8	44.5	−14.9	8.5	84.6
UG3	MEA-T	1.7	2.6	4.2	1.3	2.1	3.3	1.6	2.9	4.7	1.7	2.7	4.0
	MEA-P	−2.2	13.0	18.5	−11.6	0.1	12.9	−34.2	−12.6	8.8	−19.5	−5.8	7.4
	FRE-1	−3.3	2.0	6.9	−14.1	−5.5	4.3	−33.8	−13.1	2.4	−22.1	−10.4	−4.6
	FRE-15	−0.6	15.1	37.3	−8.2	2.6	19.6	−43.6	−15.2	12.8	−22.9	−5.8	9.6
	Q90	4.8	12.9	19.3	1.0	6.3	11.5	−12.7	−0.7	13.6	−6.1	5.3	18.2
	XCDD	−40.7	−2.1	24.4	−26.2	10.4	59.8	−5.7	25.9	61.2	−19.3	13.2	52.9

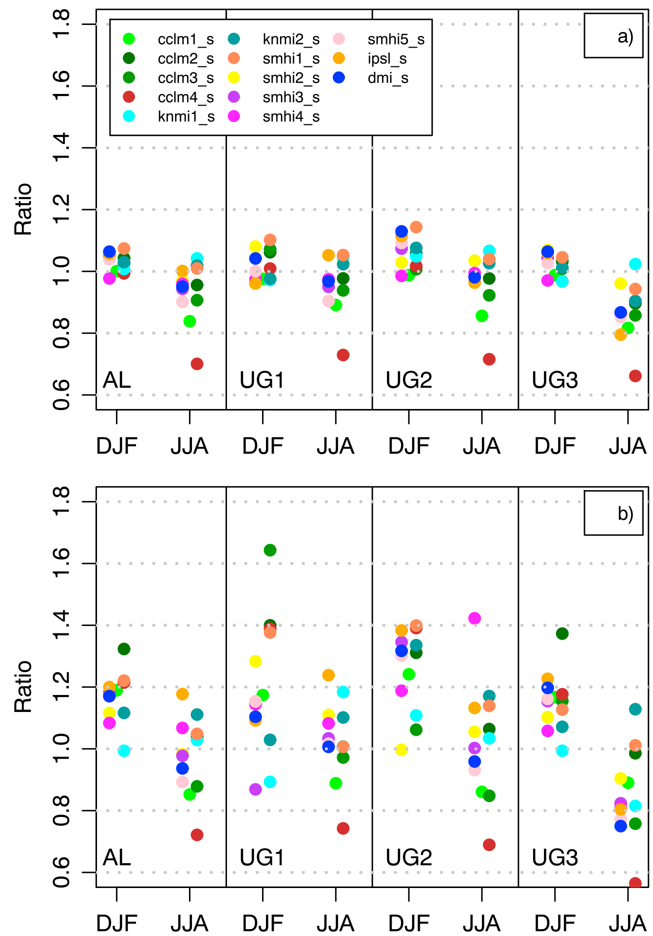

Figure 13. Changes in the domain mean frequency (a) FRE-1 and (b) FRE-15 as ratio 2071–2100 to 1971–2000 for winter (DJF) and summer (JJA) seasons in the investigation areas AL, UG1, UG2, and UG3.

The reproduction of the observed 90% quantile of the distribution function of the precipitation on wet days Q90, as well as the maximum number of consecutive dry days XCDD for 1971–2000, is depicted in Figure 10. The simulations show a similar performance as found in the ClimChAlp experiment but with a slightly larger intermodel spread. In the winter season, the Q90 value is mostly overestimated, while the XCDD is partly substantially underestimated.

Presented evaluation results show that despite the higher model resolution, the investigated simulations still reveal substantial biases in the complex Alpine terrain. No significant improvements in the reproduction of observed temperature and precipitation statistics can be seen in comparison to previous experiments such as PRUDENCE or ENSEMBLES. *Prein and Gobiet* [2016] found substantial differences between the available European gridded precipitation observations. For the Alps, however, the authors found that the majority of CORDEX RCM simulations driven with ERA-Interim boundary data revealed variabilities that are outside of the uncertainties present in the observational reference. *Casanueva et al.* [2015] and *Kotlarski et al.* [2014] concluded that in CORDEX no clear benefit of increased model resolution from 0.44° to 0.11° can be identified. The authors, however, saw some improvements in the model performance compared to prior studies, e.g., ENSEMBLES. On the other hand, *Prein et al.* [2015a] investigated the reproduction of mean and extreme precipitation in EURO-CORDEX 0.11° and 0.44° simulations and concluded that higher resolved simulations reduce the biases and improve the spatial precipitation patterns. This was even more evident when the evaluation was performed at a fine grid of 12.5 km.

Independently of improvements in model performance, one intrinsic added value of the third generation of regional modeling can be seen in the fact that, due to the increased resolution, subsequent regional impact studies do not have to rely on single cell values even though a bias correction might still be required.

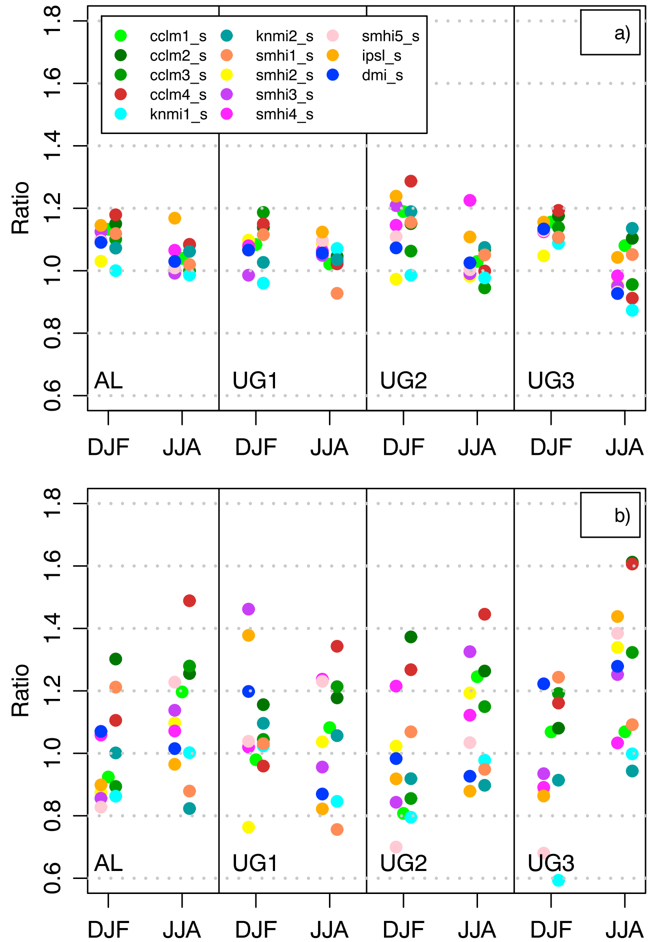

Figure 14. Changes in the (a) domain mean Q90 and (b) consecutive dry days XCDD as ratio 2071–2100 to 1971–2000 for winter (DJF) and summer (JJA) season in the investigation areas AL, UG1, UG2, and UG3.

Curry et al. [2016] concluded that limited form of spatial averaging may contribute an added value of high-resolution simulations for physical variables tied to elevation. *Prein et al.* [2015b] expected further improvements in mountainous regions from the application of convection permitting models. A bias reduction can also be achieved with improved soil and vegetation data input [*Guillod et al.*, 2013; *Smiatek et al.*, 2016] as well as with a careful choice of the RCM model setup [*Klein et al.*, 2015].

3.2. Future Climate

Figures 11 and 12 show the simulated changes in the area mean temperature and area mean precipitation for 2071–2100 compared to 1971–2000. All simulations reveal a temperature increase in both seasons and in all investigation areas with largest values simulated by the cclm4_s and smhi4_s simulations. The single simulations differ up to 3.2°C for the projected future warming.

In the AL area, the simulated ensemble mean temperature increase is 2.5°C in winter, being almost equal to the expected increase of 2.6°C in summer (Table 4). In the GAR area, the simulated temperature increases are marginally higher in summer. The PRUDENCE simulations performed with the A2 emission scenario indicated temperature increase in summer to be 1.5°C larger than in winter. Also the ClimChAlp investigation which considered a mixture of simulations applying B1, B2, A1B and A2 emission scenarios revealed larger temperature increases in summer than in winter. *Gobiet et al.* [2014] estimated from the ENSEMBLES simulations, based on the A1B scenario for the AL area, an increase range from 2.7°C in spring to 3.8°C in summer at the end of the century with an intermodel variation of 3°C.

Simulated future temperature increases in the smaller investigation areas are higher. In the northern area (UG1) and central area (UG2) the largest ensemble mean value increases are found with 2.6°C and 2.9°C in winter, while in the southern part (UG3) the largest increases of 2.9°C are simulated for summer (Table 4).

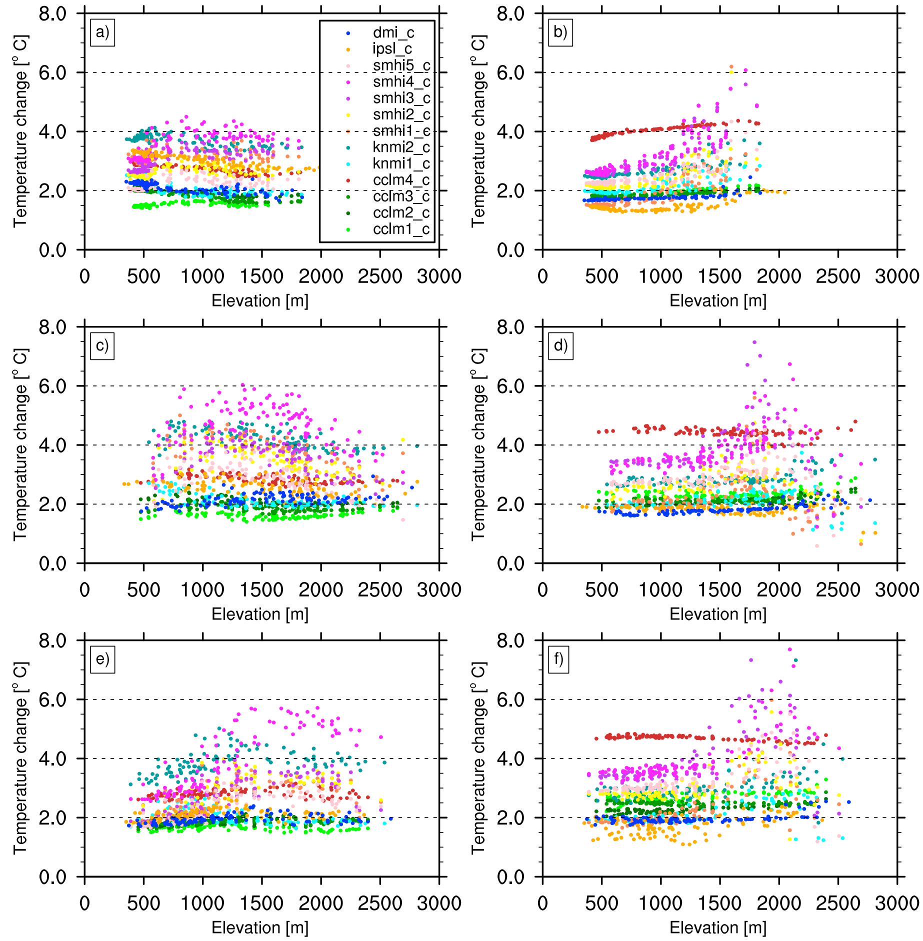

Figure 15. Elevation dependency of mean seasonal changes in 2 m temperature (MEA-T) 2071–2100 compared to 1971-2000 for the (a, c, and e) winter season and (b, d, and f) summer season. Investigation area UG1 (Figures 15a and 15b), investigation area UG2 (Figures 15c and 15d), and investigation area UG3 (Figures 15e and 15f).

In PRUDENCE, for the area AL as well as in ClimChAlp for the areas GAR, UG1, UG2, and UG3, all simulations indicated a summer precipitation decrease up to 40% in 2071–2100 compared to the period from 1961 to 1990. In their investigations with ENSEMBLES simulations, *Fischer et al.* [2012] found for Switzerland significant signals toward the end of the century with an expected summer precipitation decrease of 18 to 24%. *Gobiet et al.* [2014] estimated for the AL area at the end of the century a precipitation decrease of 20.4% in summer and a precipitation increase of 10.4% in winter. The investigated models disagreed with each other on the sign of the precipitation changes with largest agreement in the summer season. In the present investigation, the majority (23 of 39) of the investigated simulations indicates for the summer season precipitation increases with exception of the investigation area UG3. The ensemble mean values here are relatively small, ranging from −2% to +0.4%. Only in the investigation area UG3, a precipitation decrease in the order of 13% is simulated. These results imply that there is still a substantial uncertainty in the simulated changes in the transitional zone between northern and southern Europe, especially in the summer season. As in PRUDENCE and in ENSEMBLES, almost all simulations indicate a precipitation increase in the winter season. The ensemble mean values of 2071–2100 related to 1971–200 range from +8.7% in UG1 to +19% in UG2. The entire GAR area is likely to receive 12.3% more rain in the winter season.

Figure 13 shows the projected changes obtained for the number of wet days FRE-1 and the number of days with precipitation over 15 mm FRE-15. In general, there is a disagreement between the models on the sign of the change. In the areas GAR, AL, UG1, and UG2, only small changes in the range from −7.1% to + 5.9% in the ensemble FRE-1 mean can be found (Table 4). Only in the investigation area UG3, this value is larger in the summer season with a reduction of −13.1%. Projected changes in the FRE-15 value are larger with an

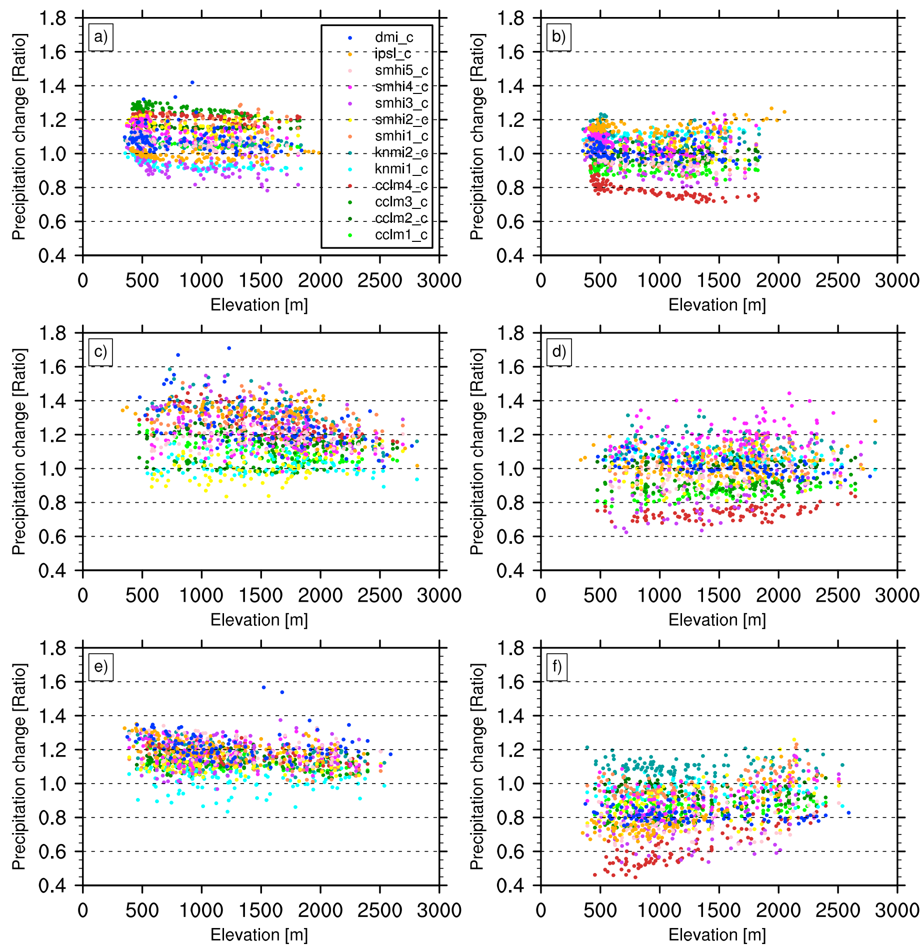

Figure 16. Elevation dependency of mean seasonal changes in mean precipitation (MEA-P) 2071–2100 compared to 1971–2000 for the (a, c, and e) winter season and (b, d, and f) summer season. Investigation area UG1 (Figures 16a and 16b), investigation area UG2 (Figures 16c and 16d), and investigation area UG3 (Figures 16e and 16f).

increased spread between the simulations. Large increases in the FRE-15 value of up to 26% are simulated for the smaller investigation areas in the winter season. In summer the ensemble mean values indicate only small changes in UG1 and UG2 but a decrease of −15.2% in UG3. In GAR and AL increases of up to 11.1% are projected for the summer season. In winter FRE-15 remains almost unchanged. In ClimChAlp all models indicated decreases in FRE-1 and FRE-15 in the summer season. In winter and in FRE-1 the situations remained unclear. In FRE-15 almost all simulations indicated increases with values of up to 50%. In ENSEMBLES no clear changes in the wet day frequency were found in winter, and a substantial decrease was projected for the summer season [*Rajczak et al.*, 2013; *Gobiet et al.*, 2014]. Despite the only moderate to small changes in the mean precipitation, the number of days with strong precipitation events was simulated to increase.

Projected changes in the 90% quantile on wet days Q90 show ensemble mean increases in all investigation areas and in all seasons with the only exception of UG3 in summer (Table 4). The majority of the simulations indicates increases in both summer and winter. Only in the investigation area UG3 that the trend remains unclear (Figure 14). In ClimChAlp, decreases were simulated for the investigation areas UG2 and UG3 in summer. In the winter season, simulations showed clearer increases. *Rajczak et al.* [2013] obtained in the investigation of the ENSEMBLES simulations increases in Q90 throughout the Alpine area in winter. In summer the results were rather unclear.

In ClimChAlp for 2071–2100 all simulations indicated an increase of the consecutive number of dry days XCDD in summer compared to the reference period from 1961 to 1990. In winter, the projections were unclear showing increases of up to 30% and decreases of up to 40%. In the present investigation (Figure 14) clear increases are only simulated in the investigation area UG3 in summer and also in UG1 in winter. The spread between the models is in all investigation areas comparatively large in all seasons. The ensemble mean values indicate increases in almost all investigations areas and seasons. Largest increases occur in the fall season for all investigation areas. The largest increase with up to 25.9% is simulated in the UG3 area. *Haslinger et al.* [2015] concluded from experiments with the CCLM model in the GAR area a higher probability of drought events in summer. *Gobiet et al.* [2014] reported, based on PRUDENCE and ENSEMBLES data, increased drought characteristic in the near and far future of which quantification is subject to substantial biases. *Jacob et al.* [2014] point out that possible decreasing length of extended dry spells is linked to an increasing number of all dry spells.

Based on the ENSEMBLES data, *Gobiet et al.* [2014] concluded in the projected 21st century climate change an anomalous warming at higher elevations. Altitudinal gradients in warming rates were observed in various mountainous regions, also in the European Alps. *Rangwala and Miller* [2012] examined possible mechanisms concluding, however, that there is not yet conclusive understanding of these processes. Our investigation gives rather a mixed picture. Pronounced elevations dependency can only be found in the shmi4_s simulation which is driven by HadGEM2-ES boundary data (Figure 15). *Kotlarski et al.* [2012] investigated elevation dependency in the CCLM model driven with HadCM3 boundary forcings. The authors conclude that near-surface warming in most parts of Europe significantly increases with elevation. Even though the already representative number of simulations analyzed in this research does not support this conclusion for the GAR, a more detailed look to the driving GCMs and a larger model ensemble would be needed to further clarify this issue. On the other hand, elevation dependency of the seasonal precipitation (Figure 16) is in agreement with the ENSEMBLES simulations, where no clear altitude dependence of the climate change signal was found [*Gobiet et al.*, 2014].

The findings of the present investigation in part disagree in the amount of future precipitation change in summer with previous SRES scenario based studies investigating expected future climate change in the Alpine area.

4. Conclusions

Simulations of 13 highly resolved RCM models run within the CORDEX initiative at 0.11° resolution with boundary forcings from four different CMIP5 global models applying the RCP4.5 scenario are employed to derive the future climate change signal for the Greater Alpine Regions (GAR) and four selected smaller investigation areas. The results show that the simulations are able to reproduce the major patterns of the Alpine climate. They reveal, however, still substantial biases in this complex terrain. Despite the increased spatial resolution of the model integrations, no significant gains in the quality of reproduction of the observed precipitation and temperature statistics compared to previous experiments can be identified.

Evaluation statistics include mean temperature and precipitation, frequency of days with precipitation over 1 mm and over 15 mm, 90% quantile of the frequency distribution, and maximum number of consecutive dry days. The evaluation for the period from 1971 to 2000 is performed against the E-OBS observational reference. In general, the simulations underestimate the seasonal mean temperature and overestimate the mean precipitation values. In GAR the ensemble seasonal mean temperature bias range from -0.8°C to -1.9°C. The bias in precipitation varies between +14.8% in summer and +41.5% in the winter season. Larger errors are found for further statistics and various regions.

Previous investigations indicated for the end of the century temperature increases in all seasons with largest values for summer season. Temperature calculations for 2071–2100 related to 1971–2000 in the GAR area show ensemble mean increases in the seasonal mean 2 m temperature of 2.5°C in fall and winter, 2.4°C in summer, and 1.9°C in spring. The spread between the single simulations is in the order of 3°C.

In the GAR area, precipitation is simulated to increase up to 12.3% in winter and 5.7% in spring, while only a mall increase of 2.3% in the ensemble mean is simulated in fall. In summer a small decrease in order of 1.7% is projected. This is partially different to previous experiments, where substantial precipitation decreases were simulated for the summer season.

The single simulations agree on the sign of the changes in winter, where only one model indicates decreasing precipitation. In summer seven models show future precipitation decrease and six models precipitation increase. Despite the comparatively small changes in the mean precipitation in summer, the ensemble mean values show increases of up to 10.9% in the number of days with precipitation over 15 mm and an increase of 10.9% in the number of maximum consecutive dry days.

The previous ClimChAlp investigation had concluded with the demand that further investigations should have been performed with RCMs that allow for resolutions finer than 10 km. The present investigation suggests that this might be not sufficient. Beside the increased spatial resolution further efforts are required in the improvement of model input, in providing adequate parameterization to the applied scales, and defining appropriate threshold values in the model physics. This is of special importance in the climate sensitive area of the European Alps.

Acknowledgments
This work was supported by the Bavarian Staatsministerium für Umwelt und Verbraucherschutz (StMUV), TKP01KPB-66747. The authors acknowledge the World Climate Research Programme's Working Group on Regional Climate and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System modeling, and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP). The authors acknowledge the E-OBS data set from the EU-FP6 project ENSEMBLES and the data providers in the ECA and D project (eca.knmi.nl).

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