PACIFIC CLIMATE IMPACTS CONSORTIUM

Climate Change Impacts on Hydro-Climatic Regimes in the Peace and Columbia Watersheds, British Columbia, Canada

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Synthesis Project

Final Report

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About PCIC

The mission of the Pacific Climate Impacts Consortium is to quantify the impacts of climate variability and change on the physical environment in the Pacific and Yukon region. The Pacific Climate Impacts Consortium is financially supported by the BC Ministry of Environment, BC Hydro, the BC Ministry of Forests and Range, as well as several regional and community stakeholders. For more information see http://www.pacificclimate.org/.

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Preface

The Pacific Climate Impacts Consortium (PCIC) has completed a hydrologic modelling and climate change impact assessment project as a part of a larger *Hydrologic Impacts* research program that has been underway at PCIC to address the consequences of climate change on water resources in British Columbia (Rodenhuis et al. 2007)[1]. The research plan is currently composed of four distinct projects: *Climate Overview*, *Hydrologic Modelling*, *Regional Climate Modelling Diagnostics*, and *Synthesis*. The objectives of the Climate Overview are to identify the scope and intensity of the threat of potential impacts to water resources by climate variability and change in British Columbia (Rodenhuis et al. 2009)[2]. The main objective of the Hydrologic Modelling project (Schnorbus et al. 2011)[3] is to provide future projections of the impacts of climate change on monthly and annual streamflow in three BC watersheds: the Peace, Campbell and Columbia, for the 2050s, with particular emphasis on sites corresponding to BC Hydro power generation assets. The objective of the Regional Climate Modelling Diagnostics project is to validate the water balance of the Canadian Regional Climate Model (CRCM) in select BC watersheds, and to use the CRCM to simulate future climate and hydrologic conditions as a parallel effort to the Hydrologic Modelling project (Rodenhuis et al. 2011)[4]. Lastly, the purpose of the Synthesis project is to compare hydro-climatic projections from both the Hydrologic Modelling and the Regional Climate Modelling Diagnostics projects.

The current report describes the final results of the Synthesis project. The scope of the Synthesis project is to compare and contrast climate and hydrologic projections derived using two very distinct approaches. One approach (Hydrologic Modelling project) was to use climate projections, statistically downscaled from a suite of eight Global Climate Models (GCMs), to force a macro-scale hydrologic model. This is contrasted with another approach (Regional Climate Modelling Diagnostics) in which a regional climate model is used to both dynamically downscale and simulate the hydrologic response from multiple runs of a single global climate model. Due to the relatively coarse resolution of the regional climate modelling approach, comparison is made on the basis of aggregating results from the individual projects over two fairly large spatial domains represented by the Peace and Colombia River basins, respectively. This is in contrast to the more site-specific projections conducted as part of the Hydrologic Modelling project.

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[1] Rodenhuis, D., A.T. Werner, K.E. Bennett, and T.Q. Murdock, 2007: *Research Plan for Hydrologic Impacts*. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 34 p.
[2] Rodenhuis, D., K.E. Bennett, A.T. Werner, T.Q. Murdock and D. Bronaugh, 2009: *Climate Overview 2007: Hydro-Climatology and Future Climate Impacts in British Columbia*. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 132 p.
[3] Schnorbus, M.A., K.E. Bennett, A.T. Werner and A.J. Berland, 2011: *Hydrologic Impacts of Climate Change in the Peace, Campbell and Columbia Watersheds, British Columbia, Canada*. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 157 pp.
[4] Rodenhuis, D., B. Music, M. Braun and D. Caya, 2011: *Climate Diagnostics of Future Water Resources in BC Watersheds,* Pacific Climate Impacts Consortium, University of Victoria. Victoria, BC, 74 pp.

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Hydro-Climatic Regimes in the Peace and Columbia Watersheds, British Columbia, Canada

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Executive Summary

Climate change is expected to influence hydro-meteorological regimes in British Columbia watersheds. Potential changes in climatic variables, especially precipitation and temperature, are likely to affect hydrologic processes, such as snow accumulation and melt, evapotranspiration and runoff generation. Changes in hydrologic response could have major implications on water resources in the region. Therefore, assessment of climate change impacts on the hydro-climatic regime is important for long-term water resources management in the province. To attain such knowledge, the Pacific Climate Impacts Consortium (PCIC) carried out a number of studies on BC watersheds. This report analyzes the potential climate induced hydro-climatic changes in the Peace and Upper Columbia watersheds based on two independent studies: Hydrologic Modelling (HM) and Regional Climate Modelling Diagnostics (RCMD).

The HM study employed the Variable Infiltration Capacity (VIC) hydrologic model to project future hydrologic scenarios with the model forcing downscaled from a set of eight Global Climate Models (GCMs) using a statistical downscaling procedure known as Bias Corrected Spatial Disaggregation (BCSD). The RCMD study analyzed output from the Canadian Regional Climate Model (CRCM) driven by dynamically downscaled Canadian Coupled Global Climate Model version 3 (CGCM3) runs. A comparative analysis of the outputs from the two approaches was conducted, which included a comparison between Ensemble GCM Bias corrected (EGB) and Ensemble GCM RCM (ensemble of CGCM3 runs driven CRCM, EGR) results. In addition, a sub-set of outputs driven by a common GCM (CGCM3 run 1 driven bias corrected, GB vs. CGCM3 run 1 driven CRCM, GR) were compared. The compared outputs consisted of precipitation, temperature (both BCSD downscaled for EGB and GB, and CRCM derived for EGR and GR), and evapotranspiration, snowfall, snow water equivalent and runoff (VIC model simulated for EGB and GB and referred to as EGB-HM and GB-HM, and CRCM derived for EGR and GR). Runoff from both approaches was considered as spatially-averaged values (without routing).

Results for the Peace and Upper Columbia watersheds are similar and discussed together. For both watersheds, the monthly precipitation and temperature outputs from EGB and GB (when compared with the EGR and GR) show appreciable differences in magnitude and range (between 95^{th} and 5^{th} percentiles). For instance, for the baseline period, the EGB and GB precipitation and temperature correctly match the range and median values of observations while the EGR and GR outputs depict a narrower range and lower median values. Since EGB and GB outputs are bias-corrected and scaled to match the distribution of observations, the results correspond well with observations. The discrepancies in the EGR and GR results can be mainly attributed to the presence of biases. EGR and GR results may also be influenced by coarser model resolution and unrepresentative temperature and precipitation variability at the watershed scale. The characteristics of the baseline precipitation and temperature are also reflected in future projections. The EGR and GR future precipitation and temperature projections are of narrower range and show lower median values compared to the EGB and GB outputs. However, since the anomalies are independent of biases, the EGR and GR anomalies (future values relative to simulated median values from the 30-year baseline period) better match those of the EGB and GB. Despite a wider range in EGB and GB outputs, the median magnitude and direction of change of the anomalies generally match with one another.

In the case of watershed runoff, the EGB-HM and GB-HM driven VIC simulations show a better match with baseline observations compared to the EGR and GR derived outputs. The watershed-specific calibration/validation of the VIC-simulated runoff is the main reason for the better reproduction of the magnitude and timing of monthly runoff. The EGR and GR both simulate earlier and higher (especially in the Peace watershed) runoff peak values compared to historical observations. The earlier spring runoff is evident in the results despite the colder temperature bias, which in principle should cause a delayed snowmelt runoff response. The higher spring runoff peak may be due to the overestimation of snow accumulation due to the higher elevation of the CRCM grids at the lower ranges (resulting from coarser

spatial resolution). The earlier peak runoff in the EGR and GR may be partly due to lack of calibration of the CRCM parameters (specifically parameters controlling the snow and runoff processes) for a specific catchment. The hydrologic responses for the baseline periods are also reflected in the future runoff simulations, with the EGR and GR showing earlier runoff peaks compared to the EGB-HM and GB-HM. However, the anomalies of the hydrologic variables (i.e., evapotranspiration, precipitation falling as snow, runoff and snow water equivalent) from the two approaches generally match with each other.

The results show similarities among the ensemble and single run outputs from the same approach (EGB vs. GB or EGR vs. GR). The close match between EGB and GB results for the baseline period can be mainly attributed to the statistical downscaling method used, which matches the cumulative distribution function of the downscaled output to observations. The differences between the EGR and GR are also small, implying that due to subsequent downscaling, the projected range of multiple GCM (CGCM3) runs driven RCM (CRCM) outputs may not vary significantly. However, considerable differences exist between the GB and GR results (both driven by CGCM3). This implies that the subsequent downscaling and hydrologic modelling lead to substantial differences in overall output.

Overall, despite the differences between the two approaches, the outputs depict similar changes in hydro-climatic variables. Both approaches project increases in precipitation and temperature. The median climate change signals from the anomalies in the four outputs show 4.5% - 15.5% increases in precipitation and 2.2ºC - 2.6ºC increases in temperature. Seasonally, the outputs project higher precipitation increases in autumn, winter and spring, and lower increases (Peace) or decreases (Upper Columbia) in summer. Temperature is projected to increase in all seasons, with higher increases in winter (Peace) or summer (Upper Columbia). The projected hydrologic changes from both approaches show an increase in runoff for both watersheds, with median increases between 3.1% - 23.4%. Changes in other hydrologic variables are also similar such as increases in summer evapotranspiration (due to higher temperature) and winter precipitation falling as snow (due to higher winter precipitation). Simulated runoff from the two approaches also show shifts to the early occurrence of spring runoff peaks, probably as a result of earlier snowmelt. The modelled outputs from the two approaches also reveal future increases in total runoff volumes, which may be accompanied by a decrease in summer runoff in both of the watersheds.

Based on the results of this synthesis study, it can be concluded that due to the presence of biases and coarser spatial resolution, RCM projections do not match the downscaled GCM and hydrologic model projections. Therefore, bias correction of the RCM output can be expected to provide a better match with the hydrologic model output. The results also show large variability in the outputs from the two approaches. An ensemble of these outputs provides a range of possible future outcomes and their associated uncertainties, which need to be evaluated when considering potential future adaptation measures. To further establish RCM capabilities, future studies should compare higher temporal resolution (i.e., daily) outputs. Application of multiple RCMs will also provide a more objective comparison of the outputs driven by the same set of GCMs from these structurally very different approaches.

Acronyms and Abbreviations

Acronym/Abbreviation	Description
BCSD	Bias Corrected Spatial Disaggregation
CGCM3	Coupled Global Climate Model, version 3 (CCCMA, Canada)
CGIAR-CSI	Consultative Group on International Agricultural Research – Consortium for Spatial Information (http://csi.cgiar.org/meeting/index.asp)
CRCM	Canadian Regional Climate Model
CSIRO	Commonwealth Scientific and Research Organization (Australia) (http://www.csiro.au/)
ECHAM5	European Centre Hamburg Model, version 5 (MPI, Germany)
EGB	Ensemble GCM Bias corrected
EGR	Ensemble GCM RCM (ensemble of CGCM3 runs driven CRCM)
GB	GCM (CGCM3 run 1) Bias corrected
GR	GCM RCM (CGCM3 run 1 driven CRCM)
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory (http://www.gfdl.noaa.gov/)
HADCM3	Hadley Centre Coupled Model, version 3 (Hadley Centre, UK)
HADGEM1	Hadley Centre Global Environmental Model, version 1 (Hadley Centre, UK)
HM	Hydrologic Modelling
IQR	Inter-Quartile Range
MIROC	Model for Interdisciplinary Research on Climate (CCSR, Japan)
MOCOM	Multi-Objective Complex evolution Method
MPI	Max Planck Institute (http://www.mpg.de/english/portal/index.html)
NCAR	National Center for Atmospheric Research (http://ncar.ucar.edu/)
NCEP	National Centers for Environmental Prediction (http://www.ncep.noaa.gov/)
RCM	Regional Climate Model
RCMD	Regional Climate Model Diagnostics
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SVATS	Soil-Vegetation-Atmosphere Transfer Scheme
UKMO	United Kingdom Meteorological Office (http://www.metoffice.gov.uk/)
VIC	Variable Infiltration Capacity

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1. Introduction

Climate change affects freshwater quantity and quality with respect to both mean states and variability (Kundzewicz et al. 2007). Potential changes in hydro-climatic variables, especially precipitation and temperature, are likely to affect future hydrologic regimes. In the mountainous watersheds of British Columbia, the hydrologic regime is dominated by snow accumulation and melt processes. Potential climate-induced hydrologic impacts in snow-dominated regions may include changes in snowpack volume and an earlier onset of spring melt (Merritt et al. 2006; Rauscher et al. 2008; Stewart 2009; Shrestha et al. 2011). Alterations in snowmelt runoff may also be accompanied by changes in low flow regimes (Merritt et al. 2006). Such changes in hydrologic response could have major implications on regional water availability (Barnett et al. 2005), and affect extremes such as floods (Loukas et al. 2002) and drought (Gan 2000).

Given these potential changes in BC water resources, improving the knowledge of potential future impacts is important for long-term water resources management in the province. Two independent studies: Hydrologic Modelling (HM) and Regional Climate Modelling Diagnostics (RCMD) were undertaken for the projection of potential future changes in the selected watersheds of BC. The HM study provided future projections of hydrologic impacts in three watersheds (Upper Columbia, Peace, and Campbell). The study employed the Variable Infiltration Capacity (VIC) model (Liang et al. 1994) to project future (2041-2070) hydrologic impacts in comparison to a baseline (1961-1990) period (Schnorbus et al. 2011). Model forcings for the future period were derived from a set of 23 climate change simulations produced with eight global climate models (GCMs) using a statistical downscaling procedure (Werner 2011) known as Bias Corrected Spatial Disaggregation (BCSD) . The RCMD study analyzed the output from the Canadian Regional Climate Model (CRCM) (Music and Caya 2009) for the same three BC watersheds (Rodenhuis et al. 2011). The CRCM is driven by the Canadian Coupled Global Climate Model version 3 (CGCM3) (Scinocca et al. 2008). Hydrologic variables from the CRCM were derived from the Canadian Land Surface Scheme (CLASS) (Verseghy 1991) integrated within the CRCM.

Both these studies provide quantitative information regarding climate change impacts on hydro-climatic processes at the watershed scale. However, there are major differences in model resolution, scale and structure between these two studies. There are also inherent uncertainties in the application of these two approaches, which arise from data and model uncertainties. The GCM and RCM outputs at a watershed scale are also typically affected by systematic biases, which is partly due to the fact that the climate models are not calibrated/validated at the watershed scale. Bias correction is a common practice when using the GCM and RCM outputs (e.g., Graham et al. 2007). Differences in the downscaling method (i.e., statistical downscaling in HM study and dynamic downscaling in the RCMD study) applied to the GCM outputs can also lead to significant differences in the results (Leung et al. 2003). In addition, different GCM and RCM outputs may differ considerably due to inter-model variability.

A comparative evaluation of the outputs will provide insight on how the future climate change signals from the GCM-driven and RCM outputs differ from and/or correspond with each other. This is especially useful given that the HM (Schnorbus et al. 2011) and RCMD (Rodenhuis et al. 2011) project reports provide future hydro-climatic projections for the same watersheds and a comparative evaluation will bring together results from the two studies. To address the issue of inter-model variability between different GCM and RCM outputs, this study considers an ensemble of GCM or RCM outputs. The hydro-climatic signals from an ensemble of downscaled GCM and VIC outputs were compared with an ensemble of CGCM3 driven CRCM outputs between the baseline (1961-1990) and future (2040-2070) periods. In addition, a sub-set of outputs driven by the same GCM (CGCM3 run 1) from each study were compared to analyze the effects of subsequent downscaling and modelling steps on the outputs. The GCM-derived outputs from the HM study were downscaled and bias-corrected, and the VIC model runoff is calibrated to the observed runoff. Although such bias correction and calibration do not guarantee reliable predictions of future climate, model agreement with observations of today's climate is the only way to assign model confidence, with the underlying assumption that a model which accurately describes present climate will make a better projection of the future (Reichler and Kim 2008). Since the RCM outputs are not bias-corrected or calibrated with catchment specific parameters, some discrepancy of the outputs compared to observations can be expected.

2. Methods

2.1 Hydrologic Modelling (HM)

Detailed descriptions of the hydrologic modelling and climate impact projection studies undertaken for the HM project are available in Schnorbus et al. (2011) and Werner (2011), respectively. In summary, the method employs downscaled GCM outputs to generate future hydrologic projections using a hydrologic model (steps d through f, Figure 2.1). The VIC model (Liang et al. 1994) was used to simulate the hydrologic response in three BC watersheds (Upper Columbia, Peace and Campbell) at a 1/16° spatial resolution and daily temporal resolution. VIC is a spatially-distributed macro-scale hydrologic model that was originally developed as a soil-vegetation-atmosphere transfer scheme (SVATS) for GCMs. The model computes the water balance from a range of hydrologic processes such as evapotranspiration, snow accumulation, snowmelt, infiltration, soil moisture and surface and sub-surface runoffs. Although the VIC model does not explicitly simulate glacier processes, the occurrence and change in glacier mass are mimicked using snow process modelling. The fluxes from the model are collected and routed downstream using an offline routing model (Lohmann et al. 1996). A set of five parameters were chosen for calibration of the VIC model based on the identification of most sensitive parameters (Demaria et al. 2007). The VIC model was calibrated with observed flows from hydrometric stations for the periods 1990-1995 (Campbell and Peace watersheds) and 1990-1994 (Upper Columbia watershed) using the Multi-Objective Complex evolution Method (MOCOM) (Yapo et al. 1998) optimization method. For a detailed description of the VIC model and its application in the study watersheds, readers are referred Schnorbus et al. (2011).

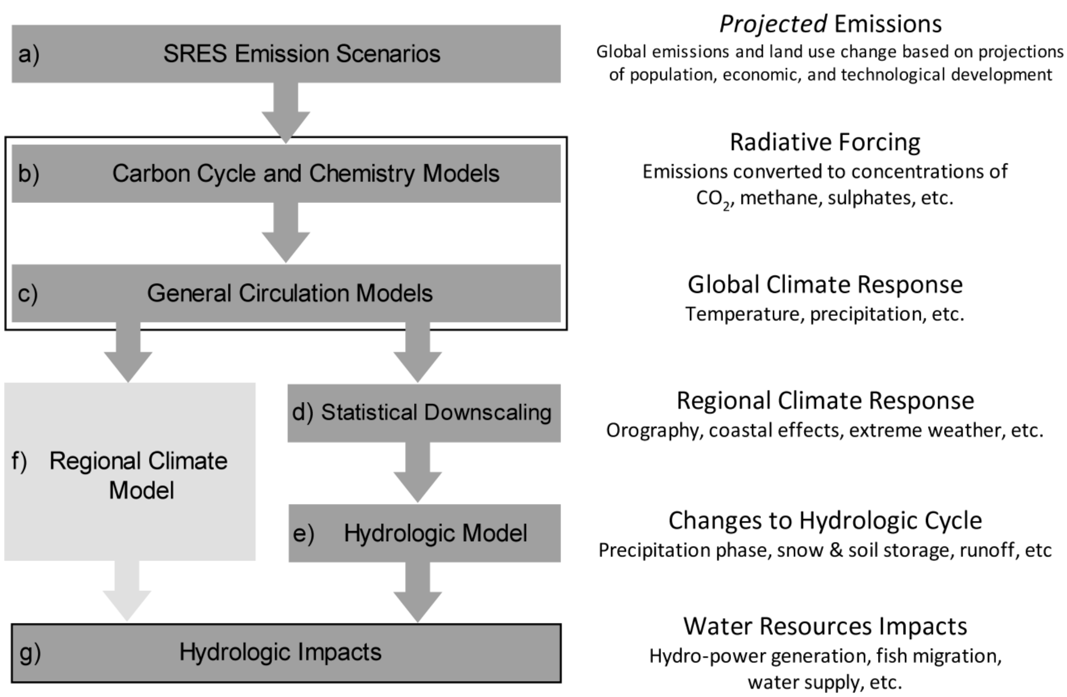

Figure 2-1. Method for quantifying hydrologic impacts under projected future climates.

In the HM study, climate forcings for the projection of future hydrologic scenarios were derived from a set of eight GCMs (see Table 2-1). 23 climate change simulations for three SRES emissions scenarios (A1B, A2 and B1) were used (the UKMO HadGEM1 model does not have output for the B1 scenario).

Since the GCM outputs are too coarse for the watershed scale hydrologic simulations, the outputs were downscaled to the resolution of the hydrologic model (1/16°) using the BCSD approach (Wood et al. 2004). BCSD is a statistical downscaling method, which performs downscaling in three steps: i) bias correction of the large-scale monthly GCM fields against aggregated gridded observations using quantile mapping (rescaled based on mean and variance); ii) spatial disaggregation of the bias-corrected monthly fields to a finer resolution (to match the VIC model) using a "local scaling" approach; and iii) temporal disaggregation of the locally scaled monthly fields corresponding to the daily historic records. The downscaled GCMs outputs were used as climate forcing for the simulation of baseline conditions and projection of future climate scenarios. For a detail description of BCSD and its application for climate impact projections in the study watersheds, readers are referred Werner (2011).

Table 2-1. GCMs used in this study

GCM	Atmospheric resolution	SRES emissions scenario used	Primary reference
CCSM3	T85 L26	A1B, A2 and B1	Collins et al. 2006
CGCM3.1 (T47)	T47 L31	A1B, A2 and B1	Scinocca et al. 2008
CSIRO-Mk3.0	T63 L18	A1B, A2 and B1	Rotstayn et al. 2010
MPI-OM ECHM5	T63 L32	A1B, A2 and B1	Roeckner et al. 2006
GFDL CM2.1	N45 L24	A1B, A2 and B1	Delworth et al. 2006
MIROC3.2 (medres)	T42 L20	A1B, A2 and B1	K-1 Model Developers 2004
UKMO-HadCM3	T42 L19	A1B, A2 and B1	Collins et al. 2001
UKMO-HadGEM1	N96 L38	A1B and A2	Martin et al. 2006

2.2 Regional Climate Model Diagnostics (RCMD)

For the RCMD study in the three BC watersheds (i.e., Upper Columbia, Peace, Campbell), hydro-meteorological outputs from the CRCM (Music and Caya 2009) were employed (Rodenhuis et al. 2011). The CRCM, developed at UQÀM/Ouranos, covers the North-American domain at a 45-km grid resolution. The latest version of the CRCM (CRCM version 4.2.3) includes the Canadian Land Surface Scheme (CLASS version 2.7) (Verseghy 1991) for the description of water and energy exchange between the atmosphere and land surface. The CRCM version 4.2.3 is driven at the boundary with the Canadian Global Climate Model version 3 (CGCM3 T47 L32) (Scinocca et al. 2008) and the future climate (2041-2070) projection corresponds to SRES A2 emissions scenario.

As shown in Figure 2.1 steps f) and g), the RCMD study uses the RCM outputs for the assessment of future hydro-meteorological variables in the study watersheds. The RCM outputs were extracted for the watershed areas. The extracted outputs for the entire watershed were averaged and analyzed based on the 30-year monthly mean values. The study used three different versions of the CRCM (CRCM versions 4.2.3, 3.7.1 and 3.6.1, all driven by CGCM2 run 3) for assessing the sensitivity of the simulated hydrologic cycle to different parameterizations, and five different CRCM runs for assessing the uncertainty due to internal model variability of the CGCM3 runs (using CRCM version 4.2.3, driven by CGCM3 run 1 to 5). For a detailed description of the CRCM readers are referred to Music and Caya (2007; 2009). Evaluation of CRCM outputs in the study watersheds are described in detail in Rodenhuis et al. (2011).

2.3 Comparison of Two Studies

Figure 2.1 shows the study watersheds and model grids employed in the HM and RCMD studies. Besides the differences in the grid resolution, the two methods differ in scale, hypsometry, model structure, climate forcing and bias correction. The differences in characteristics between the two studies are summarized in Table 2-2.

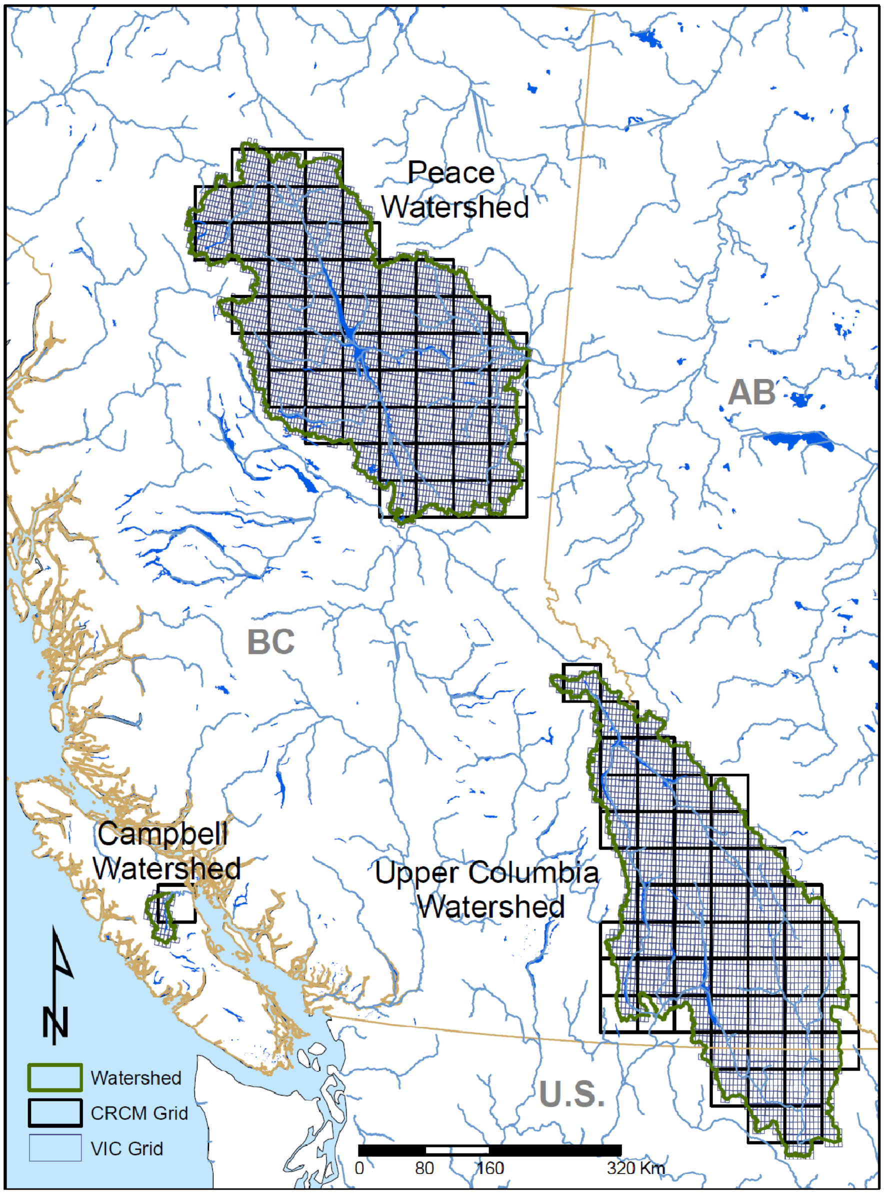

Figure 2-2. Map showing the three watersheds (Peace, Upper Columbia and Campbell). The larger and smaller squares are the RCMD and HM grids, respectively.

Table 2-2. Comparison between hydrologic modelling and regional climate model diagnostics studies

	Hydrologic Modelling (HM) study	**Regional climate model diagnostics (RCMD) study**
Resolution	Downscaling of GCM outputs and hydrologic modelling at 1/16th degree (approximately 27-31 km^2, depending upon latitude).	CRCM grid of 45-km horizontal mesh on a polar–stereographic projection (true at 60º N) with 29 vertical levels for the North-American domain.
Scale	Hydrologic modelling at a watershed scale (Campbell: 1,200 km^2, Peace: 101,000 km^2, Upper Columbia: 104,000 km^2).	Watershed scale hydro-meteorological variables extracted from the North-American domain CRCM.
Hypsometry	Representative hypsometry of the watersheds (Figures 2-3a, 2-3b and 2-3c) by 1/16th degree grids (compared to 90-m Shuttle Radar Topography Mission (SRTM) DEM (Jarvis et al. 2008).	Very approximate hypsometry of the watersheds (Figures 2-3a, 2-3b and 2-3c) by CRCM grids (Compared to 90-m SRTM DEM).
Hydrologic simulation	Hydrologic simulation from the watershed scale hydrologic model (VIC).	Hydrologic simulation extracted from the CRCM (which includes the CLASS model for water and energy exchange between the atmosphere and land surface).
Routing	Grid runoff routed through each sub-watershed to the outlet	No routing of the CRCM grid runoff
Model parameterization	The VIC hydrologic model divided into sub-watersheds and parameters calibrated by comparing simulated and observed streamflows.	CLASS model parameterized for the entire model domain, no calibration of watershed specific runoff.
Climate forcings	Climate forcings from a set of 23 climate change simulations produced with eight GCMs for three SRES emission scenarios (A1B, A2 and B1) for the future climate.	CRCM driven by different version and runs of CGCM3 for the SRES A2 emission scenario for the future climate.
Downscaling method	The GCM outputs downscaled to the resolution of the VIC model using BCSD statistical downscaling method.	CRCM dynamically downscaled CGCM3 simulations.
Bias correction	GCM biases removed using non-parametric quantile-mapping technique.	No bias correction method implemented in the CRCM (CGCM3 biases propagate into the CRCM when driven by the CGCM3, it inherits reanalysis error when driven by reanalysis).

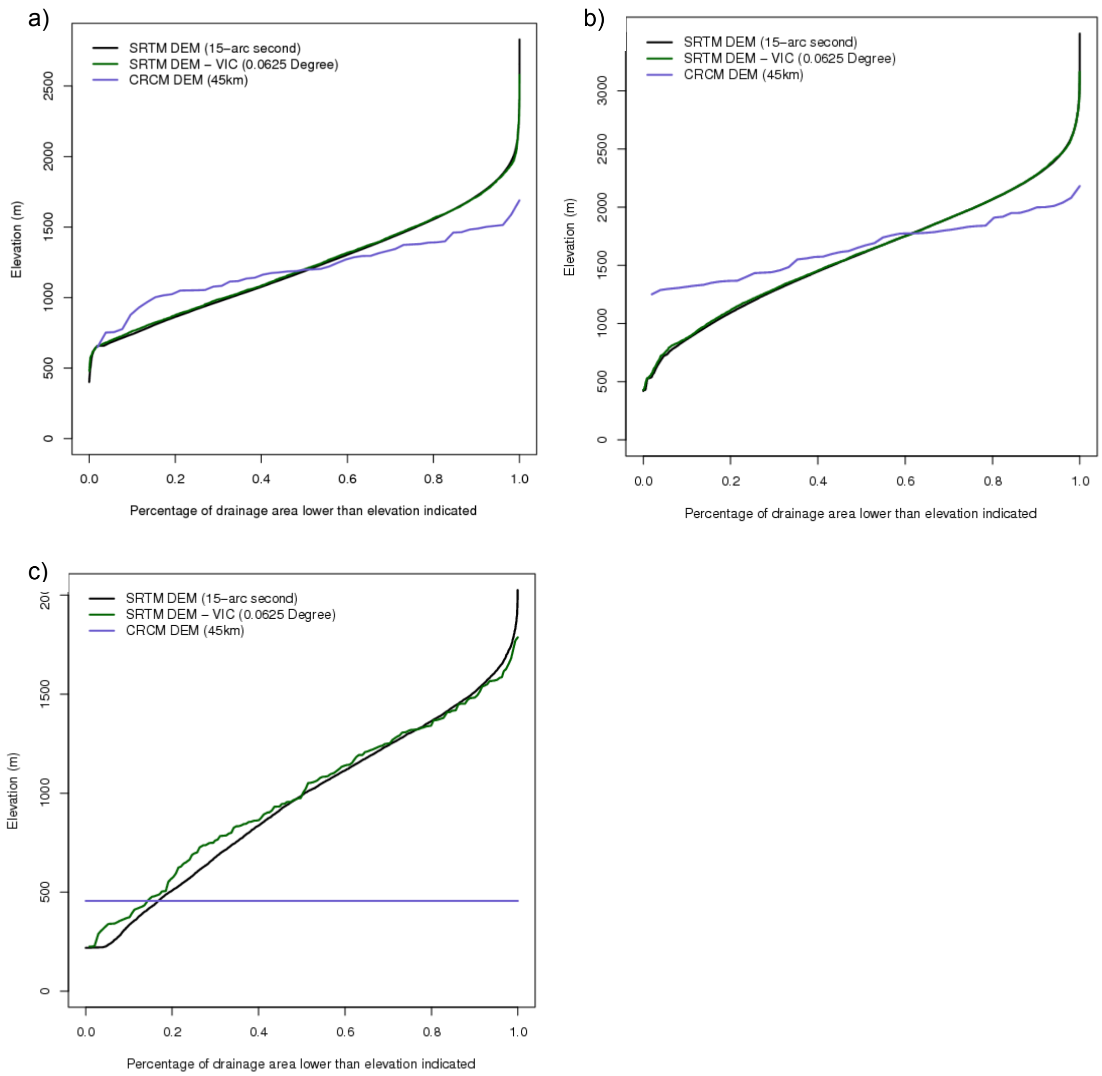

Figure 2-3. Hypsometry plots of the three watersheds: a) Peace, b) Upper Columbia and c) Campbell.

2.4 Synthesis of Two Study Outputs

This study makes a comparative assessment of selected outputs from the HM and RCMD projects. Of the three watersheds analyzed in both the studies, the Upper Columbia and Peace watersheds are further considered. The results of the Campbell watershed were not considered in this synthesis because the CRCM output for the watershed is based on a single grid cell (Figure 2-2) and considered unreliable and unrepresentative by the RCMD study (Rodenhuis et al. 2011). The hypsometry plot of the Campbell watershed (Figure 2-3c) also shows the apparent lack of representativeness of the single grid. The location and grid resolution of the watersheds are shown in Figure 2-2 and detailed descriptions of the study watersheds are available in Schnorbus et al. (2011) and Rodenhuis et al. (2011).

Since the CRCM runs are only available for the A2 emissions scenario, the A1B and B1 runs from the HM study were not considered further. As given in Table 2-2, these two approaches are characterized by considerable differences, including a major difference in the forcing data (multiple GCMs were used in the HM study and multiple runs of CGCM3/CRCM were used in the RCMD study). In this synthesis, the ensemble outputs from eight BCSD-downscaled GCM projections (hereafter referred to as the Ensemble GCM Bias corrected or EGB) are compared to the ensemble of five CGCM3-runs driven CRCM version 4.2.3 (hereafter referred to as the Ensemble GCM RCM or EGR). In addition, a sub-set of outputs driven by the common GCM (CGCM3 run 1) with subsequent processing by the BCSD (hereafter referred to GCM Bias corrected, GB) and the CRCM (hereafter referred to as GCM RCM or GR) were compared. Note that the EGB and GB temperature and precipitation values were BCSD downscaled values, while the hydrologic variables (i.e., evapotranspiration, snowfall, snow water equivalent and runoff) were VIC hydrologic model simulated values (hereafter referred to as the EGB-HM and GB-HM). The EGR and GR temperature, precipitation and hydrologic variables were CRCM-derived values.

Note that EGB and GB used CGCM version 3.1, while the EGR and GR used CGCM version 3. Both versions are of T47 L32 resolution, and the only difference between the two versions is that the model was run on two different computing systems. (The initial version of CGCM3 was developed and run on a NEC SX/6 vector supercomputer. A subsequent version, CGCM3.1, incorporates changes required to run efficiently on a new distributed memory IBM computer system, Environment Canada 2010). The model used in both studies is referred to as the CGCM3 hereafter.

For comparison, monthly outputs from the 30-year baseline (1961-1990) and future (2041-2070) periods were employed. The baseline and future values for both watersheds and both approaches were obtained by averaging individual monthly grid outputs for the entire basin. The outputs were compared for the 95th-5th percentiles and median values, with each of the 30-year monthly values treated as one instance. The outputs from the two periods were considered for precipitation, temperature (driving variables) and runoff (response). In addition, anomalies of precipitation, temperature, and hydrologic response (i.e., evapotranspiration, snowfall, snow water equivalent and runoff) were compared. The anomalies for the future values are expressed relative to simulated median values for the 30-year baseline period, and compared for the median, inter-quartile range (75th-25th percentiles) and ±3/2 inter-quartile range using box and whisker plots. The Mann-Whitney test was used to analyze the statistical significance of the differences in the anomalies from the two approaches (EGB vs. EGR or GB vs. GR), with the 30-year distribution of the monthly anomalies compared against each other. Changes in long-term water balance signals were compared in terms of cumulative runoff. Since the CRCM does not include a routing routine, runoff from both the approaches were considered without routing. Average grid runoff was derived by spatially averaging respective grid runoff for the entire watershed. The observed runoff at the watershed outlet was normalized by the watershed area to compare with the simulated values.

3. Results and Discussion

3.1 Peace Watershed

3.1.1 Precipitation and Temperature Change

Monthly precipitation results from the ensemble GCM (EGB vs. EGR) and the single GCM (GB vs GR) are shown in Figures 3-1 and 3-2, respectively. Output ranges are compared for the 5th-95th percentiles and the median values. The precipitation outputs for the baseline period show wider range for the ensemble (EGB vs. EGR) and single (GB vs. GR) model outputs (Figures 3-1a and 3-2a). The ranges and median values of the EGB and GB closely match those of the observations based on interpolated station data, gridded to 1/16° resolution (Schnorbus et al. 2011; Werner 2011) (Figures 3-1a and 3-2a; Table 3-1). This is mainly due to the BCSD algorithm, which corrects the bias and scales the output to match the cumulative distribution function of the observation. The better match may also be due to finer resolution and consequently better representation of the watershed spatial heterogeneity by the downscaled BCSD output. In the case of CRCM precipitation outputs, due to the presence of bias, the median values are lower than observations for both EGR (Figure 3-1a) and GR (Figure 3-2a). The EGR and GR also show smaller ranges because the outputs have not been scaled to match the wider distribution of observations. This lower precipitation bias in the baseline period is also reflected in the future period for most of the months, with the EGR and GR depicting lower median precipitation compared to the EGB and GB.

Average monthly temperature outputs from the ensemble and single GCM outputs are compared in Figures 3-3 and 3-4, respectively. The plots for the baseline period show good matches of the GCM/BCSD outputs with observations in terms of both magnitude (Table 3-1) and range (Figure 3-3a and 3-4a). Similar to precipitation, the bias correction and higher resolution lead to a better match of the EGB and GB downscaled temperature with observations. Although the difference between the 5th and 95th percentiles from EGR and GR temperature is similar to the observations (wider spreads between the 5th and 95th percentiles for winter, and narrower spreads for summer), the outputs depict substantial biases. Therefore, bias correction would result in a better match of the EGR and GR outputs with observations. The EGR and GR colder temperature bias in the baseline period (Figures 3-3a and 3-4a) are also reflected in the future period (Figures 3-3b and 3-4b).

Box and whisker plots of the precipitation and temperature anomalies of the EGB and EGR are shown in Figure 3-5 and GB and GR are shown in Figure 3-5. In general, the EGB and GB outputs show wider range compared to the EGR and GR for both the precipitation and temperature anomaly plots. As discussed earlier, such differences are due to differences in downscaling method and resolution used in the two approaches. The Mann-Whitney test between the EGB and EGR outputs revealed significant differences for several months (at a 95% confidence interval). Despite such differences, the plots generally show good matching of the magnitude and direction of changes between the EGB and EGR (Figure 3-5) and GB and GR (Figure 3-6) outputs. For instance, the median values of the changes show an increase in precipitation for most of the months (Figures 3-5a and 3-6a). Seasonally, all outputs consistently project higher winter and autumn precipitation increases and lower summer precipitation increases (Table 3-1). The temperature changes between the two approaches are also similar, with the mean annual increases ranging from 2.2°C to 2.6°C and higher increases in the winter and lower increases in the spring (Table 3-1). This relatively close match of the temperature and precipitation anomalies between the BCSD and RCMD approaches is because they are considered relative to the median of the baseline values, which removes biases (if biases are considered to be equal in the baseline and future periods). Therefore, although the absolute EGR and GR outputs are substantially different from the BCSD downscaled outputs, the anomalies are still similar with respect to the future climate change signal.

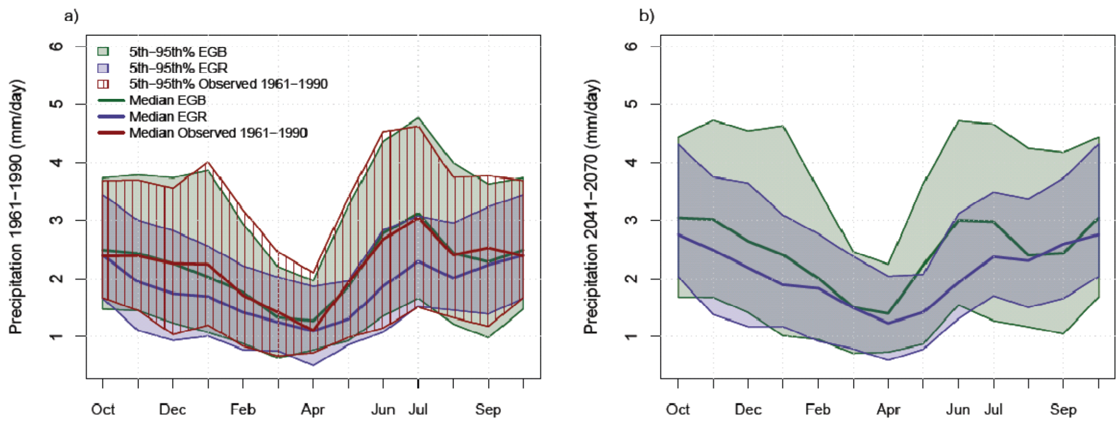

Figure 3-1. EGB and EGR monthly average precipitation in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Precipitation for the baseline period is also compared with observations.

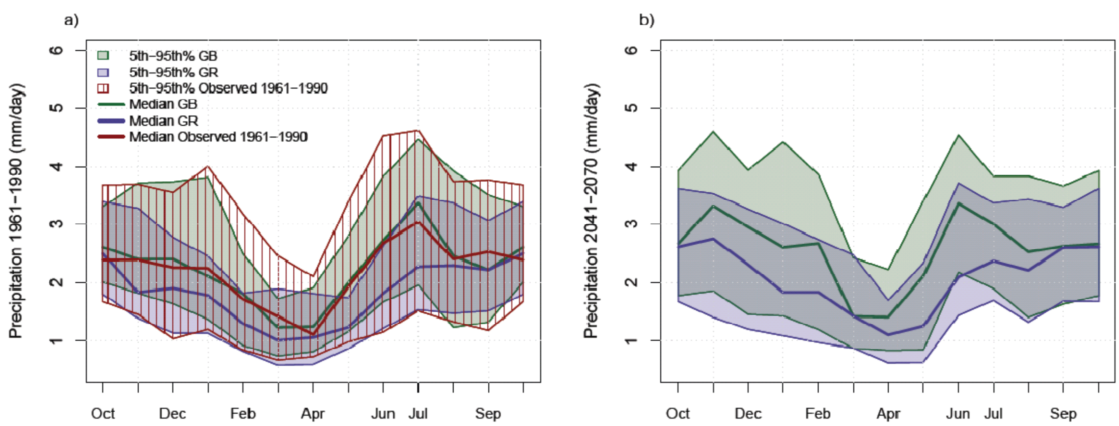

Figure 3-2. GB and GR monthly average precipitation in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Precipitation for the baseline period is also compared with observations.

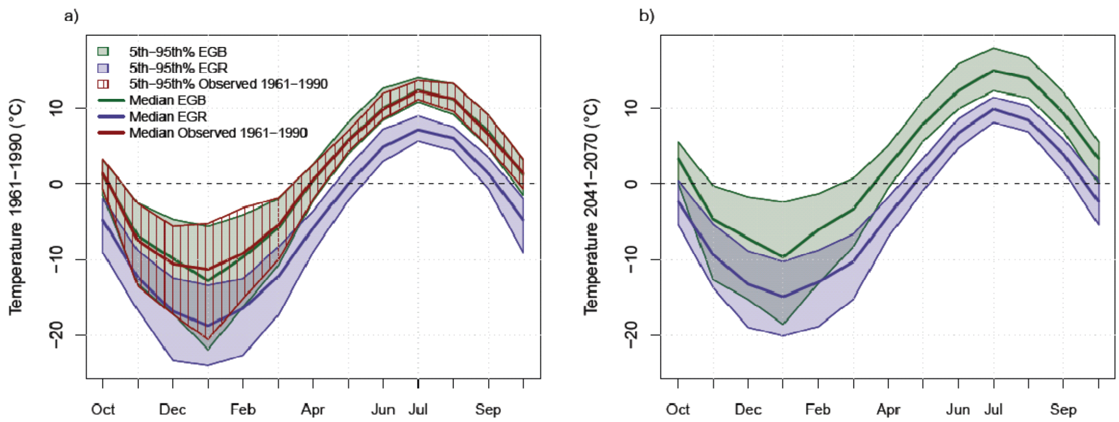

Figure 3-3. EGB and EGR temperature in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Temperature for the baseline period is also compared with observations.

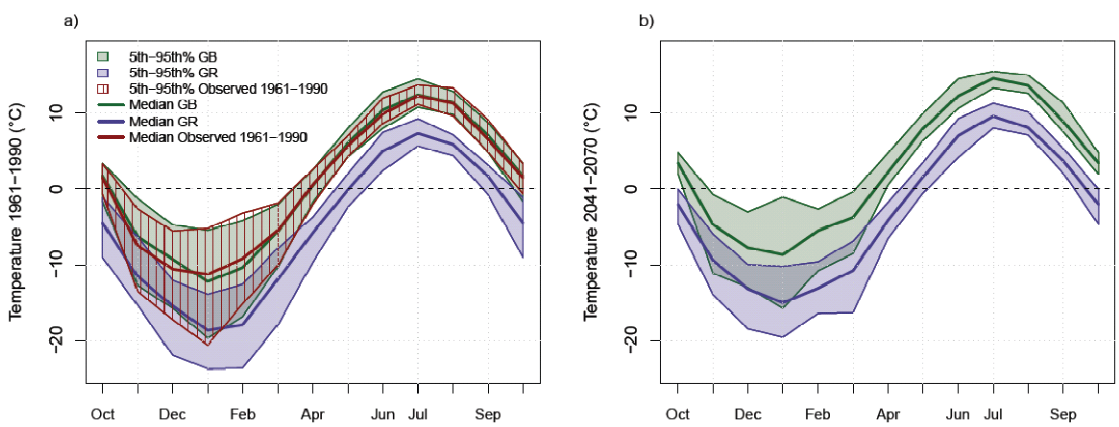

Figure 3-4. GB and GR monthly average temperature in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Temperature for the baseline period is also compared with observations.

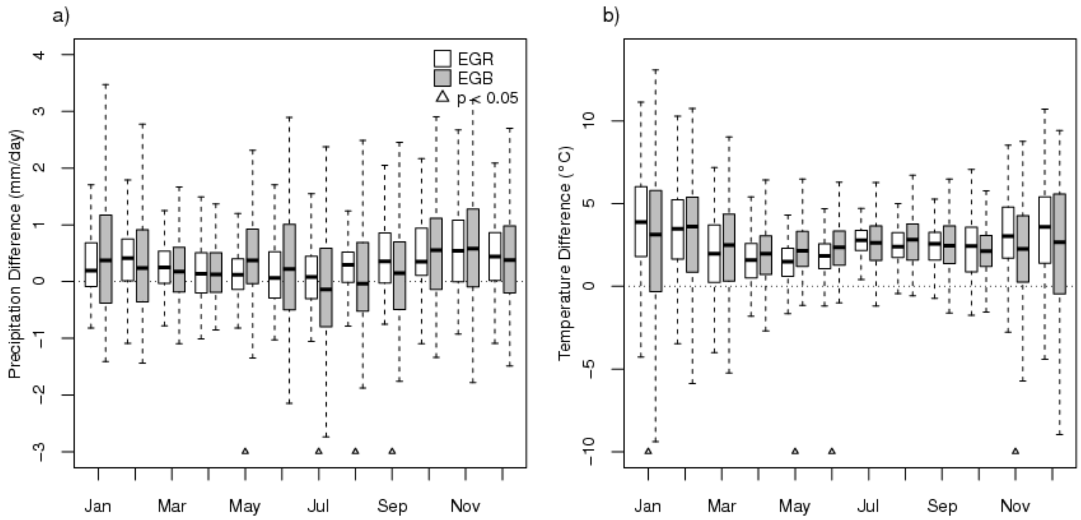

Figure 3-5. Box and whisker plots of EGB and EGR anomalies (future values relative to simulated median values from 30-year baseline period) in the Peace watershed. Illustrated changes are for monthly average a) precipitation and b) temperature. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when p < 0.05) between the distribution of anomalies evaluated with the Mann-Whitney test.

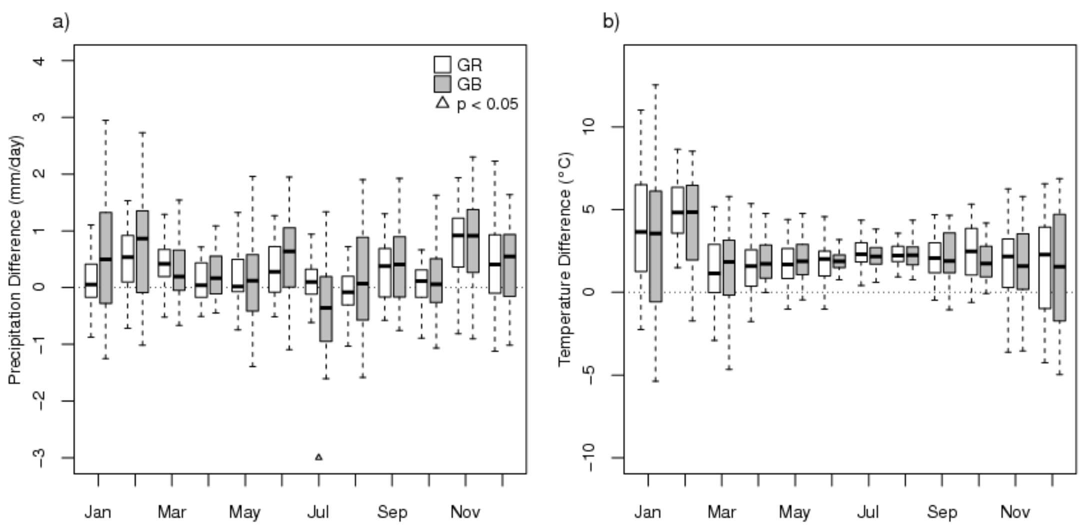

Figure 3-6. Box and whisker plots of GB and GR anomalies (future values relative to simulated median values from 30-year baseline period) in the Peace watershed. Illustrated changes are for monthly average a) precipitation and b) temperature. Each box plot summarizes the median (thick horizontal line), inter-quartile range ((75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

3.1.2 Changes in Hydrologic Variables

The runoff signals for the ensemble and single run outputs are compared in Figures 3-7 and 3-8, respectively. Note that the runoff from the EGB-HM and GB-HM are outputs from the VIC simulation driven by downscaled and bias-corrected GCMs, while the EGR and GR are derived directly from the CRCM simulations. The results generally show a good match of the VIC simulated monthly runoff with observed runoff (observed runoff is based on catchment-normalized and naturalized monthly streamflow obtained from BC Hydro (BC Hydro, unpublished data) for the Peace River at Taylor BC). Specifically, magnitude and timing of the runoff peak are reasonably well represented by the EGB-HM and GB-HM simulations (Figures 3-7a and 3-8a). Despite wider ranges of the EGB-HM and GB-HM simulated runoff, the median values of seasonal and annual runoff are close to the observed runoff (Table 3-1). The correspondence of the VIC simulated runoff with observations is due to the fact that the VIC runoff has been calibrated/validated with observed runoff (see Schnorbus et al. 2011). The EGR and GR runoff shows higher magnitude and earlier timing of the runoff peaks. The effect of the earlier runoff peaks from EGR and GR simulations is also apparent in the seasonal distribution of the runoff, with higher spring runoff and lower summer runoff (Table 3-1). The higher spring runoff peak may be partly due to the overestimation of snow water equivalent (compared to North American monthly snow water equivalent, Brown et al. 2002) by the CRCM (Rodenhuis et al. 2011). The overestimation may be partly due to unrepresentative hypsometry of the Peace watershed by CRCM grids (CRCM grids show higher elevation compared to SRTM-DEM VIC grid below 50% of the drainage area, Figure 2-3a). The earlier peak runoff in the EGR and GR, despite the colder temperature bias (which in principle should cause delayed peak runoff response due to delayed snowmelt), may be partly due to the fact that CRCM parameters (specifically parameters controlling the snow and runoff processes) have not been calibrated for a specific catchment. Nevertheless, the overall water balance in the watershed for the baseline period is represented reasonably well by EGR and GR (Figure 3-9 and 3-10). The slightly higher cumulative runoff from the EGR and GR compared to observation, despite lower precipitation, may be due to colder temperature bias causing lower evapotranspiration. The effect of the change in climatic signals is apparent in the hydrologic responses. Future increases in May-June runoff, together with decreases in July peak, are simulated by the EGB-HM and GB-HM (Figure 3-8b and 3-9b). The changes are mainly due to future temperature increases, which cause earlier snowmelt and runoff. Increase in May runoff, together with decreases in June runoff, can also be seen in the future runoff responses from the EGR and GR (Figures 3-7b and 3-8b).

The effect of changes in various hydro-meteorological variables is reflected by the future responses of actual evapotranspiration, precipitation falling as snow, runoff and snow water equivalent. Box and whisker plots of the anomalies (future values relative to simulated baseline median values) of these variables show wider range of the EGB-HM and GB-HM responses compared to the EGR and GR responses (Figures 3-11 and 3-12). As stated earlier, EGB-HM and GB-HM precipitation is characterized by a larger variability, which probably leads to a larger variability of the hydrologic response. Although the results show significant differences between the change signals from the two approaches (marked by triangles with $p < 0.05$), the direction of changes generally match with one another. There are also general agreements between the directions of hydrologic changes of the ensemble and the single model run outputs. Specifically, the median values of all results show increases in summer evapotranspiration (Figures 3-11a and 3-12a), which is mainly due to increased summer temperature. The results show increases in precipitation falling as snow between the months of November-March (Figures 3-11b and 3-12b), which is mainly due to higher precipitation in these months. Runoff increases in April and May and decreased June runoff (Figures 3-10c and 3-11c) can be attributed to an earlier start of the snowmelt (due to increased future temperature increase). The occurrence of earlier snowmelt is also evident from the snow water equivalent, whose median values show large declines in April and May (Figures 3-11d and 3-2d).

Overall, the outputs from the EGB-HM, EGR,GB-HM and GR models indicate that due to the changes in future climate (i.e., precipitation and temperature) runoff volumes are likely to increase (Figures 3-9 and 3-10). Although the minimum of EGB-HM and GB-HM output show a slight decrease in the cumulative future runoff, median values of all four outputs show increases in the future runoff. The comparison of the median values of differences between the baseline and future periods also show increases in the overall runoff volumes (Table 3-1). The changes vary seasonally, with the largest increase in spring runoff and decrease in summer runoff. The decrease in summer runoff is mainly due to the earlier onset of snowmelt. Decreases in future July-August runoff are also simulated (especially in the EGB-HM and GB-HM outputs). In summary, despite the monthly and seasonal differences, the overall hydrologic change signals from all four outputs generally agree. Therefore, despite the limitations of the EGR and GR runs to correctly simulate the timing of the snowmelt runoff response, the anomalies in the hydrologic responses (between the baseline and the future period) still provide similar results. This adds confidence to using the CRCM anomalies in projecting climate change impacts.

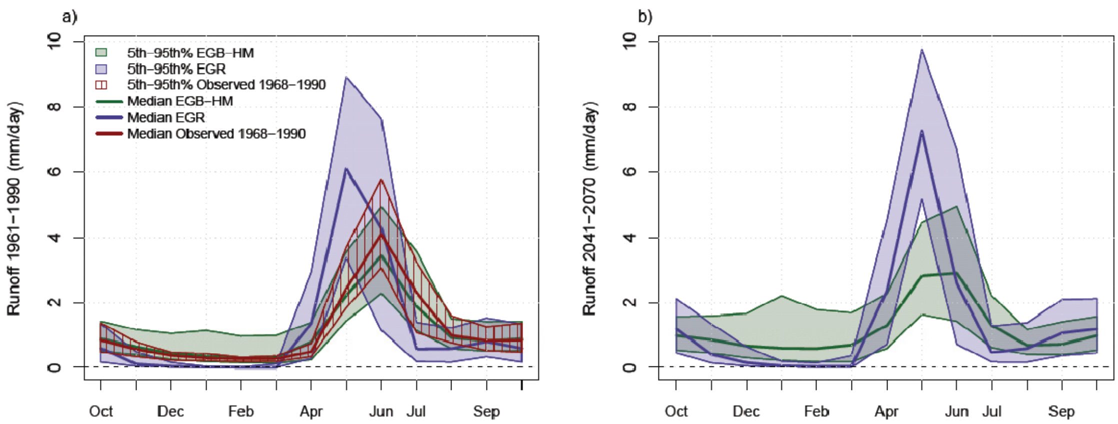

Figure 3-7. EGB-HM and EGR monthly average runoff in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Runoff for the baseline period is also compared with observations (1968-1990).

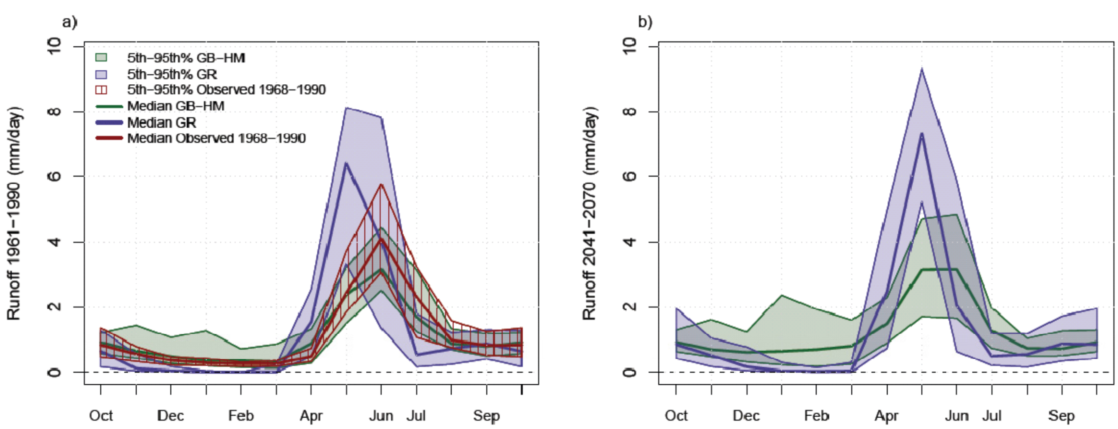

Figure 3-8. GB-HM and GR monthly average runoffs in the Peace watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Runoff for the baseline period is also compared with observations (1968-1990).

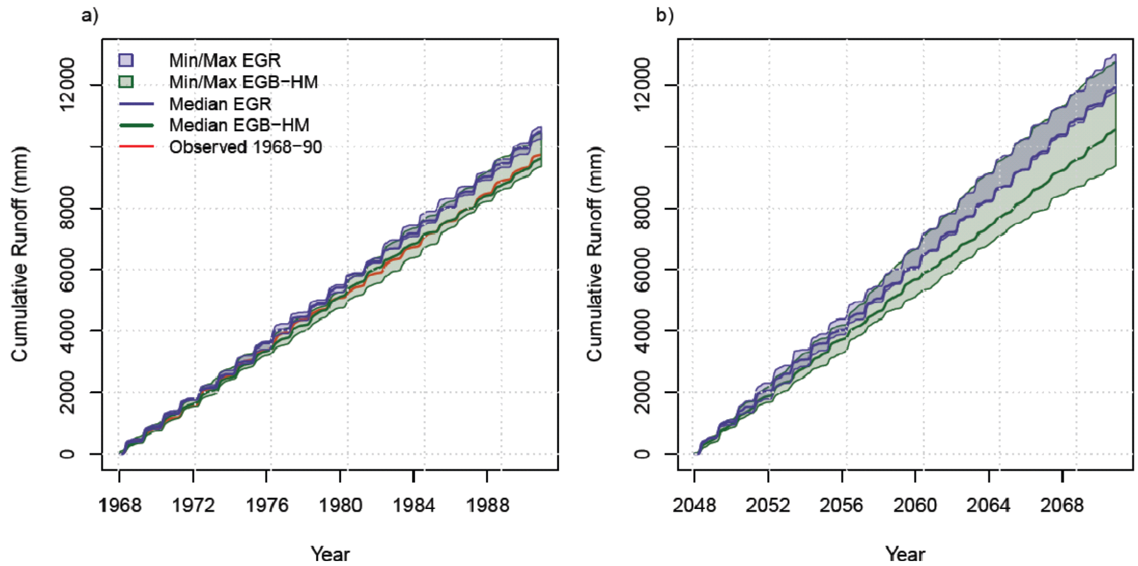

Figure 3-9. Cumulative runoff volume from the EGB-HM and EGR in the Peace watershed for a) baseline (1968-1990) and b) future (2048-2070) periods. The analysis period is limited to 23 years (1968-1990) because observations are only available for this period.

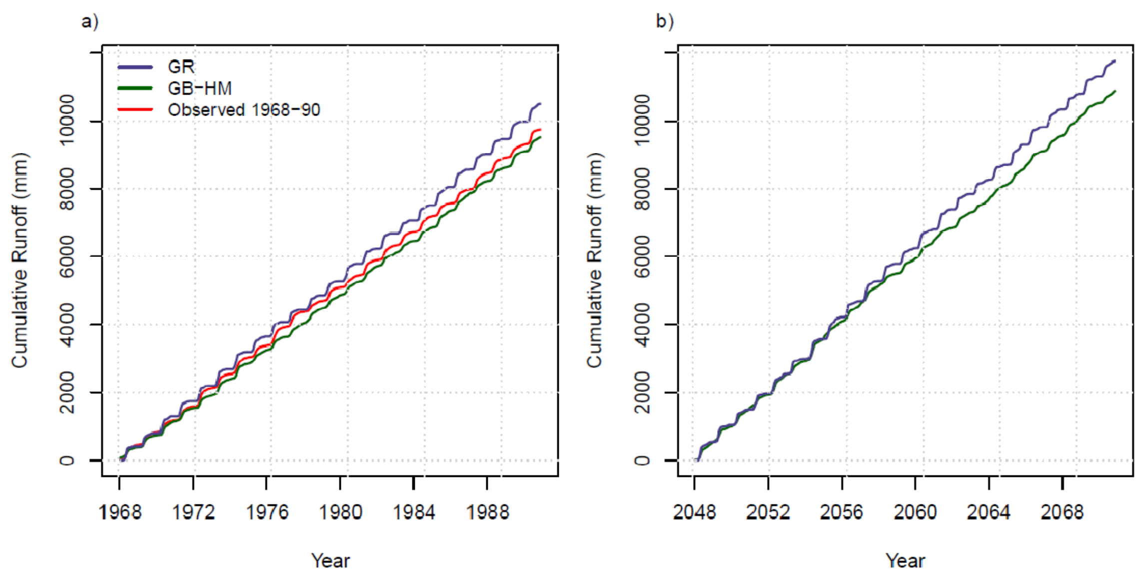

Figure 3-10. Cumulative runoff volume from the GB-HM and GR in the Peace watershed for a) baseline (1968-1990) and b) future (2048-2070) periods. The analysis period is limited to 23 years (1968-1990) because observations are only available for this period.

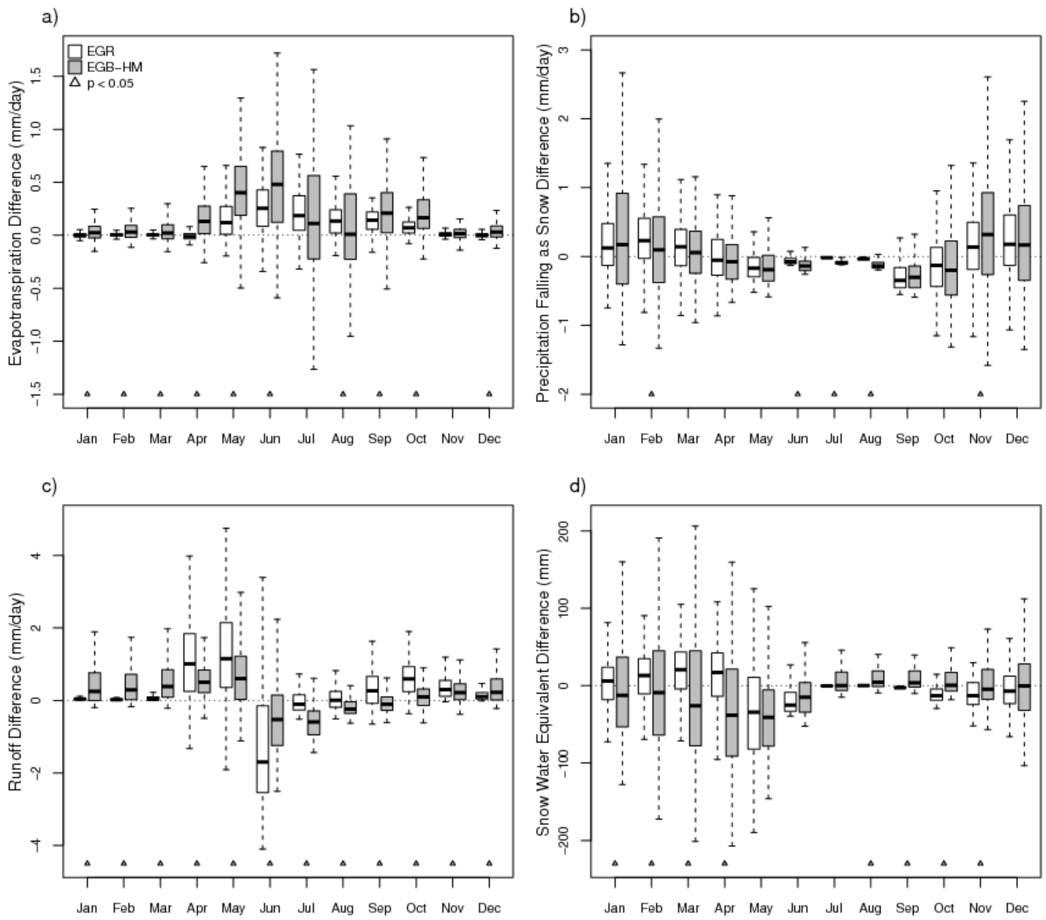

Figure 3-11. Box and whisker plots of EGB-HM and EGR anomalies (future values relative to simulated median values from 30-year baseline period) in the Peace watershed. Illustrated changes are for monthly average a) evapotranspiration, b) precipitation falling as snow, c) runoff and d) snow water equivalent. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

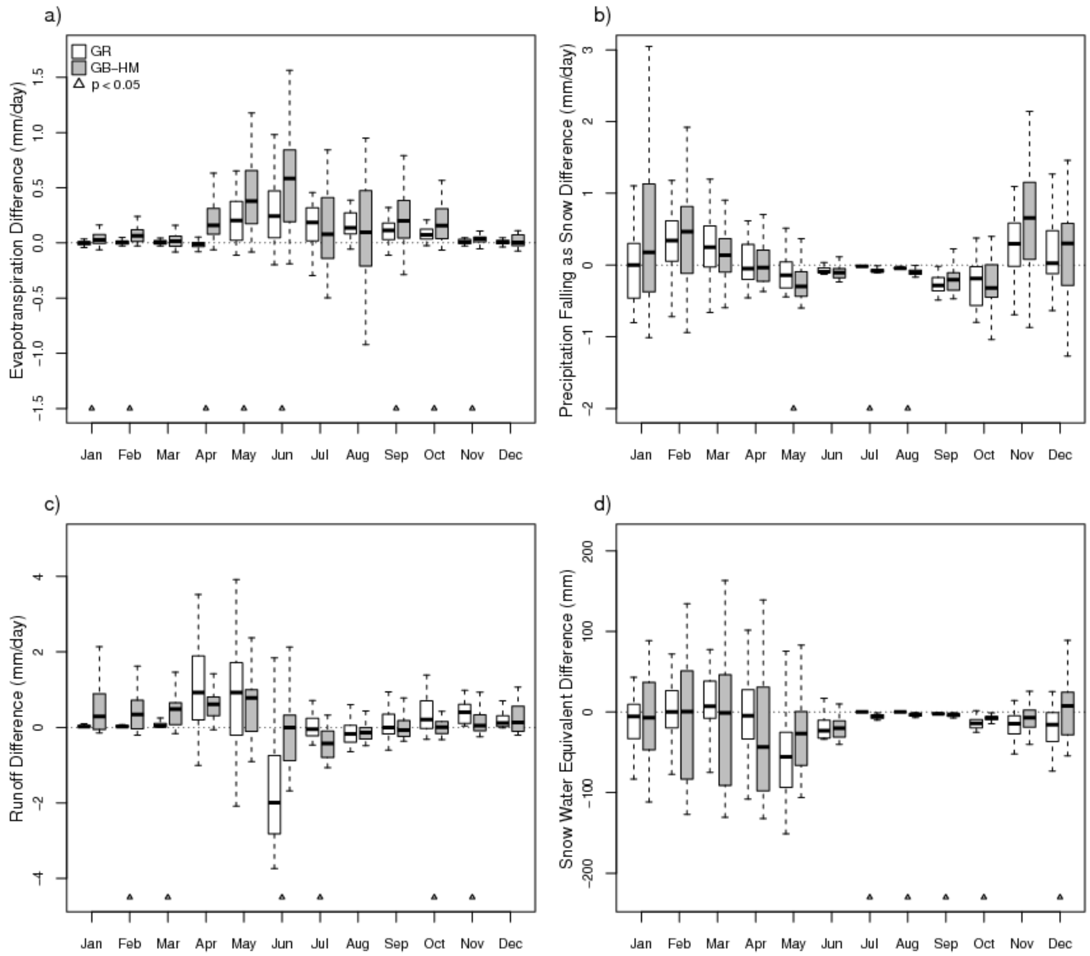

Figure 3-12. Box and whisker plots of GB-HM and GR anomalies (future values relative to simulated median values from 30-year baseline period) in the Peace watershed. Illustrated changes are for monthly average a) evapotranspiration, b) precipitation falling as snow, c) runoff and d) snow water equivalent. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

Table 3-1. Observed and modelled basin averaged median precipitation, temperature and runoff from EGB, EGR, GB and GR in the Peace watershed. The difference is given relative to the respective baseline (1961-1990) value as % change for precipitation and runoff, and °C change for temperature. 30-year modelled runoff (1961-1990) is compared with a 23-year observational record (1968-1990) because observations are only available for this period

	Observed	EGB			EGR			GB			GR		
	1961-1990	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference
Precipitation (mm)													
Winter	189.5	184.6	214.9	16.4	148.2	180.2	21.6	192.6	250.7	30.2	151.8	182.1	20.0
Spring	135.6	135.8	156.5	15.2	111.2	126.6	13.8	135.9	150.5	10.7	100.6	115.3	14.6
Summer	247.2	253.6	255.1	0.6	188.1	201.4	7.1	259.9	270.5	4.1	194.4	203.3	4.6
Autumn	222.5	219.5	258.6	17.8	200.4	238.6	19.1	220.1	262.0	19.0	199.5	242.5	21.6
Annual	**794.7**	**793.5**	**882.1**	**11.2**	**647.9**	**746.8**	**15.3**	**808.5**	**933.7**	**15.5**	**646.3**	**743.2**	**15.0**
Temperature (°C)													
Winter	-10.4	-10.8	-7.7	3.2	-17.4	-13.7	3.6	-10.6	-7.3	3.3	-17.3	-13.8	3.6
Spring	0.3	0.1	2.3	2.2	-6.0	-4.4	1.7	0.3	2.1	1.8	-5.9	-4.5	1.5
Summer	11.2	11.2	13.8	2.5	6.0	8.4	2.3	11.4	13.5	2.1	6.1	8.2	2.2
Autumn	0.1	0.4	2.7	2.3	-5.3	-2.6	2.7	0.8	2.5	1.7	-4.8	-2.6	2.2
Annual	**0.3**	**0.2**	**2.8**	**2.6**	**-5.6**	**-3.1**	**2.6**	**0.5**	**2.7**	**2.2**	**-5.5**	**-3.1**	**2.4**
Runoff (mm)													
Winter	27.6	32.3	55.7	72.4	1.4	6.6	371.4	36.0	59.4	65.0	2.0	7.2	260.0
Spring	96.5	100.7	146.3	45.3	227.1	293.9	29.4	108.7	165.8	52.5	242.6	300.2	23.7
Summer	224.5	189.3	148.4	-21.6	165.2	110.7	-33.0	174.0	157.0	-9.8	161.2	94.2	-41.6
Autumn	67.5	70.7	77.1	9.1	45.0	80.1	78.0	71.7	71.1	-0.8	49.5	68.1	37.6
Annual	**416.1**	**393.0**	**427.4**	**8.8**	**438.8**	**491.3**	**12.0**	**390.5**	**453.4**	**16.1**	**455.4**	**469.6**	**3.1**

3.2 Upper Columbia Watershed

3.2.1 Precipitation and Temperature Change

The precipitation and temperature outputs for the Upper Columbia watershed are in general similar to the Peace watershed. The EGB and GB precipitation in the Upper Columbia watershed (Figures 3-13a and 3-14a) display wider range in comparison to the EGR and GR outputs, but closely matches the range of the observations. The median values of the EGB and GB precipitation outputs are slightly higher (EGB: 5% and GB: 7.3%, calculated from Table 3-2) compared to the observed precipitation. Seasonal precipitation dynamics also follow the dynamics of the observed precipitation. However, the EGR and GR precipitation outputs show narrower ranges and lower median values compared to the EGB and GB projections and observations (Figures 3-13a and 3-14a). As stated previously, these differences are mainly due to the downscaling method used (BCSD corrects the bias and scales the EGB and GB outputs while CRCM outputs are not bias corrected or scaled). These differences (in magnitude and range) in the baseline period are also reflected in the future projections (Figures 3-13b and 3-14b).

The EGB and GB temperature outputs match closely with observations in terms of range and magnitude (median values) (Figures 3-15a and 3-16a). A dip in the future January temperature from the EGB output can be seen for the 5th percentile (Figure 3-15b). Further investigation revealed that low temperatures were projected by several models in January in this area. In the BCSD procedure, GCM data was bias corrected against the monthly cumulative distribution function of the 1950-1999 calibration datasets based on gridded historical observations. Over this period, there were several events in the gridded historical observations in January when temperatures were between -15°C and -25°C (-25°C in January 1950). Over the same period, several of the GCMs had smaller range of temperatures that did not dip below -15°C. It was in these models that future temperature was less than -15°C was converted to as low as -25°C by the quantile mapping in the BCSD procedure. Thus, because of the large range in gridded historical observations, limited range in the GCMs and their conversion through the quantile mapping procedure that BCSD downscaled future projections gave low temperature values in the EGB output. Specifically, 11 of the 210 data points for 30 years of data for seven models have values less than -19°C. A plot of the 25th and 75th percentiles, or the median range in values, eliminated this dip (not shown). The median values show a more robust output without the anomalously low January values. In the case of EGR and GR outputs, although the ranges (between 5%-95% percentile) show similar dynamics, a cold temperature bias is apparent for both the EGR and GR outputs. The colder temperature bias is also reflected in the future projections (Figures 3-15b and 3-16b). Therefore, bias correction would likely result in a better match of the EGR and GR outputs with observations.

Box and whisker plots of the precipitation and temperature anomalies (future values relative to simulated baseline median values) in the Upper Columbia watershed generally show wider ranges of the EGB and GB response as compared to the EGR and GR outputs (Figures 3-17 and 3-18). As in the case of the Peace watershed, the differences are mainly caused by the differences in downscaling methods and model resolutions. The Mann-Whitney tests revealed significant differences between the outputs (at a 95% confidence level) for several months. Despite such differences, the direction of change in the median values generally agree for both precipitation and temperature, and for ensemble and single run outputs. The median changes show an increase in precipitation for most months (except July and August, when small decreases in precipitation are projected by EGR and GR outputs) (Figures 3-17a and 3-18a). Although considerable differences exist between the median EGB and GB output (45 mm and 155 mm increase, respectively) and the median EGR and GR output (84 mm and 80 mm increase, respectively) (Table 3-2), all model predictions agree on the annual precipitation increase. Seasonally, the median values show increases in precipitation, except for the summer when EGB and GB output shows decreased precipitation and EGR and GR output shows no change.

In general, future temperature changes between the two approaches follow similar patterns (Figures 3-17b and 3-18b), with median annual increases ranging between 2.2°C - 2.6°C for EGB and GB and 2.3°C - 2.6°C for EGR and GR. Seasonally, higher increases in median summer temperature (2.3°C - 3.3°C) and lower increases in median spring temperature (1.7°C - 2.2°C) are projected. In summary, relatively close matches of the temperature and precipitation change signals can be seen from both approaches. As explained earlier, since anomalies are independent of the biases, they provide better representation of potential future scenarios compared to the biased absolute EGR and GR responses.

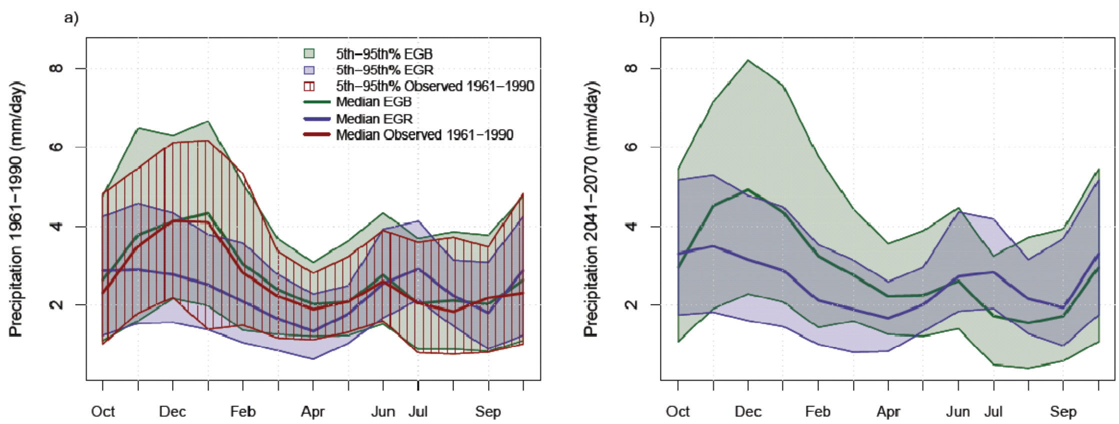

Figure 3-13. EGB and EGR monthly average precipitation in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Precipitation for the baseline period is also compared with observations.

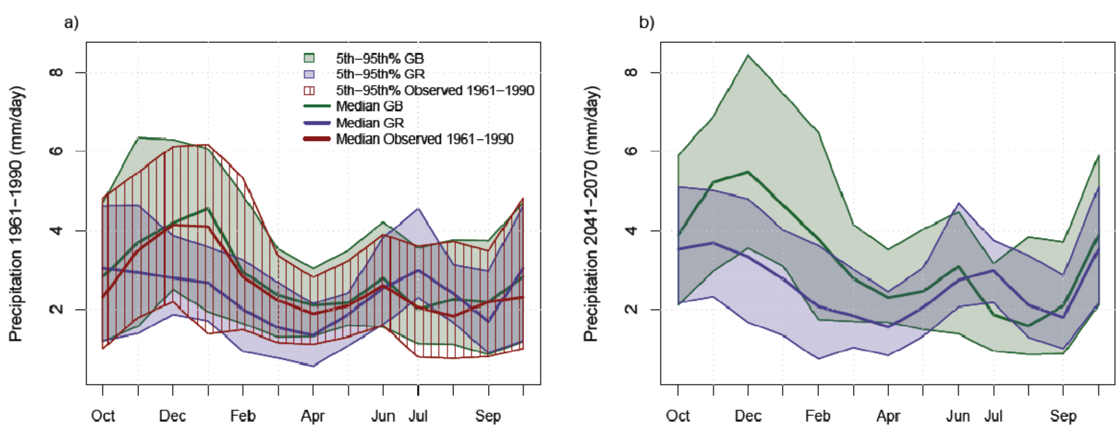

Figure 3-14. GB and GR monthly average precipitation in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Precipitation for the baseline period is also compared with observations.

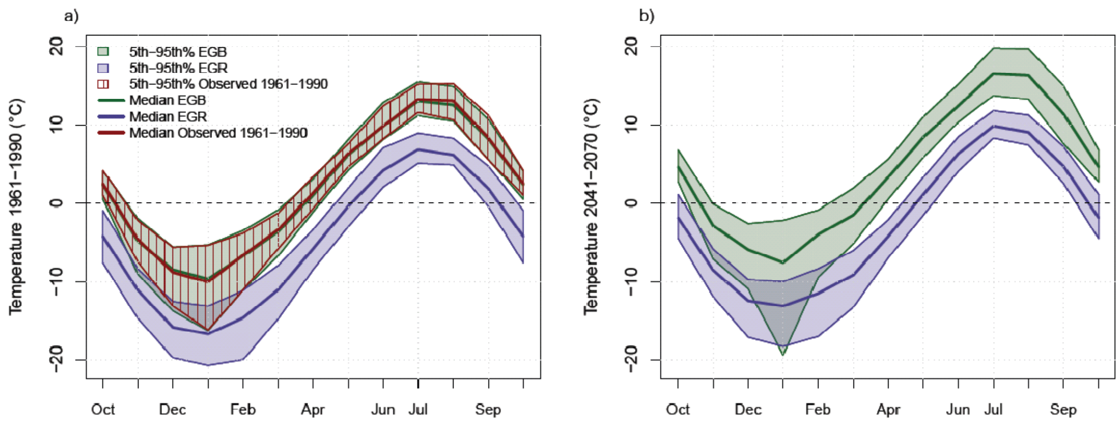

Figure 3-15. EGB and EGR monthly average temperature in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Temperature for the baseline period is also compared with observations.

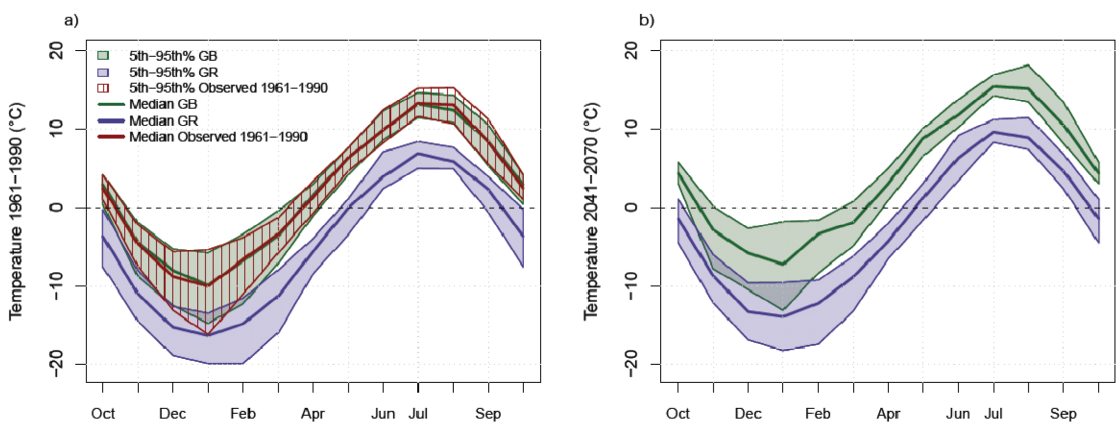

Figure 3-16. GB and GR monthly average temperature in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Temperature for the baseline period is also compared with observations.

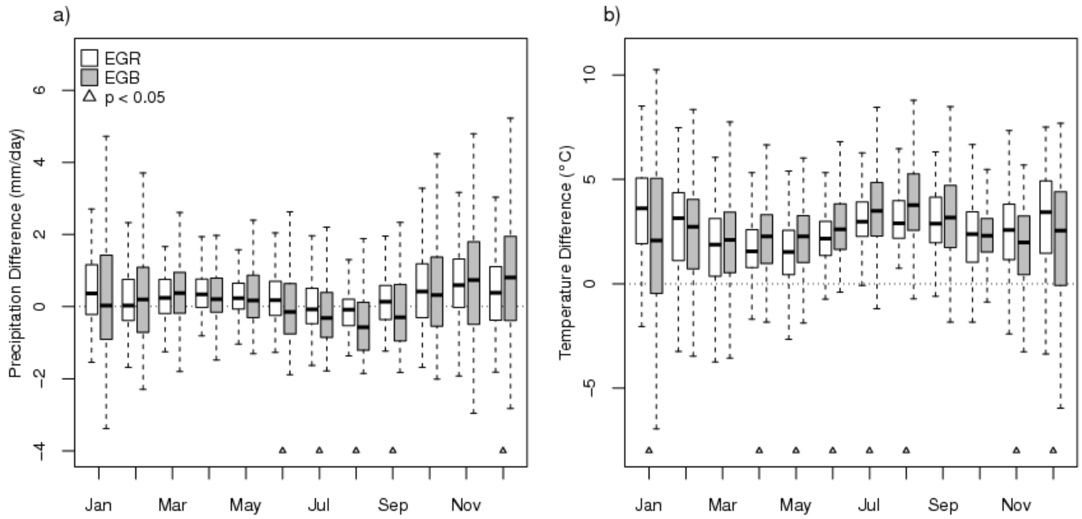

Figure 3-17. Box and whisker plots of EGB and EGR anomalies (future values relative to simulated median values from the 30-year baseline period) in the Upper Columbia watershed. Illustrated changes for monthly average a) precipitation and b) temperature. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

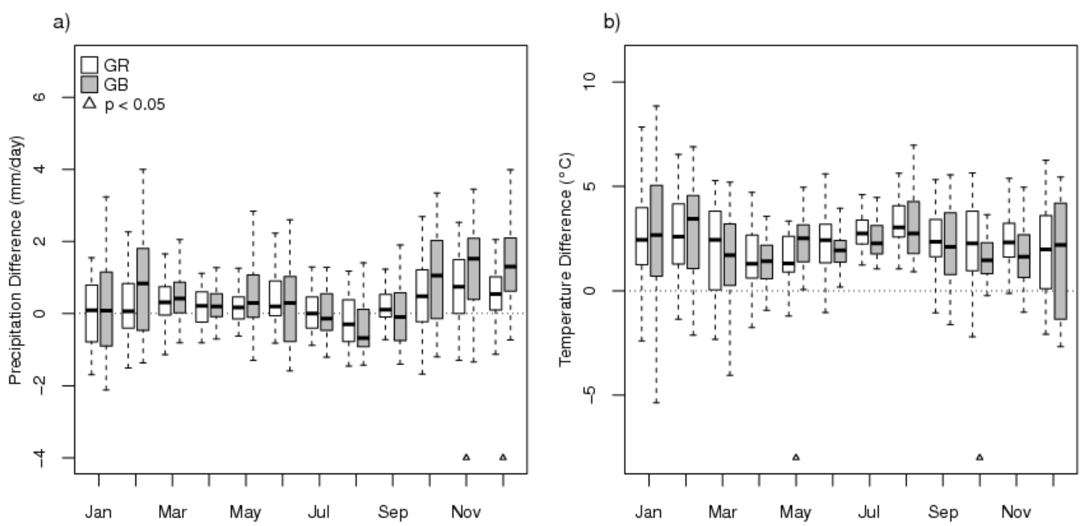

Figure 3-18. Box and whisker plots of GB and GR anomalies (future values relative to simulated median values from the 30-year baseline period) in the Upper Columbia watershed. Illustrated changes are for monthly average a) precipitation and b) temperature. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

3.2.2 Changes in Hydrologic Variables

As in the case of the Peace watershed, the runoff simulated from the ensemble and single run EGB-HM and GB-HM show better agreement with observations (for the baseline period) compared to those from EGR and GR (Figures 3-19 and 3-20). The June runoff peaks are reproduced reasonably well, but the modelled July runoff is greater than observed (Figures 3-19a and 3-20a). The median seasonal and annual runoff from the VIC model generally reproduces the dynamics of the observed runoff (Table 3-2). The EGR and GR simulated average annual runoff is also lower than observations (Table 3-2), which can also be seen in the cumulative runoff plots (Figure 3-21 and 3-22). The EGR and GR runoff simulations (for the baseline period) for the Upper Columbia watershed also show wider ranges, and earlier timing of the freshet peak (Figures 3-19b and 3-20b) in comparison to the observations. The effect of an earlier runoff peak in the EGR and GR is also apparent in the seasonal distribution of modelled runoff. Compared to the observations (for the baseline period), higher median spring runoff and lower median summer runoff are simulated by the EGR and GR (Table 3-2). The EGR and GR also simulate earlier runoff peaks despite a cold temperature bias. As in the case of the Peace watershed, the temperature bias should in principle cause a delayed runoff response (due to delayed snowmelt) in comparison to observations. The higher spring runoff peak may be due to the overestimation of snow accumulation due to the higher elevation of the CRCM grids at the lower ranges (resulting from coarser spatial resolution, Figure 2-3b). The earlier peak runoff in the EGR and GR may be partly due to the fact that CRCM parameters (specifically parameters controlling the snow processes) have not been calibrated for a specific catchment.

The hydrologic responses for the baseline period are also reflected in the runoff projections for the future period (Figures 3-23 and 3-24). Compared to the EGB-HM and GB-HM outputs, the EGR and GR model runs project an earlier runoff peak in the future period. Both approaches project some shift to earlier spring runoff. Specifically, the EGB-HM and GB-HM approach project increased May-June runoff together with decreased July-August runoff. Similarly, the EGB-HM and GB-HM approach project increased April-May runoff together with decreased June-July runoff. Such changes may be mainly due to future temperature increases, which cause earlier snowmelt and runoff (Figures 3-17b and 3-18b).

As in the Peace watershed, the projected anomalies (future values relative to simulated baseline median values) of various hydrologic variables in the Upper Columbia watershed generally show wider ranges for the EGB-HM and GB-HM outputs compared to the EGR and GR outputs (Figures 3-23 and 3-24). The wider range of EGB-HM and GB-HM simulated precipitation presumably results in the wider range of hydrologic responses. In this case too, the hydrologic changes from the two approaches differ significantly (marked by triangles with $p < 0.05$) for several months. Despite such differences, the direction of change from the two approaches, for both ensemble and the single model runs, generally follow similar patterns. Potential impacts of changes in hydro-meteorological variables are evident in the response of actual evapotranspiration, precipitation falling as snow, runoff and snow water equivalent. For instance, the median values of the results show increased median May-July evapotranspiration (Figures 3-23a and 3-24a), which can be attributed to the increase in summer temperature. The decrease in August evapotranspiration is probably due to a decrease in precipitation for the month (EGB-HM and GB-HM output). An increase in median precipitation falling as snow in November-December is due to the increase in precipitation in the corresponding months (Figures 3-23b and 3-24b). Appreciable changes in the median values for runoff occur between April and July, with increases in April-June and decreases in July for the EGB-HM and GB-HM outputs (Figure 3-23c). Similarly for the EGR and GR runoff, increases in April-May and decreases in June-July can be seen (Figure 3-24c). These changes can be attributed to an earlier start of snowmelt, which is evident from the April-May decline in the snow water equivalent in the future period (Figures 3-23d and 3-24d).

The EGB-HM and EGR results indicate potential increases in the future runoff volume (Figure 3-21). Although the EGR future runoff is less than the baseline observations, the results show increases compared to the baseline EGR simulations (Table 3-2). The changes vary seasonally, with larger increases in spring runoff and decreases in the summer runoff. Similar future changes are also projected by the EGB-HM and EGR outputs. In summary, despite large variability of the change signals, the overall hydrologic changes from the two approaches generally agree.

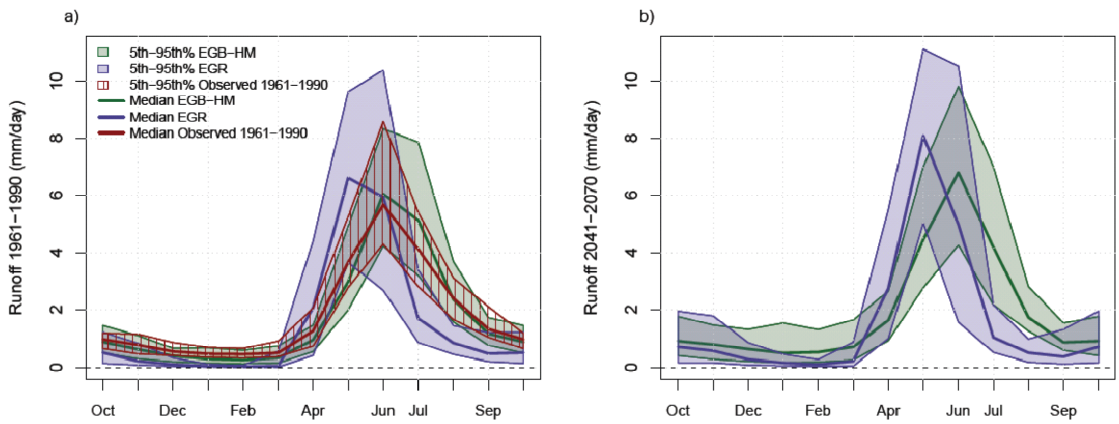

Figure 3-19. EGB-HM and EGR monthly average runoff in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Runoff for the baseline period is also compared with observations.

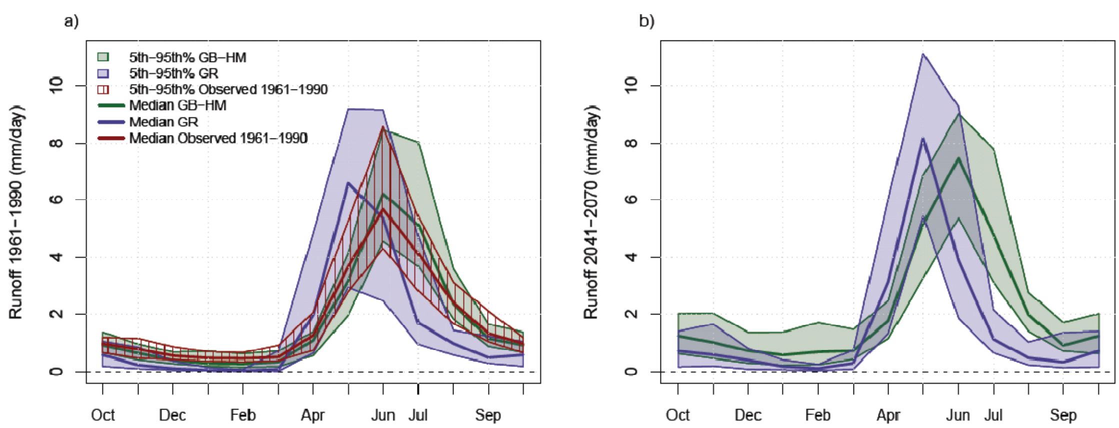

Figure 3-20. GB-HM and GR monthly average runoff in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods. Runoff for the baseline period is also compared with observations.

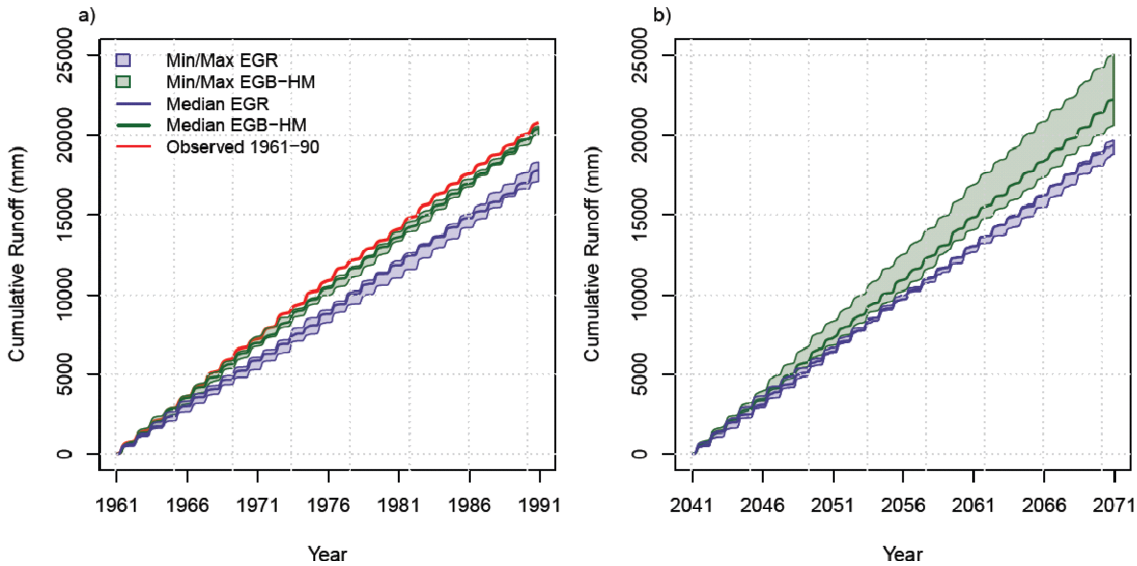

Figure 3-21. Cumulative runoff volumes from the EGB-HM and EGR in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods.

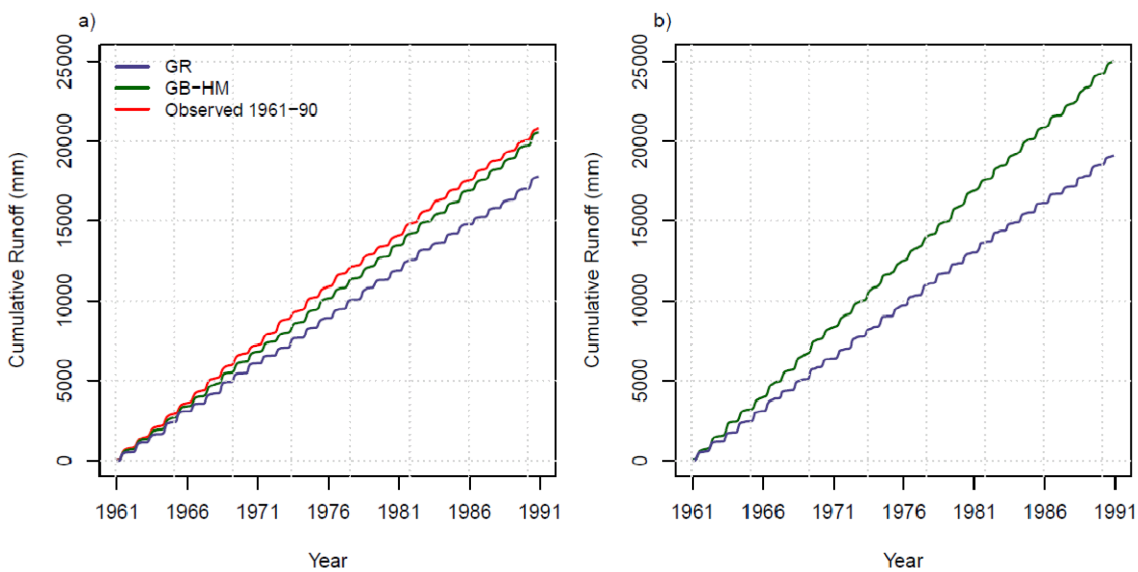

Figure 3-22. Cumulative runoff volumes from the GB-HM and GR in the Upper Columbia watershed for a) baseline (1961-1990) and b) future (2041-2070) periods.

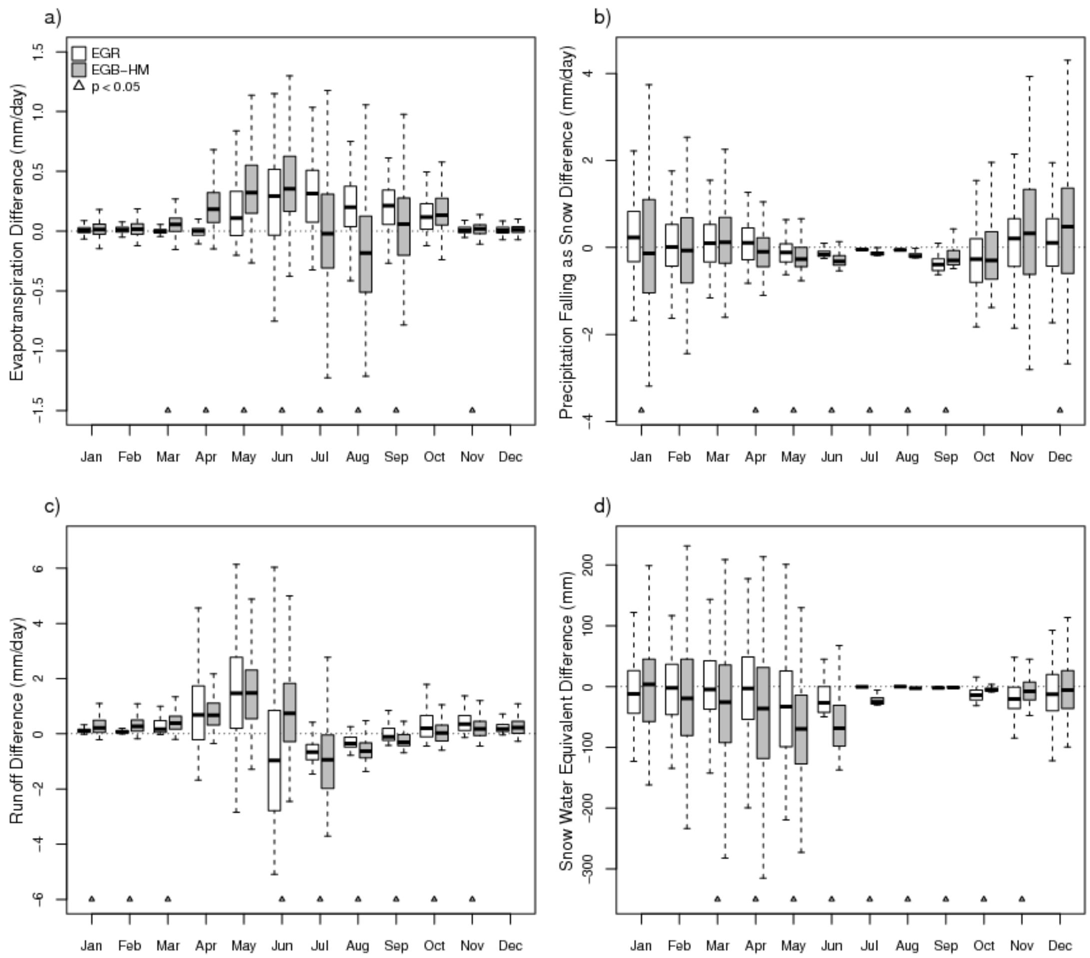

Figure 3-23. Box and whisker plots of EGB-HM and EGR anomalies (future values relative to simulated median values from 30-year baseline period) in the Upper Columbia watershed. Illustrated changes are for monthly average a) evapotranspiration, b) precipitation falling as snow, c) runoff and d) snow water equivalent. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

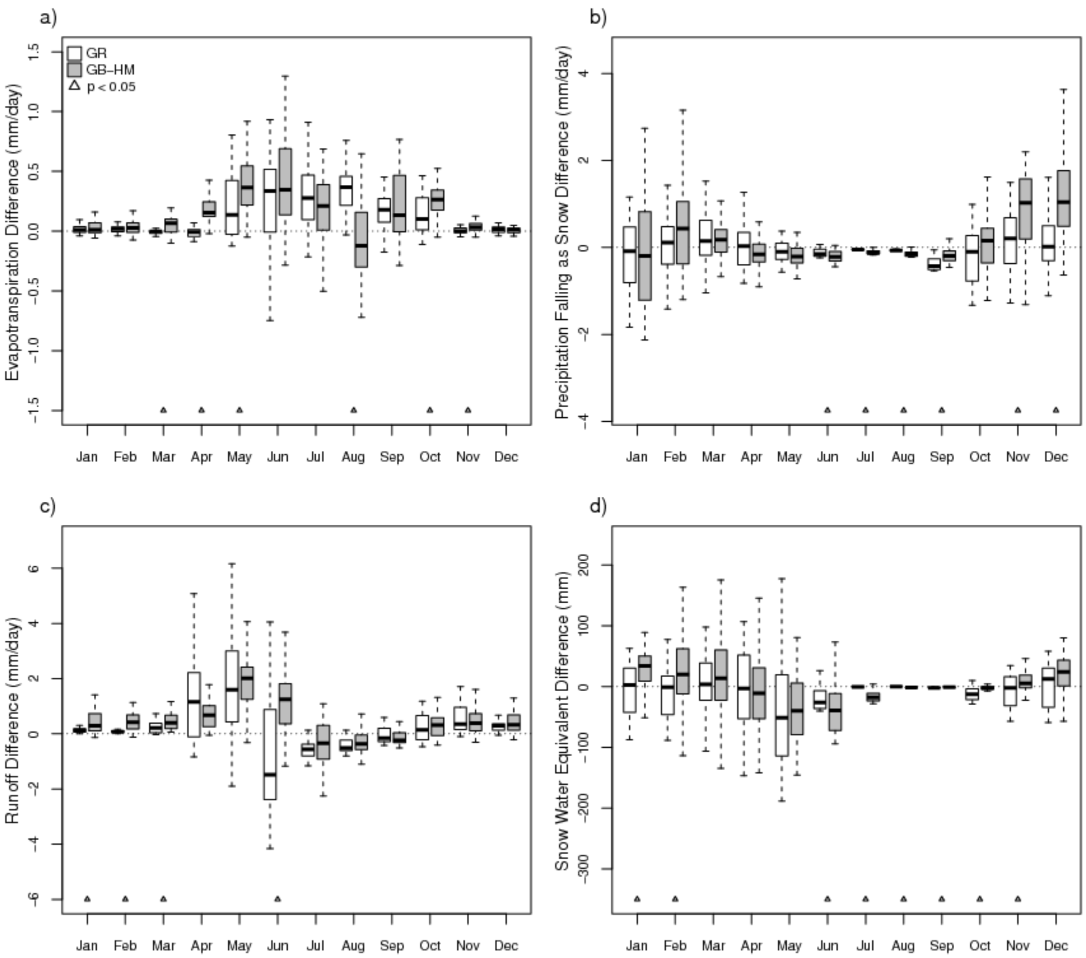

Figure 3-24. Box and whisker plots of GB-HM and GR differences between baseline (1961-1990) and future (2041-2070) periods in the Upper Columbia watershed. Illustrated changes are for monthly average a) evapotranspiration, b) precipitation falling as snow, c) runoff and d) snow water equivalent. Each box plot summarizes the median (thick horizontal line), inter-quartile range (75th to 25th percentile, IQR) box and ±3/2*IQR (dotted lines). The triangles denote statistically significant differences (when $p < 0.05$) between the distribution of anomalies evaluated with the Mann-Whitney test.

Table 3-2. Observed and modelled median precipitation, temperature and runoff from EGB, EGR, GB and GR in the Upper Columbia watershed. The difference is given relative to the respective baseline (1961-1990) value as % change for precipitation and runoff, and °C change for temperature.

	Observed	EGB			EGR			GB			GR		
	1961-1990	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference	1961-1990	2041-2070	Difference
Precipitation (mm)													
Winter	336.4	349.7	381.0	9.0	224.4	248.0	10.5	355.5	423.1	19.0	227.0	248.3	9.4
Spring	188.6	197.3	220.0	11.5	144.2	169.0	17.2	201.3	229.1	13.8	144.3	165.4	14.6
Summer	197.2	210.2	178.6	-15.0	234.2	234.7	0.2	214.3	198.6	-7.3	241.1	238.1	-1.2
Autumn	243.0	256.4	279.4	9.0	230.6	265.5	15.1	264.5	340.2	28.6	233.3	273.7	17.3
Annual	**965.1**	**1013.6**	**1059.0**	**4.5**	**833.4**	**917.2**	**10.1**	**1035.7**	**1190.9**	**15.0**	**845.6**	**925.4**	**9.4**
Temperature (°C)													
Winter	-8.5	-8.3	-5.8	2.5	-15.7	-12.3	3.4	-8.3	-5.5	2.8	-15.5	-13.1	2.3
Spring	1.4	1.2	3.4	2.2	-5.8	-4.1	1.7	1.4	3.3	1.9	-5.7	-4.0	1.7
Summer	12.1	11.8	15.1	3.3	5.7	8.4	2.7	11.8	14.1	2.3	5.5	8.3	2.7
Autumn	2.1	1.9	4.4	2.5	-4.5	-1.9	2.6	2.3	4.0	1.7	-4.1	-1.8	2.3
Annual	**1.8**	**1.7**	**4.3**	**2.6**	**-5.1**	**-2.5**	**2.6**	**1.8**	**4.0**	**2.2**	**-4.9**	**-2.7**	**2.3**
Runoff (mm)													
Winter	44.3	28.4	49.8	75.4	4.7	15.7	234.0	28.1	59.6	112.1	5.1	20.2	296.1
Spring	165.0	129.3	206.8	59.9	265.3	335.9	26.6	139.2	232.9	67.3	262.4	352.8	34.5
Summer	370.9	412.1	386.9	-6.1	258.2	198.0	-23.3	416.3	432.7	3.9	244.0	166.4	-31.8
Autumn	93.5	80.9	78.0	-3.6	36.0	49.8	38.3	82.0	96.1	17.2	38.5	48.8	26.8
Annual	**673.7**	**650.7**	**721.5**	**10.9**	**564.3**	**599.5**	**6.2**	**665.6**	**821.3**	**23.4**	**550.0**	**588.3**	**7.0**

4. Conclusions and Future Work

This study analyzed potential climate-induced change signals in the Peace and the Upper Columbia watersheds based on two independent studies: Hydrologic Modelling (HM) (Schnorbus et al. 2011; Werner 2011) and Regional Climate Modelling Diagnostics (RCMD) (Rodenhuis et al. 2011). In the HM study, downscaled GCM outputs were used as forcing data to drive the VIC hydrologic model, while in the RCMD study, outputs derived from the CGCM3 driven CRCM were used. Therefore, there are major differences in the two approaches, notably in: scale (HM: watershed scale; RCMD: North-American domain), resolution (HM: 27-31 km^2; RCMD: 45-km horizontal mesh true at 60º N), hydrologic model (HM: VIC hydrologic model calibrated for watershed runoff; RCMD: CLASS without calibration of watershed specific runoff), climate forcings (HM: statistically downscaled and bias corrected GCMs; RCMD: dynamically downscaled CGCM3, without bias correction). Given such differences in the two approaches, the outputs from the two methods can also be expected to differ.

Similar results were obtained for both Peace and Upper Columbia watersheds, and are discussed together. The results show considerable differences between the magnitudes and range (between 5th-95th percentiles) of precipitation and temperature output from the two approaches. Specifically, for the baseline period (1961-1990) the EGB and GB precipitation outputs correctly match the range of observations. The EGB and GB precipitation and temperature outputs are bias corrected and therefore, closely match the magnitudes of the observed values. The scaling effect of the BCSD algorithm (which matches the cumulative distribution function of the downscaled outputs with observations) and the finer grid resolution (which can better represent the spatial heterogeneity) contributed to the better match with the range of the observations. Since, the EGR and GR outputs are affected by biases, they are not able to accurately reproduce the range of the observed precipitation. Specifically, due to biases the upper half of the precipitation distribution extends to lower values than observed. For temperature, the 5^{th} and 95^{th} percentiles and median values are substantially lower than those of observations. The ranges and biases of the baseline precipitation and temperature are also reflected in the future (2041-2070) projections.

Since the temperature and precipitation anomalies (future values relative to simulated baseline median values) are independent of biases, GCM-driven and RCM anomalies better match each other. Despite wider ranges of the EGB and GB outputs, the median magnitude and direction of change from the projected anomalies in general, show good agreement. Prominent climate change signals depicted by the anomalies are the increases in precipitation and temperature in both of the watersheds. Median changes from the EGB, GB, EGR and GR projections range between 4.5% - 15.5% increases for precipitation and 2.2ºC - 2.6ºC for temperature. Seasonally, precipitation is projected to increase in autumn, winter and spring, with smaller increases (Peace) or decreases (Upper Columbia) in summer. Temperature is projected to increase in all seasons, with higher increases in winter (Peace) or summer (Upper Columbia).

The EGB-HM and GB-HM simulated runoff for the Peace and Upper Columbia watersheds show good agreement with observations for the baseline period. The watershed specific calibration/validation of the VIC simulated runoff led to good reproduction of the magnitude and timing of monthly runoff dynamics. However, runoff outputs from the EGR and GR match poorly with the observations. Specifically, there are problems in correctly representing the magnitude and timing of the spring snowmelt runoff. Early spring runoff is simulated by the EGR and GR despite the colder temperature bias, which in principle should cause delayed snowmelt runoff response. The CRCM runoff outputs have not been calibrated to observations, which partly explain the poorer match. The higher spring runoff peak may be partly due to overestimation of snowpack accumulation due to the higher elevation of the CRCM grids at lower elevation ranges. The hydrologic response for the baseline period is also reflected in the future runoff simulations, with an earlier runoff peak simulated by EGR and GR compared to the EGB-HM and GB-HM.

Future changes in hydrologic variables (such as actual evapotranspiration, precipitation falling as snow, runoff and snow water equivalent) are similar for the RCM and HM results for both watersheds. Although there are significant differences between the change signals from the two approaches, the direction of median changes are in general agreement. Specifically, the median values of all results show increases in summer evapotranspiration, mainly due to increases in summer temperature. The results show increases in precipitation falling as snow between the months of November-March, which can be attributed to higher precipitation in these months. Appreciable changes in spring runoff occur in May-July, with increases in the earlier month(s) and decreases in later month(s). These changes can be attributed to an earlier start of snowmelt, which is evident from large changes in show water equivalent in April and May. The results also reveal that future changes in the climatic regime are likely to bring higher runoff volume. The projected increases in the median runoff volume range between 3% - 16% increases in the Peace and 6% - 23% increases in the Upper Columbia watershed. However, the annual runoff increases may be accompanied by decreases in summer runoff in both watersheds.

Results of this study show that the differences between the ensemble and single runs (i.e., EGB vs. GB; EGR vs. GR) are usually quite small. The similarity of the EGB and GB results can be mainly attributed to the downscaling method (BCSD), which matches the cumulative distribution functions of each of the downscaled outputs to that of observations. The GR results are very similar to the EGR results, implying that due to subsequent downscaling, the use of multiple runs of CGCM3 may not significantly change the variability of the CRCM projected range. Furthermore, GB outputs are more similar to the ensemble EGB outputs than the GR outputs. This implies that the subsequent downscaling and hydrologic modelling steps lead to substantial differences in the overall output.

The study provided insights on the capabilities and limitations of the GCM-driven and RCM approach for projecting watershed-scale hydro-climatic response. Due to lack of catchment specific calibration and influence of biases, the RCM projections do not match the observations and hydrologic model projections. However, RCM projected anomalies (future values relative to simulated baseline median values) depict patterns similar to those from the GCM-downscaled and VIC-simulated results. Therefore, the anomalies provide more useful information about potential future changes. Furthermore, bias correction of the RCM outputs can be expected to provide better match with the GCM-driven and hydrologic model simulated outputs. To further establish the capabilities of the RCMs, future studies should compare the outputs from the two approaches at higher temporal resolution (such as daily). It should be noted too that one of the strengths of RCMs over BCSD downscaling is their ability to take daily information from the GCM, whereas daily outputs from the BCSD are resampled values corresponding to the daily historic records. The availability of higher spatial resolution RCMs in future can be expected to provide a better representation of watershed scale spatial heterogeneity. This study only considered output from different runs from a single RCM (CGCM3 run 1). Similar to the multiple GCMs employed in this study, the use of multiple RCMs will enable the consideration of a range of possible future scenarios based on different GCM driven RCMs. Application of multiple RCMs will also provide a more objective comparison of the future changes driven by the same set of GCMs from these two structurally very different approaches. Furthermore, the range of outputs from the ensemble GCMs and RCMs show large variability. These outputs provide a range of possible future outcomes, which need to be evaluated when considering potential future adaptation measures.

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