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Statistical precipitation downscaling for small-scale hydrological impact investigations of climate change

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SUMMARY

Impact investigations of climate change on urban drainage require projections to be made on short-duration precipitation extremes. The relevant time scales can be as low as 10 min, which requires strong statistical downscaling of climate model simulation results. In this research, two sets of methods have been suggested and tested based on Belgian data. The first set makes direct use of the precipitation results of the climate models. They involve computation of quantile perturbations on extreme precipitation intensities, and the tested assumption that the same perturbations hold for daily and sub-daily time scales. The second set of methods is based on weather typing, and accounts for the low accuracy of daily precipitation results in current climate modelling. In these methods, climate model outputs on pressure (atmospheric circulation) are used to obtain precipitation estimates from analogue days in the past. Different criteria for defining analogue days have been tested. The weather typing methods have been further advanced accounting for the fact that precipitation change does not only depend on change in atmospheric circulation, but also on temperature rise. Results have been investigated as changes to precipitation intensity–duration–frequency (IDF) relationships. It is shown that both the quantile-perturbation and advanced weather typing based methods allow precipitation biases in climate model simulation results to be largely corrected. Both types of methods moreover produce similar short-duration changes in precipitation extremes, which gives some credibility to the downscaled impacts. The corresponding changes in IDF statistics show that the extreme precipitation quantiles typically used for design of urban drainage systems, can increase up to 30% by the end of this century. Those changes mean that sewer surcharge or flooding would occur about twice more frequently than in the present climate (if no other environmental or management changes are accounted for). This would have a significant impact on future urban water management and planning.

1. Introduction

One of the major problems in current hydrological impact investigations of climate change is the spatial and temporal scale mismatch between the outputs of climate models (General Circulation Models or Regional Climate Models) and the small scale at which hydrological impact investigations are carried out. Up-to-date global and regional climate models produce results at spatial grid sizes in the range from 100 to 10 km, and at time steps of days to hours. Hydrological impact investigations, however, need information on climate changes at finer spatial scales (down to point scales), and for time scales as small as few minutes. Although river and urban drainage catchments most often have spatial sizes of at least few kilometers, the precipitation, temperature and evaporation inputs to hydrological models are most frequently based on point data (from meteorological stations). In terms of temporal scale, the flow in urban drainage systems has response times to precipitation in the order of magnitude of minutes. For Belgium, 10 min can be considered the shortest response time of our urban drainage systems.

In order to overcome this scale related gap between what climate models provide and what hydrological impact modelers need, statistical downscaling methods are traditionally applied. In the literature, they are usually classified in three types (Wilby et al., 1998; Nguyen et al., 2006; Fowler et al., 2007; Vrac and Naveau, 2007):

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- Transfer function approaches, trying to translate directly large-scale atmospheric information to local-scale meteorological data. In this class, some recent developments for enhanced downscaling of precipitation can be found in Vrac et al. (2007b), Dibike et al. (2008) and Olsson et al. (2004);
- Stochastic weather generators (Wilks and Wilby, 1999; Olsson et al., 2009), which are statistical models generating local-scale time series based on probability density functions whose parameters can be related to large-scale data (e.g. Vrac and Naveau, 2007); and
- Weather typing approaches, conditioning the simulation of small-scale data on so-called weather types over the region of interest (e.g. Vrac et al., 2007a).

Current literature on the development, application and testing of statistical downscaling methods, however, mostly focuses on hydrological impacts on larger river catchments and at daily time scales. These scales are rather coarse in comparison with the needs for finer scale urban drainage impact investigations (10-min and point scale). Most studies furthermore only cover one specific selected downscaling method. Given the high uncertainties involved in the downscaling process (see also the results of this paper), good practice would involve quantification of these uncertainties. Given that future climate conditions are highly uncertain, it is clear that such quantification is very difficult (which probably also explains why past studies most often did not deal with it). Instead of quantifying statistical uncertainties, it would, however, be possible to deal with scenario uncertainties. In the same way as it became common practice in climate change impact modelling to use an ensemble modelling approach using several climate model runs (several climate models, greenhouse gas emission scenarios and initial conditions), it should become common practice to apply several downscaling approaches. The latter would require an ensemble of statistical downscaling techniques and scaling assumptions to be considered.

This paper deals with the testing of statistical downscaling techniques with particular focus on small-scale hydrological impact investigations. In these investigations, the change in local precipitation is of primary importance. Uncertainties in the assessment of local scale precipitation changes mainly arise from (i) the significant uncertainties in the precipitation results from the climate models and (ii) the various assumptions underlying the downscaling process. Referring to reason (i), it is well-known that the uncertainties in the precipitation results of climate models are an order of magnitude higher in comparison with the climate model outputs on pressure (atmospheric circulation) and temperature (Hewitson, 1996; Baguis et al., 2009). This brings us to the two classes of statistical downscaling methods considered in this paper: methods that make use of the precipitation results of the climate models, and methods that do not make use of these results but are based on the more accurate climate models outputs, namely atmospheric pressure and related circulation patterns and temperature. When considering the former class (i.e., use of GCM precipitation), either the climate model precipitation results are used directly, or only the information of the precipitation changes. The precipitation changes can be represented in the form of "perturbation factors" (factor change φ), as commonly used in the so-called "Delta-approach" (Gellens and Roulin, 1998; Lettenmaier et al., 1999). When the precipitation results are biased (say with a factor φ_b), and assuming that the bias will be identical under future climate conditions, the same bias factor φ_b applies to the precipitation results under current climate conditions and the precipitation results under future climate conditions. It is clear that under these conditions the perturbation factor is not affected by the bias. Consequently, the results on the factor change (the perturbation factors) can be seen as being more accurate in comparison with the precipitation results themselves. This partly meets the above-mentioned problem on the poor accuracy of the climate model precipitation results.

The perturbation factors can be derived depending on different conditions, such as season, month of the year, time scale, precipitation intensity or exceedance probability of this intensity. The dependence on season and month is trivial given that climate conditions and their changes highly depend on the period in the year. Dependence on intensity or exceedance probability (or return period) might be relevant as well, given that changes in more extreme rain storms might differ from changes in less intense (i.e., more regular) storms. Given that intensities associated with given exceedance probabilities are called quantiles, the corresponding perturbation factors are in this paper called quantile-perturbation factors.

The second type of methods, which do not make direct use of the precipitation results of the climate models, tries to relate (small-scale) precipitation to the (climate model scale) atmospheric pressure and temperature results. This is commonly done by means of "weather typing" (e.g. Vrac and Naveau, 2007). For each time step (i.e., day) in the climate model simulation result, the atmospheric circulation pattern is identified from the climate model spatial atmospheric pressure results. The pattern is selected out of a limited set of patterns (or weather types). The local (downscaled) precipitation value for that day is taken from a local historical precipitation series, selecting the day in that series having analogue large-scale weather conditions (Zorita and von-Storch, 1998). "Analogue" means that the large-scale condition of the day to be downscaled is similar to that of 1 day in the historical dataset. This similarity can be defined through different distances or metrics, and can involve weather types (or more generally circulation data over a large region), as well as other criteria, such as season, month of the year and temperature.

Both types of statistical downscaling (SD) methods have been applied and tested in the paper. Because the hydrological impact investigations envisaged for this paper include the impacts on high runoff flows (in order to assess climate change impacts on floods), specific focus is given to the high precipitation extremes. Due to this focus, the perturbation factors (in the first type of methods) are considered in a quantile-based way. The quantile-perturbation based methods hereafter will be referred to as statistical downscaling methods type A: SD-A, whereas the methods based on weather typing are called methods type B: SD-B.

The downscaling approaches are calibrated and tested based on local data (including 10-min precipitation) for the main hydro-meteorological station of the Royal Meteorological Institute of Belgium at Uccle (Brussels) and a set of available climate model simulations covering that location.

Section 2 describe the data used (climate model runs and historical data). Sections 3 and 4 thereafter give an overview of the quantile-perturbation and weather typing based downscaling methods applied and evaluated in this paper. Section 5 summarizes the results and evaluates the differences, and is followed by general conclusions in Section 6.

2. Data used (climate model runs and historical data)

Use is made of global climate model simulations, specifically for the climate model grid cell covering the main meteorological station of Belgium at Uccle (Brussels). From the European ESSENCE project (http://www.knmi.nl/~sterl/Essence/), a set of 17 ensemble runs from the ECHAM5 general circulation model were provided by the Dutch Royal Meteorological Institute (KNMI). These ensemble runs are labelled as run 21 till run 37 and cover continuous simulations for the period 1950–2100 (historical forcing till