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EVALUATION OF VARIABILITY OF PRECIPITATION AND TEMPERATURE EXTREMES OVER MONTREAL REGION FOR PRESENT AND FUTURE CLIMATES

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Abstract: The City of Montreal has experienced frequent extreme weathers such as heavy storm rainfalls and heat waves. Hence, information on the variability of these extreme events for current and future climates is important for the planning and design of its urban infrastructures. This paper aims therefore at performing a detailed analysis of the variability in time and in space of the daily annual maximum rainfalls and extreme temperatures over the Montreal region for the present and future climates using the data from two different sources: the Pacific Climate Impacts Consortium (PCIC) and the National Aeronautics Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). More specifically, the evaluation was based on the climate simulation outputs from ten different Global Climate Models downscaled (i) by PCIC to a regional 1/12-degree grid using the BCCAQ and BCSD methods; and (ii) by NASA to a regional 1/4-degree grid. For the present climate, historical data for the 1961-1990 period from observed weather stations in the Montreal region were also used for this evaluation. For the future climates, climate projections corresponding to the RCP 4.5 scenario for the 2006 – 2100 period were considered. Results of this study have indicated that the downscaled regional gridded data from PCIC are generally more robust and more accurate than those given by NEX-GDDP. The downscaled data are however different from the observed data at a given station. A bias correction is hence required before these data could be used in planning and design of urban infrastructures.

1 INTRODUCTION

Global warming is currently a critical issue that every nation has to deal with due to the increase of greenhouse gases concentrations in the atmosphere. It has been recognized that the global climate has significantly changed over past 100 years (IPCC 2014). To understand and predict the climate change, past trends as well as the projections of future climates for different scenarios have been conducted in many studies (Creutin and Obled 1982; Besaw et al. 2010; Candela et al. 2012; Yeo and Nguyen 2014; Nguyen et al. 2018). In Canada, some studies have indicated an increase trend in both temperature and precipitation with an average increase of around 1.4°C for air temperature and around 12.5% for annual rainfall during the second half of the 20th century (Mekis and Vincent 2011; Zhang et al. 2011). These changes might have significant impacts on various hydrologic processes (Miller et al. 2003; Whitfield et al. 2003; Ryu et al. 2011; Assani et al. 2012).

General Circulation Models (GCMs) have been commonly used for evaluating the effects of climate change on the hydrological regime under different scenarios of greenhouse gas emissions. While these GCMs could represent well the main features of the global distribution of basic climate parameters (Randall et al. 2007), they still cannot reproduce accurately the details of regional climate conditions at temporal and spatial scales of relevance to hydrological impacts and adaptation studies (Nguyen et al. 2006). This is because outputs from these GCMs are usually at resolutions that are too coarse for many climate change impact studies, generally greater than 2.5º for both latitude and longitude (approximately 250km) as shown in Figure 1. To refine the GCM coarse grid resolution climate projection data to much finer spatial resolutions (regional or local scales) for the reliable assessment of climate change impacts, different downscaling methods have been proposed to resolve this scale discrepancy (Wilby et al. 2002; Fowler et al. 2007; Nguyen and Nguyen 2008; Maraun et al. 2010; Khalili and Nguyen 2016; Gooré Bi et al. 2017). These downscaling methods can be generally classified into two broad categories: dynamical downscaling (DD) and statistical downscaling (SD). It has been widely recognized that the SD methods offer several practical advantages over the DD procedures, especially in terms of flexible adaptation to specific study purposes, and inexpensive computing resource requirement (Xu 1999; Prudhomme et al. 2002). In addition, SD methods can be used to spatially disaggregate GCM outputs to regional scales or local/point scales (a single site or multi-sites) (Wilby et al. 2002; Khalili and Nguyen 2016; Werner and Cannon 2016). Furthermore, when dealing with a large ensemble of GCMs, the SD methods are often in favor because of their computational efficiency and effectiveness in producing physically plausible hydro-climatology data (Wood 2004; Werner and Cannon 2016).

Located on an island in the Saint Lawrence River, Montreal is the biggest city of Quebec province and second-largest city of Canada with the population of approximately 1.9 million (Statistics-Canada 2016). Every year, the city has experienced frequent extreme weather events such as heavy storm rainfalls and heat waves that cause millions of property losses, and in some cases, the loss of human lives (City-of-Montreal 2017). These types of extremes events are occurring with increasing frequency. For instance, more than 30 people were killed by a heat wave in Montreal in July 2018 (Cullinane 2018). Another example is the spring flood in 2017 that affected thousands of people and millions of dollars of damages (Lau 2017). Consequently, information on the spatial and temporal variations of these precipitation and temperature extremes for current and future climates is important for the planning and design of the City's its urban infrastructures to minimize the impacts of these natural disasters. Many studies have been conducted to assess the variability of temperature and precipitation processes in Canada and in other countries (Zhang et al. 2001; Arnbjerg-Nielsen et al. 2013; Thistle and Caissie 2013; Benmarhnia et al. 2014; City-of-Montreal 2017) However, very few studies have been carried out specifically on the daily precipitation and temperature extremes for the local City of Montreal region. Therefore, in the present study, a critical evaluation of the spatial and temporal variations of the daily annual maximum rainfalls and daily extreme temperatures over the Montreal region was conducted for the present and future climates using two different datasets that have been statistically downscaled by the Pacific Climate Impacts Consortium (PCIC 2014) and the National Aeronautics Space Administration Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) (Thrasher et al. 2012). Information of these two datasets will be detailed in section 2.

2 DATA

Figure 1 shows a network of seven weather stations in the Montreal region. However, of these seven stations only Montreal-Pierre Elliott Trudeau International Airport (Dorval) and McGill stations have good quality of data with long historical records, other stations have either short historical records or a large number of missing data. Figure 1 also indicates the grids of the two downscaled datasets (red: NEX-GDDP; black: PCIC). It can be seen that the NEX-GDDP grid size is approximately nine time larger than the PCIC grid. Information of PCIC and NEX-GDDP datasets were summarized in Table 1 below.

In the present study, only gridded daily annual maximum precipitation and daily extreme temperature data were considered. These data were statistically downscaled from 10 GCMs corresponding to the RCP 4.5 scenario (see Table 2). For the present climates, the available historical data from Dorval and McGill stations and the PCIC and NEX-GDDP gridded data for the same 1961-1990 period were used. For the future climates, climate projections from the climate models corresponding to the RCP 4.5 scenarios for the 2006 – 2100 period were selected.

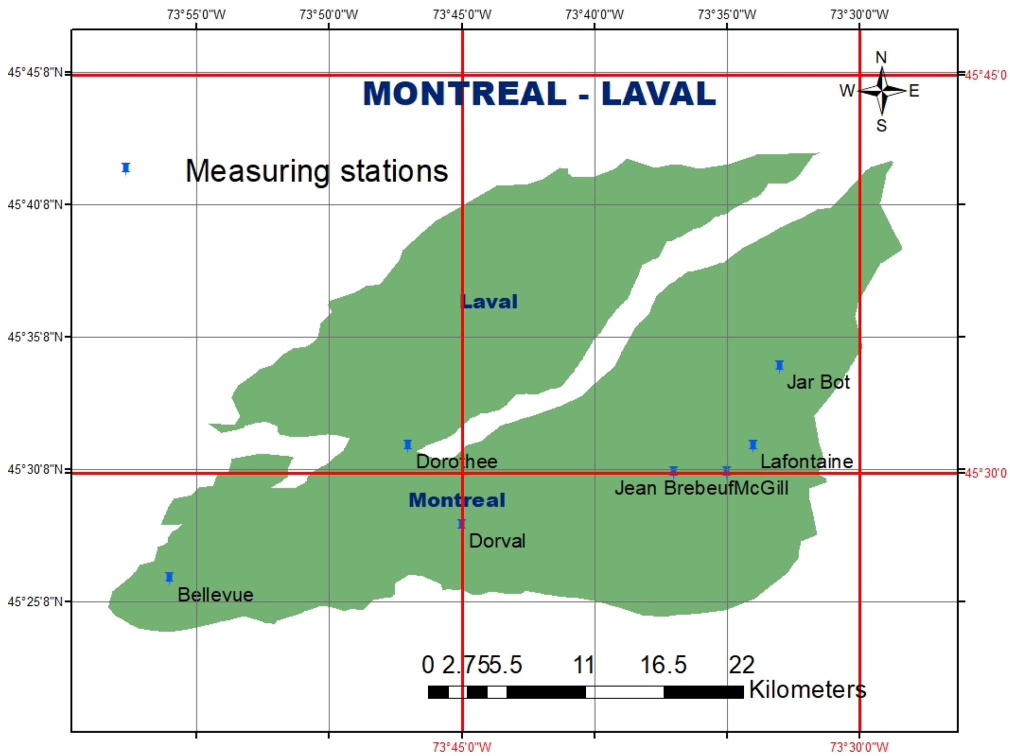


Figure 1. Location of measuring stations in Montreal region

Table 1. Summary of PCIC and NEX-GDDP datasets

	PCIC	NEX-GDDP	Note
Grid size (degree)	1/12	1/4	
Downscaling method	BCSD*, BCCAQ**	BCSD	
Number of GCMs	24	21	PCIC: 12 for BCCAQ and 12 for BCSD
Variables	T_{max}, T_{min}, Pr	T_{max}, T_{min}, Pr	
Timesteps	Daily	Daily	
Projection duration	1950-2100	1950-2100	
RCP*** scenarios	2.6; 4.5; 8.5	4.5; 8.5	

(BCSD*: bias-correction spatial disaggregation - see Werner and Cannon (2016) for further details; BCCAQ**: Bias Correction/Constructed Analogues with Quantile mapping reordering; RCP***: Representative Concentration Pathway)

3 RESULTS AND DISCUSSIONS

3.1. Present climate

Figure 2 shows the spatial distribution of the downscaled daily annual maximum precipitations (AMPs) over the Montreal region from PCIC and NEX-GDDP datasets based on the average of ten GCMs. It can be seen that the mean precipitation given by NEX-GDDP is smaller than PCIC. More specifically,

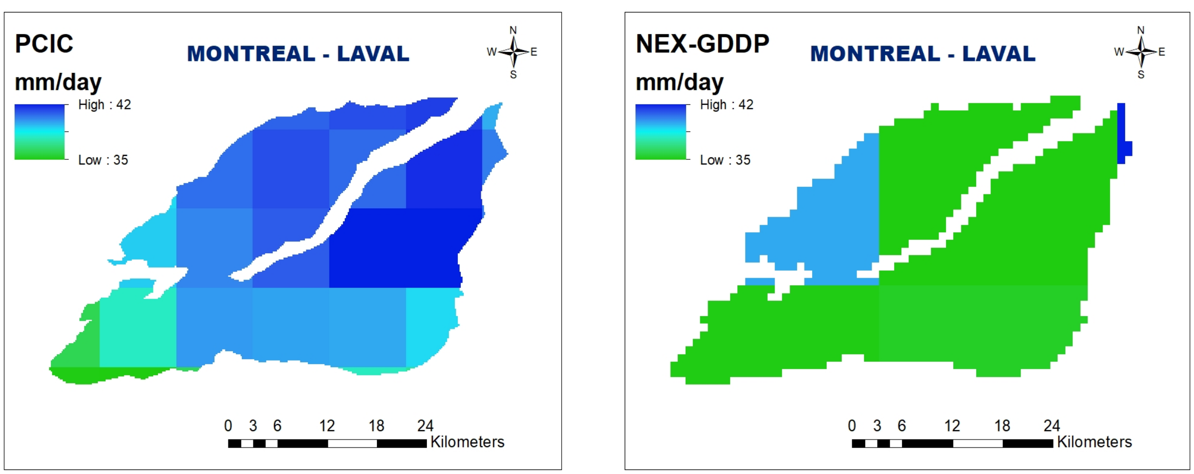
For purposes of illustration, the results for daily AMP at Dorval Airport are shown in Figures 3 using the boxplots, and the results for temperature extremes are presented in Figures 4 and 5. In addition, Table 4 presents the comparison using the root mean square error (RMSE) values for both precipitation and temperature extremes. In general, it can be seen that the PCIC data are more accurate for AMP and somewhat less accurate for temperature extremes as compared to the NEX-GDDP data. However,

Figure 4 indicates that results given by PCIC are more robust with narrow boxplots in comparison with NEX-GDDP data. Regarding the standard deviation, NEX-GDDP data is more accurate for daily minimum temperature while PCIC data are more robust for daily maximum temperature.

Table 3 shows the means of daily AMPs at Dorval and McGill stations in comparison with PCIC and NEX-GDDP data. Overall, the gridded downscaled data values are smaller than the observed data at a given station. PCIC data are 11.92% and 22.75% lower than observed AMP at Dorval and McGill stations, respectively, while the values from NEX-GDDP data are 29.24% and 35.92%, respectively. It is therefore necessary to perform a bias adjustment before these gridded downscaled data can be used in the planning and design of urban infrastructures.

Table 2. 10 IPCC-CMIP5 climate models used in this study

GCM	Institution
ACCESS1-0	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)
CanESM2	Canadian Centre for Climate Modelling and Analysis
CCSM4	National Center for Atmospheric Research
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancées en Calcul Scientifique
CSIRO-MK3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence
GFDL-ESM2G	NOAA's Geophysical Fluid Dynamics Laboratory
INMCM4	Institute for Numerical Mathematics, Moscow, Russia
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)
MRI-CGCM3	Meteorological Research Institute



PCIC NEX-GDDP

Figure 2. Daily AMPs over the Montreal region downscaled by PCIC and NEX-GDDP

For purposes of illustration, the results for daily AMP at Dorval Airport are shown in Figures 3 using the boxplots, and the results for temperature extremes are presented in Figures 4 and 5. In addition, Table 4 presents the comparison using the root mean square error (RMSE) values for both precipitation and temperature extremes. In general, it can be seen that the PCIC data are more accurate for AMP and somewhat less accurate for temperature extremes as compared to the NEX-GDDP data. However, Figure 4 indicates that results given by PCIC are more robust with narrow boxplots in comparison with NEX-GDDP data. Regarding the standard deviation, NEX-GDDP data is more accurate for daily minimum temperature while PCIC data are more robust for daily maximum temperature.

Table 3. Mean of daily AMPs at Dorval and McGill stations

No.	Station	Mean of daily AMPs (mm/day)				
		Observed	PCIC	Different (%)	NEX-GDDP	Different (%)
1	Dorval	50.75	44.7	11.92	35.91	29.24
2	McGill	54.76	42.3	22.75	35.09	35.92

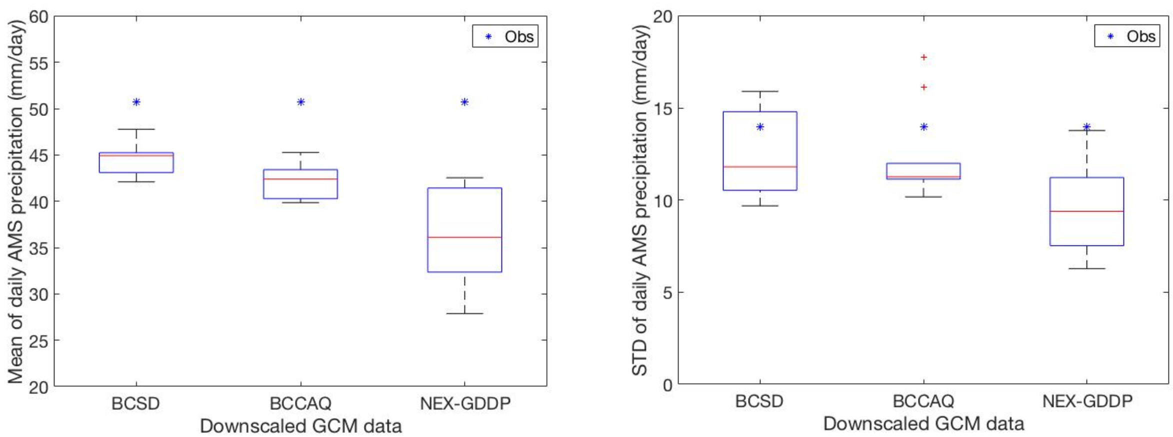


Figure 3. Mean (left) and Standard Deviation (right) of daily AMPs at Dorval station based on downscaled gridded data from ten different GCMs

Table 4. RMSE of the means of daily AMP and temperature extremes at Dorval station

RCMs	RMSE		
	T_{min}	T_{max}	Precipitation
PCIC-BCSD	6.91	5.16	**2.90**
PCIC-BCCAQ	6.47	4.75	5.00
NEX-GDDP	**5.71**	**3.99**	12.20

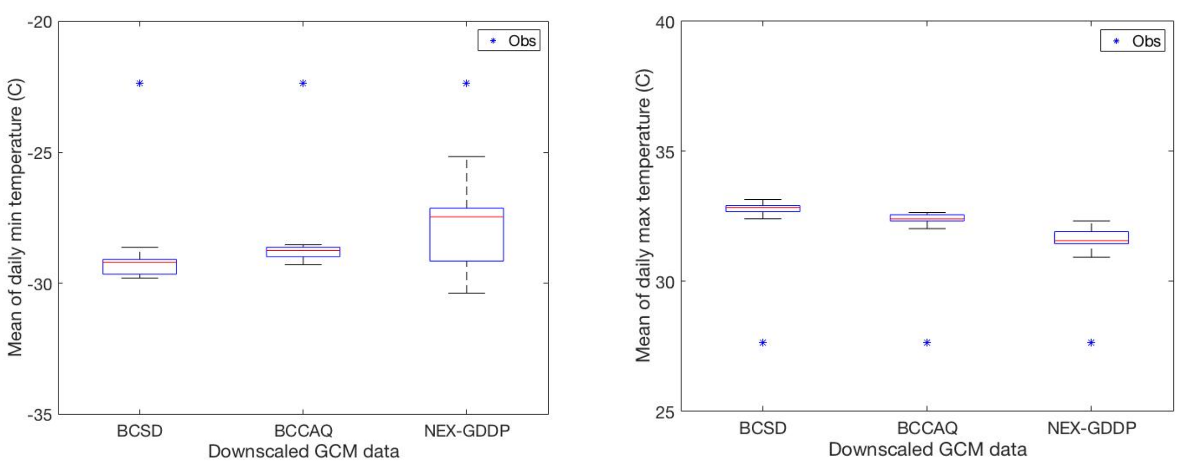


Figure 4. Mean of daily minimum (left) and maximum (right) temperatures at Dorval station based on downscaled gridded data from ten different GCMs.

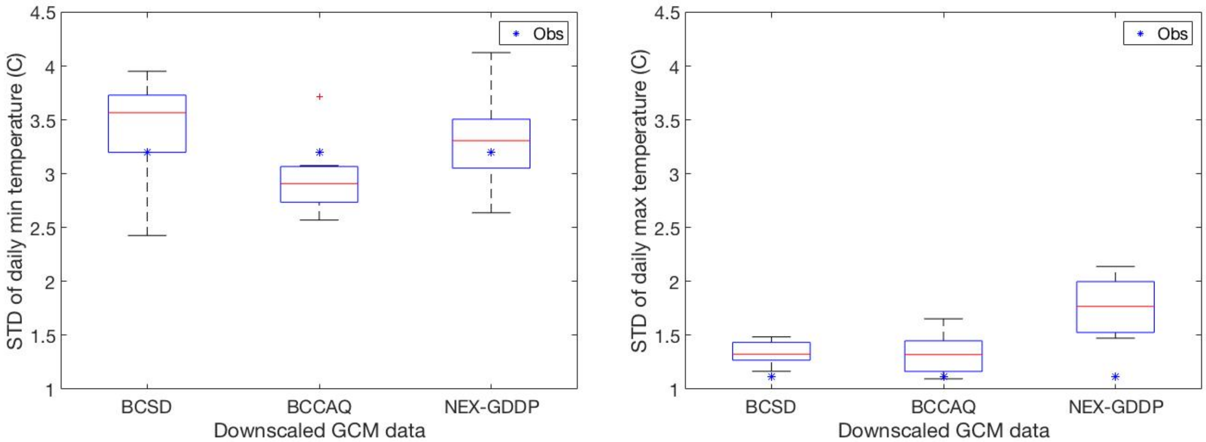


Figure 5. Standard deviation of daily minimum (left) and maximum (right) temperatures at Dorval station based on downscaled gridded data from ten different GCMs

3.2. Future climates

Daily annual temperature extremes and daily AMPs for the 2006-2100 period downscaled from PCIC and NEX-GDDP were analyzed. It can be seen from Figure 6 and Figure 7 that there are increasing trends in both temperature extremes and AMP at Dorval station. Table 5 shows the values of temperature extremes and AMPs estimated based on the fitted trend regression lines at the year 2006 and 2100. Results are based on an average of all 10 GCMs given by both datasets. It is estimated that precipitation could increase around 10.77% for the 2006-2100 period. In addition, daily maximum temperature is projected to increase around 8.06% in the same period. Daily minimum temperature could have a projected increase of around 16.69%. Hence, the Montreal region could experience more extreme rainfalls and higher maximum and minimum temperatures in the future.

Table 5. Increase of temperature and precipitation in 2006-2100 period

Variables	2006	2100	% increase
Precipitation (mm)	41.47	45.93	10.77
Minimum temperature (°C)	-26.19	-21.82	16.69
Maximum temperature (°C)	33.33	36.02	8.06

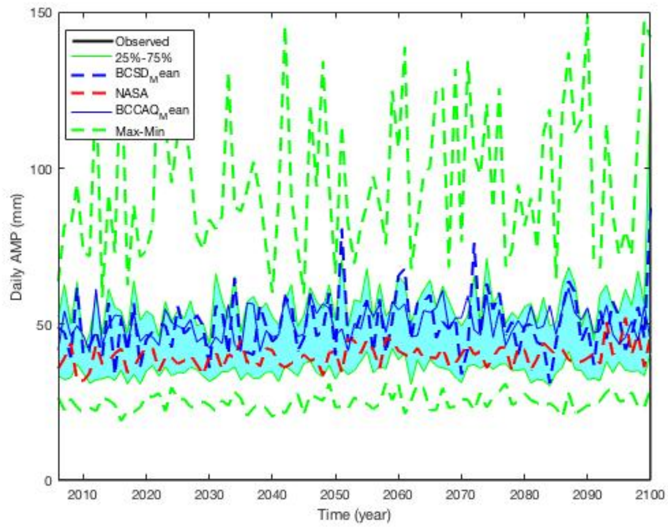
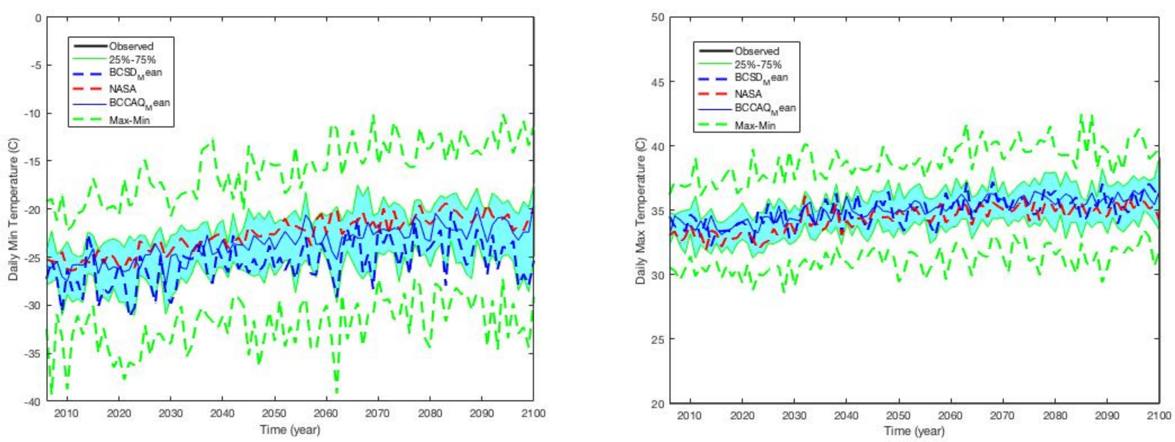


Figure 6. Projected daily AMPs at Dorval station



(a) (b)

Figure 7. Daily minimum (a) and maximum (b) temperatures at Dorval station (2006-2100)

4 CONCLUSIONS

Major findings of this present study can be summarized as follows:

1. Many climate projection studies have been commonly conducted at global or large regional scales, the present study has been performed specifically at the City of Montreal scale to provide useful information on the variability in time and in space of annual maximum precipitations and temperature extremes for the design and planning of its urban infrastructures using the regional downscaled climate projection data from ten different GCMs under the RCP 4.5 scenario provided by PCIC and NEX-GDDP. In general, the PCIC data with finer grid size of 1/12 degree (or approximately 10x10 km) could produce more robust results than the NEX-GDDP data with a coarser resolution of ¼ degree (or approximately 25x25 km).

2. According to the results downscaled by PCIC and NEX-GDDP, there are projected increasing trends in both temperature extremes and AMPs over the Montreal region. The AMP is projected to increase around 10% for the 2006-2100 period. Minimum and maximum temperatures are projected to increase approximately 16% and 8% respectively by the end of this century.

3. Downscaled gridded data are different from observed data at a given location. It is therefore necessary to perform a bias correction of the gridded data before these data could be used in the planning and design of the urban infrastructures.

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