Internal variability and temperature scaling of future sub-daily rainfall return levels over Europe

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Abstract

The range of sub-daily extreme precipitation due to internal variability is quantified within the single model initial-condition large ensemble featuring 50 members of the Canadian regional climate model, version 5 (CRCM5) under the high-emission scenario representative concentration pathway 8.5. Ten-year return levels of sub-daily precipitation are calculated for three future periods (2010–2039, 2040–2069, 2070–2099) and hourly to 24-hourly aggregations over a European domain. The return levels are found to increase by 4%–8% for every future 30 year period averaged for the study area, where short-duration rainfall intensities increase to a greater extent than longer-duration rainfall intensities. The ranges between the median of the 50 members and the 5th and 95th quantile amount to −15.6%–19.3%, −16.0%–20.1%, and −16.5%–20.9% for the near, mid and far future, respectively. It is also shown that the scaling of the precipitation increase with temperature (Clausius–Clapeyron scaling) exhibits substantial variations between the 50 CRCM5 members at regional aggregations. These findings illustrate the large impact of internal variability on the uncertainty of extreme precipitation return level estimates. Here, regions of significant changes are identified, where future median extreme precipitation exceeds the 95th quantile of the reference period (1980–2009). These regions are located in northern Europe, central Europe and the eastern part of the Mediterranean.

1. Introduction

Extreme precipitation events at a sub-daily time scale are the driver of high-impact hazards, such as flash floods, urban flooding, landslides, erosion, and riverine flooding within small to medium-sized catchments (Marchi et al 2010, Arnberg-Nielsen et al 2013, Gill and Malamud 2014, Bruni et al 2015, Ochoa-Rodriguez et al 2015, Do et al 2017, Panagos et al 2017). These impacts are of high societal and economic relevance (Forzieri et al 2018). In Europe, rainfall-driven flood events and mass movements have caused more than 4600 fatalities and financial losses of 173 billion EUR between 1980 and 2017 (EEA 2019). Hence, it is critical to understand the dynamics of the process and its alterations with a changing climate in order to design future flood protection infrastructure and to support urban planning strategies. It is common knowledge that the intensity of rainfall events will increase with rising temperatures due to global warming (e.g. Trenberth et al 2003). This has been quantified for different regions and time scales, based on both observations and climate model simulations (e.g. Trenberth 2011, Shiu et al 2012, Soares et al 2017, Colmet-Daage et al 2018).

While extreme precipitation on a daily scale increases roughly between 6%–8% K−1 (Westra et al 2013) following the Clausius-Clapeyron (CC) relationship, Lenderink and van Meijgaard (2008, 2010) and Berg et al (2013) have shown that sub-daily extremes up to a temporal aggregation of a few hours can exceed the CC scaling, which is then referred to as super-CC-scaling or superadiabatic scaling (Westra et al 2014).

Climate models are a common tool to investigate these dynamics for a future climate, even though they suffer from different sources of uncertainty.
(Hawkins and Sutton 2009): (a) emission scenarios are uncertain as the actual emissions in the future are not known but estimated. (b) Climate models differ within their representation of the physical processes, which leads to model uncertainty. (c) Internal variability is caused by non-linear dynamical processes, which are inherent to the chaotic nature of the climate system (Deser et al 2012, Von Trentini et al 2019). Hence, climate simulations based on the same climate model and emission scenario will vary if the initial atmospheric conditions of the climate model differ slightly. This can be interpreted as model representation of the internal variability of the climate system (Deser et al 2012, 2020, Von Trentini et al 2020).

In this study, the focus is set on this third source of uncertainty: internal variability. Climate simulations of a single model initial-condition large ensemble (SMILE) featuring 50 members of the Canadian regional climate model, version 5 (CRCM5) under the high-emission scenario representative concentration pathway 8.5 (RCP 8.5; Van Vuuren et al 2011) are used to assess the internal variability of extreme precipitation. Ten-year return levels of hourly to 24-hourly rainfall are calculated for three future periods. These are compared to the return levels of the reference climate (1980–2009). Furthermore, the scaling of increasing extreme precipitation with warmer temperatures is investigated and its variability within the 50 climate simulations is assessed.

2. Data and methods

2.1. The CRCM5-LE

The second generation Canadian Earth System Model (CanESM2) is run for 50 times with slightly different initial-conditions following RCP 8.5 for transient runs from 1950 to 2099 (Arora et al 2011, Fyfe et al 2017). These global climate projections were dynamically downscaled with the regional climate model (RCM) CRCM5 at a horizontal resolution of 0.11° following the EURO-CORDEX grid specifications (Leduc et al 2019). This large ensemble is called CRCM5-LE. The size and location of its European domain is shown in section 3 within figure 1. The detailed climate model setup and applied schemes are given in Martynov et al (2012) and its general performance at the European climate is evaluated in Leduc et al (2019). Furthermore, Von Trentini et al (2019) compare the CRCM5-LE with the multi-model EURO-CORDEX ensemble and investigate the spread of the 50 members compared to the variations of the 22 different EURO-CORDEX climate model combinations.

As sub-daily rainfall extremes are partly governed by convective processes, it has to be mentioned that convection is parametrized in the CRCM5. The spatial resolution of climate models has to be higher than 4 km in order to represent convective processes (Langhans et al 2012, 2013, Tabari et al 2016), whereby unresolved processes and sources for biases still remain (Hirt et al 2019). Therefore, in the CRCM5-LE, deep convection is described with the Kain and Fritsch (1990) scheme, while shallow convection is parametrized using the Kuo-transient scheme (Kuo 1965, Belair et al 2005). Even though convection is parameterized, the CRCM5-LE has proven to be able to sufficiently recreate the spatial pattern of sub-daily extreme precipitation over Europe (Poschlod et al 2021). Furthermore, the intensity of extreme precipitation is well reproduced for durations of three hours and longer. A comparison of extreme precipitation within a single realization of a convection-permitting RCM and the CRCM5-LE is given in Hodnebrog et al (2019) for different sub-regions in Europe.

2.2. Calculation of 10 year return levels

To calculate the 10 year return levels, the approach of Poschlod et al (2021) is applied. Therefore, annual block maxima are extracted for moving windows of 3-hourly, 6-hourly, 12-hourly and 24-hourly precipitation for each of the 50 CRCM5-LE members. For the hourly time scale, maxima are constrained to fixed windows at the full hour, as the precipitation data are stored in hourly resolution. Three future 30 year time periods are investigated, namely the near (2010–2039), mid (2040–2069) and far future (2070–2099). The whole course of the year is included as data base for the extreme value analysis, as rainfall extremes in Europe do not only occur during an extended summer season (Berthou et al 2018). Furthermore, in Europe their occurrence is found to shift with a changing climate towards later in the year (Mareille et al 2018 for daily rainfall).

According to Coles (2001), block maxima samples are well represented by the generalized extreme value (GEV) distribution \( G \) (equation (1)):

\[
G(x; \xi) = \begin{cases} 
\exp \left( - \left[ 1 + \xi \left( \frac{x - \mu}{\sigma} \right) \right]^\gamma \right), & \xi \neq 0 \\
\exp \left( - \exp \left( - \frac{x - \mu}{\sigma} \right) \right), & \xi = 0
\end{cases}
\]

with \( \mu \), \( \sigma \) and \( \xi \) as location, scale and shape parameters of the distribution. The GEV parameters are optimized for each of the 50 differing 30 year block maxima and three future periods applying the method of L-moments (Hosking et al 1985, Gilleland and Katz 2016). We apply this GEV approach with the simplifying assumption of stationarity within the 30 year periods. Trends within the annual maxima of the 30 year periods of all durations are investigated using the Mann-Kendall test with 5% significance level. As the test is carried out for many grid cells, we adjust the critical p-value controlling the false discovery rate (Benjamini and Hochberg 1995) following the approach of Wilks (2016).
We find no significant trends for all periods and durations, thus we can proceed with this simplifying assumption.

In order to check the goodness-of-fit of the GEV distribution, the Anderson–Darling test is applied with 5% significance level, where the critical p-value is also adjusted following Wilks (2016). This leads to a rejection of only 0.1%–0.3% of all fits for the different durations. The 10 year return levels are then derived by inverting the GEV equation (equation (1)). The median of the 50 return levels represents the estimation of 10 year rainfall, where the 5th and 95th quantiles quantify the range of uncertainty related to the spread of the 50 members.

2.3. CC scaling
The increase in saturation specific humidity is governed by the CC relation, yielding an increase of approximately 6%–8% per warming degree. However, present-day precipitation–temperature scaling relations indicate that hourly precipitation extremes may have a response to warming exceeding the CC relation (Lenderink et al 2017). When scaling the increasing precipitation with temperature, there are differing approaches for the choice of the relevant location and time scale. Westra et al (2013) use a world-wide climatological approach applying the global mean temperature to scale global precipitation increases, whereas Berg et al (2013) conducted an event-based analysis focusing on the local temperatures during the rainfall event. Here, the average temperature of the whole European domain is taken following the argumentation of Keune and Miralles (2019), who attribute the sources of European precipitation mostly to regional moisture transfers. Hence, for each of the 50 CRCM5-LE members, the increase of 10 year rainfall at the grid cell is scaled with the increase of temperature in the whole European domain. Thereby, the changes for the three future periods are calculated in comparison to the reference period. As extreme precipitation is spatially highly variable (Aalbers et al 2018, Poschlod et al 2021), the CC scaling is not only shown for each grid cell, but also provided as areal average for eight European sub-regions.

3. Results and discussion
3.1. Sub-daily extreme precipitation
The 10 year return levels are openly available for the reference period (Poschlod 2020) and the future periods (Poschlod 2021). The change of 10 year return levels of sub-daily precipitation is shown in figure 1 for the 3-hourly aggregation. It is found to increase by 7.0% until 2010–2039, by 13.9% until 2040–2069, and by 20.3% until 2070–2099. Thereby, areas are identified, where the future extreme precipitation levels leave the inter-quantile range between the 5th and 95th quantiles of the reference period, which is induced by internal variability. Exceedance of the 95th quantile is found for 2.5%, 35.5% and 57.5% of the study area during the near, mid and far future, respectively. The corresponding areas refer to Scandinavia, the British Isles, the Baltic States, central Europe, Portugal and parts of the Mediterranean. In contrast, 0.52% of the area is projected to stay below the 5th quantile of the reference period during the far future. These grid cells are located in Morocco. For the other temporal aggregations, figures S1–S4 (available online at stacks.iop.org/ERL/16/064097/mmedia) are given in the supporting information. Changes are quantified in table 1 for all durations.

We assign the resulting spatial patterns mainly to the moisture availability and the increasing contribution of convective events. In Scandinavia, the British Isles, the Baltic States, and central Europe extreme precipitation events occur mostly during the summer season. There, future extreme rainfall can strongly increase with rising temperatures due to no or low limitations related to moisture availability (see figures S5(g)–(i)). Furthermore, convective processes can increasingly contribute to extreme events (see figure 2). In the central and eastern parts of the Mediterranean, extreme precipitation occurs mainly during the fall season (Berthou et al 2018, Wood and Ludwig 2020). While mean precipitation is projected to decrease slightly also during fall (Wood and Ludwig 2020), the available moisture (figures S5(j)–(l)) still allows for intensifying extreme rainfall events, whereas in southern Spain and North Africa extreme precipitation is projected to decrease due to limited moisture availability. Similar patterns are also found for the EURO-CORDEX ensemble (Tramblay and Somot 2018). In the northwestern parts of the Iberian Peninsula, extreme precipitation events are simulated during fall and winter (Wood and Ludwig 2020), where future mean precipitation during this season is projected to increase. The intensity of extreme events can also increase without major limitations due to moisture availability (figures S5(a)–(c), (j)–(l)).

Shorter-duration rainfall is projected to increase stronger than longer-duration rainfall, whereby the spatial patterns of the changes remain similar for all durations. Also the averaged increase per 30 year period is quite stable for each of the three investigated future periods. For hourly (3-hourly, 6-hourly, 12-hourly, 24-hourly) duration, the increase amounts to roughly 8% (7%, 6%, 5%, 4%) per 30 year period, respectively. However, between the mid and far future, the change is slightly lower than during the former periods.

As the CRCM5 does not include an implementation of a three-dimensional ocean model, the ocean conditions are governed by the lateral boundary conditions of the driving global climate model (GCM) CanESM2. This is a common feature of RCMs, even though atmosphere-ocean coupling can also improve the reproduction of regional climate characteristics.
Figure 1. Median of the 10 year return levels of 3-hourly precipitation over Europe, calculated for the 50 CRCM5-LE members. Figure (a) shows the return levels for the reference period (1980–2009). Figures (b)–(d) present the change between the reference period and the respective future period. Areas with hatching mark that the future median return level leaves the inter-quantile range of the 50 members, given by the 5th and 95th quantiles of the reference period.

over Europe (Somot et al 2008, Giorgi and Gao 2018). Furthermore, the simulation of extreme rainfall over the oceans could not be evaluated within Poschlod et al (2021) due to the lack of observational sub-daily data. Hence, these return level estimations are excluded from the analysis.

Nissen and Ulbrich (2017) calculated 3-hourly and 24-hourly 10 year return levels as mean of the EURO-CORDEX ensemble. They identified similar regions, where the multi-model ensemble shows a significant increase of probability for extreme precipitation under RCP 8.5. Though, multi-model ensembles do not allow for the quantification of model uncertainty only, as the differences between the simulations are caused by model differences of the GCM and RCM, mixed with internal variability (Von Trentini et al 2019). In order to disentangle internal variability from model uncertainty, Aalbers et al (2018) analysed the 16-member SMILE of the RCM RACMO2 driven by the GCM EC-EARTH 2.3 under RCP 8.5, which is run for a smaller domain than the CRCM5–LE centred over the Netherlands with the same spatial resolution of 0.11°. They found an increase of 14.5% for the daily 10 year return level.
Table 1. Summary of the change of 10 year return levels of sub-daily precipitation over Europe. The change (areal average over the whole domain) refers to the change of the median of the 50 CRCM5-LE members. Columns three and four quantify the size of areas, where the future return levels leave the inter-quantile range of the 50 members, given by the 5th and 95th quantiles (Q5 and Q95) of the reference period. This corresponds to the hatched areas in figures 1 and S1–S4. The fifth column presents the ranges of Q5 and Q95 in relation to the median. The sixth column is the areal average of the standard deviation at each grid cell.

| Duration and future period | Increase of the 10 year return level (areal average of median) | Area below Q5 of the reference | Area above Q95 of the reference | Q5–Q95 range around the median (areal average) | Standard deviation |
|---------------------------|---------------------------------------------------------------|-------------------------------|-------------------------------|-----------------------------------------------|-------------------|
| 2010–2039                |                                                              |                               |                               |                                               |                   |
| 1 h                      | 7.9%                                                         | 0.00%                         | 3.8%                          | −15.6%–19.3%                                 | 2.12 mm           |
| 3 h                      | 7.0%                                                         | 0.00%                         | 2.5%                          | −14.9%–18.5%                                 | 3.89 mm           |
| 6 h                      | 6.0%                                                         | 0.00%                         | 1.1%                          | −14.2%–17.9%                                 | 4.89 mm           |
| 12 h                     | 5.0%                                                        | 0.00%                         | 0.50%                         | −13.6%–17.2%                                 | 5.93 mm           |
| 24 h                     | 4.1%                                                        | 0.00%                         | 0.23%                         | −13.3%–16.6%                                 | 7.20 mm           |
| 2040–2069                |                                                              |                               |                               |                                               |                   |
| 1 h                      | 15.6%                                                       | 0.00%                         | 40.0%                         | −16.0%–20.1%                                 | 2.35 mm           |
| 3 h                      | 13.9%                                                       | 0.02%                         | 35.5%                         | −15.5%–19.4%                                 | 4.33 mm           |
| 6 h                      | 12.0%                                                       | 0.02%                         | 28.3%                         | −14.8%–18.7%                                 | 5.38 mm           |
| 12 h                     | 10.0%                                                       | 0.03%                         | 21.0%                         | −14.1%–17.7%                                 | 6.41 mm           |
| 24 h                     | 8.2%                                                        | 0.13%                         | 14.6%                         | −13.6%–17.0%                                 | 7.66 mm           |
| 2070–2099                |                                                              |                               |                               |                                               |                   |
| 1 h                      | 23.0%                                                       | 0.30%                         | 60.3%                         | −16.5%–20.9%                                 | 2.59 mm           |
| 3 h                      | 20.3%                                                       | 0.52%                         | 57.5%                         | −16.0%–20.4%                                 | 4.78 mm           |
| 6 h                      | 17.5%                                                       | 0.60%                         | 54.4%                         | −15.3%–19.6%                                 | 5.89 mm           |
| 12 h                     | 14.6%                                                       | 1.0%                          | 49.3%                         | −14.5%–18.5%                                 | 6.94 mm           |
| 24 h                     | 11.8%                                                       | 2.2%                          | 43.2%                         | −13.9%–17.6%                                 | 8.16 mm           |

Figure 2. Relative change of the contribution of convective rainfall to 3-hourly annual maximum precipitation compared to 1980–2009, calculated for the 50 CRCM5-LE members and near (a), mid (b) and far future (c).
these numbers, which are aggregated for the whole domain, figure 3 shows the 50-member variability at six locations with differing local climates. This illustrates the uncertainty range at local scales. Generally, larger absolute variability is projected for locations with higher absolute return levels. For short durations of one or three hours, the range is larger in the southern cities, where rainfall extremes are dominated by convective processes. Coppola et al. (2018) also expect higher impacts of internal variability in convective events and convection-permitting model simulations, which is why they recommend the use of ensembles in order to produce robust findings.

For Europe, Berg et al. (2019) have investigated the increase of 10 year rainfall return levels for a changing climate under RCP 4.5 and RCP 8.5. They explored the projections for present and future rainfall within nine selected RCMs of the EURO-CORDEX framework, and they evaluated the present rainfall levels with observations of five European countries. While they reported reasonable biases at country-wide aggregations, big deviations are shown at the reproduction of spatial patterns and gradients for the hourly duration. Poschlod et al. (2021) evaluated the 10 year return levels of the CRCM5-LE during 1980–2009 at 16 European countries, where return levels and spatial patterns were well reproduced, especially for durations of 3 h and above. Topographically complex areas, such as the Alps or the Norwegian coast could not be resolved due to the spatial resolution of the RCM. Hence, they concluded that the CRCM5-LE is able to recreate the features of extreme sub-daily rainfall over Europe, even though convective processes are parametrized.

Most studies within climate science analyse high quantiles of precipitation (e.g. 99.7% for annual maxima) or indices as the RX1h. Here, the impact-oriented 10 year return level is calculated, which has already been found to be relevant by Nissen and Ulbrich (2017) based on legislation and stakeholder interviews. Therefore, the analysis in this study gives a valid insight to the variability of projected alterations of future extreme sub-daily precipitation due to a changing climate, with the same restrictions as reported by Poschlod et al. (2021) and governed by the scenario uncertainty.

3.2. Internal variability of the CC scaling
The scaling of the 3-hourly return levels by the temperature increase is presented in figure 4 for the land area of the whole domain. These scalings are given...
Clausius–Clapeyron scaling (CC scaling) of the median of the 10 year return levels of 3-hourly precipitation over Europe compared to 1980–2009, calculated for the 50 CRCM5-LE members and near (a), mid (b) and far future (c).

Superadiabatic scaling is found for central Europe, the British Isles and Scandinavia. Generally, many studies discuss the origin of superadiabatic scaling. Haerter and Berg (2009) argue that it can be caused by a shift of the rainfall-generating processes from less large-scale precipitation to more frequent convective events. They found that this behaviour emerges for sub-daily rainfall extremes but disappears for daily rainfall. This ties in with our results for the scaling of the 10 year return levels at different durations (see figures S6–S9). For the 24-hourly duration, only 2% of the area shows superadiabatic scalings for the mid and far future.

Lenderink et al (2017) assume a physical origin resulting from the dynamics of convective clouds, which show stronger updrafts due to increased latent heat release with rising temperature (Lenderink and van Meijgaard 2009). However, in the CRCM5-LE the relevant processes are parametrized due to the spatial resolution of the model. We argue that shifts of the rainfall-generating processes from stratiform to convective precipitation contribute to the superadiabatic scaling in the CRCM5-LE. The contribution of convective rainfall to extreme precipitation is projected to increase in Scandinavia, the Baltic states, the British Isles, the Alps, and parts of the Mediterranean coastal areas due to the temperature rise (see figure 2). Moreover, apart from the Mediterranean, there is enough moisture available in these regions to exceed the CC scaling (figure S5). Below CC scaling is projected for large parts of the Mediterranean and eastern Europe. This reduced intensity results from limited moisture availability and changes of the atmospheric large-scale patterns (Westra et al 2014, Wood and Ludwig 2020). The decreasing moisture availability indicated by the change of relative humidity in the CRCM5-LE is given in figure S5, where especially the Mediterranean shows the strongest decline of relative humidity. Furthermore, these areas will be affected by a northward expansion of the subtropical dry zone due to alterations of large-scale patterns (Levine and Schneider 2015, Kröner et al 2017, Pfahl et al 2017, Grise et al 2019). The Hadley circulation is projected to expand polewards and, therefore, subsidence in the descending branch of the Hadley cells is found to lower the frequency and intensity of precipitation (Kröner et al 2017). However, Seager et al (2014) argue that an increase in the opposing mean
flow moisture divergence leads to the drying tendency in the Mediterranean. Generally, figure 4(a) shows a patchy spatial pattern, even though the median of the 50 members at each grid cell is presented. In order to give a regionally aggregated overview of the CC scaling, eight sub-regions are introduced (see figure 5). These sub-regions are defined by the boundaries of Christensen and Christensen (2007) and often called ‘PRUDENCE regions’. Water bodies are again removed from the investigated sub-regions due to their limited representation within the RCM.

Figure 6 displays the ranges of the CC scaling averaged for the sub-regions within the 50 RCM members, which are induced by internal variability. The CC scaling is found to be higher for shorter durations, as the contribution of the shift from stratiform to convective rainfall decreases for longer durations. For the 24-hourly aggregation, no super-CC-scaling is reported by the medians of the ensemble for the sub-regions.

The patchiness of the spatial patterns (figures 4(a)–(c)) as well as the ranges of CC scaling (figure 6) are found to decrease for future periods. This is due to the dependence of the CC scaling on the temperature forcing, as the scaling is expressed relatively to the warming. The internal variability of the temperature also contributes to the overall variability of the CC scaling. Annual mean temperature generally shows less variability than precipitation (Von Trentini et al. 2019) and averaging for the whole RCM domain smoothes the effect of local internal variability. Here, the range of the temperature increase within the 50 members amounts to 0.6 K for all future periods, where the median increase amounts to 1.2 K (2.6 K, 4.3 K) for the near (mid, far) future, respectively. Therefore, the variability of precipitation and temperature in relation to the warming decreases for each future 30 year period, whereas the absolute variability of precipitation slightly rises (see section 3.1). To disentangle the contribution of precipitation variability and temperature variability to the overall variability of the CC scaling, figure 6 is replicated in the supporting information in two different ways: The 50-member range of extreme precipitation changes is scaled by the median change in temperature (figure S10) and the median change in extreme precipitation
is scaled by the 50-member range of temperature changes (figure S11), respectively. This comparison illustrates the larger contribution of precipitation variability to the overall variability of the CC scaling.

Even though averaging for large sub-regions, the CC scaling shows high variability. For central Europe (MID), the hourly scaling shows a range of 3.5% K⁻¹%–10% K⁻¹ for 2070–2099, which illustrates that the same climate model configuration simulates subadiabatic, adiabatic and superadiabatic scalings only due to slightly perturbed initial conditions of the driving GCM in 1950. Additional uncertainty is induced as annual mean temperatures are used to scale the changes of extreme precipitation, while the increase in temperature varies within the seasons. Also, the timing of extreme precipitation events in the domain is different for varying sub-regions (see section 3.1). The effect of seasonal scaling is given in Wood and Ludwig (2020).

In sum, our findings show that any results of a single climate model member should be carefully interpreted. Such results should not be misinterpreted as model-specific as long as no ensemble with a sufficient number of members quantifies the uncertainty from internal variability (Milinski et al. 2020).

In recent studies, there have been different results, whether super-CC-scaling is simulated for Europe or not. Some studies found superadiabatic scalings (e.g. Lenderink and Van Meijgaard 2008, Kendon et al. 2014, 2019), whereas some studies did not (e.g. Ban et al. 2015). Again it should be emphasized that internal variability is a major source of uncertainty when investigating CC scaling, which has not been quantified within the forementioned studies. Considering internal variability as uncertainty source, Hodnebrog et al. (2019) found that the CRCM5 shows a relatively pronounced scaling when compared to other RCM configurations. Furthermore, in this study, the projected superadiabatic scalings can be attributed to the extreme level of 10 year return periods, as rarer events lead to higher scalings (Hodnebrog et al. 2019).

4. Conclusions

The findings of this study emphasize that internal variability plays a major role for the uncertainties of projected sub-daily extreme precipitation. The application of a RCM SMILE has provided the data base to analyse this variability for 10 year return levels over Europe and also to identify regions, where future extreme rainfall levels evolve from the variable range of present extreme rainfall levels. These return levels show a high degree of variability at the local and regional scale. The calculation of return levels based on the fit of a theoretical extreme value distribution using precipitation data of 30 year periods is a common procedure. Although the fitting of a theoretical extreme value distribution to the empirical distribution of annual maxima can smooth individual outliers in the data, the internal variability nevertheless causes such a range of climate realizations that the return levels still show deviations between up to −16.5% and +20.9% around the median. The increase of extreme sub-daily rainfall is projected to be significant over large parts of Europe. Thereby the intensity of short-duration rainfall events is found to rise stronger than for longer-duration rainfall.

Also the scaling of extreme precipitation with temperature is affected by internal variability. Even for regional aggregations, the same model configuration simulates both subadiabatic to superadiabatic scalings. Hence, it is shown that an analysis of single members of different GCM–RCM combinations have only a limited meaningfulness, when investigating the probability of sub-daily extreme rainfall events and exploring their scaling with temperature. In this study, only the uncertainty ranges of internal variability are assessed, whereby model uncertainty and scenario uncertainty were excluded from the assessment. In order to get a comprehensive impact-relevant ensemble of projections for future rainfall, the authors suggest multi-model initial-condition large ensembles (multiple RCM SMILES). Furthermore, for improving the resolution of complex topography and the representation of convectional processes, these ensembles would have to be carried out at convection-permitting scales. Of course, these simulations would place enormous demands on high-performance computing. First research on slightly differing initial conditions of convection-permitting models in a four-month time frame over a small domain centred over London provides information on the enormous influence of internal variability on (heavy) precipitation, which should be reflected by the regional climate modelling community (Bassett et al. 2020).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.4577988.

Ten-year return levels for the reference period are openly available at https://doi.org/10.5281/zenodo.3878887. The CRCM5-LE precipitation data is available to the scientific community at climex-project.org/en/data-access?language=en.

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