Urban Drainage Systems Design in the Context of Climate Change

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Abstract

The effects of climate change on precipitation extremes in southern Quebec have been assessed using the observed gridded precipitation data set (ANUSPLIN) and the simulations from different Regional Climate Models (RCMs). Firstly, a detailed uncertainty analysis of the RCM simulation outputs was carried out, and secondly an improved statistical downscaling approach was proposed for the construction of the IDF relations in consideration of the projected climate change for Dorval airport station. In general, the performance error due to internal dynamics and physics of the RCMs appears to be the largest source of uncertainty. Analyses of ensemble-averaged projected climate changes show that the extreme precipitations will increase in future and the highest increase will happen for short durations and less frequent extreme events.

Keywords: precipitation extremes, uncertainty analysis, downscaling method, IDF curves, climate change impacts

1. Introduction

The occurrence of extreme storms is a critical consideration in the design and management of urban drainage systems. In current engineering practice, the estimation of extreme rainfalls is accomplished based on statistical frequency analysis of maximum precipitation data. The objective of precipitation frequency analysis is to estimate the amount of precipitation falling at a given point or over a given area for a specified duration and return period. Results of precipitation frequency analyses are often summarized by “intensity-duration-frequency” (IDF) relationships for a given site. Recently, climate change has been recognized as having a
profound impact on the occurrence and intensity of extreme storm events [1, 2]. It is hence necessary to take into account this climate change impact in the development of the IDF relations for the design of urban drainage systems.

General Circulation Models (GCMs) and Regional Climate Models (RCMs) have been recognized to be able to represent reasonably well the main features of the distribution of basic climate parameters at global and regional scales, but outputs from these models are often characterized by biases and coarse resolutions that limit their direct application for many impact studies including extreme weather event analysis [3]. RCMs have higher spatial resolutions (in the order of 40 km) comparing to that of the GCMs (in the order of 200 km) and their finer-scale atmospheric dynamics along with their smaller domain allow for better representation of extreme events at sub-daily duration. Although RCMs have better representation of extreme events comparing to that of GCMs, but different sources of uncertainty [4, 5], including (1) performance uncertainty due to the internal dynamics and physics of each RCM, (2) lateral boundary forcing uncertainties due to the choice of GCM, (3) structural uncertainty associated with model formulation including choice of domain size and configuration, process representation and parameterization that necessitate the use of multi-RCM ensemble and statistical downscaling to reduce the RCM biases.

In view of the above-mentioned issues, the main objectives of this study are (i) to evaluate the different sources of RCM uncertainty in the simulation of precipitation extremes at selected daily and sub-daily intervals (i.e., 15-, 30-, 60- minute and 3-, 6-, 9-, 12-, and 24-hour intervals) over 69 grids spread mainly across southern Quebec region, using North American Regional Climate Change Assessment Program (NARCCAP) multi-RCM ensemble data and the Ouranos RCM simulations; and (ii) to propose an improved statistical downscaling (SD) method for constructing IDF relations for a given site in consideration of the potential climate change impacts for a future period (e.g., 2040-2070). Notice that the impacts of climate change on the sub-daily extreme rainfalls (or on the IDF relations) in urban areas are a critical issue in the design and management of urban drainage systems due to substantial investment involved, but so far no similar study has been carried out for this Quebec region. A few recent studies [5-7] have looked at the uncertainty and projected changes of daily and multi-day precipitation extremes for grid points covering Canada and 21 northeast Canadian watersheds across the province of Quebec using regional frequency analysis approach and ensemble of NARCCAP simulations. Their results have indicated significant increases in daily and multi-day precipitation extremes for these regions and have found that performance uncertainty and the structural uncertainty appears to be larger than lateral boundary forcing uncertainty [5].

2. Climate simulations and observations

The RCM precipitation extremes are derived from fifteen NARCCAP simulations and four Canadian RCMs. NARCCAP involves six RCMs (identified as CRCM, ECP2, HRM3, MM5I, RCM3, and WRFG) and each RCM has driven by the NCEP reanalysis and by two distinct GCMs data [8]. Among these RCMs, four models (CRCM, HRM3, RCM3 and WRFG) have NCEP reanalysis and two GCM simulations as boundary conditions for current and future periods and the remaining two models (ECP2 and MM5I) have only one GCM as lateral boundary conditions. All these simulations use the same 50-km horizontal resolution grids to simulate the precipitation depth for each 3-h time interval for the current and future 2041-2070 periods. The NARCCAP simulation period of NCEP-driven and GCM-driven RCMs are slightly different at current period and they overlap for the 1979-2000 period. The NARCCAP simulation domain covers most of North America region; this study focuses however on 69 grid points located in the southern part of Quebec in Canada (Figure 1).
The CRCM data used in this study is the latest version (the 4th generation) of the CRCM and this model was driven by the ERA40 reanalysis and by three distinct GCMs (CCSM, CGCM, and ECHAM5). An extensive description of its physical parameterization can be found in [9] and a complete description of the model is presented in [10] and a recent modification is described in [11]. The model covers the North American domain and provides the precipitation simulations for each 15 minutes time intervals.

The observed data used in the present study consists of the observed daily precipitation data set at 10-km resolution developed by Agriculture and Agri-Food Canada and the observed hourly precipitation data at Dorval airport station. These gridded data were based on the 10-km grid interpolation of observed daily precipitations from a network of 2700 raingages across Canada using trivariate thin-plate smoothing splines method. In order to adapt to the large variation in station density over Canada the fitted trivariate splines incorporated a spatially varying dependence on ground elevation. Also a two-stage approach was adopted in which precipitation occurrence was estimated and then used in conjunction with a surface of positive precipitation values, to overcome the daily precipitation challenges such as short correlation length scales, the preponderance of zeros, and significant error associated with the measurement of snow. Generally, interpolation of precipitation data to gridded data produces some error which is inevitable; however, seasonal precipitation at upper 95th percentiles were attenuated on average only by 8% during 1961-2003 interpolation period [12].

3. Methodology

3.1 Uncertainty analysis

The climate change uncertainty could be categorized into four main components including (1) the GCM uncertainty, (2) the RCM uncertainty, (3) the downscaling approach uncertainty, and (4) the uncertainty related to the climate change scenarios. The main focus of the present study is to quantify the first two sources of uncertainty related to GCMs and RCMs. In particular, the performance error due to the internal dynamics and physics of each RCM can be assessed by comparison of the NCEP-driven RCM simulations to those of observed at each grid point for different return period levels and rainfall durations. Furthermore, to analyse the uncertainty of various NARCCAP RCM simulation results, a common reference grid with a horizontal
resolution of 45 km was used. All RCM simulated data and the ANUSPLIN observed data were interpolated to the reference grid using the inverse distance squared weighting method. The reference grid was defined in such a way that covers all the population centres in southern part of Quebec. Finally, since only daily observed gridded precipitation series are available, the performance uncertainty could be assessed for the daily time scale.

The lateral boundary forcing quantifies the GCM uncertainty and it is evaluated by comparing annual precipitation extremes derived from NCEP-driven RCM simulations at current period to those derived from GCM-driven RCM simulations for the same period.

Structural uncertainty associated with model formulation including choice of domain size, configuration, process representation and model parameterization. To quantify the structural uncertainty, the coefficient of variance (CV) could be defined as the ratio of the standard deviation to mean value of return level at each grid point for all the NCEP-driven RCM simulations.

The precipitation characteristics considered in the uncertainty analysis are annual maximum precipitations at different return periods (2, 5, 10, 25, and 50 years) and for different time scales (15, 30, and 60 minutes, as well as 2, 3, 6, 12, and 24 hours). In addition, only rainfall data in the summer (May-October) period were considered in the development of the IDF relations for Dorval airport station.

3.2 Downscaling

Downscaling procedures attempt to resolve the scale discrepancy between large scale climate variables and the local scale resolution required for impact assessment studies, and these methods are based on the assumption that large-scale weather exhibits a strong influence on local-scale weather [14]. In general, dynamical downscaling and statistical downscaling are two broad categories of downscaling methods[15]. Dynamic downscaling methods or Regional Climate Models (RCM) are based on physical dynamics between synoptic variables (as predictors) and local-scale variables (as predictands) and it uses GCM variables to define time-varying atmospheric boundary conditions around a finite domain, while the statistical downscaling methods rely on the empirical relationship between regional scale predictors and local scale predictands [16]. Statistical downscaling methods could be classified into three categories based on the nature of the chosen predictors: Perfect Prognosis (PP), Model Output Statistics (MOS), and stochastic Weather Generators (WGs).

The main idea of MOS is to establish statistical relationships between variables simulated by RCMs and local-scale observations in order to correct the RCM errors. Among the MOS approaches, the Bias correction and Quantile mapping (QM) are two methods which have been commonly used in climate change impact assessment studies. QM maps the daily precipitation to a two-parameter gamma distribution [17, 18] by first finding the rain day threshold. Then rain day threshold was subtracted from RCM simulations and the parameters of the gamma distribution were estimated for non-zero precipitation values for both calibration and validation periods. The modified form and scale parameters of the validation period were then estimated as a ratio of the observed to simulated parameter times the validation period parameters. Finally, model precipitation during the validation period was mapped to the gamma distribution using the inverse of the gamma distribution and the modified parameters. The recent studies suggested that estimating two different sets of form and scale parameters for the non-zero precipitation could map the extremes better than a single set. The first set fitted to the less than 95 % non-zero precipitations and the second one fitted to the rest of the precipitation values.
3.3 IDF relations

There are three types of climate and weather-related variables that have been traditionally used in the design of stormwater infrastructures: rainfall intensity-duration-frequency (IDF) data, temporal rainfall distributions or design storms, and critical rain-plus-melt sequences [19]. An IDF relation is a graphical representation of the probability that a given average rainfall intensity for a given duration will occur. It summarizes the results of precipitation frequency analysis using long term rainfall records collected at a rainfall monitoring station. IDF curve analyses start by gathering time series records of different durations and after time series data have been gathered, annual extremes are extracted from the record for each duration. A probability distribution is then fitted to these annual extreme data in order to estimate the rainfall quantities.

To develop the IDF relations in the context of the climate change at Dorval station, the ensemble of NARCCAP simulations for the current 1979-2000 period and future 2041-2070 period were applied to estimate the precipitation extremes for 3-, 6-, 9-, 12-, and 24-hour duration and as the shorter duration data are not available for NARCCAP, the CRCM simulations with 15-min time interval has been used to find the projected changes in precipitation extremes for 1-, and 2-hour durations.

4. Results

The complete uncertainty analysis was performed for precipitation extremes at different time scales (15-, 30-, 60-minutes, and 2-, 3-, 6-, 9-, 12-, and 24-hour) and for different return periods (2, 5, 10, 25, and 50 years). For purposes of illustration, detailed results are presented in the following only for 3-, 12-, and 24- hr time intervals and for 2-, 10-, and 50- yr return periods.

4.1 Uncertainty analysis

The spatial distribution of observed daily precipitations was calculated using ANUSPLIN gridded data and the results for different return periods are presented in Figure 2. In general, the precipitation extremes increase from West to East for all the return period levels and the extreme precipitations mainly happened at the grids close to Montreal.

As the observed precipitations are available for 24-hour duration, the RCM performance error can be assessed by comparing the extreme precipitations derived from NCEP-driven RCM daily simulations with the observed values as shown in Figure 3. It can be seen that there is a large variation among RCMs, with CRCM underestimating the extremes for most of grid points while the other RCMs overestimated the extremes. Performance error evaluation for other return periods has indicated that the CRCM and ECP2 error increases with return periods (i.e. higher errors for higher return periods) and the other RCM simulations had no specific trend. Table 1 shows that the magnitude of under/overestimation is generally smaller for CRCM, MM5I and WRFG. Using a multi-RCM ensemble gives the possibility of averaging results of different models, thereby reducing the uncertainty associated with a single model. In this study, ensemble average is calculated with equal weights for each member of the ensemble. In general the differences are slightly smaller than those obtained for most of the individual models (Table 1).

The lateral boundary forcing errors are assessed by comparing GCM-driven versus NCEP-driven RCM simulations for 1979-2000 period using scatter plots for precipitation extremes at 2-, 10-, and 50-yr return periods for all grid points. Among the RCM simulations only four have been driven by two GCMs and the lateral boundary forcing errors are shown for those
simulations in Figure 4. In majority of cases (64% of the total cases summarized in Table 2), the difference between GCM and NCEP-driven RCM simulations is less than 10%. Among the RCM simulations, CRCM-CGCM has the smallest lateral boundary forcing error and RCM3-GFDL has the biggest for combination of all return period and durations. Also, Table 2 shows that the RCM simulations driven by the GCM boundary condition has the best fit with those of NCEP-driven simulations and GFDL-driven RCMs have the worst.

Figure 2. Observed daily precipitation extremes (in mm) for the reference 1979-2000 period for (a) 2-year; (b) 5-year; (c) 10-year; (d) 25-year; (e) 50-year return periods in southern Quebec.

Figure 3. Relative difference between daily extreme precipitations from NCEP-driven RCM simulations and ANUSPLIN observed data for the reference period 1979-2000 at 2-yr return level for (a) CRCM-NCEP; (b) ECP2; (C) HRM3; (d) MM5I; (e) RCM3; (f) WRFG.

Comparison of RCM performance errors and lateral boundary forcing errors prove the results of the previous studies [5] and it suggest that performance errors are larger than the boundary forcing errors analyzed for different durations and return periods.
Coefficient of variation of NCEP-driven RCMs was applied to quantify the spread of extreme precipitations at study area and the corresponding structural uncertainty. Figure 5 shows that the structural uncertainty generally increases with return period and there is a big deviation between models for 3-hour precipitation for different return periods which is mainly due to underestimation of 3-hr precipitation by CRCM in the study area.

**Table 1. Average performance errors for daily precipitation extremes of NARCCAP RCMs**

<table>
<thead>
<tr>
<th>Model</th>
<th>50Yr</th>
<th>25Yr</th>
<th>10Yr</th>
<th>5Yr</th>
<th>2yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCM</td>
<td>25.3</td>
<td>19.8</td>
<td>14.7</td>
<td>12.1</td>
<td>10.5</td>
</tr>
<tr>
<td>ECP2</td>
<td>42.5</td>
<td>39.7</td>
<td>37.4</td>
<td>36.1</td>
<td>34.7</td>
</tr>
<tr>
<td>HRM3</td>
<td>23.3</td>
<td>20.8</td>
<td>19.9</td>
<td>20.1</td>
<td>19.1</td>
</tr>
<tr>
<td>MM5I</td>
<td>17.0</td>
<td>14.1</td>
<td>13.2</td>
<td>14.5</td>
<td>16.2</td>
</tr>
<tr>
<td>RCM3</td>
<td>19.9</td>
<td>18.2</td>
<td>20.2</td>
<td>22.9</td>
<td>25.9</td>
</tr>
<tr>
<td>WRFG</td>
<td>21.4</td>
<td>16.3</td>
<td>14.0</td>
<td>15.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Ensemble</td>
<td>18.2</td>
<td>15.7</td>
<td>15.1</td>
<td>16.6</td>
<td>18.1</td>
</tr>
</tbody>
</table>

**Table 2. Lateral boundary forcing errors of NARCCAP RCMs simulations**

<table>
<thead>
<tr>
<th>Model</th>
<th>GCM</th>
<th>2-yr</th>
<th>10-yr</th>
<th>50-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-h</td>
<td>12-h</td>
<td>24-h</td>
<td>3-h</td>
</tr>
<tr>
<td>CRCM</td>
<td>-3.8</td>
<td>0.7</td>
<td>10</td>
<td>-3.1</td>
</tr>
<tr>
<td>CGCM</td>
<td>1.2</td>
<td>-2.2</td>
<td>6.7</td>
<td>1.2</td>
</tr>
<tr>
<td>GFDL</td>
<td>-11.2</td>
<td>-1.1</td>
<td>-6.5</td>
<td>-9.3</td>
</tr>
<tr>
<td>HadCM</td>
<td>-9.8</td>
<td>-18.0</td>
<td>-9.8</td>
<td>-9.3</td>
</tr>
<tr>
<td>HRM3</td>
<td>1.0</td>
<td>0.1</td>
<td>2.9</td>
<td>-0.8</td>
</tr>
<tr>
<td>RCM3</td>
<td>25.0</td>
<td>12.0</td>
<td>10</td>
<td>28.5</td>
</tr>
<tr>
<td>WRFG</td>
<td>-2.6</td>
<td>1.4</td>
<td>0.3</td>
<td>-9.9</td>
</tr>
<tr>
<td>ECP2</td>
<td>12.0</td>
<td>3.1</td>
<td>4.9</td>
<td>13.3</td>
</tr>
<tr>
<td>MM5I</td>
<td>-9.5</td>
<td>4.8</td>
<td>11.6</td>
<td>-7.1</td>
</tr>
</tbody>
</table>

Figure 4. Scatter plots of 2- (red), 10- (green) and 50-yr (blue) return levels (in mm) of 3- (top), 12 (middle) - and 24-hour (bottom) precipitation extremes for the 1979–2000 period. Numbers in each panel represent average percentage difference between the NCEP and GCM driven RCM simulations.
Figure 5. Coefficient of variation of extreme precipitations given by NCEP-driven RCM simulations for 2-, 10- and 50-year return period and for 3- (top), 12- (middle), and 24- hour (bottom) duration.

4.2 Downscaling

The quantile mapping statistical downscaling method was applied to remove the RCMs biases and also to downscale the precipitation at Dorval airport station. Figure 6 shows the performance error of ERA40 driven CRCM and also the absolute changes for the same model after quantile mapping has been applied in the study area. The results suggest that quantile mapping does not improve the RCM simulations and it even increase the model biases for 2-yr return level; however, quantile mapping remove the biases for other return levels and the performance error decreases for 57 to 75 % of the grid points. These results could be the effect of the application of the quantile mapping method in this case, as we are fitting a gamma to the top 5% of non-zero daily precipitations and the other values are fitted with another gamma distribution. Hence, there are a few precipitation values at the top 5% category and the quantile mapping can remove the biases quite well while it does not have the same performance for the other categories with many non-zero precipitation values.

As mentioned previously, the present study is focused on the development of the IDF relations for Dorval airport station. Hence, a more detailed evaluation of quantile mapping performance at the grid point covering this station shows that the quantile mapping reduces the performance uncertainties by 2 to 32 % at this location for 5- to 50-yr return periods and the performance uncertainty reduces 10% for 50-yr and 14% for 5-yr return period. It is possible to assess the quantile mapping effect on lateral boundary and structural uncertainties as well. However, the uncertainty analysis suggests that the performance error is larger than the errors from other
sources of RCM uncertainty. Consequently, only the effect of quantile mapping on performance error has been considered in this study.

![Diagram](image)

Figure 6. Relative difference between daily extremes derived from ERA40-CRCM and observed data (top) and the relative changes due to quantile mapping (bottom) for the 1979-2000 period.

### 4.3 IDF relations

In this paper, the IDF relations at Dorval airport station have been derived using the ensemble of 10 NARCCAP RCM simulations and three simulations from the Ouranos consortium CRCM model. Figure 7 and Table 3 show the IDF curves for current and future periods. Average change for all durations and return periods is 21.4%, with minimum changes in the 12.7% to 17.5% range for 3-hour storms and maximum of 20.6% to 42.8% for 1-hour storm. The maximum precipitation change generally occurs for short duration events with high return periods and as the duration and frequency of the storms increase the precipitation changes decrease.

![Table](image)

**Table 3.** Dorval airport station precipitation extremes for observed, ensemble of current RCM simulations (1979-2000), and future RCM simulations after QM.
The RCM errors have been assessed by comparing the hourly observed precipitation extremes with those given by the ensemble of RCM simulations for different return periods. The results suggest that the application of the quantile mapping method generally decrease these errors and the precipitation extremes will increase for different durations and return periods. Table 4 compares the relative error at current period and the precipitation changes in the context of climate change and it suggests that generally for all combination of durations and return periods the change is greater than the relative error and the increase of the precipitation is inevitable.

Table 4. Extreme precipitation changes at Dorval station

<table>
<thead>
<tr>
<th>Return Period (year)</th>
<th>Change (mm/hr)</th>
<th>Duration (min)</th>
<th>Error (mm/hr)</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>60 120 180 360 720 1440</td>
<td>50</td>
<td>60 120 180 360 720 1440</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>13.7 5.6 2.1 2.6 1.0 0.7</td>
<td>5.07 2.59 0.56 1.18 0.73 2.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10.1 4.1 1.7 2.1 1.5 0.5</td>
<td>3.86 1.64 0.31 0.66 0.61 0.84</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.4 2.6 1.5 1.6 1.3 0.8</td>
<td>2.57 0.79 0.11 0.17 0.29 0.54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.5 1.9 1.4 1.3 0.8 0.6</td>
<td>1.90 0.51 0.06 -0.05 0.34 0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3 1.7 1.3 1.0 0.6 0.4</td>
<td>1.66 0.87 0.12 -0.14 0.09 -0.05</td>
<td></td>
</tr>
</tbody>
</table>

5. Conclusions

Uncertainty of RCM simulations of daily and sub-daily precipitation extremes was assessed for southern Quebec region. The 12 GCM-driven and six NCEP-driven RCM simulations provided by NARCCAP and the Ouranos consortium were considered. The following main conclusions can be drawn from the present study:

1. Comparison between observed extreme precipitations and those derived from the NCEP-driven RCM simulations suggested that most RCMs, except the CRCM, overestimated the precipitation extremes for most locations at different return periods.
2. Lateral boundary forcing error analyses suggested that GCM-driven RCM simulations had the best fit with those of NCEP-driven RCMs and generally the lateral boundary forcing error is less than the performance error.

3. Spread of coefficient of variance for NCEP-driven RCM simulations have been analysed. The structural uncertainty analyses showed that the RCMs simulations diverge as the return period increases and underestimation of 3-hr precipitation data by CRCM is the main reason for high structural uncertainty for that duration.

4. QM method was applied to remove the RCM biases and has been used to downscale precipitations at Dorval station. The results suggested that QM reduced the RCM biases for most of return period levels except for the 2-yr return level.

5. IDF relations have been developed using the ensemble of RCM simulations. The analyses of extreme precipitations at Dorval station showed that the precipitation extremes will increase for future 2041-2070 period with the highest increase for short duration and low frequency storms.

6. References


7. Acknowledgements

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8. Biography

Alireza Zareie is PhD candidate and research assistant in Department of Civil Engineering and Applied Mechanics at McGill University. His PhD research topic mainly focuses on extreme precipitations analysis in the context of climate change. He received the Graduate Excellence Award in 2012 and the Pierre-Brace Research Institute Award in 2009-2012.

Van Nguyen is Professor and Chair of Department of Civil Engineering and Applied Mechanics as well as Director of the Brace Centre for Water Resources Management at McGill. His scientific and professional contributions over more than 30 years have been mostly in the areas of Hydrology and Water Resources Management. He is author or co-author of over 200 articles in refereed journals, specialized monographs and conference proceedings.