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Hydrological response to dynamical downscaling of climate model outputs: A case study for western and eastern snowmelt-dominated Canada catchments

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ABSTRACT

Study region: An analysis of hydrological response to a dynamically downscaled multi-member multi-model global climate model (GCM) ensemble of simulations based on the Canadian Regional Climate Model (CRCM) is presented for three snowmelt-dominated basins in Canada. The basins are situated in the western mountainous (British Columbia) and eastern level (Quebec) regions in Canada, providing comprehensive experiments to validate the CRCM over various topographic features.
Study focus: The evaluation of the CRCM as a tool to improve GCM simulations of catchment scale hydrology is investigated within the bounds of uncertainty associated with RCM simulations. Daily climate variables were extracted from a 30-year CRCM and GCM ensemble simulations. The hydrological response was assessed through the comparison of catchment water components simulated by SWAT.
New hydrological insights for the region: Results show that the CRCM captures the primary features of observed climate, but there are significant biases. Most noteworthy are a positive bias in precipitation and a negative bias in temperature over the BC basin. When looking at the hydrological modeling results, the benefit of using the RCM *versus* GCMs emerged distinctly for the mountainous BC basin where the RCM is preferred over the GCMs. The sensitivity experiments show that uncertainty in the GCM/RCM's internal variability must be assessed to provide suitable regional hydrological responses to climate change.

1. Introduction

The economic value of freshwater in Canada makes this resource one of the highest-priority issues with respect to the impact of and adaptation to climate change. While climate change is an inherently global issue, impacts on water resources will vary at regional and local scales. Preserving these natural resources will require complex trade-offs to deal with regional economic, social and environmental issues related to water across the country. This is particularly challenging in Canada since its large geographic, climatic and hydro-ecologic diversity means that the projected effects of climate change on water resources can be expected to vary significantly across the country. In addition to nation-wide challenges for adaptation to

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climate change, Canada already experiences water-related problems linked to extreme hydrologic events and associated water quality issues (Warren et al., 2004). Spring snowmelt-driven flows are the major flood-producing mechanism in many Canadian watersheds (Simonovic and Li, 2003; Cunderlik and Ouarda, 2009). The spring snowmelt-driven flows also provide most of the surface water for many regions (Shrestha et al., 2012a,b). A disturbance of the hydrologic regime in snow-dominated regions in Canada could result in regional water shortages since built storage capacity could be inadequate to cope with streamflow seasonal shifts. Since water in both British Columbia and Quebec is already under mounting socio-economic pressure, the potential effects of climate change on overall availability of water has stimulated research efforts to develop appropriate water management tools to support regional management decisions.

The most comprehensive approach to studying climate change impacts on water management combines global climate models (GCMs) outputs with hydrological models. However, hydrological modeling depends on reliable information about relevant variables and their distribution in time and space from the regional to the local scale to ensure accurate simulations of streamflow trends for the past and present, and to make realistic predictions of future climate scenarios. However, GCMs are limited in their ability to represent fine-scale climate processes (Duffy et al., 2003), and may overlook important physical processes governing regional climate variability, especially over watersheds with complex topography (Xu, 1999; Arora, 2001; Diffenbaugh et al., 2005). Dynamical downscaling is a physically consistent approach to overcome this scale mismatch. In dynamical downscaling, a higher-resolution regional climate model (RCM) is driven by a GCM which provides the RCM with its boundary conditions. Due to their higher resolution, and to a dedicated physics adapted to this resolution, RCMs can improve simulations of climate variables (Hagemann et al., 2009; Maraun et al., 2010). Various worldwide initiatives (CORDEX, Giorgi et al., 2009 North America – NARCCAP, Mearns et al., 2009 Europe – PRUDENCE, Christensen et al., 2002 and ENSEMBLES, van der Linden and Mitchell, 2009; South America – CREAS, Marengo and Ambrizzi, 2006 and Asia – RMIP, Fu et al., 2005) have produced and continue to regularly produce ensembles of RCM simulations to serve the community of scientists studying climate change impacts.

Despite substantial efforts to enhance the spatial resolution of regional climate models in recent years, the additional information provided by RCMs for hydrological applications (which is often referred to as “added value”) has yet to be thoroughly evaluated (Hay et al., 2002; Freser et al., 2011). Many studies have demonstrated that RCMs can realistically simulate fine-scale climate features and climate statistics in comparison to observations (Semmler and Jacob, 2004; Früh et al., 2010; Kunz et al., 2010), and by extension, are somewhat successful in representing historical flows (Hay and Clark, 2003; Wood et al., 2004). However, they only use RCM outputs and implicitly assume that these outputs are superior to the driving GCM data, even though this is not explicitly demonstrated. Moreover, RCM simulations may add specific uncertainties tied to the model configuration (e.g., choice of driving GCM, choice of domains, regional model imperfections, etc.). Besides the problem related to partitioning bias sources in RCM outputs (i.e., boundary conditions or regional model errors), one of the most pertinent issues for hydrological applications is whether the magnitude of such troublesome biases in the GCM–RCM model chain is lower than that of biases already found in the GCM. If anything, the confidence placed in RCM simulations remains questionable in many hydrology-related studies.

The present study focuses on the evaluation of the RCM as a tool to improve GCM simulations for hydrological applications. Assessment of the benefits of the RCM is conducted for climate simulations of catchment scale hydrology, when the hydro-climate model chain is applied over three seasonally snow-covered catchments in both mountainous and leveled regions in Canada. The value of regional climate modeling is determined by evaluating the success of the RCM in reproducing present-day climate characteristics, along with the simulation of dominant components of the catchment water balance. The streamflow sensitivity to various sources of uncertainties associated with generating present-day regional climate simulations is also analysed with the prospect of providing additional insight into the reliability of an RCM for hydrological applications. More specifically, the derivated estimates of uncertainty in climate models are discussed with regards to winter and summer flows as well as annual extreme floods, based on our specific interest of snowmelt processes which dominate the hydrologic regime of the catchments under investigation.

Daily precipitation and temperature time series are derived from two ensembles of simulations from the Canadian Regional Climate Model version 4.3 (CRCM; Music and Caya, 2007) and two associated GCM ensemble simulations (the Canadian CGCM3 and the German ECHAM5) that are used to force the CRCM. CRCM and GCM climate variables are then used as input to the process-based Soil Water Assessment Tool (SWAT) model (Arnold et al., 1998) to simulate the catchments' hydrology over the 1971–2000 period. Since the hydrological response of a catchment results from the integration of the regional climate (in time and space), the results presented here provide comparison of the realism of the CRCM driven hydro-climatic response with those of the parent GCMs for two widely different snowmelt-dominated regions of Canada.

Section 2 describes sources of uncertainty associated with generating regional climate information when using a chain of climate models. Section 3 presents the study area and the ensembles of the CRCM and the two GCMs used in this study. A description of the SWAT hydrological model is given in Section 4. The relevant results of the evaluation of the added value of the RCM against that of the GCMs are analyzed in Section 5. The streamflow's sensitivity to uncertainties in regional climate simulations is presented and discussed in Section 6. Concluding remarks appear in Section 7.

2. Sources of uncertainty in the generation of regional climate information

RCM simulations are subject to various sources of uncertainty stemming from model structure and nesting configuration, and also from the natural variability of the climate system.

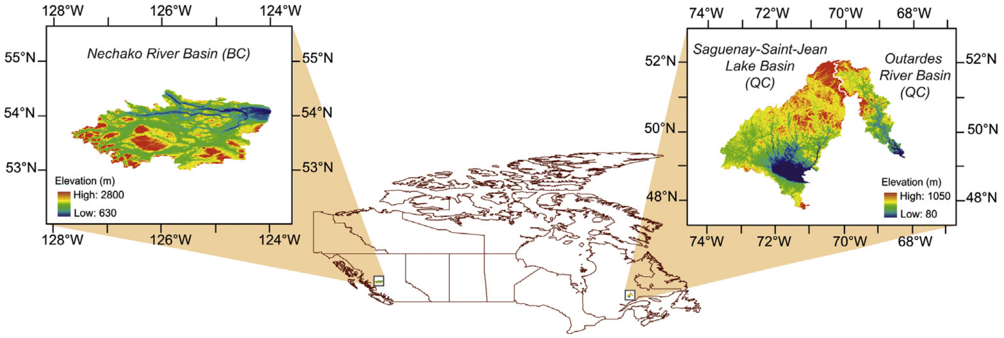

Fig. 1. Location map of study basins.

The first source of uncertainty arises from imperfect knowledge and representation of physical processes, limitations due to numerical approximations of the model's equations, and other simplifications and assumptions (Giorgi et al., 2001; Stainforth et al., 2007). Structural uncertainty can be explored using different models (Graham et al., 2007; Mearns et al., 2012; Woldemeskel et al., 2012) and is usually referred to as inter-model variability. On the side of RCM simulations, there are some additional sources of structural uncertainty related to the nesting configuration (i.e., choice of driving model and their ensemble of simulations, driving technique, size and location of the regional domain). An RCM driven by an ensemble of different global models is usually used to address the impact of variability in driving GCMs on regional simulations (Hudson and Jones, 2002; Salzmann and Mearns, 2012). Among these, model biases are probably most used to characterize structural uncertainty. Criteria to evaluate the model biases are based on the skill of the models at reproducing patterns of the observed climate. However, the observed climate is sometimes characterized by a high level of uncertainty due to measurement errors and sparseness of stations, especially in regions of complex topography and in northern environments. Another source of uncertainty emanates from natural variability, which refers to the variability present in the absence of forcings (Ghil, 2002; Deser et al., 2012). Uncertainty due to natural variability is typically estimated by imposing slight perturbations on a series of GCM simulations, usually by using different initial conditions. The differences between the members within an ensemble is used to quantify internal variability (or inter-member variability; IV) of a climate model (Lucas-Picher et al., 2008). Although the IV of both the global and regional climate system may not be the largest source of uncertainty, this latter generates a degree of uncertainty in regional climate simulation that cannot be reduced or removed. The uncertainty related to IV therefore becomes the lowest level of uncertainty that can be achieved in climate projections.

The above uncertainties can be assessed by analyzing an ensemble of regional and global climate simulations that adequately samples the various sources of uncertainty. Based on a comprehensive ensemble of CRCM simulations driven by two multi-member global model ensembles, the uncertainty assessment is performed on the catchments' streamflow, when focusing on annual extreme floods (extreme spring events), summer high flows and winter low flows. Given the emerging need for RCM simulations in hydrology-related applications, this knowledge provides valuable insights concerning the confidence level of the Canadian regional model.

3. Study area and dataset

3.1. Study catchments

Three catchments with areas from 15 267 to 73 000 km^2 are selected as test cases representing typical Canadian climatic conditions and land cover types. Snowmelt processes dominate the surface hydrology of these basins. The Nechako River Basin in the province of British Columbia (BC) is a high-elevation catchment, whereas the Saguenay-Saint-Jean Lake Basin and the Outardes River Basin in the province of Quebec (QC) are characterized by lower, smoother topography. Fig. 1 shows the location of each basin and Table 1 lists some of their main features.

3.2. Observational datasets

Daily observational data from stations are provided by Environment Canada climatological station observations for the Nechako River Basin, by Rio Tinto Alcan for the Saguenay-Saint-Jean Lake Basin and by the Institut de Recherche d'Hydro-Québec (IREQ) for the Outardes River Basin. These data come from eight stations in the Nechako River Basin, ten stations in the Saguenay-Saint-Jean Lake Basin and eight stations in the Outardes River Basin over the 1960–2005 period. The IREQ further treated the observations of the Outardes River Basin with a geostatistical kriging algorithm with external drift (based on a digital elevation model with 10-km resolution) to optimise information in both space and time (Tapsoba et al., 2005). The 29 locations generated by the geostatistical algorithm are used in this study. The meteorological statistics for each basin are summarized in Table 1.

Table 1
General characteristics of study basins.

	Basins		
	Nechako River	Saguenay-Saint-Jean Lake	Outardes River
Province	British Columbia	Quebec	Quebec
Drainage area (km^2)	25105	73000	15267
Elevation range (m)	630–2800	80–1050	80–1050
Main land cover type	Forest (86%)	Forest (86%)	Forest (80%)
Hydrology			
Discharge gauging station			
Latitude (N)	54.01	48.91	49.70
Longitude (W)	−124.00	−72.20	−68.88
Mean daily discharge (m^3/s)	193	204	358
Minimum daily discharge (m^3/s)	21	23	24
Maximum daily discharge (m^3/s)	1311	1560	3371
Climate			
Number of meteorological stations	8	10	29
Annual average precipitation total (mm)	824	938	931
Snow ratio (%)	41	24	36
Annual daily temperature (°C)			
Min.	−40.2	−44.0	−45.9
Max.	+33.1	+32.5	+32.4
Mean	+2.5	+0.8	−1.5
Number of CRCM grid points	15	41	9

Table 2
List of model name and version used in this study.

Model	Country	Model grid points/spatial resolution (Longitude × Latitude)	Atmospheric resolution	Primary reference
CRCM 4.2.3	Canadian	200 × 192 (AMNO) with a horizontal grid-point spacing of 45-km (true at 60° N)	/	Caya and Laprise, 1999; Laprise et al., 2003
ERA40	Europe	1.125° × 1.125°	/	Uppala et al., 2005
CGCM 3	Canadian	3.75° × 3.75°	T47L31	Flato et al., 2000; Scinocca et al., 2008
ECHAM 5	German	1.875° × 1.875°	T63L32	Jungclaus et al., 2006; Roeckner et al., 2003

3.3. *RCM and GCM ensemble simulations*

The Canadian Regional Climate Model (CRCM) version 4.2.3 is the regional model used for the present investigation. The CRCM lateral boundary conditions are produced by a one-way nesting method inspired by Davies (1976) and refined by Robert and Yakimiw (1986). CRCM is driven by the time evolution of vertical profiles of winds, air temperature, humidity and pressure at its lateral boundaries. The driving data is interpolated linearly to provide input at every CRCM time step. A three-year spin up is performed for each 30-year simulation to allow the simulated climate system to reach equilibrium (Paquin et al., 2006).

The analysis is carried out on an ensemble of CRCM simulations driven at its lateral boundary by: ECMWF ERA40 global reanalysis data; a 5-member ensemble of the third generation Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM3); and a 3-member ensemble of the fifth generation of the German Coupled Global Climate Model (ECHAM5) developed at the Max Planck Institute for Meteorology atmosphere and ocean (MPI-OM) (Table 2). The ensembles of CRCM and GCMs simulations cover the same 30-year period extending from January 1971 to December 2000. The acronyms used in this study are listed in Table 3.

The comparison of the CRCM-C3 and CRCM-E5 ensemble means with the respective driving CGCM3 and ECHAM5 ensemble means estimates the value added by regional climate modeling (Table 4). The above ensembles also serve as sensitivity experiments to assess structural uncertainties in the regional model and uncertainty from the driving boundary conditions (reanalysis-driven *versus* GCM-driven simulations) and inter GCM driving variability (CRCM-C3 *versus* CRCM-E5), along with GCM uncertainty (inter-model variability). Uncertainty due to the RCM's IV, defined as the inter-member spread between members in an ensemble of RCM simulations driven by different GCM simulation members, is compared to that of the driving GCM's IV. Finally, it is worth mentioning that the IV experiments provide a reference point for the significance of sensitivity results.

Table 3
Definition of acronyms used in this study.

Acronyms	
CRCM-C3	CRCM driven by CGCM3
CRCM-E5	CRCM driven by ECHAM5
CRCM-ERA	CRCM driven by ERA40
IV	Inter-member variability
GCM-ES	GCM ensemble simulations
CGCM3-ES	CGCM3 ensemble simulations
ECHAM5-ES	ECHAM5 ensemble simulations
CRCM-ES	CRCM ensemble simulations
CRCM-C3-ES	CRCM-C3 ensemble simulations
CRCM-E5-ES	CRCM-E5 ensemble simulations

Table 4
List of the ensemble simulations from CRCM and the GCMs used in this study to investigate the value added of regional climate model over global model data for simulating catchment's hydrology. They also serve as experiments to assess some uncertainties in regional climate modeling related to model structure (model biases, driving boundary conditions and inter GCM driving variability) and climate variability (inter-member variability: differences between members in an ensemble of CRCM simulations driven by different GCM simulation members), and in global modeling related to model structure (model biases and inter-model variability) and natural variability of the climate system (inter-member variability: differences between simulation members in an ensemble of GCM simulations differing only in their initial conditions), along with the propagation of climatic uncertainties in the hydrological modeling experiments over the 30-year period (1971–2000).

Analysis			Model ensemble simulations and comparison
Added value of regional climate modeling			CRCM-C3 5-member ensemble mean (45-km) *vs* CGCM3 5-member ensemble mean (~400-km) CRCM-E5 3-member ensemble mean (45-km) *vs* ECHAM5 3-member ensemble mean (~200-km)
Model validation and sampling climatic uncertainties			
RCM			
	• Structural	Model biases	CRCM-ERA *vs* OBS
		Driving boundary conditions	CRCM-ERA *vs* CRCM-C3 5-member ensemble mean *vs* CRCM-E5 3-member ensemble mean
		Inter GCM driving variability	CRCM-C3 5-member ensemble mean *vs* CRCM-E5 3-member ensemble mean
	• Climate variability	Inter-member variability	CRCM-C3#1 to #5 & CRCM-E5# 1 to #3
GCMs			
	• Structural	Model biases	CGCM3 5-member ensemble mean *vs* OBS & ECHAM5 3-member ensemble mean *vs* OBS
		Inter-model variability	CGCM3 5-member ensemble mean *vs* ECHAM5 3-member ensemble mean
	• Natural variability	Inter-member variability	CGCM3#1 to #5 & ECHAM5#1 to #3

4. Catchment scale hydrological modeling

The hydrological catchment model used for this study is the Soil Water Assessment Tool (SWAT) model developed at the United States Department of Agriculture (USDA) by Arnold et al. (1998). The hydrologic and water quality SWAT model is chosen so that its performance in modeling Nordic watersheds in British Columbia and Quebec was evaluated before extending the model application to water quality issues in those environments.

SWAT is a process-based semi-distributed model that operates on a daily time step. The model represents the spatial variability of land use and soil types by dividing the watershed into multiple Hydrologic Response Units (HRUs) that represent a unique combination of land cover, soil and slope. The climate variables required to run SWAT are daily precipitation along with daily maximum and minimum air temperatures.

The HRU water balance is expressed as,

$$W_{\mathrm{t}} = W_0 + \sum_{i=1}^{t} \left(P\mathrm{i} - Q_{\mathrm{isurf}} - ET\mathrm{i} - W_{\mathrm{iseep}} - Q_{\mathrm{igw}} \right) \tag{1}$$

where W_{t} is the soil moisture content at time t (mm of water); W_{o} is the initial soil moisture content (mm of water); P_{i} is the precipitation on day i (mm of water); Q_{isurf} is the surface runoff on day i (mm of water); ET_{i} is the evapotranspiration on day i (mm of water); w_{iseep} is the percolated water through the soil profile on day i (mm of water); and Q_{igw} is the groundwater flow on day i (mm of water).

A description of snow hydrology processes included in SWAT is provided in Troin and Caya (2014). A detailed description of the model's components is presented in Neitsch et al. (2005). A comprehensive review of SWAT applications is given in Gassman et al. (2007).

Table 5
SWAT performance during the calibration and the validation periods for the study basins.

	Periods	Calibration 1983–1988[c]			Validation 1966–1983[d]			Validation 1988–2005[e]		
	Statistics	r^2	NSE	Dv (%)	r^2	NSE	Dv (%)	r^2	NSE	Dv (%)
Nechako River Basin (BC)	Daily discharge	0.81	0.80	−7.57	0.77	0.75	−6.77	0.77	0.74	+3.35
	Daily summer high flow[a]	0.86	0.82	−14.59	0.83	0.80	−15.78	0.85	0.83	−7.35
	Daily winter low flow[b]	0.85	0.81	−3.59	0.82	0.81	−6.45	0.83	0.82	−12.28
Saguenay-Saint-Jean Lake Basin (QC)	Daily discharge	0.86	0.83	−1.06	0.81	0.80	+2.83	0.83	0.81	+2.13
	Daily summer high flow[a]	0.87	0.86	−3.84	0.85	0.81	−2.60	0.85	0.83	−2.17
	Daily winter low flow[b]	0.86	0.85	−3.59	0.73	0.71	+6.45	0.77	0.72	−2.35
Outardes River Basin (QC)	Daily discharge	0.85	0.83	+0.28	0.82	0.82	−2.64	0.80	0.78	+1.00
	Daily summer high flow[a]	0.85	0.83	−4.35	0.87	0.85	−13.77	0.86	0.85	−10.86
	Daily winter low flow[b]	0.88	0.82	−7.54	0.78	0.72	−0.28	0.76	0.71	−6.03

Coefficient of determination $(r^2) = \left[\sum_{i=1}^{N}(O_i - \bar{O})(S_i - \bar{S}) / \sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}\right]^2$ with $\bar{O} = \frac{1}{N}\sum_{i=1}^{N} O_i$Nash-Sutcliffe efficiency (NSE) $= 1 - \left[\sum_{i=1}^{N}(O_i - S_i)^2 / \sum_{i=1}^{N}\left(O_i - \bar{O}\right)^2\right]$ Percent deviation of streamflow volume $(D_v) = \left[\sum_{i=1}^{N}(S_i - O_i) / \sum_{i=1}^{N}(O_i)\right] \times 100$, where O is observed discharge and S is simulated discharge.

[a] Estimated during the high-flow period from March to August when the snowmelt-generated peak flow occurs.
[b] Estimated during the low-flow period from September to February.
[c] The calibration period is from 1 October 1983 to 30 September 1988.
[d] The first validation period is from 1 October 1966 to 30 September 1983.
[e] The second validation period is from 1 October 1988 to 30 September 2005.

Naturalized or observed daily discharge data at the basins outlet are provided by the Water Survey of Canada hydrometric stations for the Nechako River Basin, by Rio Tinto Alcan for the Saguenay-Saint-Jean Lake Basin and by Hydro-Québec for the Outardes River Basin. The natural or observed values for the three catchments were reconstituted using a water balance approach to remove the influence of the dam of streamflow (M. Minville, pers. comm.). The database of daily discharge for the study basins covers the 1966–2005 period. Once configured, SWAT is run on a daily time step from 1 October 1960 to 30 September 2005. The first six years of the hydrological simulation (1960–1966) serve as a spin-up for the model to equilibrate the basin conditions. In order to compare the SWAT results over the integrated catchments, the calibration and validation strategies previously adopted for the Outardes River Basin in Troin and Caya (2014) are followed for the Nechako River Basin and the Saguenay-Saint-Jean Lake Basin; the hydrological years 1983–1988 are used for calibration while validation is done over the 1966–1983 and 1988–2003 periods. The implemented two-step calibration consists in conducting a sensitivity analysis to identify the dominant hydrological and snowmelt parameters for simulating and adjusting the values of the selected sensitive parameters. All 28 parameters describing the hydrological cycle are included in the sensitivity analysis performed with the Latin Hypercube One-factor-At-a-Time method (LH-OAT; van Griensven et al., 2006). The 17 most sensitive parameters are adjusted using the autocalibration procedure included in SWAT (Parameter Solutions Method; PARASOL; van Griensven et al., 2002) and manual refinements are made until the required parameter set is obtained. Technical details of model implementation along with sensitivity analysis and model calibration are provided in Troin and Caya (2014).

Table 5 presents SWAT's statistical performance for each basin, which is obtained by comparing daily observed and simulated discharges. Overall, the model performs well in simulating daily mean discharges in all basins with a low value in volume biases over the calibration and validation periods ($D_V < 15\%$). For instance, the *NSE* criterion for the study basins is above 0.8 for the calibration period and above 0.7 for the validation period. Seasonal analysis shows that the model tends to better predict daily summer high flows (the period of interest in the present study; *NSE* = 0.84) than daily winter low flows (*NSE* = 0.78) for the integrated catchments. These results are consistent with the results in Troin and Caya (2014), thereby providing confidence in SWAT's ability to simulate snowmelt flows in Nordic regions.

5. Evaluating the hydrological response to downscaled climate model outputs

5.1. Climate model evaluation and uncertainty analysis

The mean annual cycles for precipitation, maximum and minimum temperatures as simulated by the ensemble simulations from CRCM and the GCM over the 30-year period over the basins are displayed in Fig. 2. Comparison of the CRCM ensemble mean with station observations shows some differences in the amplitude of the mean annual cycle of simulated precipitation over each basin. In the Nechako River Basin, CRCM-C3 and CRCM-E5 show an overly vigorous annual cycle in precipitation with an overestimation in mean monthly precipitation except in winter. Overall, CRCM-ERA leads to an overestimation of mean monthly precipitation more pronounced than the GCM-driven simulations. For the Saguenay-Saint-Jean Lake Basin, CRCM-C3 and CRCM-E5 exhibit higher precipitation values during the summer half-year (May–September) compared to the winter half-year (October–April), while CRCM-ERA overestimates the observed mean annual cycle of pre-

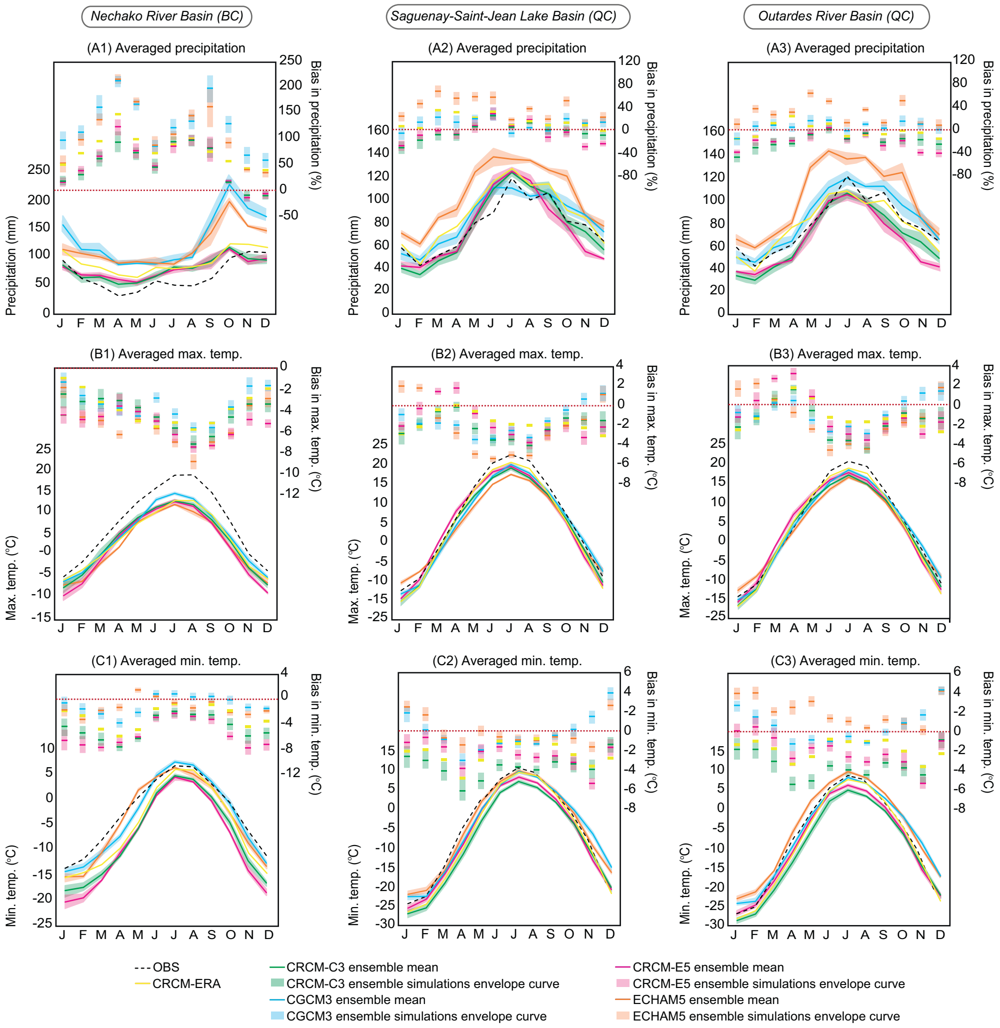

Fig. 2. Comparison of observed and simulated mean seasonal cycle of (A) precipitation totals (mm), (B) maximum and (C) minimum temperatures (°C) from the ensemble of CRCM simulations and of the driving GCMs simulations, averaged over a 30-year period (1971–2000) over the Nechako River Basin (BC), the Saguenay-Saint-Jean Lake Basin (QC) and the Outardes River Basin (QC). The ensemble mean is the mean of simulation members. Each ensemble mean is characterized by an envelope of uncertainty based on the range and spread of the individual simulation members.

cipitation all year round. Over the Outardes River Basin, CRCM underestimates the amplitude of the observed mean annual cycle of precipitation, although CRCM-ERA shows an early increase in spring.

As for the mean annual cycle of temperature, CRCM-C3 and CRCM-E5 display temperature values significantly lower than observations, particularly over the Nechako River Basin (Fig. 2). CRCM-ERA is quite similar to observations but the amplitude of the mean annual cycle of temperature is only approximate with a persistent underestimation worth noting in the basins.

Comparing both CRCM and GCM against observations indicates that the RCM adds value over the driving GCM in representing precipitation patterns over the high-elevation BC basin (Fig. 2). For the level QC basins and the specific CGCM3, though, the differences between the CGCM and observations coincide with even greater differences between the CRCM and observations; such a finding is somewhat more mixed for the ECHAM5-driven simulations. The RCM does not provide added value for temperature compared to the driving global data, and both GCMs perform well in reproducing the observed mean annual cycle of temperature over the mountainous and level basins. Also shown in Fig. 2 and Table 6 is that, though the catchment scale precipitation averages are quite similar in the GCM-driven simulations, the catchment scale temperature averages display a larger spread of errors depending on which driving GCM is used. This indicates that the CRCM-simulated temperature is more sensitive to the driving models than is precipitation.

Nevertheless, we do emphasize the pronounced cold bias of CRCM for the BC basin (Fig. 2 and Table 6); the cold biases in mean temperature are higher in summer (CRCM-GCM: −5.1 °C; CRCM-ERA: −4 °C) than in winter (CRCM-GCM: −4.4 °C; CRCM-ERA: −3 °C) irrespective of the driving global data used. Besides the plausible role of errors related to internal model physics in explaining part of the cold bias, one other source of bias can be found in GCM boundary conditions since both GCMs show the largest cold bias in mean temperature in summer (CGCM3: −2.5 °C; ECHAM5: −3.8 °C), but with lower magnitude

Table 6

Seasonal and annual bias in precipitation totals (%) and mean temperature (°C) as simulated by the ensemble simulations of the CRCM and of the driving GCMs relative to observations, averaged over a 30-year period (1971–2000) for (A) the Nechako River Basin (BC), (B) the Saguenay-Saint-Jean-Lake Basin (QC) and (C) the Outardes River Basin (QC). The range of bias for the ensemble simulations is displayed on either side of the mean value, as an indication of the inter-member variability. DJF: December–February; JJA: June –August.

(A)

	The Nechako Basin					
	Precipitation (%)			Mean temperature (°C)		
	DJF	JJA	Annual	DJF	JJA	Annual
CRCM-ERA	20	53	36	−3	−4	−3.2
CRCM-C3	-6_{-10}^{-2}	43_{41}^{47}	20_{17}^{23}	$-3.8_{-4.4}^{-3.2}$	$-4.1_{-4.3}^{-4}$	$-4.4_{-4.6}^{-4}$
CRCM-E5	-4_{-7}^{-1}	41_{39}^{46}	19_{16}^{22}	$-5.1_{-5.5}^{-4.5}$	$-6_{-6.2}^{-5.8}$	$-5.4_{-5.6}^{-5.2}$
CGCM3	66_{64}^{71}	76_{71}^{81}	95_{91}^{100}	$-1.5_{-2.1}^{-0.6}$	$-2.5_{-3}^{-2.2}$	$-2.1_{-2.6}^{-1.8}$
ECHAM5	38_{34}^{40}	77_{70}^{80}	75_{70}^{80}	$-2.8_{-3.7}^{-2.1}$	$-3.8_{-4}^{-3.5}$	$-3.3_{-3.7}^{-2.8}$

(B)

	The Saguenay-Saint-Jean-Lake Basin					
	Precipitation (%)			Mean temperature (°C)		
	DJF	JJA	Annual	DJF	JJA	Annual
CRCM-ERA	0	17	16	−2.5	−1.6	−1
CRCM-C3	-20_{-25}^{-15}	13_{7}^{17}	0_{-4}^{7}	$-2.3_{-3}^{-1.5}$	$-3.9_{-4.1}^{-3.7}$	$-2_{-2.4}^{-1.7}$
CRCM-E5	-21_{-23}^{-15}	17_{8}^{21}	-4_{-8}^{2}	$-1.7_{-2.1}^{-0.8}$	$-3_{-3.2}^{-2.5}$	$-1.7_{-2.1}^{-1.5}$
CGCM3	5_{3}^{8}	6_{2}^{9}	10_{5}^{12}	$0.5_{0.7}^{1}$	$-2_{-2.2}^{-1.9}$	$-0.1_{-0.3}^{-0.1}$
ECHAM5	24_{22}^{27}	33_{30}^{38}	37_{33}^{39}	$2_{1.6}^{2.2}$	$-3.2_{-3.4}^{-3}$	$-0.2_{-0.4}^{0}$

(C)

	The Outardes Basin					
	Precipitation (%)			Mean temperature (°C)		
	DJF	JJA	Annual	DJF	JJA	Annual
CRCM-ERA	−10	−2	−1	−2	−1.3	−1.5
CRCM-C3	-31_{-37}^{-24}	-5_{-10}^{0}	-15_{-17}^{-10}	$-1.7_{-2}^{-0.7}$	$-3.9_{-4.2}^{-3.6}$	$-2_{-2.4}^{-1.5}$
CRCM-E5	-29_{-36}^{-25}	-4_{-8}^{1}	-17_{-21}^{-13}	$-0.6_{-1.2}^{-0.2}$	$-2.7_{-3.3}^{-2.5}$	$-1.7_{-2.1}^{-1.4}$
CGCM3	-3_{-5}^{1}	6_{5}^{13}	10_{6}^{12}	$1.6_{1.3}^{2}$	$-21_{-2.3}^{-1.8}$	$-0.2_{-0.4}^{0}$
ECHAM5	18_{17}^{21}	30_{27}^{33}	33_{30}^{35}	$3.5_{3.7}^{3.1}$	$-3_{-3.3}^{-3}$	$0.2_{0}^{0.5}$

than the CRCM-GCM simulations (CRCM-C3: −4.1 °C; CRCM-E5: −6 °C). Such a regional feature falls within the tendency of regional models to simulate cold-biased temperature over mountainous regions in many areas of the world (Solman et al., 2008; Akhtar et al., 2009).

The GCM ensemble simulations (CGCM3-ES and ECHAM5-ES) allow identification of variables and catchments with large inter-member variability which is essential for the validation of both the global and regional models. Table 6 shows comparable IV in annual precipitation for both GCM-ES. However, for individual basins, the GCMs' IV in precipitation is largest over the BC basin. This indicates that variability in precipitation between catchments as simulated by the GCM-ES is controlled by large-scale features such as topography. The BC basin is particularly influenced by its high-elevation where weather systems interact with local topography, resulting in non-uniform precipitation with a large variability. Also, the GCMs' IV in precipitation is greater in summer than in winter, which is mirrored in all basins. Regarding simulations for the CRCM-ES driven by the two GCMs (CRCM-C3-ES and CRCM-E5-ES) we find a nearly identical IV in the 30-year mean of downscaled precipitation (Table 6). When compared to the driving GCMs' IV, some differences are observed in the magnitude of CRCM's IV, depending on the geographical localization of the basins under investigation. The larger IV of CRCM-ES in precipitation relative to their GCM-ES counterparts over the QC basins is likely related to the fact that the catchments are located far from the western inflow boundary of the regional domain; thus the RCM has more freedom to generate its own climate and variability which can differ from the driving GCMs' variability.

Both GCM-ES exhibit low values of IV for annual mean temperature over the basins (Table 6). The IV in annual temperature is largest over the BC basin in both GCM-ES. The models lead to the greatest IV of mean temperature in winter. The two GCM display similar IV for mean temperature (and precipitation) over the basins despite strong inter-model variability. Analyzing the CRCM-ES shows similar annual and seasonal IV in downscaled mean temperature over the basins (Table 6). Comparable annual and seasonal IV in mean temperature (and precipitation) in both CRCM-ES provides overall indications of RCM behavior in representing characteristics of the basins' weather regimes in a similar way whether the CGCM3 or ECHAM5 data are used at the boundary. Again, the CRCM's IV in temperature is sensitive to the analyzed catchments' location: both CRCM-ES display an IV in mean temperature higher than the GCM-ES in annual and seasonal values over

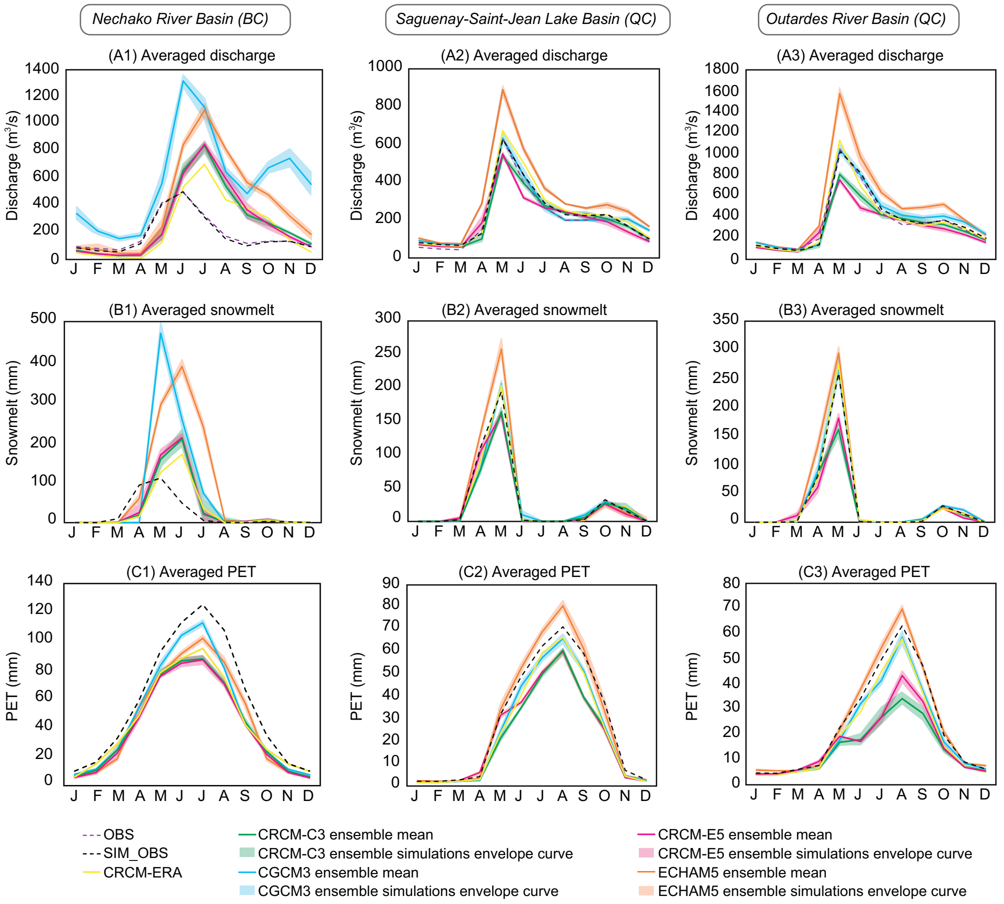

Fig. 3. SWAT-simulated mean monthly (A) discharge (m^3/s), (B) potential evapotranspiration (PET in mm) and (C) snowmelt (mm) driven by observed meteorological data (SIM_OBS) and by the ensemble of the CRCM simulations and of the driving GCMs simulations, averaged over the 30-year period (1971–2000) over the Nechako River Basin (BC), the Saguenay-Saint-Jean Lake Basin (QC) and the Outardes River Basin (QC). The ensemble mean is the mean of the individual ensemble members and each ensemble mean is characterized by an envelope of uncertainty based on the range and spread of the individual ensemble members. Observed (OBS) discharges are also plotted to illustrate hydrological uncertainties.

the QC basins. As discussed above, the lower influence of the driving boundary fields on the CRCM's IV over the QC basins can be attributed to the larger distance of these catchments from the western inflow boundary. Nevertheless, such findings can be somewhat nuanced since the CRCM's IV and GCMs' IV are not significantly different, with values lower than 5% for precipitation and 1 °C for temperature over the QC basins. Finally, it should be emphasized that, to some extent, the IV of both the hydrologically relevant climate variables is of roughly the same order of magnitude both in CRCM-ES and GCM-ES; these points are important for the significance of further hydrological modeling experiments.

5.2. Annual cycle of hydrologic conditions over the selected catchments

The hydro-climate model chain is then assessed to its reliability to reproduce the dynamic of key water balance components at the catchment scale. For this purpose, SWAT is forced with daily precipitation and temperature derived from previously described ensembles of CRCM and GCM simulations over the 1971–2000 period. Then, the water balance components of the catchment are simulated over the 30-year period using the calibrated parameter set derived for SWAT from observed station data.

The simulated catchment water balance is evaluated with respect to the mean annual cycles of three hydrologically relevant variables: discharges, snowmelt and potential evapotranspiration (PET). The simulated discharges, snowmelt and PET obtained from SWAT forced by observed meteorological data are considered as references for further analysis (labelled SIM_OBS in Fig. 3). Since the datasets of observed snowmelt and PET are unavailable for the basins under study, only the observed discharges (labelled OBS in Fig. 3) are displayed in the modeling results. It is noted that the 30-year mean annual cycles of monthly mean SIM_OBS discharges are remarkably close to OBS discharges with small biases introduced by the hydrological model (biases associated with model inputs, parameter and model structure uncertainties).

Fig. 3 shows that CRCM significantly overestimates the peak in annual discharge over the BC basin. A persistent time-offset is present regardless of the data used to drive the CRCM. The large magnitude of the peak spring flow is clearly linked to the large snowmelt peak. This overestimated snowmelt peak likely results from both the cold bias in temperature and the mis-representation of the catchment's topography by the CRCM. The model grid displays higher elevation compared to the SRTM3 DEM grid (53-m DEM obtained from the Shuttle Radar Topography Mission) over 50% of the drainage area. The time-offset in the snowmelt-generated peak flow is linked to the pronounced cold bias over that catchment (Fig. 2), which delays the snowmelt peak. The constant underestimation of CRCM-PET also reflects the below-normal maximum temperature throughout the year (Fig. 2). Over the QC basins, CRCM results in mean annual discharge cycles closer to SIM_OBS than in the BC basin. The timing of the spring-snowmelt-generated peak is successfully captured in all CRCM simulations. The discharge magnitude is consistently underestimated in the CRCM-GCM simulations and somewhat overestimated in the CRCM-ERA experiments (Fig. 3). This might be explained by the amount of water stored in snowpack, which is underestimated (overestimated) in the CRCM-GCM (CRCM-ERA) simulations leading to lower (higher) amount of snowmelt (Fig. 3). The cold bias also explains the low rates of PET over the QC basins, particularly obvious in the Outardes River Basin (Fig. 2).

Interesting aspects of the comparison between the CRCM and GCM discharge simulations appear in Fig. 3. CGCM3 exhibits more realistic 30-year mean annual cycles of monthly mean discharges than CRCM-C3 over the QC basins. Such features result from the fact that the CGCM3 simulated temperature and precipitation present less pronounced biases compared to CRCM-C3, leading to adequate reproductions of the snowmelt peak and PET (Fig. 2). Besides the CGCM3-based results for the QC basins, ECHAM5 gives larger discharge values compared to SIM-OBS. As for the CRCM-E5/ECHAM5 comparison, CRCM-E5 yields more consistent discharge reproductions in the QC basins. Although large differences between the CRCM simulated discharges and observations are evident over the BC basin, the CRCM provides a better reproduction of the observed magnitude of snowmelt-dominated streamflow than the driving GCMs. This might indicate that GCMs lower spatial resolution restricts variations in local topography affecting the simulation of observed precipitation patterns which translates into unrealistic simulations of seasonal distribution of discharges in the mountainous basin.

6. Sensitivities of streamflow to uncertainties in regional climate model simulations

The ensemble of CRCM discharge simulations that have been completed for each basin contains: one ERA reanalysis-driven simulation, CRCM-C3 5-member ensemble simulations (and their complementary CGCM3 5-member ensemble simulations) and CRCM-E5 3-member ensemble simulations (and their complementary ECHAM 3-member ensemble simulations). Given the nature of the CRCM ensemble used in this study, it is possible to provide a thorough evaluation of the RCM outputs for hydrology-related applications by exploring the relative streamflow sensitivity associated with the type of driving boundary conditions (reanalysis-driven *versus* GCM-driven simulations), the inter GCM driving variability (CRCM-C3 *versus* CRCM-E5) and the IV (the natural variability of the driving GCM and the internal variability of the CRCM combined). The relative importance of RCM and GCM in quantifying uncertainty in the present-day hydrological simulations is also determined through an analysis of the long term variability. This evaluation will help yield a more complete picture of the Canadian RCM data's application in impact studies.

For this purpose, the cumulative distribution functions (CDFs) of summer high flows (March–August), winter low flows (September–February) and annual extreme flood (defined as 1-day maximum flow that occurs in spring due to snowmelt) are constructed for each basin. The CDFs are established using the kernel smoothing density estimate (Bowman and Azzalini, 1997) with 30 values over 30 years (1971–2000, one value per year) for seasonal mean flows and extreme hydrologic events. The distribution of the CRCM-simulated seasonal mean discharges and annual extreme floods resulting from the reanalysis-driven simulations is evaluated against the corresponding distribution found for the pair of GCMs-driven simulations. The variability of seasonal mean discharges and annual extreme floods as simulated by both CRCM-ES is compared along with the variability predicted by the driving GCM-ES.

6.1. Sensitivity of streamflow to changes in the RCM's driving boundary conditions

The distribution of seasonal mean discharges and annual extreme floods as simulated by the ensembles mean of the CRCM, and the GCMs plotted against the corresponding SIM-OBS values for each basin is presented in Fig. 4. The results show that using the ERA reanalysis and GCMs' data as boundary conditions lead to significant differences in the prediction of the CRCM-simulated summer high flows, where the differences in CDFs between the reanalysis-driven and GCM-driven simulations are particularly large over the basins. The CRCM-simulated summer high flows for the study basins are quite insensitive to the driving GCMs; both CRCM-C3 and CRCM-E5 simulate similar summer high flows while the driving GCMs generate different summer high flows. This interpretation can be extended to annual extreme floods where the CRCM is still strongly influenced by the type of driving boundary conditions (reanalysis *versus* GCMs), which leads to various hydrological responses to catchment levels. The most significant sensitivity of the simulated streamflows associated with the GCMs boundary conditions is found for the winter low-flow period. The model chain reacts differently to changes in the boundary conditions for all sets of driving data, which suggests that the CRCM fields under investigation (precipitation and temperature) are dependent on the driving global data to a large degree for that period. This means that the quality that can be achieved for the simulated winter low flows through the hydro-climate model chain will be limited by the quality of the boundary conditions used to drive the RCM. We note, though, that this analysis strictly relies on the sensitivity of the

Table 7
Analysis of hydrological variability as simulated by the CRCM ensemble simulations (CRCM-C3 5-member and CRCM-E5 3-member ensembles) and GCMensemble simulations (CGCM3 5-member and ECHAM5 3-member ensembles) for the study basins over the 30-year (1971–2000) period.

		CRCM-C3		CRCM-E5		CGCM3		ECHAM5	
		CV[d]	Range	CV[d]	Range	CV[d]	Range	CV[d]	Range
Nechako River Basin (BC)	Mean summer high flow[a]	0.20	0.04	0.21	0.05	0.17	0.04	0.16	0.04
	Mean winter low flow[b]	0.30	0.11	0.3	0.12	0.19	0.09	0.20	0.08
	Annual extreme flood[c]	0.29	0.10	0.28	0.10	0.21	0.08	0.21	0.08
Saguenay-Saint-Jean Lake Basin (QC)	Mean summer high flow[a]	0.14	0.02	0.18	0.03	0.16	0.03	0.19	0.03
	Mean winter low flow[b]	0.20	0.10	0.20	0.10	0.21	0.06	0.21	0.06
	Annual extreme flood[c]	0.21	0.11	0.21	0.11	0.22	0.08	0.22	0.09
Outardes River Basin (QC)	Mean summer high flow[a]	0.12	0.03	0.14	0.04	0.15	0.02	0.16	0.02
	Mean winter low flow[b]	0.14	0.11	0.14	0.11	0.18	0.06	0.18	0.06
	Annual extreme flood[c]	0.17	0.10	0.19	0.11	0.24	0.05	0.22	0.05

[a] Estimated during the summer high-flow period from March to August when the snowmelt-generated peak flow occurs.

[b] Estimated during the low-flow period from September to February.

[c] Defines as 1-day maximum flow that occurs in spring due to snowmelt.

[d] Coefficient of variation (CV) = (σ μ)where σ is the standard deviation and μ is the mean.

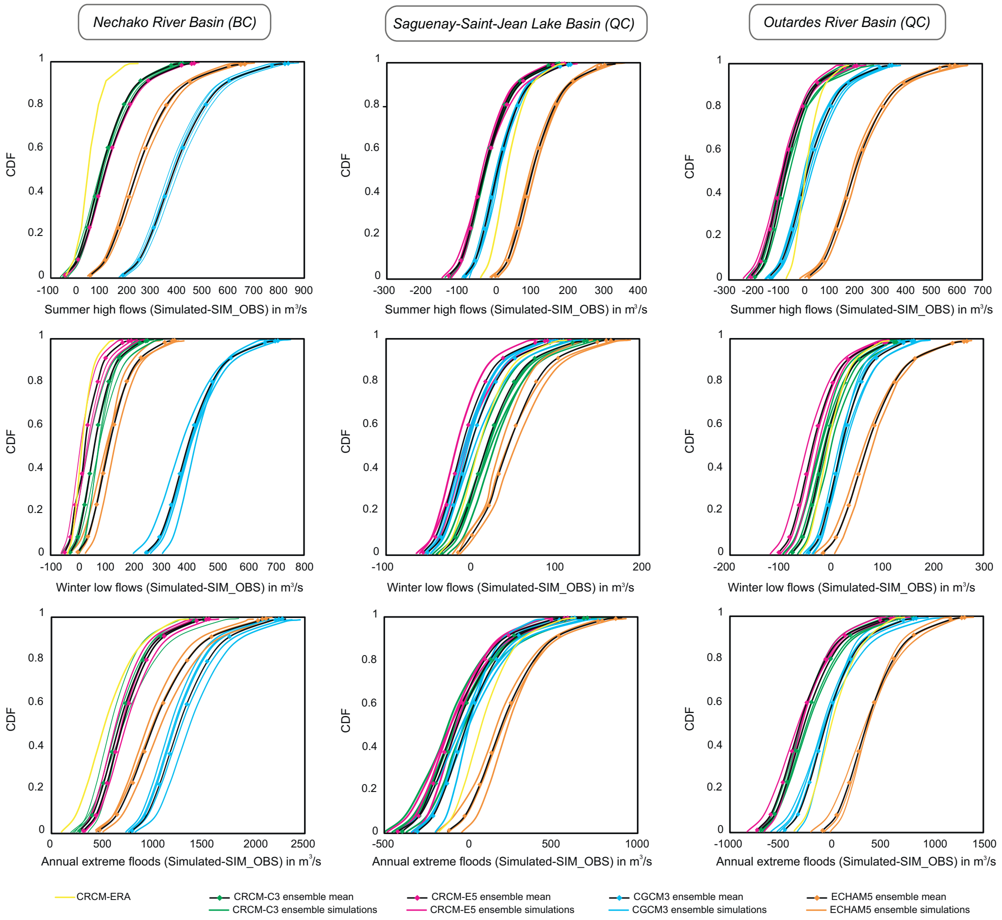

Fig. 4. Sensitivity of the CRCM-SWAT discharge simulations to changes in the driving boundary conditions (CRCM-ERA, CRCM-C3 and CRCM-E5) and to climate variability (CRCM-C3-ES and CRCM-E5-ES) for the Nechako River Basin (BC), the Saguenay-Saint-Jean-Lake Basin (QC) and the Outardes River Basin (QC). The CDFs of 30 years of CRCM-SWAT (A) summer high flows (B) winter low flows and (C) annual extreme floods are expressed as the difference between the simulated ensemble mean and observed (SIM_OBS) values for each basin. Both GCM-SWAT results are plotted to illustrate uncertainties related to inter-driving GCM variability on the CRCM-SWAT discharge simulations and inter-model variability (CGCM3 and ECHAM5); both GCM-ES-SWAT experiments give a comparison of uncertainty in the RCM's IV with that of the driving GCM's IV on the discharge simulations.

Canadian RCM to the changes in the driving boundaries of the regional domain caused by the ERA reanalysis and by fields from CGCM3 and ECHAM5 only alone.

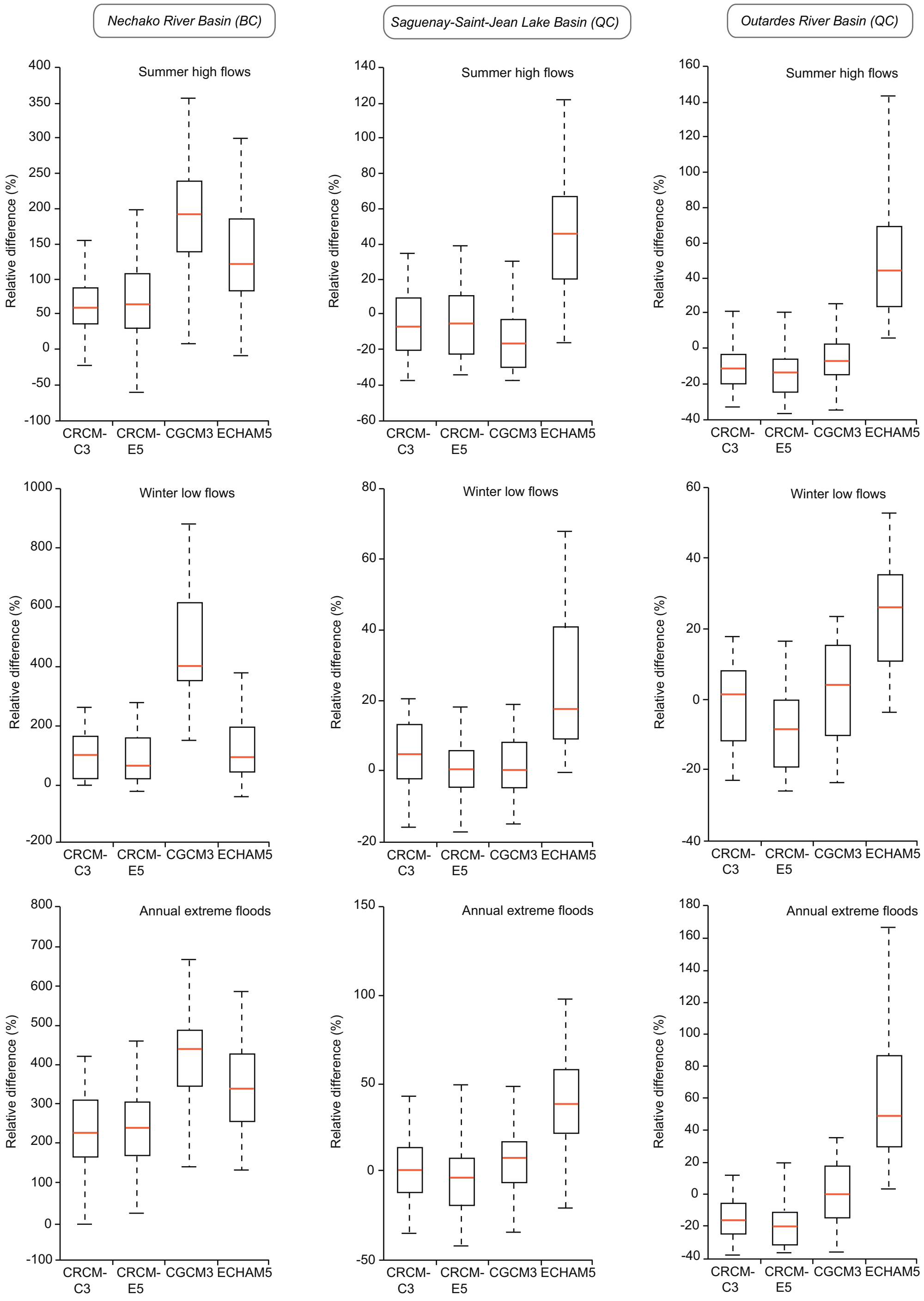

Fig. 5. Box plots of the relative difference (%) of summer high flows, winter low flows and extreme annual floods simulated by the ensemble simulations of CRCM-C3, CRCM-E5, CGCM3 and ECHAM5 for the Nechako River Basin (BC), the Saguenay-Saint-Jean-Lake Basin (QC) and the Outardes River Basin (QC) over the 1971–2000 period.

6.2. Sensitivity of streamflow to climate variability

A general feature of the CRCM-ES seasonal mean discharge simulations performed with the pair of driving GCM-ES is that the variability of the CRCM-C3-ES and CRCM-E5-ES simulated seasonal mean flows is quite similar over the basins (Fig. 4 and Table 7). We also find a nearly identical magnitude of variability in the annual extreme floods between both CRCM-ES.

A comparable variability in the simulated flows is expected for the two CRCM-ES since no significant difference in the IV of precipitation and temperature is seen between the GCM-driven simulations at the catchment scale (see section 5.1).

To estimate whether the discharge variability is 'large' or 'small' the variability of the seasonal mean flows and annual extreme floods as simulated by the two CRCM-ES is compared to the variability derived from the driving GCM-ES. The analysis of the coefficient of variation (*CV*) in Table 7 shows that the differences in the discharge variability's magnitude as simulated by the CRCM-ES and the driving GCM-ES depend on the hydrological period under investigation. The CRCM-ES-simulated streamflow variability is close to that of the driving GCM-ES for the summer high flows whereas, the CRCM-ES simulated streamflow variability displays larger values than those of the driving GCM-ES for the winter low flows and annual extreme floods. Inspecting Table 7, we also emphazise that the CRCM-ES-simulated streamflow variability is greater for the winter low flows and annual extreme floods than for the summer high flows, which is similar to the two GCM-ES. These results generally agree well with previous studies which underlined a large uncertainty associated with natural climate variability on extreme hydrologic events (Kay et al., 2008; Velázquez et al., 2013; Merz et al., 2014). In this respect, the analysis illustrates the importance of opting for several climatic members (IV) of a climate model to encompass the uncertainty associated with natural variability in order to provide comprehensive streamflow responses to climate variability and climate change. However, it should be kept in mind that the present study rests upon the CRCM-C3/CGCM3 5-member ensemble and the CRCM-E5/ECHAM5 3-member ensemble only, which naturally limits IV estimates' statistical robustness.

6.3. *Sensitivity of streamflow to climate model outputs*

To further examine the relative contributions of RCM and GCM to the uncertainty in streamflow, the variability in seasonal mean flows and annual extreme floods is estimated for the 30-year period over the basins (Fig. 5). The results reveal that the long term seasonal mean flows and annual extreme floods are highly variable depending on which climate model outputs are used to drive the hydrological model. The choice of using a RCM instead of a GCM only has more influence on the variability of hydrological simulations than the choice of the driving GCM for CRCM. Regarding the results of individual basins, ECHAM5 displays greater relative differences of seasonal mean flows and annual extreme floods than CRCM-E5 over the BC basin. Looking at the CRCM-CGCM3 comparison, the RCM does enhance the ensemble performance over that catchment by clearly reducing both the spread of results and the average error. When compared to CGCM3, CRCM-C3 does not greatly improve both seasonal mean flows and annual extreme floods over the QC basins. For both, CRCM-C3 and CGCM3 yield a median close to zero and similar variability as expressed by the box plots. The same conclusion cannot be transposed to the CRCM-ECHAM5 comparison, where large differences in the long term variability of seasonal mean flows and annual extreme floods are observed between CRCM-E5 and ECHAM5 over the QC basins. ECHAM5 leads to an overestimation of seasonal mean flows and annual extreme floods, and hence the median and the spread of errors are significantly improved by CRCM-E5.

Therefore, the CRCM improves the representation of simulated hydrological regimes to some extent. It reduces both the average and the maximum error of the simulated seasonal mean flows or annual extreme floods in similar ways. Nevertheless, such findings cannot be generalized to all catchments under investigation. Even if the CRCM ensures a better representation of hydro-climate patterns at the catchment scale by definition, the use of GCM outputs can also provide a fairly consistent reproduction of the hydrological regime depending on the study area (high-elevation *versus* low-elevation catchment) and the model (ECHAM5 *versus* CGCM3) considered.

7. Conclusions

Three snowmelt-dominated Canada catchments' hydrological response to dynamically downscaled outputs from the Canadian RCM is investigated. The selected basins are situated in the western mountainous BC and eastern level QC regions in Canada, and thus provide unusually comprehensive experiments to validate the RCM over various topographic features on both sides of the larger North American (AMNO) domain. Along with evaluating the value of CRCM outputs in simulating catchment scale hydrology, this study focuses on streamflow sensitivity to some uncertainties associated with generating present-day regional climate simulations in order to provide a more complete picture of the application of the Canadian RCM for impact studies.

The analysis of the present-day CRCM simulations at the catchment scale shows that the RCM captures the primary features of observed climate, but there are significant biases. Most noteworthy are a positive bias in precipitation and a negative bias in temperature over the BC basin. Overall, CRCM leads to a deterioration of the driving GCM results for temperature in all basins. The RCM does not show added value in describing precipitation patterns over the level QC basins, while it does for the high-elevation BC basin. Therefore, the RCM needs more highly resolved topography to achieve more realistic results than the already well-described GCMs for precipitation.

The direct use of the CRCM data into the hydrological model leads to unrealistic simulations of the catchments' hydrology. The spring-snowmelt-generated streamflow is overestimated over the BC basin and reproduced only in timing over the QC basins. More remarkable are the results for the CGCM3 simulations over the QC basins, as the CGCM3 captures the peak spring flows both in timing and magnitude. This indicates that the RCM does not add value to GCM in simulating snowmelt flows over the level basins, while it does for the high-elevation basin. In this respect, the added value of regional climate modeling is very distinct for the mountainous basin, where the RCM is preferred over the GCM; this justifies the additional computational effort of RCM simulations for hydrology-related applications.

By analyzing the relative streamflow sensitivity to CRCM uncertainty stemming from the driving boundary conditions, we show that the type of driving data (reanalysis *versus* GCMs) has an influence on the CRCM-simulated high flows and annual extreme floods. The use of CGCM3 or ECHAM5 to drive the CRCM leads to a hydrological response that is insensitive to changes in the GCM boundary conditions, except for winter low flows. The sensitivity analysis also reveals a large uncertainty associated with the natural variability of climate as simulated by the ensembles of GCM and CRCM-GCM combinations on the winter low flows and annual extreme floods. Using these ensemble simulations in impact studies, we underline the need to evaluate uncertainty related to natural climate variability, as expressed by the GCM/CRCM's IV, in order to assess comprehensive streamflow responses to climate variability and climate change.

Perhaps one of the most pertinent questions in the context of the present study is whether the outputs of the Canadian RCM should be preferred to develop streamflow projections under future climate scenario conditions, in light of low value compared to the GCMs in the present-day period. This is a difficult problem to address since it is hard to quantify the extent to which biases in the current period will be conserved in the future period. In this respect we would be cautious in using raw CRCM outputs for the western BC region of Canada where the RCM displays fairly large errors that translate into somewhat unrealistic reproductions of streamflow. Hence, this study supports the need to correct bias in the Canadian RCM outputs before evaluating the climate change induced hydrological impacts. In that scope, a companion paper (Troin et al., 2015) presents the details of this analysis for two catchments in Canada. However, the CRCM simulations used in the present study are conducted with a horizontal resolution of 45 km. The forthcoming very high-resolution CRCM simulations (15 km) might considerably improve original representation of observed climate patterns in the basins and lead to more realistic streamflow simulations. Using such high resolution RCM simulations has potential future implications for assessing climate change impacts on water resources in both western and eastern regions of Canada.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.09.003.

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