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Climate change impacts on urban rainfall extremes: influence of time and space scales

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Summary

The quantile mapping or perturbation method is frequently applied as statistical downscaling method for impact analysis of climate change in urban hydrology. It is based on the assumption that the change factors, describing the change from the current to the future climate - as obtained from climate model outputs at a given space and time scale (e.g. GCM/RCM grid size, daily), are also applicable at the smaller (i.e. point, sub-daily) scales. This assumption is in this paper tested by means of new generation, super resolution climate models. This is done for extreme rainfall in central Belgium.

The following three main findings are obtained:

- Validation of the climate model results based on intensity–duration–frequency (IDF) curves shows a better match with historical observations for the higher resolution models.
- Results moreover indicate that one has to be careful in assuming spatial and temporal scale independency of climate change signals in the statistical downscaling.
- Climate change impact analysis based on coarser resolution models may lead to significant underestimations of the future rainfall extremes (up to 70% by the end of the century).

Keywords

Climate change, precipitation, statistical downscaling, sub-daily time scales, IDF, design storms, urban hydrology

Introduction

Climate change impact analysis is typically based on coarse resolution regional and/or global climate models. Due the small spatial and temporal scales of urban hydrological processes, their results need to be downscaled (Arnbjerg-Nielsen et al., 2013). The common approach here is the use of a statistical downscaling and/or bias correction method. The statistical downscaling methods are, however, based on one of more assumptions, which are difficult to evaluate. This means that the validity of the statistical downscaling approach is highly unclear in practice. One solution would be to apply an ensemble of downscaling methods and test the sensitivity of the climate change impact results on the method and assumptions selected (e.g. Gregersen et al., 2013; Sunyer et al., 2015). Another approach is to validate the assumptions based on super-resolution climate models for which first results become available these days.

The current paper focuses on the validation of one of the statistical downscaling methods that is frequently applied in (urban) hydrology: the quantile mapping or quantile perturbation approach (Sunyer et al., 2015; Willems & Vrac, 2011). This approach is an advanced version of the delta change method. In this method, climate change signals are derived by comparing the climate model results for a future scenario period with the ones for a historical control period. For rainfall, these climate change signals often take the form of change factors. They represent the ratio of the rainfall intensity for the future period over the intensity for the historical period, and can be computed for different return periods and time scales. However, they cannot be computed for time scales smaller than the smallest time step for which climate model outputs are available. The same applies to the spatial scales: the change factors cannot be computed for spatial scales smaller than the grid resolution of the climate models. Although sub-daily outputs become more and more available, public databases often provide the outputs at the daily time scale. These databases contain results from global climate models (GCMs) with spatial resolutions of 125-350 km, and regional climate models (RCMs) with resolutions in the range 0.11° – 0.44° (25-50 km). Most authors applying the delta change or quantile mapping or perturbation statistical downscaling method then assume that the change factors obtained for the GCM or RCM scales (or the time or spatial scales of the climate model outputs) are also applicable at the smaller (i.e. point, sub-daily) scales.

This assumption has been tested based on super resolution climate models for which few runs became available recently for Belgium. Comparison has been made of climate model outputs at different resolutions.

Material and methods

Climate model runs

Two super resolution climate models, CCLM and ALARO, have been considered. They are Local Area Models (LAMs) with spatial resolutions of 2.8-4 km (De Troch, 2016; De Troch et al., 2013; Hamdi et al., 2013; Brisson et al., 2016; Saeed et al., 2017). Thanks to this high spatial resolution, the LAMs allow convection to be simulated explicitly; they are therefore also called convection-permitting models. For the same reason, it is expected that the LAMs have a higher accuracy in simulating extreme precipitation intensities as a consequence of convection induced thunderstorms. In order to inter-compare climate model results at various resolutions, the LAMs were complemented by an ensemble of all available regional and global climate models. The regional climate model (RCM) results were obtained from the EURO-CORDEX database (http://www.euro-cordex.net/); the global climate model (GCM) results from the CMIP5 archive (http://cmip-pcmdi.llnl.gov/cmip5/).

For all LAM, RCM and GCM runs, precipitation data were extracted for the pixel covering the Uccle station in Central Belgium. This was done as high quality 10-min precipitation data measured with the same instrument are available at this station for more than a century, of which the data for the period 1961–2010 were used in this study. In addition to the 10-min station observations, daily E-OBS gridded data for 27.8 km and 55.7 km were used. These gridded data were aggregated to larger pixels of 167 km and 501 km for a comparison with the gridded CMIP5 GCMs.

Change factors

From the climate model runs for the historical and future periods, change factors were computed for different return periods, also called quantile perturbation factors. They were obtained for the future period 2071-2100 for each of the RCP greenhouse gas scenarios (RCP8.5, 6.0, 4.5 and 2.6; Moss et al., 2008) separately, and also for all RCP scenarios combined. Comparison was made between the LAM, RCM and GCM based change factors. By comparison of the change factors of the higher resolution models with the coarser resolution models in which the higher resolution models were nested, the influence of the spatial resolution of the climate model on the climate change signals could be evaluated. Moreover, for the LAMs, model outputs are available for time scales down to 15 minutes.

Results

Validation based on IDF curves for historical period - LAMs

Results show that the high-resolution ALARO and CCLM models reveal an added value to capture sub-daily precipitation extremes during summer compared to the driving GCMs and reanalysis data. Further validation of historical climate simulations based on design precipitation statistics derived from intensity–duration–frequency (IDF) curves shows indeed a better match of the convection-permitting model results with the observations-based IDF statistics (Fig. 1). For the ALARO model, the CNRM-CM3 GCM in which the ALARO model was nested for one of the runs, shows strong underestimations, particularly for the daily time scale. The same was the case for the ERA40 and ERA-Interim dataset, which was applied at the boundary the ALARO model for other runs, but to a lower extent. Note that the model results and the observations should be compared at same or similar spatial scales. That is why the IDF curves for the observed intensities are shown for various spatial resolutions: for point observations, for pixel averaged (interpolated) observations at 27.8 km and 167 km grid sizes. Details on the spatial interpolations can be found in Tabari et al. (2016).

The higher resolution ALARO results (3 – 4 km resolution) clearly show less biased results (good spatial downscaling), and also reliable temporal downscaling down to a 1-hour time scale.

For the CCLM model (2.8 km resolution), similar conclusions are obtained. The EC-EARTH GCM used as boundary condition for some of the CCLM runs, shows more biased results, particularly for the smaller time scales. At the smallest time scale at which EC-EARTH results are shown, which is 3 hours, the bias is largest. The CCLM results are less biased, with a relative error that remains similar down to a time scale of about 30 minutes. For the lowest duration at which results were obtained, 15 minutes, CCLM results tend to underestimate the extreme precipitation intensities more.

The overall finding from these two high resolution LAMs is that they produce higher and less biased intensities in comparison with the GCM or other data in which they were nested.

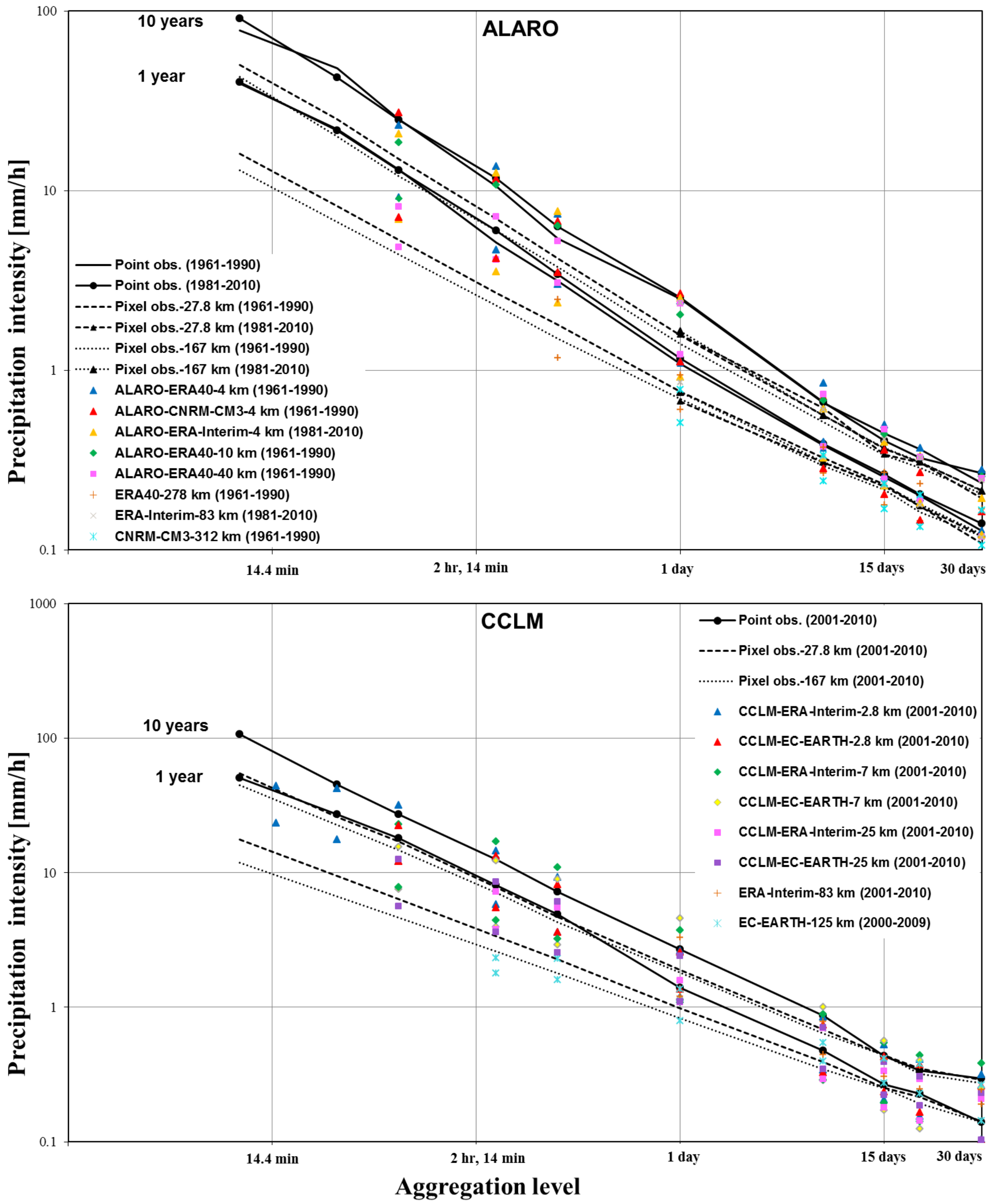

***Fig. 1**. Comparison of historical IDF relationships based on point and pixel interpolated observations, with CCLM, ALARO and the driving GCM or reanalysis results for the summer season and return periods of 1 and 10 years (IDF curves for the E-OBS pixel data were extrapolated for the sub-daily timescales based on extreme value distribution) (adopted from Tabari et al., 2016).*

Validation based on IDF curves for historical period - RCMs

That finer resolution models may show larger rainfall intensities was also confirmed after analysing 88 RCM runs available for 0.11° and 0.44° spatial resolutions from the EURO-CORDEX project. The comparative analysis in Fig. 2 shows that the precipitation intensities for time scales between 1 and 15 days and for return periods of 1 month, 1 year and 10 years are systematically higher for the 0.11° resolution models in comparison with the 0.44° resolution models.

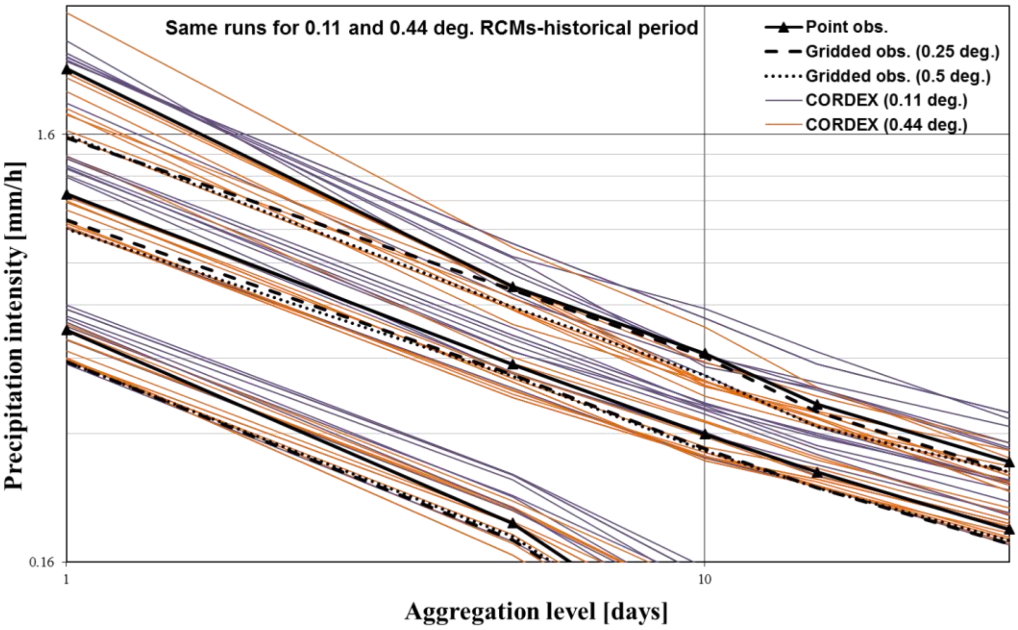

***Fig. 2**. Comparison of the current climate IDF curves between the EURO-CORDEX RCMs of 0.11° and 0.44° resolutions for return periods of 1 month, 1 and 10 years.*

Future changes

Next to the comparison of the LAM, RCM and GCM results for the historical control period, also the future changes were analysed. The change factors of the available ensemble set of CMIP5 GCM runs, EURO-CORDEX RCM runs and the two LAMs (ALARO and CCLM) all show a clear tendency of the expected extreme precipitation intensities for the future to increase.

Results for the LAMs indicate (Tabari et al., 2016) that one has to be careful in assuming spatial scale independency of climate change signals for the delta change downscaling method, as high-resolution models may show larger changes in extreme precipitation. These larger changes appear to be dependent on the climate model, since such intensification is observed for the CCLM model but not for the ALARO model. For the CCLM model, 3-hour summer precipitation extremes (average change for return periods between 1 year and 30 years) show maximum changes of 55, 11 and 14 %, respectively, for 2.8, 7 and 25 km runs vs. a maximum change of 8% for the driving EC-EARTH GCM. Results from the same model reveal that sub-daily precipitation extremes during summer change at a higher rate compared to daily extremes. It hence can be inferred that there is an increase in the change factors of sub-daily precipitation when going from parameterized convection (as considered in the GCM) to the convection-permitting scale (for the LAM).

That the finer resolution models may show larger changes in extreme intensities was confirmed after comparison of the 88 EURO-CORDEX RCM runs available for 0.11° and 0.44° spatial resolutions. In the case of the daily aggregation level, based on the 0.11° RCMs the 10-year return period rainfall intensity for RCP4.5 and RCP8.5 can increase up to around 50% and 70% respectively, whereas smaller increases are projected for the 0.44° RCMs: 25% and 50% for RCP4.5 and RCP8.5, respectively. Results on the future rainfall shown in Fig. 3 reveal that making a temporal stationarity assumption for the climate system, may lead to underestimation of design precipitation quantiles up to 70% by the end of this century. This shows the importance to incorporate fine resolution models in the analysis, and to consider statistical downscaling that accounts for the scale dependency.

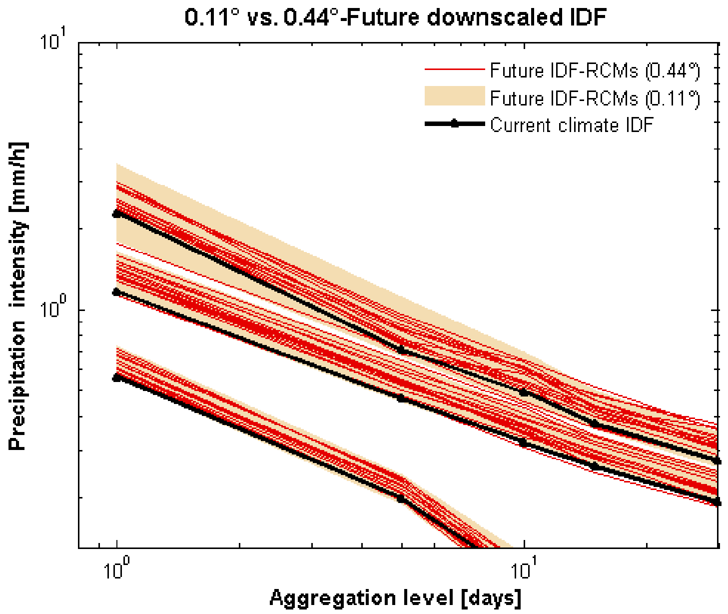

Fig. 3. *Comparison of the future climate IDF curves (2071-2100) between the EURO-CORDEX RCMs of 0.11° and 0.44° resolutions for same model runs for return periods of 1 month, 1 and 10 years (current climate IDF curves based on the station observations are shown in black color).*

Considering the higher intensities of precipitation (return periods higher than 1 year), the amount of increase is higher for smaller time scales and larger return periods (Fig. 4). The precipitation intensity with hourly time scale and 10-year return period may increase up to about 100%. Furthermore, the increase in the design storm intensities as derived from the CMIP5 ensemble increases with the CO_2 concentrations in the RCP scenarios, ranging from 37% in the RCP2.6 scenario to 64% in the RCP8.5 scenario (Fig. 5). The changes depend on the return period and the aggregation level, with an amplification for larger return periods and smaller aggregation levels.

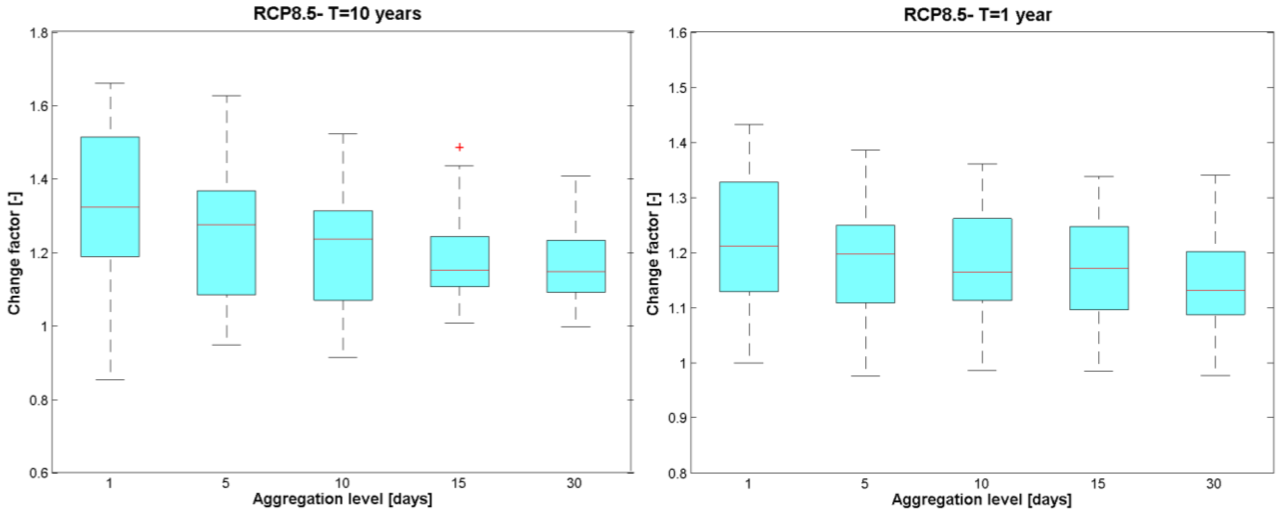

Fig. 4. *Change factors of the EURO-CORDEX 0.11° RCMs for different durations and return periods.*

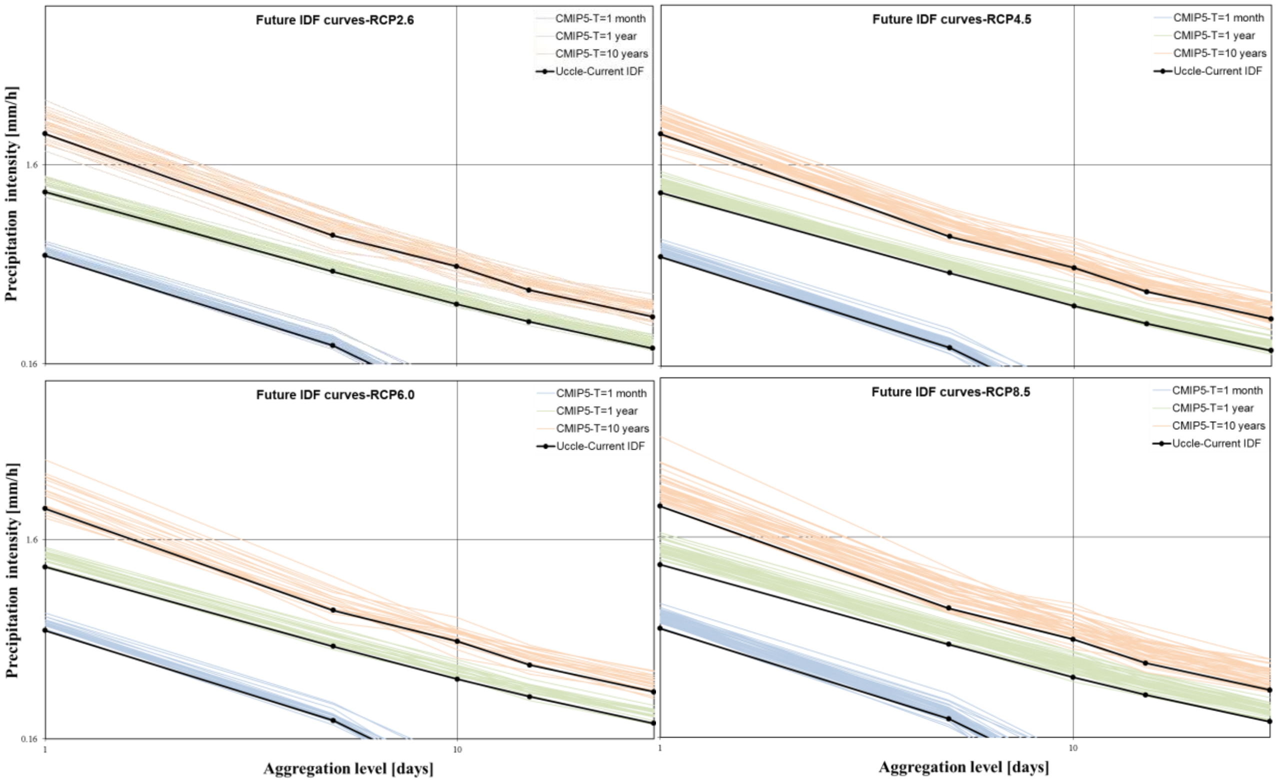

***Fig. 5**. Future climate IDF curves (2071–2100) after quantile perturbation based on the CMIP5 GCMs versus the current climate IDF curves for return periods of 1 month, 1 and 10 years.*

Conclusions

Results of the inter-comparison between the higher and coarser resolution climate models indicate that one has to be careful in assuming spatial and temporal scale independency of climate change signals for the delta change downscaling method. The high-resolution models may show larger changes in extreme precipitation. At the smaller scales, which are of highest relevance for urban hydrological applications, atmospheric processes controlling the extreme precipitation intensities at these scales – such as convection – get an enhanced, more explicit, description in the models. It is clear that urban hydrologists need to keep a close eye on the super resolution convection permitting local area climate models, which are quickly progressing at climate modelling centres worldwide. The number of simulations so far is still very limited and simulation periods still relatively short, mainly due to the huge computational burden. This means that one does not have a large ensemble of super resolution climate model runs available yet. There is a need for such ensemble as different models, not only the high resolution models themselves, but also the GCMs or RCMs in which they are nested, still project large differences in results. Climate model based variance analysis for extreme precipitation by Hosseinzadehtalaei et al. (2017) indicated that at least 10 to 15 different models should be considered for a reliable uncertainty analysis. However, our understanding of the climate physics and computational capacities are progressing to quickly that more coherent and accurate results are expected in the years to come. In the meantime, urban hydrological impact modellers have to rely on combining available climate change projections from GCMs (large ensemble available; CMIP5), RCMs (smaller ensemble available; CORDEX) and LAMs (few models and runs available for some regions), to be further downscaled applying statistical methods. As indicated in this paper, the statistical downscaling assumptions have to be applied with caution and validated as much as possible.

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