# Short-term precipitation extremes in regional climate simulations for Sweden

Jonas Olsson and Kean Foster

## ABSTRACT

Climate change is expected to generate higher short-term precipitation intensities, which may have negative consequences in terms of, for example, increased risk of flooding and sewer overflow. In this study, extreme precipitation for durations between 30 min and 1 day in simulations with the RCA3 regional climate model (RCM) for Sweden are analysed. As compared with daily observations in the period 1961–2010, the simulated extremes are found to be overall realistic with respect to magnitude, spatial homogeneity and temporal variability. In the ensemble of future projections, from 1981 to 2010 the 10-year 30-min precipitation will increase by 6% until 2011–2040, 15% until 2041–2070 and 23% until 2071–2100. The increase decreases with increasing duration and at the daily scale the percentage values are approximately halved. The values are largely consistent with earlier estimates. Assessment of the impacts on the results of the spatial resolution and the specific RCM used indicated possibilities of both smaller and larger future increases.

**Key words** | local flooding, rainfall, regional climate model, urban hydrology

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## INTRODUCTION

Global climate change is generally expected to affect the temporal and spatial distribution of precipitation. This conclusion is based on both theoretical reasoning (e.g., Trenberth *et al.* 2003) and climate model projections (e.g., Kjellström *et al.* 2011; Nikulin *et al.* 2011). One expected consequence is a change towards more intense short-term precipitation, as a warmer atmosphere may contain more water vapour and thus provide conditions for higher instantaneous precipitation rates (with 'short-term' we mean from daily down to sub-hourly time scales). Such an intensification would affect, for example, urban runoff, which is closely linked to short-term precipitation rates in light of the large amount of impervious surface and the resulting fast runoff generation. Increased flow rates would potentially produce, for example, treatment plant inflows exceeding the capacity, sewer overflows above legal limits and an increased flood risk.

As global warming is already being observed (Trenberth *et al.* 2007), a recent trend towards higher short-term extremes may be assumed. A small number of investigations have aimed at identifying trends in sub-daily precipitation extremes in Sweden and Scandinavia (e.g., Arnbjerg-Nielsen 2006; Bengtsson & Milotti 2008), but the collective result is inconclusive. Often only one or a few stations are analysed, often the measurement period is rather short for climate studies (which is especially critical when it comes to extremes), often trends found are weak and statistically insignificant. At a daily scale, the observational support is often substantially better and more suitable for trend analyses. Analyses of daily precipitation extremes during the second half of the 20th century in different parts of Europe have often indicated increasing trends, although the results are strongly dependent on, for example, region and season (e.g., Klein Tank & Können 2003; Haylock & Goodess 2004; Hundecha & Bárdossy 2005). Wern (2012) analysed daily extremes in Sweden and found an overall increase since the 1970s, preceded by a decrease since the 1930–1940s. In AR4 of the Intergovernmental Panel on Climate Change (IPCC), the overall global picture is summarised as a likely increase of rare precipitation events (with a return period of 10 years or more) since the end of the 19th century (Trenberth *et al.* 2007).

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One main way to estimate future changes in short-term precipitation is by analyses of regional climate model (RCM) projection data, but to date the number of studies focusing on sub-daily precipitation is small (e.g., Lenderink & van Meijgaard 2008; Onof & Arnbjerg-Nielsen 2009; Kyselý *et al.* 2012). A main reason for the limited interest is likely the scarcity of sub-daily observational precipitation products with which to meaningfully compare and validate gridded RCM output. Furthermore, when such products are available, evaluations indicate a higher bias in sub-daily RCM precipitation (extremes) than in longer accumulations (e.g., Hanel & Buishand 2010). Despite these limitations and uncertainties, future changes in RCM-simulated sub-daily precipitation extremes need to be thoroughly explored and compared with alternative estimation methods, e.g., statistical precipitation modelling and analogue region approaches (e.g., Arnbjerg-Nielsen 2012). Concerning Sweden, the few studies of short-term precipitation extremes performed to date, based on single or a few RCM projections, have generally indicated an increase of 0–25% until the middle of the century and 5–30% until the end of the century (e.g., Lenderink & van Meijgaard 2008; Olsson *et al.* 2009, 2013) but also larger increases have been found (e.g., Larsen *et al.* 2009).

The main aim of this paper is to provide an updated and more complete picture of what current climate projections indicate with respect to future short-term precipitation extremes in Sweden, than what is currently available. This is obtained by analysing 30-min precipitation in an ensemble of RCM simulations forced by GCM (general circulation model) projections in the period 1961–2100. Additionally, observed daily precipitation extremes in the period 1961–2010 are compared with RCM simulations forced with both meteorological re-analyses (e.g., ERA-40) and the above GCM projection ensemble in order to assess the realism of the RCM simulations. After some complementary analyses to assess the impacts of the spatial resolution and the specific RCM used on the results, the results are finally compared with other relevant studies.

## DATA

The main source of data is an ensemble of six climate projections for the period 1961–2100 (Table 1). All GCM projections were dynamically downscaled over Europe to 50 × 50 km resolution by the regional climate model RCA3 (Kjellström *et al.* 2005). The ensemble contains three GCMs (including two versions of the same model, ECHAM), three IPCC SRES scenarios and three model initialisation members. The SRES scenarios represent the uncertainty related to the future global development in terms of population, technology and socio-economy (Nakićenović *et al.* 2000). The initialisation members represent the uncertainty related to the projections' initial conditions and, in turn, reproduction of natural variability and low-frequency climate oscillations.

**Table 1** | Climate projections used in this study

| Denotation | General circulation model (institute) | IPCC | Member |
|---|---|---|---|
| E4_A2 | ECHAM4 (Max Planck, Germany) | A2 | – |
| E4_B2 | ECHAM4 (Max Planck, Germany) | B2 | – |
| E5_A1B_1 | ECHAM5 (Max Planck, Germany) | A1B | 1 |
| E5_A1B_2 | ECHAM5 (Max Planck, Germany) | A1B | 2 |
| E5_A1B_3 | ECHAM5 (Max Planck, Germany) | A1B | 3 |
| HC_A1B | HadCM3 (Hadley Centre, UK) | A1B | – |

From the projections, time series of total precipitation with a time step of 30 min were extracted in the RCA3 grid boxes covering Sweden (Figure 1). Five different 30-year time periods were defined: 1961–1990, 1981–2010 (main reference period; note the 10-year overlap with the earlier reference period), 2011–2040, 2041–2070 and 2071–2100.

Besides RCA3 simulations forced with GCM projections, we also use 30-min precipitation in the Swedish grid boxes (Figure 1) from an RCA3 simulation in the period 1961–2010 forced with meteorological reanalyses. The boundary fields in this simulation are based on the ERA-40 re-analysis until mid-2002 and operational European Centre for Medium-Range Weather Forecasts (ECMWF) analyses during the rest of the simulation period. This simulation represents RCA3 performance under optimal forcing, as the boundary is to a large degree based on observed meteorological fields. The simulation period was divided into two 30-year periods, in line with the GCM-based projections: 1961–1990 and 1981–2010.

Finally, precipitation time series with a 1-day time step in the period 1961–2010 from the national Swedish network were analysed. Similarly to the ERA-driven historical simulations, the periods 1961–1991 and 1981–2010 were

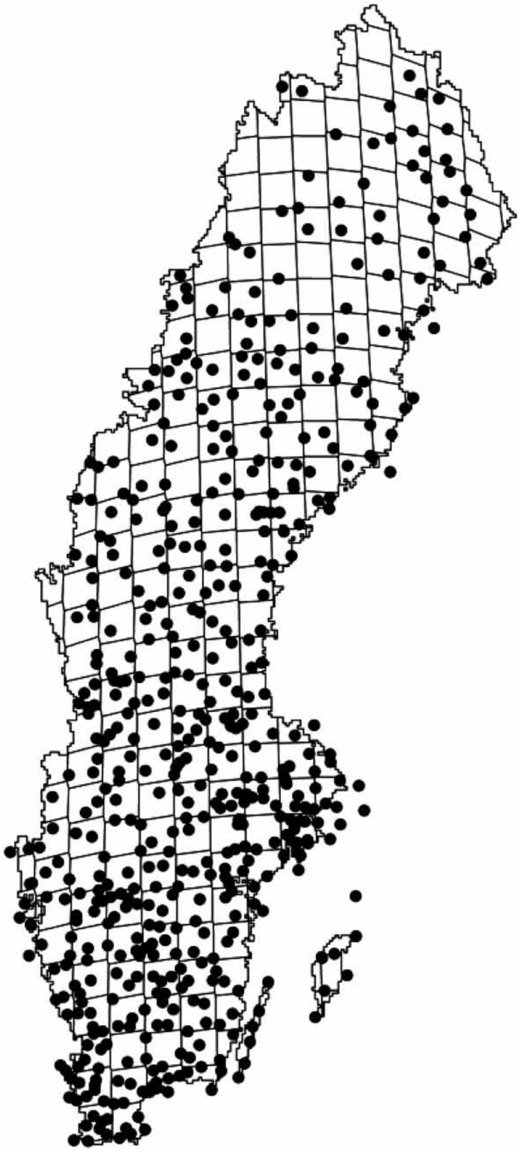

**Figure 1** | RCA3 model grid over Sweden and observation stations used in the analysis.

defined. From all available stations, the ones with at least 15 years of data in each period were selected for further analysis, producing a total of 540 stations rather evenly distributed over the Swedish land area, although the network density is somewhat lower in the north (Figure 1).

## METHODOLOGY

For each 30-year time series from each RCA3 grid cell, annual maxima of durations 30 min, 1 h, 3 h, 6 h, 12 h and 1 day were calculated by using a moving time window. For each duration, the Gumbel distribution was fitted to these sets of 30 annual maxima. The Gumbel distribution belongs to the generalized extreme value (GEV) family of distributions, whose members are defined by the value of the shape parameter $\theta$. The case $\theta = 0$ gives a Gumbel distribution, $\theta > 0$ a Fréchet distribution and $\theta < 0$ a Weibull distribution (also termed GEV types I, II and III; WMO 1981).

Prior to the Gumbel distribution fitting, an analysis of the $\theta$ parameter was made by optimising the GEV distribution (with free $\theta$ parameter) to RCA3-simulated maximum values of different durations over all of Sweden. The results showed that on average over different (30-year) time periods and durations considered, $\theta = -0.026$ with limited spread (standard deviation $= 0.14$) towards both positive and negative values. No clear dependence on time period or duration was found and no clear geographical patterns. This indicates that the Gumbel distribution is a suitable choice for a general investigation and the fit to annual maxima is generally good for all durations (Figure 2). For each combination of time period ($t$), location ($l$), duration ($d$) and projection ($p$), the precipitation amounts corresponding to return periods ($T$) 10 and 100 years $P_t^{l,d,T,p}$ (generally abbreviated to only $P$) were calculated from the fitted Gumbel distribution. In the analysis of observations, the GEV distribution with free $\theta$-value was used.

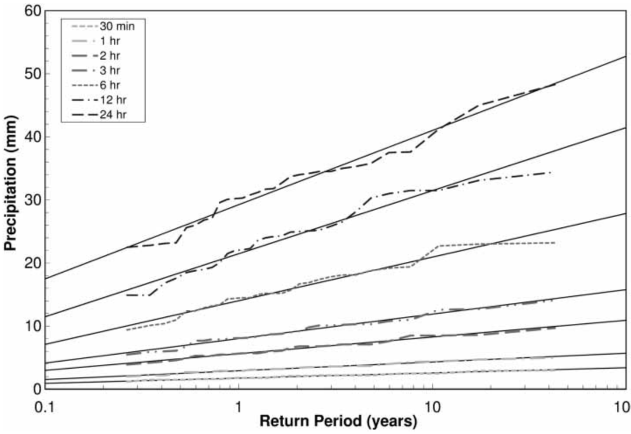

**Figure 2** | Example of fit of Gumbel distribution (solid lines) to annual maxima of different duration (dashed and dotted lines).

The most recent analyses of observed short-term precipitation extremes in Sweden indicate that they have no clear spatial dependence, at least below $d = 6–12$ h (Wern & German 2009). The national guidelines concerning precipitation data for urban hydrological design and analysis (Svenskt Vatten 2011) recommend a common intensity–duration–frequency formula for all of Sweden for durations between 5 min and 24 h (Dahlström 2010). Concerning daily extremes, Wern (2012) however found a tendency towards higher values in the south and lower in the north (for the same return period), but also that very high daily amounts (>90 mm/d) have been registered essentially all over Sweden.

In light of these results, and also an analysis of spatial dependence in the RCM simulations (see below), we focus mainly on nationally averaged extreme precipitation amounts, i.e.,

$$\overline{P^{d,T,p}_{t}} = \frac{1}{n}\sum_{l=1}^{n} P^{d,T,p}_{t} \tag{1}$$

where $n$ denotes the number of RCM grid cells covering Sweden. For simplification, in the following we use $P^S$ to denote the result of Equation (1), where $S$ denotes an average over Sweden. The relative difference between two periods is expressed as

$$\Delta P^{d,T,p}_{t1-t2} = 100\left(\frac{\overline{P^{d,T,p}_{t2}} - \overline{P^{d,T,p}_{t1}}}{\overline{P^{d,T,p}_{t1}}}\right) \tag{2}$$

where $t1 - t2$ denotes the change from time period $t1$ to time period $t2$ ($\Delta P^{d,T,p}_{t1-t2}$ will be abbreviated as $\Delta P^S$). The return period is 10 years unless explicitly mentioned.

For each combination of time periods, location, duration and return period, the relative change according to Equation (2) may be averaged over all six projections $p$ in the GCM-driven RCA3 ensemble as

$$\overline{\Delta P^{d,T}_{t1-t2}} = \frac{1}{6}\sum_{p=1}^{6} \Delta P^{d,T,p}_{t1-t2} \tag{3}$$

which is in the following simplified to $\overline{\Delta P^S}$. Despite that the projections cannot be assumed independent, as climate models as well as emission scenarios overlap, for simplicity and transparency we use equal weights in the averaging (Equation (3)). Also the standard deviation among the relative differences from different projections was calculated as

$$S^{d,T,P}_{t1-t2} = \sqrt{\frac{1}{6}\sum_{p=1}^{6}\left(\Delta P^{d,T,p}_{t1-t2} - \overline{\Delta P^{d,T}_{t1-t2}}\right)^2} \tag{4}$$

which will be simplified to $S^S_{\Delta P}$.

Some assessment was also made of spatial dependence in the estimated future changes, i.e., whether short-term precipitation extremes are expected to change differently in different parts of Sweden. For this purpose, the relative change in every RCM grid cell was calculated as

$$\Delta P^{l,d,T,p}_{t1-t2} = 100\left(\frac{P^{l,d,T,P}_{t2} - P^{l,d,T,P}_{t1}}{P^{l,d,T,P}_{t1}}\right) \tag{5}$$

which is in the following simplified to $\Delta P^l$ ($\overline{\Delta P^l}$ when referring to the mean value of the GCM-driven ensemble).

To assess whether calculated changes between time periods $t1$ and $t2$ are significant at the national scale, statistical testing was performed. The general null hypothesis is that for specific values of $d$, $T$ and $p$, the mean precipitation amounts in $P^{l,d,T,p}_{t1}$ and $P^{l,d,T,p}_{t2}$, $1 \leq l \leq n$, are equal. If this null hypothesis is rejected, the estimated change is statistically significant. Different types of tests may be used for this purpose. One common choice is the $t$-test for identical mean values, which however assumes a Gaussian distribution of $P^{l,d,T,p}_{t}$. The validity of this assumption was tested using the Lilliefors test. The results showed that the hypothesis of a Gaussian distribution was rejected at 5% significance in all cases (i.e., combinations of return period, projection and time period) for duration 30 min and in around half of the cases for duration 24 h (with a gradual change in between). From visual inspection of histograms, the rejection was mainly due to an elevated frequency of high extremes. Therefore, instead of the $t$-test, we use the Wilcoxon rank sum test (a.k.a. Mann–Whitney $U$ test) for equal medians (e.g., Helsel & Hirsch 1992).

## RESULTS AND DISCUSSION

Before characterising future changes in precipitation extremes, an analysis of data from the recent 50-year period 1961–2010 is made. The aim is to assess the realism of the RCM-simulated daily extremes, as compared with the observed ones, concerning magnitude, spatial dependence and temporal variability. The second section in this chapter deals with the future changes of short-term precipitation in Sweden at different time horizons. As these results are based on one single RCM, which is set-up and run at one single spatial resolution, some complementary analyses are reported in the following section, aiming at assessing the impacts of these limitations on the final results. Finally, the estimated future changes are compared with other studies to provide a state-of-the-art picture.

### Analysis of extremes in the historical period 1961–2010

As discussed above, no clear spatial dependence has been found for observed sub-daily precipitation extremes but they may be assumed equal for all parts of Sweden. For daily extremes, a weak north–south gradient was found by Wern (2012). This observed gradient is hardly visible in our main reference period 1981–2010 (Figure 3(a)), although it is clear that the 10-year precipitation $P$ in southern Sweden is generally higher than the one in northern Sweden. The mean value for all of Sweden, $P^S$, is 46.4 mm. The higher values along the eastern coast of central Sweden appear to be associated with a few particularly intense events in that area.

Turning to the RCA3 simulations, in the ERA-40-driven run a level of 40–45 mm is found in all parts of the country with higher $P$-values in some western regions, including the north-western mountains, and lower values in some extended eastern regions (Figure 3(b)). Neither do the GCM-driven RCA3 simulations exhibit any clear spatial patterns in the daily 10-year precipitation. Figure 3(c) shows the ensemble mean, which is by construction highly smoothed, but the individual simulations are overall similar and without clear gradients. In the ERA-40-driven simulation $P^S = 41.8$ mm and in the GCM-driven ensemble mean $\overline{\Delta P^S} = 43.5$ mm. As compared with the station-based estimates, lower values of $P$ are expected in the RCM simulations because of spatial averaging to the model grid ($50 \times 50$ km). It may be mentioned that Nikulin *et al.* (2011) found RCA3 to overestimate daily 20-year precipitation in Sweden by generally ~10–20% as compared with gridded observations (E-OBS; Haylock *et al.* 2008).

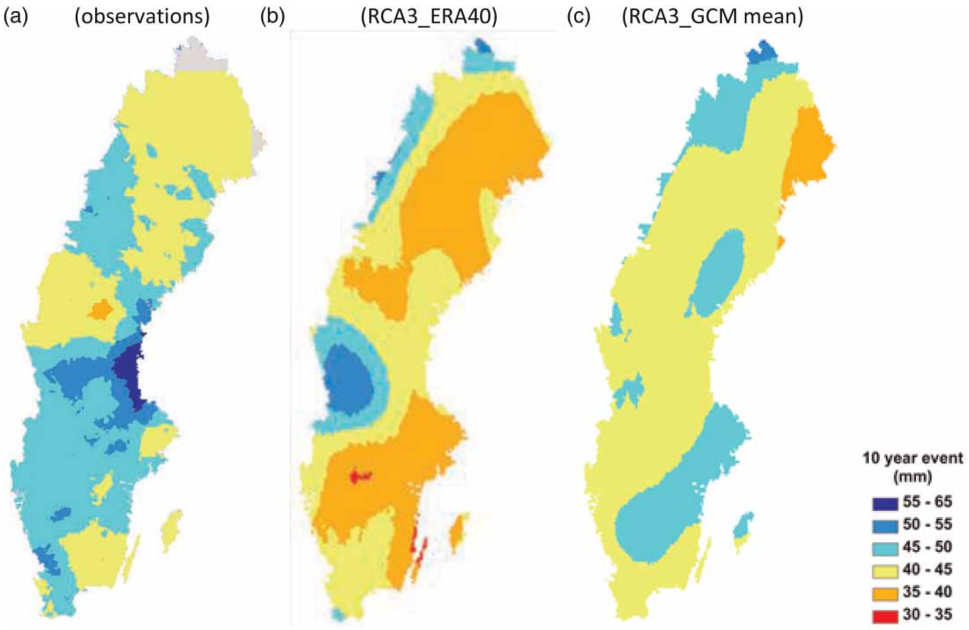

**Figure 3** | Daily 10-year rainfall amount $P$ (mm) in the period 1981–2010 in observations (a), ERA-40-driven RCA3 (b) and ensemble mean of GCM-driven RCA3 (c).

Based on these results, as well as analyses of shorter durations than 1 day, we conclude that (i) RCA3 generates daily $P$-values of a realistic magnitude and (ii) we may for this study consider Sweden as one homogeneous region with respect to short-term extreme precipitation. Thus, in the following we focus mainly on the nationally averaged value, $P^S$, and its difference between 30-year time periods, $\Delta P^S$.

Wern (2012) found a gradual increase in the annual maximum daily precipitation in Sweden from the 1960s until today. In the observations used here, $P^S$ increases by 6.4% from the period 1961–1990 to the period 1981–2010 (i.e., $\Delta P^S = 6.4\%$) and the difference is statistically significant according to the Wilcoxon rank sum test. In the ERA-40-driven RCA3 run $\Delta P^S = 3.6$ and also this difference is statistically significant. In the GCM-driven RCA3 ensemble $\Delta P^S$ varies between 0.4% and 7.6% with $\overline{\Delta P^S} = 3.7\%$; the difference is statistically significant for four out of the six projections used, as well as for the ensemble mean. It should be emphasised that due to the relatively short time period considered (50 years), the signal-to-noise ratio is very low and any agreement between observed and simulated differences may be coincidental. The results do not prove that the RCA3 simulations accurately reproduce temporal trends of extreme daily precipitation, but they indicate an overall realistic magnitude of the variability between two commonly used reference periods.

## Analysis of extremes in the future period 2011–2100

The results are summarised in Table 2 and Figure 4. Concerning the change of $P^S$ from period 1981–2010 to period 2011–2040, $\overline{\Delta P^S}$ is rather stable around 4% although exhibiting a slight increase with decreasing duration (Table 2, Figure 4(a)). Concerning the spread between individual projections, there is a distinct increase of $S^S_{\Delta P}$ with decreasing duration. At 1 day, the range is <10% but at 30 min the range is ~25% (Figure 4(a)). Projection E5_A1B_3 stands out with markedly higher values of $\Delta P^S$ than $\overline{\Delta P^S}$ for all durations. For $d \leq 6$ h projections, E4_B2 and E5_A1B_1 indicate a decrease of the 10-year precipitation between the two periods. The striking difference between projections E5_A1B_1 and E5_A1B_3 illustrates the potential impact of initial conditions (i.e., natural variability) on near-future changes. Judging from the two E4 projections, the impact

**Table 2** | Mean value $\overline{\Delta P^S}$ and standard deviation $S^S_{\Delta P}$ of the relative change (%) in 10-year precipitation amount averaged over Sweden in the GCM-driven RCA3 ensemble for all durations and time horizons

| | (1981–2010) to (2011–2040) | | (1981–2010) to (2041–2070) | | (1981–2010) to (2071–2100) | |
|---|---|---|---|---|---|---|
| **Duration** | $\overline{\Delta P^S}$ | $S^S_{\Delta P}$ | $\overline{\Delta P^S}$ | $S^S_{\Delta P}$ | $\overline{\Delta P^S}$ | $S^S_{\Delta P}$ |
| 30 min | 5.9 | 8.9 | 15.0 | 6.8 | 23.1 | 9.0 |
| 1 h | 4.2 | 8.1 | 10.8 | 5.9 | 18.2 | 8.3 |
| 3 h | 3.7 | 7.0 | 9.7 | 5.5 | 16.3 | 7.6 |
| 6 h | 3.8 | 5.3 | 9.5 | 4.9 | 15.2 | 6.3 |
| 12 h | 3.9 | 3.6 | 8.7 | 4.7 | 14.1 | 5.9 |
| 1 d | 3.4 | 3.1 | 8.1 | 5.1 | 12.6 | 6.0 |

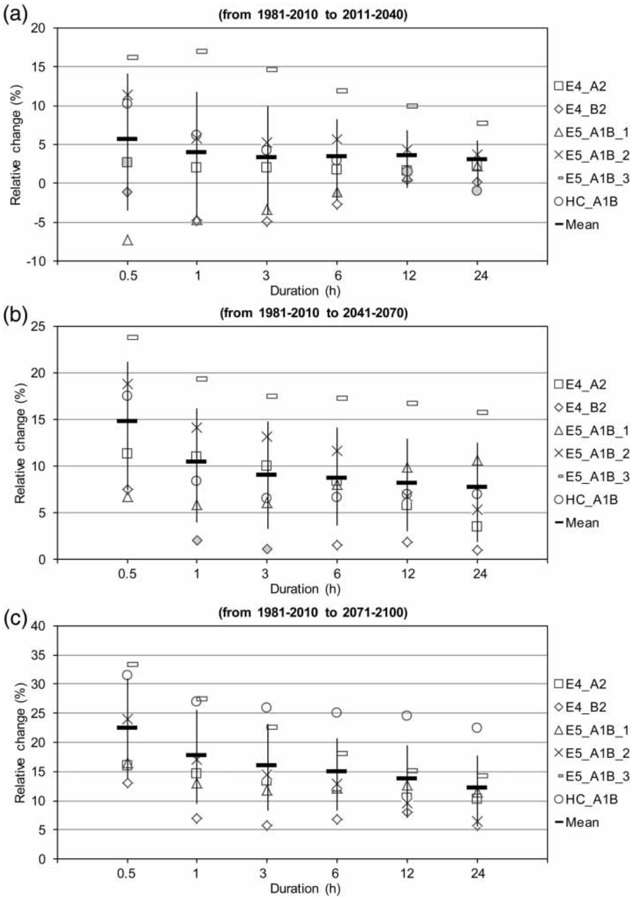

**Figure 4** | Relative change in 10-year rainfall amount averaged over Sweden in the projections ($\Delta P^S$) and in the ensemble mean ($\overline{\Delta P^S}$) from 1981–2010 to 2011–2040 (a), to 2041–2070 (b) and to 2071–2100 (c), as a function of duration. Vertical line represents ± one standard deviation ($S^S_{\Delta P}$). Grey symbol represents a change that is not statistically significant.

of IPCC emission scenario is limited on this time horizon, the change is generally within ±3% and in several cases not statistically significant. The change of E4_B2 is consistently lower than that of E4_A2, in line with the assumptions behind the scenarios.

From period 1981–2100 to period 2041–2070, a distinct increase of $\overline{\Delta P^S}$ with decreasing duration is evident, from 7% at 1 day to 14% at 30 min (Table 2, Figure 4(b)). The spread between the projections is overall similar at all durations; $S^S_{\Delta P}$ changes from ~5% at 1 day to ~7% at 30 min. Also on this time horizon, projection E5_A1B_3 stands out with very high values of $\Delta P^S$. The difference between the three initialisation members is large, especially for the shortest duration, indicating that natural variability is a major factor also on this horizon. Projection E4_B2 shows only a minor increase at all durations except 30 min, two of them not statistically significant.

Also until period 2071–2100 the value of $\overline{\Delta P^S}$ clearly increases with decreasing duration, from 12% at 1 day to 22% at 30 min (Table 2, Figure 4(c)). The spread is overall similar with $S^S_{\Delta P}$ ranging between 6% and 8.5%. At the longer durations, the spread between the initialisation members E5_A1B_1, E5_A1B_2 and E5_A1B_3 is limited, indicating that the impact of natural variability is small on this horizon, but at the shorter durations the spread is still large. This illustrates well the pronounced natural variability of very short-term ($\leq$1 h) precipitation extremes. The impact of IPCC emission scenario on changes of precipitation extremes in Sweden until the end of the century is limited, judging from the relatively small differences between projections E4_A2 and E4_B2 at all durations. Also the fact that two of the A1B-based initialisation members consistently show larger future changes than the E4_A2 projections indicate that the IPCC scenario plays a minor role (assuming that ECHAM4 and ECHAM5 behave similarly with respect to the process under study).

Concerning spatial dependence of the future changes in 10-year precipitation, some tendency towards a higher future increase in western Sweden was found in the ensemble mean of local changes, $\overline{\Delta P^l}$, most pronounced for the shortest durations and the farthest time horizon (2071–2100). If dividing Sweden vertically into a western and an eastern part of equal size, the mean value of $\overline{\Delta P^l}$ until period 2071–2100 becomes 3–5 percentage points higher than $\overline{\Delta P^S}$ (Table 2) in the west and lower than $\overline{\Delta P^S}$ in the west for $d \leq 1$ h. The difference decreases with increasing duration and at $d = 1$ d there is no difference. A look at the individual projections reveals that the east–west gradient is largely influenced by projection E5_A1B_3 but that the trend is weakly suggested also in most other projections.

Also a return period of 100 years was analysed. Overall the results are very similar to the ones reported above for 10-year precipitation. A marginally larger future increase was found, with values of $\overline{\Delta P^S}$ being on average less than one percentage point larger than the ones in Table 2. It should be emphasised that extrapolation to 100 years' return period from the 30-year time series is associated with large uncertainties, and in total no clear dependence on return period can be inferred from this study. It may be noted however that Andréasson *et al.* (2011) investigated 100-year 1-day precipitation using a large 16-member projection ensemble and found an increase by ~20% from 1961–1990 until 2071–2100, overall similar in all parts of the country. This is somewhat higher than the corresponding increase of 16.3% found in this study, taking into account the estimated increase (3.7%) between periods 1961–1990 and 1981–2010.

## Complementary assessment

It is well known that different RCMs produce different results, not least in terms of precipitation (i.e., Lenderink 2010). In a study of 1-h precipitation maxima in climate model projections, Hanel & Buishand (2010) used an ensemble of RCM projections that all were forced with the same GCM projection as projection E5_A1B_3 in this study and downscaled to a spatial resolution of 25 km over the Netherlands. Four RCMs were used, except RCA3 also RACMO, REMO and HIRHAM (see Hanel & Buishand (2010) for references and further information). Two versions of the GEV distribution were fitted to annual maxima in periods corresponding to the periods 1961–1990 and 2071–2100 used here, and the future changes were estimated.

Future changes for single projections are not reported in Hanel & Buishand (2010), but the first author kindly provided these results for the present assessment (Martin Hanel, personal communication). The results indicate that RCA3 generates a comparatively low future increase.

Averaged over both GEV versions, an increase of the 10-year precipitation by 14% is found for RCA3, which is the lowest value among the four projections; the mean value from the other projections is 35%. Assuming that the results are representative also of RCM performance in Sweden, this suggests that future changes in Sweden may exceed the numbers in Table 2. However, this possibility must be viewed with caution in light of the limited material used and the required assumption of transferability to Swedish conditions.

The RCA3 ensemble used in this study has a spatial resolution of 50 km. This is rather low today, when 25 km is standard and often ~10 km is used, but it was chosen because of data availability and the desire to include some older projections (E4_A2 and E4_B2). It is thus of interest to evaluate whether RCM grid size has any impact on the result. For this purpose, results from another ongoing study focused on the impact of RCM grid size on precipitation bias were used for a limited assessment.

Projection E5_A1B_3 is available with three different grid sizes: 50, 25 and 12.5 km. From these projections, precipitation time series from 1981–2010 and 2071–2100 were extracted for five locations corresponding to Swedish cities. To reduce statistical scatter, time series from five RCA3 grid boxes at the 50 km scale were extracted and analysed (one box centred over the city and one in each quarter). At the 25 (12) km scale, time series from the 20 (80) boxes covering the same area as the five 50 km boxes were extracted. For each time series, the Gumbel distribution was fitted to annual maxima of different duration in the way described above, after which the future change in 10-year precipitation was calculated and averaged over all grid boxes at the same scale.

In four locations, the future increase is smaller at the 25 km scale than at the 50 km scale, when averaged over all durations. In three of them, the increase is larger at the 12.5 km scale than at the 25 km scale but in the fourth the increase is further reduced to almost zero, i.e., at 12.5 km the 10-year precipitation is almost the same in the two periods. On average, over all locations and durations, the future increase at both 25 and 12.5 km scale is ~30% lower than the corresponding increase at 50 km scale. This indicates that future changes in Sweden may be lower than the numbers in Table 2. However, also this assessment is highly uncertain considering the limited material and the absence of clear tendencies.

## Comparison with related studies

The number of analyses of short-term precipitation extremes in RCM simulations over Sweden or Scandinavia is still rather low, although the subject has been studied for more than 10 years. In the following, some selected results are reviewed and finally compared with the results of this study. Unless stated, the reviewed studies have compared results from the earlier reference period 1961–1990 with the future period 2071–2100.

Concerning 1-day extremes, Räisänen & Joelsson (2001) in an early study calculated future changes in the annual maximum 1-day precipitation in two projections with different time horizons. For Scandinavia, an increase by 15–20% was indicated. In an analysis of four projections, Räisänen *et al.* (2004) found an increase of the annual maximum 1-day precipitation in Sweden by 5–15%. Frei *et al.* (2006) analysed eight projections and found an increase of the 10-year 1-day summer precipitation in southern Scandinavia by 5–40%. Nikulin *et al.* (2011), based on a six-member ensemble, found an increase of the 20-year 1-day summer precipitation in Sweden by 10–30%.

Concerning sub-daily extremes, Räsisänen & Joelsson (2001) estimated the future increase of annual maximum 6-h precipitation over Scandinavia to 20–25%. Lenderink & van Meijgaard (2008), based on one projection (reference period 1971–2000), found an increase of the extreme 1-h intensity in central Europe (including southern Scandinavia) by 30–40%, compared with a 20–25% increase of the extreme 1-day intensity. Larsen *et al.* (2009) found a very large future increase of 1-h extremes in Sweden, 50–100% depending on return period, but this was attributed partly to RCM temperature bias in the Baltic Sea region. Members of the ensemble used in this study have previously been used for local analyses in Swedish cities and generally an increase of the extreme 30-min and 1-h intensity by 20–30% has been found (e.g., Olsson *et al.* 2009, 2013).

From the review, it may be concluded that estimates of the future changes are overall rather consistent despite the use of different projections: combinations of GCM, RCM and emission scenarios, and different analysis procedures, for example, definition of extreme precipitation and selection of theoretical distribution. Generally, the increase of (sub-)hourly extremes exceeds that of 1-day extremes and this study is, to our knowledge, the first that explicitly investigates the gradual change between these scales. It may also be noted that early estimates of the future changes have proved overall accurate. The recent development of climate models and emission scenarios as well as the generation of large projection ensembles have not markedly changed the level of the expected future change in short-term precipitation extremes, but of course improved the possibility of uncertainty assessment.

## CONCLUSIONS

The main conclusions from this study can be summarised as follows:

- The RCA3-simulated daily 10-year precipitation in Sweden appears overall realistic, both when forced with meteorological re-analyses and an ensemble of six GCM projections, in terms of magnitude, (absence of) spatial dependence and variations between historical 30-year periods.
- According to the GCM-based ensemble, the future increase in 10-year precipitation increases with increasing time horizon and decreasing duration. From 1981 to 2010, the 10-year precipitation at duration 30 min (1 day) will increase by 6% (3%) until 2011–2040, 15% (8%) until 2041–2070 and 23% (13%) until 2071–2100.
- Other RCMs may generate higher future increases and a smaller RCM grid size may generate smaller future increases, but these indications are highly uncertain.

The results suggest that short-term precipitation intensities may increase by 20–30% until the end of the century, which is largely consistent with previous estimates. This is likely to affect in particular urban drainage structures and sewer networks, with increased risk of flooding and overflow, but also an increased frequency of flash floods and debris flow in rural areas is to be expected. Adaptation to minimise the damage and create a more 'hydrologically resilient' (urban and rural) environment is likely an important task for the future.

An issue not considered in this study is bias in RCM-simulated sub-daily precipitation extremes. Some general sub-daily precipitation characteristics may be meaningfully assessed using short-term station data. For example, Jeong *et al.* (2011) found that RCA3 is not able to match the observed diurnal cycle in some respects, notably the warm season afternoon peak which is closely related with short-term extremes. To assess the magnitude of simulated extremes at hourly scales requires a long observation-based gridded data set with this high time resolution; various efforts to generate such data sets are ongoing. The significance of the results from the study presented in this paper thus requires an assumption that any bias does not invalidate the RCA3 model's ability to credibly simulate future changes of short-term extremes. It is our hope that the new generation of more spatially resolved, convection-permitting RCMs, that are currently being developed and evaluated (e.g., Kendon *et al.* 2012), will more accurately reproduce all aspects of observed precipitation and thus increase the confidence in simulated future changes.

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