Climate Diagnostics of Future Water Resources in BC Watersheds

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Regional Climate Modelling Diagnostics 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 regions. 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/.

Disclaimer

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I would like to acknowledge the collaboration of my co-authors and the commitment of Dr. Daniel Caya to the development of the Regional Climate Model Diagnostics project at PCIC. A special thanks goes to Mourad Labassi for technical support at the Ouranos computing facilities. At PCIC staff members of the Hydrologic Impacts Project also helped with the transfer of map files to Ouranos and accepted the output of time series for subsequent analysis. Finally, the support of BC Hydro and the Ministry of Environment over several years of development of the project is very gratefully acknowledged. In this regard, I would like to note especially the vision and encouragement from Brian Fast of BC Hydro, and Ben Kangasniemi of the BC Ministry of Environment for using climate models to assess future water resources for hydroelectric power generation.

The reviewers of this report have challenged us to explain more fully the technical issues and thereby have also greatly contributed to the clarity of the report. I am sincerely grateful for their time, critical remarks, and their encouragement.

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Preface

In 2007 the Pacific Climate Impacts Consortium (PCIC) initiated a *Hydrologic Impacts Program* with support from BC Hydro to address the consequences of climate change on water resources in British Columbia. The program was divided into four distinct projects: *Climate Overview*, *Hydrologic Modelling*, *Regional Climate Modelling Diagnostics*, and *Synthesis*. For this project on Regional Climate Modelling Diagnostics, PCIC relied heavily on external collaboration with the Ouranos consortium in Montréal and the Université du Québec à Montréal (UQÀM). Both organizations have a distinguished record in regional climate modelling (RCM) diagnostics.

PCIC provided partial support for two postdoctoral researchers, Biljana Music and Marco Braun, under the supervision of Dr. Daniel Caya (Ouranos) and Prof. Laxmi Sushama (UQÁM), respectively. These researchers applied their experience to the watersheds of British Columbia and were asked to support the project at PCIC in two ways: i) by preparing analysis tools that could be used by PCIC, and ii) by investigating the uncertainty of the Canadian Regional Climate Model (CRCM) at 45 km resolution and the limits of this technology over the mountainous terrain of British Columbia.

The objectives of this study and report are to validate the water balance of the CRCM in select BC watersheds, and to use the CRCM to simulate future climate and hydrologic conditions, including surface runoff. Because of the experimental nature of results from the regional climate model, a companion study using a hydrologic model with a resolution of about 5-1/2 km was also conducted (Schnorbus et al. 2011)[1]. This is the traditional approach for determining streamflow. Those results utilize detailed river routing of sub-basins that are not used by this regional modelling approach. However, the hydrologic model is also driven by future climate states with a large-scale forcing from a Coupled Global Climate Model (CGCM). Results from both studies are incorporated in a Synthesis Report (Shrestha et al. 2011)[2].

This report relies heavily on the research investigations of the co-authors, emphasizing the uncertainties that arise from different models, different version of models and different physical parameterizations. The capability of the RCM methodology has been demonstrated on major watersheds in mountainous regions of British Columbia.

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[1] 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.

[2] Shrestha, R.R., A.J. Berland, M.A. Schnorbus, A.T. Werner, 2011: *Climate Change Impacts on Hydro-Climatic Regimes in the Peace and Columbia Watersheds, British Columbia, Canada*. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 37 pp.

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Climate Diagnostics of Future Water Resources in BC Watersheds

Executive Summary

Climate modelling technology was used to estimate future hydrologic conditions under the influence of climate variability and change. The objectives for this work were: i) to validate the water balance in selected watersheds, ii) to simulate future conditions in the 2050s and, iii) to contribute to estimates of future streamflow. The selected watersheds for this project included the Upper Columbia and Upper Peace rivers in British Columbia. Results for the smaller Campbell watershed were also reviewed, but were not considered reliable. Results for other watersheds, the Upper Fraser and the entire Columbia Basin, were computed as a reference.

The A2 emissions scenario was used to drive several versions of a Canadian Coupled Global Climate Model (CGCM). Those results were used subsequently to drive several different versions of the Canadian Regional Climate Model (CRCM) at 45 km horizontal resolution. The CRCM employs an implicit Land Surface Scheme (LSS) to resolve the hydrologic components: precipitation, surface evapotranspiration, snow accumulation, and surface runoff.

The results from climate models were compared to historical records (1961-1990) to determine model bias, the effects of internal (and natural) variability, and to test for structural uncertainty due to different parameterizations of physical processes. These results are used to estimate the overall uncertainty of hydro-climatic projections in the future (2050s). The experimental setup allows the estimation of several sources of uncertainty associated with hydro-climatic projections. A *Results Matrix* was developed as an analysis tool for systematically analyzing hydrologic impacts and their variability from climate models.

The monthly mean time series of historical and future conditions were examined for bias, internal variability, and climate change signal. The annual average results from the integrated response of both the global and regional climate models in selected major watersheds of British Columbia are:

- The CGCM has a significant cold bias that is accompanied by excess snow accumulation during winter. However, the bias may be removed by considering anomalies between the future and historical projections taken from the same model.
- Most of the internal variability comes from the global climate model, which is the source of our best estimate of the natural variability in the real climate system. The influence of internal variability on estimates of the projected change in the climatological values of the hydrologic components in the major watersheds of British Columbia is estimated to be less than 6% for both snow accumulation and runoff.
- The impact of the climate change signal in the 2050s decreased the annual mean value of the snow accumulation by about 2% in the Upper Peace, 6% in the Upper Columbia, and a decrease of almost 20% for the entire Columbia Basin, relative to projected mean annual climatology. The peak period in surface runoff is shifted to earlier in the spring. The impact in the Upper Peace (and Fraser watershed) is an increase in runoff by 17-18%, but less in the south for the Upper Columbia (9%) and the entire Columbia Basin (7%).

Finally, ensembles of time series of monthly averaged runoff and hydrologic components for future conditions in the designated watersheds were computed from both global and regional climate models (Attachment 1). These were used for comparison with detailed hydrologic modelling in a synthesis report, *Climate Change Impacts on Hydro-Climatic Regimes in the Peace and Columbia Watersheds, British Columbia, Canada* (Shrestha et al. 2011).

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1. Introduction and Background

The future of water resources in British Columbia will be influenced by climate change on a global scale (Rodenhuis et al. 2007a). Temperature and precipitation will change both in their mean values and in their variability. This report presents a study of future conditions for the 2050s of water balance on several watersheds in British Columbia as projected by the Canadian Regional Climate Model (CRCM) at a resolution of about 45 km. The regional climate model depends on forcing of large-scale atmospheric circulation from a Coupled Global Climate Model (CGCM). A regional water balance for the entire watershed is obtained from an embedded Land Surface Scheme (LSS). These complex calculations are necessary to estimate the primary output parameter: watershed runoff in the future.

The study of future streamflow and runoff estimated from regional climate models has been investigated by Sushama et al. (2006), Plummer et al. (2006), Music and Caya (2007), Music et al. (2009) and Xu et al. (2005). Another study was completed by Frigon et al. (2010) using similar methods that addressed 21 watersheds in the Province of Québec. The application of a climate model with modest spatial resolution to the relatively smaller watersheds in British Columbia was unusually challenging and ambitious, and the results need to be interpreted carefully. On the other hand, a successful application of this method opens up additional possibilities for understanding future hydrologic impacts. Early reports on this work in the watersheds of British Columbia were presented in a status report (Schnorbus et al. 2010), in presentations at a joint workshop (Schnorbus and Rodenhuis 2010; Caya et al. 2010), and at an international conference (Music et al. 2010).

A companion study using a hydrologic model with a resolution of about 5 km was also conducted to estimate future streamflows (Schnorbus et al. 2011). The hydrologic model in that case was driven by future climate conditions taken from the same global-scale CGCM as the one used for our CRCM regional water balance analysis. The use of a hydrologic model forced by climate model data is the traditional approach for the determination of future streamflows. However, detailed river routing of sub-basins of the hydrologic model are not used in the CRCM modelling approach reported in this study. Results from both studies have been incorporated into a synthesis report (Shrestha et al. 2010).

The quantitative results of the present analysis must be understood within the bounds of uncertainty associated with future projections. There are three sources for the uncertainty implicit in these results:

- Structural uncertainty – Consequences of approximations and assumptions in the climate modelling system (GCMs, RCMs and associated LSSs).
  - Model physics – Every climate and hydrologic model produces somewhat different results due to different implementation of the climate processes. Furthermore, limitations in the spatial resolution, and in the empirical specification of sub-grid-scale processes, create additional uncertainty in the results.
  - Model bias – Part of the uncertainty is model bias that can be minimized by calculating the difference between a future estimate and a simulation of present conditions, rather than absolute values of the output parameters.
- Natural variability –The non-linear nature and the strong interactions between the components of the climate system (ocean-land-ice-atmosphere) induce important variability at all temporal scales. Part of this variability is stochastic, and climate models should reproduce the observed statistics of the climate system, including monsoons and El Niño events, even though regional differences in model climate may occur for short periods of time. The uncertainty associated with this variability cannot be reduced, but can be identified and estimated.
  - When strong interactions occur between components with non-linear processes, different responses that incorporate the resulting natural variability may lead to an entirely different climate state—a radical climate change. However, this situation is outside the scope of the present study and is considered to be unlikely in the foreseeable future (IPCC 2007).

- Uncertainty in anthropogenic forcing – The magnitude of global greenhouse gas (GHG) emissions is also a major source of uncertainty since it depends on future societal development , as well as natural emissions and absorption by the climate system. A common assumption is to accept the A2 emissions scenario associated with a growing population and industrial development in “a more divided world”. In fact the choice of global emissions scenario is not critical to this study, which is focused on the near future (2050s horizon) when all realistic emissions scenarios produce similar impacts (IPCC 2007; Figure SPM-5).

Some estimates of uncertainty in the final results have been made, but this is a complex subject and a complete uncertainty analysis of the results has not been fully evaluated. The larger context for this study is a project of targeted research at the Pacific Climate Impacts Consortium (PCIC) that is directed to the following watersheds: the Upper Peace, the Upper Columbia, and the Campbell. The objectives for this project were stated in the research plan by Rodenhuis (2007b):

1. to validate the current water balance in selected regions and watersheds of British Columbia using the CRCM,
2. to simulate future climate conditions using the global CGCM to drive a regional CRCM over the domain of the watersheds of interest, and
3. to estimate future streamflow conditions and describe “surrogate streamflows” using estimates of runoff from the CRCM, including an uncertainty analysis of the estimates.

The present report on Regional Climate Modelling Diagnostics (Project 3) is directed primarily to the first two objectives. In addition, monthly time series of hydro-climatic components, spatially averaged over the watershed, are presented. They are used in the subsequent analysis described in the synthesis report (Shrestha et al. 2010) that addresses the third objective outlined above.

The work plan for these studies was guided by a schematic concept developed in the first phase of the project to summarize existing downscaling approaches (Figure 1-1). Among the methods identified in this figure, this report focuses on method “b”, which is the most straightforward approach for transferring climate information through the CRCM and hydrologic models.

In undertaking this work, we have attempted to describe uncertainties associated with the sources outlined above to the extent possible within the available timeframe and with the resources of available CGCM and CRCM simulations. The study of climate projections, internal variability, and climate change signals is a developing field of climate research and requires massive computational resources that use an ensemble of computations from diverse models of the global climate system. Fully exploring the uncertainty associated with projections of future streamflows is entirely beyond the scope of this project. However, a first step has been taken with a limited set of models to establish a sense of the potential for regional climate modelling diagnostics when applied to specific watersheds of limited extent. The intention is to estimate future hydrologic conditions in the 2050s and present an estimate of uncertainty within the limits of available time and technical resources. This is an application of research technology to address important questions concerning future precipitation, snowpack, and runoff within several important watersheds in British Columbia. Although the results of this report are limited by the scope of our objective, a methodology has been established for finding answers and tentative conclusions have been made.

The results of this analysis are presented in three parts. The next two sections introduce the Canadian Regional Climate Model (CRCM) and the issue of natural variability of climate. This is followed by an explanation of methods, and a description of the watersheds of interest. The next section (B. Music) evaluates the CGCM and CRCM capabilities for adequately simulating annual mean values and annual cycles of hydro-meteorological variables over the Upper Peace watershed. The effects of natural variability as estimated by the CGCM3, the effects of differences in the CRCM lateral boundary conditions, and the effects of the physical parameterizations on simulated hydrological conditions for the reference period (1961-1990) are also presented. This is followed by projections of future hydrological regimes over the Upper Peace, Campbell, Fraser and entire Columbia watersheds, based on an ensemble of CRCM (Version 4.2.3) simulations. Finally, a systematic analysis is presented (M. Braun) of the three selected watersheds in BC: the Upper Peace, Upper Columbia, and the Campbell watershed on Vancouver Island. Quantitative estimates of the impacts of the climate change signal on precipitation, evaporation and runoff are accompanied by estimates of the uncertainty that results from the internal variability of the CGCM.

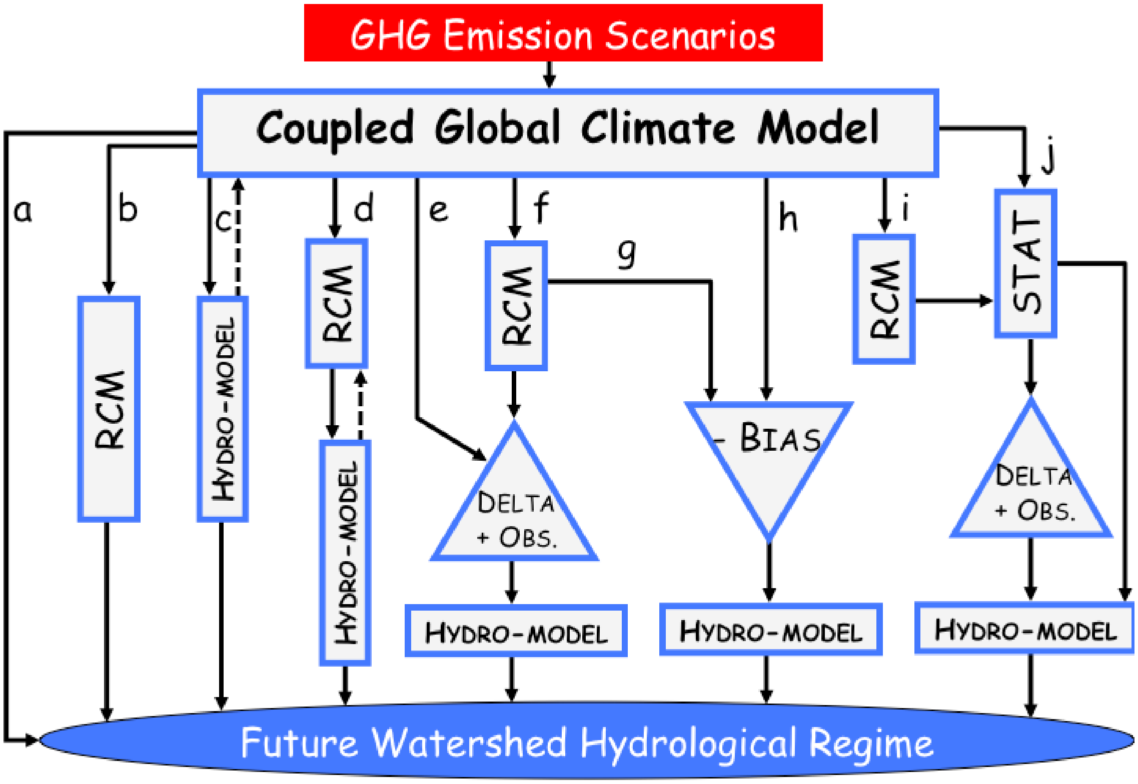

Figure 1-1. Schematic of different methods of assessing watershed hydrological response to global climate change simulated by coupled ocean-atmosphere global climate models (CGCMs) under a given greenhouse gas (GHG) emissions scenario. Music et al. (2010) summarized the methods: (a) direct CGCM hydrological output; (b) direct RCM hydrological output; (c) one/two-way coupling of a GCM with a hydrological model; (d) one/two-way coupling of a RCM and a hydrological model; (e, f, g, h) transfer GCMs/RCMs climate change signal to a hydrological model with perturbation (delta) and bias-correction methods; (i and j) statistical downscaling of a GCM/RCM output to a scale appropriate for a hydrological model. The analysis of this report uses method "b", where the land surface hydrology scheme is implicitly embedded in the CRCM.

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2. Regional Climate Models (RCMs)

Coupled Global Climate Models (CGCMs) are sophisticated tools designed to simulate Earth's climate system. Based on well-established laws of physics, CGCMs simulate the main characteristics of atmospheric and oceanic circulation quite well. However, the coarse horizontal resolution of these models limits their ability to reproduce details at the regional scale, especially for complex surface characteristics such as topography, coastlines, and inland water bodies that strongly influence the regional climate. In order to better represent the characteristics that control regional climate, higher spatial resolution climate models are required.

High resolution versions of a CGCM are limited by available computing resources. This limitation is more severe because an *ensemble* of long-term simulations is needed to assess uncertainties associated with climate projections. Two approaches have been developed in order to increase the resolution over a limited, specific area of interest: the global variable-resolution stretched-grid approach (e.g., ARPEGE-Meteo-France), and the nested-grid approach used by RCMs.

Since RCMs simulate climate only over a specific area of interest, they require forcing information describing the state of the atmosphere at their lateral boundaries. Thus, output from a CGCM must be selected to simulate future climate conditions. RCMs can also be nested within a current global reanalysis of historical data to test the ability of the RCM to reproduce current climate conditions. Reanalysis products such as the NCEP/NCAR reanalysis (Kalnay et al. 1996) and the ERA40 reanalysis (Uppala et al. 2005) are well developed for current climate simulations.

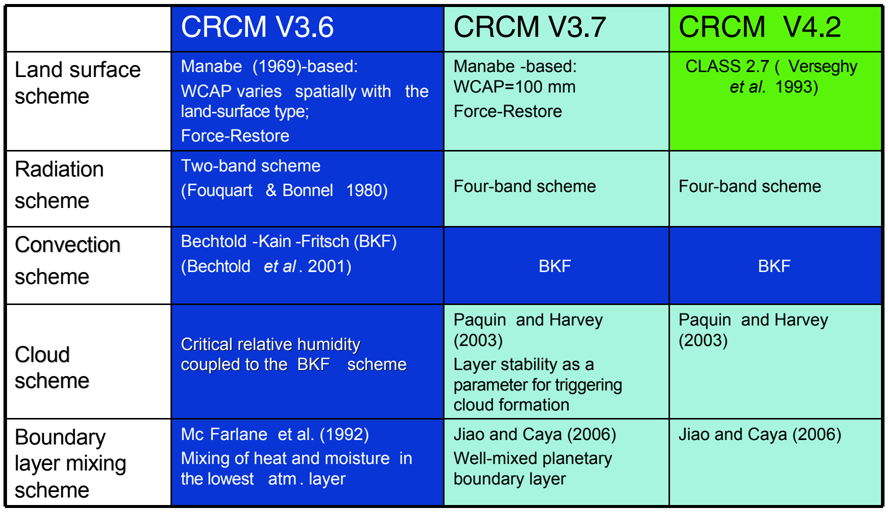
2.1 The Canadian Regional Climate Model (CRCM)

The operational versions of the CRCM were developed by the Ouranos consortium from the research version (Caya and Laprise 1999) developed at the Université du Québec à Montréal (UQÀM). The CRCM is a state-of-the-art model of regional climate based on high-performance numerical integration techniques (Laprise et al. 1998; Caya and Laprise 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, and is used operationally at a 45-km grid mesh. This spatial resolution (45 km) is much higher than that used by the global-scale CGCM (about 200 km) and allows a relatively good representation of the processes important for the regulation of hydrological regimes at a regional scale.

Recently, more realistic physical parameterizations were implemented into the CRCM (Table 2-1), including changes to the radiative scheme, treatment of cloud cover, atmospheric boundary mixing scheme, and a land-surface parameterization scheme. For more details related to these modifications, the reader is referred to Music and Caya (2007; 2009).

Table 2-1. Parameterization methods for different versions of the Canadian Regional Climate Model (CRCM) used in the present analysis.

PARAMETERIZATIONS USED IN DIFFERENT CRCM VERSIONS



	CRCM V3.6	CRCM V3.7	CRCM V4.2
Land surface scheme	Manabe (1969)-based: WCAP varies spatially with the land-surface type; Force-Restore	Manabe -based: WCAP=100 mm Force-Restore	CLASS 2.7 (Verseghy *et al.* 1993)
Radiation scheme	Two-band scheme (Fouquart & Bonnel 1980)	Four-band scheme	Four-band scheme
Convection scheme	Bechtold -Kain -Fritsch (BKF) (Bechtold *et al*. 2001)	BKF	BKF
Cloud scheme	Critical relative humidity coupled to the BKF scheme	Paquin and Harvey (2003) Layer stability as a parameter for triggering cloud formation	Paquin and Harvey (2003)
Boundary layer mixing scheme	Mc Farlane et al. (1992) Mixing of heat and moisture in the lowest atm. layer	Jiao and Caya (2006) Well-mixed planetary boundary layer	Jiao and Caya (2006)

2.2 Canadian Land Surface Scheme (CLASS)

Runoff is a crucial hydrological component produced by the land-surface scheme (LSS), which is an important component of any climate model. A sophisticated state-of-the-art LSS (second and following generations) incorporates an explicit formulation of canopy processes and allows vegetation to determine the way in which the land-surface interacts with the atmosphere (e.g., Dickinson 1983;1984; Sellers et al. 1986; 1996; Verseghy 1991; Verseghy et al. 1993; Dickinson et al. 1998). This complex calculation is needed to supply accurate water, energy and momentum fluxes across the land-surface-atmosphere interface. This in turn allows an adequate partitioning of soil moisture into evapotranspiration, and the subsequent determination of surface runoff.

The CRCM utilizes the Canadian Land Surface Scheme (CLASS) (Verseghy 1991; Verseghy et al. 1993). This scheme is also implemented in the third generation of the Canadian Coupled Global Climate Model (CGCM3) (Scinocca et al. 2008; Flato and Boer 2001). The CRCM V4.0 utilizes an updated version of CLASS (V2.7). At every time step, CLASS receives the following information from the atmosphere: the precipitation rate, the incoming short-wave and outgoing long-wave radiative fluxes, air temperature, humidity and wind speed. Each land surface grid cell can have up to four sub-areas: bare soil, vegetation-covered soil, snow-covered soil, and soil covered by both vegetation and snow. There are four vegetation types in CLASS: coniferous trees, deciduous trees, crops, and grass. Snow in CLASS is simulated as a separate layer for both thermal and hydrological processes. The moisture and energy budgets are calculated for each land-surface sub-area, and then the surface fluxes are averaged over the grid cell and passed back to the atmospheric model.

Water and energy fluxes at the land surface are influenced by available soil moisture. Soil in CLASS is divided into three horizontal layers: a 10-cm surface layer, a 25-cm vegetation root zone, and a 375-cm deep soil layer. The liquid and frozen moisture contents in each layer are prognostic variables and respond to moisture fluxes at the top and bottom of each layer. The classic Darcy theory of drainage and capillary rise is used to determine fluxes between the soil layers. Infiltration into the upper soil layer is calculated following the Mein and Larson (1973) method. Total runoff in CLASS is composed of surface runoff and water drainage from the deep soil column (subsurface runoff). Surface runoff is generated if the surface infiltration capacity is exceeded and water is allowed to pond on the surface up to the surface retention capacity.

The overflow of the surface retention capacity is assumed to be surface runoff. The subsurface runoff is calculated as $Q_d = k_{sat}(w_d w_{sat}^{-1})^{2b+3}$, where w_d is the volumetric water content (m^3 m^{-3}) in the deep soil layer, w_{sat} is the saturation soil water content, k_{sat} is the saturation hydraulic conductivity, and b is soil texture parameter. The surface retention capacity varies with land cover type, while the hydraulic properties of the soil layers as well as the parameters b, w_{sat}, and k_{sat} depend on soil texture. The global dataset of Webb et al. (1993) is used to derive the overall depth of each soil layer for each grid box down to bedrock, while the land cover data is obtained from Bartholomé and Belward (2005).

2.3 Variability in the Climate System and in Climate Models

An ensemble of simulations from climate models that differ very slightly in their initial conditions, or that contain small differences in the modelling system configuration, will produce a different result (a different weather map) on any single day in the future. This model result is also an intrinsic property of the real climate system. Thus, each of these simulations can be viewed as equally probable. The results of these simulations (time series of meteorological variables) are available on a regularly spaced grid and can be viewed as "observations" in a virtual station network. It is assumed that ensembles of these simulations are the best available source of information for estimating future climate conditions of the real climate system under the influence of increasing concentrations of greenhouse gases. In order to validate this assumption, the statistical properties of climate models are first evaluated against observations for the recent past. Subsequently, multiple simulations of future conditions are conducted to assess the climate change signal in the specific area of interest.

The differences between simulations within an ensemble described above are a measure of the *internal variability* of the climate model. However, the internal variability in the global climate model simulations is present in the real climate system (the ocean, land and atmosphere of planet Earth) as *natural variability*. The natural variability of the real climate system cannot be estimated accurately for many reasons, including a major shortage in observations. Therefore, the internal variability from an ensemble of CGCM simulations is our best estimate of natural variability in the real climate system. This natural variability is a result of the chaotic nature of the climate system and strong interactions between its main components (atmosphere, hydrosphere, lithosphere and cryosphere). Since CGCMs provide time-dependent lateral boundary conditions for regional climate simulations, RCM simulations are also affected by global model internal variability, and RCMs themselves induce an additional, intrinsic internal variability that must be assessed. However, we can anticipate that this internal variability of the regional model is about an order of magnitude smaller than the primary source of internal variability in the driving CGCM.

In summary, internal variability is present in the climate system because of its chaotic nature and because of the strong interaction between the various components of the climate system. Estimates of the global internal variability obtained by the statistical analysis of a CGCM ensemble provide an estimate of natural variability of the real climate system. Regional climate models (RCMs) are based on the same fundamental physical principles as GCMs, and they also contain intrinsic internal variability. Thus, an RCM simulation driven by a CGCM is affected by two sources of internal variability, and both need to be estimated. The internal variability also affects the 30-year climatological statistics.

With all this in mind, both sources of internal variability are examined in Section 4 for the Upper Peace, Columbia, Fraser and Campbell watersheds. The relative contributions of global and regional internal variability are presented systematically for the designated watersheds in Section 5.

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3. Methods

In the two sections that follow, climate variables are taken from simulations of the CRCM (Caya and Laprise 1999; Music and Caya 2007; Brochu and Laprise 2007). Subsequently, we analyze the averaged hydrologic components over the area of the designated watersheds.

3.1 Application to BC Watersheds

The simulation of climate using a RCM requires information about the atmospheric conditions outside the domain. These conditions at the boundaries of the RCM domain can be provided by reanalysis of historical observations, or they can be taken from a simulation of a CGCM.

To assess BC water resources, the Canadian Regional Climate Model was driven by boundary conditions from ERA-40 reanalysis (Uppala et al. 2005) and simulations performed with the Canadian Global Climate Model (Scinocca et al. 2008; McFarlane et al. 2005; Flato and Boer 2001). The A2 greenhouse gas (GHG) emissions scenario (Nakicenovic and Swart 2000) was applied to incorporate anthropogenic forcing in the simulations. The choice of emissions scenario is not critical for the present study, since there is not a widespread difference between the various emissions scenarios for the 2050s time horizon[3].

The data used in the presented studies were taken exclusively from dynamically downscaled CGCM3 simulations. No further statistical downscaling is used. Most of the analyses were focused on the 2050s time horizon by choosing (2041-2070) as the future time period and comparing results with the (1961-1990) reference period. The hydrologic components of interest include precipitation, atmospheric moisture convergence, snow water equivalent, evapotranspiration, surface runoff and surface temperature. These components were used to study the annual cycle, the model bias, the internal variability, and the climate change signal in the primary watersheds of British Columbia (Figure 3-1). The three embedded watersheds designated for this project included:

- The Upper Peace River drainage of 101,000 sq. km (above Taylor; Figure 3-2). This area is resolved by 52 grid cells at 45 km resolution. The Peace River is important because major power generation facilities are located at W.A.C. Bennett dam which forms Williston Reservoir and the Peace Canyon dam.
- The Upper Columbia drainage of 104,000 sq. km (primarily in Canada; Figure 3-3). This area is resolved by 49 grid cells at 45 km resolution. The Upper Columbia is important because of power generation facilities at Mica, Revelstoke and Hugh Keenleyside dams, and also downstream in the USA. In addition, negotiations of the Columbia River Treaty between the United States, and Canada (British Columbia) will be initiated during the coming decade. Several sub-basins were not analyzed, but are important reference points for subsequent comparison of streamflows at gauging stations or estimates at project sites. These include:
    - Kinbasket Reservoir above the Mica Dam (21,148 sq. km) (the upper Mica watershed has a gauging station at Donald),
    - Arrow Lakes above Keenlyside Dam (36,669 sq. km),
    - Kootenay Lake above Kootenay Canal (47,718 sq. km),
    - Okanagan Lake (17,156 sq. km), which is an important natural reservoir in the Columbia Basin, and not used for power generation.
- Campbell drainage (1,193 sq km) to Strathcona (Figure 3-4). The Campbell is important because it is an example of a small drainage basin located on Vancouver Island with power generation facilities at Strathcona Dam. In contrast to other watersheds under consideration, this small areal

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[3] It is acknowledged that actual emissions in the past few years are greater and closer to the A1F1 scenario (Raupach and Canadel 2010).

extent contains only a single grid cell, and challenges the ability of current models, both the VIC hydrologic model and the CRCM regional climate model at 45 km resolution.

Although it is outside the scope of this report, results were also obtained for several large watersheds (Figure 3-1) and used for comparison:

- The entire Columbia watershed (668,433 sq. km). This is an important, large watershed in which the Upper Columbia is embedded. The outflow is at The Dalles near Portland, Oregon. Water and power resources from the Columbia are shared by Canada and the US. This region is represented by 394 grid cells of 45 km resolution.

- The Fraser watershed above Hope (217,000 sq. km). This is part of another large and important Fraser watershed in British Columbia that drains the interior plateau and mountain glaciers with outflow at Vancouver, BC. This region is represented by 123 grid cells at 45 km resolution.

Figure 3-1. Major watersheds of British Columbia. The Campbell watershed on Vancouver Island was also used in this study. The gridding is the computational grid (45 km at 60 deg. Latitude) of the Canadian Regional Climate Model (CRCM).

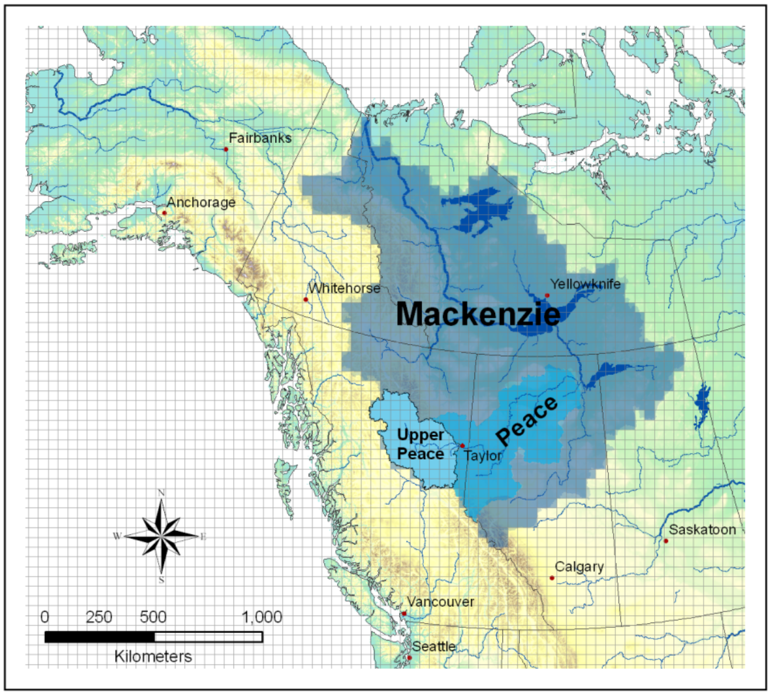

Figure 3-2. Mackenzie basin with the sub-basins identified, including the Peace River watershed and gauging site for the Upper Peace watershed at Taylor, BC.

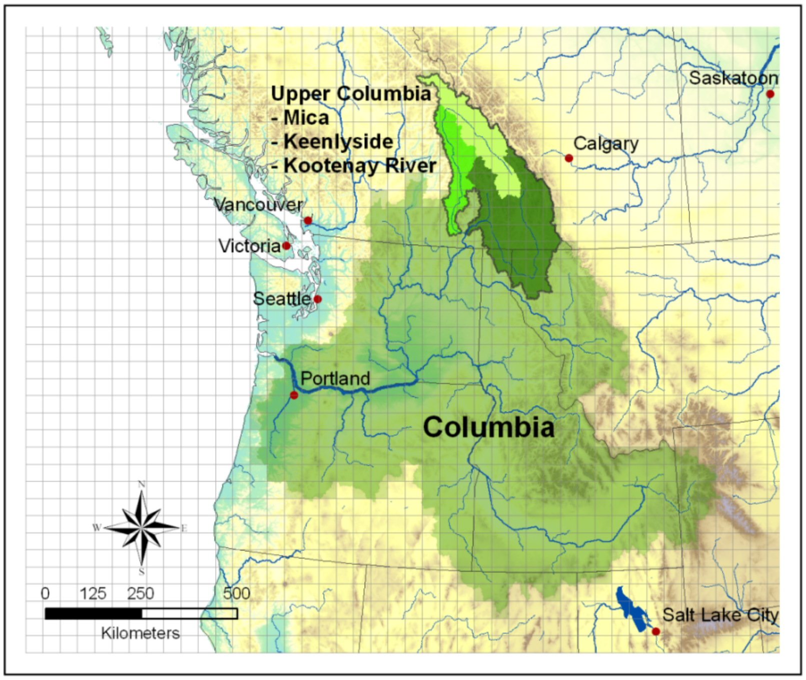

Figure 3-3. The Columbia River watershed. The watersheds of the Upper Columbia at the Canadian-US boundary and north (shades of green) are defined above the outflow site at the junction of the Columbia and Kootenay Rivers in British Columbia. The names of sub-basins are noted.

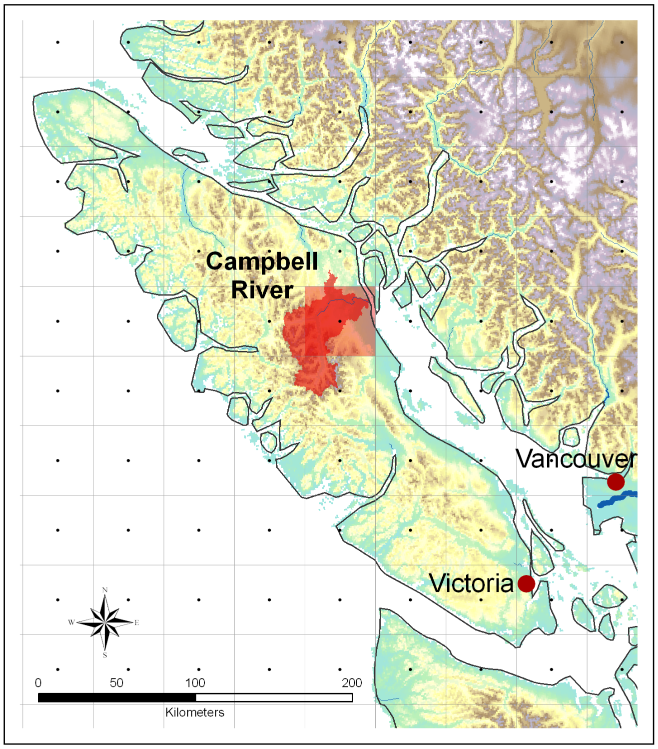

Figure 3-4. Campbell River watershed on Vancouver Island. It is recognized that the RCM grid cannot reproduce the characteristics of the Upper Campbell drainage to the Strathcona Dam.

3.2 Physics of Water Balance

Analysis of the water budget involves the application of water mass conservation in a given control volume. In this section, the atmospheric, terrestrial and combined water budget equations are presented.

The water budget equation for an atmospheric column (per unit area) may be written as:

$$\frac{\partial W}{\partial t} = -\nabla_H \cdot \boldsymbol{Q} - (P - E) \tag{1}$$

where W (kg m^{-2}) is the precipitable water in the atmosphere, which represents the amount of water that would precipitate if all the water vapour in a column of the atmosphere were condensed (note that the contribution of cloud water in the column is neglected), E (kg m^{-2} s^{-1}) is evapotranspiration, and $\boldsymbol{P}$ (kg m^{-2} s^{-1}) is precipitation. The operator "∇_H" represents the horizontal divergence and $\boldsymbol{Q}$ is the vertically integrated horizontal water vapour transport:

$$\boldsymbol{Q} = \int_{p_s}^{p_{top}} q\boldsymbol{V}\frac{dp}{g}, \tag{2}$$

Where q, $\boldsymbol{V}$ and g represent specific humidity, horizontal velocity vector, and gravitational acceleration, respectively. The lower limit in the integral (P_s) is the surface pressure and $\boldsymbol{P_{top}}$ is the pressure at the top of the climate model.

The water balance requirement for the terrestrial branch of the hydrological cycle in a layer below the ground is:

$$\frac{\partial(M+S)}{\partial t} = (P - E) - R \quad , \tag{3}$$

where $M + S$ (kg m^{-2}) represents the storage of soil moisture (M) and the accumulated snowpack (S) , and R (kg m^{-2} s^{-1}) is the total runoff, which includes the surface runoff and recharge from the groundwater reservoir (subsurface runoff).

The term ($P – E$) is common for equations (1) and (3), and it establishes the connection between the terrestrial and atmospheric branches of the hydrological cycle. Elimination of ($P – E$) between these two equations yields a combined budget equation:

$$-\frac{\partial W}{\partial t} + C = \frac{\partial(M+S)}{\partial t} + R \quad , \tag{4}$$

With $C = -\nabla_H \cdot \boldsymbol{Q}$.This equation links the two branches of the hydrological cycle (Peixoto and Oort, 1991). A schematic illustration of the combined water balance is shown in Figure 3-5.

The CRCM computes each of the variables of these equations at each grid point, and by the nature of the basic equations, maintains an internal water balance in the model. However, independent observations are only irregularly and sporadically available. Therefore, in order to compare results to observations, these equations of water mass balance were spatially averaged over an entire watershed and temporally averaged over a 30-year period. Within the multi-annual time scale, temporal changes of W, M, and S are small, so that the transient term may be neglected to estimate evapotranspiration. Therefore, the estimated observed evapotransporation is equal to (P_{OBS}- R_{OBS}) and was used to validate only the annual mean evapotranspiration from the observed precipitation, P_{OBS}, and observed runoff, R_{OBS}. These results can be compared to annual average evapotranspiration from a climate model.

However, temporal changes of atmospheric and terrestrial water storage can be particularly large during spring and fall, and these variables cannot be neglected for monthly means. It is difficult to determine the annual cycle of the real evapotranspiration with precision, and therefore no validation of this variable was performed.

The observational data that were used for validation of the averaged model output of precipitation, vertically integrated moisture flux convergence over a watershed, snow water equivalent, and runoff are described in the following section.

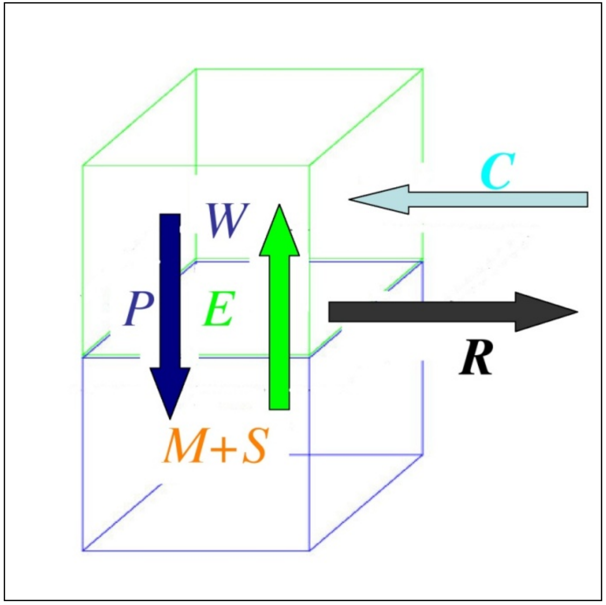

Figure 3-5. Schematic illustration of combined atmospheric and terrestrial water balance.

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4. Model Validation and Uncertainty

As explained in Section 2.3, climate impact studies should be based on a multi-member, multi-model ensemble. The difference between members of the ensemble of simulations generated by running a single GCM several times with different initial conditions (or by introducing any other small perturbation in the modelling system) provides estimates of uncertainty due to internal variability of that climate model (the estimation of the “natural variability” for that GCM). A comparison of results from different models gives an estimate of structural uncertainties associated with the various model designs. A comparison of the internal variability of several different GCMs would result in the best estimate of natural variability.

- *Uncertainty due to natural variability* reflects the chaotic interactions between components of the climate system. This uncertainty is irreducible, since it cannot be reduced in practice by constructing better climate models or taking more accurate or comprehensive observations of the physical climate system.
- *Structural uncertainty* related to the model design may be another important source of uncertainty in climate simulations. The climate system is extremely complex and it is simply impossible to accurately represent all of its processes in climate models. In addition, sub-grid scale processes, such as cloud formation, convection and turbulent diffusion, must be parameterized because the actual spatial resolutions of climate models cannot simulate them explicitly. Different models use different parameterization schemes and do not necessarily include the same processes. The choice of the computational grid and an appropriate numerical method to resolve model equations contributes also to the model structural uncertainty. For RCM simulations, there are some additional sources of structural uncertainty related to nesting configuration (choice of driving model, driving technique, size and location of simulation domain).

In the following sections some of these uncertainties are addressed through comparison of water budget components over the Upper Peace River watershed derived from six GCM and eight RCM simulations. An evaluation of these simulations against available observations for the recent past (1961-1990) is included in the analysis. Finally, a map is presented of projected changes from (1961-1990) to (2041-2070) under the A2 emissions scenario for several watersheds of interest: Upper Peace (above Taylor), Campbell, Fraser (above Hope), and the entire Columbia River basin along with associated uncertainties.

4.1 Experimental Design and Observational Datasets

An appropriate experimental protocol was designed to answer the questions below:

1. What is the influence of the CGCM’s structure and internal variability on the simulated hydrological regime?
2. What is the consequence of the CGCM’s internal variability on the CRCM (dynamically downscaled) hydrological cycle?
3. What is the sensitivity of the water budget components to different physical parameterizations being used in the CRCM?

Table 4-1 describes simulations that are used to address the first two questions. The simulations named AA, BB, CC, DD and EE, are generated with the same model version (CGCM3) but differ in initial conditions. These experiments assess internal variability of CGCM3 as a surrogate for the natural variability of the physical climate system in the past century (1961-1990). The simulation FF is generated with the CGCM Version 2, which differs from version 3 in resolution and physical parameterizations package used. Therefore, by comparing FF with the first five simulations, an estimate of the influence of structural uncertainty of the CGCM can be obtained.

Note that the CGCM2 uses spectral dynamics and resolution of T32 with 10 vertical atmospheric levels (T32; L10). The CGCM3 simulations were generated at finer spatial resolution (T47; L32). The resolution of the spectral model is defined by a truncation of a "Triangular" (T) space in wave numbers with 32 (or 47) horizontal wave numbers and "Levels" (L) chosen to describe vertical variations with 10 (or 32) intervals above the ground. The global CGCM3 has a horizontal resolution[4] in mid-latitudes of about 300 km, while the regional CRCM has a horizontal resolution of about 45 km. The parameterization package for the CGCM3 includes several important changes compared to CGCM2: (a) an improved treatment of solar radiation, (b) a new treatment of cumulus convection (Zhang and McFarlane 1995), (c) a revised surface turbulent transfer mechanism (Abdella and McFarlane 1996), (d) a hybrid moisture variable (Boer 1995), (e) an optimized spectral representation of topography, and (f) a new land surface scheme (Verseghy 1991; Verseghy et al. 1993; Verseghy 2000). For a detailed description of the CGCM2 and CGCM3, see Flato et al. (2000) and Scinocca et al. (2008).

The second question is further addressed through the CRCM simulations by comparing simulations listed in Table 4-2. Dynamical downscaling of five CGCM3 simulations differing only in initial conditions is performed by the CRCM version 4.2.3 using a 45 km horizontal mesh on a polar-stereographic projection (true at 60 °N) with 29 vertical levels (see Section 2 for a detailed description of the CRCM Version 4.2.3). Thirty-year means (1961-1990) of dynamically-downscaled values of near surface temperature and water budget components were calculated and compared to the corresponding value derived from CGCM3 simulations. This allows for an assessment of the effects of the CGCM's internal variability (surrogate for the natural variability) on the CRCM hydrological cycle.

In order to assess the sensitivity of water budget components to different physical parameterizations used in the model (question 3), three additional CRCM simulations were analyzed (Table 4-3). Differences in parameterization packages of the three CRCM model versions listed in Table 4-3 were described in Section 2, Table 2-1. Note that regional models in this experiment were nested within the same CGCM simulation (CGCM2#3).

Table 4-1. List of simulations used to assess internal variability, as expressed in the CGCM, as well as effects of the CGCM structure on simulated hydrological cycle.

EXPERIMENT 1	MODEL VERSION and #MEMBER	GHG EMISSIONS SCENARIO	ANALYZED PERIOD
AA (magenta)	CGCM3#1	A2	1961-1990
BB "	CGCM3#2	A2	1961-1990
CC "	CGCM3#3	A2	1961-1990
DD "	CGCM3#4	A2	1961-1990
EE "	CGCM3#5	A2	1961-1990
FF (pink)	CGCM2#3	A2	1961-1990

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[4] - http://www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=89039701-1

Table 4-2. List of CRCM simulations used to assess the effects of internal variability of the CGCM (driving model) on regional simulations.

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EXPERIMENT 2	MODEL AND VERSION	DRIVING DATA	ANALYZED PERIODS
A (green)	CRCM Ver. 4.2.3	CGCM3#1	1961-1990; 2041-2070
B “	CRCM Ver. 4.2.3	CGCM3#2	1961-1990; 2041-2070
C “	CRCM Ver. 4.2.3	CGCM3#3	1961-1990; 2041-2070
D “	CRCM Ver. 4.2.3	CGCM3#4	1961-1990; 2041-2070
E “	CRCM Ver. 4.2.3	CGCM3#5	1961-1990; 2041-2070

Table 4-3. List of CRCM simulations used to assess sensitivity of the downscaled hydrological cycle to different parameterizations.

EXPERIMENT 3	MODEL AND VERSION	DRIVING DATA	ANALYZED PERIODS
F (blue)	CRCM Ver. 4.2.3	CGCM2#3	1961-1990
G (red)	CRCM Ver. 3.7.1	CGCM2#3	1961-1990
H (purple)	CRCM Ver. 3.6.3	CGCM2#3	1961-1990

Several observational datasets are used to validate simulated near-surface temperatures and water budget components over the recent past (1961-1990). Gridded analyses of precipitation and near-surface temperature are available from the Climate Research Unit (CRU) with a spatial resolution of 0.5 ° (Mitchell and Jones 2005) and from the Center for Climate Research (CCR) (Willmott and Matsuura 2001) at the same resolution. For precipitation, two additional gridded datasets were used: the Global Precipitation Climatology Project (GPCP) (Adler et al. 2003) and Canadian gridded precipitation dataset (CAN) (Louie et al. 2002). The spatial resolution of these datasets is 2.5° and 0.5°, respectively. Gridded datasets are preferable for model evaluation, since gridding helps to reduce biases arising from irregular station distribution. By using datasets from different research centres, an evaluation of uncertainty in the observations is also possible, since: i) different research centres use different techniques to interpolate station observations to a selected grid; ii) the selection of surface observing stations is not necessarily the same; and iii) some centres (e.g., GPCP) merge information coming from the surface gauge with data from satellite measurements.

For runoff validation, the unregulated (naturalized) flow dataset has been provided by BC Hydro. This dataset was generated using an existing hydrological model (WATFLOOD) developed for the Peace-Athabasca Delta project (for more details see Lee 2004). The observed streamflows at Taylor (Peace River) is available from Environment Canada - Water Survey of Canada (HYDAT; CD-ROM-version 99–2.00) and was used in this study to illustrate the effects of water regulation on runoff annual cycle. The observed/naturalized flow is divided by drainage area in order to compare it to the simulated runoff. Snow water equivalent of the accumulated snowpack was validated against a dataset from Brown et al.

(2003) that is based on observed and estimated snow depths from a simple snow model. The dataset from Brown has a spatial resolution of 0.3°.

Finally, a dynamic *reanalysis* of daily observations in the atmosphere as assimilated by a global weather model gives an internally consistent dataset from which climate variables can be calculated. Two atmospheric reanalyses has been used in this study: NCEP/NCAR (Kalnay et al. 1996) and ERA-40 (Uppala et al. 2005). The monthly time series of vertically integrated moisture flux convergence were derived from these reanalyses at their full resolution. The NCEP/NCAR reanalysis is available at T62 spectral resolution[5] (about 210 km) and 28 sigma levels in the vertical with five of those levels in the atmospheric boundary layer. The ERA40 used the so-called Gaussian grid in the horizontal with a grid spacing of about 112 km. A vertical coordinate is a hybrid sigma-pressure coordinates with 60 vertical levels (15 of those levels are in the first 2000 m).

4.2 Uncertainty in Simulated and Observed Annual Means: Upper Peace Watershed

The first part of the present section shows results of the evaluation of CGCM internal variability (as an estimate for the natural variability of the climate system) and sensitivity of the simulated hydrological variables to the structural changes in the model (Table 4-1). Analysis is carried out for six hydrologic variables: precipitation, near surface temperature, moisture flux convergence, snow water equivalent (SWE), evapotranspiration and runoff. These are spatially and temporally averaged over the Upper Peace River watershed, and over the 30-year period (1961-90). Figure 4-1 shows that the sensitivity of the 30-year annual means to internal variability of the CGCMs is relatively small (magenta bars in the figure). Maximum differences between values simulated by different CGCM3 members are 0.09 mm/day (3%) for precipitation, 0.4 °C for temperature, 0.09 mm/day (4%) for runoff and moisture flux convergence, 9 mm (6%) for SWE, and 0.01 mm/day (2%) for evapotranspiration.

However, the simulated climate may be quite different when changes in model structure are introduced. Comparing FF simulated by CGCM2 (pink) to the CGCM3 simulations (magenta), a large difference in simulated temperature (of about 5°C) can be noticed. This is consistent with the large difference in SWE and evapotranspiration between the FF and the CGCM3 simulations: -120 mm (-84%) and 1.13 mm/day (200%), respectively. Precipitation in FF is 1.43 mm/day (51%) greater than the CGCM3 ensemble mean. As runoff and moisture flux convergence are not available as direct output from the CGCM2, these were estimated as the difference between simulated annual mean precipitation and evapotranspiration from the water budget equation ((Music and Caya 2007). This method gives a runoff and moisture flux convergence that is 0.30 mm/day (13%) greater than CGCM3 values.

<u>In summary</u>, the results indicate that uncertainties induced by the CGCM internal variability are less than half a degree for simulated temperature and about 5% for water budget components. It should be kept in mind that these values are for an area of about 101,000 sq. km in the Upper Peace River basin above Taylor and refer to the 30-year annual means. For smaller watersheds with fewer grid points of coverage in the CRCM, the uncertainty may be higher. The structural uncertainty related to the model design is much larger. For climate change projections, this uncertainty needs further evaluation. Parameterization of physical processes in climate models is under rapid development. However, the model bias is relative to the uncertainty in the observations themselves.

A basic evaluation of model performance can be obtained by computing the model bias from observed current climate. Model evaluation is crucial for model development and improvement. A model capable of successfully simulating historical climate is more reliable for assessing potential change due to greenhouse gas emissions. However, observational datasets are not free from errors, and in this regard, the use of multiple observational datasets can provide the best estimate of historical climate conditions.

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[5] - http://dss.ucar.edu/pub/reanalysis/rean_model.html

The maximum difference between annual mean precipitation values derived from various observational datasets (see black bars in Figure 4-1) is 0.18 mm/day (10% difference), while for runoff it is 0.06 mm/day (5%). For temperature, this difference is about 0.8°C. A substantial difference in moisture flux convergence was found: the value derived from NCEP/NCAR reanalysis is larger than that of ERA-40 by 1.66 mm/day (66% difference). Note that the water budget over the multi-year period under consideration imposes a requirement that moisture flux convergence over the basin exactly balances runoff, as well as the difference between precipitation and evapotranspiration (equations (3) and (4); Music and Caya 2007). However the moisture flux convergence derived from the atmospheric reanalysis data with observed runoff does not balance the observed watershed runoff. The moisture flux convergence from ERA-40 agrees better with observed runoff. Also note that an estimate of the evapotranspiration as the difference between ensemble means of observed precipitation and runoff is used as a surrogate for the true evapotranspiration to be compared with simulated values. Figure 4-1 compares observed/estimated water budget components and temperature to those simulated by two global model versions. In general, the CGCM3 has smaller biases, and hence better performance, than the older version of the global model, CGCM2. However, important biases still remain in the CGCM3: the calculated temperature is about 2°C colder than the observed mean. Precipitation, SWE and runoff are larger than observed by 1.12 mm/day (67%), 73 mm (105%) and 1.01 mm/day (82%), respectively.

The regional simulations listed in Table 4-2 are compared with observations, as well as with global model simulations (Figure 4-2). This gives an idea of the influence of driving model internal variability on the 30-year means of downscaled temperature and water budget components. In general, variations between values derived from the CRCM simulations (green bars) are a bit smaller than those between the CGCM3 members (magenta). When compared to observations, the improvement is substantial relative to the results from the global model. Precipitation and runoff are now within the range of observational error, and the evapotranspiration values in both models, are close to that estimated from observations. However, simulated SWE remains almost two times greater than observed, and the cold bias in near-surface temperature increased to almost 5°C. This apparent discrepancy may be the inevitable result of high-resolution models that simulate surface temperatures at elevations higher than the sites where observations were taken.

The sensitivity of simulated climate to different physical parameterizations (Figure 4-3; cyan, red and blue) in the regional model is larger than the effects of CGCM internal variability. For these three simulations the older version of the global model (CGCM2; McFarlane et al. 1992) was used to drive the CRCM (Table 4-3). It is apparent that the use of more sophisticated parameterizations does not necessarily result in an improvement in all simulated variables: biases in simulation F are reduced for precipitation, runoff and evapotranspiration, but not for SWE and temperature. Simulated SWE in F (CRCM V4.2.3) and G (CRCM V3.7.1) shows overestimations comparable to those found for simulations A-E (CRCM V4.2.3 driven by 5 CGCM3 members), despite the fact that their cold temperature biases are smaller. In simulation H (CRCM V3.6.3), SWE is slightly underestimated and temperature is too warm. It seems that simulated SWE is not so sensitive to the change in simulated temperature while temperature remains below 0°C. This could be partly related to the predefined threshold for solid precipitation occurrence, which is set at 0° C in both CGCM and CRCM, thus allowing excessive snow accumulation. Finally, it is interesting to note that simulated variables, in general, are in better agreement with observations when the CRCM V4.2.3 is driven by the latest version of the global model (CGCM3; green bars) compared to experiment F (cyan) that is driven by the older CGCM2.

<u>In summary,</u> these studies identify some of the sources of uncertainty in model estimates of present (1961-90) hydrologic components due to the global CGCM internal variability due to the differences in the CRCM lateral boundary conditions and the choice of different physical parameterizations. In comparison to observations, important biases are acknowledged, especially in temperature (cold model bias) and SWE (positive model bias).

4.3 Annual Cycle: Upper Peace Watershed

The next objective is to evaluate the capability of the Canadian global and regional climate models to adequately simulate the mean annual cycle of hydro-meteorological variables over the Upper Peace River basin. In order to gain visual clarity, Figure 4-4 compares only simulations listed in Tables 4-1 and 4-2 (i.e., simulations designed to assess CRCM sensitivity to the changes in physical parameterizations are omitted).

The annual cycle of near-surface temperature is well simulated by the latest versions of global and regional models (CGCM3; solid magenta, and CRCM Version 4.2.3; solid green), but the cold bias is present throughout the year in both models. Large warm biases from October to February are found in the old model (CGCM2; dotted pink). The annual cycle of precipitation simulated by the CGCM2 also shows large biases throughout the year. The CGCM3 reduces these biases, but a large overestimation in the fall season is still present. The CRCM captures the observed annual cycle of precipitation.

The moisture flux convergence of the CRCM is within the range of values derived from ERA-40 and NCEP/NCAR reanalyses. The SWE is overestimated by the CRCM and CGCM3 in the winter months. Moreover, snowmelt begins in April, one month later than in observations. Simulated runoff by both CGCM3 and CRCM show large annual amplitudes due to an excessive snow accumulation that melts from April to May. The spring peak is too early, partly due to the absence of a routing model. Moreover, a true annual cycle of runoff is actually unknown because the observed annual cycle (the gauging station at Taylor, HYDAT) is strongly affected by water regulation, while naturalized runoff (provided by BC-HYDRO) is affected by hydrological model approximations.

In summary, this analysis of annual cycle indicates that the regional CRCM improves (in comparison to the CGCM) the annual cycle of precipitation over the Upper Peace watershed and reduces the precipitation, SWE and runoff biases. This occurs in spite of an increased (cold) bias throughout the year.

4.4 Watershed Scale Pattern of Climate Change Impact on Hydrological Regime

The analyses carried out in the previous sections have demonstrated better agreement between simulated and observed hydroclimatic regimes when the latest CRCM version (CRCM Version 4.2.3) is used. In the present section, we estimate the climate change signal in water budget components and near-surface temperature by using the CRCM V4.2.3 simulations described in Table 4-2. With this experimental design, a range of projected climate change should cover uncertainties arising from CGCM internal variability, which is calculated as a maximum deviation from the ensemble mean.

The climate change signal is estimated by computing differences between simulated future climate conditions under the A2 GHG emissions scenario (period 2041-2070) and those with recent GHG concentrations (period 1961-1990). This method assumes that model biases with respect to observations in present climate should be similar for the future conditions, thus allowing partial reduction of the errors in projected change due to model imperfection. Therefore, looking at climate difference, rather than at future climate itself, should give a best estimate of climate change impact on the watershed. However, as discussed by De Elia and Coté (2010), extending this assumption too far would be a mistake. Results from their study have shown that the effects of changes in the CRCM experimental configuration (such as domain size, CRCM version, driving GCM, nesting technique, and initial conditions) on the simulated historical climate are sometimes offset by a similar effect on future climate, but this is not always the case. This hypothesis has a weaker basis for water budget related variables than for temperature.

Maps of several watersheds in western North America (Upper Peace, Fraser, Campbell and Columbia; Figure 4-5) show projected changes and associated uncertainty of near-surface temperatures in the 2050s (under the A2 emissions scenario). The bar-graphs are used to indicate projections for each specific

CRCM simulation, and the numerical values associated with each watershed denote the interval of projected change as [ΔT±uncertainty], where ΔT is the ensemble mean of simulated differences between the future (2041-2070) and present (1961-1990) temperature, and "uncertainty" is defined as the maximum deviation from this ensemble mean. For the investigated watersheds, projected warming ranges from 2.4°C for the Fraser to 2.7°C for the Campbell. Uncertainty in the 30-year means due to the chaotic nature of climate varies from 0.2°C to 0.3°C.

Projected changes in the water budget components are shown in the map of Figure 4-6. The bar graphs present the balance of evapotranspiration and runoff change when temperature increases to indicate the partition of precipitation change that goes into runoff and the one that goes into change in evapotranspiration. As can be seen, higher temperatures in the future imply an intensification of the water cycle over all basins.

For example, for the Upper Peace watershed an increase in temperature (of about 2.6°C) is associated with enhanced evapotranspiration. An increase is also projected for precipitation (0.29 mm/day), which is actually higher than the projected intensification in evapotranspiration (0.08 mm/day), thus resulting in an increase in runoff (0.21 mm/day).

Over the Upper Peace, Fraser and Campbell, a larger portion of the precipitation increase goes to runoff rather than to an increase in evapotranspiration, while over the Columbia, this partition is reversed. The values stated on the watersheds are the projected changes and associated uncertainty of precipitation, runoff and SWE. The largest relative increases in precipitation and runoff are projected for the Upper Peace (16±4% and 17±6%, respectively), and for the Fraser (16±3% and 17±4%, respectively), but less for the Campbell and Columbia. Concerning SWE, the ensemble mean of projected changes indicates a decrease in SWE for all watersheds, with the largest values towards the south.

4.5 Unresolved Issues

Results presented in the above sections contribute to the challenging task of evaluating the uncertainties associated with the projection of climate change impacts on the hydrological regime at a watershed scale. The uncertainty in projected changes in 30-year climatologies related to the chaotic nature of the climate system has been quantitatively assessed using the CRCM to dynamically downscale several CGCM3 simulations with only small perturbations in initial conditions. Some questions related to the sensitivity of the simulated climate to model structure (structural uncertainty) have also been addressed. However, there are further uncertainties involved in the projection of future climate scenarios for impact assessments.

New research in probabilistic climate projections (PDFs) attempt to represent the uncertainties that are employed by a spectrum of modelling choices, and by the inherent imperfection of each of them (note especially: UKCP 2009; and Tebaldi and Knutti 2007.) Many issues related to this appealing approach need to be better understood in the coming years. For example, one of the important questions is how to design model experiments in order to cover a wider range of fundamental uncertainties. Also, it is not clear yet how to take into account model performance when constructing future climate projections (e.g., whether model results should be combined in a weighted average, or even if model weighting can be determined from model biases taken from the historical record). Some examples of the projected seasonal cycle for precipitation and runoff computed from different models are given in Attachment 1 for the Upper Peace watershed. A suite of these products was provided for comparison with streamflow estimates from the hydrologic model.

Finally, it should be understood that uncertainty due to differences in emissions scenarios becomes increasingly important when projecting for a time horizon beyond 50 years. Even if a perfect model existed, climate projections would always depend on the external forcing from a pre-selected future emissions scenario.

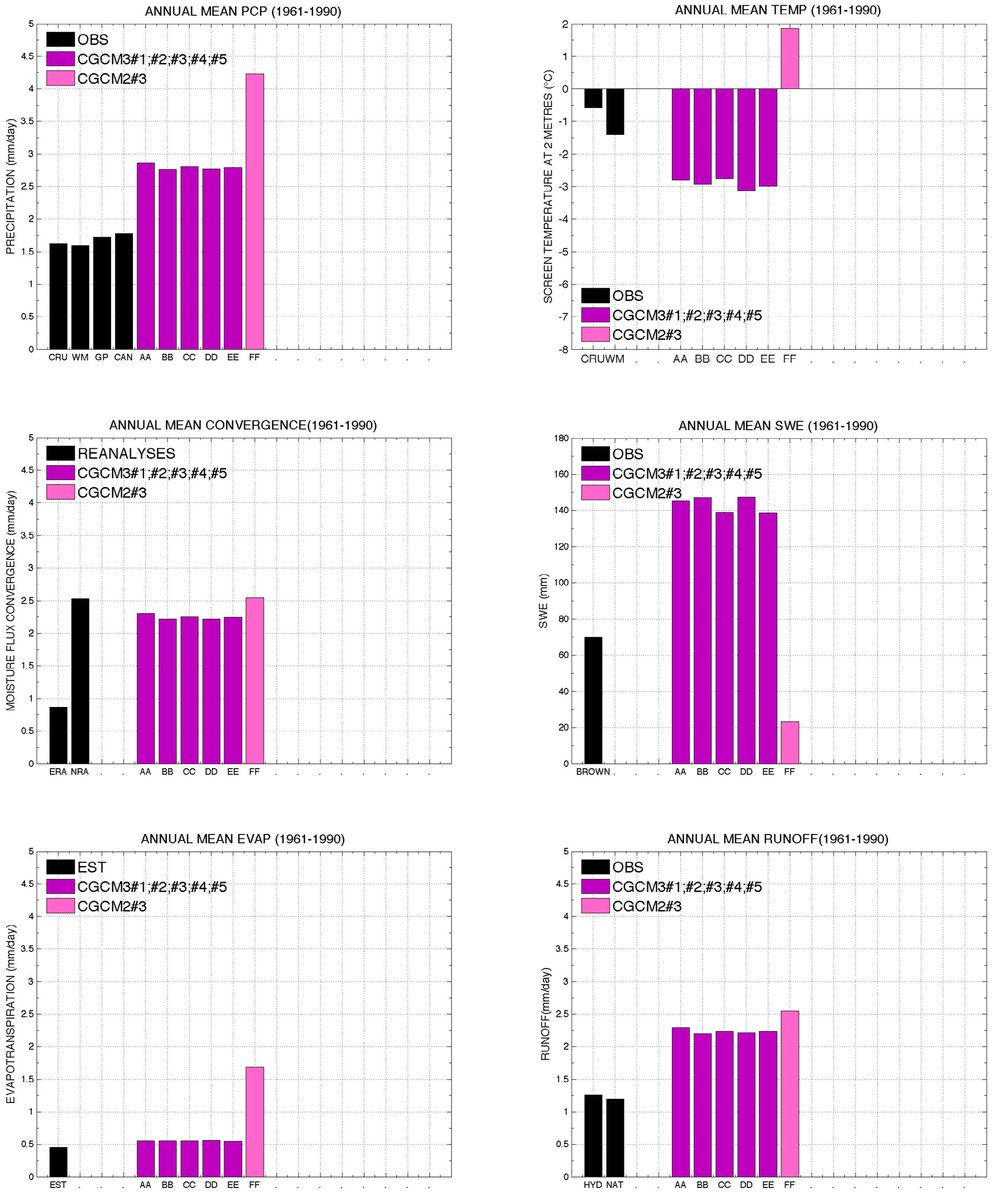


Figure 4-1. Observed (black bars) and CGCM3 (magenta bars) hydro-meteorological variables spatially and temporally averaged over the Upper Peace watershed and over the period 1961-1990. A single run from an older model (CGCM2) is shown for comparison (pink). The color coding was established in Table 4-1.

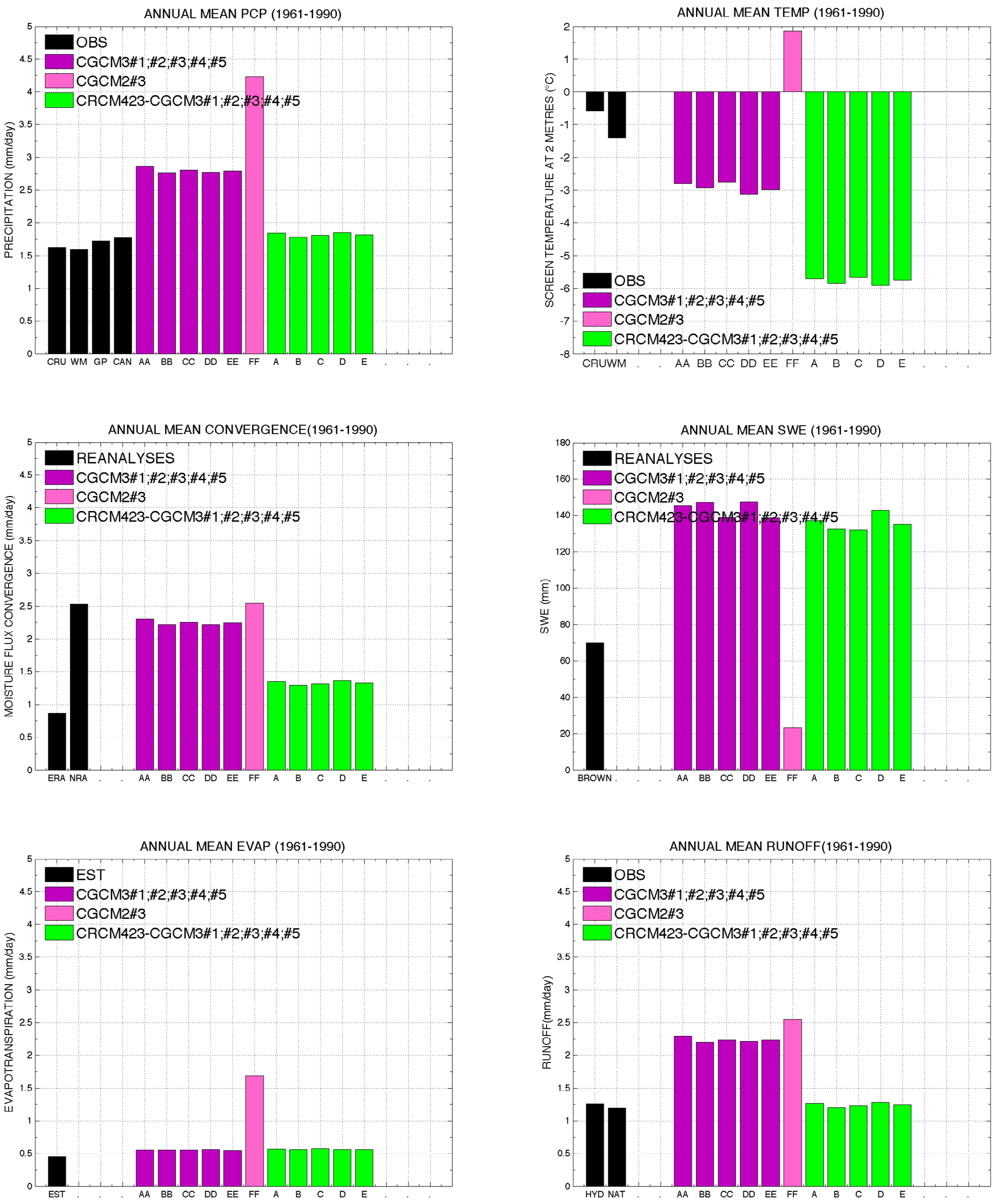


Figure 4-2. Same as previous figure, but with added values derived from and the regional CRCM Version 4.2.3 simulations (green). The color coding was established in Tables 4-1 and 4-2.

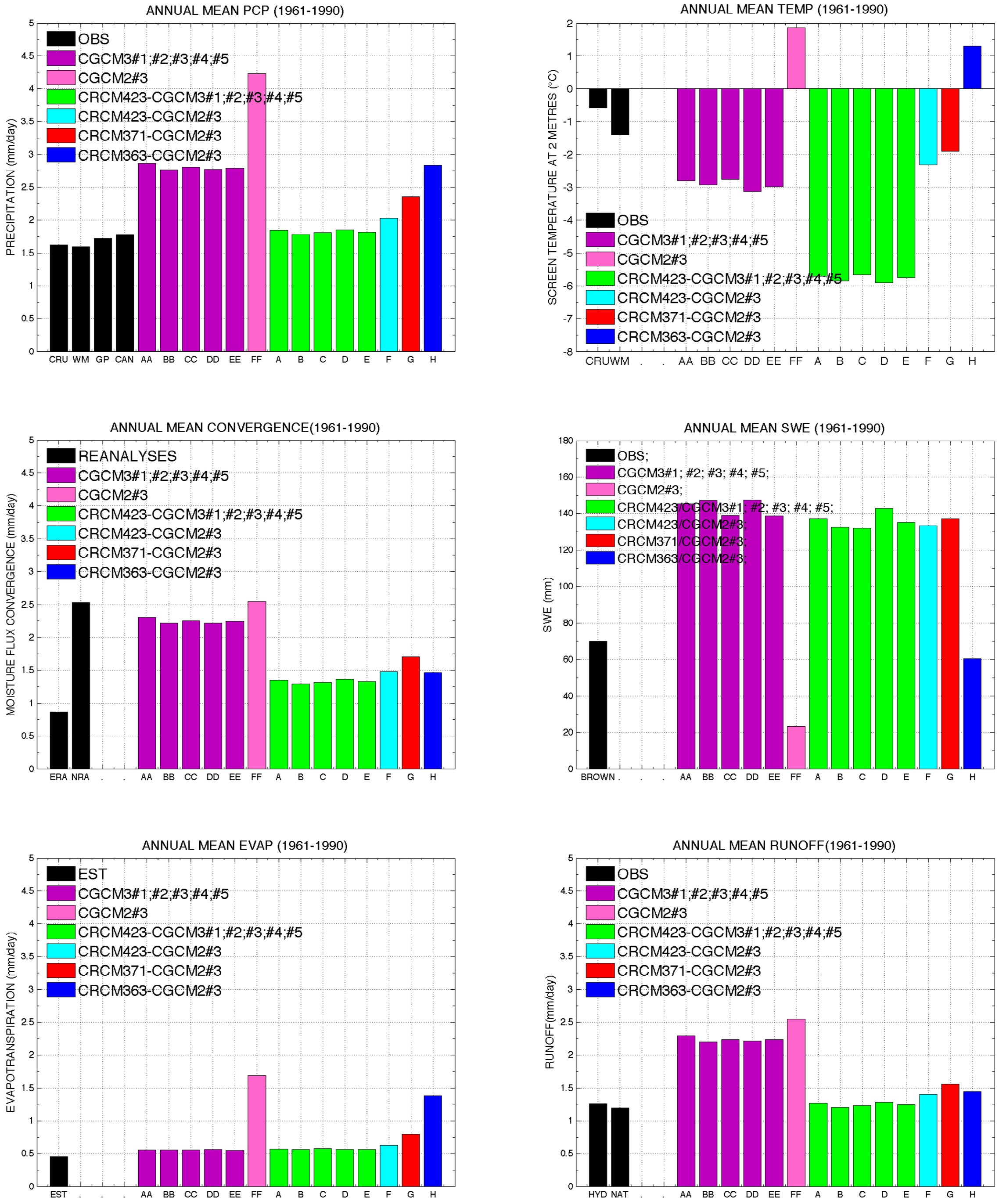


Figure 4-3. Same as previous figure, but with added values from simulations designed to evaluate the CRCM hydrological cycle to different parameterizations (Table 4-3). The color coding was established in Tables 4-1, 4-2, 4-3.

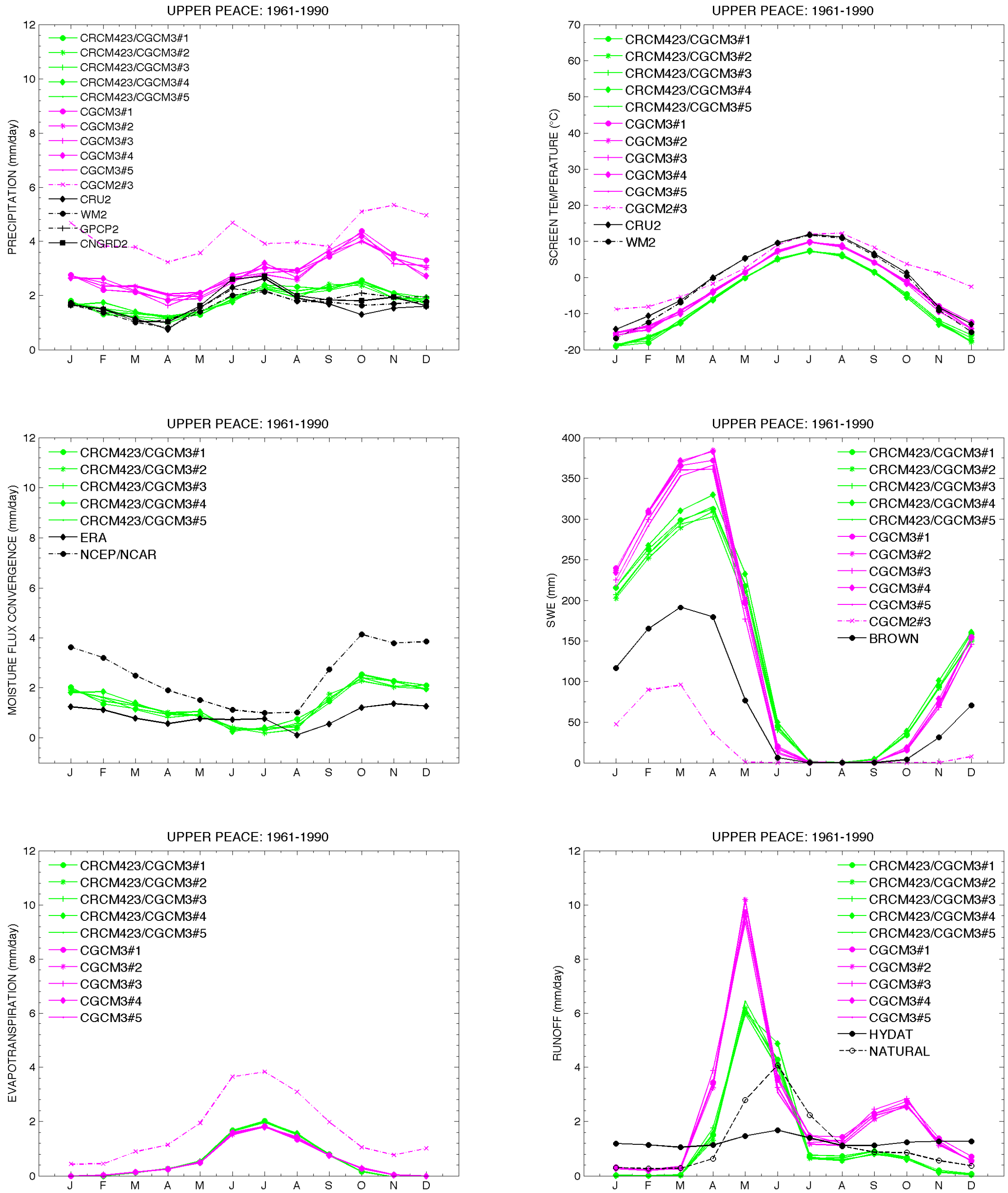


Figure 4-4. Mean annual cycle (1961-1990) of hydro-meteorological variables over the Upper Peace watershed. Results for each variable come from global models (CGCM (magenta), regional models (green), and observations (black).

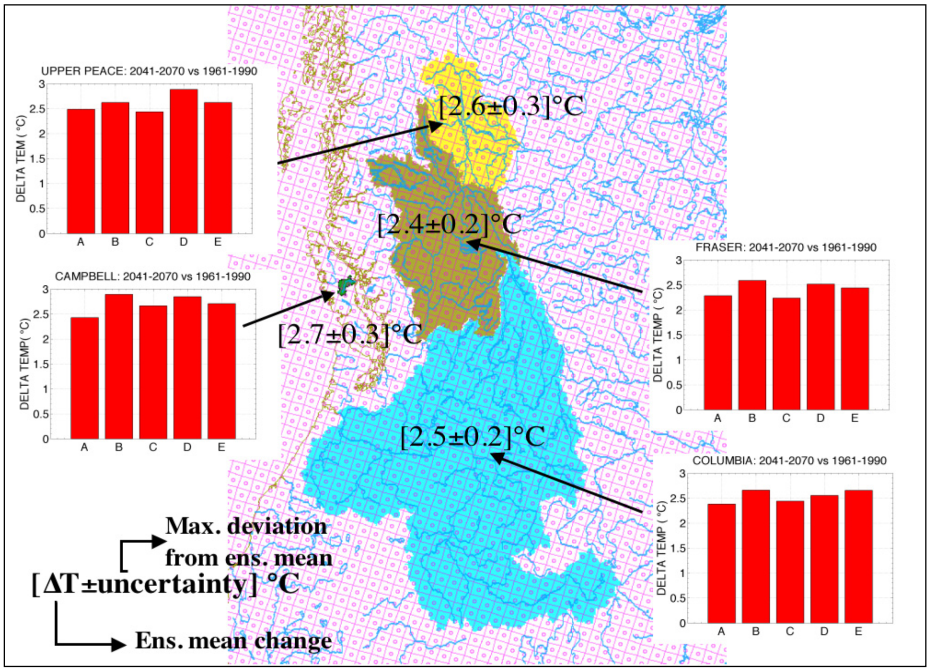


Figure 4-5. The climate change signal (between the 1961-1990 and 2041-2070 periods) and associated uncertainties projected by the CRCM ensemble for near-surface temperature over the Upper Peace, Fraser, Campbell and Columbia watersheds under the A2 emissions scenario.

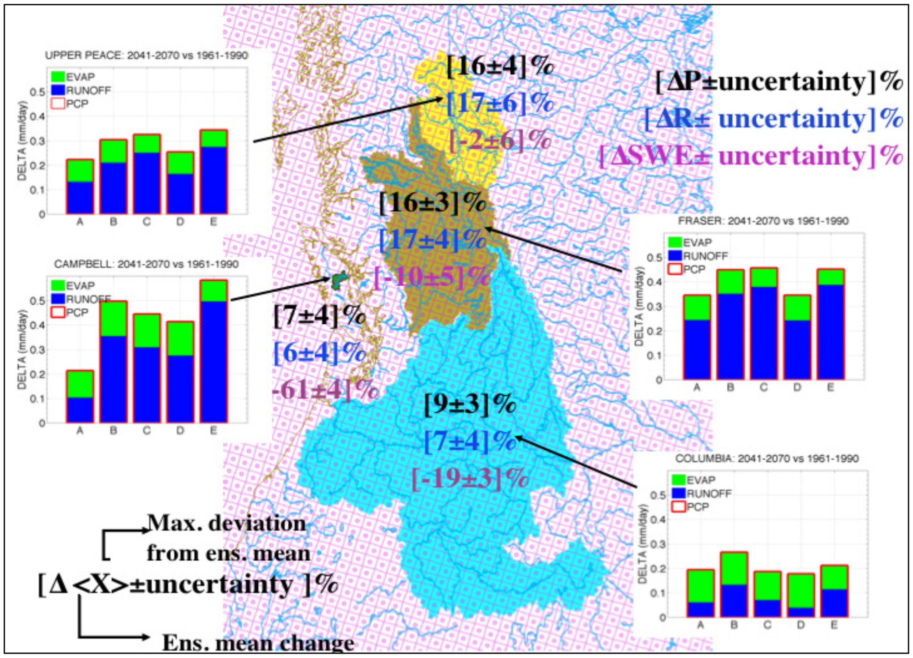


Figure 4-6. The climate change signal (between the 1961-1990 and 2041-2070 periods) and associated uncertainties in water budget components projected by the CRCM ensemble over the Upper Peace, Fraser, Campbell and Columbia watersheds, under the A2 emissions scenario. The bar graphs associated with each watershed show projected change in precipitation (entire bar, outlined in red), in evapotranspiration (green) and in runoff (blue).

5. Annual Cycle of Hydrologic Conditions in Selected Watersheds

The previous section of this report focused on the Upper Peace watershed and its mean statistics of hydrometeorological variables. It detailed the structural uncertainties in means due to the use of different versions of the CGCM and its effect on simulations with the CRCM. It also discussed the effect of the internal variability from global climate models on the simulation by regional models. Finally, it casts a light on the improvements in high-resolution CRCM simulations over direct application of the global simulation results when analyzing the annual cycle of monthly climatological mean values of hydrologic components. Therefore, the previous section compared CGCM and CRCM output and put the downscaled CRCM results into context.

The present section focuses on the analysis of the mean annual cycle in simulations performed with the CRCM and broadens the analysis to include additional watersheds: the Upper Peace River, the Upper Columbia River and the Campbell River. The analysis includes the study of the mean annual cycle and the presentation of bias of components of the hydrological cycle relative to observations. It then quantifies the impact of the internal variability of regional models as compared to that from global models that was discussed in Section 4. Finally, the climate change impact on the water balance components and their annual cycle is studied. Furthermore, an investigation of the long-term trends of the hydrologic variables reveals their variability through time. This variability is an important qualification on an assessment of the climate change impacts within a watershed where trends in the recent past are often used as a proxy for future changes.

5.1 Experimental Design

The study of the mean annual cycle of water balance components, their uncertainty and the consequences of the climate change signal on these components, are conducted using a choice of nine 30-year CRCM simulations driven by the global Canadian GCM, and one driven by the ERA40 reanalysis of historical conditions. The limitations of this methodology were studied by Diaconescu et al. (2007). Table 5-1 summarizes the datasets used, lists the model version, the source of the driving data, and the internal names used for the simulations. The colors in this table are also used in the Results Matrix presented below. The simulations cover the period (1961-1990) as the reference period for current climate, and the period (2041-2070) as a 2050s future horizon. Four of the 30-year periods are time slices taken from longer integrations covering 140 years from (1961-2100) in simulation adj (green), and simulation adl (red). All but one pair of present and future simulations for the experiment was performed with the CRCM Version 4.2.0. The single exception was performed with the newest CRCM Version 4.2.3. This simulation provides a link to the analysis presented in Section 4 of this report, which relies heavily on simulations from that version. The choice of simulations from CRCM version 4.2.0 allows for different approaches to analyzing the data and answers the guiding questions of this research (below). All assessments are conducted with monthly 30-year averages of the four hydrologic variables: precipitation, snow water equivalent (SWE; monthly mean of daily maximum snow), evapotranspiration, and runoff.

The results are presented in the form of a Results Matrix described in Figure 5-1. The columns of the matrix refer to the analysis of the individual variables. The rows of the matrix are used to address three different questions (following). The fourth question is addressed in Subsection 5.6.

Question 1: What is the model bias and how does the model reproduce the mean annual cycle?

The five simulations of present climate (1961-1990) are compared against gridded observational data by first resampling the observations on the CRCM grid, and then computing the difference between model output and these resampled datasets. One of the simulations is driven by ERA-40 reanalysis data at approximately 1° resolution, and serves as a reference when examining present climate statistics obtained from simulations forced by CGCM3 simulated climate. Observed precipitation fields at a resolution of

0.5° from the Climatic Research Unit (CRU) were used to estimate the bias (Mitchell et al. 2004; Mitchell and Jones 2005). This dataset corresponds to the time period (1961-1990). In the validation of runoff the fields provided by the Global Runoff Data Center were applied (the GRDC dataset at 0.5° resolution, Fekete et al. 2000). This dataset incorporates data from outside the validation time period. However, most of the observations originate from the (1961-1990) time period, and therefore these data are combined to represent the best estimate of observed runoff. The validation dataset for the snow water equivalent was derived from the gridded North American monthly snow water equivalent (SWE) dataset at a resolution of 0.3°, as compiled by Brown et al. (2003). Although this last dataset corresponds to the (1980-1996) period only, it is the best available reference for snow water equivalent data and provides a valuable estimate of actual snow conditions in the watersheds. A dataset of observed evapotranspiration is unavailable, and thus the model bias could not be computed. All observational data were resampled to the 45 km resolution grid of the CRCM.

Rows one and two of the Results Matrix show the results for both present and future conditions in the designated watershed. The first row shows the mean annual cycle of each variable and simulation along with the observation datasets. Solid lines with markers represent simulations of the present climate (1961-1990). Dotted lines with markers represent the simulations of future climate (2041-2070). The observations are shown as a black dashed line. The bar graphs in the second row indicate the bias of the present climate simulations against the observed climatologies.

Question 2: What is the uncertainty due to the internal variability of climate models?

Six of the CGCM3 driven simulations identified in Table 5-1 are used to investigate the internal variability of the CRCM: (aeb-adj)/present and (adk-adj)/future and the internal variability of the driving data from the CGCM3: (adj-adl)/present, and (adj-adl)/future.

To assess the internal variability of the CRCM, "twin simulations" are used (yellow and green). Twin simulations are CRCM runs with minor perturbations in their initial conditions but sharing otherwise identical configurations. The perturbation is achieved by starting the twin simulations with an offset of one month (e.g., simulation aeb: December 1, 1957, and simulation adj: January 1, 1958). The difference between the 30-year monthly means gives an estimate of the sensitivity of the CRCM climate to the CGCM internal variability. The CRCM twins are framed by a dotted line in Table 5-1.

In order to compare the CRCM internal variability to the internal variability of the driving CGCM3 data, members #4 and #5 from the CGCM3 ensemble are included in the choice of driving data of the simulations (green and red). They are framed by a solid line in Table 5-1. The differences between these simulations provide an estimate of the internal variability in the results caused by the GCM internal variability. As previously mentioned in Section 2.3, this internal variability in the CGCM 30-year climatologies is the best estimate of *natural variability* from the global climate model. Both investigations of internal variability were done with the simulation pairs for both present and future climate. The results for the four hydrologic components examined can be found in the third row of the Results Matrix.

Question 3: What is the climate change signal in the four components of the water balance?

The climate change signal was assessed by computing the difference between the 30-year monthly statistics of the future simulations (2041-2070) and the present simulations (1961-1990) for the four pairs of present and future simulations. In Table 5-1 these pairs are marked in the same color. The climate change signal for the four variables is presented in the bar graphs of the fourth (bottom) row of the Results Matrix.

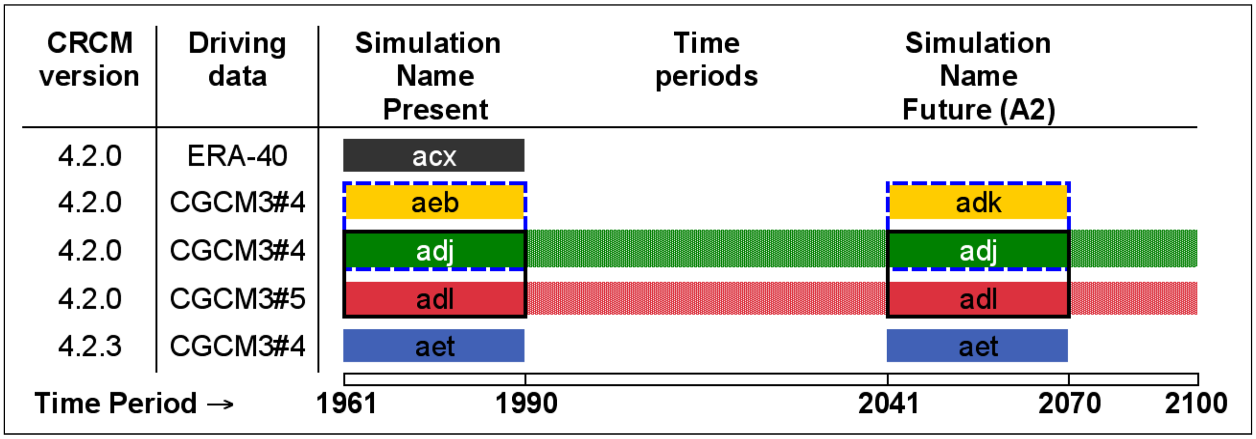
Question 4: What is the long-term trend in CRCM climate projections, and how could a user make prudent use of climate change projections?

The natural variability of the climate system makes the use of climate statistics challenging, both for observed and modelled climates. With the confidence that the CRCM simulates climate characteristics that are close to the ones from the natural climate system, the future evolution of climate can be estimated.

The long-term trend of water balance components is assessed using two 140-year simulations identified in Table 5-1: adj (green) and adl (red). Time series of annual values are used to demonstrate the interannual variability of the climate system over the duration of 140 years. A moving 30-year average of those annual means illustrates the fluctuation of classical watershed-based climate statistics and allows visualization of the variability associated with a climate change signal estimated from two 30-year periods, compared to the 140-year linear trend. Simulations from two CGCM3 members in this analysis demonstrate the consequences of natural variability of the climate system on the estimation of the climate change signal from 30-year climates. The analysis also shows how the choice of future and reference time period can impact the computed climate change signal.

This analysis is preliminary since very few long-term simulations are available due to the extensive computer resources required to generate such long integrations. (Each of the 140-year simulations took approximately 15 months of high-performance computer CPU time.)

Table 5-1. CRCM4 simulations, model version, driving data, and time periods with their internal names. The colored bars indicate the period covered by the simulations. Their colors are the same as the ones used in the Results Matrix in Figure 5-1. "Twin" simulations representing different CRCM members that are different only by their initial conditions are framed by a blue dashed line. The black solid line frames simulations driven by different CGCM ensemble members. These marked pairs are used in the study of CGCM and CRCM internal variabilities.



CRCM version	Driving data	Simulation Name Present	Time periods	Simulation Name Future (A2)
4.2.0	ERA-40	acx		
4.2.0	CGCM3#4	aeb		adk
4.2.0	CGCM3#4	adj		adj
4.2.0	CGCM3#5	adl		adl
4.2.3	CGCM3#4	aet		aet
Time Period →		1961 1990		2041 2070 2100

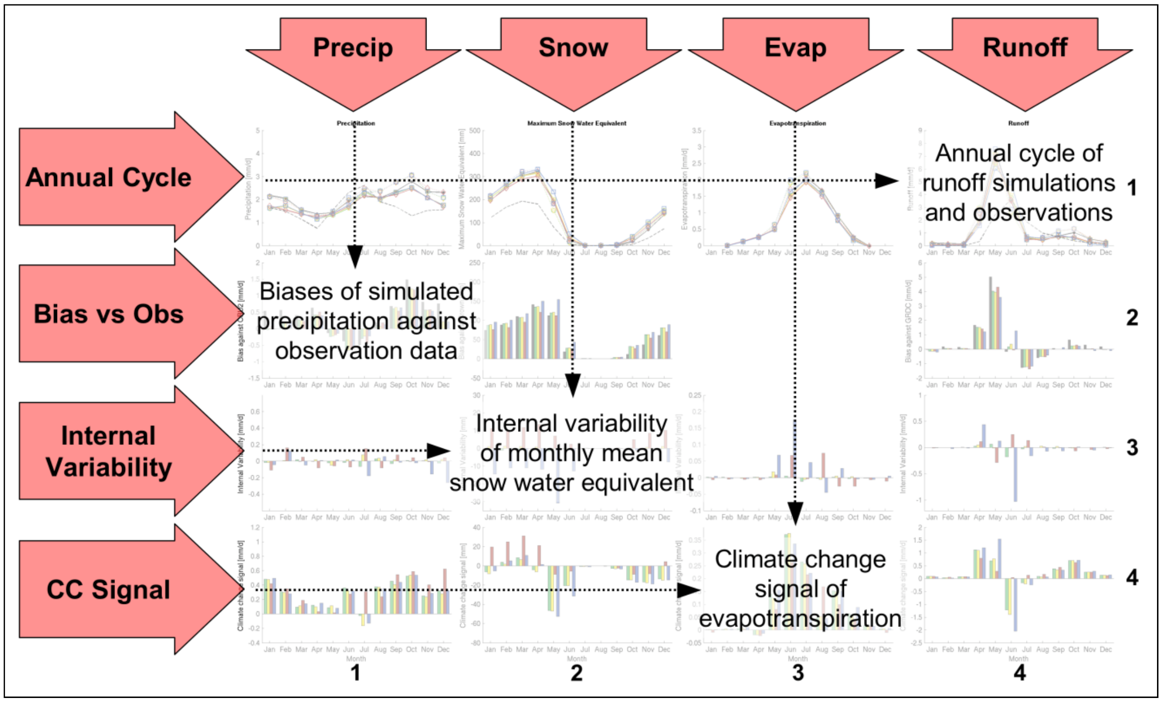


Figure 5-1. Overview of the structure and examples of the Results Matrix. The (row, column) coordinates are used in the text to address individual graphs.

5.2 Results Matrix (RM)

The present section gives the results for the three BC watersheds from the CRCM simulations. They are structured as outlined in Figure 5-1. The coordinates for each (row, column) are used to identify individual graphs in the text.

5.2.1 Results – Upper Peace (above Taylor)

The Upper Peace watershed is comprised of the mountainous terrain and delineated by the watershed above Taylor, British Columbia. The Results Matrix (Figure 5.2) presents the hydro-climatological analysis of the Upper Peace basin. These results are comparable to Figure 4-5, but are derived from the experimental design of Table 5-1.

The first and second rows of the Results Matrix show the 30-year mean annual cycle of monthly mean hydrologic variables from the CRCM simulations, as well as the bias compared to the observational CRU dataset. In RM(1,1) the CRCM simulated precipitation over the Upper Peace basin peaks in October, contrary to the CRU observations, and this leads to the largest biases in the fall season, RM(2,1). (Note that the GPCP dataset of Adler et al., 2003 does not exhibit the same fall minimum as the CRU data.) Nevertheless, based on the CRU dataset, the mean annual bias is 0.25 mm/d (Table A2-1).

The ERA40 reanalysis driven simulation bias to observation is commensurate to those of the CRCM simulations (acx – black solid line). The snow water equivalent in RM(1,2) and RM(2,2) is overestimated throughout the year, a feature regularly observed in the CRCM simulations over mountainous regions. This overestimation of snow results in overly pronounced peak flows in May due to snow melt in RM(1,4) and RM(2,4). The peak in the observed runoff occurs one month later in June. This difference is due to a combination of the overestimation of snow and the fact that the GRDC runoff dataset (Fekete et al. 2000) is based on streamflow, while the CRCM output is surface runoff without streamflow routing.

No validation data are available for the estimates of evapotranspiration shown at RM(1,3). However, some estimates of evapotranspiration can be inferred from the CRU/precipitation data and the GRDC/runoff data, and these comparisons suggest that the annual mean modelled evapotranspiration over the Upper Peace River is too low (not shown). This is consistent with the cold model bias, and as a consequence, the annual mean simulated runoff exceeds the observations by about 0.4 mm/d.

The Results Matrix (row 3) compares the effect of internal variability of the CRCM (green/yellow) to the effect of internal variability of the driving global model CGCM3 on the CRCM simulation (red/purple). As mentioned earlier, this is an estimate of the natural variability of the global climate system. The CGCM3 internal variability represents uncertainty in the climate model output that cannot be reduced, but that needs to be estimated.

A summary of mean annual results for all variables is presented in Attachment 2, Table A2-1. The annual mean uncertainty in the CRCM hydrologic variables due to internal variability is generally less than 1% for all variables. However, the mean annual internal variability due to the driving CGCM3 is relatively larger, reaching up to 6% in the annual mean SWE. The climate change signal relative to present climate is larger than this uncertainty in all variables except for the SWE. (Note that the sign of the internal variability is irrelevant.)

Notwithstanding the bias of model results, or the uncertainty introduced by internal variability of the climate system, the Results Matrix (row 4 of Figure 5-2) presents the annual cycle of the future anomalies (the climate change signal) of four hydrologic components. All the pairs of present and future time periods exhibit good agreement on the sign and magnitude of the climate change signal. Precipitation has a positive climate change signal throughout the year in RM (4,1). During the first four months of the year the snow water equivalent shows little change in the simulations driven by CGCM3 member #4 (Table 5-1), but an increase for simulations driven by CGCM3 member #5. The climate change signal of SWE is accompanied by large internal variability, which is exceptional compared to all other hydrologic variables. All simulations mark a decrease of snow accumulation in the climate change signal, both at the beginning and end of the snow season RM(4,2).

Evapotranspiration of the future climate is enhanced during the warm seasons shown in RM(4,3). The changes in runoff in RM(4,4) are dominated by future increases in spring and fall due to earlier snow melt (lower SWE) and later formation of the snow pack. Since the increased precipitation is almost entirely compensated by increased evapotranspiration, the marked decrease in runoff in June is attributed to a shift of the annual peak runoff towards earlier in the year due to the change of water storage in the snow pack.

5.2.2 Results - Upper Columbia

The Upper Columbia basin is defined above the point of confluence of the Columbia River and the Kootenay River. The Results Matrix (Figure 5-3) shows a mean annual cycle of precipitation well reproduced, but with maximum biases in the winter season in RM(1,1) and RM(2,1). Snow water equivalent is overestimated throughout the season in RM(1,2) and RM(2,2). While snow biases have very similar magnitudes to those of the Peace River, relative bias is lower due to generally larger amounts of snow. The observed mean annual cycle of runoff is well reproduced for the Upper Columbia watershed, but with moderate biases throughout the year in RM(1,4) and RM(2,4).

The effect of the internal variability from the forcing by the CGCM and the internal variability from the CRCM for the Upper Columbia River are shown in row 3 of the Result Matrix. They exhibit features similar to the Upper Peace River with larger internal variability resulting from the CGCM3 driving data, rather than from the CRCM itself. A summary of mean annual internal variability is presented in

Attachment 2, Table A2-2. The annual mean internal variability in the hydrologic variables resulting from the driving global model (CGCM) is less than 6%, while the internal variability in the regional model (CRCM) is less than 1%. With the exception of results for SWE, these values of internal variability are substantially smaller than the climate change signal throughout the year, resulting in a large signal-to-noise ratio.

The watershed response to the climate change signal in RM(4,1) shows an increase in precipitation with a small decrease in the summer. The amount of snow decreases throughout the season in the simulation driven by CGCM member #4 (Table 5-1), but has a positive signal from CGCM member #5 in the beginning of the year, as shown in RM(2,4). Evapotranspiration change in RM(4,3) is most pronounced during the growing season. In the climate change signal, the change in sign of the runoff from May to June RM(4,4) indicates the shift of the peak flows to earlier in the year in the Upper Peace.

5.2.3 Results – Columbia and Fraser Watersheds

Although it is outside of the scope of this report, results for two large basins were also analyzed and presented in result matrices for the entire Columbia River basin and the Fraser basin above Hope (Figures 5-4 and 5-5).

The Fraser basin is larger in size but the results exhibit features similar to the Peace River and the Upper Columbia River. This corroborates the results from basins of similar terrain characteristics. The differences in the results for the full Columbia basin compared to the Upper Columbia can be interpreted as the influence of different climate and hydrologic conditions over a large latitudinal band.

5.2.4 Results - Campbell

The terrain above the Strathcona Dam defines the watershed of the Campbell River on Vancouver Island. Results are shown in the Results Matrix (Figure 5-6) and are representative of the area, but are highly uncertain, since they are based on a single CRCM grid point that cannot be an adequate representation of the watershed complexity (Figure 3-4). In addition, differences exist in the gridded observation datasets. The validation of SWE and runoff are highly uncertain because grid cell values are near zero throughout the year. Similarly, assessment of internal variability and the climate change signal computed for the Campbell River are uncertain, particularly for SWE and runoff, where the mean annual cycle of present and future simulations differ significantly in RM(1,2) and RM(4,2), and also in RM(1,4) and RM(4,4).

It is clear that the current 45 km resolution of the CRCM simulations is insufficient for application to small watersheds that are the size of the Campbell basin. The use of CRCM using next generation simulations with a 15 km grid will produce an areal coverage of about nine grid cells over the Campbell watershed. There is no firm opinion on the minimum number of grid cells necessary for computing a coherent climate change signal in mountainous terrain.

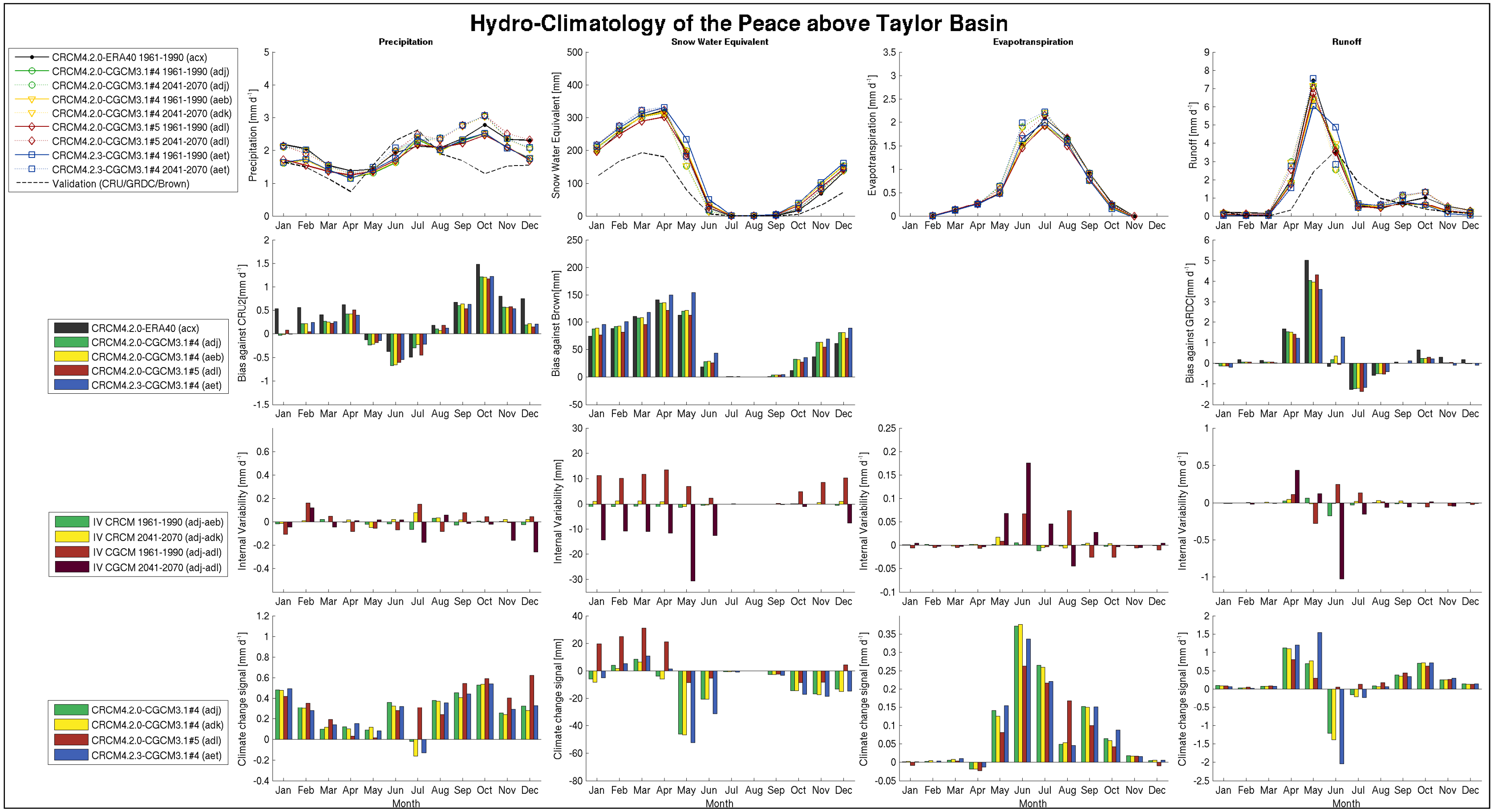


Figure 5-2. Results Matrix of the analysis of CRCM 4 simulations for the Upper Peace River above Taylor. Future simulations are based on the A2 emissions scenario.

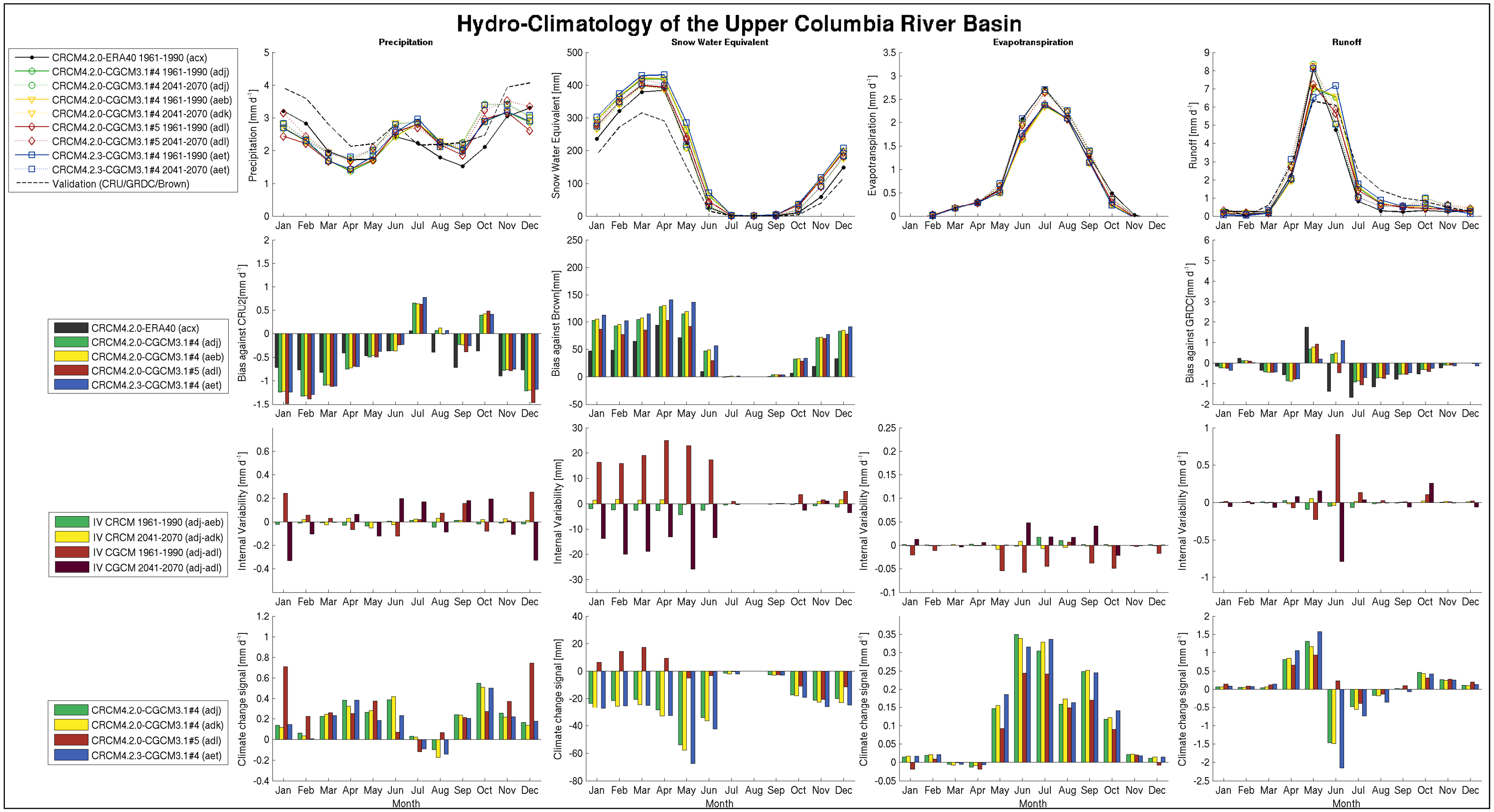


Figure 5-3. Results Matrix of the analysis of CRCM 4 simulations for the Upper Columbia River (at the confluence of Columbia River and Kootenay River). Future simulations are based on the A2 emissions scenario.

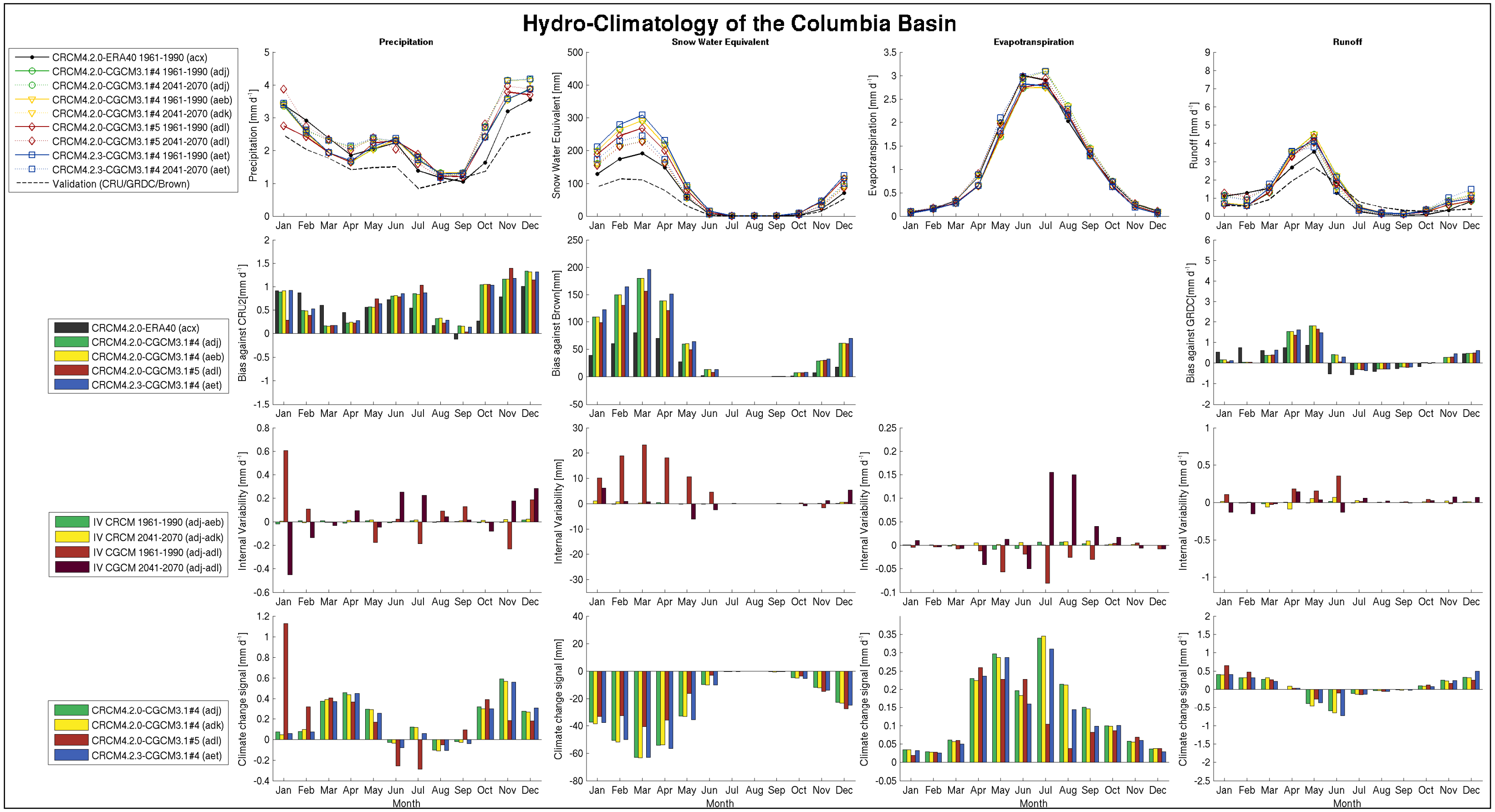


Figure 5-4. Results Matrix of the analysis of CRCM 4 simulations for the entire Columbia River Basin. Future simulations are based on the A2 emissions scenario.

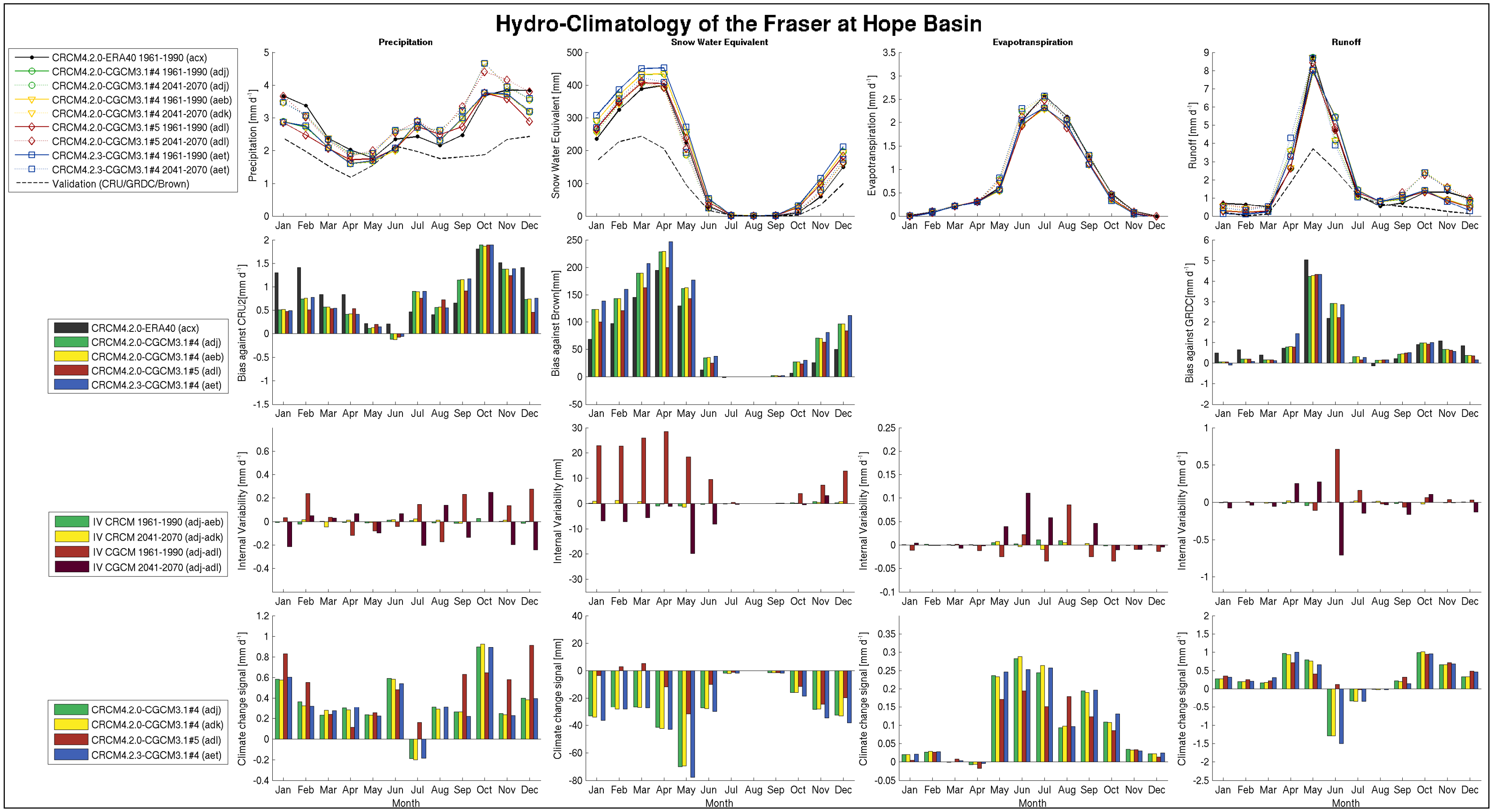


Figure 5-5. Results Matrix of the analysis of CRCM 4 simulations for the Fraser River above Hope. Future simulations are based on the A2 emissions scenario.

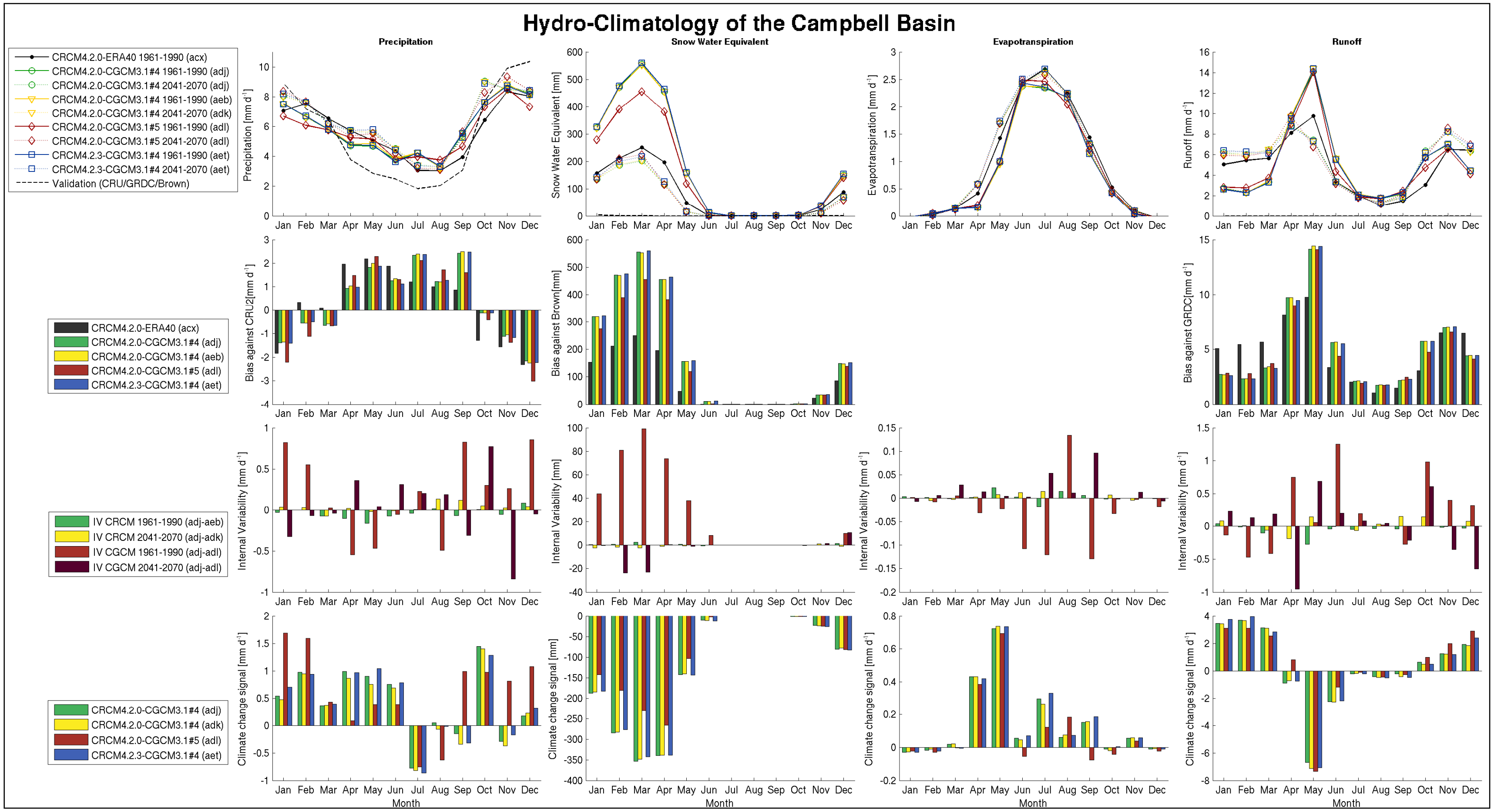


Figure 5-6. Results Matrix of the analysis of CRCM 4 simulations for the Campbell River. Future simulations are based on the A2 emissions scenario.

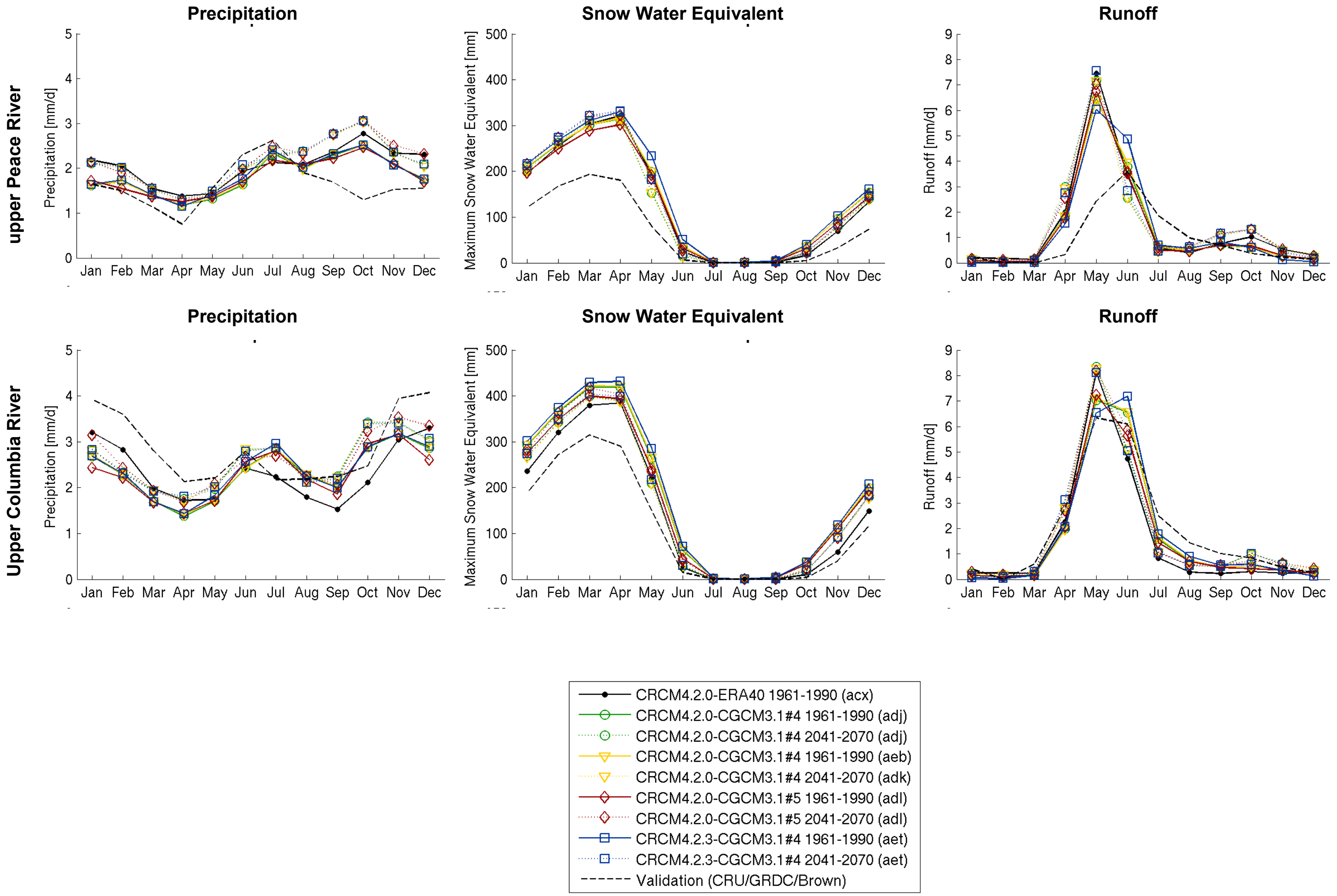


Figure 5-7. CRCM 4 simulations compared to observations. Mean annual cycles of current (solid), future (A2 emissions scenario, dashed) results from the CRCM compared to the observed (dashed black) precipitation, snow water equivalent and runoff for the Upper Peace watershed in the top row, the Upper Columbia watershed in the top row, and the Upper Columbia watershed in the bottom row. Other notation is taken from the Results Matrix (row 1).

5.3 CRCM Model Bias and Annual Cycle on the Upper Peace and Upper Columbia

The mean annual hydrologic cycle of the Upper Peace and Upper Columbia basins are directly compared in Figure 5-7. The performance of the CRCM simulations were evaluated for 3 out of 4 hydrologic components: precipitation, snow water equivalent and runoff. Graphs in Figure 5-7 are taken from the results matrices (rows 1 and 2) that show the mean annual cycle and the monthly bias compared to observational datasets.

For the Upper Columbia basin both the observed summer and winter peaks in precipitation are present in the simulated precipitation. However, in the Upper Peace basin the fall precipitation peak appears later than it occurs in the observation dataset. As mentioned previously, other observational data have a less pronounced local minimum (or even a local maximum) in October. The annual biases of modelled precipitation for the Upper Columbia and Upper Peace basins are –0.53 mm/d (-23%) and 0.25 mm/d (13%) respectively (Attachment 2, Table A-1 and A-2). Given the amount of differences in the available observational data, the CRCM provides a reasonable approximation of the precipitation at the watershed scale.

The mean annual cycle of the snow water equivalent is also well reproduced. The curve of the modelled seasonal development of the snow pack follows the observational data, except for an earlier onset of snow accumulation (October) and the delay in the decline of the snow cover (May instead of April). However, the bias (overestimate) in the annual snow pack is large for the mountainous regions of the Upper Peace (62 mm; 46% bias) and Upper Columbia (58 mm; 34%) basins.

The simulated runoff agrees well with the GRDC observational data both in phase and magnitude for the Upper Columbia basin, while in the Upper Peace basin simulated runoff peaks too early and too high. The latter can be explained by the overestimation of snow pack by the CRCM, and the fact that the CRCM runoff was not routed. In the Upper Columbia, the overestimation of snow pack (Figure 5-7, middle column) is mitigated by a smaller bias of SWE, and by an underestimation of precipitation in the first half of the year. Therefore, the agreement of modelled and observed runoff for both basins may be somewhat fortuitous, and attributable both to uncertainties in the observation datasets, as well as to the discrepancy between runoff and naturalized flows within the watersheds.

In summary, a realistic representation of the annual cycle of hydro-meteorological variables in the watershed was obtained with the CRCM Version 4.2.0. However, substantial biases in SWE and runoff remain. Nevertheless, the effect of these biases is minimized when present and future simulations are subtracted to obtain the climate change signal. Thus the simulations are useful for the assessment of the climate change signal imposed by greenhouse gas forcing.

5.4 Consequences of Internal Variability

The internal variability occurs with different levels of intensity in the global CGCM3 driving data as well as within the regional CRCM simulation. The former was assessed by comparing two simulations driven by different CGCM3 ensemble members and is used to estimate the natural variability of the real climate system. The CRCM internal variability is limited by the control exerted by the lateral boundary forcing and makes a smaller contribution to the total uncertainty in regional climate projections.

The internal variability in climate models contributes to the uncertainty in the estimates of the climate statistics of the hydrologic components: precipitation, evapotransporation, SWE, and runoff. These are summarized in row 3 of the Results Matrix and restated for three components in Figure 5-8 for a comparison of conditions in the Upper Peace and the Upper Columbia River watersheds. As explained in Section 5.1, Figure 5-1, and in the captions of the Results Matrix, the internal variability results are obtained by computing the difference between different members ("twin") of CRCM using the same driving data, and the difference between CRCM simulations with different CGCM members, both for the present (1961-1990) and the future (2041-2070). The results appear as four values (colored bars) for each month of mean annual cycle. The green and yellow bars correspond to the consequence of CRCM internal variability; the red and purple bars correspond to the consequence of internal variability of CGCM3 driving data on the CRCM simulation, and this estimate is a surrogate for natural variability. Note that the sign of the internal variability is irrelevant.

These results are a measure of uncertainty in hydrologic components due to internal variability. They are quite similar in each basin, but the components show different seasonal behaviour. The presence of seasonality in the internal variability of the CRCM and the response of precipitation has been shown by Caya and Biner (2004) and De Elía et al. (2008). However, there is little seasonal effect in the uncertainty of precipitation (Figure 5-8, left column), but the small sample size of two simulations for each time period is too small to permit a good estimate.

The uncertainty in annual precipitation from the regional model (CRCM) is 0.6 % for the Upper Peace River basin, and 0.4 % for the Upper Columbia basin (Attachment 2). The CGCM3 uncertainty is larger (i.e., 1.3 % of the annual mean for the Peace River basin and 1.5 % for the Upper Columbia basin).

The consequences of climate model internal variability in the CRCM and in the driving CGCM are much larger for the snow water equivalent (SWE), but show little variation during the snow season (Figure 5-8, middle column). In relative terms the effect of CRCM internal variability is about 10% of the effect of the driving CGCM3's internal variability on the CRCM simulation. The mean annual uncertainty due to internal variability of the CRCM is 0.4 % for the Upper Peace River, and 0.7 % for the Upper Columbia. The uncertainty of SWE due to the CGCM3 internal variability is 6 % for both the Upper Peace River and the Upper Columbia basins, as shown in the Tables of Attachment 2.

For the runoff, an indication of strong seasonality in the consequences of climate model uncertainty is especially evident (right column in Figure 5-8). The enhanced variability in the results in spring originates partially from the large variability in the accumulated snowpack that is the main contributor to the spring runoff, and to the enhanced summer season uncertainty in precipitation due to stronger convective activity (Alexandru et al. 2007). From Attachment 2, the consequences of the CRCM internal variability in the mean annual runoff reach 0.8% in the Upper Peace watershed, and 0.7 % in the Upper Columbia basin. This is substantially smaller than the uncertainty caused by internal variability of the CGCM: 2.6% for the Upper Peace basin and 3.8 % in the Upper Columbia basin.

In summary, the estimate of internal variability in paired CGCM simulations is larger than the contributions from the CRCM (computed from the difference between twin simulations). This can be easily observed in the monthly values of the seasonal cycle in Figure 5-8.The present analysis for BC watersheds provides (i) a sense of the relative importance of the two sources of internal variability, and (ii) the consequences of internal variability from climate models on the uncertainty of hydrologic components.

5.5 The Climate Change Signal

The objective of this section is to estimate the climate change signal in the Upper Peace and Upper Columbia watersheds as expressed by the hydrologic components, including an estimate of the uncertainty associated with this signal. As described in Section 5.1 and in the caption of the Results Matrix, the climate change signals of monthly mean precipitation, SWE, and monthly mean runoff were computed from the four pairs of CRCM simulations by subtracting the results for present climate from future climate simulations. It is assumed that similar biases in present and future simulations result in a close to unbiased climate change signal. The two CGCM3 climate simulations driving the CRCM runs represent upper and lower limits from a larger sample of five runs (not shown).

All simulations with the same CGCM forcing (Figure 5-1; green, yellow, blue bars; CGCM-Run #4) generally exhibit the same sign of climate change signal. The exception occurs in the SWE with a different forcing (Figure 5-9; red bar, CGCM-Run #5).

The climate change signal in precipitation indicates an increase during most of the year for both watersheds (Figure 5-9; left section) for both CGCM forcings. Only the summer months are estimated to receive less precipitation, a feature much clearer for the Upper Columbia watershed. The mean annual increase in precipitation from the two CGCM members is 16.9 % in the Upper Peace and 10.8 % in the Upper Columbia watershed (Attachment A2).

The average annual decrease of SWE in the Upper Peace watershed is -1.4% (Table A2-1), but this result is composed of conflicting results (+4.4% and -7.1%, respectively) for the two different CGCM forcings: Run #5/red, and Run #4/green in Figure 5-9. In the Upper Columbia basin (Table A2-2) the average annual decrease is greater (-5.9%) with similar variability in SWE from the two different CGCM forcings.

Although this uncertainty in SWE is acknowledged, all simulations agree in sign for periods of onset and on the loss of simulated snow cover. As shown in seasonal variability of Figure 5-9 (centre section), the decreasing SWE is most pronounced in the winter-spring seasons, and is more pronounced in the south (Upper Columbia) than in the north (Upper Peace).

A shift in the annual cycle of the runoff (Figure 5-9, right section) towards earlier in the spring season is pronounced. The increased runoff towards the end of the year is due to the combination of reduced snow accumulation in a warmer climate and increased precipitation. For the year, the average annual increase due to climate change based on CRCM simulation driven by two different CGCM members is 17.9% for the Upper Peace River and 9.2 % for the Upper Columbia (Attachment A2).

In summary, two different CGCM climate forcings produced coherent climate change signals in precipitation and runoff, but with some uncertainty in SWE. The climate change signal includes an increase in precipitation, especially in the north (Upper Peace watershed), and a decrease in SWE, especially in the south (Upper Columbia). In both watersheds there is agreement on the shift to earlier spring peak runoff, and elevated autumn season runoff is sustained by an increase in precipitation and reduced storage of water in the snow pack.

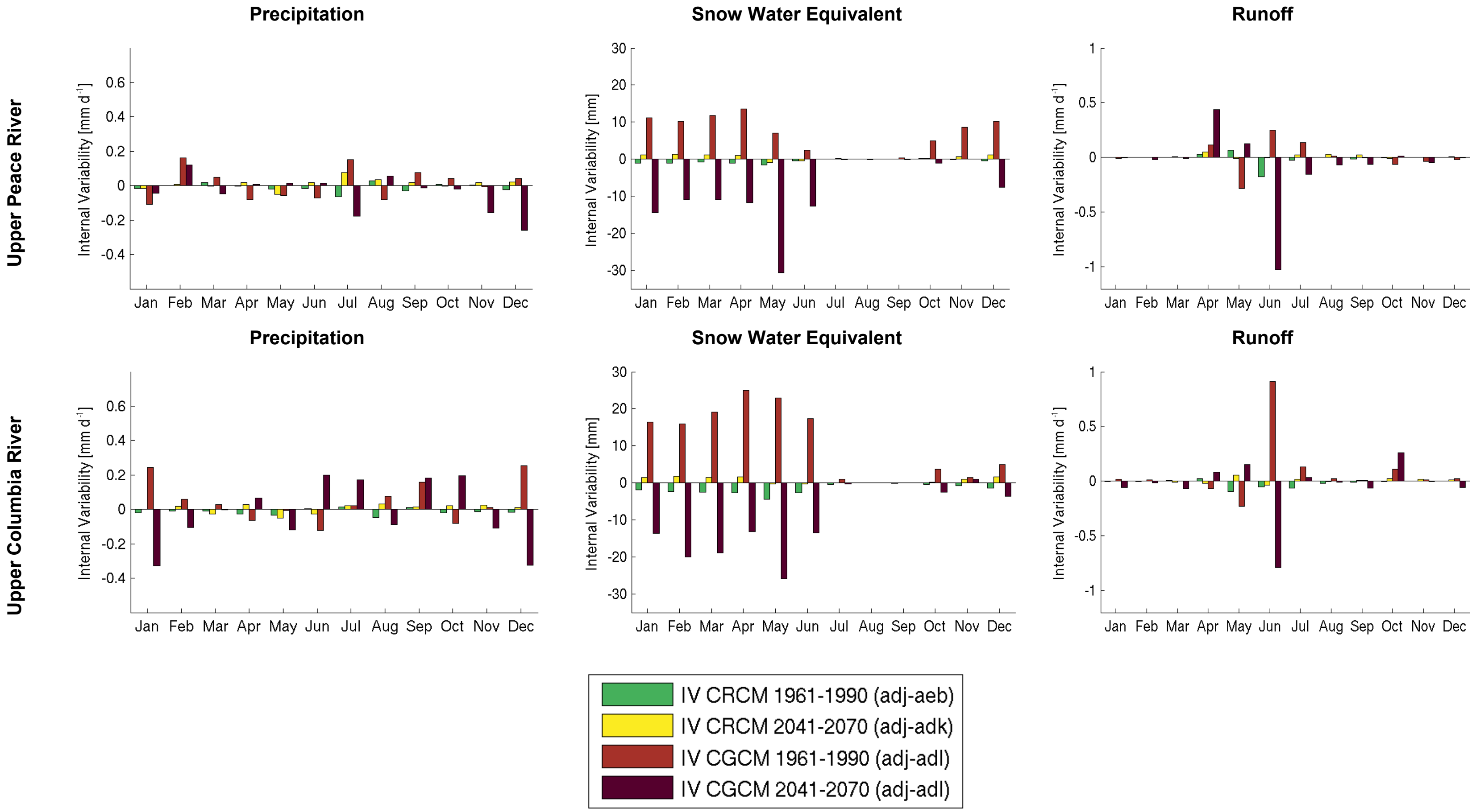


Figure 5-8. Mean annual cycle of the consequences of CRCM internal variability on precipitation, snow water equivalent and runoff for the Upper Peace (top row) and the Upper Columbia watersheds(bottom row). Results from both the present and future conditions are used as identified in the legend. Notation is taken from the Results Matrix (row 3).

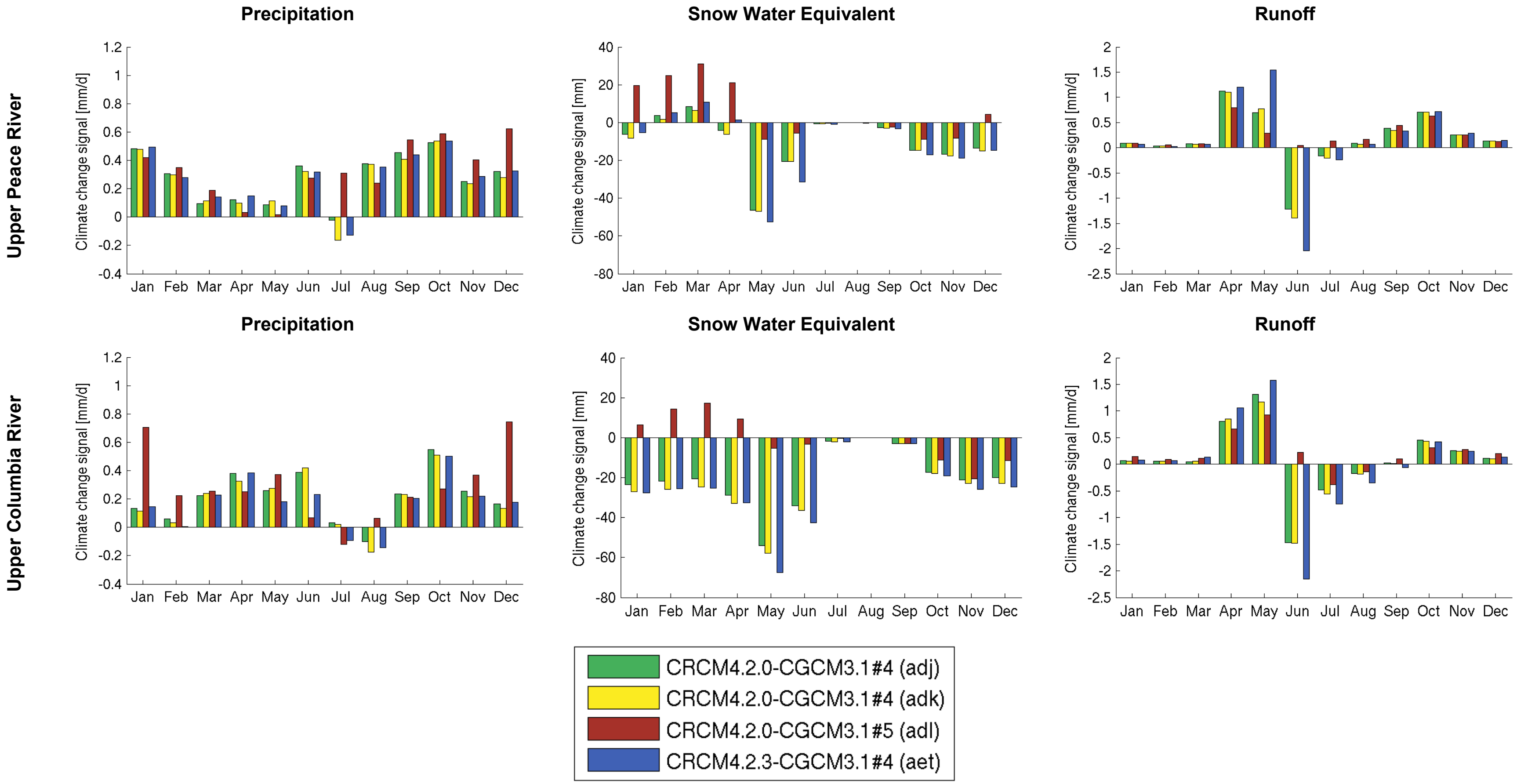


Figure 5-9. Monthly mean climate change signal from present (1961-1990) and future (2041-2070) CRCM 4 simulations of precipitation, maximum snow water equivalent and runoff for the Upper Peace (top row) and the Upper Columbia watersheds (bottom row).

5.6 Long Term Trends (Beyond the 2050s) and Climate Variability in the Upper Peace and Upper Columbia

The analysis presented above revealed the biases in model estimates of hydrologic components and the consequences of internal variability that produce differences between ensemble members. It also showed that a climate change signal derived from 30-year time windows in the present and future changes when a different GCM member is used for the assessment. This change may even include a change in sign of the climate change signal.

Another way to look at this concept is to analyze a longer simulated record of climate. The study of 140-year long simulations allows an examination of the implications of climate variability when using 30-year climate averages to derive a climate change signal. Two 140-year long CRCM simulations (adj and adl in Table 5-1) are used to demonstrate the temporal variability of the climate.

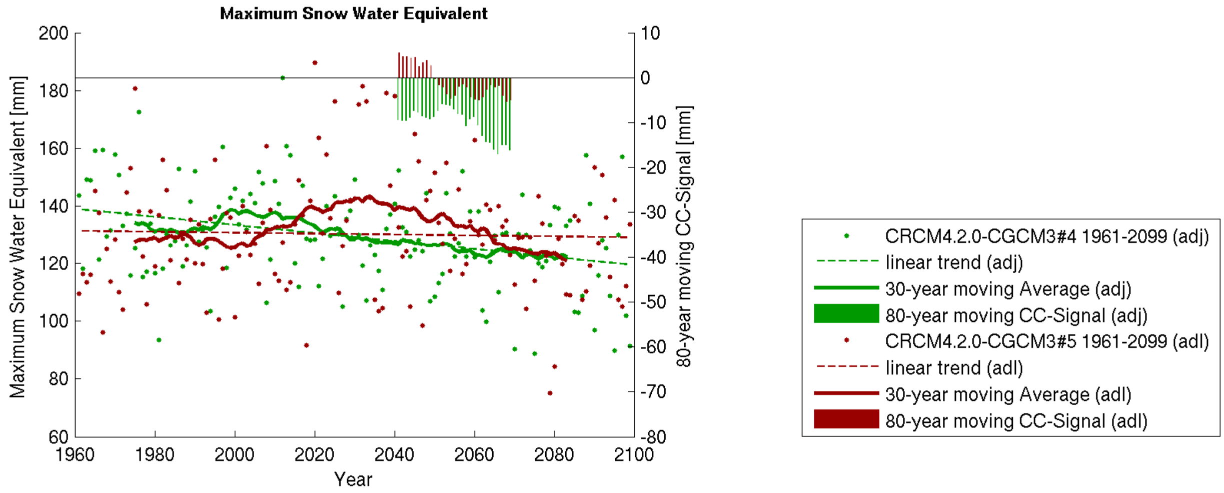


Figure 5-10. Long-term trends of annual maximum snow water equivalent for the Upper Peace watershed. The inserted bar graph shows the magnitude of 30 climate change signals obtained by “moving” reference and future 30-year windows simultaneously maintaining their 80-year offset. The location of the bars indicates the first year of the future 30-year period used in the computation (see text for details).

The long-term trend in the annual maximum snow water equivalent in the Upper Peace watershed is compared in two 140-year simulations using the same climate models (Figure 5-10). A linear trend (dashed lines) is fitted to the annual values (dots). This linear trend suggests a negative trend for the simulation driven by CGCM member #4 (adj-green, see Table 5-1), but only small changes in SWE for member #5 (adl-red). The solid lines in Figure 5-10 show the 30-year moving average and can be interpreted as the evolution of a 30-year climate. While the moving average of member #4 simulation follows the linear trend with little deviations, member #5 shows considerable fluctuation in the 140 years of the simulation. Note that in the second half of the 21st century, this latter simulation shows a positive climate trend that persists over several decades. As a consequence, this behaviour affects the apparent climate change signal derived from a choice of two 30-year time periods. This situation is commonly addressed by considering ensembles of multiple climate model simulations, although in this report only two members were used. However, the graphical presentation of simultaneously moving present and future 30-year periods shows the dependency of climate signal computation on natural variability in the system.

In all analyses presented above, an 80-year offset between two periods, (1961-1990) and (2041-2070), was used to assess the estimates of the climate change signal. The arbitrary choice of the two periods was used to compute climate change trends over 80 years. A larger sample of 80-year climate change signals can be generated by using the full length of the 140-year simulation. The climate change signal of moving pairs of present and future time periods were computed, maintaining the 80-year offset of the two periods in each case: (2041-2070) minus (1961-1990); (2042-2071) minus (1962-1991), etc. This experiment produces 30 cases of an 80-year climate change signal based on multiple paired time periods statistics that fall into different phases of the oscillation of the 30-year moving average. The results are shown in a bar graph at the edge of Figure 5-10. The bar graph starts at the location of the first year of the future time period used in their computation. The values associated with the bar graphs are indicated on the right-hand side of each plot.

For the 30 climate change signals in simulation adj (green, Table 5-1) driven by CGCM3 member #4, there is uniform agreement on a negative climate change signal of about 10 mm maximum SWE in the Upper Peace watershed (green bars in Figure 5-10). Two-thirds of the 30 climate change signals computed from the CGCM3 member #5 simulation also indicate a negative climate change signal (red bars in Fig 5-10). However, for the first third of the series, the climate change signal in the CGCM3 member #5 simulation is positive.

Looking at long series has the same effect as looking at multiple members of 30-year climates in creating a larger number of simulations with different initial conditions. The linear 140-year trend is a more reliable climate change signal estimate than compiling it from only two 30-year time slices. Of course multiple 140-year linear trends will also improve the estimate of the climate change signal.

In summary, a comparison of the bar graphs for different watersheds indicates variability in the 80-year climate change signal that differs between variables and regions. For the Upper Peace watershed the variables precipitation, runoff and surface temperature that are presented in Figure 5-11 exhibit a more stable climate change signal than the maximum SWE discussed above. The same analysis for the Upper Columbia basin (Figure 5-12) shows a stable behaviour of the maximum SWE climate change signal, but larger variability in precipitation and runoff changes, particularly when comparing the different simulations.

5.7 Unresolved Issues

The current study has focused on estimates of the climate change signal in the Upper Peace and Upper Columbia basins and the uncertainty that can be attributed to internal variability. The consequences of the climate change signal on the seasonal cycle of hydrologic components were estimated for a 30-year period in the 2050s, using a specific selection of CRCM simulations driven by two CGCM3 members. This study provides insight into the properties, quality and uncertainty associated with climate projections. To what extent can output from climate models be accepted by users who wish to apply these results? For prudent decision-making, larger ensembles of driving data from CGCM3 and/or other GCM simulations would need to be taken into account. This would generate more stable estimates of internal variability, the climate change signal, and the uncertainty that is associated with them.

Similarly, determining the climate change signal from CRCM projections for individual watersheds would also require more CGCM ensemble members. This has been conducted for the Upper Peace watershed (Section 4) and may be pursued for other BC watersheds, particularly those relevant for hydroelectric power generation like the sub-basins of the Upper Columbia.

The smaller size of sub-basins reduces the number of CRCM grid cells available for analysis and adds noise to the results, as the analysis of the Campbell basin revealed. Investigations on such a small watershed could perhaps be addressed by CRCM simulations at a 15 km spatial resolution, which would increase the sample size by a factor of nine. Preliminary investigation of such higher resolution simulations suggests an improvement of regional climate simulation, particularly in areas of mountainous terrain which the watersheds of British Columbia are embedded. Such an increase in resolution must be accompanied by other advances from climate modelling research in order to obtain the maximum benefit. This is the objective of *targeted research* in the future.

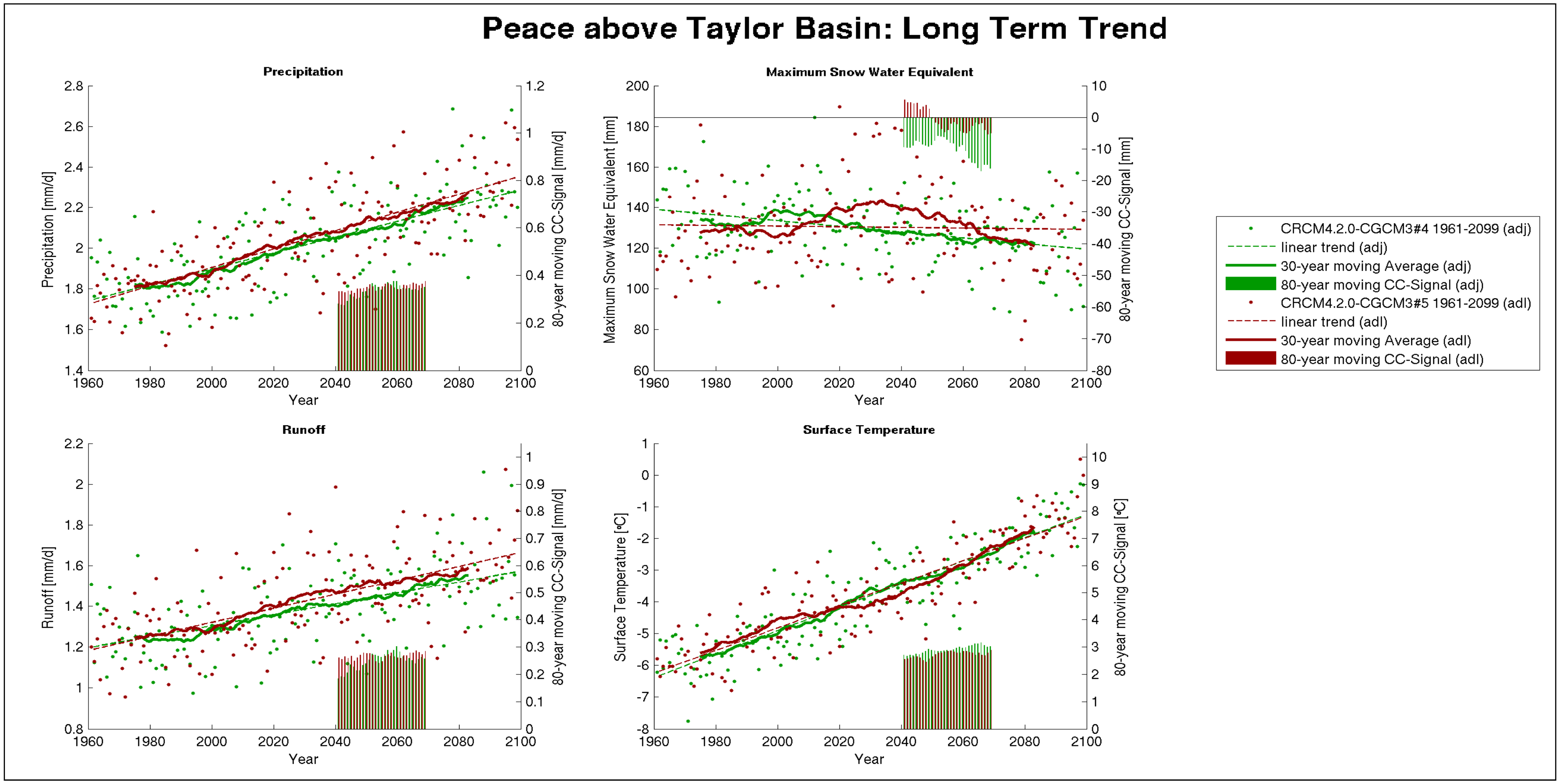


Figure 5-11. Long-term trends of precipitation, runoff, annual maximum snow water equivalent and surface temperature from the CRCM for the Upper Peace watershed. The inserted bar graph shows the magnitude of 30 climate change signals obtained by "moving" reference and future 30-year windows simultaneously maintaining their 80-year offset. The location of the bars indicates the first year of the future 30-year period used in the computation (see text for details).

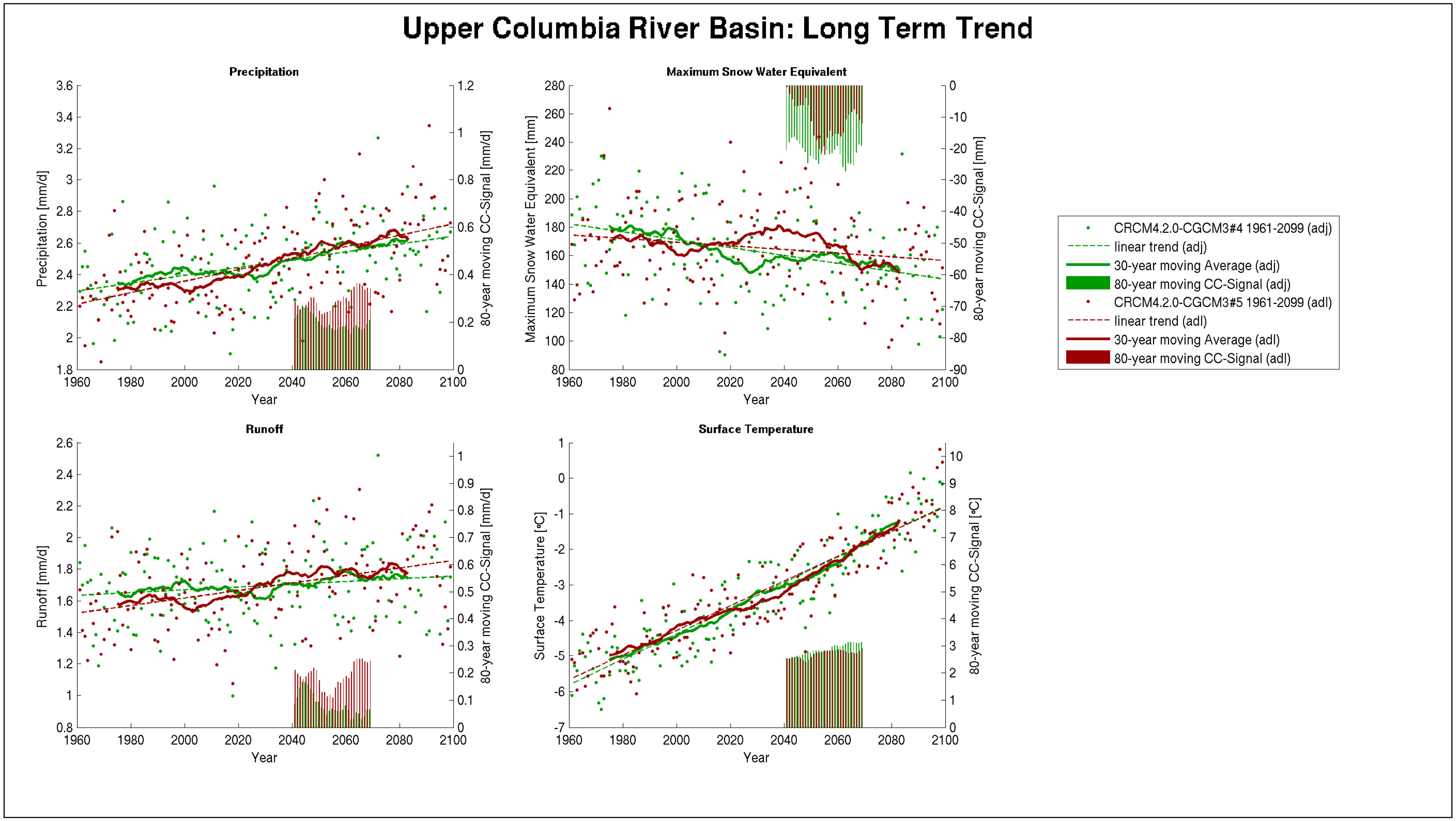


Figure 5-12. Long-term trends of precipitation, runoff, annual maximum snow water equivalent and surface temperature for the Upper Columbia watershed. The inserted bar graph shows the magnitude of 30 climate change signals obtained by “moving” reference and future 30-year windows simultaneously maintaining their 80-year offset. The location of the bars indicates the first year of the future 30-year period used in the computation (see text for details).

6. Summary

Earlier studies have projected the climate of the 2050s in BC to be warmer, especially the average daily minimum temperatures in the winter season, and especially in the northern half of the province. The climate of BC was also estimated to be wetter in the winter season, especially in the northern part of the province, and drier in the southern and inland part of the province in the summer season (Rodenhuis et al. 2007; Walker et al. 2008, especially Section 8.2; and Christensen et al. 2007, especially Section 11.5). These results were derived from climate trends and projections of global climate models with assumptions about the evolution of greenhouse gasses following several emissions scenarios.

This report applies these concepts to estimate future impacts of climate change on the hydrology of several specific BC watersheds. These estimates are built on results (Section 4) from a set of eight simulations of the Canadian Regional Climate Model (CRCM, primarily V4.2.3) that were driven by two versions of the Canadian Coupled Global Climate Model (CGCM) chosen from a selection of six 30-year runs (Tables 4-1, 4-2 and 4-3). Secondly, results (Section 5) from a series of eight 30-year runs with Version 4.2.0 of the CRCM that were all driven by the same version of the global model CGCM3 (Table 5-1). Finally, two long runs of 140 years were made with the CRCM V4.2.0, driven by two simulations from the CGCM3. The purpose was to explore the uncertainty associated with the traditional 30-year averaging period in making projections of the climate change signal on hydrologic components within the context of watersheds of the Upper Peace and Upper Columbia River basins.

Time series data of all hydrologic components and supporting model output were prepared for an accompanying document, the synthesis report (Shrestha et al. 2010). An inventory of these runs is presented in Attachment 1 with an example of a time series for the Upper Peace basin of monthly precipitation in the 2050s (compared to the historical record, 1961-1990). A summary of the annual statistics for the Upper Columbia and Upper Peace is presented (Attachment 2) for the mean annual values of hydrologic components with their bias, internal variability (%), and climate change signal (%).

A new format was designed for the concise and systematic presentation of climate modelling results—a *Results Matrix* that presents the annual cycle, bias, interannual variability and climate change signal for the primary hydrologic components: precipitation, snow water equivalent (SWE), evaporation, and runoff (Attachment 3).

The results for the Campbell River watershed on Vancouver Island are noted, but were based only on a single grid cell of the CRCM. Consequently, these results may not be representative, even though the results are generally consistent with those from other watersheds under investigation. Therefore, the results of this study focus on the watersheds of the Upper Peace and Upper Columbia, although comparative results have been presented for the Fraser Basin and the entire Columbia Basin as well. The projections of the *annual climate change signal and its uncertainty,* as well as its impact on hydrologic components in the Upper Peace and Upper Columbia watersheds for the 30-year period covering the 2050s may be summarized:

- For the 2050s, projections from global and regional climate models were used to estimate future hydrologic response to climate change for the Upper Peace, Upper Columbia, and selected BC watersheds. These projections are based on the A2 emissions scenario. However, until the end of the century, climate modelling results are not expected to be substantially different for any alternative emissions scenario (IPCC 2007). The climate change signal indicates an increase in the mean annual temperature of about 2.5°C, and an increase in mean annual precipitation of up to 17% in the north (Upper Peace), and almost half that amount to the south (Upper Columbia, 11%; and 9% for the entire Columbia basin). Comparable values for the climate change signal are projected for the Fraser basin above Hope.
- This *climate change signal* (warmer temperatures and increased precipitation) in the 2050s will have an impact on the hydrologic components: an increase in evapotransporation and a decrease

in snowpack (Snow Water Equivalent, SWE). The effect on the snowpack is small in the north (Upper Peace): a 2% decrease in annual maximum snowpack (SWE), but stronger in the south: a 6% decrease in the Upper Columbia, and a 19 % decrease for the entire Columbia Basin. Consequently, the impact of the climate change signal is a sizable increase (17-18%) in annual runoff in the north (Upper Peace), but about half that much to the south (Upper Columbia), and less for the entire Columbia basin. However, a shift in the timing of the peak flow occurs (next subsection). The implications for water resources and power generation have not yet been estimated.

- The *uncertainty* in these results due to natural variability of the global climate system is estimated from the internal variability of the global climate model that force regional climate variability. The uncertainty related to internal variability for temperature is less than ±0.3°C in all the watersheds studied. This uncertainty is roughly 10% of the climate change signal. The additional uncertainty introduced by the regional climate model (CRCM) is even smaller by about an order of magnitude. Structural uncertainty of the climate model is detected (Table 4-3 and Figure 4-3) and may introduce additional uncertainties into some hydrological components. Although a cold temperature bias in the climate model and a positive bias in maximum SWE are acknowledged, these biases have only a small effect on climate projections of differences from a reference state, and they have little influence on internal variability. The uncertainties in the hydrologic components in BC watersheds due to natural variability (internal variability of the global model) are summarized in Table 6-1 in comparison with the annual climate change signal.

The projections of an *annual cycle of hydrologic components* that are impacted by the climate change signal in the Upper Peace and Upper Columbia watersheds for the 30-period covering the 2050s may be summarized:

- Model Bias - There is a cold bias (-5°C) in the annual temperature of the regional climate model that is apparent throughout the year. In addition, there is a positive bias in annual precipitation (13%) that is seasonally distributed in the Upper Peace watershed, and negative (-22%) in the Upper Columbia. During the spring season, these biases in precipitation can be much larger, but are considered to be within the limits of the verifying datasets for these watersheds. However, larger biases are evident in the SWE and runoff, especially during the spring season. These biases are more difficult to assess because of discrepancies between computed runoff and naturalized streamflow, as well as uncertainties in estimating bulk precipitation rates and snowpack from historical observations or reanalysis products. Nevertheless, these discrepancies remain a concern for the modelling of the physics of water substance within the climate model. However, for the purpose of estimating the climate change signal, this bias occurs in both the current model climatology and future projections. Therefore, the influence on the climate change signal should be minimal. The bias has no effect on the computation of internal variability.
- Internal Variability – The uncertainty due to natural variability of the climate system is estimated from internal variability in global simulations. The impact on the seasonal growth of SWE and the annual cycle of runoff occurs mostly in the spring season. Although the internal variability is usually less than 6% for annual maximum SWE and runoff, it influences a substantial fraction of the climate change signal (Table 6-1). Furthermore, there are exceptional values (uncertainty) in the spring season (Section 5.4). The contribution from regional models to the internal variability has only a fractional impact throughout the year on all hydrologic components.
- Climate Change Signal, Precipitation – By the 2050s the annual climate change signal in precipitation is positive: about 17 % increase in the Upper Peace and 11% in the Upper Columbia. The changes are strongest during the cool seasons of the year, and smaller changes occur during the summer months. The annual climate change signal in precipitation is substantially larger than estimates of uncertainty (Table 6-1).

- Climate Change Signal, SWE – Although the impact of the climate change signal reduces the annual maximum SWE, the monthly SWE increases in the spring in the north (Upper Peace), but is strongly reduced in the south (Upper Columbia) throughout the year. However, the relative uncertainty is larger in the Upper Peace because the annual climate change signal in SWE is weaker (+4% to -7%) on this watershed, and the relative uncertainty in climate change signal is comparable to the magnitude of annual average internal variability of the seasonal cycle of SWE (Table 6-1).
- Climate Change Signal, Runoff – The increase in precipitation throughout most of the year from the climate change signal is accompanied by a decrease in SWE – especially in the north, and especially in the spring – and is consistent with increases in runoff up to 1.5 mm/day in late spring and decreases in the early summer season. This change implies a shift in the timing of the peak flow in the Upper Peace to earlier in the spring, but the influence is less in the Upper Columbia. The seasonal climate change signal in precipitation and SWE have a perceptible north-south gradient that is not present in the annual cycle of runoff. To the north (Peace) the annual increase in runoff is 17-18 % and occurs more than a month earlier in the spring. To the south (Columbia) the increase is approximately 9 %, but occurs with only a small change in timing of the peak flow.
- Long-term trends and variability – Beyond the time horizon of the 2050s, results from the regional climate model indicate a systematic trend of increasing temperature for the Upper Peace and Upper Columbia. The long-term trend of increasing precipitation is much stronger in the Upper Peace. In both basins, the SWE trend is negative and the trend towards increasing runoff is positive but much stronger in the Upper Peace. These simulations especially demonstrate the large variability in annual snow cover (SWE) and runoff that are filtered by climate trends obtained from 30-year averages.

Table 6-1. Comparison of results: the annual climate change signal in the 2050s and its impact on the annual average of hydrologic components, including uncertainty due to internal variability. Results for different watersheds are arranged from north to south, and for the study of uncertainty in Section 4: a), c) and e), using the CRCM V4.2.3; and the study of annual cycle in Section 5: b) and d), using the CRCM V4.2.0.

	Climate Change Signal	**Uncertainty from Internal Variability**
Temp	2.6 deg C	± 0.3 deg. C
Precip	16 %	± 4 %
SWE	-2 %	± 6 %
Runoff	17 %	± 6 %
Evapotranspiration	--- %	± ---%

a) Upper Peace (Chapter 4)

b) Upper Peace (Chapter 5)

	Climate Change Signal	**Uncertainty from Internal Variability**
Temp	--- deg.C	---- deg. C
Precip	17 %	± 1.3 %
SWE	-1.4 %	± 5.8 %
Runoff	18 %	± 2.6 %
Evapotranspiration	14 %	± 2.2 %

	Climate Change Signal	**Uncertainty from Internal Variability**
Temp	2.4 deg C	± 0.2 deg. C
Precip	16 %	± 3 %
SWE	-10 %	± 5 %
Runoff	17 %	± 4 %
Evapotranspiration	---	± ---

c) Fraser (Chapter 4)

d) Upper Columbia

(Chapter 5)

	Climate Change Signal	**Uncertainty from Internal Variability**
Temp	--- deg. C	---- deg. C
Precip	11 %	± 1.5 %
SWE	-5.9 %	± 5.8 %
Runoff	9.2 %	± 3.8 %
Evapotranspiration	14 %	± 2.3 %

	Climate Change Signal	**Uncertainty from Internal Variability**
Temp	2.5 deg C	± 0.2 deg. C
Precip	9 %	± 3 %
SWE	-19 %	± 3 %
Runoff	7 %	± 4 %
Evapotranspiration	---	± ---

e) Entire Columbia (Chapter 4)

7. Future Directions

The results from this study have quantified the magnitude of both the threat and the opportunity that will be imposed by climate change over the decades ahead. In particular, the water resources for BC will increase, but will be unevenly redistributed in both space and time. While acknowledging these results from sophisticated global and regional climate models with coupled surface hydrology, there are limitations in the physical assumptions and substantial uncertainty remains. However, these results and their consistency with other studies and watersheds is encouragement for further work to refine these estimates of future conditions, understand the sources of uncertainty, and improve the determination of impacts on the hydrological system in British Columbia.

The Pacific Grid – This study has worked with available datasets from the regional climate model (CRCM4) developed by Ouranos, and the global climate model (CGCM3) developed by Environment Canada. More advanced versions of the regional model, and the surface hydrology model, including an improved land surface scheme, could be applied at high resolution to a specific section of Pacific North America. An improved resolution (15 km) could be used on a Pacific Grid that is nine times greater than that used in the present study and would more fully resolve important topographic differences. This work has already been initiated, and the Dynamic Downscaling Project for PCIC is underway in collaboration with Ouranos and the Climate Modelling Group at the University of Victoria.

Uncertainties – This study has made clear that the uncertainties in the results are small, but may be significant in comparison with the changes anticipated in the hydrological system over the next few decades (Table 6-1). The sources of these uncertainties include the natural variability of the climate system itself, and to some extent the model bias and the structural uncertainty. These are a significant barrier to providing a specific and unequivocal answer to the question of the future hydrological state and streamflow that may be imposed by climatic changes in temperature and precipitation on regions within Pacific North America. In future work, a greater number of simulations are needed so that the probability distribution of future climate conditions, as well as internal variability, may be taken into account by water resource managers.

Glaciers – An important component of the hydrologic system within the full cryosphere has been omitted from climate models and the land surface scheme embedded in the models. In particular, glaciers are important contributors to streamflow in the warm season, and this will become increasingly important in the future. The recent work of the Western Canadian Cryospheric Network (WC2N) should be acknowledged (Moore et al. 2009; Stahl et al. 2008; and WC2N 2010). The strategy for incorporating the glacier component involves utilizing existing glacier models to interact with the CRCM on a slow time scale, while using the current hydrological model on the fast time scale.

Extreme Events – This study has viewed global climate change as a slow decadal change of climatic conditions on which natural variability is imposed. In fact, the change of average climate conditions conceal periods of extreme events, such as multi-year droughts, spring floods, or extreme winds connected with intense Pacific storms. Although an increased occurrence of these short-term events contributes only incrementally to decadal changes in average conditions, they are specific threats to community infrastructure and ecosystems. The estimate of future probabilities of extreme events is a research problem of enormous practical significance. The CRCM at high resolution on the Pacific Grid is an extraordinary resource to make this investigation. This is one of the topics that will be addressed in the Joint Climate Diagnostics Project at PCIC in collaboration with specialists at BC research universities.

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Attachment 1: Climate change signal in monthly mean precipitation for the Upper Peace watershed for the 2050s horizon and for all GCM and RCM models and runs (Biljana Music)

For the third objective—to create surrogate runoff with an estimate of uncertainty—a request was made to Ouranos to provide examples of computed runoff from the Canadian Regional Climate Model (CRCM) coupled with the Canadian Land Surface Scheme (CLASS) as well as from the Canadian Coupled Global Climate Model (CGCM) for the selected watersheds in the 2050s. These data were presented in Section 4 of this report and were used in the synthesis report (Shrestha et al. 2010). Additional time series from Section 5 of this report were studied and presented in Figures 5-8 and 5-9 but were not used in the synthesis report.

In addition to runoff, Ouranos supplied monthly mean values of other hydrologic components, both for the historical period and for the future (2050s). These seven variables are: precipitation (mm/day), runoff (mm/day), evapotranspiration (mm/day), solid precipitation rate falling as snow (mm/day), atmospheric moisture flux convergence (mm/day), surface temperature (at 2 metres, deg. K), and surface snow cover (snow water equivalent, mm).

An inventory of the monthly mean times series and the associated model runs are indicated in Table A1-1. The identity of these time-series is established and related to those used in this report (Tables 4-1 and 4-2).

Table A1-1. An inventory of both historic and future monthly mean time series supplied by Ouranos from the CRCM and CGCM using the CLASS. The global and regional climate models are indicated; the CGCM and the CRCM use the A2 GHG emissions scenario for future projections. Each dataset contains subsets for the three watersheds (Upper Peace, Upper Columbia, and Campbell) and seven hydrologic components.

Name, (Tables4-2& 4-3)	Period: historical		Period: 2050s		CRCM Version	CGCM model run
	Name	Period	Name	Period		
H	ABB	1961-1990	ABE	2041-2070	3.6.3	CGCM2 #3
G	ABI	1961-1990	ABJ	2041-2070	3.7.1	CGCM2 #3
F	AFP	1961-1990	AFQ	2041-2070	4.2.3	CGCM2 #3
A	AEY	1961-1990	AFB	2041-2070	4.2.3	CGCM3 #1
B	AEZ	1961-1990	AFC	2041-2070	4.2.3	CGCM3 #2
C	AFA	1961-1990	AFD	2041-2070	4.2.3	CGCM3 #3
D	AET	1961-1990	AEU	2041-2070	4.2.3	CGCM3 #4
E	AEV	1961-1990	AEW	2041-2070	4.2.3	CGCM3 #5

Examples of the monthly projected anomalies (“delta”) derived from time series of output from the CRCM and CGCM climate models are shown for precipitation and runoff for the Upper Peace watershed.

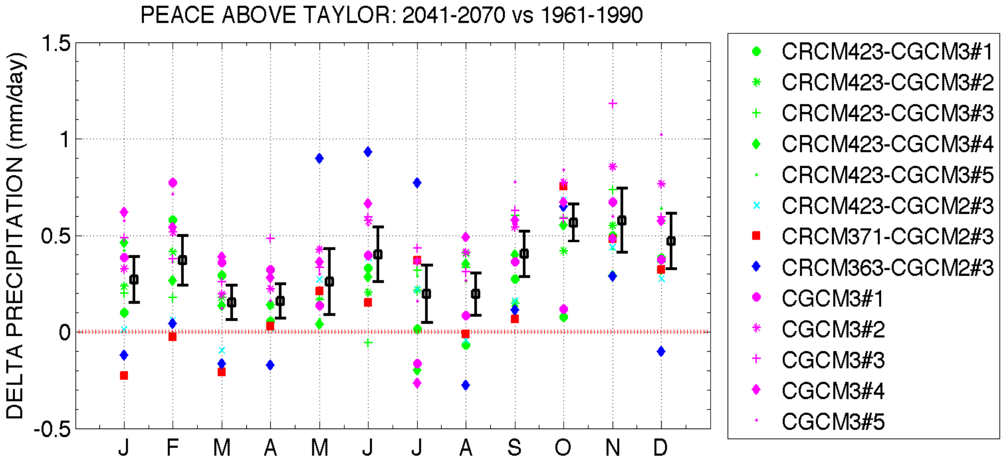

Figure A1-1. CRCM and CGCM3 projected changes of monthly mean precipitation over the Upper Peace River watershed from 1961-1990 (reference climate) to 2041-2070 (future climate under the A2 emissions scenario). The black confidence boxes denote the 95% confidence interval and the mean computed using a bootstrap resembling method on results from all the models indicated on the right.

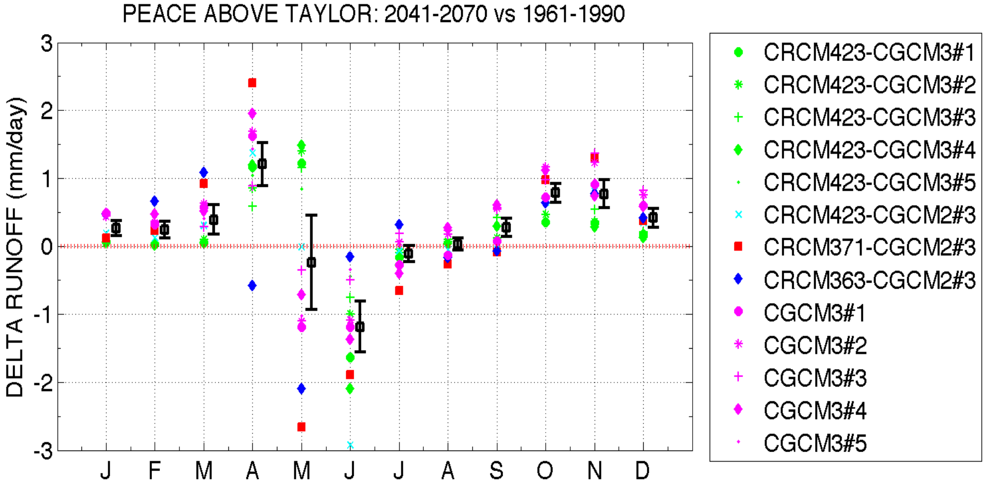

Figure A1-2. Same as Figure A1-1, except this time series is for the projected changes of monthly mean runoff.

Attachment 2: Annual Statistics of Watershed Analysis

The following tables give an overview of annual values of means, biases to observation, relative internal variability and relative climate change signal as assessed for the BC watersheds.

Table A2-1. Annual statistics for the Upper Peace watershed. CRCM simulation names refer to Table 5-1.

Peace above Taylor	**CRCM Simulations**						
annual mean of present simulations	**acx**	**adj**	**aeb**	**adl**	**aet**	**mean**	**obs**
Precipitation [mm/d]	2.04	1.82	1.83	1.81	1.85	1.87	1.62
Snow water equivalent [mm/d]	126.2	134.2	134.7	127.5	143.4	133.2	71.6
Evapotranspiration [mm/d]	0.60	0.56	0.56	0.55	0.57	0.57	-
Runoff [mm/d]	1.42	1.26	1.27	1.25	1.28	1.29	0.90
annual bias to observation data	**acx**	**adj**	**aeb**	**adl**	**aet**	**mean**	
Precipitation [mm/d]	0.42	0.20	0.21	0.19	0.23	0.25	
Snow water equivalent [mm]	54.6	62.6	63.1	55.9	71.8	61.6	
Evapotranspiration [mm/d]	-	-	-	-	-	-	
Runoff [mm/d]	0.52	0.35	0.36	0.35	0.38	0.39	
internal variability in CRCM [%]	**adj-aeb**	**adj-adk**				**mean**	
Precipitation	±0.58	±0.55				±0.56	
Snow water equivalent	±0.39	±0.34				±0.37	
Evapotranspiration	±0.08	±0.16				±0.12	
Runoff	±0.80	±0.71				±0.75	
internal variability from CGCM driving data [%]	**adj-adl**	**adj-adl**				**mean**	
Precipitation	±0.55	±1.98				±1.27	
Snow water equivalent	±5.25	±6.27				±5.76	
Evapotranspiration	±0.81	±3.53				±2.17	
Runoff	±0.71	±4.48				±2.60	
climate change signal [%]		**adj-adj**	**adk-aeb**	**adl-adl**	**aet-aet**	**mean of adl & adj**	
Precipitation		15.40	14.10	18.37	14.77	16.89	
Snow water equivalent		-7.06	-7.74	4.36	-7.39	-1.35	
Evapotranspiration		15.79	15.52	12.75	15.02	14.27	
Runoff		14.75	13.04	20.99	14.28	17.87	

Table A2-2. Annual statistics for the Upper Columbia watershed. CRCM simulation names refer to Table 5-1.

Upper Columbia River	**CRCM Simulations**						
annual mean of present simulations	**acx**	**adj**	**aeb**	**adl**	**aet**	**mean**	**obs**
Precipitation [mm/d]	2.33	2.35	2.36	2.30	2.39	2.35	2.88
Snow water equivalent [mm]	148.8	181.1	182.7	170.4	188.7	174.3	115.9
Evapotranspiration [mm/d]	0.80	0.69	0.68	0.71	0.70	0.72	-
Runoff [mm/d]	1.50	1.66	1.68	1.58	1.69	1.62	1.90
annual bias to observation data	**acx**	**adj**	**aeb**	**adl**	**aet**	**mean**	
Precipitation [mm/d]	-0.55	-0.53	-0.52	-0.58	-0.49	-0.53	
Snow water equivalent [mm]	32.9	65.2	66.8	54.5	72.8	58.4	
Evapotranspiration [mm/d]	-	-	-	-	-	-	
Runoff [mm/d]	-0.40	-0.23	-0.22	-0.31	-0.20	-0.27	
internal variability in CRCM [%]	**adj-aeb**	**adj-adk**				**mean**	
Precipitation	±0.59	±0.22				±0.41	
Snow water equivalent	±0.90	±0.44				±0.67	
Evapotranspiration	±0.44	±0.19				±0.32	
Runoff	±0.99	±0.34				±0.67	
internal variability from CGCM driving data [%]	**adj-adl**	**adj-adl**				**mean**	
Precipitation	±2.07	±0.87				±1.47	
Snow water equivalent	±6.24	±5.41				±5.83	
Evapotranspiration	±3.38	±1.24				±2.31	
Runoff	±5.09	±2.46				±3.77	
climate change signal [%]		**adj-adj**	**adk-aeb**	**adl-adl**	**aet-aet**	**mean of adl & adj**	
Precipitation		9.14	8.26	12.37	7.09	10.76	
Snow water equivalent		-11.32	-12.50	-0.40	-13.09	-5.86	
Evapotranspiration		16.66	17.40	11.34	17.31	14.00	
Runoff		5.15	3.75	13.28	2.00	9.21	

Attachment 3: Software Package, *dataextractor*

A software package named "dataextractor" was developed and used in the analysis presented in this report. The *dataextractor* package is designed to extract and analyze data from the database at Ouranos and similarly structured data. It is based on the assumption that analysis of data output from the CRCM simulations will be performed on data of:

- different areas or regions (e.g., watersheds) represented by a selection of grid points
- different sources (e.g., RCM simulations, observations, GCM, …)
- different time periods
- different variables
- different temporal resolution (input and output)
- spatially aggregated data (one value per time of the temporal resolution for the subset) or spatially distributed
- different domains

The program attempts to provide a universal approach to extracting this type of data from the Ouranos database. The starting point for any analysis of these data is a number of grid points of a simulation domain. The grid points to be analyzed form a subset of the domain. This subset can be an arbitrary region. The program will:

- extract, compress and store data for this subset as MATLAB files and
- provide a framework for analyzing and plotting the data

In the process it allows the user to freely alter the region, data source, time period, and variables.

At its core the *dataextractor* establishes a connection between the physical files in the Ouranos archive, each containing a month's data, and the conception of analyzing data based on the above mentioned criteria. The structure of the program and the classes used in the object-oriented structure resemble this conception. On the one end a "Region" class is used to represent the subset. This class allows querying different datasets that relate to the subset. On the other end objects of the "Month" class encapsulate the data of a certain month. Month objects are organized as years in objects of the Year class. Years in turn are organized as time periods and aggregated in the "Time Period" class. The object oriented layout of the program separates the data model from the file access model to achieve independence from file type and data structure. The project is still 'work in progress' so the software grows as new functionality is added.

The *dataextractor* package is software written in object oriented MATLAB. It requires MATLAB version R2008a (7.6) or higher in order for the new version of object oriented MATLAB syntax to work properly. The code follows the naming conventions for identifiers as proposed for the Java language. Figure A3-1 shows a Unified Modelling Language (UML) Class Diagram of the current development stage of the *dataextractor* package.

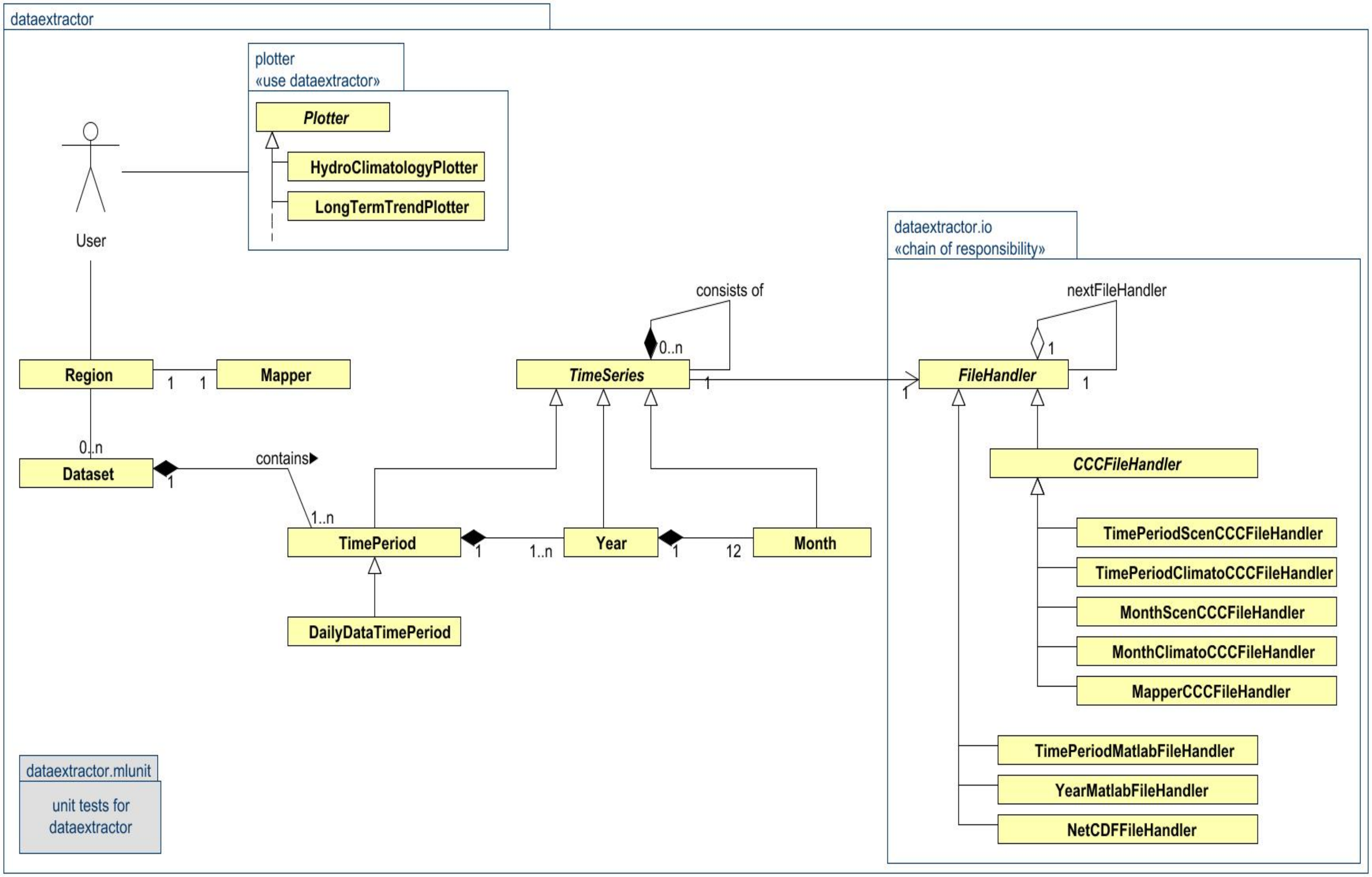

Figure A3-1. Unified Modelling Language (UML) Class diagram of the *dataextractor* package used in the analysis for this report.