Environmental Research Letters

LETTER

Regionalization of anthropogenically forced changes in 3 hourly extreme precipitation over Europe

Parisa Hosseinzadehtalaei 1, Hossein Tabari 1,2 and Patrick Willems 1,2
1 KU Leuven, Department of Civil Engineering, Hydraulics Division, Belgium
2 Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, Belgium
E-mail: parisa.hosseinzadehtalaei@kuleuven.be

Keywords: sub-daily precipitation extremes, EURO-CORDEX, signal robustness, internal variability, spatial pooling, climate change

Abstract
Future extreme precipitation events are expected to be influenced by climate change; however, the robustness of this anthropogenically forced response in respect to projection uncertainty especially for sub-daily extremes is not fully understood. We analyze the impact of anthropogenic climate change on 3 hourly extreme precipitation with return periods ranging between 5 and 50 years over Europe using the RCA4 model ensemble simulations at 0.11° resolution. The robustness of the signals is examined based on a regionalized signal-to-noise (S2N) technique by taking the spatial pooling into account and the efficacy of the regionalization is tested by a sensitivity analysis. The results show an increasing signal in 3 hourly extreme precipitation over Europe for all seasons except summer for which a bipolar pattern (increase in the north and decrease in the south) is discerned. For the business-as-usual scenario RCP8.5, the regionalized winter 3 hourly extreme precipitation signals over 9 x 9 model grid cells are statistically significant in roughly 72%, 65%, 59% and 48% of the European area for 5, 15, 25 and 50 year return periods respectively, while 16%—21% of the area will experience significant changes in summer. The S2N values for 3 hourly extreme precipitation changes rise after the spatial pooling by about a factor of 1.4—1.7 for all seasons except summer when they decline by about a factor of 0.78. The results of sensitivity analysis reveal that the regionalization influence is sensitive—in order of decreasing importance—to season, precipitation time scale, precipitation intensity, emission scenario and model spatial resolution. The precipitation time scale is particularly important seasonally in summer and regionally in south Europe when/where short-duration convective precipitation is dominant.

1. Introduction

An intensification of extreme precipitation is projected by climate models by the end of the 21st century (e.g. Willems et al 2012, IPCC 2013, Fischer et al 2013, Scoccimarro et al 2013, Pendergrass and Hartmann 2014, Donat et al 2016, Hosseinzadehtalaei et al 2017, Prein et al 2017, Wang et al 2017, Kendon et al 2018). This intensification is due to several factors. The increase in atmospheric moisture content in a warming climate plays the most important role, which leads to an increase of precipitation intensities by about 7% per degree of surface warming based on the Clausius–Clapeyron (C–C) relationship (Westra et al 2014, Ban et al 2015, Lenderink and Fowler 2017). Other influencing factors are the changes in the temperature lapse rate and anomaly and in vertical wind velocities (Pfahl et al 2017).

The projected increases of extreme precipitation under anthropogenic climate change have crucial implications for future water management and urban planning, especially in terms of flood hazards (Kendon et al 2017). Future water resources are more under stress as precipitation is less but more intense, which at the same time emphasizes the need for more precise projection of extreme precipitation changes (Pall et al 2007, Kendon et al 2010). The projections are usually performed by means of global climate models
(GCMs). GCM simulations are, however, typically at coarse spatial (hundreds of kilometers) and temporal (daily) resolutions which poses some limitations to accurately capture more details such as land topography or orographic effects and mesoscale processes (Tabari et al 2016). Therefore, dynamical downscaling has been implemented using regional climate models (RCMs), which provide an improved representation of the physical processes in the atmosphere and the topographic variability which cannot be captured by the coarse resolution of GCMs (Dosio and Fischer 2018, Soares and Cardoso 2018). Several RCM ensembles have been developed applying GCM results as boundary conditions covering Europe. For example, through the projects PRUDENCE (Christensen et al 2007, Jacob et al 2007) and ENSEMBLES (van der Linden and Mitchell 2009), RCM projections were obtained at the daily time scale and with a spatial resolution of 50 km for the former and 25 and 50 km for the latter. The EURO-CORDEX project (Coordinate Downscaling Experiment over Europe; Jacob et al 2014) currently provides the new generation of RCM simulations (Feser et al 2011, Casanueva et al 2016, Giorgi et al 2016, Prein et al 2016). This ensemble provides the highest spatial and temporal resolution precipitation simulations over Europe at the grid size of 12 km and 3 hourly scale compared to the previous continental simulations, making this ensemble more relevant and suitable for local impact analysis.

The assessment of extreme precipitation signals over Europe by applying RCMs have been performed in several studies (Frei et al 2006, Fowler et al 2007, Kendon et al 2008, Rajczak et al 2013, Jacob et al 2014, Lehtonen et al 2014, Scossimarro et al 2015, Nissen and Ulbrich 2017, Rajczak and Schär 2017). However, the robustness of these signals is less quantified which provides indispensable information for implementing proper adaptation strategies to cope with extreme events. Robust extreme precipitation signals are mainly influenced by projection uncertainty. The projection uncertainty in RCMs can be largely forced by the lateral boundaries, i.e. GCMs, caused by downscaling of large-scale meteorological fields and representation of more details such as topography (Giorgi et al 2001). A larger projection uncertainty of precipitation changes compared to temperature changes has been pointed out in several studies (e.g. Murphy et al 2004, Hawkins and Sutton 2011), owing to the nonlinearity and local character of precipitation (Maraun 2013, Sieck and Jacob 2016, Aalbers et al 2018, Madsen et al 2017).

The large noise in extreme precipitation changes can be reduced by regionalization through spatial pooling over neighboring grid cells, boosting the robustness of extreme precipitation changes. In this way, longer time series with a homogenous statistical behavior are obtained (Kendon et al 2008, 2010, Hanel et al 2009, Maraun et al 2010, Sharkey and Winter 2019). Such longer series also have the advantage that the changes in extreme events can be obtained with higher confidence. Kendon et al (2008) demonstrated that robustness in winter and summer daily extreme precipitation noticeably increases by applying the spatial pooling. This method was also applied by Aalbers et al (2018) to evaluate climate change signals in mean and extreme daily precipitation in Western Europe. Li et al (2019) recently exploited the spatial pooling method to identify robust annual extreme precipitation-temperature scaling relationships across North America.

Although some efforts have been made to regionalize extreme precipitation changes using spatial pooling, the sensitivity of regionalization results to the duration of precipitation extremes and the spatial resolution of climate models remains unquantified. Furthermore, the previous studies have mostly overlooked the spatial dependency among neighboring model grid cells, which is generated when the neighboring cells from time to time are affected by the same storm (Weiss et al 2014). The regionalization is only effective when this spatial dependency is considered, especially for extreme precipitation compared to mean precipitation as the former is more influenced by natural variability at the local scale (Maraun et al 2010, Martel et al 2018). Ignoring the spatial dependence will result in an underestimation of the extremes (Hosking and Wallis 1988, Bardet et al 2011, Weiss et al 2014, Goudenhoofdt et al 2017). Other disputable issues for regionalization are the response of precipitation extremity to regionalization, seasonality of regionalization results and their sensitivity to greenhouse gas concentrations. In this paper, we assess the robustness of the projected changes in 3 hourly and daily extreme precipitation over Europe using the RCA4 RCM ensemble through applying a signal-to-noise (S2N) analysis including a spatial pooling technique with a spatial dependency consideration to decrease the noise due to internal variability. The effectiveness of the regionalization (spatial pooling) is evaluated by a sensitivity analysis to precipitation times scale (3 hourly and daily), precipitation intensity (5 and 15 year return periods), season (four seasons), climate model resolution (12 and 50 km) and greenhouse gas concentration (RCP4.5 and RCP8.5).

2. Materials and methods

2.1. Climate model simulations
In the present study, high temporal and spatial EURO-CORDEX RCMs are utilized whose data are publicly available through the Earth System Grid Federation server (ESGF archive, http://esgf.org/). EURO-CORDEX RCMs contain scenarios based on the latest phase of the Coupled Model Inter comparison project (CMIP5, Taylor et al 2012). These high resolution simulations have horizontal grid resolutions of 0.44° (50 km) and 0.11° (12 km) over the European domain,
both of which are used in this study. To obtain climate change signals, daily and 3 hourly simulations for the periods 1971–2000 and 2071–2100 are considered as the historical and scenario (future) periods, respectively. Two Representative Concentration Pathway (RCP, Moss et al 2010) scenarios of RCP4.5 and RCP8.5 respectively corresponding to mid and high concentration levels are used. Because of limited available simulations for the other two scenarios of RCP2.6 and RCP6.0, they were excluded. The used ensemble contains four RCMs of CCLM, RCA4, REMO and WRF nested in five CMIP5 GCMs (table S1 is available online at stacks.iop.org/ERL/14/124031/mmedia). The 3 hourly precipitation data are available only for the RCA4 model with 12 km resolution, while the remaining RCMs and the RCA4 model with 50 km resolution provide daily data. The precipitation simulations of the EURO-CORDEX RCMs have been validated in several studies (e.g. Prein and Gobiet 2017).

2.2. Analyses of signal and S2N for extreme precipitation

This study investigates the climate change impact on European extreme precipitation. Extreme precipitation is defined as precipitation with return periods of 5, 15, 25 and 50 years on the basis of the empirical distribution. The analyses are performed on a seasonal base in which defined seasons are winter (December–February), spring (March–May), summer (June–August) and autumn (September–November). Climate change signal is calculated for each model grid point over the domain as the ratio between the precipitation intensity for the scenario period and the corresponding intensity in the historical period for the same return period. For 3 hourly data, the changes in the maximum 3 hourly precipitation per day are considered to ensure that the extremes are taken from independent events. To assess the robustness in the 3 hourly and daily extreme precipitation changes, S2N ratio is applied to determine the locations where anthropogenic forcing (i.e. signal S) is higher than projection uncertainty (i.e. noise N), which can be obtained from inter-simulations of an ensemble (Kay et al 2015, Martel et al 2018). S2N is calculated as below:

\[ S2N(d, T) = \frac{C_{\text{ensemble}}(d, T)}{\sigma_{\text{ensemble}}(d, T)}, \]

where \( C_{\text{ensemble}}(d, T) \) is the median of climate change signals over the five-member ensemble of the RCA4 model for an intended return period (T) and precipitation duration (d), and \( \sigma_{\text{ensemble}}(d, T) \) is the standard deviation across the RCA4 model ensemble for the same return period and duration.

2.3. Regionalization of extreme precipitation changes and its sensitivity analysis

To reduce grid-box noise for extreme precipitation arising from internal variability and to achieve improved statistics, we apply a spatial pooling method (Kendon et al 2008) in which 3 hourly and daily precipitation data within neighboring grid cells centered on the grid cell of interest are pooled to obtain a longer time series. Different degrees of spatial pooling are examined in this study: 3 × 3, 5 × 5, 7 × 7 and 9 × 9 arrays of neighboring grid cells corresponding to the spatial scales of 36 (150), 60 (250), 84 (350) and 108 (450) km for a 12 (50) km model, respectively. For instance, by pooling the data from nine grid cells in the case of 3 × 3 pooling, each of which with a 30 year record, the total sample size is expected to be equal to the sum of all the local sample sizes (i.e. 9 × 30 = 270 years). However, due to a spatial dependency among neighboring cells, the effective sample size (ESS) is smaller than that. The spatial dependency is created when the entire region is influenced by the same storm, causing a similar behavior of extremes in the neighboring cells. Based on the method developed by Weiss et al (2014), the ESS for the time series in each model grid cell is given by

\[ ESS = n \times \lambda_s, \]

where \( n \) is the length of data (30 years in our case), \( \lambda_s \) is the total number of extremes in the model grid box \( 3 \times 3, 5 \times 5, 7 \times 7, 9 \times 9 \) and \( \lambda_c \) is the number of extremes in the target model grid cell. \( \frac{\lambda_s}{\lambda_c} \) varies between 1 and \( n \), where \( n \) is the number of model grid cells (e.g. nine for 3 × 3 spatial pooling). It is close to one when the spatial dependency in the region is strong. Owing to a regionally and seasonally varying precipitation over Europe, a grid cell specific threshold (rather than an absolute value) is selected to define extremes, that is extreme precipitation with a 5 year return period for both daily and 3 hourly time scales.

The spatial pooling is performed for extreme precipitation of the historical and scenario periods separately, and the return periods (T) of extreme precipitation for each grid cell are estimated as \( T = ESS/i \) where ESS is the ESS calculated by equation (2) and \( i \) is the rank of precipitation quantiles. Later on, extreme precipitation changes at each grid cell over the domain are determined for each model run for different seasons and return periods. With the regionalization of the signals, we expect smaller noises and subsequently larger S2N values. To test this hypothesis, the S2N results after and before the spatial pooling are compared. Finally, the significance of S2N is tested based on the ensemble size (m) using the t test (Kendon et al 2008):

\[ t = \frac{S2N}{\sqrt{\frac{m}{2}}} \]
The effectiveness of the regionalization is examined by computing a ratio between signal, noise and S2N after and before regionalization (spatial pooling), which is called hereafter ‘regionalization factor’. The regionalization sensitivity to precipitation time scale (3 hourly and daily), precipitation intensity (5 and 15 year return periods), season (four seasons), climate model resolution (12 and 50 km) and greenhouse gas concentration scenario (RCP4.5 and RCP8.5) is also analyzed. To this end, the sensitivity to precipitation time scale is determined by comparing S2N values between 3 hourly and daily precipitation, while the variations among all other factors are excluded by averaging. A similar procedure is adapted for the sensitivity analysis to the other factors. For the sensitivity analysis of the regionalization to model spatial scale, precipitation data of the 12 km RCMs are first regridded to a 50 km grid size using the bilinear interpolation method and then spatial pooling is performed.

### 2.4. Scale dependency of extreme precipitation changes

In addition to the sensitivity analysis of regionalization to spatial and temporal scales, the scale dependence of extreme precipitation signals without spatial pooling is further analyzed for different seasons and four considered return periods (5, 15, 25 and 50 years). In order to examine the effect of model spatial resolution on the projection of extreme precipitation, a spatial downscaling signal (SDS) statistic is defined. To calculate this statistic, climate change signals in percent obtained from the EURO-CORDEX RCMs with 12 and 50 km spatial resolutions (CF\textsubscript{RCM}\textsubscript{12, 50/daily}) are compared with those from the driving CMIP5 GCMs (CF\textsubscript{GCM/daily}):

$$SDS = \frac{CF_{RCM_{12, 50/daily}}}{CF_{GCM/daily}}$$

To compare the results of the models with different spatial resolutions by the SDS statistic, the native grid sizes of the GCMs and the 12 km RCMs are regridded to a 50 km grid size using the bilinear interpolation method. Similar to the SDS statistic, a temporal downscaling signal (TDS) is defined to evaluate the influence of the temporal resolution of model simulations for extreme precipitation. For the calculation of this index, 3 hourly EURO-CORDEX extreme precipitation signals (CF\textsubscript{RCM}\textsubscript{3 h}) in percent from the RAC4 model ensemble are compared with the daily signals from the same model ensemble (CF\textsubscript{RCM}\textsubscript{daily}) for each model grid point in percent:

$$TDS = \frac{CF_{RCM_{3 h}}}{CF_{RCM_{daily}}}$$

Negative SDS and TDS values denote opposite signal signs between GCMs and RCMs and between daily and sub-daily precipitation, respectively. The robustness of TDS and SDS is quantified based on the ensemble member agreement on the direction of the signal. TDS and SDS are robust when more than 80% of the ensemble members agree on the direction of the signal. Otherwise, they are interpreted as ‘unreliable’.

### 3. Results and discussion

The projected seasonal changes in 3 hourly extreme precipitation of 5, 15, 25 and 50 year return periods along with their robustness in the form of S2N over the European domain are presented in figures 1, 2, S1 and S2. The results indicate that 3 hourly extreme precipitation is projected to intensify in winter, spring and autumn for most of Europe for both RCP4.5 and RCP8.5 with more pronounced changes for RCP8.5. Following Kröner (2016), the main controlling factor for these changes in European winter extreme precipitation is the thermodynamic effect rather than the lapse-rate and circulation effects. In summer, a decline in 3 hourly extreme precipitation is projected in the southern part of Europe over Spain, Italy, southern France, the northern part of the Mediterranean Sea and the southern and eastern parts of the Black Sea, which is in agreement with the study of Scoccimarro et al (2015) for a less extreme 3 hourly precipitation (90th percentile) by employing the CMCC-CM model. This decrease can be as a consequence of the northward displacement of the subtropical high and the increase in mean sea level pressure change over Europe (Kjellström et al 2017). Also, the changes in the lapse-rate are an important factor as the sensitivity of convective precipitation to change in atmospheric stability is higher (Kendon et al 2010, Kröner et al 2017). The warm air moves slowly from the Atlantic Ocean to land and gets warmer and dryer and causes a significant fraction of decrease in precipitation in the Southern part of Europe, especially the Mediterranean region. In contrast to southern Europe, extreme precipitation changes are projected to increase in all seasons in the northern and northeastern parts. Comparing the 3 hourly extreme precipitation changes among different seasons, the largest changes are expected in winter and the smallest in summer (figures S3(a), (b)). In contrast, noise in 3 hourly extreme precipitation projections is largest in summer and smallest in winter (figure S4). In turn, changes in 3 hourly extreme precipitation are more robust in winter, and less robust in summer (figures S3(c–(f)). Although the signals get larger when precipitation gets more extreme from a return period of 5 to 50 years, their robustness has an opposite pattern. A less significant change in more extreme precipitation is because of the larger internal variability of more extreme events (Räisänen and Joelsson 2001, Hosseinzadehtalaei et al 2018) or of high spatial heterogeneity in physical processes resulting in extreme precipitation intensification (Fischer et al 2014, Vautard et al 2014, Aalbers et al 2018). The robustness is also more
pronounced under RCP8.5. For RCP8.5 (RCP4.5), approximately 72% (42%), 65% (33%), 59% (29%) and 48% (24%) of the European area have significant changes ($\alpha = 0.05$) in winter 3 hourly extreme precipitation for 5, 15, 25 and 50 year return periods, respectively, while significant changes in summer extremes are seen in 21% (10%), 20% (10%), 19% (10%) and 16% (9%) of the area for the mentioned return periods. It shows the low climate signals compared to the high uncertainties in summer extreme precipitation as reported in the literature (Aalbers et al 2018, Tabari and Willems 2018). The decrease of the European area with significant changes from less extreme daily precipitation towards more extreme daily precipitation and from winter to summer was also reported using the HadRM3H RCM under the SRES A2 forcing scenario (Kendon et al 2008).

The significance and magnitude of the changes in daily extreme precipitation are also analyzed. After the spatial pooling, the significant changes in daily extreme precipitation over Europe are less widespread compared to 3 hourly extreme precipitation for all seasons and return periods (figures S5–8). Significant changes in daily extreme precipitation are found in less than 16% of the European area (figures 3(b), (d)). This highlights the importance of precipitation time scale in climate change impact assessment. The importance of precipitation time scale has been highlighted in many previous findings such that short-duration extreme precipitation increases with rising temperatures twice the rate expected from the $C$–$C$ relation, the so-called 'super C–C rate' (Lenderink and van Meijgaard 2008, Haerter et al 2010). A comparison of daily 50 year extreme precipitation signals after $9 \times 9$ spatial pooling between different EURO-CORDEX RCMs shows a high similarity in the spatial pattern and the magnitude of changes between the RCMs with
the same parent GCM (figures S9 and S10), confirming the results derived from the RCA4 model.

To discern the regionalization influence on the robustness of the 3 hourly extreme precipitation signals, the percentage of the European area with significant S2N at the 95% confidence level and S2N values before and after the spatial pooling are compared in figures 3 and 4, respectively. The results indicate that the 3 hourly extreme precipitation changes are more significant and robust on applying the spatial pooling across all seasons and return periods for both RCPs compared to daily precipitation. The regionalization through the spatial pooling slightly decreases the signals of 3 hourly extreme precipitation and remarkably decreases the noises, ending up with a S2N increase (figures 4 and S11). The longer the return period is, the larger the influence of the spatial pooling will be. In fact, the spatial pooling reduces the higher noise in more extreme precipitation, leading to a noticeable increase in S2N. The S2N values increase by the spatial pooling levels from 3 × 3 to 9 × 9 grid cells. The S2N values for 3 hourly extreme precipitation of a 15 year (5 year) return period under RCP8.5 increase after the 9 × 9 spatial pooling by about a factor of 1.70 (1.61), 1.37 (1.24), 1.38 (1.15) for winter, spring and autumn, respectively and decreases by about a factor of 0.78 (0.64) for summer (figure 4). The European area with significant S2N becomes about 4 and 6 times larger after the 9 × 9 spatial pooling for 5 and 15 year return periods, respectively (figure 3). The regionalization factors are mostly larger for RCP4.5 than RCP8.5 (figures 4 and S11). This is due to a slightly larger decrease of extreme precipitation signals under RCP8.5 after the spatial pooling compared to RCP4.5, owing to its patchier spatial pattern which is more smoothed out.

To examine the effectiveness of the regionalization, a sensitivity analysis is implemented. The results

| Figure 2. Signal (S; first and third columns) and signal-to-noise (S2N; second and fourth columns) for European 3 hourly extreme precipitation of 50 year return period after spatial pooling over 9 × 9 grid cells based on the five-member ensemble of the RCA4 model with 12 km resolution for different seasons (winter: first row; spring: second row; summer: third row; autumn: fourth row) under RCP4.5 (first and second columns) and RCP8.5 (third and fourth columns). In signal-to-noise maps, regions of insignificant changes are masked by gray color, while S2N larger than 1.35 and 1.76 denotes significant changes at the 90% and 95% confidence levels, respectively. See figures S1 and S2 for the signal and signal-to-noise for 3 hourly extreme precipitation of 15 and 25 year return periods, respectively. |
indicate that the regionalization influence is sensitive —in order of decreasing importance—to season, precipitation time scale, precipitation intensity, emission scenario and model spatial resolution (figure 5). The highest sensitivity to the seasons can be attributed to different types of precipitation in different seasons: mainly convective in summer and large-scale in winter. The regionalization factors in winter is 29%, 31% and 32% higher than the ones in summer for 3 × 3, 5 × 5, 7 × 7 and 9 × 9 spatial pooling levels, respectively (figure 5(e)). Precipitation time scale is the second most influential factor on regionalization, with a higher regionalization factor for 3 hourly extreme precipitation compared to daily extremes. The sensitivity to time scale rises with the spatial pooling level from 12% regionalization factor difference in 3 × 3 level to 23% in 9 × 9 level (figure 5(a)). While precipitation intensity is not important for a regionalization over small areas (5% regionalization factor difference for 3 × 3 spatial pooling), its importance substantially rises for the regionalization over larger areas, so that regionalization factors of 15 year extremes are up to 18% higher than those for 5 year extremes for 9 × 9 spatial pooling (figure 5(d)). In contrast, the sensitivity to RCP is independent of the spatial pooling level and regionalization factors for RCP4.5 are about 10% larger in comparison to RCP8.5 for all levels (figure 5(c)). The model spatial resolution is the least important factor for the regionalization of extreme precipitation changes. The regionalization factors of the RCA4 runs with a 12 km spatial scale are 8%–12% larger than the ones for the 50 km RCA4 runs (figure 5(b)), while considering all EURO-CORDEX RCM runs the difference is between 6% and 9% (figure S12(a)). Kendon et al (2008) found a regionalization factor of 1.2 for daily extreme precipitation in winter and summer for 3 × 3 spatial pooling, while a factor in the order of 1.1 is found in this study for 5 year extreme precipitation under RCP4.5 from the 50 km RCM. The smaller regionalization factor for daily extremes obtained here is mainly attributed to considering the spatial dependency among neighboring grid cells for the spatial pooling in our case. Other possible reasons for the difference can be the use of a different climate model (HadRM3H in Kendon et al 2008), different extreme precipitation indicators (mean daily precipitation exceeding the 95th percentile of wet days in Kendon et al 2008) and a different emission scenario (SRES A2 scenario in Kendon et al 2008).

As the extreme precipitation signals are independent of spatial pooling (figure 4), their scale dependency is further investigated before the spatial pooling at a regional scale (for four European regions). The research question here is which of spatial and time scales is more important for future changes in extreme precipitation. The results will identify the potential areas of improvement in climate modeling and provide a future outlook for climate change impact studies. Figure 6 shows the temporal (TDS) and spatial (SDS) downscaling signals for different European regions. The TDS (SDS) values greater than one point to larger changes for 3 hourly extreme precipitation (RCMs) compared to the daily ones (GCMs). Larger signals of 3 hourly extreme precipitation in comparison to daily extremes (TDS > 1) are generally

![Figure 3. Comparison between the European area (%) with the significant S2N at the 95% confidence level before (+SP) and after (-SP) spatial pooling over 9 × 9 grid cells, for (a), (c) hourly and (b), (d) daily extreme precipitation of (a), (b) 5 and (c), (d) 15 year return periods based on the five-member ensemble of the RCA4 model with 12 km resolution.](image-url)
projected for all regions. TDS is robust in all regions except north Europe where only summer TDS is robust (not shown). The largest TDS is seen seasonally in summer and regionally in south Europe when/where short-duration convective precipitation is the dominant type of precipitation. On sub-daily time scales, the highest precipitation intensities during the summer season are usually associated with convective showers (Lenderink and van Meijgaard 2008), while the life cycle of individual storms is not resolved at daily precipitation statistics and the effects of more intense storms are potentially masked (Singleton and Toumi 2013). Our results also show a larger TDS for RCP8.5 compared with RCP4.5, both peaking for summer extremes in south Europe at the rate of 1.67 and 1.25 for RCP8.5 and RCP4.5, respectively. This is because of a larger increase of sub-daily extreme precipitation with the emission level (from RCP4.5 to RCP8.5) than daily extremes, enlarging the difference between sub-daily and daily changes.

Although the importance of the model spatial resolution for the simulation of summer extreme precipitation has also been emphasized in previous studies (Tabari et al. 2016, Karmacharya et al. 2017, Gadian et al. 2018, Tabari and Willems 2018), a clear pattern is not found in this study. Nevertheless, SDS is mostly less than one except for winter in north and west Europe (figures 6 and S12(b)–(e)). Similar to TDS, south Europe shows the highest sensitivity to model spatial resolution, with a robust SDS in almost all cases (season, RCP and return period). A comparison between the magnitude and the direction of TDS and SDS reveals that the temporal resolution is of more significance than the spatial resolution for climate change impact analysis on extreme precipitation.

4. Conclusions

This research was performed at the European scale, addressing the projected changes in 3 hourly and daily extreme precipitation using the RCA4 model ensemble simulations along with testing the robustness of the changes for different return periods (5, 15, 25 and 50 years) and seasons. Moreover, the effectiveness of the spatial pooling in the reduction of noise was evaluated by considering the spatial dependency for extreme precipitation. The significance of the projected forced response was assessed by the S2N ratio and the sensitivity analysis of the regionalization to precipitation time scale and intensity, model spatial scale, season and RCP was performed by comparing the S2N values after and before the spatial pooling.

The results indicate an intensification of 3 hourly extreme precipitation over Europe for all seasons except summer for which an approximately north–south bipolar pattern is found. This summer pattern with an increasing extreme precipitation in northern Europe and a decreasing signal in southern Europe is
Figure 5. Sensitivity analysis of regionalization to (a) precipitation time scale, (b) model spatial resolution, (c) RCP, (d) return period and (e) season. The results are based on the five-member ensemble of the RCA4 model. Note that S2N values are smoothed because of averaging. The median of regionalization factors over all model grid cells across Europe is shown by black cross in panels (a)–(d) and by black horizontal line in panel (e). See figure S12 (a) for the sensitivity analysis of regionalization to model spatial resolution based on the eight-member ensemble of all EURO-CORDEX RCMs (RCA4, CCLM, REMO, WRF).

Figure 6. Comparison between the spatial downscaling signal (SDS) and the temporal downscaling signal (TDS) of extreme precipitation changes based on the five-member ensemble of the RCA4 model over different European sub-regions for (a), (c) 5 and (b), (d) 15 year return periods and under (a), (b) RCP4.5 and (c), (d) RCP8.5 (North EU: −11° to 40° longitudes and 54.5°–71° latitudes; West EU: −11° to 12° longitudes and 44°–54.5° latitudes; East EU: 12°–40° longitudes and 44°–54.5° latitudes; South EU: −11° to 40° longitudes and 36°–44° latitudes). See figures S12(b)–(e) for SDS based on the eight-member ensemble of all EURO-CORDEX RCMs (RCA4, CCLM, REMO, WRF).
more apparent for less extreme precipitation. The amount of extreme precipitation changes is highly influenced by season, return period and RCP. From a seasonal aspect, the percentage of the European area with significant S2N is less in summer compared to the other seasons, demonstrating that summer 3 hourly precipitation extremes are more uncertain. For the non-mitigation scenario RCP8.5, the regionalized winter 3 hourly extreme precipitation changes are statistically significant in approximately 72%, 65%, 59% and 48% of the European area for 5, 15, 25 and 50 year return periods respectively, whereas the percentage area goes down to less than 21% for summer extremes.

The internal variability plays an important role in the projections of 3 hourly extreme precipitation changes for most of Europe especially for the higher return periods and the summer season. However, this uncertainty weakens as one applies regionalization through the spatial pooling. The results emphasize that the spatial pooling is an effective method to obtain less noisy extreme precipitation. The S2N values for 3 hourly extreme precipitation changes increase after the spatial pooling by a factor in the range 1.4–1.7 for all seasons except summer when S2N values decrease by about a factor of 0.78. The efficacy of the spatial pooling on the robustness of extreme precipitation changes greatly appartains to season, precipitation time scale and intensity, while regionalization is less sensitive to greenhouse gas concentration and climate model spatial resolution. Whenever and wherever short-duration convective precipitation is dominant, the precipitation time scale is found to be more important, which is the case seasonally for summer and regionally for south Europe.

Albeit the use of larger multi-model ensemble is always recommended for climate change impact assessment, less attention has been paid to the role of internal variability and the robustness of the climate change signals. Our results reveal that even large climate change signals can be insignificant due to a larger internal variability. This highlights the importance of assessing the robustness of extreme precipitation changes. The superiority of internal variability to anthropogenic changes should not be a barrier for decision making for adaptation strategy implementation, as the robustness of signals is strongly dependent on the model grid scale noise which can be effectively reduced by regionalization.

The spatial pooling results in this study are based on the five-member ensemble of the RCA4 RCM. Further research using a multi-model ensemble is needed to explore whether the results are sensitive to climate models. A multi-model multi-member convection-permitting model experiments, which are able to explicitly represent local convective events, are required to assess the effectiveness of the spatial pooling for local convective precipitation storms.

Acknowledgments

The authors acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling—phase 5 (CMIP5), and the climate modelling centers for the EURO-CORDEX simulations for the free availability of the data. The work described in this paper has received funding for projects for the European Union’s Horizon 2020 research and innovation programmes under grant agreement No. 700699, project BRIGAID (BRIdges the Gap for Innovations in Disaster resilience), and grant agreement No 730004, project PUCS (Pan-European Urban Climate Service). The second author has received funding from the Flemish regional government through a contract as a FWO (Research Foundation—Flanders) post-doctoral researcher.

Data availability

EURO-CORDEX RCM and CMIP5 GCM data are available from the Earth System Grid Federation (ESGF) Peer-to-Peer system (https://esgf-node.llnl.gov/).

ORCID iDs

Hossein Tabari @ https://orcid.org/0000-0003-2052-4541

References

Aalbers E E, Lenderink G, van Meijgaard E and van den Hurk B J 2018 Local-scale changes in mean and heavy precipitation in Western Europe, climate change or internal variability? Clim. Dyn. 50 4745–66

Ban N, Schimidli J and Schar C 2013 Heavy precipitation in a changing climate: does short-term summer precipitation increase faster? Geophys. Res. Lett. 42 1165–72

Bardet L, Duluc C M, Rebour V and Lher J 2011 Regional frequency analysis of extreme storm surges along the French coast Nat. Hazard Earth Syst. 11 1627–39

Casanueva A et al 2016 Daily precipitation statistics in a EURO-CORDEX RCM ensemble: added value of raw and bias-corrected high-resolution simulations Clim. Dyn. 47 719–37

Christensen J H, Carter T R, Rummukainen M and Amanatidis G 2007 Evaluating the performance and utility of regional climate models: the prudence project Clim. Change 81 1–6

Donat M G, Lowry A L, Alexander L V, O’Gorman P A and Maher N 2016 More extreme precipitation in the world’s dry and wet regions Nat. Clim. Change 6 508–13

Dosio A and Fischer E M 2018 Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1.5 C, 2 C, and 3 C global warming Geophys. Res. Lett. 45 935–44

Feser F, Rockel B, von Storch H, Winterfeldt J and Zahn M 2011 Regional climate models add value to global model data: a review and selected examples Bull. Am. Meteorol. Soc. 92 1181–92

Fischer E M, Beyerle U and Knutti R 2013 Robust spatially aggregated projections of climate extremes Nat. Clim. Change 3 1033–8
Hawkins E and Sutton R 2011 The potential to narrow uncertainty
Hanel M, Buishand T A and Ferro C A 2009 A nonstationary index
Goudenhoofdt E, Delobbe L and Willems P 2017 Regional
Jacob D, Barring L, Christensen O B, Christensen J H, Castro M D, 
Fischer E M, Sedláček J, Hawkins E and Knutti R 2014 Models agree on forced response pattern of precipitation and temperature extremes Geophys. Res. Lett. 41 8554–62
Fowler H, Ekström M, Blenkinsop S and Smith A 2007 Estimating change in extreme European precipitation using a multimodel ensemble J. Geophys. Res. Atmos. 112 D18104
Frei C, Scholl R, Fukutome S, Schmidli J and Vidale P L 2006 Future changes of precipitation extremes in Europe: intercomparison of scenarios from regional climate models J. Geophys. Res. Atmos. 111 D06105
Gadian A M et al 2018 A case study of possible future summer convective precipitation over the UK and Europe from a regional climate projection Int. J. Climatol. 38 2314–24
Giorgi F et al 2001 Regional climate information—evaluation and projections Climate Change 2001: the Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) 583–638 (https://lib.dr.iastate.edu/ge_at_pubs/110)
Giorgi F, Torma C, Coppola E, Ban N, Schar C and Somot S 2016 Enhanced summer convective rainfall at Alpine high elevations in response to climate warming Nat. Geosci. 9 584–9
Goudsmit E, Delobbe L and Willems P 2017 Regional frequency analysis of extreme rainfall in Belgium based on radar estimates Hydrolog. Earth Syst. Sci. 21 5385–99
Haerter J O, Berg P and Hagemann S 2010 Heavy rain intensity distributions on varying time scales and at different temperatures J. Geophys. Res. 115 D17102
Hanel M, Buishand T A and Ferro C A 2009 A nonstationary index flood model for precipitation extremes in transient regional climate model simulations J. Geophys. Res. Atmos. 114 D15107
Hawkins E and Sutton R 2011 The potential to narrow uncertainty in projections of regional precipitation change Clim. Dyn. 37 407–18
Hosking J R M and Wallis J R 1988 The effect of intersite dependence on regional flood frequency analysis Water Resour. Res. 24 886–900
Hosseinizadehtalaei P, Tabari H and Willems P 2017 Uncertainty assessment for climate change impact on intense precipitation: How many model runs do we need? Int. J. Climatol. 37 1105–17
Hosseinizadehtalaei P, Tabari H and Willems P 2018 Precipitation intensity–duration–frequency curves for central Belgium with an ensemble of EURO-CORDEX simulations, and associated uncertainties Atmos. Res. 200 1–13
IPCC 2013 Summary for Policymakers Climate Change 2013 The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate change ed T F Stocker et al
Jacob D, Barring L, Christensen O B, Christensen J H, Castro M D, Déqué M, Giorgi F, Hagemeier S et al 2007 An intercomparison of regional climate models for Europe: model performance in present-day climate Clim. Change 81 31–52
Jacob D et al 2014 EURO-CORDEX: new high-resolution climate change projections for European impact research Reg. Environ. Change. 14 563–78
Karmacharya J, New M, Jones R and Levine R 2017 Added value of a high-resolution regional climate model in simulation of intraseasonal variability of the South Asian summer monsoon Int. J. Climatol. 37 1105–16
Kay J E et al 2015 The Community Earth System Model (CESM) large ensemble project: a community resource for studying climate change in the presence of internal climate variability Bull. Am. Meteorol. Soc. 96 1333–49
Kendon E J et al 2017 Do convection-permitting regional climate models improve projections of future precipitation change? Bull. Am. Meteorol. Soc. 98 79–93
Kendon E J, Blenkinsop S and Fowler H J 2018 When will we detect changes in short-duration precipitation extremes? J. Clim. 31 2945–64
Kendon E J, Rowell D P and Jones R G 2010 Mechanisms and reliability of future projected changes in daily precipitation Clim. Dyn. 35 489–509
Kendon E J, Rowell D P, Jones R G and Buonomo E 2008 Robustness of future changes in local precipitation extremes J. Clim. 21 4280–97
Kjellström E et al 2017 European climate change at global mean temperature increases of 1.5 and 2 °C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models Earth. Syst. Dyn. 9 459–78
Kröner N 2016 Identifying and quantifying large-scale drivers of European climate change PhD Thesis ETH Zürich (https://doi.org/10.3929/ethz-a-010793497)
Kröner N, Kotlarski S, Fischer E, Lüthi D, Zuber E and Schar C 2017 Separating climate change signals into thermodynamic, lapse-rate and circulation effects: theory and application to the European summer climate Clim. Dyn. 48 3425–40
Lehtonen I, Ruosteenoja K and Jylhä K 2014 Projected changes in European extreme precipitation indices on the basis of global and regional climate model ensembles Int. J. Climatol. 34 1208–22
Lenderink G and Fowler H J 2017 Hydroclimate: understanding rainfall extremes Nat. Clim. Change 7 391–3
Lenderink G and van Meijgaard E 2008 Increase in hourly precipitation extremes beyond expectations from temperature changes Nat. Geosci. 1 511–4
Li C, Zwiers F, Zhang X and Li G 2019 How much information is required to well constrain local estimates of future precipitation extremes? Earth’s Future 7 11–24
Madsen H, Gregersen I B, Rosbjerg D and Arnbjerg-Nielsen K 2017 Regional frequency analysis of short duration rainfall extremes using gridded daily rainfall data as co-variate Water Sci. Technol. 78 1971–81
Maraun D 2013 When will trends in European mean and heavy daily precipitation emerge? Environ. Res. Lett. 8 014004
Maraun D et al 2010 Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user Rev. Geophys. 48 RG3003
Martel J L, Mailhot A, Brissette F and Caya D 2018 Role of natural climate variability in the detection of anthropogenic climate change signal for mean and extreme precipitation at local and regional scales J. Clim. 31 4241–63
Moss R H et al 2010 The next generation of scenarios for climate change research and assessment Nature 463 747–56
Murphy J M, Sexton D M H, Barnett D N, Jones G S, Webb M J, Collins M and Stainforth D A 2004 Quantification of modelling uncertainties in a large ensemble of climate change simulations Nature 430 768–72
Nissen K M and Ulbrich U 2017 Increasing frequencies and changing characteristics of heavy precipitation events threatening infrastructure in Europe under climate change Nat. Hazard Earth. Syst. 17 1177–90
Pall P, Allen M R and Stone D A 2007 Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO2 warming Clim. Dyn. 28 351–63
Pendergrass A G and Hartmann D L 2014 Changes in the distribution of rain frequency and intensity in response to global warming J. Clim. 27 8372–83
Pfahl S, O’Gorman P A and Fischer E M 2017 Understanding the regional pattern of projected future changes in extreme precipitation Nat. Clim. Change 7 423–7
Prein A F and Gobiet A 2017 Impacts of uncertainties in European gridded precipitation observations on regional climate analysis Int. J. Climatol. 37 305–27
Prein A F et al 2016 Precipitation in the EURO-CORDEX 0.11° and 0.44° simulations: high resolution, high benefits? Clim. Dyn. 46 383–412
Prein A F, Rasmussen R M, Ikeda K, Liu C, Clark M P and Holland G J 2017 The future intensification of hourly precipitation extremes Nat. Clim. Change 7 48–52
Raissänen J and Joensson R 2001 Changes in average and extreme precipitation in two regional climate model experiments Tellus A 53 547–66

11
Rajczak J, Pall P and Schär C 2013 Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine region J. Geophys. Res. Atmos. 118 3610–26
Rajczak J and Schär C 2017 Projections of future precipitation extremes over Europe: a multimodel assessment of climate simulations J. Geophys. Res. Atmos. 122 10773–800
Scoccimarro E, Gualdi S, Bellucci A, Zampieri M and Navarra A 2013 Heavy precipitation events in a warmer climate: results from CMIP5 models J. Clim. 26 7902–11
Scoccimarro E, Villarini G, Vichi M, Zampieri M, Fogli P G, Bellucci A and Gualdi S 2015 Projected changes in intense precipitation over Europe at the daily and subdaily time scales J. Clim. 28 6193–203
Sharkey P and Winter H C 2019 A Bayesian spatial hierarchical model for extreme precipitation in Great Britain Environmetrics 30 e2529
Sieck K and Jacob D 2016 Influence of the boundary forcing on the internal variability of a regional climate model Am. J. Clim. Change. 5 373–82
Singleton A and Touni R 2013 Super-Clausius–Clapeyron scaling of rainfall in a model squall line Q. J. R. Meteorol. Soc. 139 334–9
Soares P M and Cardoso R M 2018 A simple method to assess the added value using high-resolution climate distributions: application to the EURO-CORDEX daily precipitation Int. J. Climatol. 38 1484–98
Tabari H, De Troch R, Giot O, Hamdi R, Termonia P, Saeed S, Brisson E, Van Lipzig N and Willems P 2016 Local impact analysis of climate change on precipitation extremes: are high-resolution climate models needed for realistic simulations? Hydrol. Earth Syst. Sci. 20 3843–57
Tabari H and Willems P 2018 Seasonally varying footprint of climate change on precipitation in the Middle East Sci. Rep. 8 4435
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Bull. Am. Meteorol. Soc. 93 485–98
van der Linden P and Mitchell J F B (ed) 2009 ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project (Met Office Hadley Centre FitzRoy Road Exeter EX1 3PB) 160 pp
Vautard R et al 2014 The European climate under a 2 C global warming Environ. Res. Lett. 9 034006
Wang G, Wang D, Trenberth K E, Erfanian A, Yu M, Bosilovich M G and Parr D T 2017 The peak structure and future changes of the relationships between extreme precipitation and temperature Nat. Clim. Change 7 268–74
Weiss J, Bernardara P and Benoit M 2014 Modeling intersite dependence for regional frequency analysis of extreme marine events Water Resour. Res. 50 5926–40
Westra S, Fowler H J, Evans J P, Alexander L V, Berg P, Johnson F, Kendon E J, Lenderink G and Roberts N M 2014 Future changes to the intensity and frequency of short-duration extreme rainfall Rev. Geophys. 52 522–55
Willems P, Arnbjerg-Nielsen K, Olsson J and Nguyen V T V 2012 Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings Atmos. Res. 103 106–18