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# Local impact analysis of climate change on precipitation extremes: are high-resolution climate models needed for realistic simulations?

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**Abstract.** This study explores whether climate models with higher spatial resolution provide higher accuracy for precipitation simulations and/or different climate change signals. The outputs from two convection-permitting climate models (ALARO and CCLM) with a spatial resolution of 3-4 km are compared with those from the coarse scale driving models or reanalysis data for simulating/projecting daily and sub-daily precipitation quantiles. The high-resolution ALARO and CCLM models reveal an added value to capture sub-daily precipitation extremes during summer compared to the driving GCMs and reanalysis data. Further validation of historical climate simulations based on design precipitation statistics derived from intensity–duration–frequency (IDF) curves shows a better match of the convection-permitting model results with the observations-based IDF statistics. Results moreover indicate that one has to be careful in assuming spatial scale independency of climate change signals for the delta change downscaling method, as high-resolution models may show larger changes in extreme precipitation. These larger changes appear to be dependent on the climate model, since such intensification is not observed for the ALARO model.

## 1 Introduction

It becomes evident that climate change will increase the frequency and intensity of extreme events (IPCC, 2007, 2013). Therefore, the impacts of climate change on hydrological extremes such as heavy precipitation events have to be considered when designing and optimizing water infrastructures. The future projection of climate change impact on precipitation usually relies on the simulation results of General Circulation Models (GCMs). However, these results need to be validated against historical precipitation observations prior to any use for local impact studies of climate change. When GCM results are validated based on observations, sometimes large biases are observed especially for extreme precipitation values (van Pelt et al., 2012; van Haren et al., 2013; Tabari et al., 2015), imposing an uncertainty to the GCM projections for the future. The biases in the coarse-resolution GCMs come from the fact that they disregard some governing features of precipitation at local scale, next to the scale differences when comparing GCM results with local observations (Maraun et al., 2010; Willems et al., 2012). Some previous studies that attempted to assess GCM skill as a function of resolution showed that the performance of GCMs is independent of their resolution (Johnson et al., 2011; Masson and Knutti, 2011). However, given that deep convective phenomena are sufficiently resolved only at spatial resolutions down to less than about 4 km, such dynamical downscaling is expected to be one of the solutions for decreasing the systematic biases and narrowing the gap between GCM outputs and needs for fine-scale precipitation in hydrological and water engineering studies.

One of the methods to dynamically downscale GCM outputs is to drive a Regional Climate Model (RCM) using GCM as initial and boundary conditions. RCMs usually provide an improved description of surface features (topographical, land cover, etc.) and more complex description of atmospheric processes compared to GCMs. This often results in more realistic representation of precipitation variability and of climate feedback mechanisms (IPCC, 2001; Mearns et al., 2004; Christensen and Christensen, 2007; Mayer et al., 2015). Whatever climate models are used, verification of their results under the current climate is needed, because some high-resolution RCMs fail to adequately describe local-scale surface processes (especially in inhomogeneous regions with complex topography) due to the convective parameterization scheme or the characteristics of the GCM they are nested in (Hohenegger et al., 2008; Willems et al., 2012).

High-resolution (convection-permitting resolutions) climate models are of great added value to simulate large convective storms and mesoscale organization (Kendon et al., 2014; Prein et al., 2015). At these resolutions, deep convection is partly resolved and does not need to rely entirely on parameterizations. The representation of the daily cycle in precipitation, extreme events and spatial variability strongly improves for convection-permitting models (Kendon et al., 2012; Prein et al., 2013a, 2013b, 2015; Brisson et al., 2015; Ban et al., 2014, 2015, Fosser et al., 2015). However, their simulation for long time scales is restricted due to high computational costs. They are consequently mainly applied for numerical weather prediction (Done et al., 2004; Baldauf et al., 2011; Tang et al., 2013). First simulations for decadal time periods using convection-permitting models point to a stronger increase in extremes compared to coarser resolution integration, but the number of climate change impact studies with these models is limited so far (Hohenegger et al., 2008; Kendon et al., 2012, 2014; Prein et al., 2015).

The use of regional climate models for local impact studies of climate change on precipitation (totals or extremes) has been increased in recent years (e.g. Willems and Vrac, 2011; Olsson et al., 2012; Mearns et al., 2013; Rajczak et al., 2013). Nevertheless, in some studies, climate scenarios have been based on a broad set of coarse-resolution GCM results (Deng et al., 2013; Rana et al., 2014; Sun et al., 2015). Now, the question is whether high-resolution climate models truly improve extreme precipitation simulations, and if so, to what extent. This study intends to answer this research question by comparing high-resolution models (RCMs with resolutions between 40 and 3 km) with their driving GCM or reanalysis data for simulating sub-daily and daily precipitation quantiles. Further comparisons are performed for simulating design precipitation statistics derived from intensity–duration–frequency (IDF) curves.

Second research question considered, in case the high resolution climate models show improved extreme precipitation results, is whether this improvement in absolute precipitation values also significantly changes the

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relative climate change signal. Hydrological applications of climate change impact analysis often assume that the change factors, defined as the relative change from historical to future climate conditions, can be obtained from GCM or RCM simulations and applied for impact analysis at finer spatial scales. This is the case for any delta change or perturbation based statistical downscaling method (e.g. Ntegeka et al., 2014; Sunyer et al., 2015). In this study, the validity of this hypothesis is investigated by comparing the climate change signals on IDF statistics between the high and coarse scale resolution models. Central Belgium is considered as the study location.

## 2 Climate models

### 2.1 ALARO model

The ALARO-0 model is a high-resolution regional climate model developed by the Royal Meteorological Institute (RMI) of Belgium based on the numerical weather prediction model called Aire Limitee Adaptation Dynamique Developpement International (ALADIN). Hereafter, ALARO is used as shorthand name for the ALARO-0 model described in De Troch et al. (2013). The ALADIN model is the limited area model (LAM) version of the Action de Recherche Petite Echelle Grande Echelle Integrated Forecast System (ARPEGE-IFS). The physics parameterization package of the ALARO model was designed specifically for running at resolutions between 3 and 8 km. The specific characteristics of the Modular Multiscale Microphysics and Transport (3MT) convection scheme used in the ALARO model lead to a good multiscale performance, particularly in convection-permitting resolutions (De Troch et al., 2013). The ALARO simulations for the present climate conditions over Belgium were performed for the periods 1961-1990 and 1981-2010 at resolutions ranging from 40 km down to 4 km, both using a set of simulations forced with ERA-40 or ERA-Interim reanalysis as well as with the CNRM-CM3 GCM for the historical control run (Table 1). For the future climate projections (2071–2100), the CNRM-CM3 GCM under the A1B scenario was used to force the ALARO model (Hamdi et al., 2014).

### 2.2 CCLM model

The other high-resolution climate model used in this study is the COSMO-CLM (CCLM) model. The CCLM is a non-hydrostatic limited area climate model developed by the climate limited-area modeling (CLM) community. The CCLM model is based on the COSMO model (Steppeler et al., 2003), designed by the Deutsche Wetterdienst (DWD) for operational weather prediction. In order to perform climate simulations with the COSMO model, the CLM community provided extensions such as dynamic surface boundaries, a more complex soil model and the possibility to use various $CO_2$ concentration values (Böhm et al., 2006; Rockel et al., 2008).

The model settings are based on a previous study by Brisson et al. (2015), which provide recommendations for performing climate simulations at convection permitting scale. The one-moment microphysical parameterization includes a representation of graupel hydrometeors. In addition, the domain size of this simulation (192x175 gridpoints) is large enough to ensure that the analysis is not affected by the spatial spin-up described in Brisson et al. (2015). A three-step nesting strategy was applied with the driving data, either from ERA-Interim reanalysis data or the EC-EARTH GCM, forcing a CCLM at 25 km grid mesh size, which in turn forces a CCLM at 7 km grid mesh size, and next at the final 2.8 km grid mesh size. Model simulations were performed for the period 2001-2010, and a thorough evaluation of decadal statistics of precipitation, temperature and cloud characteristics was recently performed (Brisson et al., 2016). The CCLM driven by EC-EARTH was performed for the period 2000-2010 and 2060-2069 using the RCP4.5 emission scenario (Table 1). Hereafter, the driving GCM or reanalysis dataset is shown as subscript to the name of the RCM. As the control run of the EC-EARTH GCM ends in 2009, its data for the period 2000-2009 were used for comparing with the driven CCLM simulations.

## 3 Methodology

In this study, simulations of sub-daily and daily precipitation quantiles from the climate models are analyzed. For the future climate analysis, the climate change signals are obtained as relative changes of precipitation intensities calculated as the ratios of precipitation quantiles derived from each climate model scenario simulation over those from the corresponding climate model control simulation with same non-exceedance probability or return period. This methodology has been applied in several recent climate change studies, e.g. on the basis of statistical downscaling applying quantile mapping or quantile perturbations (Willems and Vrac, 2011; Gudmundsson et al., 2012; Maraun, 2013; Ntegeka et al., 2014; Rana et al., 2014; Sunyer et al., 2015) and also a similar procedure for analyzing decadal precipitation anomaly (Willems, 2013; Tabari et al., 2014; Tabari and Willems, 2016). Extreme precipitation is defined in this study as precipitation with return period (T) higher than 1 year and the return period is calculated empirically based on the rank of precipitation values (n/i, where n and i are the length of the study period and rank, respectively; i = 1 for the highest value).

In addition to the quantile analysis, the historical simulations of the climate models are validated based on precipitation intensity–duration–frequency (IDF) curves which are typically used for design storm calculations and related designs, e.g., urban drainage systems and hydraulic structures. The IDF curves for 1-month, 1-year and 10-year return periods and for durations from 10-15 minutes up to one month are developed for the control runs of the climate models as well as the observations. The IDF curves are derived based on Peak Over Threshold (POT) extreme value statistics after calibration of two-component exponential distributions, following Willems (2000). In this paper, the precipitation intensities of given return periods are referred to as design precipitation quantiles.

For the climate models, precipitation data are extracted for the model grid cell covering Uccle station in Central Belgium. This station is selected because it has high quality 10-min observations recorded with same instrument since 1898 (Demarée, 2003). In addition to the 10-min station observations, daily E-OBS gridded data (v12.0, Haylock et al., 2008) for 27.8 km and 55.7 km are used. These gridded data are aggregated to larger pixels of 167 km and 334 km to be consistent with the grid mesh size of the driving GCMs and reanalysis data.

## 4 Validation of precipitation simulations

The capability of the climate models to simulate the present-day precipitation is evaluated before investigating future precipitation changes. The validation of the daily precipitation quantiles simulated by the ALARO and the CCLM convection-permitting models and their boundary conditions based on the point and pixel interpolated Uccle observations for the summer season (June-July-August: JJA) is shown in Fig. 1. This is done for the historical model simulation periods 1961-1990 for ALARO and 2001-2010 for CCLM. The results reveal that the $ALARO_{ERA40}$ model overestimates the observed summer extremes. The extreme simulations of the $ALARO_{CNRM\text{-}CM3}$ model with 4 km resolution are in between the point observations and the gridded ones with a grid size of 27.8 km which shows good accuracy of these simulations. The CNRM-CM3 GCM and ERA40 reanalysis data used as the boundary conditions of the ALARO model show a systematic underestimation especially for the higher return periods. This confirms the finding that higher resolution results in more extreme precipitation in climate models (Jacob et al., 2014).

As for the CCLM model (Fig. 1), the simulations of summer extremes for 2.8 km resolution are nearly unbiased for the events with $T > 2$ years. The increasing skill of RCMs with increasing model resolution for simulation of the spatio-temporal characteristics of summer precipitation has also been found by using the high-resolution models, although limited in application (Rauscher et al., 2010; Kendon et al., 2012). For $T < 2$ years, the CCLM model tends to underestimate the summer precipitation extremes particularly for the runs with coarser resolutions. These underestimations for lower T appear to be explained by underestimations in the EC-EARTH GCM and ERA-Interim reanalysis rather than in the CCLM model itself.

As the difference between climate model outputs and observations may be partly attributed to the spatial scale difference, the extreme precipitation (averaged over the extreme events with $T > 1$ year) simulations of the climate models versus spatial scale for both summer and winter seasons are shown in Fig. 2. Taking the spatial scale difference into account and averaging the extreme values with $T > 1$ year, the $ALARO_{ERA40}$ simulations are closer to the observations compared with the $ALARO_{CNRM\text{-}CM3}$ model. Decease in systematic biases in the large-scale climate in reanalysis-driven RCM simulations was also reported by Maraun et al. (2010). They also pointed out that these RCMs are capable of reproducing the actual day-to-day sequence of weather events. The great ability of the CCLM model, large underestimations of CNRM-CM3, EC-EARTH and ERA40, and slight overestimation of ERA-Interim data for summer precipitation extremes are also obvious from these plots. As expected, the percentage bias of the climate models decreases as the time scales get larger (i.e., weekly and monthly).

The validation of the climate model simulations for the summer season in terms of IDF statistics is shown in Fig. 3 for time scales in the range between 10-15 minutes and 30 days. The IDF curves are plotted with reference to design precipitation intensities from the station and E-OBS pixel data over the Uccle location (Central Belgium). Comparing the hourly simulations of the $ALARO_{ERA40}$ model with different resolutions shows the greater intensities for finer resolutions. In terms of accuracy, most of the ALARO runs underestimate the station observations and overestimate the gridded observations (extrapolated). Regarding 3- and 6-hourly time scales, the ALARO model simulates more intense precipitation of 10-year return period in comparison to both the station and gridded observations. The model underestimates (overestimates) design storms of 1-year return period and 3- and 6-hourly durations when compared with the station (gridded) observations. For larger time scales, design precipitation is still overestimated by most of the ALARO runs.

The CCLM model simulates less intense 15-min precipitation of 10-year return period (Fig. 3). However, this underestimation changes to overestimation for larger sub-daily aggregation levels. For the sub-daily design storms of 1-year return period, the CCLM model generally underestimates the station observations, while both over- and underestimations are seen in comparison with the gridded observations. However, the EC-EARTH GCM extremely underestimates both the gridded and raingauge observations. This supports the recent findings for underestimation of heavy hourly precipitation during summer by large scale climate models and more accurate simulations of convection-permitting models (Chan et al., 2013, 2014; Ban et al., 2014; Fosser et al., 2015). In the case of daily to monthly durations which are less important for urban drainage and hydraulic structure design, the precipitation intensities are both overestimated and underestimated by the CCLM model.

For the winter season (December-January-February: DJF), the results show overestimations of the ALARO and CCLM models (Fig. 2). As winter precipitation over Belgium is mainly controlled by large scale circulation, an improvement in the simulations of convection-permitting models in comparison to the parent large scale models is less expected for the winter season. Although improved simulations of winter precipitation by convection-permitting model have been reported for regions with complex topography (Ikeda et al., 2010; Rasmussen et al., 2011) due to better resolved orography (Prein et al., 2015), this effect is less relevant for Belgium which is more flat.

Whereas winter daily precipitation extremes are systematically overestimated by the ALARO model, the driving CNRM-CM3 GCM and ERA40 reanalysis data slightly underestimate the winter extremes (Fig. 2). Deficiency of very high resolution climate models in simulation of winter precipitation extremes is because the fronts and synoptic depressions that cause the dynamical processes driving winter precipitation events have scales of $10^2$-$10^3$ km. This deficiency has been demonstrated by Hong and Leetmaa (1999) and Chan et al. (2013). For the CCLM model, when the $\mathrm{CCLM}_{\mathrm{EC\text{-}EARTH}}$ 2.8 km simulations are compared with those of the $\mathrm{CCLM}_{\mathrm{ERA\text{-}Interim}}$ 2.8 km for the winter extremes, the overestimations of the earlier run is higher than the later one which can be attributed to a large overestimation of the EC-EARTH GCM results taken as the boundary conditions.

After validation of design precipitation simulations by the convection-permitting models for summer and winter seasons separately, further analysis was performed in the framework of IDF relationships, considering the extremes for all seasons as usually done for developing design standards (Fig. 4). Based on this analysis, the $\mathrm{ALARO}_{\mathrm{ERA\text{-}Interim}}$ model underestimates hourly design precipitation derived from the IDF curves based on the station observations. Although sub-daily gridded precipitation are not available, by imaginary extending the IDF curves for the daily gridded data still a small underestimation of the $\mathrm{ALARO}_{\mathrm{ERA\text{-}Interim}}$ simulated hourly design precipitation can be noted. In the case of 3- and 6-hourly design precipitation, the $\mathrm{ALARO}_{\mathrm{ERA\text{-}Interim}}$ model provides closer results to the existing IDF curves and probably a slight overestimation in comparison with the gridded data. As for the daily time scale, the $\mathrm{ALARO}_{\mathrm{ERA\text{-}Interim}}$ simulates larger precipitation intensities compared to the $\mathrm{ALARO}_{\mathrm{CNRM\text{-}CM3}}$ model and the ERA-Interim reanalysis. For aggregation levels between 5 days and 1 month, the difference between the model simulations is smaller except for the CNRM-CM3 GCM with a remarkable underestimation.

For the CCLM model, the 2.8 km run tends to underestimate the precipitation intensities at 15 and 30 minutes, which are typically used for sewer and drainage system design. For instance, for a storm of 10-year return period and 15-min duration, this underestimation can be up to 63 mm/h. Although this underestimation may be partially due to spatial scale difference, in practice IDF curves based on station observations (and not gridded observations) are typically used for the design of hydraulic structures. For sub-daily durations (hourly, 3-hourly and 6-hourly), design precipitation intensities are underestimated by almost all the CCLM model runs except for some 2.8 and 7 km runs. In the case of daily to monthly durations, the precipitation intensities simulated by the models are very close to each other. No improvements in the simulations of daily mean precipitation by the convection-permitting models compared with large scale climate models were reported by Chan et al. (2013) and Fosser et al. (2015), while some other researchers found improvements especially over mountainous areas (Prein et al., 2013b; Ban et al., 2014), implying region and model dependency for simulation of daily mean precipitation. Nevertheless, it can be concluded from the IDF plot (Fig. 4) that design precipitation intensities are overestimated by the driving ERA-Interim reanalysis data and underestimated by the driving EC-EARTH GCM. The underestimation of sub-daily precipitation by the EC-EARTH GCM is remarkable.

## 5 Future precipitation changes

To cope with the scale difference and the biases shown in the previous section, state-of-the-art climate change impact analysis makes use of statistical downscaling. One of the popular downscaling methods is the delta change method. Different versions exist for that method: from the simple basic method to more advanced methods such as the quantile perturbation method. In this type of methods, the intrinsic assumption is made that the bias under future climate conditions is identical to the bias in current climate conditions. This is implemented through the use of "change factors" applied for historical precipitation quantiles. Another important assumption that is made by these methods is that the change factors are spatial scale independent, such that the scale difference, although it is an issue for the absolute precipitation intensity values, is less an issue for the delta change methods at which relative changes are applied. The latter assumption is tested next. In this context, the relative changes in precipitation quantiles between the future and historical simulations of climate model runs were calculated to compare the convection-permitting models and their driving GCMs. These change factors were computed for winter and summer seasons as sub-daily and daily precipitation quantiles from the scenario period divided by those from the control period with the same return period (change factor equal to one means no change).

The change factors in precipitation extremes for winter and summer seasons computed by the $ALARO_{CNRM\text{-}CM3}$ model are shown in Fig. 5. The $ALARO_{CNRM\text{-}CM3}$ projects an increasing signal in the range of 14% to 74% for winter, implying a substantial wetter winter. A drier summer is expected from the $ALARO_{CNRM\text{-}CM3}$ model projections with a decreasing signal down to -23%. When the change factors computed for $ALARO_{CNRM\text{-}CM3}$ are compared with those obtained from the driving CNRM-CM3 GCM, more or less the same conclusion can be made: an increasing signal for winter between 17% and 61% and a decreasing signal for summer which goes as low as -18%. Generally, it can be inferred from the results that, at synoptic (daily) scale, the projections by the ALARO model are consistent with those from the driving GCMs. De Troch et al. (2013) pointed out that an increase in spatial resolution in the ALARO model is not as important as the parameterization scheme used for extreme precipitation modeling at daily scale.

Fig. 6 shows change factors for daily and 3-hourly precipitation computed using the $CCLM_{EC\text{-}EARTH}$ model with different spatial resolutions for winter and summer seasons. The change factors for all extreme events with T > 1 year are shown in this figure. To simplify the interpretation of the results, the change factors for extreme precipitation averaged over the extreme events with T > 1 year versus the models' spatial scale are presented in Fig. 7. For the winter season, the change factors for both daily and 3-hourly precipitation decrease as the model's resolution increases. Nevertheless, the change factors for all the CCLM runs are higher than those for the driving EC-EARTH GCM. A larger change is projected for 3-hourly precipitation compared with daily precipitation. For summer, the change in 3-hourly precipitation obtained from the $\mathrm{CCLM}_{\mathrm{EC\text{-}EARTH}}$ 2.8 km run is greater than that from the $\mathrm{CCLM}_{\mathrm{EC\text{-}EARTH}}$ 7 and 25 km runs, while the pattern for the daily time scale is similar to that of the winter season: decreasing change factors with increasing the model's resolution. Similar to winter, the results show an amplification of the future climate change signals for 3-hourly extremes in the CCLM 2.8 km model compared with the driving EC-EARTH GCM (18% average relative changes for the $\mathrm{CCLM}_{\mathrm{EC\text{-}EARTH}}$ 2.8 km run versus 6% change for the EC-EARTH GCM). This amplification is not evident for the daily scale. Intensification of change in sub-daily precipitation extremes that are not simulated by large scale models was also found by Kendon et al. (2014). The results also reveal that sub-daily precipitation extremes during summer are expected to change at a higher rate compared to daily extremes. Generally, it can be inferred that there is an increase in the change factors of sub-daily precipitation when going from parameterized convection to the convection-permitting scale.

## 6 Concluding remarks

A comparative study between the convection-permitting climate models with a spatial resolution from 2.8 km up to 40 km and driving GCMs or reanalysis data was performed to check whether the models with higher resolution provide more accurate precipitation simulations. Another analysis was performed to validate the spatial scale independency assumption of climate change signals for the delta change downscaling method. The results show that whereas winter daily precipitation extremes are generally overestimated by the ALARO and CCLM models, improved (unbiased) results for summer precipitation extremes are observed. This suggests the added value of convection-permitting climate models to simulate summer extremes because of either better representation of deep convection or larger detail of the land surface. The results moreover indicate that the difference between the convection-permitting models and the parent GCMs or reanalysis data decreases as the time scales get larger (i.e., weekly and monthly). Based on the precipitation statistics derived from IDF curves, the ALARO and CCLM models mostly underestimate sub-daily precipitation, but still better simulate it compared with parent GCM or reanalysis data when available. For summer IDFs, higher precipitation intensities are simulated by finer resolution models as a result of better representation of small-scale convective precipitation by these models.

To investigate whether or not the climate change signals from the convection-permitting models are more or less the same as those from the large scale driving GCMs, the relative changes were computed for precipitation extremes during summer and winter. For the ALARO model, it can be concluded that, at synoptic (daily) scale, the change factors for the ALARO model are comparable with the ones from the driving CNRM-CM3 GCM. In the case of the CCLM model, the results reveal an intensification of climate change signals for the CCLM model compared with the driving EC-EARTH GCM, for both 3-hourly and daily time scales for winter and sub-daily scale for summer. In a similar pattern, the change factors of 3-hourly summer precipitation extremes for the $\mathrm{CCLM}_{\mathrm{EC\text{-}EARTH}}$ 2.8 km run are larger than those from the 7 and 25 km runs. Comparing change factors for 3-hourly and daily precipitation, a larger change is projected for 3-hourly precipitation for both winter and summer seasons.

In summary, because the results of this study indicate that the summer extreme precipitation simulations of the high-resolution climate models are closer to the observations, their future projections are expected to be more accurate than those of the driving GCMs. These climate change signals obtained from the high-resolution models may differ from the ones based on the coarse-resolution models. However, the resulting precipitation change from these high-resolution climate models should not be interpreted as an exact number because of their limited number. More runs with high-resolution models are required to check the consistency among models. In the same way as an ensemble approach on climate models provides uncertainty estimates on the climate change signals, an ensemble of the high-resolution models provides uncertainty estimates on the difference between the climate change signals of fine versus coarse scale as a result of improved representation of complex landscape and land surface processes, which may provide more realistic statistics of precipitation including extremes for regional hydrological modeling. Also, the statistical significance of the difference in climate change signals at fine versus coarse scale can be tested in such approach. From the comparison in this study, the results of the $CCLM_{EC\text{-}EARTH}$ model indicate an increase in the change factors in summer when going from parameterized convection to the convection-permitting scale. This is different for the ALARO model, where the higher resolution models show changes in the same range as the coarse resolution models. Different procedures for convection parameterization in the CCLM and ALARO models and different boundary conditions (the first one is nested in the EC-EARTH model from CMIP5 and the later in the CNRM-CM3 model from CMIP3) might explain the discrepancy between the results of the two models.

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**Table 1** The convection-permitting model runs used in this study.

| Climate model | Driving GCM/reanalysis | Spatial scale (km) | Temporal scale | Control period | Scenario period | Data coverage |
|---|---|---|---|---|---|---|
| CCLM | ERA-Interim | 2.8 | hourly | 2001-2010 | - | whole year |
| | ERA-Interim | 7 | hourly | 2001-2010 | - | whole year |
| | ERA-Interim | 25 | hourly | 2001-2010 | - | whole year |
| | EC-EARTH | 2.8 | 15 min[1] | 2001-2010 | 2060-2069 | whole year |
| | EC-EARTH | 7 | hourly | 2001-2010 | 2060-2069 | whole year |
| | EC-EARTH | 25 | 3 hourly | 2001-2010 | 2060-2069 | whole year |
| ALARO | ERA-Interim | 4 | hourly | 1981-2010 | - | whole year |
| | ERA40 | 4 | daily | 1961-1990 | - | whole year |
| | CNRM-CM3 | 4 | daily | 1961-1990 | 2071-2100 | whole year |
| | ERA40 | 4 | hourly | 1961-1990 | - | summer |
| | ERA40 | 10 | hourly | 1961-1990 | - | summer |
| | ERA40 | 40 | hourly | 1961-1990 | - | summer |

[1] $CCLM_{EC\text{-}EARTH}$ 2.8 km data for the scenario period are available for hourly time scale.

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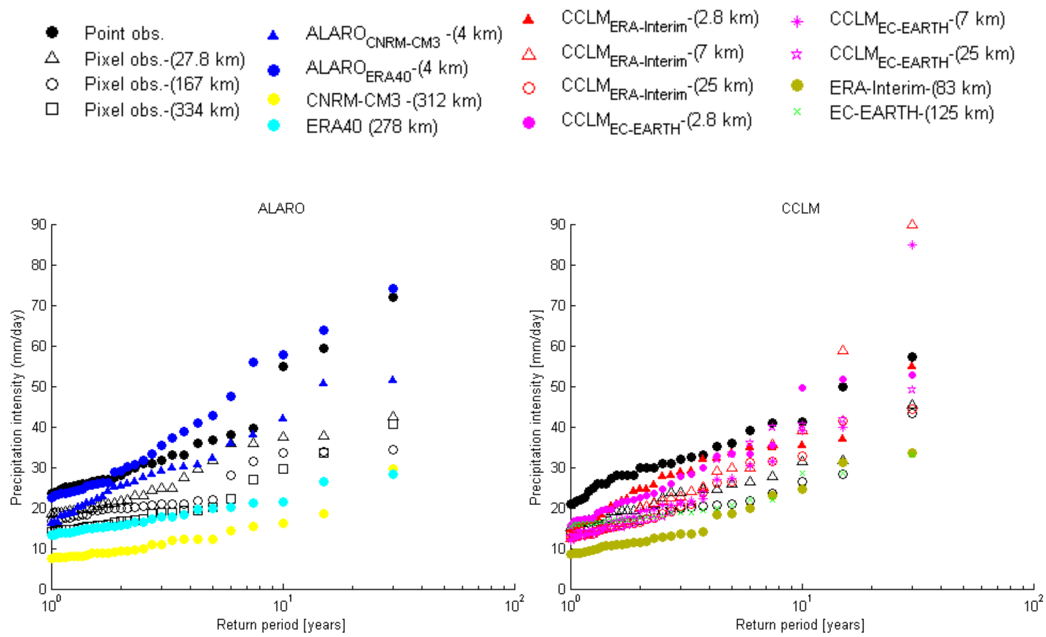


**Figure 1**. Validation of the daily precipitation quantiles for the ALARO (left) and CCLM (right) models and their driving GCMs or reanalysis data based on point and pixel interpolated Uccle observations, for summer season (historical climate: 1961-1990 for ALARO and 2001-2010 for CCLM).

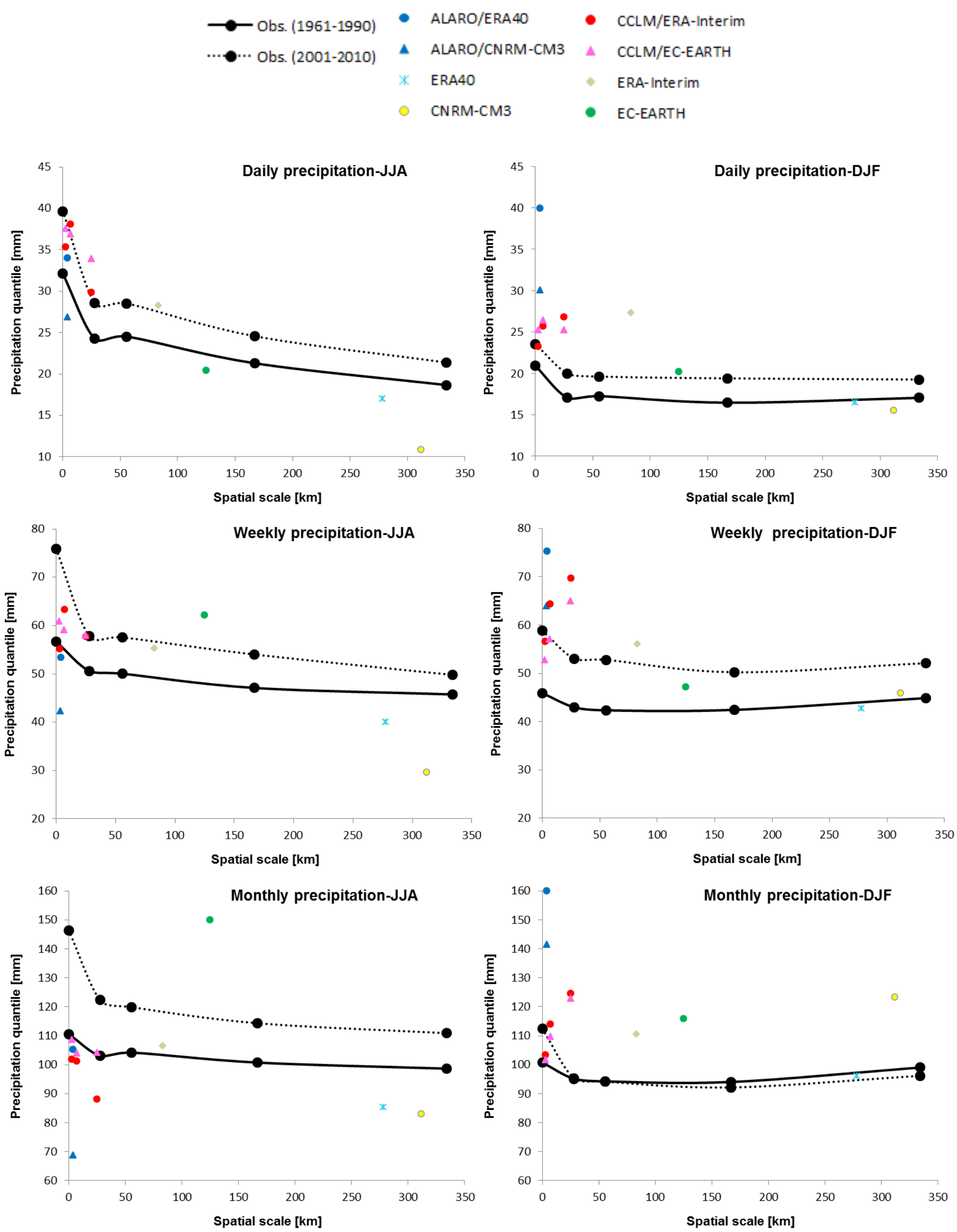


**Figure 2.** Validation of the extreme precipitation (averaged over the extreme events with T > 1 year) simulations for the ALARO, CCLM and the driving GCMs or reanalysis data based on point and pixel interpolated Uccle observations for summer (left) and winter (right) seasons, versus the models' spatial scale.

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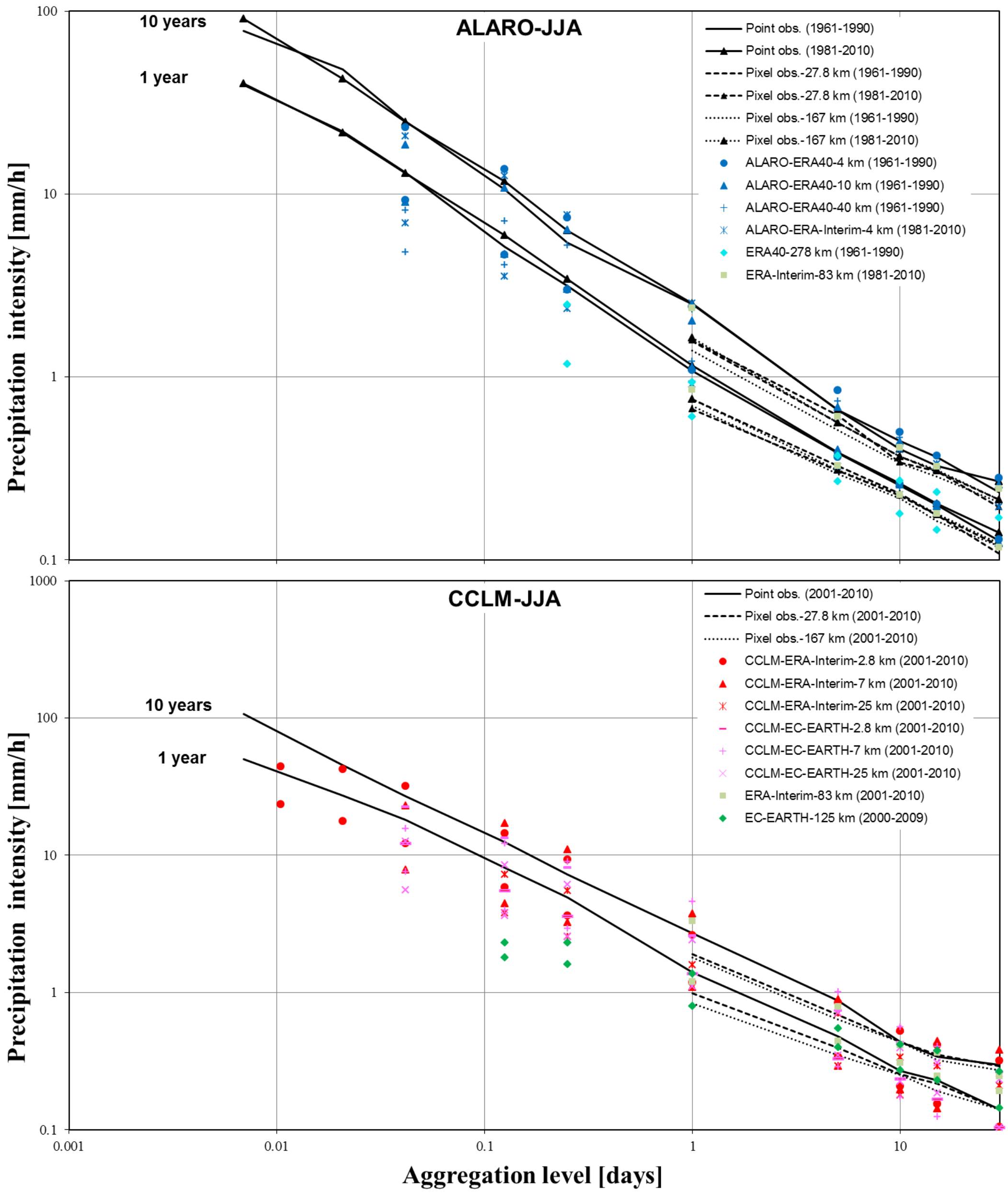


**Figure 3.** Comparison of historical IDF-relationships based on point and pixel interpolated Uccle observations, with the CCLM, ALARO and the driving GCM or reanalysis results for summer season.

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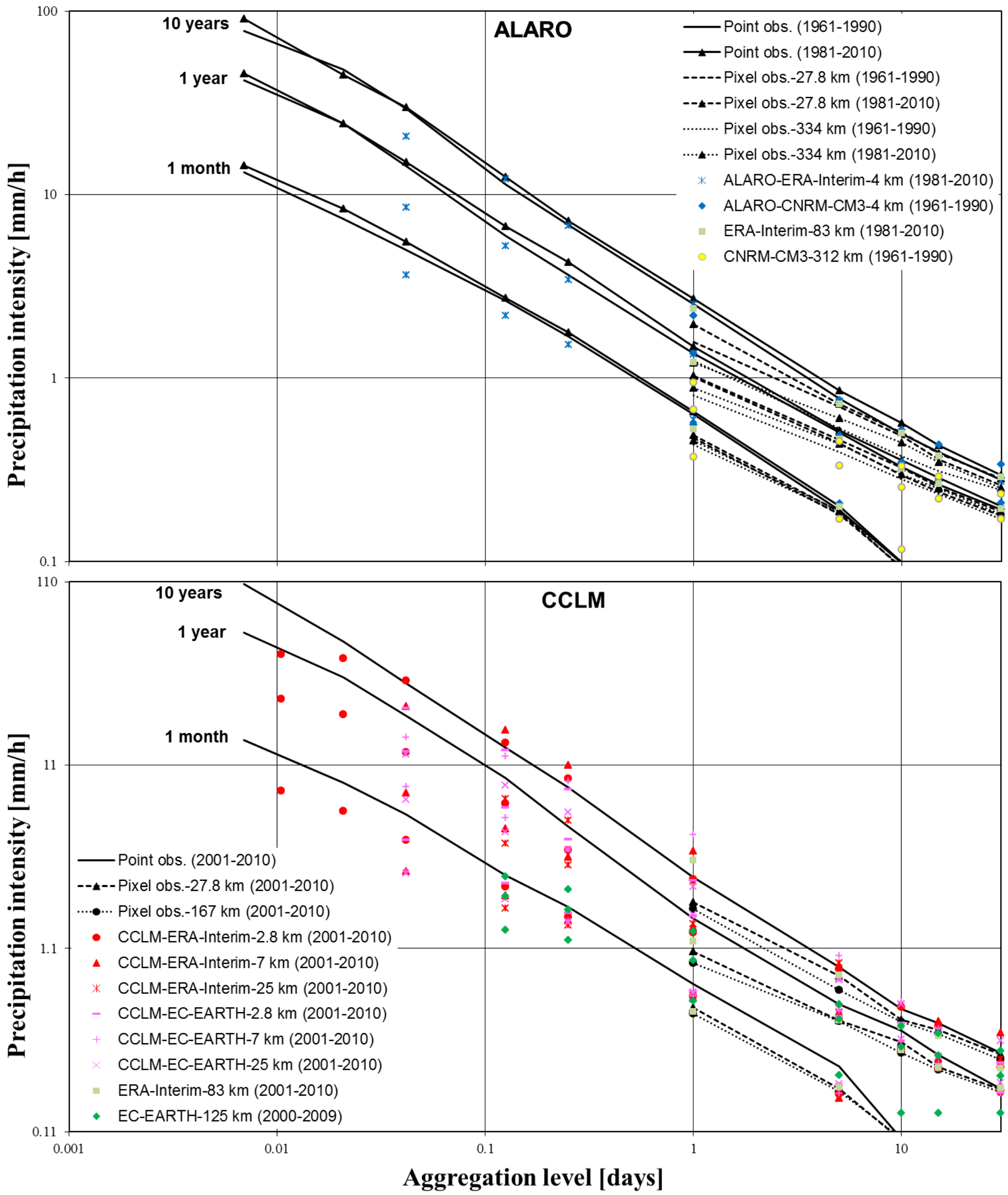


**Figure 4.** Comparison of historical IDF-relationships based on point and pixel interpolated Uccle observations, with the CCLM, ALARO and driving GCM or reanalysis results.

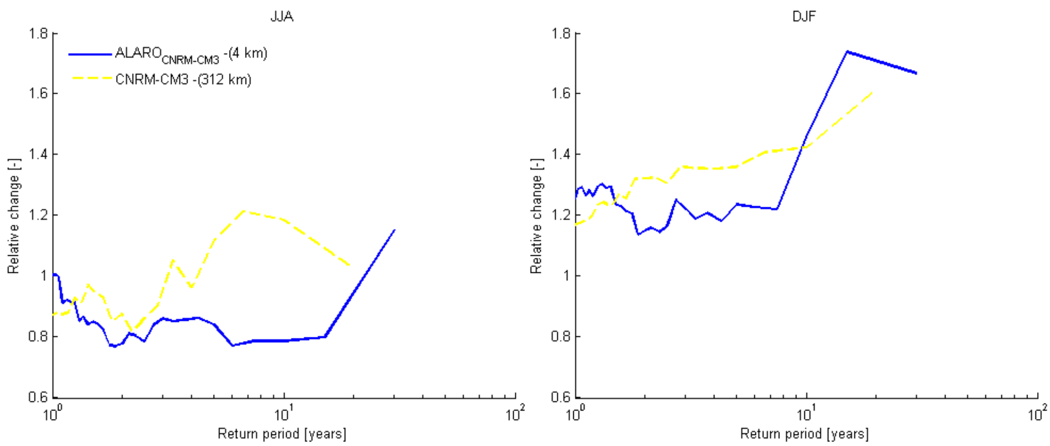


**Figure 5**. Change factors for daily precipitation quantiles computed using the ALARO$_{CNRM-CM3}$ 4 km and the driving CNRM-CM3 (A1B) for summer (left) and winter (right) seasons.

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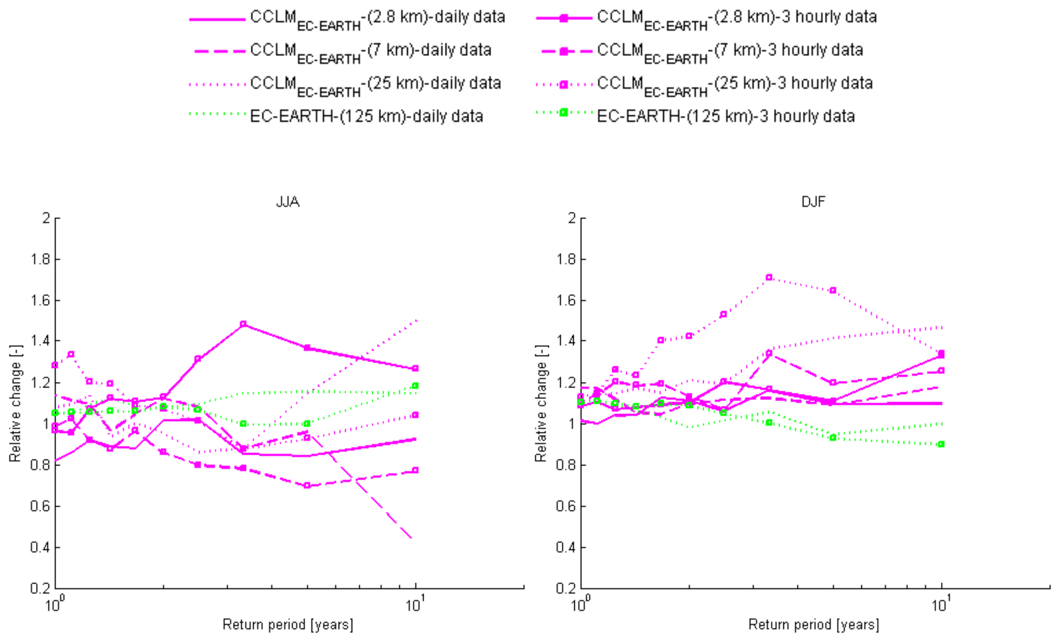


**Figure 6**. Change factors for daily and 3-hourly precipitation quantiles computed using the CCLM$_{EC-EARTH}$ 2.8, 7, 25 km for summer (left) and winter (right) seasons.

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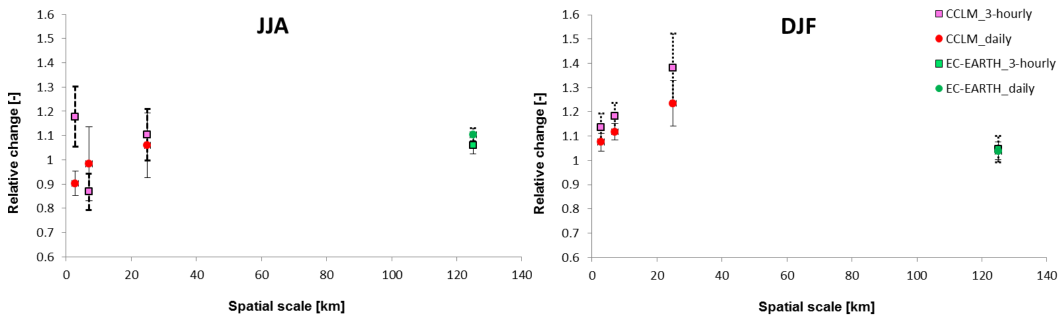


**Figure 7**. Change factors for extreme daily and 3-hourly precipitation (averaged over the extreme events with T > 1 year) computed using the CCLM$_{\text{EC-EARTH}}$ 2.8, 7, 25 km and the driving EC-EARTH GCM for summer (left) and winter (right) seasons, versus the models' spatial scale (vertical bars show the 95% confidence intervals calculated using t test).