Impact of Horizontal Resolution on Precipitation in Complex Orography Simulated by the Regional Climate Model RCA3*

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ABSTRACT

The hydrostatic regional climate model RCA, version 3 (RCA3), of the Swedish Meteorological and Hydrological Institute was used to dynamically downscale ERA-40 and the ECMWF operational analysis over a 22-yr period. Downscaling was performed at four horizontal resolutions—50, 25, 12.5, and 6.25 km—over an identical European domain. The model-simulated precipitation is evaluated against high-resolution gridded observational precipitation datasets over Switzerland and southern Norway, regions that are characterized by complex orography and distinct climate regimes.

RCA3 generally overestimates precipitation over high mountains: during winter and summer over Switzerland and during summer over central-southern Norway. In the summer, this is linked with a substantial contribution of convective precipitation to the total precipitation errors, especially at the coarser resolutions (50 and 25 km). A general improvement in spatial correlation coefficients between simulated and observed precipitation is observed when the horizontal resolution is increased from 50 to 6 km. The 95th percentile spatial correlation coefficients during winter are much higher for southern Norway than for Switzerland, indicating that RCA3 is more successful at reproducing a relatively simple west-to-east precipitation gradient over southern Norway than a much more complex and variable precipitation distribution over Switzerland. The 6-km simulation is not always superior to the other simulations, possibly indicating that the model dynamical and physical configuration at this resolution may not have been optimal. However, a general improvement in simulated precipitation with increasing resolution supports further use and application of high spatial resolutions in RCA3.

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1. Introduction

To accurately monitor precipitation and its changes at both regional and local scales, high-resolution observational and modeling systems are needed. In situ and remote sensing measurements provide information on precipitation amounts and types. These measurements, often spatially sporadic, may be combined using geostatistical methods into gridded precipitation data at locations with no measurements. It is expected that high-density in situ measurements over an area provide the best estimates of precipitation in such

gridded products. Generally, gridded datasets are of key importance for the evaluation of simulated precipitation obtained from meteorological and climate models.

Since climate models can simulate precipitation from a subdaily scale to the scale of hundreds of years, they are indispensable for analysis and for a better understanding of the processes that govern precipitation patterns and evolution at various spatial scales. While global climate models (GCMs) are suitable for simulating global and continental changes in precipitation, in regional climate models (RCMs) a higher spatial resolution helps to quantify additional information of local patterns and processes. A typical resolution in contemporary RCMs ranges from 10 to 50 km, thus approaching the resolution of convection-resolving models (e.g., Hohenegger et al. 2008; Kendon et al. 2012; Ban et al. 2014). Possible advantages in simulating precipitation and precipitation extremes, particularly in the coastal and complex orography regions (e.g., Grell et al. 2000; Seth et al. 2007; van Roosmalen et al. 2010; Rauscher et al. 2010; Di Luca et al. 2012), further motivates the use and development of RCMs. Consistent with numerical weather prediction, a tendency is seen in climate research to increase the RCM resolution, for example, in major projects concerning the modeling of European climate: a 50-km resolution was used for RCM simulations in the PRUDENCE project (Christensen and Christensen 2007), 25 km was used in ENSEMBLES (van der Linden and Mitchell 2009), and a 12.5-km resolution in the European domain of the Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX; Giorgi et al. 2009). Driving a hydrostatic version of a regional climate model up to its limit and beyond enables an evaluation that may be compared to nonhydrostatic models in the future. Nonhydrostatic RCMs at horizontal resolutions ≤ 10 km were recently applied over the Alpine region (e.g., Grell et al. 2000; Hohenegger et al. 2008; Suklitsch et al. 2011; Haslinger et al. 2013; Ban et al. 2014; Montesarchio et al. 2014). However, because of high computational demand, in the abovementioned studies, either relatively short model integrations were made or small-to-moderate sized domains were used. Nevertheless, they agree that relatively high spatial resolution should be used in regions with complex orography.

Neither model simulations nor observations are successful at depicting precipitation statistics in complex terrain realistically. Whereas the quality and realism of observational gridded precipitation products clearly increase with increased station density or satellite resolution (Mass et al. 2002), an increase in the model horizontal resolution may yield no improvements in

simulating precipitation correctly (e.g., Branković and Gregory 2001). Using an ensemble of nine RCMs, Rauscher et al. (2010) have shown, for example, that the skill of simulated summer precipitation over Europe was improved when the models' horizontal resolution was increased from 50 to 25 km. However, in the winter, when convective processes play a less active role, no such improvement was detected. Similar results were obtained by Kotlarski et al. (2014) in experiments using seven different RCMs. They found no clear improvement in seasonal-mean precipitation for various European regions when the horizontal resolution was increased from 50 to 12 km. On the other hand, van Roosmalen et al. (2010) documented an improvement in the mean monthly precipitation climatology over Denmark derived from an ensemble of the HIRHAM¹ RCM. In their simulations, the horizontal resolution was increased from 50 to 25 km, and further to 12 km, and precipitation from the 12-km experiment was the closest to the observations. In climate simulations with the HadGEM3-RA² model, Chan et al. (2013) documented a systematic reduction of the bias in winter orographic precipitation over the United Kingdom when the horizontal resolution was increased from 50 to 12 km. For the same set of experiments, Kendon et al. (2012) showed that simulated precipitation diurnal cycle was improved when the model resolution was increased. However, when the horizontal resolution was increased from 12 to 1.5 km, neither study reported any improvement in the mean climate.

Model estimates of precipitation can be evaluated by comparing model results against, for example, gridded observations. Gridded data have a practical advantage over in situ observations because they can be compared directly to model output on the same or similar horizontal-resolution grid. However, they still may contain errors and uncertainties due to either low station density over some areas or methodological constraints (e.g., Rubel et al. 2004; Hofstra et al. 2009; Kysely and Plavcová 2010; Isotta et al. 2014). Precipitation extremes in gridded datasets can be affected by insufficient station density and particularly by spatial representativity of measurements with respect to extreme events (e.g., Hofstra et al. 2009, 2010; Lenderink 2010). In addition to poor sampling, there are other problems related to gridded datasets in regions of complex orography. These include, for example, the undercatch during windy

¹ HIRHAM is an RCM based on 1) the dynamical core of the High Resolution Limited Area Model (HIRLAM) and 2) physical parameterizations from the ECHAM GCM.

² Limited-area version of the Hadley Centre Global Environmental Model, version 3.

episodes but also uncertainties in reconstruction algorithms for satellite data. Nevertheless, available gridded products with relatively high spatial resolution over regions with complex orography are crucial for evaluating RCMs (e.g., Frei et al. 2003; Isotta et al. 2014). The employment of such novel, highly resolved, gridded observational datasets enables model evaluation on those small scales that have rarely been done before. This supports model development, but it is also important for the providers of such datasets to liaise with their users with the aim of improving their products.

The aim of this study is to evaluate simulated precipitation from the third version of the Rossby Centre Regional Atmospheric Model (RCA3; Samuelsson et al. 2011) in experiments with horizontal resolutions of 50, 25, 12.5, and 6.25 km over a common European domain. The use of the same domain in our four experiments with different horizontal resolutions is a unique feature and an advantage of our study when compared to similar studies. RCA3 is widely used for downscaling simulations over various domains. It was employed in the ENSEMBLES project for Europe together with many other RCMs (Christensen et al. 2010). While the RCA3-simulated seasonal-mean precipitation over Europe is comparable with the ensemble mean of all ENSEMBLES RCMs (Christensen et al. 2010), RCA3 underestimates precipitation extremes (Kjellström et al. 2010), including those over the Alpine and Scandinavian subregions (Boberg et al. 2010). Furthermore, RCA3 generally overestimated precipitation in the summer and underestimated it in the winter at most locations of complex orography in the Croatian Adriatic region (Branković et al. 2013) and over the Slovenian Alpine region (Ceglar et al. 2015). Elucidating model errors supports multiple communities: model developers and climate modelers, as well as other activities in the climate research context, for example, development of bias adjustment techniques, uncertainty assessment, and so on.

Evaluation of the RCA3 precipitation is performed by using high-resolution gridded observations. We focus on two regions, Switzerland and southern Norway, where complex orography plays a dominant role in precipitation formation and its spatial distribution. The observational high-resolution gridded datasets used for model evaluation were the RhiresD dataset³ (MeteoSwiss 2011) for Switzerland, an approximately 2-km-resolution product of the Swiss National Meteorological Service (MeteoSwiss) available for the period

1961–present, and the KLIMAGRID dataset (Mohr 2008; METNO 2011) for Norway, a 1-km-resolution product of the Norwegian Meteorological Institute (METNO) available for the period 1957–present. Both datasets were used to evaluate precipitation from RCMs. For example, the RhiresD dataset was used by Ban et al. (2014) to evaluate the Consortium for Small-Scale Modeling in Climate Limited-Area Model (COSMO-CLM), which was integrated at the 2.2- and 12-km horizontal resolutions, whereas KLIMAGRID was used by Orskaug et al. (2011) to evaluate HIRHAM running at a 25-km horizontal resolution. In this study we assume that deviations of the gridded datasets from the actual observational values are smaller than the RCA3 model systematic errors discussed.

The layout of the study is as follows. The regional climate model RCA3 and the methodology of assessing the model's performance measures are described in section 2. In section 3 analysis and model evaluation over Switzerland and southern Norway are presented in terms of seasonal precipitation climatology, spatial variability, the 95th percentile, and annual cycles estimated from the gridded observed and simulated precipitation amounts. Section 4 summarizes the main results of the study.

2. Data and methodology

a. RCA3 model description and experiments

RCA3 is a hydrostatic limited-area model designed for regional climate studies. Its dynamical core includes the two-time-level, semi-Lagrangian, semi-implicit scheme (Unden et al. 2002; Jones et al. 2004). Parameterizations of subgrid processes include the tiled land surface scheme described in Samuelsson et al. (2006), the numerically efficient one-band longwave and one-band shortwave radiation scheme based on Savijärvi (1990) and Sass et al. (1994), subgrid-scale vertical mixing based on prognostic moist turbulent kinetic energy (Cuxart et al. 2000; Lenderink and Holtslag 2004) and a diagnostic mixing length following Bougeault and Lacarrere (1989), resolved (large scale) cloud microphysical and precipitation processes from Rasch and Kristjánsson (1998), and deep and shallow convection based on the entraining/detraining plume model of Kain and Fritsch (1990, 1993) and Kain (2004). Large-scale cloud fraction is diagnosed as a function of gridbox-mean relative humidity beyond a vertically varying threshold relative humidity for cloud onset (Slingo 1980). Convective cloud fraction uses the semiprognostic scheme of Xu and Randall (1996). Horizontal diffusion is explicitly a function of model horizontal resolution,

³ Technical description available online (http://www.meteoswiss.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-niederschlag/doc/ProdDoc_RhiresD.pdf).

while the Kain–Fritsch convection scheme also has resolution-dependent parameters influencing convective triggering and the CAPE closure scheme, respectively [for more details, see [Kain and Fritsch \(1990\)](#) and [Kain \(2004\)](#)]. Further details about the RCA3 model description and performance are available in [Samuelsson et al. \(2011\)](#). The RCA3 simulations of the European climate at a 50-km horizontal resolution are documented in detail in [Kjellström et al. \(2011\)](#) and [Nikulin et al. \(2011\)](#), while RCA3 at a 25-km resolution is compared with several other RCMs, for example, in [Christensen et al. \(2010\)](#) and [Branković et al. \(2013\)](#).

We analyze four RCA3 simulations with horizontal resolutions of approximately 50, 25, 12.5, and 6.25 km ([Table 1](#)) for the period 1987–2008. The corresponding orography at the abovementioned resolutions for southern Norway and Switzerland is shown in [Fig. 1](#).

In all simulations, the model was forced by ERA-40 ([Uppala et al. 2005](#)) from January 1987 to August 2002, followed by the ECMWF operational analysis ([Bechtold et al. 2008](#)) from September 2002 to December 2008. This 22-yr period overlaps with the common period for which the evaluation data (RhiresD and KLIMAGRID) and all four RCA3 simulations were available. Precipitation differences between the two periods as simulated by the model—that is, between ERA-40 and the ECMWF operational analysis—are generally comparable to the differences in the observational datasets for the same periods [cf. [Pryor et al. \(2012\)](#) for the discussion of wind climatology in the same simulations and between the two periods]. Although ERA-40 and the ECMWF operational analysis differ in spatial resolution and in the ECMWF model version, all four RCA3 simulations are treated in the same manner. The [Davies \(1976\)](#) relaxation method is applied in the eight-point wide boundary (buffer) zone. The updating frequency of the lateral forcing data was 6 h, with a linear interpolation in between.

The geographical domain ([Fig. 1](#)), the RCA3 model version, and 24 vertical levels remain the same in all four simulations. For all four resolutions considered, downscaling was applied directly from ERA-40 and the ECMWF operational analysis. The identical downscaling approach in all experiments enables a direct intercomparison of the model results for four different horizontal resolutions. Direct nesting and a resolution jump by a factor of 10 between forcing data and a limited-area model is generally acceptable in dynamical downscaling over regions where strong surface and topography forcing is present ([Beck et al. 2004](#)). However, a resolution jump between the ERA-40 (or ECMWF analysis) boundary conditions and the 6-km resolution as in our experiments, by a factor of approximately 23, may

TABLE 1. Model configuration. Model resolution and the ratio between the horizontal resolution of the forcing data and RCA3 (Ratio) are approximate; N_x and N_y denote the number of grid points in the longitudinal and latitudinal directions, respectively.

Resolution (km)	Resolution (°)	Ratio	$N_x \times N_y$	Time step (min)
50	0.44	2.8	85×95	30
25	0.22	5.7	170×190	20
12.5	0.11	11.4	350×380	10
6.25	0.055	22.7	710×760	7.5

not be beneficial for such a high model horizontal resolution. This factor is between 12, which [Denis et al. \(2003\)](#) have shown to be still appropriate for downscaling (for their RCM integrated at a 45-km resolution), and 24, for which they noticed a reduction in precipitation rates compared to those when the resolution changes were by a factor 1, 6, or 12.

From the same set of experiments considered here, [Walther et al. \(2013\)](#) evaluated the precipitation diurnal cycle over Sweden, and [Pryor et al. \(2012\)](#) studied the wind climate over the northern parts of Germany and Denmark. These studies have shown that an increase of spatial resolution from 50 to 6 km improved the simulation of the afternoon peak in the daily cycle of convective precipitation during the summer ([Walther et al. 2013](#)) and resulted in increased wind speed variability at synoptic time scales ([Pryor et al. 2012](#)). In the latter, a spectral analysis of the wind flow does not indicate numerical noise, which might be related to a large resolution jump between the lateral boundary data and the 6-km resolution.

The orography of Switzerland is characterized by the flat Central Plateau and the contrasting mountain ranges: a moderately high Jura in the northwest and the Swiss Alps, with many mountain peaks higher than 4000 m, occupying about half of the country in the south ([Fig. 1b](#)). Over southern Norway, a highly variable coastline with steep mountains dominates in the west; farther east, the mountains transform into a central high plateau and descend more gently into the eastern lowlands ([Fig. 1c](#)). For both Switzerland and southern Norway, the land surface features are much better characterized in higher-resolution than in coarse-resolution model experiments.

b. Gridded evaluation data

The basic steps in generating the gridded evaluation datasets RhiresD and KLIMAGRID used in this study are briefly outlined in the online supplemental material. These datasets represent the highest-quality high-resolution gridded precipitation data available over the two countries.

FIG. 1. (a) RCA3 domain and the GTOPO30 topography data (U.S. Geological Survey, <http://eros.usgs.gov/>); model orography over (b) Switzerland and (c) southern Norway; and (d) the GTOPO30-based masks for grid cells upscaled to 50-km resolution and with altitude higher than 1000 m over Switzerland and southern Norway.

c. Evaluation methods

Daily values of the high-resolution precipitation national datasets for Norway and Switzerland and model outputs at the 25-, 12-, and 6-km resolutions were aggregated (upscaled) to the coarsest RCA3 horizontal grid considered—that is, to approximately 50 km—by applying the first-order conservative remapping (Jones 1999; Chen and Knutson 2008; Gervais et al. 2014). This technique conserves the total area integral of the desired variable and it is assumed to be appropriate for analysis of precipitation fluxes at different resolution grids (e.g., Chen and Knutson 2008; Di Luca et al. 2012). By aggregating model data to the same (coarsest) resolution grid, model errors on higher grids become comparable with those of a coarser-resolution grid (e.g., Pryor et al. 2012).

For Switzerland, the analyzed area covers the whole country. In the case of Norway, we have focused on its southern half (for the purpose of our study, defined between 57.5° and 64.5°N and 4° and 15°E), where most of the country's stations are located [cf. Fig. 2 in Heikkilä et al. (2011)] and because it contains a reasonable number of grid boxes at the 50-km resolution. Furthermore, steep mountains along the western coastline of southern Norway have precipitation extremes among the highest in Europe. For example, in Brekke in Sogn (61°N, 5°E; station 52930 of the Norwegian Meteorological Institute) 5596 mm of rain was recorded in 1990. Because of its long and narrow shape, fewer stations are located in the northern half of Norway. In this region only between two and four grid boxes at the 50-km resolution cover the area from the coast to the Norwegian political border and therefore cannot be considered suitable for intercomparison of the upscaled data. In the coastal areas of Norway and in the border regions of both Switzerland and Norway, the gridcell values are weighted by taking into account the overlapping area between the 50-km grid and the grid of the high-resolution observations. Thus, if the real coastline is located inside a specific model grid cell, only the land-covered part of this grid cell is included when computing the area mean.

The following performance measures are shown and discussed.

- *Mean seasonal statistics*

Summer [June–August (JJA)] and winter [December–February (DJF)] means and the 95th percentiles (dry days included) are calculated from daily precipitation values for the observations and for the model fields for the period 1987–2008. We present relative differences between simulated and observed precipitation amounts [(RCA3 – OBS)/OBS,

respectively]. Statistical significance of mean seasonal absolute differences (i.e., RCA3 – OBS) when up-scaled to the coarsest model resolution grid is assessed using the Student's *t* test at the 0.05 significance level (e.g., von Storch and Zwiers 1999).

- *Spatial correlation coefficient*

Another estimate of the model's performance is based on spatial correlation coefficients computed from the model and observed precipitation fields.

- *Annual cycles*

Annual cycles of monthly total precipitation amounts are constructed from the 1987–2008 area-mean precipitation amounts.

- *Definition of the height mask*

We also analyzed the precipitation annual cycles for a specific orographic height range by defining the height “masks.” Because topographic heights for the RhiresD and KLIMAGRID datasets were not available, a high-resolution GTOPO30 orography dataset (USGS 1996) was upscaled to the coarsest 50-km model grid, and grid cells with an altitude equal to or higher than 1000 m were used to define the “1000-m mask.” The height mask was then applied to the different precipitation data at the 50-km-resolution grid. In this way, it is assessed how RCA3 with different horizontal resolutions simulates total precipitation for different orographic heights.

Some performance measures described above were also computed at the original model resolution grids other than 50 km, that is, at 25-, 12-, and 6-km grids (see online supplemental material). For this purpose, the RhiresD and KLIMAGRID data were also aggregated to the appropriate RCA3 horizontal resolutions.

3. Results and discussion

In this section, the main features of the winter and summer precipitation climate, spatial variability, extremes, and annual cycles are analyzed from the four different RCA3 resolution experiments. They are compared with the gridded observations over Switzerland and southern Norway.

a. Mean seasonal precipitation

1) SWITZERLAND

When compared with the observations, the simulated mean DJF precipitation (aggregated to the 50-km model grid) is, at all model resolutions, higher across central and southern Switzerland than in the central-southern (Ticino region) and northern parts of the country (Fig. 2). The largest overestimation is seen in the southwestern and

FIG. 2. DJF mean seasonal total precipitation over Switzerland. (top) The RhiresD (OBS) and RCA3 precipitation (increments of 2 mm day^{-1}). (middle) Relative errors (%) in the 50-, 25-, 12-, and 6-km RCA3 simulations when compared with the RhiresD. (bottom) The Student's t test at the 0.05 significance level with significant differences marked in red.

southeastern mountainous regions, where small observed amounts of $1\text{--}3 \text{ mm day}^{-1}$ are often more than doubled in the model. The area of overestimated precipitation varies from one resolution to the other: it is increased from 50 to 25 km and again from 12 to 6 km (Table 2). Part of the overestimation in model precipitation could be attributed to the undercatch, which in RhiresD was not corrected—unlike in the KLIMAGRID dataset—and is potentially present in the Swiss evaluation data. The undercatch occurs for both solid and liquid precipitation during windy episodes because of wind flow deformation near the observational field gauge (e.g., Neff 1977; Adam and Lettenmaier 2003). Frei and Schär (1998) found that in some cases the undercatch can reduce the total winter precipitation by up to 40%. This observational uncertainty implies that some positive biases in the modeled precipitation amounts, particularly in the mountainous regions where the undercatch is more pronounced, may

not be as substantial as shown in Fig. 2 (see also Fig. S.1 in the online supplemental material for more details of winter systematic errors at the original model resolutions).

The largest underestimation of precipitation in the winter, of approximately between -10% and -40% , is observed in the central southern part (Fig. 2, middle), which is the Swiss mountainous region most exposed to the influence of atmospheric flows from the Po River valley. Such an underestimation can be at least partly linked to the errors in the flow patterns over this region due to 1) differences between the (real) local orography and the RCA3 orography at different resolutions and 2) a higher-than-observed mean sea level pressure (MSLP) in all RCA3 simulations extending over the western and northern Mediterranean (not shown). In climatological terms, an erroneously high MSLP in the northern Mediterranean would act so as to potentially suppress the intensity or/and duration of the winter

TABLE 2. Fractions of the area (%) where the relative difference between mean seasonal simulated and observed precipitation D is $\geq 10\%$ and where relative differences are $\leq -10\%$. Values of the RCA3 output from the 25-, 12-, and 6-km simulations upscaled to the 50-km-resolution grid are marked in boldface. Values of the RCA3 output at original resolutions are in regular font.

Model resolution (km)	(a) Switzerland				(b) Southern Norway			
	DJF		JJA		DJF		JJA	
	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$
50	59.9	6.1	38.6	47.7	9.2	64.5	32.5	51.8
25	72.2	7.7	37.5	48.0	20.1	56.7	23.7	46.9
	76.6	5.3	39.7	56.5	18.0	59.6	20.6	49.8
12	54.6	19.6	39.9	31.3	5.9	75.0	23.4	42.6
	66.2	1.4	44.8	23.3	0.5	85.1	19.0	42.5
6	63.1	13.8	54.2	18.8	12.0	62.7	23.0	36.5
	81.0	4.7	61.0	3.5	5.3	68.0	20.8	32.3

TABLE 3. Spatial correlation coefficients between the mean seasonal precipitation simulated by RCA3 and the mean seasonal precipitation from observations. Coefficients of the RCA3 output from the 25-, 12-, and 6-km simulations and corresponding observations upsampled to the 50-km-resolution grid are marked in boldface. Coefficients of the RCA3 output at the original resolutions are in regular font.

Model resolution (km)	(a) Switzerland		(b) Southern Norway	
	DJF	JJA	DJF	JJA
50	0.34	0.11	0.82	0.09
25	0.53	0.17	0.94	0.42
	0.57	0.21	0.95	0.44
12	0.64	0.49	0.94	0.61
	0.71	0.50	0.97	0.60
6	0.62	0.62	0.90	0.70
	0.77	0.80	0.96	0.74

cyclogenetic effects in the Gulf of Genoa, which is a well-known regional feature (e.g., Trigo et al. 2002). A similar erroneous MSLP was also noted by Samuelsson et al. (2011) in their 50-km RCA3 experiment, which covers a different time period from the one considered here.

The model biases are, in general, statistically significant in the central part of the country and in the high-orography Alpine region (Fig. 2, bottom). The total area with statistically significant biases is the largest at the 25- and 6-km resolutions (around 65% of the country's total area). This is confirmed by the values in Table 2a, which shows a fraction of the total area with the precipitation error being larger than 10% or smaller than -10% relative to the observed amount, where 10% is taken as an arbitrary threshold of the

total precipitation relative error. Table 2a (DJF) shows that, the size of the area with positive precipitation biases is much larger at all horizontal resolutions than that with negative biases, suggesting that over Switzerland the model to a large extent overestimates precipitation relative to the observations.

From Fig. 2 and Table 2a it is not entirely evident that the increase in horizontal resolution generally yields an improvement, that is, a reduction of errors in the DJF climatology. However, an advantage of the increasing horizontal resolution in the model is indicated by an increase of spatial correlation coefficients between the mean simulated and observed DJF precipitation (Table 3a). From Table 3a (DJF), it is clear that the largest improvement is achieved when the model resolution is increased from 50 to 25 km. A further increase to the 12- and 6-km resolutions brings about an improvement as well, though not as marked as between the lower resolutions.

The simulated mean summer precipitation (Fig. 3) is at the coarser resolutions underestimated up to 50% or more in the northern and central parts of the country. In the south, over the high mountains, the positive sign of the error prevails with the error magnitude declining as the model resolution increases. Table 2a (JJA) shows that the fraction of the total area with negative relative precipitation errors is larger at the coarser resolutions than at the higher resolutions. The opposite, a larger fraction of positive errors, is seen at the higher resolutions: at the 6-km resolution, for example, positive bias prevails over 60% of the country's total area. The area of statistically significant JJA precipitation errors is much larger at the coarser resolutions than at the higher resolutions (Fig. 3, bottom). This possibly indicates the

FIG. 3. As in Fig. 2, but for JJA.

FIG. 4. As in Fig. 2, but for southern Norway and the METNO KLIMAGRID observations.

(inherent) difficulty of the coarser resolutions to accurately simulate summer precipitation over complex orography, which is partly influenced by convective processes. The largest improvement in simulating the spatial variability of summer precipitation over Switzerland is attained when the model resolution is increased from 25 to 12 and from 12 to 6 km—the spatial correlation coefficient is first increased from 0.21 to 0.50 and then from 0.50 to 0.80 (Table 3a, JJA). The summer systematic errors at the original model resolutions are shown in Fig. S.2 in the online supplemental material.

In the southern mountainous regions, the fraction of the model summer convective precipitation to the total precipitation (aggregated to the coarsest grid) is largest at the 50-km resolution, amounting to between 80% and 90% (Fig. S.5 in the online supplemental material). It gradually decreases as the model resolution increases and at 6 km it is between 30% and 50%. Such a high contribution of convective precipitation to total precipitation at coarser resolutions indicates that convective precipitation is “smeared” over much larger areas than would normally occur in reality. The overestimation of the total precipitation at coarser resolutions over southern regions seen in Fig. 3 (middle) is thus dominated by inadequately resolved convective precipitation.

2) SOUTHERN NORWAY

The RCA3 performance for southern Norway is presented by simulated seasonally averaged total precipitation and associated relative errors based on daily precipitation aggregated to the 50-km-resolution grid for DJF (Fig. 4) and JJA (Fig. 5). In the coastal regions, RCA3 underestimates the observed precipitation during DJF up to -60% at all horizontal resolutions considered

(Fig. 4, middle). As the model horizontal resolution increases, this underestimation extends deeper inland. On the other hand, over high orography and in the easternmost parts precipitation is overestimated, up to 30% on average. This overestimation is more pronounced at the coarser resolutions than at the higher model resolutions. A similar overestimation on the *lee* side of the Scandinavian mountains in the RCA3 50-km simulation was also documented in Samuelsson et al. (2011), whereas Heikkilä et al. (2011) and Mayer et al. (2015) detected an underestimation of precipitation on the *windward* side of the Norwegian mountains in their WRF⁴ and HIRHAM simulations, respectively, with horizontal resolutions ≤ 10 km.

Table 2b (DJF) confirms that, irrespective of resolution, an underestimation of precipitation is the main systematic deficiency of the winter precipitation over southern Norway. This deficiency is in contrast to what is seen for Switzerland (cf. DJF in Table 2a). The fraction of the total area with a negative (relative) precipitation error is the highest for the 12-km resolution, whereas for the other resolutions it is somewhat smaller and similar. This metric thus may indicate that the simulation of winter precipitation over southern Norway is not much improved with the increased RCA3 horizontal resolution. However, when analyzed at the original model resolutions, spatial distribution and positioning of observed local maxima do improve with the increased model resolution [Fig. S.3 (top) in the online supplemental material]. During DJF, these maxima in the

⁴The Weather Research and Forecasting Model (<http://www.wrf-model.org>).

FIG. 5. As in Fig. 4, but for JJA.

observations are most pronounced in the western coastal part and in the (western) mountainous windward regions. They are caused by the heavy precipitation brought in by moist Atlantic westerlies.

In JJA (Fig. 5), precipitation is again underestimated along the western coast but also over the southern regions. However, this underestimation is spatially less extensive than in DJF. The overestimation of precipitation dominates central-southern Norway and the easternmost parts, and it is more widespread than in DJF. In terms of the error amplitude, the 6-km resolution clearly shows an improvement relative to the coarser resolutions in simulating summer precipitation over the high orography of central-southern Norway. This is confirmed by a monotonous reduction of the area with statistically significant errors when the resolution increases (Fig. 5, bottom): from 82% of the region's total area at 50 km to 48% at 6 km. Such an improvement is associated with a better representation of convective precipitation in the high-resolution model: when model data are aggregated to the 50-km-resolution grid, the 6-km simulation has the lowest ratio of convective precipitation to total precipitation (Fig. S.6 in the online supplemental material). This ratio again indicates that a large overestimation of the total precipitation seen at the coarser resolution in Fig. 5 (middle) is mainly caused by an erroneous representation of convective precipitation.

The spatial correlation coefficients in Table 3b further confirm the abovementioned spatial analysis. The wintertime correlations are quite high, indicating that the physical causes of precipitation (the large-scale Atlantic westerlies) are well reproduced at all model resolutions. In the summer, when the westerlies are not dominant,

the correlation dramatically increases from 0.09 in the 50-km simulation to 0.74 in the 6-km simulation, implying an important benefit of the better resolved processes at local scales.

Some common features in precipitation biases emerge over both Switzerland and southern Norway in spite of different climate regimes over the two regions. RCA3 generally overestimates the total precipitation in high-orographic regions. This overestimation occurs during both winter and summer over Switzerland, and predominantly during the summer over southern Norway. In the summer, the contribution (fraction) of convective precipitation to the total precipitation over high orography is much larger at the coarser resolutions than at the higher resolutions. In addition, convective precipitation at the coarser resolutions also covers a much larger fraction of the total area of the regions considered. Thus, inadequate representation of convective precipitation, particularly at the coarser resolutions, is the main reason for markedly overestimated total summer precipitation over the high mountains of Switzerland and Norway.

b. Extreme precipitation: The 95th percentile

The largest precipitation amounts usually occur in regions with high orography, and it is important to assess the model's ability to simulate these observed extremes. In this section, the simulated 95th percentile of precipitation, determined from daily amounts, is assessed and compared with the 95th percentile derived from observed values, which is assumed here to be a proxy for observed precipitation extremes.

The distribution of the DJF errors in the 95th percentile over Switzerland is generally similar at all four

FIG. 6. The 95th percentile of the DJF total precipitation over Switzerland: (a) the MeteoSwiss RhiresD (OBS) and RCA3 (increments of 5 mm day⁻¹) and relative errors (%) in the 50-, 25-, 12-, and 6-km RCA3 simulations when compared with the RhiresD; (b) as in (a), but for JJA.

resolutions (Fig. 6a, bottom): a dry bias prevails in the northern parts and in the central south, whereas an overestimation of extreme precipitation is dominant in the central and southern regions. The dry bias in the north gradually decreases with increasing resolution, while the wet bias is smallest in the 12-km simulation. When the DJF 95th percentile errors in Fig. 6a (bottom) are compared with the errors in the mean precipitation (Fig. 2, middle), a general shift toward drier values can be seen: the dry bias in the 95th percentile is larger than that in the mean, and the wet bias in the 95th percentile is generally smaller than the wet bias in the mean. This is confirmed by higher values of the fraction of the total

area with the DJF precipitation error being smaller than -10% in Table 4a relative to Table 2a. However, regardless of the horizontal resolution, an overestimation of extreme precipitation by the model remains a main characteristic in Fig. 6a.

In JJA, a relatively strong dry bias in the 95th percentile dominates over a large portion of Switzerland at the 50-km resolution (Fig. 6b, bottom). This bias is gradually reduced as the resolution increases. In terms of area fractions, the JJA 95th percentile wet biases are smaller than those for the mean fields, particularly in the higher-resolution simulations (cf. JJA in Table 2a and Table 4a). This reduction of the wet biases in the

TABLE 4. As in Table 2, but for the 95th percentile of simulated and observed precipitation.

Model resolution (km)	(a) Switzerland				(b) Southern Norway			
	DJF		JJA		DJF		JJA	
	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$	$D \geq 10\%$	$D \leq -10\%$
50	44.7	41.5	32.0	47.7	1.2	93.2	16.1	64.3
25	49.3	21.7	32.8	53.1	2.2	81.6	4.3	73.9
	52.2	19.9	36.6	56.5	0.0	81.4	2.5	73.6
12	32.0	40.9	22.0	45.4	1.2	90.8	2.0	78.6
	33.7	23.9	16.7	34.7	0.0	95.8	0.0	78.6
6	41.2	29.4	23.5	39.7	6.2	78.5	2.0	79.7
	61.3	11.9	13.0	19.9	0.0	86.8	0.0	83.7

TABLE 5. As in Table 3, but for the 95th percentile of simulated and observed precipitation.

Model resolution (km)	(a) Switzerland		(b) Southern Norway	
	DJF	JJA	DJF	JJA
50	0.40	0.20	0.91	0.26
25	0.60	0.22	0.96	0.51
	0.64	0.23	0.97	0.52
12	0.67	0.50	0.92	0.63
	0.80	0.52	0.96	0.65
6	0.61	0.62	0.87	0.68
	0.81	0.83	0.94	0.78

95th percentile relative to the mean can be expected because extreme precipitation events are more localized and cover a smaller area than, for example, large-scale frontal precipitation events in both observations and simulations. The aggregation to the coarsest 50-km grid introduces additional smoothing of extreme precipitation events from the high-resolution simulations. Spatial correlation coefficients between the Swiss observed and simulated 95th percentiles are in both seasons similar to those for the mean fields (cf. Table 3a with Table 5a) and they are higher in the high-resolution simulations than in the low-resolution simulations. Thus, we may summarize that over Switzerland, the increase of horizontal resolution in

RCA3 can be considered beneficial for the 95th percentile precipitation.

Over southern Norway RCA3 reproduces reasonably well the spatial distribution of the 95th percentile winter precipitation (Fig. 7a, top). This is also seen by high correlation coefficients for all the resolutions (Table 5b). The winter spatial correlation coefficients for southern Norway are higher than those for Switzerland (cf. DJF values in Table 5b and Table 5a). These high correlations indicate that the model reproduces well a relatively simple observed spatial distribution of extreme precipitation over southern Norway, that is, the west-to-east gradient in precipitation over Norway is reproduced much better than a much more complicated and variable distribution over Switzerland. However, the amplitude of the 95th percentile over southern Norway is underestimated throughout the region.

During JJA, the model fails to reproduce the high values of the 95th percentile (e.g., when the precipitation amount is larger than 25 mm day^{-1}) over the western part of southern Norway in all resolution simulations (Fig. 7b, top). The spatial distribution of the 95th percentile errors is comparable to that of the mean errors (cf. Fig. 5, middle). However, the dry bias is now dominant. This overwhelming underestimation of the 95th percentile is clearly seen in Table 4b (JJA); at the higher resolutions, the dry bias covers about 80% of the region's total area. Over some areas in the mountains

FIG. 7. As in Fig. 6, but for southern Norway and KLIMAGRID data.

FIG. 8. Annual cycle of the total precipitation over (a) Switzerland, (b) southern Norway; annual cycle for orography higher than 1000 m for (c) Switzerland and (d) southern Norway.

an overestimation prevails, possibly indicating again that localized convective activity in the model is too strong.

c. Annual cycles

All precipitation values shown and discussed in this subsection are aggregated to the 50-km-resolution grid. The area-mean annual cycle of the observed total precipitation over Switzerland peaks close to 5 mm day^{-1} during the summer months (Fig. 8a). This recorded amount reflects the maximum in convection activity and its importance over central continental Europe. The

minimum of around 3 mm day^{-1} is reached in January. The RhiresD precipitation is generally overestimated by the model throughout the year, less in the summer, and more in the cold period of the year. The largest errors are seen at the 50-km resolution in the spring and early summer. The 6-km simulation is not always the best: from June to August, it is outperformed by both the 12- and 25-km simulations. This is also confirmed by the largest fraction of the area with positive JJA biases found for the 6-km simulation (Table 2a). Nevertheless, when compared with the observation, the 6- and 12-km

FIG. 9. Scatter diagrams of the summer convective and large-scale precipitation in RCA3 simulations over (a) Switzerland and (b) southern Norway upscaled to the common 50-km grid. The grid cells where the GTOPO30 orography upscaled to the 50-km grid is higher than 1000 m are marked by open red circles, while the grid cells below 1000 m are marked by open blue circles.

RCA3 simulations over Switzerland seem to capture well the month-to-month variations in the annual cycle.

The shape of the observed precipitation annual cycle for southern Norway (Fig. 8b) is almost the opposite of that for Switzerland. The maximum value of more than 6 mm day^{-1} is in January. The largest amounts of precipitation extend throughout the cold season, when strong North Atlantic westerlies are blasting over northern European shores. A gradual decrease in precipitation amounts to the minimum in May (3 mm day^{-1}) is associated with the weakening of the westerlies. The annual cycle is simulated reasonably well by RCA3 at all resolutions. However, the winter and autumn maxima are underestimated, which is in contrast to the results for Switzerland. The performance of the 6-km resolution cannot be distinguished from the other resolutions (cf. also Table 2b).

When considering precipitation amounts at Switzerland's high elevations—that is, at the 50-km grid cells with orography heights equal to or higher than 1000 m (Fig. 1d)—both observed and simulated annual cycles are shifted toward the higher amounts relative to the full area-mean values, that is, when all grid cells are included (cf. Fig. 8c and Fig. 8a). This is expected because more precipitation reaches the ground at higher altitudes than at lower altitudes, partly due to the orographic uplifting mechanism (e.g., Roe 2005); that is, in the high-orography regions, clouds and precipitation are formed more often, or persist longer, when relatively humid air ascends toward regions with the lower (surrounding) air temperature. The latent heat release, a condensation by-product in the orographic uplift, may further fuel convective instability and trigger the formation of

convective clouds and precipitation (e.g., Kotlarski et al. 2010; Williamson 2013).

From Fig. 8c it is clear that the model largely overestimates high-orography precipitation, more so for the coarser-resolution simulations than for the higher-resolution simulations. In terms of mean monthly amounts, the two higher-resolution simulations are quite similar. A relatively large model bias can be partly associated with a possibly inadequate representation of the high-altitude precipitation in the observations. Above 1000 m a relatively small number of measuring stations contribute to the gridded precipitation dataset because most stations in high mountains are located in the valleys. Such a station arrangement hampers the actual recording of precipitation maxima and contributes to (erroneously) reduced observed precipitation amounts in the mountains (e.g., Frei and Schär 1998). In addition, the undercatch, which is more pronounced in wintry conditions [see the discussion in section 3a(a)], also contributes to a reduced observed precipitation, particularly in regions with high orography.

Large biases seen in Fig. 8c during the warm part of the year could be, on the other hand, associated with the (possibly erroneous) representation of convective precipitation in the model high-orography regions, particularly at the coarser resolutions. In Fig. 9, the partitioning of the model total precipitation to its convective and large-scale components is shown for grid cells with an orographic height below 1000 m and for grid cells with an orographic height above 1000 m. Such partitioning was not possible for the observational data. For Switzerland, convective precipitation above 1000 m (open red circles in Fig. 9, top) at the 50- and 25-km resolutions increases

dramatically when compared with convective precipitation below 1000 m (open blue circles), whereas large-scale precipitation (described by the x axis) remains almost unchanged or increases only a little. Thus, a large overestimation of the total precipitation during JJA seen in Fig. 8c for the 50- and 25-km resolutions could be linked to such increased convective precipitation shown in Fig. 9 (top). At the higher resolutions, convective precipitation above 1000 m is also increased with respect to that below 1000 m, but this increase is markedly smaller than at the coarser resolutions.

When the 1000-m mask is applied over southern Norway, the model simulates the observed annual cycle reasonably well, but it overestimates the observed amounts, notably in the warm part of the year (Fig. 8d). This overestimation is, as for Switzerland, larger at the coarser resolutions than at the higher resolutions. This is in contrast to the full area-mean values (Fig. 8b), confirming again that most stations in this region are located in the low-elevation valleys (Mohr 2008).

Over southern Norway no clear differentiation of the summer convective and large-scale precipitation with respect to the 1000-m mask is found (Fig. 9, bottom), although a weak tendency of increased convection at terrain heights above 1000 m is indicated at the 50-km resolution. As for Switzerland, a reduction in the fraction of convective precipitation to the total precipitation as the model resolution increases is clearly seen in Fig. 9 (bottom). This again could be linked to a reduction of model precipitation error shown in Fig. 8d.

4. Summary and conclusions

In this study, the simulated total precipitation produced by the hydrostatic regional climate model RCA3 and integrated at four different horizontal resolutions is analyzed over the regions of Switzerland and southern Norway. These two regions have variable and complex orography, specific geographical locations in Europe, and quite different precipitation climate characteristics. The RCA3 simulations were performed by dynamically downscaling ERA-40 (for the period 1987–August 2002) and the ECMWF operational analysis (September 2002–08) at four horizontal resolutions—50, 25, 12, and 6 km—over a wider European domain. The identical model setup at the four horizontal resolutions provides a unique test of RCA3's ability to simulate precipitation climatology over regions of complex orography. The resolution-dependent model results are compared to each other in terms of climate mean, annual cycle, and extremes. They are evaluated against gridded high-resolution national precipitation data derived from observations and defined at 2 km for Switzerland and at

1 km for Norway. For comparison and evaluation purposes, all model outputs and gridded observational datasets were aggregated to the model's coarsest resolution (50 km). Although various assumptions in this model setup (scaling factor, scale-independent representation of physical processes, etc.) may have been applied beyond generally accepted limits, we were able to explore the impact of the increasing horizontal resolution on precipitation in a regional climate model in a strictly controlled manner.

The gridded precipitation data based on observations are still far from perfect (e.g., Kysely and Plavcová 2010). Over high orography, they could be underestimated for at least two reasons: 1) because of the undercatch, particularly in the winter; and 2) because most measuring stations in the high mountains are located in the valleys and may fail to record large precipitation amounts occurring at high altitudes (Frei and Schär 1998). Observational data for Norway are corrected for the undercatch, whereas for Switzerland they are not. Irrespective of possible observational data inadequacies, we may claim that the differences between modeled and gridded data (model biases) analyzed in this study are generally associated with model deficiencies. Nevertheless, over Switzerland and southern Norway, RCA3 does not generate the same precipitation error pattern and amplitude. For example, in DJF, RCA3 underestimates the mean precipitation over the mountains of southern Norway, but over the high ranges of the Swiss Alps an overestimation of winter precipitation is noted. This difference in the model winter biases can be also partly attributed to the fact that the Norwegian data are corrected for the undercatch, but the Swiss data are not. In the summer the model overestimates precipitation over the highest central-southern Norwegian mountains and the eastern lowlands, whereas for Switzerland the overestimation is found mostly over the mountains. The model overestimation of precipitation over the Swiss Alps, found in both winter and summer seasons, could be (partly) ascribed to the fact that the Swiss gridded observational data are not corrected for the undercatch and therefore are possibly underestimated.

The summer underestimation is widespread in the western and southern parts of southern Norway and in Switzerland it is mostly confined to the central and northern parts of the country, away from the Alps. The summer overestimation of precipitation over the Alps of southern Switzerland, particularly at the high altitudes of the coarser model resolutions, can be associated with a large increase of the fraction of convective precipitation to the total precipitation. Thus, it is difficult to summarize the error patterns common to both countries;

they depend on specific climate characteristics, defined mainly by the country's latitude, the prevailing seasonal circulation, and proximity to the sea, as much as on orographic features. Nevertheless, at the coarser resolutions the RCA3 convection parameterization scheme has a strong deteriorating impact on model biases over both domains.

Despite different climate regimes and uncertainties in the gridded evaluation datasets, some common resolution-dependent features for the two regions do emerge. Generally, an improvement in terms of the spatial correlation coefficient between the modeled and gridded evaluation data is found when the model horizontal resolution is increased. In the summer, for both total precipitation and the 95th percentile, this increase in spatial correlation is monotonous with the resolution increase, indicating the benefit of the higher model resolution in simulating small-scale precipitation phenomena, primarily convective precipitation. The winter spatial correlation is always higher at the 25-km resolution than at the 50-km resolution, but it does not necessarily increase with a further increase in horizontal resolution. This suggests that 25 km is the minimal resolution required to represent reasonably well the total winter precipitation over the two regions analyzed in this study. Correlation for the 6-km experiment during the winter is not always better than in the 12-km-resolution experiment, implying that the increase in the horizontal resolution should be achieved in parallel with improvements in other modeling aspects, such as dynamical core and advection schemes (e.g., Hohenegger et al. 2008; Ban et al. 2014). However, in terms of spatial correlation, summer precipitation, particularly over high orography, is always represented best in the 6-km-resolution simulation, in spite of RCA3 being a hydrostatic model. This is primarily due to a much better representation of convective precipitation at the highest resolution, seen as a reduction of the fraction of convective precipitation to the total precipitation. At the coarser resolutions, the fraction of convective precipitation to the total precipitation is much larger than at the higher resolutions, thus contributing to an overall overestimation of the modeled precipitation.

Regardless of the horizontal resolution, the expected increase of total precipitation amounts over high-orography regions (in our study above 1000 m) is much more pronounced in the model output than in the observations and can be possibly attributed to an overestimated orographic uplifting mechanism in the model. On the other hand, this mechanism may not be sufficiently intrinsic to the gridded observational data, because station locations in high mountains are often found in mountain valleys, where the orographic uplifting is

weaker or nonexistent (e.g., Frei et al. 2003; Isotta et al. 2014). Nevertheless, the gridded high-resolution observational datasets are crucial for evaluating high-resolution RCMs.

Since we have analyzed only one RCM, our results may be considered to some extent limited in their scope. A better insight into the added value of a higher resolution, particularly in reproducing extreme precipitation diagnostics, could be gained from multimodel investigations—for example, by comparing the EURO-CORDEX (e.g., Kotlarski et al. 2014) ensembles for the 0.11° horizontal resolution and for 0.44° resolution against each other. Although the gradual increase in the model horizontal resolution may not always bring about a gradual improvement in precipitation climate, annual cycle, and extremes (cf. Rauscher et al. 2010; Kotlarski et al. 2014), we conclude that the increase of the model horizontal resolution has an overall beneficial effect on total precipitation in the RCA3 simulations over Switzerland and southern Norway.

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