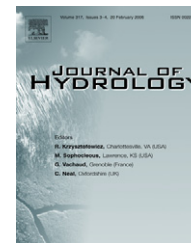




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# Assessment of future change in intensity–duration–frequency (IDF) curves for Southern Quebec using the Canadian Regional Climate Model (CRCM)

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## KEYWORDS

Extreme rainfall;  
Climate change;  
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model;  
Spatial correlation;  
Return period

**Summary** Intensity–duration–frequency curves are used extensively in engineering to assess the return periods of rainfall events. The estimation and use of IDF curves rely on the hypothesis of rainfall series stationarity, namely that intensities and frequencies of extreme hydrological events remain unchanged over time. It is however expected that global warming will modify the occurrence of extreme rainfall events. In order to assess how extreme rainfall events will be modified in a future climate, an analysis of the Canadian Regional Climate Model (CRCM) simulations under control (1961–1990) and future (2041–2070) climates was performed. May to October annual maximum (MOAM) rainfall for 2-, 6-, 12- and 24-h durations were extracted and analyzed using regional frequency analysis for grid boxes covering the Southern Quebec region. Comparison with available rainfall records shows that CRCM estimates are consistent with those based on observed data considering the different spatial scales related to observed data (meteorological stations) and to simulated ones (grid boxes). Comparison of regional estimates in control and future climate at the grid box scale reveals that return periods of 2- and 6-h events will approximately halve in future climate while they will decrease by a third for 12- and 24-h events. Regional IDF curves at the grid box and the station scales are proposed. The analysis of spatial correlation of simulated MOAM series in control and future climates for the region under study suggests that, for a given duration, spatial correlations will decrease in a future climate suggesting that annual extreme rainfall events may result from more convective (and thus more localized) weather systems. Multi-model ensemble systems (different GCMs with different RCMs) as well as multi-member ensembles (investigation of possible sensitivity to initial conditions) are needed to investigate the impact of model structures on future change in extreme rainfalls. © 2007 Elsevier B.V. All rights reserved.

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## Introduction

It is expected that global warming will lead to an increase in intense rainfall events (intensity and/or frequency), since a warmer atmosphere can contain more humidity (and therefore more energy) and therefore produce a more active hydrological cycle (Trenberth, 1999; Trenberth et al., 2003). Allen and Ingram (2002) have suggested, based on a globally integrated view, that the extreme precipitation is constrained by moisture availability and would therefore increase faster than the mean precipitation, constrained by the energy balance. Trend analysis suggests that it appears to be the case in several regions (e.g. South Africa, Siberia, eastern Mediterranean; see Groisman et al., 2005). Such modifications in rainfall events can result in significant impacts over many sectors (e.g. urban drainage, dam design, definition of flood plains, etc.; Kunkel et al., 1999). In urban hydrology, for example, the design of drainage infrastructures (whose life expectancy is comparable to the time scale associated to the induced climate change (CC)) has been traditionally based on statistical analyses of historical records, assuming that the intensity and frequency of past events are statistically representative of what could happen in the near future (Mailhot et al., 2006). However, in a context of CC, this hypothesis must be revisited and the design criteria for drainage infrastructures should be revised to take into consideration the expected changes in the intensity and frequency of heavy rainfall events (He et al., 2006; Grum et al., 2006; Papa et al., 2004).

It is generally difficult to detect a clear trend in extreme rainfall intensity and/or frequency since, by definition, these events rarely occur, that the inter-annual variability of heavy rainfalls is high and that records for rainfall series are usually rather short. Despite these constraints, many studies have reported an increased frequency of heavy precipitation events in the USA (Karl et al., 1995; Karl and Knight, 1998), Australia (Plummer et al., 1999), Japan (Iwashima and Yamamoto, 1993), Germany (Hundecca and Bárdossy, 2005), Denmark (Arnbjerg-Nielsen, 2006), Switzerland (Schmidli and Frei, 2005), China (Zhai et al., 2005), southern and western African countries (New et al., 2006), United Kingdom (Fowler and Kilsby, 2003) and India (Goswami et al., 2006).

Alexander et al. (2006), while analyzing daily precipitation and temperature data from many sources over the globe, have concluded that most precipitation indices show a tendency towards wetter conditions throughout the last century even though not all of them are statistically significant. These authors also observed that, when average conditions over the globe are considered, the percentage contribution from the most extreme precipitation events to the annual precipitation total has been increasing. A similar analysis, realized by Groisman et al. (2005), showed a widespread increase in the frequency of very heavy precipitations (99–99.7 percentiles) during the past 50–100 years (see also Tebaldi et al., 2006; Groisman et al., 1999 who performed trend analyses of heavy rainfall using multinational data sets). Finally, the last report from the Working group 1 (WG1) of the International Panel on Climate Change (Summary for Policy Makers, SPM WG1-IPCC 2007) reported that heavy precipitations have increased on most of the planetary land surface during the 20th century.

More specifically for Canada, the analysis of precipitation indices (e.g. number of days with precipitation, maximum total precipitation for a five-day interval) related to daily rainfalls using historical records from all over this country, has revealed an increase in the annual total precipitation during the second half of the past century, mainly due to an increase in the number of days with precipitation, while no consistent pattern is observed for extreme wet events (Vincent and Mekis, 2005). Stone et al. (2000) also reported seasonally increasing trends in total precipitation during the 20th century for southern areas of Canada. These authors also mentioned that heavy and intermediate events are responsible for the increases observed during the past 50 years.

The estimation of future modifications in precipitation indices due to variations in greenhouse gas concentrations must rely on climate models. In previous studies, global climate model (GCM) simulations have been used to assess changes in extreme rainfall under enhanced greenhouse conditions (e.g. Zwiers and Kharin, 1998). In more recent studies, regional climate models (RCMs) have been used (e.g. Ekström et al., 2005; Fowler et al., 2005; Jones and Reid, 2001; Semmler and Jacob, 2004). RCMs present the advantage, over GCMs, that finer spatial information can be derived from these physically based models. The finer spatial resolution of RCMs is expected to be a more trustworthy representation of processes involved during heavy precipitations and therefore more adequate for water management applications which involve smaller spatial scales (e.g. urban drainage).

Recently, Frei et al. (2006) reported the results of an inter-comparison of daily (and multi-day) precipitation extremes as simulated by six different European RCMs. Evaluation of the performance of these models to simulate extreme precipitation in present climate was assessed (European Alps data were used) and led these authors to the conclusion that RCMs were capable of representing mesoscale spatial patterns in precipitation extremes that are not currently resolved by GCMs. Frei et al. (2006) also showed that a general tendency is observed between the 1961–1990 and the 2071–2100 periods towards an increase in the five-year return period value of one-day precipitation intensity over northern and eastern Europe and a decrease over southern Europe. Using the MM5 simulation model to generate daily precipitation at a 27-km horizontal resolution during the period of 1971–2100, Boo et al. (2006) showed that Korea will experience very important increases in heavy precipitation events. The change in the pattern of heavy precipitation for Korea reported by Boo et al. (2006) is consistent with previous results observed for Japan and China (Easterling et al., 2000).

Grum et al. (2006) used simulation results from the regional climate model HIRHAM to assess possible changes in amplitude and frequency of maximum 1-h events (corresponding to the maximum rainfall depth to fall during one clock-hour time; as far as we know, this is the only study considering sub-daily extreme events). An approach was proposed to estimate the expected changes at point measurement according to the simulated changes in heavy precipitation at the grid box size (25 km × 25 km) over Denmark. According to the results of Grum et al. (2006), return period for a 1-h maximum intensity in present climate

(1979–1996) will approximately halve in future climate (2071–2100). Important research programs in the European Community have generated numerous simulations over Europe using many RCMs for both current and future climate. Unfortunately, such structured collaborations are still in their infancy in North-America and the number of available investigations of change in extreme precipitations is very limited.

Even if the RCMs grid box size is much smaller than the GCMs' (e.g. for the Canadian Regional Climate Model (CRCM), the grid box size is 45 km  $\times$  45 km while, typically, it is in the order of 300 km  $\times$  300 km for GCMs), the comparison with rainfall data from stations is still challenging especially when short duration and very localized intense events are considered (Osborn and Hulme, 1997; Osborn, 1997). Therefore, in order to use RCMs output to compute statistical indices related to extreme rainfall events in a future climate, it is crucial to investigate how these estimated indices compare with those based on available rainfall data. This will be achieved in this paper using the areal reduction factor (ARF).

The objectives of this paper are twofold. First, statistical characteristics of extreme rainfall events for the period spanning 1961–1990, computed from a simulation of the Canadian Regional Climate Model (CRCM), are compared to the statistical characteristics computed from rain-gauge observations. The region analyzed covers the southern part of the Province of Quebec (Canada). Maximal rainfall depth (period from May to October) for 2-, 6-, 12- and 24-h events are considered. Secondly, similar analyses for the future climate (2041–2070) are used to estimate the expected changes in extreme rainfall events.

## Climate models (CRCM\_3.7.1 and CGCM2) and experimental set-up

Model data used in this investigation were taken from simulations generated by the Ouranos' Climate Simulation Team as part of the Canadian Regional Climate Projections Program. The regional model used for this study is the Canadian Regional Climate Model. CRCM\_3 utilizes most of the sub-grid-scale physical parameterization package of the second-generation Canadian Atmospheric General Circulation Model (GCM2: McFarlane et al., 1992; Boer et al., 1992). The reader is referred to McFarlane et al. (1992) for an extensive description of the physical parameterizations, to Caya and Laprise (1999) for a complete description of the model, to Laprise et al. (1998, 2003) for modifications appearing in CRCM\_3 and to Plummer et al. (2006) for the additional modifications in CRCM\_3.7.1. used for this study. The CRCM simulations were performed at a horizontal resolution of 45 km (true at 60°N). The domain covers Canada, the continental United States and most of Mexico, with 201  $\times$  193 grid points, and is referred to as the *Amérique du Nord*, or simply the AMNO domain. The domain and the topography, as resolved by the CRCM, is very large in the context of regional climate simulations, which typically use domains in the order of 100 by 100 grid points. In the vertical, 29 unequally spaced Gal-Chen scaled-height levels were used (Gal-Chen and Somerville, 1975); the lowest thermodynamic level is about 25 m above the surface, and

the computational rigid lid was located near 29 km. The CRCM time step at this 45 km resolution is 15 min. In their analysis of the present climate as simulated by CRCM-3.7.1, Plummer et al. (2006) showed that the main characteristics of observed precipitation are reproduced by the model over most North America. This is true for both mean amounts and coefficient of variation. Plummer et al. (2006) also showed that the climate change signal in the precipitation is robust between versions of the model. This finding improves our confidence in the climate change signal in the simulations used in the present investigation.

Two simulations were considered in the present investigation. This pair of simulations makes a climate projection over the AMNO domain with the CRCM being driven by the Canadian global coupled climate model (CGCM2). The first simulation covers a period representative of the actual climate (GHG concentrations for the 1961–1990 period) and the second one the future climate (GHG concentrations for the 2041–2070 period).

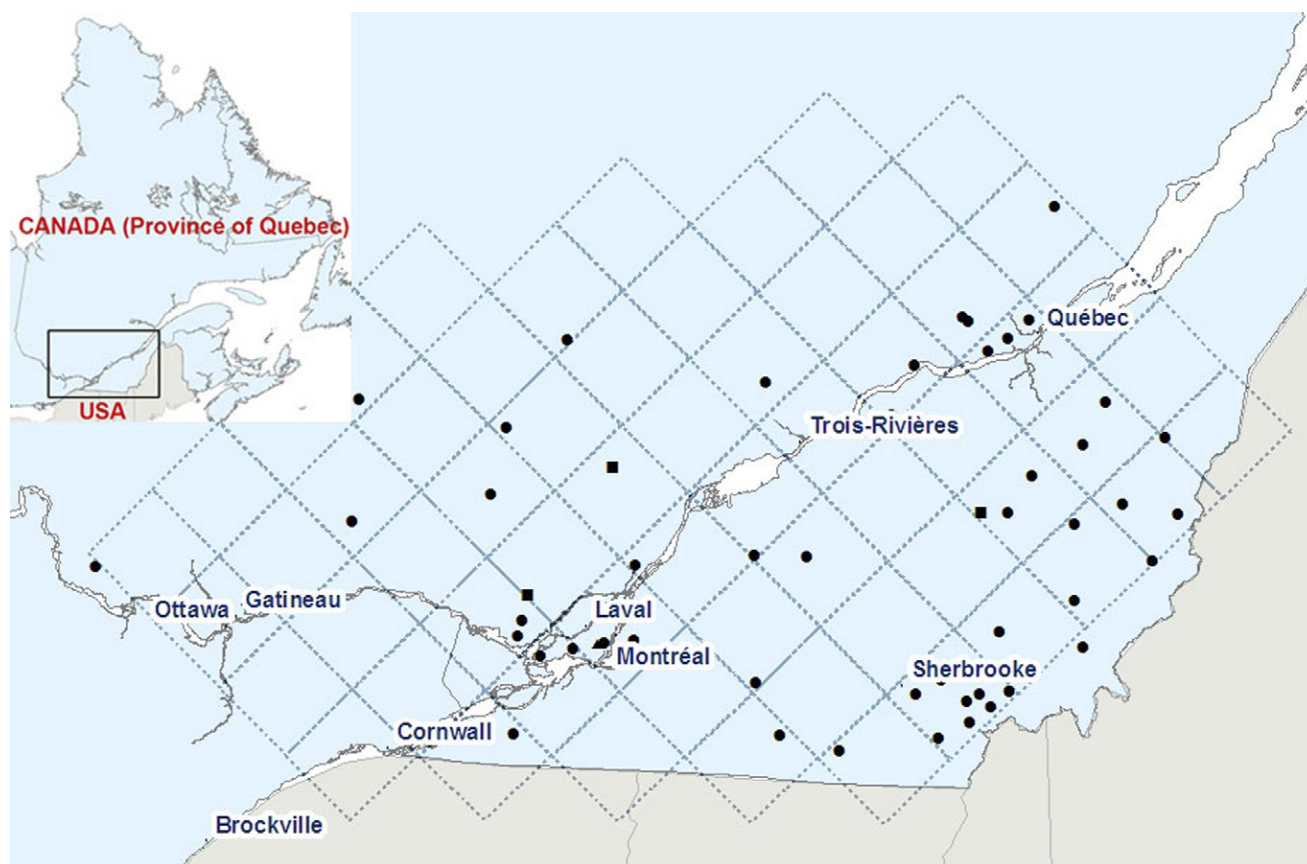
The CRCM simulations were driven from CGCM2 (Flato et al., 2000) data, a model that uses spectral dynamics and was run, for the simulations presented here, at a resolution of T32 with 10 vertical levels between the surface and 10 hPa. The ocean model is a three-dimensional grid-point model based on the GFDL MOM1.1 code (Pacanowski et al., 1993) and uses a horizontal resolution of 1.875°  $\times$  1.875° and 29 vertical levels. Sea surface temperatures and sea-ice cover, as simulated by the CGCM2, were interpolated in space and time to serve as time-dependent lower boundary conditions for the CRCM over oceans. As the North American Great Lakes are not resolved by the CGCM2 at its resolution, lake-surface temperatures and ice cover were calculated from the Goyette et al. (2000) lake model. Geophysical fields over land points, such as liquid and frozen soil water content, snow amount and ground temperature, were initialized with monthly mean values from CGCM2 climatology. The CGCM2 ocean sea-surface temperature and sea-ice distribution were used as surface boundary conditions over the CRCM ocean grid cells.

The CRCM simulations were driven by data from a CGCM2 transient greenhouse gas (GHG) concentration simulation covering the period from 1850 to 2100 (Flato and Boer, 2001). In both the CRCM and the CGCM2, the greenhouse gas and aerosol concentrations follow the SRES-A2 scenario (Houghton et al., 2001). According to historical levels of greenhouse gases, the effective concentration of CO<sub>2</sub> has increased from 408 to 476 ppmv (parts per million by volume) during the 1971–1990 period. The SRES-A2 scenario increases the effective CO<sub>2</sub> concentration from 714 to 950 ppmv for the years 2041–2070.

## Available rainfall data sets

The area under study covers the southern part of the Province of Quebec (Canada), as shown in Fig. 1. This area was selected because it covers the three most important urban areas of the province (Montreal, Québec City and Sherbrooke) and also because the region is relatively well covered by a reasonably dense network of rain-gauge stations.

Over Southern Quebec, 25–35% of the annual total precipitation falls as snow, mainly from December to April.



**Figure 1** Area under study. Dashed lines represent the contour of the 61 CRCM grid boxes; the 48 circles are rain gauge stations used for the analyses of rainfall on 2-, 6-, 12- and 24-h durations; the triangle is a station used for the analysis of rainfall on the 24-h duration only; the three squares are rain gauge stations used for the analysis of rainfall on the 2-, 6- and 12-h durations.

Due to the cold weather conditions during winter, most of the tipping bucket rain-gauge stations are inoperative from early November each year to late April of the following year; the exact dates vary for each year and for each station. In order to achieve a uniform analysis, maximal annual values over moving windows of 2, 6 and 12 h were extracted from the May to October period for each year and for each station. Therefore, all statistical analyses carried on these duration windows are defined as May to October Annual Maxima (MOAM). However, the 24-h duration MOAM values were obtained from a different database comprising only 24-h annual maxima (AM) values (i.e. no daily or monthly information are available to get the exact timing of the maximum event).

To be retained in the analysis, MOAM values had to be taken from a May to October period having no more than 34 days of missing data (out of a possible total of 184 days). For the 24-h AM values, however, this verification was not possible since only annual values were available. From all Environment Canada rain gauge stations located in the study area, only the stations having precipitation records for at least 15 valid years were selected. This resulted in a total of 51 stations for the analyses on 2- to 12-h durations, which have record lengths varying from 15 to 38 valid years (average 24 years), and of 49 stations for the analyses on the 24-h duration, records for these stations varying from 16 to 57 years (average 23 years). Fig. 1 shows the location of the selected stations. Most records end in 1990 for the 24-h

duration and in 1995 for the 1- to 12-h durations. This is due to the fact that the more recent data are not yet available at the time this paper is being written.

### Statistical analysis of extreme rainfall

The statistical analysis of the MOAM series for a given duration (observed and simulated) allows the estimation of the MOAM rainfall intensity of a given return period at a given site (observed) or for a given grid box (simulated). Although many distributions were considered in this study, two statistical distributions were selected for use: the Generalized Extreme Value (GEV) and the Generalized Logistic (GLO) distributions (see Hosking and Wallis, 1997 for a complete description of these distributions).

The proposed statistical approach supposes that the data are independent, homogeneous and stationary (this last property is important as it is the one that will presumably be affected by climate change). Tests were then performed on simulated and observed MOAM series. Wald-Wolfowitz, Wilcoxon (Mann-Whitney) and Mann-Kendall tests were systematically used to test respectively data independency, homogeneity and stationarity. Acceptance level was fixed at the 5% confidence level.

Distribution parameter sets have been first estimated for each duration at every grid point (simulated) and station (observed) for comparison purposes. The L-moment method

(Hosking et al., 1985) was preferred to the maximum likelihood estimation because it induces lower bias for small-sample data sizes (Hosking et al., 1985). Regionalization of rainfall extremes was then realized following the methodology proposed by Hosking and Wallis (1997). Many authors have previously reported works using the regional analysis (see e.g. Alila, 1999; Alila, 2000; Onibon et al., 2004). Regionalization procedures present numerous advantages over a single-site frequency analysis since it is a convenient way of pooling statistics from different sample data. More reliable estimations of the long return-period rainfall events, specifically when only single-site short records are available, can be achieved using Regional Frequency Analysis (RFA). In the present study, the initial region under consideration is Southern Quebec and simulation results as well as station data were pooled to seek for a regional statistical description of rainfall extremes. The regionalization technique supposes that frequency distributions for  $n$  sites are identical apart from a site-specific scaling factor which can be related to the average value or the median value at that site. The approach used here encompasses three steps: (1) the statistical testing of the regional homogeneity, (2) the selection of the regional distribution and, (3) the estimation of regional quantiles. A brief description of these steps is given in Appendix A. The reader is referred to Hosking and Wallis (1997) for further details regarding RFA.

### Station records

The data for 51 (or 49 for 24-h accumulations) meteorological stations were compiled and analyzed (see Fig. 1). The methodology was applied to the MOAM for 2-h, 6-h, 12-h and 24-h accumulated precipitations. A preliminary analysis of these data reveals that a only few MOAM series (between 0 and 4 for the various durations) do not satisfy independency, homogeneity or stationary criteria at the 5% confidence level.

Once parameter estimates have been obtained using the L-moment method, the  $\chi^2$  test was used to validate the selection of the GEV distribution for each MOAM series. According to this test, the hypothesis that the GEV distribution fitted the data was accepted at the 5% or the 1% level for all stations and durations with more than 20 years of data. The GEV distribution was thus selected and fitted to all MOAM data sets using the L-moments.

Regional analysis was then performed. The hypothesis that the region under study can be considered "acceptably" homogeneous was verified for 12-, 6- and 2-h rainfall durations ( $H$  values of  $-0.77$ ,  $-0.99$  and  $0.19$ , respectively). For 24-h rainfall durations, a regional analysis was done despite the "possible" heterogeneity ( $H = 1.34$ ) according to the Hosking and Wallis criteria.

The selection of the parent distribution was achieved using the standard approach of Hosking and Wallis (1997). Among the usual distributions that can be considered, GEV and GLO distributions were retained as candidate parent distributions. Results demonstrate that, except for the 24-h duration (for which only the GEV distribution was suitable), both distributions could reasonably fit the data. However, since it is the most frequently used distribution,

the GEV distribution was preferred and selected as the regional distribution for observed data in Southern Quebec. The corresponding regional parameter values were estimated using the average  $\bar{l}_1$ ,  $t^R$ ,  $t_3^R$  values (note that a regionally averaged value of  $l_1$  was considered).

### CRCM simulated data

CRCM results for the grid boxes covering the region (see Fig. 1 for the location of the grid boxes) under study were analyzed. The MOAM series for each grid box for 2-, 6-, 12- and 24-h precipitations were extracted from the simulation results for control and future climates using "sliding windows" of corresponding duration. It is important to note that, since the simulation time step of the CRCM is 15 min, maximum values extracted from the simulation results may not exactly correspond to maximum values that would be obtained if precipitation data were simulated using a time step much smaller than the duration considered (this is especially true for 2-h duration). No correction factor was applied to adjust this distortion, meaning that the simulated 2-h values for example potentially underestimate the "true" values.

A preliminary analysis, similar to the one achieved for the observed data, was first realized to test data homogeneity, independency and stationarity. These results globally validate the hypothesis of independent and identically distributed (IDD) series (in general, no more than 4 grid boxes series do not satisfy these tests for each duration), the only exception being 12-h MOAM series in control climate where 9 grid boxes series are diagnosed as non-homogeneous and 8 as non-stationary. These series were considered in the following analysis despite these litigious results. It is important to note that, since it is expected that climate change will induce trends in MOAM series and lead to non-stationary series, stationarity test confirms that this trend, if present, cannot be detected using 30-year MOAM series for most grid boxes and durations even in future climate where the trend should presumably be more pronounced.

To test the adequacy of the GEV or the GLO distributions as a parametric model for the grid box MOAM values, the parametric bootstrap technique was used. Results show that individual grid box MOAM series can be fitted either by GEV or GLO distributions. This is a consequence of the short simulation period available in control and future climates. The GEV distribution was however preferred. A comparison of MOAM estimates obtained using GEV or GLO distributions confirms that GEV and GLO estimates are very close for return periods shorter than 50 years.

A regional frequency analysis of CRCM simulation results was also performed. Results of the homogeneity test for grid box MOAM values confirm that simulated values over Southern Quebec for control and future climates can be regarded as "acceptably" homogeneous for all durations. It is worth mentioning that almost all  $H$  values are negative (and some are smaller than  $-2$ ; e.g.  $H = -2.05$  for 24-h event in future climate and  $H = -2.35$  for 2-h event in future climate) suggesting a positive correlation between the data values at different grid boxes (Hosking and Wallis, 1997). In fact, the most negative  $H$  values generally occur for longer durations and increase as durations decrease. The only

exception is the 2-h duration in future climate which shows the smallest value. This result is not surprising considering that (1) the grid boxes completely cover the studied region, (2) the correlation between adjacent MOAM grid box series certainly exists and extends over many grid boxes and finally (3) the inter-grid box variability of MOAM values is lower than the inter-station variability. All this put together leads to a regional homogeneity larger (smaller  $H$ ) than would be expected if grid box frequency distributions were independent. Regional homogeneity was assumed despite this limitation.

Here we should note that regional frequency analysis makes a few assumptions, among which is that the observations at the different sites are independent. However, as stated by Hosking and Wallis (1997), meteorological events (like intense rainfall) are almost always positively correlated for areas on which regional analysis is commonly performed. Hosking and Wallis (1997) showed that their procedure for regional analysis (applied here) yield suitably robust and accurate quantile estimates for homogeneous region even when correlations exist between sites. Although we did not explicitly take into account the correlation between MOAM grid box series for the calculation of rainfall mean estimates for different durations and return periods, this correlation was taken into consideration for the calculation of confidence intervals on these estimates (Section "Regional frequency analysis at the grid box scale").

Results for the selection of the parent distribution reveal that the GLO distribution gives acceptable close fit to the regional average L-moments for control climate while it is the GEV distribution that best fits regional average L-moments in future climate except for the 2-h event (for which the GLO distribution is more suitable). This result suggests that, at the grid box scale, the distribution that best suits the data may change from control to future climate. This means that non-stationarity induced by climate change can translate not only in a modification of parameter values but also in a changed form of the distribution itself. Regional parameter values were finally estimated using  $\bar{l}_1$ ,  $t^R$ ,  $t_3^R$  for each climate and duration depending on the selected parent distribution.

## Comparison of observed and simulated MOAM estimates

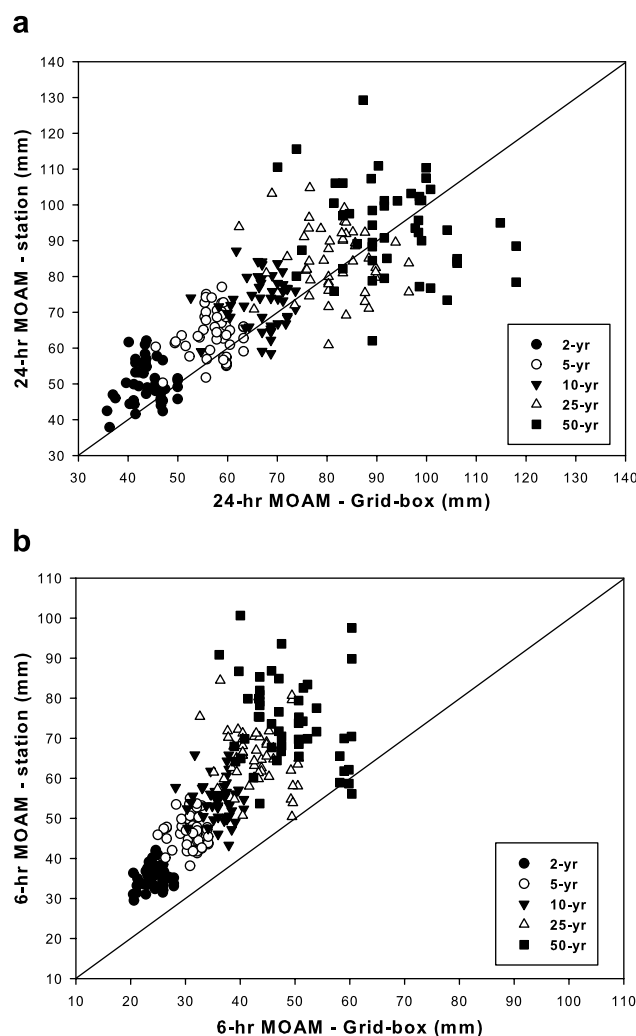
Validation of climate models is a difficult task. Two main reasons explain this situation. One is the lack of observational data and the other is the low spatial resolution of climate models (Emori et al., 2005). In this section, the ability of the CRCM to reproduce the statistical characteristics of annual extreme rainfall is investigated.

Two different approaches have been applied to compare heavy rainfall statistics based on observed and simulated data. The first approach compares grid box values with values estimated from stations located within the grid box (grid box analysis (GBA); Ekström et al., 2005). The second is based on the regionalization frequency analysis (RFA) where the comparison is achieved using regional estimates obtained from observed and simulated data. For both approaches, the concept of areal reduction factor (ARF) (Allen

and DeGaetano, 2002, 2005) is used to assess the performance of the CRCM in the simulation of extreme rainfall over Southern Quebec.

Fig. 2 shows scatter plots comparing MOAM estimates for different return periods obtained from CRCM simulations (x-axis) and from station data (y-axis). Many similar y-values are expected for a given x-value since a grid box can include many stations. Perfect agreement would result in points located on the line of slope one. Twenty four hour simulated MOAM estimates slightly underestimate the observed MOAM estimates while this underestimation is more pronounced for 6-h events (this underestimation increases as duration decreases). This is consistent with the fact that spatial resolutions of observed and simulated data are very different. It was suggested that the grid box rainfall of GCM and RCM has the spatial characteristics of areal averages (Osborn and Hulme, 1997) and, accordingly, CRCM would operate in a world drawn using  $45 \text{ km} \times 45 \text{ km}$  pixels (Fowler et al., 2005).

The concept of areal reduction factor (ARF) can be used to relate the maximum areal average rainfall rate to the



**Figure 2** Comparison of 24-h (a) and 6-h (b) MOAM estimates obtained from simulated (grid boxes) and observed (stations) values for the various return periods considered.

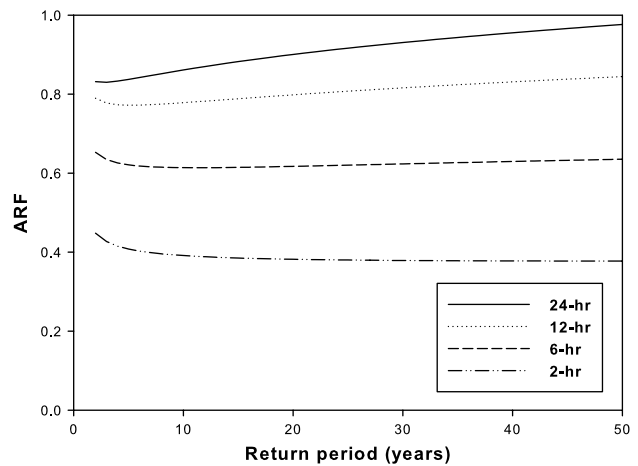
maximum rate estimated at a point. It has been shown that ARFs vary with duration and size of the averaging area (Srikanthan, 1995). ARFs will noticeably decrease when, for a fixed area, annual maxima of shorter durations (less than 24 h) are considered, since events involved in shorter duration extreme rainfalls are spatially smaller than those involved in longer duration extreme rainfalls (Srikanthan, 1995). The use of ARF derived from past records to relate areal and point estimates in a future climate has also been examined by Osborn (1997). Since ARF values depend on the proportions of convective and stratiform rainfall and on the spatial scale of events, these can change in future climate if the spatial scale of rainfall events changes (Osborn, 1997). However, since these eventual modifications cannot be confirmed or quantified at that time, analyses of future rainfall extremes are usually based on the assumption that, for a given area, duration and return period, ARF will not change in a future climate (Ekström et al., 2005; Fowler et al., 2005).

The observed differences between simulated and observed estimates can be related to the average sizes of meteorological systems involved. Systems responsible for 2-h annual extremes are probably of convective nature (summer thunderstorms) and therefore spatially localized thunderstorms have spatial scales in the order of 10 km (Müller and von Storch, 2004) when compared to the size of a CRCM grid box. Water depths generated by those intense but spatially limited systems are therefore much lower once distributed over the whole grid box (as when parameterized in a regional climate model). On the other hand, meteorological systems responsible for 24-h annual extremes are mostly larger in scale (systems that last for longer periods and leads to bigger accumulations) and therefore can possibly completely cover one or more CRCM grid boxes. The 'smoothing' effect will thus increase as the duration of annual extreme events decreases and this is in agreement with the model underestimation increases as time window decreases. The fact that 24-h extreme precipitation estimates are close to observed estimates suggests that the average system size is larger than the grid box size in that case (small smoothing effect). This is consistent, although the local climatology of the two regions differs, with a result obtained by Osborn and Hulme (1997) that showed that the characteristic scale of 24-h annual maxima in Western Europe is in the order of a few hundred kilometres.

In order to further investigate the relationship between sites and grid box values, we have defined the average ARF values as follows:

$$\text{ARF}(T, d) = \frac{x_p^{(g)}(T, d)}{x_p^{(s)}(T, d)} \quad (1)$$

where  $x_p^{(s)}(T, d)$  and  $x_p^{(g)}(T, d)$  are the average regional rainfall depths associated to events of duration  $d$  and return periods  $T$ , respectively at the station scale (superscript  $s$ ) and the grid box scale (superscript  $g$ ) in control climate (subscript  $p$ ).  $\text{ARF}(T, d)$  is thus the average areal rainfall factor between sites and grid box values obtained using regionalized values. Fig. 3 shows how  $\text{ARF}(T, d)$  values evolve as a function of return periods  $T$  for different durations  $d$ . To our knowledge, no ARF value has previously been estimated for the region under study. However, these values are coherent



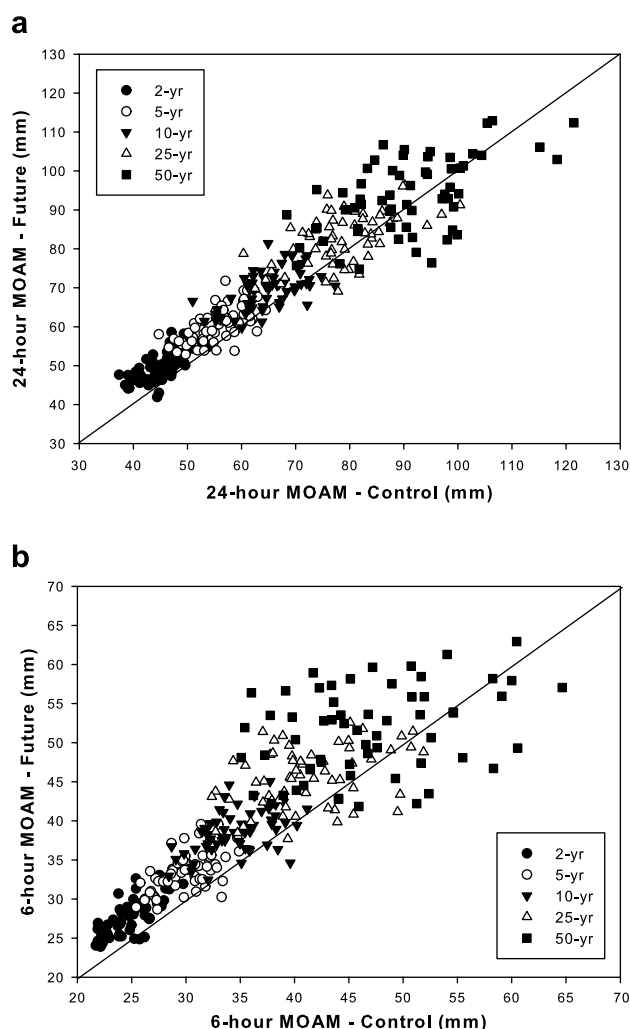
**Figure 3** Areal reduction factor (ARF) between regional average rainfall depth values at the grid box and station scale in control climate as a function of return period for different durations.

with reported ARF values. For example, using the values of Allen and DeGaetano (2005) for 24-h extreme rainfalls on a 2025-km<sup>2</sup> basin in New Jersey and North Carolina, we obtained ARF values ranging respectively from 0.89 to 0.84 for 2-year return period and from 0.89 to 0.88 for 50-year return periods. Although these values are comparable with those reported in Fig. 3, it is important to note that if we observe increasing ARF values as a function of a return period, Allen and DeGaetano (2005) reported lower ARF values for higher return periods for 24-h events (this tendency is however very weak for North Carolina). One possible explanation for this difference is related to the nature of meteorological systems involved in these different regions during those extreme events. In the Southern Quebec region, one can think that meteorological systems responsible for 24-h MOAM rainfalls have a more important contribution from stratiform precipitation for smaller return periods, and therefore, their spatial extension increases as the return period gets longer.

## Comparison of MOAM estimates in control and future climates

### Grid box analysis

For the grid box analysis, the MOAM magnitude for 2-, 6-, 12-, and 24-h and 2-, 5-, 10-, 25- and 50-year return periods were computed and compared on a box-to-box basis between control and future climates. Fig. 4a and b presents respectively these results for 24-h and 6-h events. As can be observed, estimates in future climate are predominantly higher than their corresponding values in control climate. It is therefore expected that the region of interest will experience increasing MOAM intensity in future climate for all durations at the grid box scale (similar results are obtained for 12- and 2-h events). The amplitude of this shift between control and future periods will be estimated through a regional frequency analysis.



**Figure 4** Comparison of 24-h (a) and 6-h (b) MOAM estimates obtained from CRCM simulations in control (x-axis) and future (y-axis) climates for the various return periods considered.

### Regional frequency analysis at the grid box scale

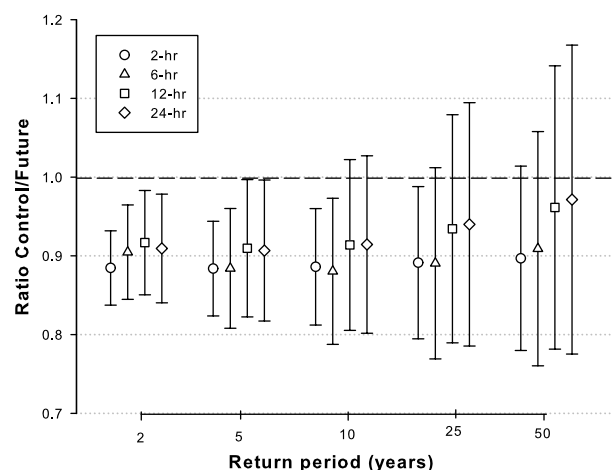
Results of regional frequency analysis in future and control climate have been compared. As mentioned previously, the main motivation supporting this approach is that regional estimates (integrating many grid boxes) of CRCM simulations are probably more meaningful than those based on single grid box values. Even though the comparison achieved in the previous section (box-to-box comparison) is instructive, we believe that reliable estimates of MOAM values in control and future climates must be computed on a regional basis. In order to assess if differences between control and future climates are statistically significant, 90% bootstrap confidence intervals of the ratio of MOAM regional estimates in control and future climates (control/future) have been estimated. These were estimated using the method proposed by Hosking and Wallis (1997) which assumes that the sample L-moments are normally distributed. According to this method, rainfall series for the region under study are stochastically generated using regional values. Each realization considers the same number of sites (grid boxes) and record lengths at each site. In our case, 10,000 realizations were

performed and inter-site dependence was taken into account. The selected structure of inter-site dependence assumes that if each site frequency distribution was transformed to a normal distribution, then the joint distribution for these  $N$  sites would be multivariate normal. The mean correlation coefficient between grid boxes was used meaning that the sites are assumed equicorrelated within the simulated region. The observed sample L-moment ratios were used as the population L-moment ratios of the simulated region, even if Hosking and Wallis warn that this could lead to simulated regions with higher heterogeneity than observed. Some preliminary tests showed that this does not happen in our case study.

Fig. 5 summarizes these results. Ninety percent confidence intervals of the ratio between estimates in control and future climates are presented (vertical lines) for the different return periods and durations. Two main conclusions can be drawn from this graph. The first one is that differences between control and future estimates are significant (at the 90% confidence level) for 2-h event up to 25-year return period and for 6-h event up to 10-year return period while for 12- and 24-h event significant differences are observed only for the 2- and 5-year return periods. The second conclusion is that, although 90% confidence intervals often cross the unit value, all ratio mean values are lower than one. Even if confidence intervals can be large essentially because we have short series (30 years) and since the spatial correlations between grid boxes are rather large (see next section), the fact that future values are systematically higher than their corresponding values in control climate is certainly an indication towards more intense heavy rainfalls in a future climate over Southern Quebec.

### Grid box correlation between simulated MOAM series

The spatial correlation structure between the simulated MOAM series at different grid boxes was investigated. It is



**Figure 5** Ratio of regionally averaged MOAM estimates in control and future climates (control/future) at the grid box scale for the various durations and return periods. Vertical bars are 90% bootstrap confidence intervals.

expected that these correlations could give information on the spatial scale of events generating annual maximum rainfall depths. In fact, slow decaying spatial correlations between contiguous grid boxes may be an indication that “large” (covering many grid boxes) systems are involved and that the same system is responsible for the annual maximum in adjacent grid boxes. However, it must be remembered that a lower spatial cut-off exists (the grid box) under which no information is available. The following correlation between grid box MOAM series  $i$  and  $j$  was estimated as

$$r_{ij} = \frac{\sum_{k=1}^{n_t} (x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{n_t} (x_{ik} - \bar{x}_i)^2 \sum_{k=1}^{n_t} (x_{jk} - \bar{x}_j)^2}} \quad (2)$$

where  $x_{ik}$  is the MOAM value at site  $i$  at year  $k$ ,  $n_t$  the number of years for which both sites have data and

$$\bar{x}_i = \frac{1}{n_t} \sum_{k=1}^{n_t} x_{ik} \quad (3)$$

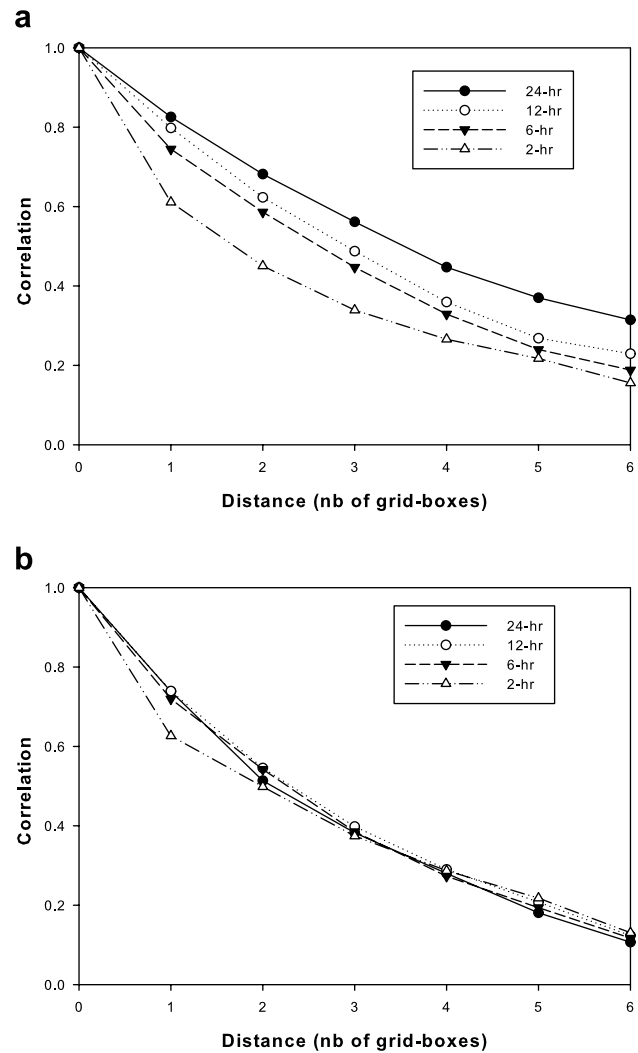
is the time averaged MOAM at site  $i$ . The average correlation between first, second, third, etc. neighbouring grid boxes was then computed as

$$\rho_m = \frac{1}{n_m} \sum r_{(ij)} \quad (4)$$

The sum is over all pairs of grid boxes separated by  $m$  grid boxes (along the two axes of the spatial domain). Fig. 6a and b presents the resulting correlations in control and future climates, respectively. For control climate, spatial correlation between neighbouring grid boxes is decaying more rapidly as duration decreases, as expected under the hypothesis that systems of smaller spatial extensions are involved for extreme precipitation events of short duration. A very different behaviour is observed in future climate where spatial correlation for the various durations has approximately the same structure. This result is interesting as it suggests that systems generating heavy precipitations for given durations will be more localized in a future climate and presumably more convective in nature even for the 24-h events. Although it is not possible to make a clear assessment about the evolution of the spatial extension of systems generating annual maximum rainfalls for sub-daily events, this result suggests that they could be more localized (within grid boxes) and that the increases accounted for by the CRCM at the grid box scale may be much more important when transposed to the site scale.

### IDF curves in control and future climates at the grid box scale

Regional average estimates at the grid box scale have been used to generate intensity–duration–frequency (IDF) curves in control and future climates (Fig. 7). A more convenient way to visualize the expected changes is to express these in terms of return periods. Fig. 8 presents the corresponding return period in control (x-axis) and future (y-axis) climates for MOAM of a given duration and intensity. As previously observed, smaller modifications of return periods are expected for 24-h and 12-h events, while larger and more significant changes (see Fig. 5) are expected for 6-h

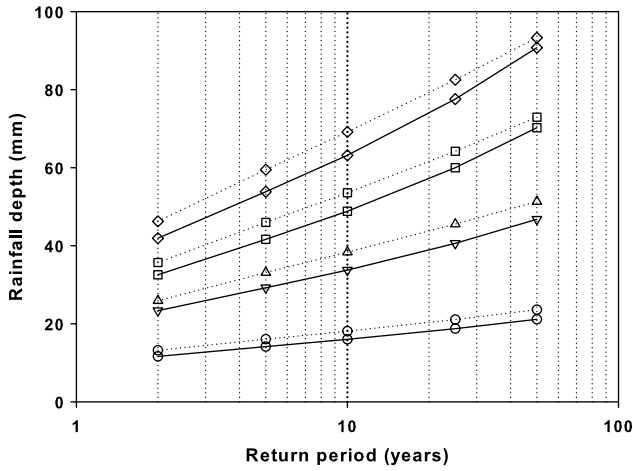


**Figure 6** Average correlation between grid box MOAM series as a function of distance (1 = neighbouring grid boxes; 2 = second neighbour grid boxes, etc.) for various durations in (a) control and (b) future climates.

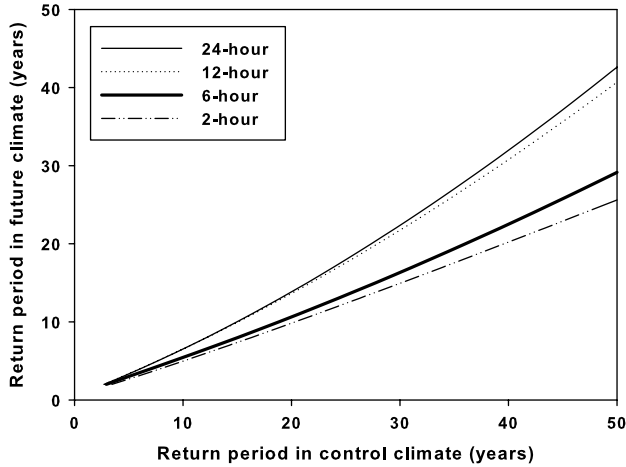
and 2-h events. In these cases, return periods can be approximately halved for events with return periods ranging between 20 and 50 years in present climate. However, it must be remembered that the confidence interval on MOAM estimates increases as a return period increases so that changes for larger return periods are more uncertain.

### Estimation of regional MOAM rainfalls at the station scale

IDF curves are usually developed from site-specific records. Therefore, some sets of hypotheses must be put forward in order to transpose the estimated regional average MOAM rainfall intensities at the station scale from the estimated values at the grid box scale. Two approaches were considered in the following. According to the first one, named the intensity-dependent ARF assumption, it is assumed that the ARF, for a given duration and a given rainfall intensity, will remain unchanged in a future climate. In other words,



**Figure 7** IDF curves at the grid box scale. Continuous curves refer to control climate while dotted curves refer to future climate. Circles, triangles, squares and diamonds are respectively for 2-, 6-, 12-, and 24-h events.



**Figure 8** Return periods in control climate and corresponding return periods in future climate at the grid box scale.

the ARF in control climate corresponding to a given rainfall depth is used in future climate to transpose grid box scale value to the station scale. The second approach, named the constant ARF assumption, assumes that the average relative change in extreme events between control and future climates at the site scale is equal to the corresponding relative changes at the grid box scale for the same duration and quantile. This is equivalent to saying that the expected relative increases at the grid box scale will uniformly affect the sites within the grid box.

#### Intensity-dependent ARF approach

It is important to realize that, according to the intensity-dependent ARF hypothesis, the spatial extent of meteorological systems generating an intense rainfall of a given intensity and duration at the grid box scale in future climate will remain approximately unchanged when compared to systems with same intensity and duration in control climate.

Only the probability of occurrence of these events at the grid box scale will change according to this hypothesis. However, it is expected that the convective component of extreme precipitation events will be more important in future climate meaning that, for a given rainfall intensity at the grid box scale, the meteorological systems could be more localized (or have a more pronounced convective nature) in future climate and that accordingly, the ARF could be smaller. The observed reduction of spatial correlation from control to future climate (as seen in Fig. 6) may be an indication of this more localized character of systems (see Section “Grid box correlation between simulated MOAM series”). If so, this suggests that the following estimates of rainfall intensities at the station scale in future climate would correspond to a lower bound of the expected increase in rainfall values. More important increases can be expected justifying the development of higher RCMs resolution.

Expressing the first hypothesis (intensity-dependent ARF) in mathematical form, following the previously defined sets of hypotheses, the ARF value applicable to the future MOAM estimates  $x_f^{(g)}$  is given by the corresponding ARF for events of same intensity in control climate and we have

$$\text{ARF}_f(x_f^{(g)}) = \text{ARF}_p(x_p^{(g)} = x_f^{(g)}) \quad (5)$$

and therefore from Eq. (1):

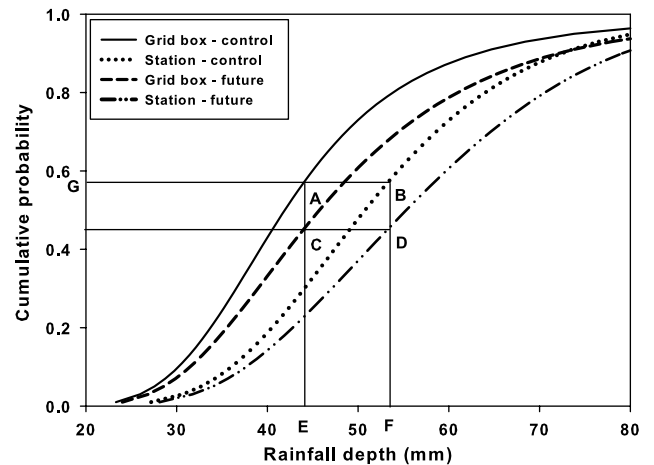
$$x_f^{(s)} = \frac{x_f^{(g)}}{\text{ARF}_f(x_f^{(g)})} = \frac{x_f^{(g)}}{\text{ARF}_p(x_p^{(g)})} \quad (6)$$

Given  $x_f^{(g)}$  (E value in Fig. 9), the corresponding probability of non-exceedance in control climate at the grid box scale is  $F_p^{(g)}(x_f^{(g)})$  (G value) and the corresponding rainfall depth in control climate at the station scale is given by (F value) (brackets indicate that  $x_p^{(s)}$  is a function of  $F_p^{(g)}(x_f^{(g)})$ ):

$$x_p^{(s)} [F_p^{(g)}(x_f^{(g)})] \quad (7)$$

And thus

$$\text{ARF}_f(x_f^{(g)}) = \frac{x_f^{(g)}}{x_p^{(s)} [F_p^{(g)}(x_f^{(g)})]} \quad (8)$$



**Figure 9** Construction of the IDF curves at the station scale in future climate from grid box curves and stations cumulative probability curves in control climate.

and finally

$$x_f^{(s)} = x_p^{(s)} [F_p^{(g)}(x_f^{(g)})] \quad (9)$$

The intensity-dependent ARF approach was applied to the grid box regional distributions for the various durations under study. Regional average IDF curves at the station scale were estimated and are presented in Fig. 10. It is important to note that, according to the hypothesis used to build the IDF curves at the station scale, the resulting relations between return periods in control and future climates remain identical to the ones obtained at the grid box scale and correspond accordingly to those presented in Fig. 8.

### Constant ARF approach

Another approach (the constant ARF approach) was used to generate IDF curves at the station scale. In that case, increases in rainfall depths for a given duration and return period at the grid box scale were used to estimate the rainfall depth at the station scale in future climate, namely

$$x_f^{(s)} = x_p^{(s)} [1 + \Delta_{p-f}^{(g)}(d, T)] \quad (10)$$

where

$$\Delta_{p-f}^{(g)}(d, T) = \frac{x_f^{(g)} - x_p^{(g)}}{x_p^{(g)}} \quad (11)$$

Once simplified, we see that this formulation is equivalent to

$$x_f^{(s)} = x_p^{(s)} \frac{x_f^{(g)}}{x_p^{(g)}} \quad (12)$$

and means that, for a given duration and return period, we suppose

$$ARF_f = ARF_p \quad (13)$$

This last approach is similar to the well-known delta approach where the model simulated change between present

and future climate (the delta) is applied to actual observations to get future values at the station. A comparison of these two approaches indicates similar results, the average absolute relative difference being estimated at 1.8% over all durations and return periods, a value much smaller than the uncertainties associated to these estimates.

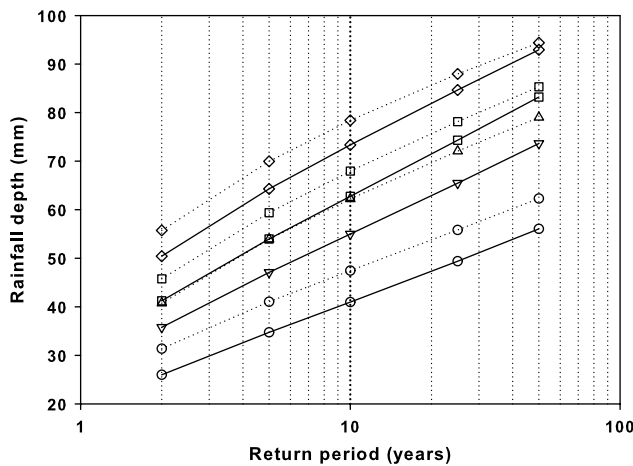
## Summary and conclusions

CRCM-simulated Annual May to October maximum rainfall depth (MOAM) series (2-, 6-, 12- and 24-h durations) over Southern Quebec have been analyzed and compared to available historical records. The CRCM simulations were driven by the Canadian Coupled Global Climate Model (CGCM2) following the SRES-A2 greenhouse gas emission scenario. Two periods were simulated, 1961–1990 and 2041–2070, representative of control and future climates. A total of 61 CRCM grid boxes (45 km × 45 km) and 51 rain gage stations were considered in the statistical analysis achieved at individual grid boxes and stations. A regional frequency analysis (both for stations and grid boxes) was performed mainly for two reasons: (1) it leads to more accurate statistical estimates than a local analysis and (2) the CRCM results should be interpreted at a regional scale (integrating many grid boxes) since grid boxes represent the simulation “fundamental” spatial unit (“pixels”) (any interpretation of the results at individual grid boxes is not recommended even though still common in practice).

The comparison of MOAM estimates based on CRCM simulations with the corresponding values estimated from available data must take into consideration the fact that the spatial scale related to these estimates are different even when a regional climate model is used (areal vs. point estimates). The areal reduction factor (ARF) was used to assess the ability of CRCM to reproduce the observed statistical characteristics of MOAM. Regional ARF values (ratio of regional grid box and stations MOAM estimates) were therefore computed. The resulting ARF values seem reasonable and are consistent with what has been reported in the literature for other regions of the globe (to our knowledge, no ARF values have been estimated for the area under study). ARF dependence on return periods and durations can be related to the characteristic spatial scale of the systems generating extreme rainfalls. We believe that, although this result is not a validation *sensu stricto* of the ability of the model to simulate extreme precipitations, it is a good indication that CRCM simulations lead to results that are statistically consistent with observations in terms of extreme rainfall estimates.

In summary, the major findings of this study are:

- No clear indication of non-stationarity in MOAM series (for all durations) is observed either at the stations (historical records) or for the 30-year simulated series in both control and future climate. Results for Southern Quebec in control climate are therefore consistent since CRCM simulations suggest that, for a 30-year period in control climate, no trend could be detected even if such a trend is building up in the data, due to the change in model GHG concentrations. Since the trend analysis (Mann-Kendall) was realized at individual stations, it is



**Figure 10** IDF curves at the station scale using intensity-dependent ARF. Continuous curves refer to control climate while dotted curves refer to future climate. Circles, triangles, squares and diamonds correspond respectively to 2-, 6-, 12-, and 24-h events.

not impossible, as mentioned by Goswami et al. (2006) and Groisman et al. (1999), that a "regional trend analysis" would reveal a trend otherwise difficult to detect using individual stations (or grid boxes).

- Increases in regional MOAM values at the grid box scale are detected for Southern Quebec between CRCM simulated control and future periods. Confidence intervals on regional estimates show that uncertainties about these changes increase as return periods or durations increase. Thus, at the 90% confidence interval, increasing MOAM rainfall depths are expected for 2-h MOAM of return periods between 2 and 25 years while for 24-h MOAM rainfall depths, statistically significant increases are reported for 2- and 5-year return periods. Improvement of these estimates would necessitate the analysis of larger samples. However, it must be noted that simulated regional average MOAM rainfall depths are systematically larger in future climate.
- The analysis of the spatial correlation of simulated MOAM series in control and future climates for the region under study shows that: (1) for a given duration, these correlations will decrease in a future climate, and (2) the spatial correlation in future climate is very similar for all durations. This correlation is thought to be related to the spatial dimension of the meteorological systems generating the MOAM rainfall depth. A smaller correlation in a future climate for a given duration means annual extreme rainfall events resulting from more convective (and thus more localized) weather systems.
- Return periods of MOAM rainfall depths for 2- and 6-h events are approximately halved in future climate when compared to corresponding values in control climate. Reduction of return periods in future climate for 12- and 24-h MOAM rainfall depths decreases as return periods increase.

Estimation of future MOAM rainfall depths at the station scale for the area under study was achieved based on the hypothesis (intensity-dependent ARF) that the ratios of return periods between control and future climates are the same at the station scale and at the grid box scale. This hypothesis on ARF values is equivalent to assuming that the spatial distribution of rainfalls inside grid boxes remains unchanged in future climate for a same total rainfall depth on the grid box. This may be an "optimistic" projection since a wetter and more convective climate will possibly lead to more localized thunderstorms and, consequently, lower ARF values. Therefore, once transposed to the station (or site) scale, the increases of MOAM rainfalls at the grid box scale may result in even higher increases at the site scale. This important issue could be further investigated as higher-resolution RCM simulations become available.

Emori et al. (2005) showed that the simulation of extreme daily precipitations can be highly dependent on their parameterization, meaning that higher resolution models do not necessarily result in better simulations of climate than lower resolution models. This observation is probably also valid for extreme sub-daily precipitations. Frei et al. (2006) reach a similar conclusion and suggest that the formulation of RCMs contributes significantly to uncertainties in extreme precipitation assessment. Such uncertainties

were not taken into consideration in this study since only one RCM and one RCM experiment were analyzed. Clearly, multi-model ensemble systems need to be analyzed in order to quantify uncertainties. These multi-model ensemble systems must include the use of the output of different GCMs, as well as different RCMs to estimate how model structure can modify extremes in future climate. Multi-member ensembles should also be considered to investigate possible sensitivity to initial conditions. Results obtained in this study remains model dependent since the use the output of different global climate models (GCM) might bring very different results.

## Acknowledgements

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## Appendix A. Regional frequency analysis of rainfall extremes

The regionalization technique supposes that frequency distributions for  $n$  sites are identical apart from a site-specific scaling factor which can be related to the average value or the median value at that site. The approach used here encompasses three steps: (1) the statistical testing of the regional homogeneity, (2) the selection of the regional distribution and, (3) the estimation of regional quantiles.

### Statistical testing of the regional homogeneity

In order to test for the regional homogeneity, weighted average L-moments are used to estimate representative regional parameters. Average L-moments ratios ( $t^R, t_3^R, t_4^R$ ) are computed as follows:

$$\begin{aligned} t^R &= \frac{1}{N} \sum_{j=1}^n n_j t^{(j)} \\ t_3^R &= \frac{1}{N} \sum_{j=1}^n n_j t_3^{(j)} \\ t_4^R &= \frac{1}{N} \sum_{j=1}^n n_j t_4^{(j)} \end{aligned} \quad (\text{A.1})$$

where  $t^{(j)}, t_3^{(j)}, t_4^{(j)}$  are the L-moments ratios at site  $j$ ,  $n_j$  is the length of the record at site  $j$ ,  $n$  is the number of sites and  $N$  is the total number of available data:

$$N = \sum_{i=1}^n n_i \quad (\text{A.2})$$

Monte Carlo simulations have been used to generate stochastic samples at each site of the region under consideration. These samples were drawn from the Kappa distribution (Hosking, 1994) fitted to the weighted average L-moments  $1, t^R, t_3^R, t_4^R$ . A large number of samples  $N_s$  are generated and the following values are estimated for each sample:

$$V = \sqrt{\frac{\sum_{i=1}^n n_i (t^{(i)} - t^R)^2}{\sum_{i=1}^n n_i}} \quad (\text{A.3})$$

This value corresponds to the weighted standard deviation of  $t$ . Defining  $V^{(\text{obs})}$ , the observed network values, the homogeneity measure is given by

$$H = \frac{(V^{(\text{obs})} - \mu_V)}{\sigma_V} \quad (\text{A.4})$$

where  $\mu_V$  and  $\sigma_V$  are the mean and standard deviation of the  $N_s$  values synthetically generated. According to Hosking and Wallis (1997), a region may be regarded as “acceptably” homogeneous if  $H < 1$ , “possibly” heterogeneous if  $1 \leq H < 2$  and “definitively” heterogeneous if  $2 \leq H$ .

## Identification of the regional distribution

Once the homogeneity test confirms that weighed average values are representative of regional values, a goodness-of-fit test must be defined to select the appropriate regional distribution. A candidate distribution is first selected (in our case the GEV and GLO distributions were considered) and the L-kurtosis of the fitted distributions is denoted by  $t_4^{\text{DIST}}$ . A large number of realizations for a region is then simulated using the Kappa distribution fitted to the regional average L-moment ratios (the Kappa distribution includes the GEV and GLO distributions as special cases; a description of the Kappa distribution can be found in Hosking, 1994). The following statistic is used (Hosking and Wallis, 1997) to identify the regional distribution:

$$Z^{\text{DIST}} = \frac{1}{\sigma_4} (t_4^{\text{DIST}} - t_4^R + B_4) \quad (\text{A.5})$$

where  $t_4^R$  is the weighted regional average L-kurtosis, and  $B_4$  and  $\sigma_4$  are given by

$$B_4 = \frac{1}{N_{\text{sim}}} \sum_{m=1}^{N_{\text{sim}}} (t_4^{(m)} - t_4^R) \quad (\text{A.6})$$

$$\sigma_4 = \left\{ \frac{1}{(N_{\text{sim}} - 1)} \left[ \sum_{m=1}^{N_{\text{sim}}} (t_4^{(m)} - t_4^R)^2 - N_{\text{sim}} B_4^2 \right] \right\}^{1/2}$$

$t_4^{(m)}$  corresponds to the regional average L-kurtosis for the  $m$ th simulated region. The goodness-of-fit is adequate if  $|Z^{\text{DIST}}| \leq 1.64$ .

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