Comparison of perturbation methods for rainfall and temperature data: case of a Belgian catchment

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Abstract: Analyses of hydrological impacts of climate change require appropriate methods for perturbing meteoric time-series to represent future climate conditions. Two readily available tools for perturbing rainfalls and temperatures are tested for a medium-sized catchment in Belgium. CCI-HYDR provides three scenarios, tailored for Belgium every decade until 2100. In contrast, KNMI-ADC tool provides 191 scenarios, at a regional level and for two horizons (near and far future). With its three contrasted scenarios of possible future climate conditions, CCI-HYDR is found suitable for forcing computationally intensive detailed hydrological models. With its broader spectrum of climate scenarios, KNMI-ADC tool is suitable for forcing multiple runs of fast conceptual hydrological models. As the two perturbation tools deliver stationary time-series, they are also compared to an alternate method producing transient time-series. Transient stochastic tools are particularly computationally demanding due to their stochastic nature, which is not optimal when combined with detailed distributed hydrological models.

Keywords: rainfall perturbation; climate change scenarios; hydrological modelling.

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1 Introduction

Climate change is expected to affect the hydrological cycle on Earth in many aspects (IPCC, 2014), which still need to be further assessed to guide adaptation and risk management policies. The current practice for estimating the hydrological impacts induced by climate change in a given watershed consists in running multiple hydrological simulations based on different scenarios of future climate and to compare them with a baseline situation (e.g., Mujere and Eslamian, 2014; Gohari et al., 2015). To this end, the forcing used in the hydrological model is generally derived from meteorological data (e.g., rainfall, temperature) *perturbed* to reflect the future climate conditions.

In this article, two different perturbation tools for estimating future meteorological time-series are compared for the estimation of high flows in the case of a catchment in Belgium (Dewals et al., 2015; Saadi et al., 2016). Both perturbation tools are based on the delta change method (Baguis et al., 2008; Te Linde et al., 2010; Van Pelt et al., 2012; Seaby et al., 2013) and produce stationary time-series of at least 30 year, centred on a target year in the future. The main novelty and objective of the study is to provide a critical review and intercomparion of available tools for perturbing meteorological data in a Belgian catchment. The suit-ability of each method for performing climate change impact assessment is considered, as well as the relative efficiency of each approach in terms of necessary computational resources.

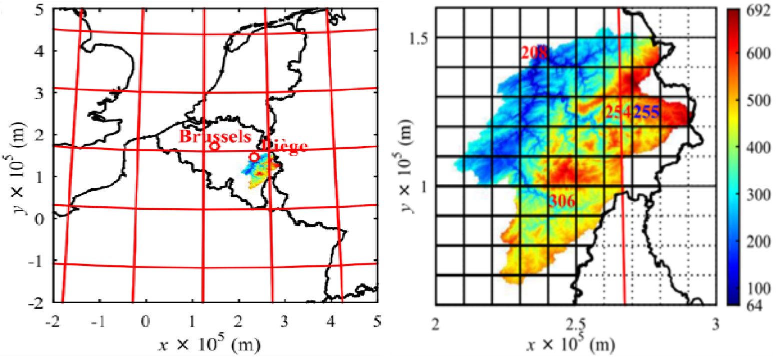
In Section 2, the case study is briefly described. Next, the two perturbation tools are presented (Section 3) and applied to meteorological data from the case study (Section 4). Finally, the pros and cons for each method are highlighted and discussed (Section 5). In particular, the CCI-HYDR and KNMI-ADC tools are compared to an alternate method based on a weather generator and producing stochastic climate-evolving time-series (Goderniaux et al., 2011).

2 Case study

The River Ourthe is one of the main rivers in the Meuse basin, which extends over parts of France, Belgium and the Netherlands. The Ourthe catchment (~3,600 km^2) is located south-east of the city of Liege (Belgium). The northern and the western parts of the catchment are alluvial plains of the Meuse River and remain below 300 m (Figure 1); they are covered by urban areas and arable lands. The eastern and southern parts of the catchment are above 400 m in elevation (Figure 1); they are less urbanised and are mainly covered by forests, grasslands and moorlands.

Meteorological (rainfalls and min/max temperatures) were obtained from the Belgian Royal Meteorological Institute (RMI). These data are distributed on a regular grid of 10 km × 10 km cells [Figure 1(b)] and they are available at a daily time step from 1961 onwards.

Figure 1 (a) Dem of the Ourthe catchment: localisation in northern Europe (b) Localisation of the DEM in the Walloon region and identification of the cells of the spatialised meteorological data (plain black squares) (see online version for colours)



(a) (b)

Notes: In red: positions of the reference cells of the KNMI method. The red line corresponds to the boundary of one KNMI cell. Coordinates system is Lambert 72

Source: Belgium datum

3 Perturbation tools

Two perturbation tools are introduced here. They are freely available for the generation of perturbed meteorological data to be used as inputs for hydrological modelling.

3.1 CCI-HYDR

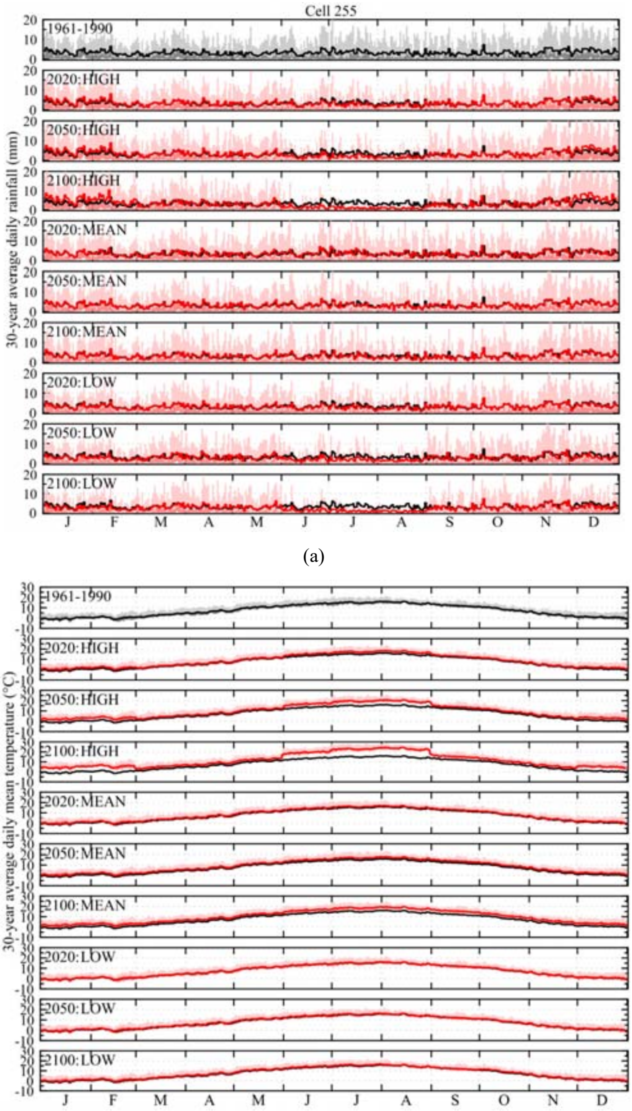
The tool CCI-HYDR is implemented in R. It uses the quantile perturbation method (Baguis et al., 2008; Willems and Vrac, 2011). Rainfall, evapotranspiration (ETo), temperature and wind speed time series (Ntegeka et al., 2014; Tabari et al., 2015) are perturbed according to three 'tailored scenarios' specific to Belgium: the 'HIGH' scenario assumes highly wet winter and dry summer (frontal rainfall), the 'MEAN' scenario corresponds to mildly wet winter and dry summer, while the whole year is dry for 'LOW' scenario.

For each scenario, perturbation factors are used for modifying:

1 the rainfall time-series in wet-day frequency and wet-day intensity quantile

2 the ETo – based on the Penman method and specifically calibrated for Belgium – in intensity, while temperature and wind speed time-series are modified based on correlations with the rainfalls and the ETo.

Figure 2 30 year-average of daily rainfall and daily mean temperature at the cell 255 (see online version for colours)



(a)

Notes: Black line: mean of baseline time-series; red line: mean of perturbed series with CCI-HYDR, light area: percentiles 30–60 and dark area: percentiles 60–90.

These perturbation factors were extracted from a broader set evaluated on a daily (rainfall) or monthly-basis (ETo) by comparing measured / simulated data of the control period 1961–1990 to the results of the perturbed period 2071–2100:

1. coming from regional climate models (RCM) of the PRUDENCE project (Christensen and Christensen, 2007; Christensen et al., 2007) with the SRES scenarios A2 and B2
2. using the global climate models (GCM) of the IPCC4 AR4 database, with emission scenarios A1B and B1.

The set of perturbation factors was then updated by Tabari et al. (2015), who used the scenarios of the 5th IPCC Assessment Report (Moss et al., 2010). The specificity of these new scenarios is that they are no more based on storylines defining the drivers of the emissions, but consider radiative concentration pathways (RCP) covering the whole range of climate change scenarios of the literature. The HIGH (resp. MEAN, LOW) scenario perturbation factors are therefore the maximum (resp. mean, minimum) perturbation factors amongst all those worked out for every day/month or frequencies (when using probability exceedance). Notice that the calculation of the perturbation factor used for the rainfall is reinforced by the use of a comparison of a 100 year-long rainfall time series at Uccle in Belgium (Willems, 2013a) with the perturbed rainfalls of the period 2071–2100.

The tool allows projections every five years from 2020 to 2100, the perturbation factor being linearly interpolated between those of the control and the perturbed period 2071–2100. The resulting perturbed time-series are 30 year-long, stationary and they are representative of the climate conditions at the target year. It should be noticed that even if more recent time-series are now available, the authors still recommend to use the control period 1961–1990, because the latter:

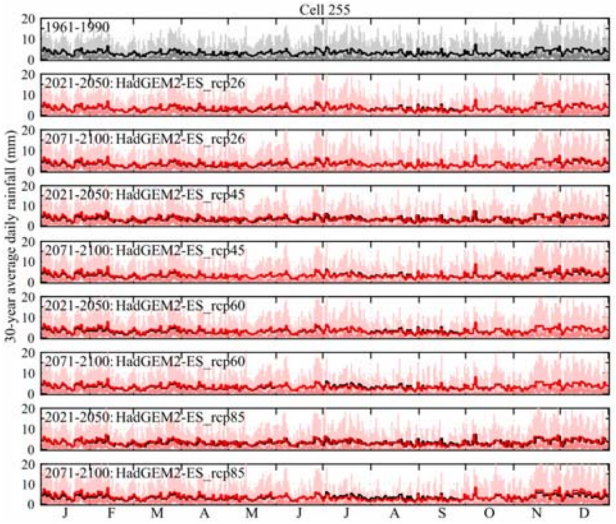
- coincides with a multi-decadal climate oscillation (Willems, 2013a, 2013b, 2013c), which ensures that peak and low climate oscillations are considered in the modelling.
- was used by the PRUDENCE project for the projection in 2071–2100.

The way the rainfall time-series are impacted in CCI-HYDR is highlighted in Figure 2, where the 30-year average of the daily rainfalls and mean temperatures at the cell 255 [position defined in Figure 1(b)] is displayed for the control and the three target periods for the three scenarios.

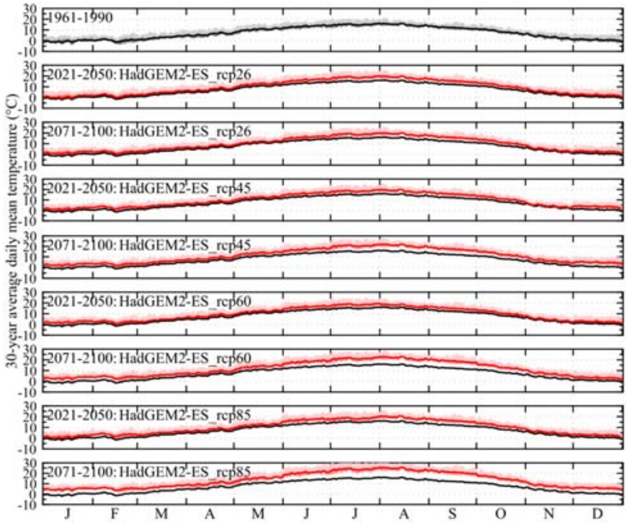
3.2 KNMI-ADC

The tool developed by the Dutch Meteorological Institute (KNMI) uses the advanced delta change method (ADC) (Kraaijenbrink, 2013a, 2013b). It applies a modified delta change method on rainfall and temperature time series only. This delta change method was improved for accounting for extreme value changes by using a non-linear transformation based on the 60% and 90% percentiles of the rainfall distribution (Van Pelt et al., 2012).

Figure 3 30 year-average of daily rainfall and daily temperature at the cell 255 for the near and far future periods of the KNMI-ADC tool using the runs of the GCM HadGEM2-ES for the four RCPs (see online version for colours)



(a)



Notes: Black line: mean of baseline time-series; red line: mean of perturbed series, light area: percen-tiles 30–60 and dark area: percentiles 60–90.

The parameters used in the method were evaluated by comparing the time series of the control period 1961-1995 of the observation data-set E-OBS 0.25° (Haylock et al., 2008) with time series of three simulated periods (control period: 1961–1995, near future: 2021–2050 and far future: 2071–2100) coming from 199 runs of 31 GCMs from the CMIP5 project (Moss et al., 2010), which applies four climate-forcing of the atmosphere (Kraaijenbrink, 2013a). Using these parameters, a change factor was defined for each cell of the common grid [red grid in Figure 1(a)] on a five-day sum basis for each future period and GCM. The main interest of this method is that the perturbation factors can be computed for numerous GCM (common grid definition: 2°E, 1.25°N).

As for the CCI-HYDR tool, the resulting perturbed time-series are 30 year-long and stationary. According to the authors, the perturbed time-series are representative of the weather (in terms of statistical distribution of rainfalls and temperatures) in the near or far future periods as displayed in Figure 3 for the GCM HadGEM2-ES with the four RCP scenarios.

4 Results

The perturbation tools were evaluated using data from four cells, as shown in Figure 1(b):

- Cell 208: outflow of the catchment. This cell covers mainly the city of Liege and its elevation does not exceed 200 m.
- Cell 306: source of river Ourthe. This cell corresponds mainly to forest and agricultural land. Altitudes are in-between 200 and 450 m.
- Cells 254 and 255 are located at higher elevations, where orographic rainfalls are expected.

The choice of cells 254 and 255 was motivated by the fact that the reference grid used in the KNMI-ADC tool passes between these two cells (red lines in Figure 1). By comparing the perturbed data in these two cells, it is thus possible to appreciate how the meteorological data are affected by a change in the perturbation factors of the KNMI-ADC tool.

The effects of the data perturbation are evaluated for each method in two ways:

1 by simply analysing the 30-year distribution of daily rainfall and mean temperatures

2 by comparing the probability of exceedance of the maximum of daily and/or the five-day sum rainfall intensity in a wet event computed for the control period 1961–1990 and the target periods.

The wet events were identified using the following rules:

- a day (resp. a five-day sum period) is dry if the daily rainfall intensity is smaller than 0.2 mm/d (resp. smaller than 5 × 0.2 mm/d)
- a wet event is bounded by at least one dry day at its beginning and its end
- dry or wet events are considered as independent.

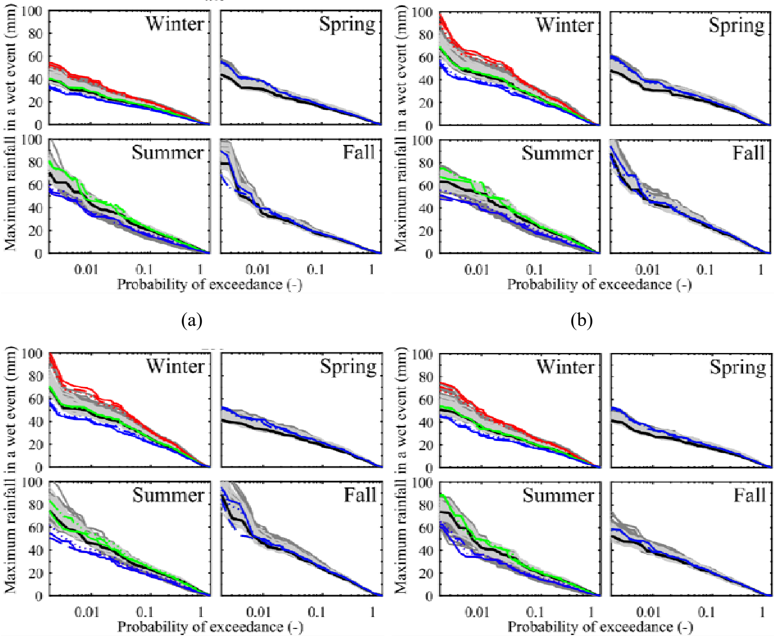
Next, the maximum values in each wet event were identified and then ranked in descending order (from $i = 1 : n_{ranks}$). The probability of exceedance,

$pe(i) = (i + c_1) / (n_{ranks} + c_2)$, was finally calculated as prescribed by Willems (2009) with Weibull variables c_1 and c respectively equal to 0 and 1. This probability exceedance computation corresponds to a standard peak over threshold method.

4.1 CCI-HYDR

The distribution of the 30-year average daily rainfall in Figure 2 for the cell 255 shows how CCI-HYDR affects the rainfall intensity and the distribution of wet/dry events in the series. For the HIGH scenario, the number of dry events increases with time, while the intensity of the rainfall decreases. In the LOW scenario, winter (December, January and February) and summer (June, July and August) are affected in the same way, i.e., a strong decrease of the number of wet events with increasing target years. Regarding, the MEAN scenario, changes are hardly visible in the distribution.

Figure 4 Exceedance probability of maximum daily rain intensity in a wet event, (a) 208 (b) 254 (c) 255 (d) 306 (see online version for colours)



(a)

(b)

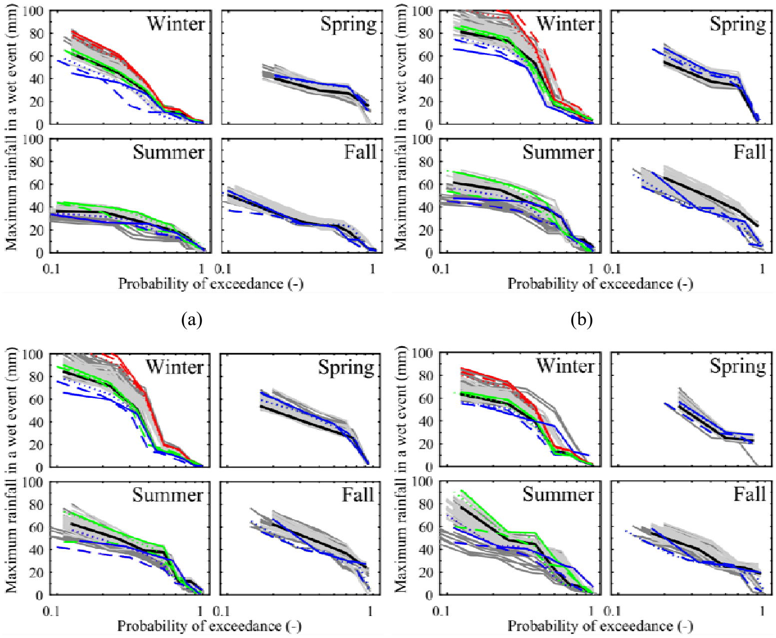
(c)

(d)

Notes: Black line: baseline; light grey lines: near future period of KNMI-ADC tool; dark grey lines: far future period of KNMI-ADC tool; red lines: HIGH winter scenario of CCI-HYDR; green lines: MEAN scenario of CCI-HYDR; blue lines: LOW scenario of CCI-HYDR (dotted lines: target year 2020; dashed lines: target year 2050; plain lines: target year 2100).

In the sequel, looking at the probability of exceedance of the maximum daily rainfall in a wet event, allows a better understanding of how the wet events are distributed in the perturbed series. These probabilities are displayed in Figure 4 for the four RMI cells. Winter and summer rainfall distributions are modified in terms of intensity and probability (i.e., frequency), while spring and fall seasons, by construction, are only modified in intensity and linearly follow the trends imposed by the multi-decadal climate evolution between the control periods1961–1990 and 2100. Considering summer results, HIGH and LOW scenarios collapse in term of exceedance probability, which indicates that wet events become less frequent in these two scenarios compared to the MEAN scenario.

Figure 5 Exceedance probability of maximum five-day sum rain intensity in a wet event, (a) 208 (b) 254 (c) 255 (d) 306 (see online version for colours)



(a)

(b)

Notes: Black line: baseline; light grey lines: near future period of KNMI-ADC tool; dark grey lines: far future period of KNMI-ADC tool; red lines: HIGH winter scenario of CCI-HYDR; green lines: MEAN scenario of CCI-HYDR; blue lines: LOW scenario of CCI-HYDR (dotted lines: target year 2020; dashed lines: target year 2050; plain lines: target year 2100).

Nevertheless, as pointed out by Kraaijenbrink (2013a) for the Rhine River, using daily statistics for evaluating the hydrological impact of climate changes may not be relevant depending on the size of the catchment. In the Rhine River, only long wet events of ten days and above are responsible for massive floods. Kraaijenbrink (2013a) therefore evaluated the climate changes' impacts using probability exceedances worked out with ten-day sums statistics. In our case, the Ourthe River is much smaller than the Rhine River. Using five-day sums statistics was found more relevant for computing the probability of exceedance of large wet events likely to generate floods in the catchment. The probability of exceedance based on the maximum of the five-day sum is displayed in Figure 5 with the same colour scale as in Figure 4. Results emphasise that the rainfalls are mainly impacted in winter by the perturbation method: strong five-day sum rainfalls can be easily obtained in winter, while for the other seasons the tendencies remain equivalent.

4.2 KNMI-ADC

In Figure 3, the distribution of 30-year average daily rainfall and mean temperature perturbed using the perturbation factors extracted from the comparisons with the results of the GCM HadGEM2-ES and the four RCP scenarios for the cell 255 emphasises that the changes in-duced by KNMI-ADC tool cannot be easily identified for the rainfalls, while an overall in-crease in temperature can be seen for all RCP simulations.

In Figure 4 and Figure 5, the exceedance probability of the maximum of the daily and five-day sum rainfalls in a wet event is represented for all the GCM runs. There were no significant differences between the seasons defined for CCI-HYDR for the present data. Nevertheless, the number of runs enables to scan a large range of perturbed rainfalls to be used for hydrological modelling runs.

Cells 254 and 255 of the reference grid are affected by different sets of KNMI-ADC perturbation factors. This has however only a minor influence on the rainfall perturbations (Figure 4 and in Figure 5): the distributions of exceedance probability are indeed similar in terms of maximum values and shapes. The comparison with the two other cells clearly indicates that the perturbation does not affect the intrinsic characteristics of the cells (plain, orographic area …).

5 Discussion

5.1 Comparison of the methods

The CCI-HYDR tool and the KNMI-ADC tool are compared together in term of performance for perturbing rainfall and mean temperature time series. Figure 4 and Figure 5 highlight that both tools are not tailored for the same kind of applications.

The CCI-HYDR tool allows scanning a whole range of perturbations using only three scenarios, including two extreme ones, the perturbations being mainly visible in winter and summer. In contrast, the KNMI-ADC tool allows testing a large number of scenarios, with perturbations better distributed all over the year. Nevertheless, in winter, the KNMI-ADC tool shows a smaller magnitude in the perturbations than CCI-HYDR. The contrary is observed for the other seasons, especially for spring and fall, were little changes are observed for CCI-HYDR. When looking at the exceedance probability in winter for the KNMI-ADC tool, the latter is close to the MEAN scenarios of CCI-HYDR, which indicates a slight increase in wet events in winter, but not as large as the HIGH scenario. A similar trend as the MEAN scenario is obtained in summer; the drought generated by CCI-HYDR is not as important with the KNMI-ADC tool. On the other hand, the climate in spring and fall is quite equivalent in terms of probability of exceedance for both methods, but the variability between GCM results for KNMI-ADC tool is larger.

Both methods also differ by another important aspect. While in the KNMI-ADC tool, the perturbations are distributed since they are linked to a reference grid (Figure 1), the CCI-HYDR tool assumes that data are spatially correlated. Indeed, this method uses a stochastic process to change dry and wet events frequencies at each considered meteorological station (Ntegeka et al., 2014). Consequently, if each station was treated independently and not aggregated into one for the studied catchment, their real correlations would be broken. This issue has been addressed in the latest version of the tool (Tabari et al., 2015). Still assuming that the meteorological data are correlated, the stochastic component of the transformation is evaluated at the first station and then applied consistently to all the other stations.

5.2 Generation of transient perturbed time series

One limitation of the discussed methods is that the resulting time series are stationary. One solution to overcome this issue is to use a stochastic weather generator coupled to one of the previous tools for producing unsteady meteorological time-series. A similar method was pro-posed by Goderniaux et al. (2011) for studying water evolution in an aquifer under climate evolution conditions. It used RCMs results and a stochastic weather generator (Kilsby et al., 2007; Burton et al., 2010a; 2010b; 2013) for generating several equiprobable transient time-series of weather (rainfall, temperature, …) from a start year to an end year. Goderniaux et al. (2011) used six RCMs ran 30 times based on a GCM with A2 scenario (PRUDENCE project) for evaluating the change factor of 2085 (centre of the 2070–2100 simulations) with respect to the period 1961–1990. The change factors from every year from 2010 to 2085 were evaluated, considering that the changes vary in proportion to the global temperature of the GCM. Finally, they generated equiprobable time-series for each year using a weather generator and the change factor of the corresponding year.

This kind of method is clearly of interest for impact analyses, as it gives access to non-stationary rainfall and temperature time-series, which enable to simulate a continuous evolution from current days to a future horizon. Nevertheless the quality of these time-series is conditioned by the proper use of the GCM/RCM for deriving the adapted change factors or other parameters for perturbing the time-series. The stochastic nature of the weather generator is an additional source of uncertainty, which therefore requires the generation of several time-series as highlighted by Goderniaux et al. (2011) for characterising this uncertainty. Under these conditions, running simulations, especially for distributed physically based hydrological modelling, would be particularly time consuming.

6 Conclusions

Two existing tools available for generating perturbed meteorological time series were com-pared. These tools can subsequently be used for forcing hydrological models to assess the hydrological impacts of climate change, particularly in terms of flood hazard evolution.

The two considered tools are:

1. CCI-HYDR tool from KU Leuven
2. KNMI-ADC from KNMI.

They are both based on a modified delta change method for evaluating the perturbation factor from the comparison between the control period 1961–1990 and the results from various GCM and RCM at various future horizons. This perturbation factor is then used for perturbing rainfall or temperature time series. The resulting perturbed time-series are 30-year long, stationary and they are representative of the climate at the designated target year/period. These time-series do not account for the climate oscillations that should occur during the 30 years they are supposed to cover: i.e., they represent thirty distributions of one year at the target year.

More specifically, the CCI-HYDR tool proposes three distinct scenarios tailored for Belgium inlands every ten years until 2100. The major changes are observed on the rainfall data, as periods of large drought or large rainfall events are obtained. This tool is suitable in combination with computationally intensive hydrological simulations, as it proposes a limited number of distinctively different scenarios representing the possible spectrum of future climate conditions.

On the other hand, the KNMI-ADC tool proposes 191 scenarios for spatially distributed data to be perturbed, which enables to scan a broad range of possible climate changes (in Northern Europe). However, the proposed changes are less extreme than those provided by the CCI-HYDR tool and are only available for two periods in the future. This tool is more suitable for forcing fast hydrological models, such as conceptual ones, that can efficiently perform multiple runs.

As a prospect, a transient stochastic tool has been discussed for perturbing time-series, nevertheless this tool is particularly computationally demanding due to its stochastic component for determining on a daily-basis the required time-series.

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Abbreviation

ADC	Advance delta change
DEM	Digital elevation model
DCM	Delta change method
GCM/RCM	Global/regional climate model
IPCC	Intergovernmental panel on climate change
KNMI	Royal Meteorological Institute of the Nederland
RCP	Radiative concentration pathway
RMI	Royal Meteorological Institute of Belgium