Integrated Resource Plan

Appendix 2C

Hydrologic Impacts of Climate Change

BC hydro

Hydrologic Impacts of Climate Change

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Executive Summary

This document provides an introduction to the science of climate change and its impact on the hydrology in British Columbia, and summarizes the implications of historical and future climate change on the water cycle and water availability in watersheds managed by BC Hydro. This document uses the IPCC definition of climate change, which is "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity."

As part of BC Hydro's climate change adaptation strategy, BC Hydro has been working with some of the world's leading scientists in climatology, glaciology, and hydrology to determine how climate change has affected the water supply and what we can expect in the future. BC Hydro has formed partnerships with the Pacific Climate Impacts Consortium (PCIC) and the Western Canadian Cryospheric Network (WC^2N). In addition, BC Hydro has conducted internal studies to investigate historic impacts of climate change on inflows.

When working with climate change scenarios it is important to realize that the goal of working with scenarios is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures. The hydrologic climate change impact studies that were commissioned by BC Hydro included a comprehensive assessment of uncertainties in predictions for the 2050s that considered uncertainties in general circulation modeling, hydrologic modeling, and uncertainties in possible emission trajectories. Despite substantial uncertainty in the magnitude of projected changes, there is a general consensus of the direction of climate change:

- Historical trends in annual reservoir inflows are small and not significant. There is some evidence for a modest historical increase in annual inflows into BC Hydro's reservoirs.
- There is evidence for historical changes in the seasonality of inflows. Fall and winter inflows have shown an increase in almost all regions; there is weaker evidence for a possible modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack.
- For the period of inflow records (35 to 47 years, depending on the reservoir), the severity of year-to-year fluctuations in annual reservoir inflow volumes has not changed.
- Projected warming in the 21st century shows a continuation of patterns similar to those of recent decades.
- All emission scenarios project higher temperatures in all seasons in all areas of British Columbia during the 21st century that will *very likely* be larger than those observed during the 20th century.

- Precipitation projections suggest *likely* increases in winter, spring, and fall for all study areas under all scenarios.
- A modest increase in annual water availability is likely for BC Hydro's hydroelectric system.
- Annual discharge in most Upper Columbia watersheds is projected to likely increase.
- In the Columbia and Kootenay regions, late fall and winter flows will increase slightly; the onset of the snowmelt freshet will be earlier; spring and early-summer flows will be substantially higher; earlier peak flows and higher monthly peak flows can be expected; and late-summer and early-fall flows will be substantially lower.
- Annual discharge is projected to increase in the Peace region, where late-fall and winter flows will increase slightly; the snowmelt freshet will begin earlier due to higher spring temperatures; and summer flows will be lower.
- Snow processes on the South Coast will become less important to the hydrology of the watersheds; fall and winter flows will increase, with a larger fraction of precipitation falling as rain; and spring and summer flows will decrease.
- The Campbell River area will see negligible changes to annual discharges.

The hydrological impact studies constitute the first step in BC Hydro's climate change adaption strategy: identify current and future climate changes relevant to the system. Next steps are to assess the vulnerabilities and risks to climate change across the BC Hydro system and then to develop an adaptation strategy using risk-based prioritization schemes. The BC Hydro Adaptation Working Group will determine where there may be vulnerabilities to climate change, and then specific hydrologic scenarios will be input into existing planning models that simulate the current and future operation of the Generation system to assess whether the operation of the system might need to be adapted in the future.

Remarks

- When working with climate change scenarios it is important to realize that the goal of working with scenarios is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures.
- Uncertainty in specific outcomes is assessed using expert judgments is based on statistical values and expressed with the following probabilities of occurrence:
  very likely = greater than 90%; likely = greater than 66%; more likely than not = greater than 50%; about as likely as not = between 33% and 66%; unlikely = less than 33%; very unlikely = less than10%.

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1 Introduction

More than 90% of the electricity in British Columbia comes from falling water. The amount of available water is directly affected by variations in climate. Land use, volcanic activity, ocean circulation, solar cycles, and the composition of the atmosphere all influence the global climate. An understanding of climate change, and its effect on the water cycle, is critical to ensuring a reliable supply of hydroelectric power for generations to come.

This document uses the IPCC definition of climate change, which is "a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity." Climate change is natural in both the short and long term. Among the most influential short-term events are ocean circulation patterns, such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), which wax and wane every few years as they exchange heat between the oceans and the atmosphere. In the long term, changes in the Earth's orbit around the sun trigger ice ages every 100,000 years or so. Other cycles operate on the scale of millions of years. But the recent global warming trend associated with rising concentrations of greenhouse gases (GHG) that trap heat in the atmosphere is taking place at an unprecedented rate. Understanding the impacts of these accelerated changes is crucial for planning adaptive strategies.

The scientific evidence that global warming is at least partially caused by the emissions produced by burning fossil fuels, and is likely to continue for many decades, is compelling. In its 2007 Fourth Assessment Report, the UN Intergovernmental Panel on Climate Change (IPCC) concluded that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations." Since about AD 1860, temperature records from surface weather stations show an increase of about 1°C over the Northern Hemisphere. Although precipitation records are less reliable, climatologists agree that precipitation over North America has increased by about 10% during the 20th century

Precipitation can fall as rain or snow. It can return to the atmosphere through evaporation, replenish groundwater aquifers, or run off into streams, rivers, and oceans. Higher temperatures increase evaporation, which in turn alters both precipitation and runoff. In humid regions, increases in precipitation will likely lead to more runoff. In dryer regions, extra precipitation tends to evaporate, causing only small changes in runoff. While the effects of a changing climate may reduce water supplies in some regions, it could also increase supplies elsewhere.

Precipitation that falls as snow is temporarily stored as a seasonal snowpack or, after being transformed to ice, as a glacier. Snow and ice are important reservoirs that provide water for rivers in spring and summer. Analysis of historical snow water equivalent (SWE) records since 1950 revealed that nearly all regions in the Pacific Northwest show a negative trend. Snowpacks at 85% of the nearly 600 snow-measurement sites throughout the West decreased over the past 50 years. In the Northern Rockies, rising temperatures since the 1950's (0.8°C in the American West) caused snow pack declines in the range of 15 to 30% (Pederson et al., 2011; Service, 2004). These snowpack reductions are almost unprecedented when compared to snowpack reconstructions from tree-ring chronologies over the past millennium. Lower elevated mountain ranges such as the Northern Rockies are particularly sensitive to temperature changes since a marginal change in temperature can shift a snowpacks energy input from freezing to melting conditions. The role of recent warming on snowpack variability foreshadows future impacts to water supply, streamflow, and hydroelectric power generation.

In many mountainous regions, glacier melt makes a significant contribution to streamflow, particularly in late summer during periods of warm weather following winters with low snow accumulation. This is not only true for small, heavily glaciated headwater catchments but also for large basins with moderate glaciation (less than 10%) such us the Upper Columbia River. Stahl and Moore (2006) found that the effects of glaciers on late summer streamflow can be detected in catchments with as little as 2 to 5% glacier cover. For example, contributions of glacier ice melt to inflows into Mica dam, dominantly occurring in August and September, vary between 3 to 9% on an annual basis but can make up to 35% of late summer inflows. With a warming climate, those contributions are *very likely* to decrease as glaciers retreat.

Thanks to the size and geography of the province, BC Hydro has a diverse portfolio of hydroelectric facilities in various climate zones. This offers a degree of flexibility to adjust to changes in water supplies and reservoir inflow. Still, a rapidly changing climate could overwhelm that capacity to adapt, and climate change can have dramatic effects on other aspects of the hydrological cycle. For example, an increase in forest fires can easily affect water supplies by reducing canopy interception, changing dominant runoff processes, and increasing snow melt energy input. More frequent extreme events tend to undermine system resiliency and could reduce operating flexibility. Changes in temperatures may change the seasonal electricity demand profile. In addition, secondary impacts to habitat, fisheries and infrastructure may require changes to the operation of the generation system.

This document provides an introduction to the science of climate change and its impact on the hydrology in British Columbia, and summarizes the implications of historical and future climate change on the water cycle and water availability in watersheds managed by BC Hydro. It builds on a large body of peer reviewed literature as well as on grey literature (i.e., preprints or internal 'know-how' material) and summarizes key findings of recent studies conducted internally by BC Hydro hydrologists and external studies that were conducted for BC Hydro.

2 BC Hydro's Climate Change Adaption Strategy

BC Hydro's Climate Action Strategy supports and considers both British Columbia's efforts to reduce greenhouse gas (GHG) emissions and the implications of climate change on BC Hydro's operations and infrastructure. Anticipated impacts of climate change in BC include increases in average annual temperature, changes in precipitation patterns, and a greater frequency of extreme events, such as floods, droughts, and wild fires. Hydrological changes could alter the timing and volume of spring run-off, with implications for hydroelectricity generation and the dispatch of resources. An increasing frequency of extreme events may affect system resiliency and operations. BC Hydro must incorporate these potential impacts, many of which have a high level of uncertainty, into long-term planning and operations in order to adapt business practices and change our business infrastructure as required. A climate change adaptation strategy ensures a coordinated approach to understanding and adapting to the impacts of climate change on BC Hydro's operations. For the purposes of the climate change strategy, adaptation is defined as the required measures taken to understand the potential and likely unavoidable impacts of climate change over time and ensure that changes in the climate regime are incorporated into BC Hydro planning and operations.

The objectives of the climate change adaptation strategy are:

1. To enable a coordinated and cost-effective approach to understanding the impacts of climate change on BC Hydro's operations;
2. To provide direction in decision-making or research information and needs related to climate change adaptation based on a consistent risk-based framework;
3. To ensure that mitigation and adaptation measures are complimentary;

4. To partner with external agencies for applied research; and,
5. To ensure that BC Hydro has the adaptive capacity to power BC with clean, reliable electricity for generations.

2.1 Strategy Framework and Development

An Adaptation Working Group (AWG) was established by Safety, Health & Environment to facilitate and ensure the coordination of adaptation activities across BC Hydro and to advise the Executive Team on adaptation issues. Climate adaptation work at BC Hydro seeks to follow the strategy framework developed by the US National Academy of Sciences[1] (see Fig. 1), which includes six steps:

1. Identify current and future climate changes relevant to the system.
2. Assess the vulnerabilities and risk to the system.
3. Develop an adaptation strategy using risk-based prioritization schemes.
4. Identify opportunities for co-benefits and synergies across sectors.
5. Implement adaptation options.
6. Monitor and re-evaluate implemented adaptation options.

This report summarizes information for Step 1 in the framework.

[1] National Academy of Sciences, 2010. "Adapting to the Impacts of Climate Change", National Academies Press, Washington, D.C.

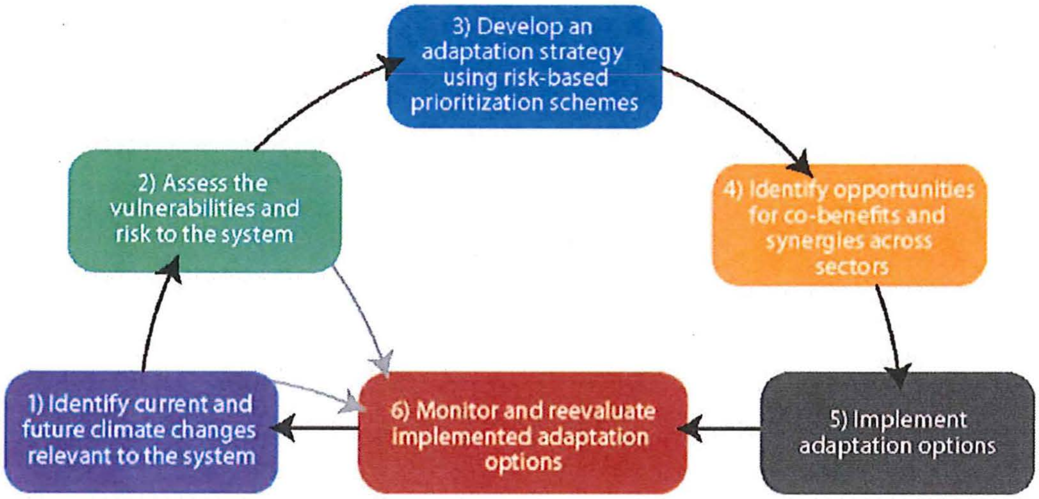

Figure 1. Adaptation Strategy Framework

3 Overview of the Approach to Assess Future Climate Change Impacts

Climate change impact assessments are investigations designed to find out how climate change could impact the natural world and human activities. Climate change impact assessments are largely based on scenarios. Originally used only in military planning, the use of scenarios was extended to strategic planning in businesses and other organizations where decision makers wanted to analyze long-term consequences of strategic decisions. It is important to realize that the goal of working with scenarios is not to predict the future. Scenarios are developed to better understand uncertainties in order to make decisions that are robust under a wide range of possible futures (inherent in this definition is the somewhat low emphasis on likelihoods for a given scenario). In the context of climate change, scenarios are stories about what the future could look like, developed from combining qualitative narratives with quantitative modelling. Climate change scenarios help researchers and managers better understand the consequences of alternative trends in societal development.

Hydrological climate impact studies, including the three studies that produced planning data sets described in this document (PCIC, WC^2N, and UW-CIG), usually follow a similar approach when assessing the impact of climate change on hydrology. In most climate change assessments, numerical modelling, a commonly used method for solving complex water resources problems, is the central tool. Hydrological assessments of future climate change impact relies on a numerical modeling chain that usually entails (i) macro-economic and systems-engineering models to generate future greenhouse gas emission scenarios, (ii) general circulation models (GCMs) to resolve the large-scale global circulation and simulate present and future climate, (iii) downscaling techniques to add regional detail to the coarse GCM simulations, and (iv) hydrological models to convert climatic scenarios into discharge scenarios at the watershed scale (Figure 2).

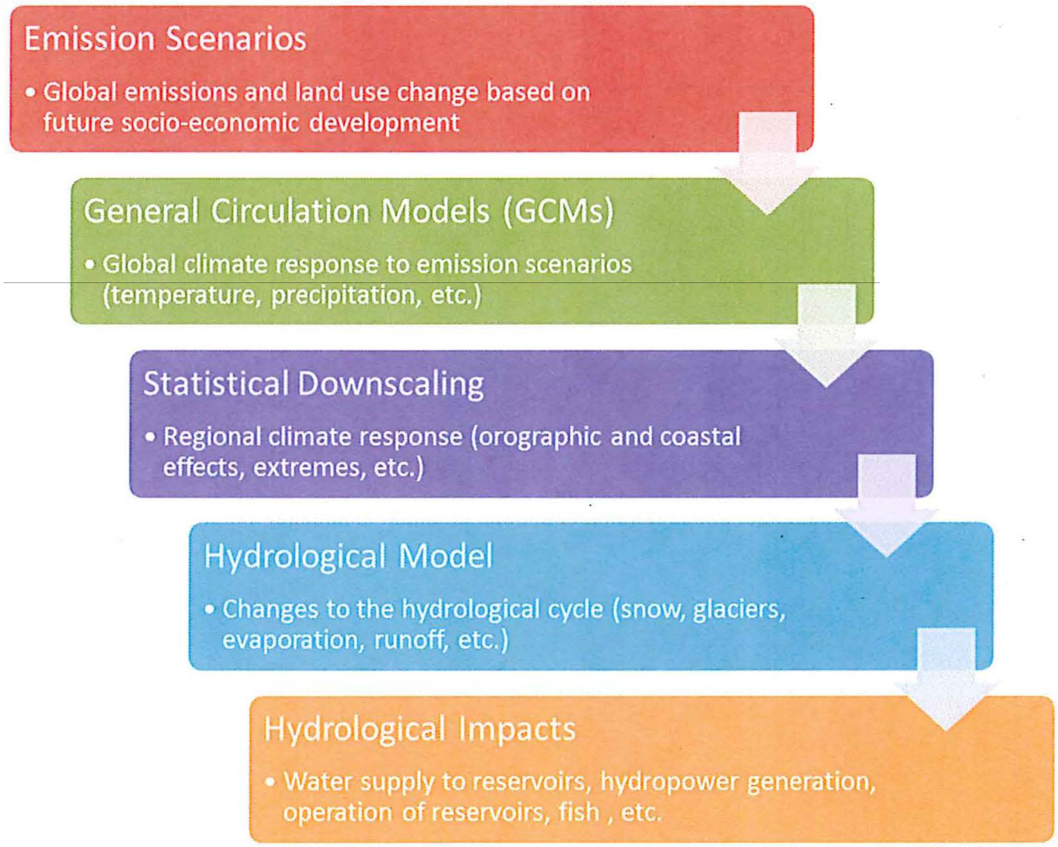

Figure 2. Method for quantifying hydrologic impacts under projected future climates.

3.1 Emission Scenarios

Projections of future greenhouse gas emissions are based on demographic, social, economic, technological and environmental developments. In 2000, the Intergovernmental Panel on Climate Change (IPCC) published its Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000), describing four scenario families, A1 and A2, B1 and B2, for future greenhouse-gas emissions along with sets of storylines derived from integrated assessment models. Scenario family A denotes more economic focus, while B denotes a greater focus on the environment. Suffix 1 refers to a homogeneous, globalized world while suffix 2 refers to a heterogeneous, regionalized world. The most optimistic scenario, B1 with emissions-reducing technologies spreading throughout a world with low population growth, projects a doubling of pre-industrial CO_2 levels by 2100. At the other end of the spectrum, the A1FI scenario (which belongs to the A1 scenario family) with an emphasis on fossil fuels, aka business as usual, projects a tripling of CO_2 to roughly 950 ppm by 2100. The A1B scenario, often seen as the most realistic scenario, belongs to the A1 family of scenarios with a balance use of different energy sources, whereas balanced is defined as not relying too heavily on one particular energy source.

Emissions trajectories for A2 and A1B are such that the projected climate response to A1B is generally larger compared A2 by the mid-21st century, but reversed for the end of the 21st century. At the time the scenarios were developed, all scenarios were considered equally *likely*. However, recent observations show that the emissions growth rate since 2000 is most closely described by the most pessimistic and fossil-fuel intensive IPCC emission scenario, iA1F1 (Raupach et al., 2007).

3.2 Global Climate Models (GCMs)

Global climate models (GCMs) are mathematical models, based on the Navier-Stokes equations, which represent physical processes in the atmosphere, hydrosphere, cryosphere, lithosphere, and in the biosphere. Model output from 23 GCMs are currently available from the Coupled Model Intercomparison Project phase 3 (CMIP3)(Covey et al., 2003; Meehl et al., 2000) and were used in BC Hydro-commissioned studies. An example of such a model is the Canadian coupled global climate model (CGCM) developed by Environment Canada. In some cases multiple runs are made with the same model and with the same emission scenario, but with slightly changed initial conditions. GCMs have been found to broadly reproduce observed features of historical climate at global scales, but fail to reproduce details of the climate at regional and local scales and observed weather sequences. The typical spatial resolution of a GCM is approximately 200 x 200 km^2, which means that processes that occur on scales smaller than 200 x 200 km^2, such as the effects of mountain ranges and coastlines on atmospheric processes such as cloud formation, cannot be resolved.

3.3 Downscaling

Downscaling techniques have been devised to bridge the scale mismatch between climate models and regional impact assessments. The intent of downscaling is to better resolve storm track, to better represent local phenomena such as the effect of mountain ranges in climate forcings, and to better resolve key features of regional climate such as the ENSO cycle, amongst other things. There are two broad categories of downscaling: statistical downscaling and dynamical downscaling (Figure 2). Statistical downscaling uses models that are based on relationships between large-scale atmospheric variables and local-scale variables. In dynamic downscaling, finer scale regional climate models (RCMs) are nested within coarse GCMs over the region of interest. All three future climate change impact studies, UW-CIG, PCIC and WC^{2}N, used statistical downscaling techniques. UW-CIG and PCIC methods are based on the common Bias-Correction Statistical Downscaling technique (Wood et al., 2004). WC^{2}N used a statistical method described in Stahl et al. (2008), which uses TreeGen, a model developed by Alex Cannon and Environment Canada.

3.4 Hydrological Modelling

The catchment response to meteorological forcings is simulated using watershed simulation models or, in the case of regional climate modeling, land surface schemes. Modeling groups typically select their models based on the uniqueness of their goals, familiarity with the model, model forcing requirements, the model's reputation and other practical considerations. PCIC as well as UW-CIG used the Variable Infiltration Capacity Model (VIC), a spatially distributed physically based model, for their hydrologic impact assessments. WC^2N used the Environment Canada version of the Hydrologiska Byråns Vattenbalansavdelning model (HBV-EC), a widely used semi-distributed, conceptual model.

In the WC^2N study, a unique additional modeling step was used to explicitly account for non-stationary land cover. A physically-based glacier dynamics model, the University of British Columbia Regional Glaciation Model (UBC-RGM, Moore et al. 2011), was applied to project the transient response of glaciers to future climate scenarios and to provide boundary conditions for hydrologic modelling. The UBC-RGM was forced with dynamically downscaled GCM simulated data.

4 Study Areas

Hydrological impacts of historical and future climate change on reservoir inflows were assessed for watersheds located in six hydroclimatic regions across British Columbia (Figure 3). These regions represent a range of hydroclimatic conditions from nivo-glacial regimes (snow and glacier dominated) to nival (snow dominated) and pluvial (rain dominated) flow regimes. Table 1 presents BC Hydro reservoirs for which historical and future inflows were analysed. Historical trends reservoir inflows were analysed by BC Hydro hydrologists. For the Mica basin (i.e, the Kinbasket Reservoir), future projections from all three studies were available (Table 1), which allowed a comparison of studies and modelling approaches. The WC^2N (Moore et al., 2011) study focused on the Mica basin only. The UW-CIG data describes total flows for the entire drainage area of each watershed while the PCIC data describes local inflows, i.e., the incremental flows for the local drainage area between two reservoirs. As a result, the raw UW-CIG data can only be directly compared to PCIC (Schnorbus et al., 2011) and WC^2N data at the Mica basin. While summary statistics in this document are given for most watersheds listed in Table 1, the assessment of the impact of future climate change on inflows focuses on three watersheds, each one representative of a hydroclimatic region. The Mica basin is chosen to represent future changes for the nivo-glacial (snow and glacier) and nival (snow) dominated hydrological regimes in the Upper Columbia region since data from all three studies can be directly compared. Williston basin (W.A.C. Bennett Dam), hereafter referred to as GMS, and Strathcona at the Upper Campbell River, hereafter referred to as SCA, are chosen to represent the nival (snow) to nivo-pluvial (snow and rain) hydrological regimes in the Peace River region and the hybrid nivo-pluvial to pluvial (rain) dominated regimes of South Coastal watersheds, respectively.

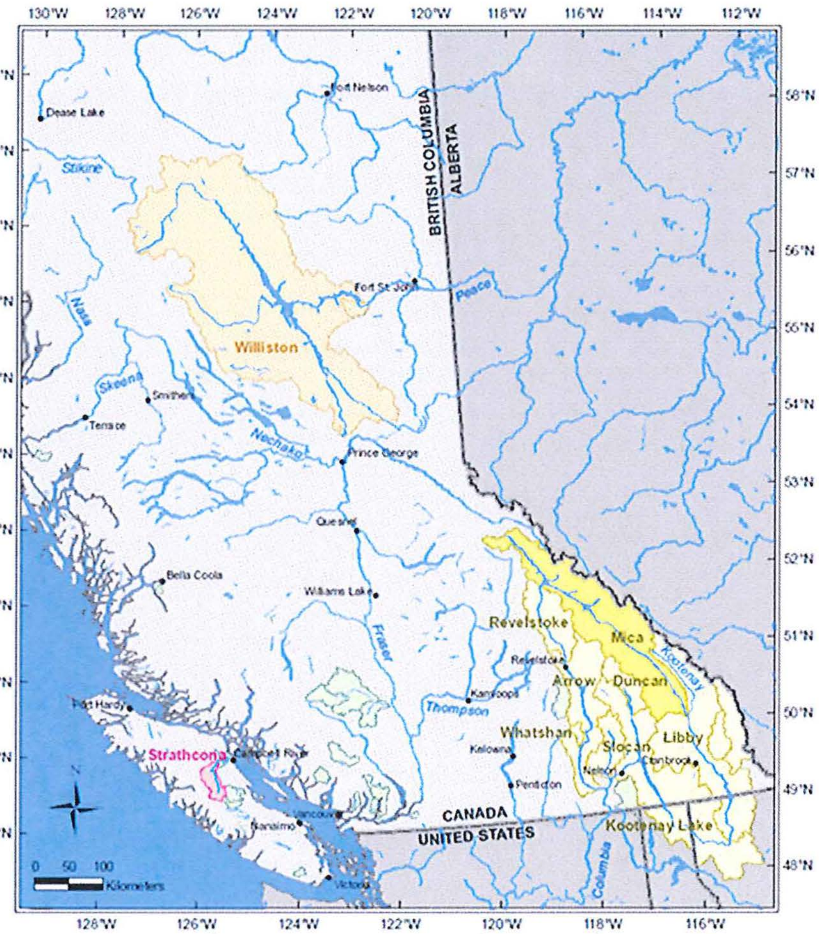

Figure 3. Regions with BC Hydro watersheds and representative watersheds for each region (Mica=yellow, Strathcona=pink, Williston=brown).

Table 1. Description of BC Hydro watersheds that were analysed for historical and future changes in streamflow. Availability of a historical or future (PCIC, UW-CIG, and WC^{2}N studies) analysis for a watershed is marked with 'X'.

Study Region	BC Hdyro Project	roject Lab	Local Drainage Area [km^2]	Elevation min [m]	Elevation med [m]	Elevation max [m]	Glacier Cover [%]	Historical Changes	Future projections PCIC	Future projections RMJOC	Future projections WC^{2}N
Vancouver Island	Strathcona Dam	SCA	1193	139	978	2200	1.8	X	X	n/a	n/a
Vancouver Island	Comox	CMX	464	135	763	2034	0.7	X	n/a	n/a	n/a
Vancouver Island	Ash River	ASH	238	330	717	2034	0.4	X	n/a	n/a	n/a
Vancouver Island	Jordan River	JOR	143	325	646	1081	0.0	X	n/a	n/a	n/a
Lower Mainland	Alouette	ALU	202	114	661	2055	1.4	X	n/a	n/a	n/a
Lower Mainland	Coquitlam	CQD	188	150	802	1790	0.1	X	n/a	n/a	n/a
Lower Mainland	Stave Falls	SFL	956	51	887	2256	2.9	X	n/a	n/a	n/a
Lower Mainland	Wahleach	WAH	88	630	1189	2414	1.2	X	n/a	n/a	n/a
South Coast	Clowhom	COM	381	16	1105	2588	2.4	X	n/a	n/a	n/a
South Coast	Cheakamus	CMS	721	341	1401	2677	8.0	X	n/a	n/a	n/a
Bridge	Bridge	BRR	2719	649	1809	2902	1.5	X	n/a	n/a	n/a
Bridge	Lajoie	LAJ	988	717	1926	2933	19.3	X	n/a	n/a	n/a
Peace	W.A.C. Bennett	GMS	72078	515	1269	2711	0.2	X	X	n/a	n/a
Peace	Site C	SiteC	11822	418	922	2468	0.0	n/a	X	n/a	n/a
Peace	Peace Canyon	PCN	17100	409	1097	2406	0.0	n/a	X	n/a	n/a
Columbia	Spillimacheen	SPN	1430	783	1916	3171	7.6	n/a	X	n/a	n/a
Columbia	Mica Dam	MCA	21134	617	1851	3548	7.8	X	X	X	X
Columbia	Revelstoke Dam	REV	5253	536	1601	3322	4.5	X	X	X	n/a
Columbia	Arrow Dam	ARD	10272	411	1504	3232	1.7	X	X	X	n/a
Columbia	Whatshan Dam	WGS	393	685	1208	2282	0.0	X	X	n/a	n/a
Columbia	Aberfeldie	ABF	1530	914	1795	3136	3.3	n/a	X	n/a	n/a
Columbia	Elko Dam	ELK	3530	913	1866	3044	0.0	n/a	X	n/a	n/a
Columbia	Duncan Dam	DCN	2426	548	1862	3038	5.9	X	X	n/a	n/a
Columbia	Kootenay Canal	KLK	20700	519	1402	3047	0.2	X	X	x	n/a
Columbia	Slocan River	n/a	3320	481	1611	2639	1.3	n/a	X	n/a	n/a
Columbia	Salmo River	SEV	1230	610	1487	2285	0.0	n/a	X	n/a	n/a

5 Observed and Future Climate Change Impact Assessments

Climate change as defined by the IPCC refers to "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity." The IPCC usage of the term climate change differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change is defined as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods." The more general IPCC definition of climate change does not mean that the IPCC does not address anthropogenic causes for climate change. In its assessment reports, the IPCC just separates climate change detection from the assessment of its causes in a different topic (the IPCC assessment report from 2007 is broken into six topics). For the remainder of this document, the IPCC definition of climate change will be used.

To assess the impact of climate change on historical and future water supply of BC Hydro's watersheds, HTS has taken a multi-thread assessment approach. Some studies were conducted internally (Fleming, 2010; Gobena, 2010) whereas others were done in partnerships with the Pacific Climate Impacts Consortium (PCIC) and the Western Canadian Cryospheric Network (WC^2N). Further, due to international status of the Columbia River, BC Hydro has access to U.S. studies of the Columbia River basin, led by the University of Washington – Climate Impacts Group (UW-CIG)(UW-CIG, 2010), and hereafter referred to as the University of Washington – Climate Impacts Group (UW-CIG) data set. The UW-CIG data set has been adopted by the Bonneville Power Administration (BPA) through the River Management Joint Operating Committee (RMJOC) for their long term planning activities of the Columbia-Snake River basin.

5.1 Historical Climate Change Impact Assessment

5.1.1 Historical Climate Trend Analysis by PCIC

Rodenhuis et al. (2007) from the Pacific Climate Impact Consortium (PCIC) conducted a study, commissioned by BC Hydro, to assess the climatology of British Columbia. For the assessment of historical changes in climate, observed temperature and precipitation station data were transformed into high-resolution (50 km) gridded temperature and precipitation data sets using the PRISM (Parameter-elevation Regressions on Independent Slopes Model) methodology. The PRISM methodology accounts for topographic effects and hence is better suited to calculate trends across BC than point station data, which are predominantly derived from climate stations located in the valley bottoms. Long term trends (>50 years) in April 1st snowpack were analysed using a comprehensive snowpack data set across British Columbia.

5.1.2 Analysis of Historical Reservoir Inflow by HTS

A detailed analysis of climate change signals in BC Hydro reservoir inflow was conducted internally by the Hydrology and Technical Services group (Fleming 2010). Inflows into BC Hydro's reservoirs were directly analysed by combining a relatively simple linear technique with direct estimation of signal-to-noise ratios. The analysis was applied to monthly and annual mean inflow data over a common period of record for all basins. The result identifies changes in both seasonal runoff patterns and annual net water supply. An auxiliary analysis was performed to investigate the sensitivity of these results to data selection, processing, and analysis choices.

5.2 Future Climate Change Impact Assessment

5.2.1 Future Climate Analysis by PCIC

Precipitation and temperature projections of future climate using the GCM simulations from the IPCC Fourth Assessment Report were analysed by Rodenhuis et al. (2007). The Canadian Regional Climate Model (CRCM) was also used to obtain climate projections at a regional scale including changes to future snowpack.

5.2.2 Analysis of Future Reservoir Inflows: Planning Data Sets

5.2.2.1 Western Canadian Cryospheric Network (WC²N) Data Set

BC Hydro commissioned a study to assess the glacier and streamflow response to future climate scenarios in the Mica basin, Upper Columbia River (Moore et al., 2011). This study employed the UBC Regional Glaciation Model (UBC-RGM), a dynamic glacier model, along with the HBV-EC hydrologic model. Calibration and testing of the glaciation model was based on available historic mass balance records from glaciers in British Columbia and the Alberta Rockies. The hydrologic model was calibrated using historic streamflow data and changes in glacier volume. Effects of uncertainty in the calibrated parameters and in recent glacier volume change were assessed using an approach based on the Generalized Likelihood Uncertainty Estimation (GLUE) procedure. This study focused on the Mica basin only.

5.2.2.2 Climate Impacts Group at the University of Washington (UW-CIG) Data Set

The Bonneville Power Administration (BPA), the U.S. Army Corps of Engineers (USACE), and the Bureau of Reclamation (BR) collaborated to adopt climate change data sets in their long term planning, which was coordinated by the River Management Joint Operating Committee (RMJOC). The RMJOC performed no modelling studies themselves but analysed and evaluated projections of future climate and hydrology over the Pacific Northwest that were produced by the Climate Impacts Group at the University of Washington (UW-CIG, 2010)). The data relevant to BC Hydro covers the entire Upper Columbia River. For this document, we directly accessed the Upper Columbia River data from the UW-CIG ftp site Instead of taking results from the RMJOC work. This enabled us to perform the same analysis for all three data sources and hence compare results from different studies.

UW-CIG used the physically based, spatially distributed variable Infiltration Capacity (VIC) model. This model does not contain a glacier routine to make the future hydrological projections. Uncertainty in model parameterization was not addressed in this study. The UW-CIG data for future projections has been bias corrected using historical observed streamflow data.

5.2.2.3 Pacific Climate Impact Consortium (PCIC) Data Set

BC Hydro commissioned the PCIC to perform a modelling study with the aim of quantifying the hydrological impacts of climate change in selected watersheds that reflect BC Hydro's power generation assets. The resulting data set (Schnorbus et al., 2011) covers the Peace, Campbell, and Columbia River basins. For the Upper Columbia River, where data was available from all three sources, BC Hydro hydrologists analysed the raw model output in order to compare all three studies. With permission of PCIC, BC Hydro hydrologists used figures and numbers produced by PICIC for regions other than the Upper Columbia to summarize findings for this document. PCIC also relied on the VIC model for their future hydrological projections. However, PCIC implemented a conceptual representation of glaciers into VIC to account for glacier ice melt contributions to late summer streamflow. To mimic glacier ice melt, glaciers where modelled as snow. In this study, glacier dynamics were not accounted for and model parameter uncertainty was not addressed.

6 Historical and Future Changes in Climate

6.1 Historical Changes in Climate

6.1.1 Long Term Historical Changes in Climate

The Earth's climate has always changed throughout geologic time. Paleo reconstructions of temperature indicate that in history, the planet has been both much cooler and much warmer than present. During the past 2 billion years the Earths' climate has alternated between a cold state with large ice caps and a warm state with vast areas of tropical vegetation.

A number of factors contributing to natural climate variations have been identified, including changes in the location of continents, variations in solar output, orbital variations, variations in the composition of the atmosphere, specifically CO_2 levels, volcanic activity, changes in ocean circulation and heat transport, to name the most important ones. As a result, over longer, geologic time scales there are few if any truly permanent, monotonic trends in geophysical series. Further complicating is the fact that quasi-periodic natural planetary climate variability on time scales of years to decades is superimposed on long-term climate change, which can both mask or amplify long-term trends.

Natural variations in the climate system are marked by changes in sea surface temperatures and shifts in the location and intensity of the semi-permanent high- and low-pressure cells that are related to changes in jet stream and predominant storm tracks, which in turn control weather and water availability. Examples of periodical climate variations with annual to decadal time scales that have influence on hydroclimatology of all or parts of western Canada are the El Niño Southern Oscillation (ENSO), Pacific-North America pattern (PNA), North Pacific Gyre Oscillation (NPGO) and Pacific Decadal Oscillation (PDO) (e.g., Gobena 2009).

For the northern hemisphere, paleoclimatic proxies of near surface air temperature, such as tree rings, corals, ice cores, glacier moraines, lake and ocean sediments, ancient rock types that form under specific climate conditions and organisms that are sensitive to climate, indicate a slow cooling from AD 1000 until around AD 1880 (Figure 4) culminating in a period commonly referred to as the 'little ice age' (NASA defines 'little ice age' as the period between 1550 and 1880). The cooling was not constant but interrupted by several warmer periods, most prominently the medieval warm period. Since about 1860 AD, instrumental temperature records from weather stations around the globe indicate an increase in near-surface temperatures of approximately 1°C for the Northern Hemisphere, including North America and north-western Canada. The scientific evidence that global warming is at least partially caused by anthropogenic activity is increasingly compelling. IPCC in its 4th assessment report in (AR4, 2007) concludes that "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations". The far right hand side in Figure 4 visualizes the anthropogenic effect on temperature by comparing simulated temperatures during the last 1000 years with (thick lines) and without (thin lines) anthropogenic forcings.

Although historical precipitation records are far more difficult to establish, there is scientific agreement that precipitation over North America has increased by about 10% during the 20th century (IPCC, 2007).

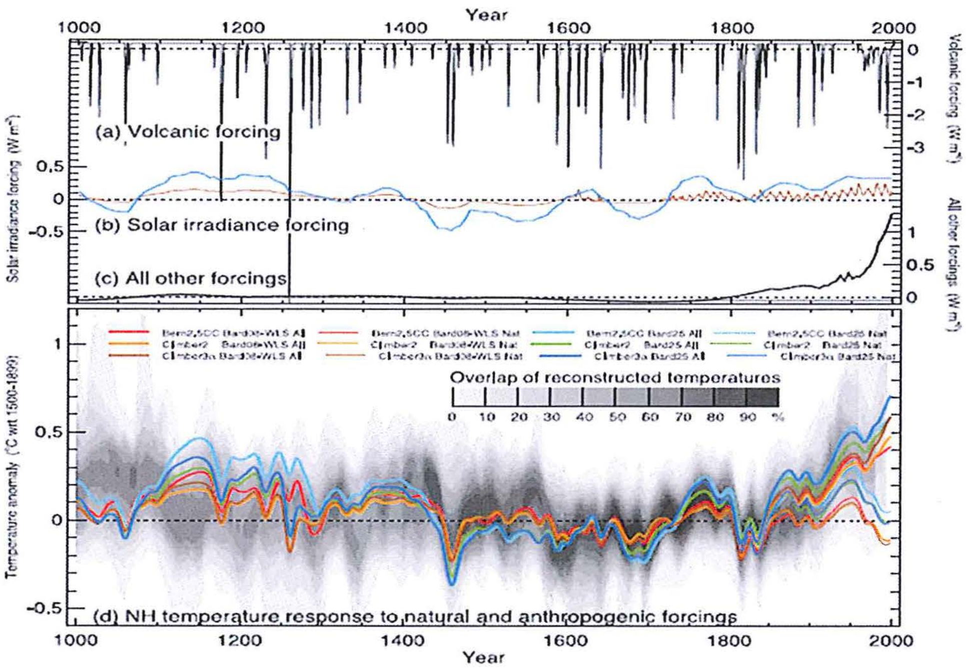

Figure 4. Simulated temperatures during the last 1000 years with (thick lines) and without (thin lines) anthropogenic forcing and overlap with temperature reconstructions. Source: National Oceanic and Atmospheric Administration http://www.ncdc.noaa.gov/paleo/pubs/ipcc2007/fig614.html.

6.1.2 Historical Changes in Climate at an Instrumental Time Scale

For assessing the background of historical climate variability in British Columbia, it is important to place 21st century changes into historical context. Historical trends in precipitation and temperature are indicators of climate change. British Columbia's temperature and precipitation trends from 1900 to 2004 are generally consistent with trends observed elsewhere in North America. British Columbia as a whole has become warmer and wetter. Trends are not uniform during all periods of the year and across all regions. Climate trends in British Columbia for the 1900 to 2004 period were analyzed by (Rodenhuis et al. 2007). All parts of British Columbia became warmer (Figure 5 a), with mean annual temperature increases of about 1°C (Figure 5a). Most of the temperature increase is a result of increasing daily minimum temperatures (Figure 7), i.e., "it got less cold, rather than substantially warmer". Winter temperatures in the north of British Columbia increase more than temperatures in the south (Figure 7 a and b). Daily maximum temperatures in summer and fall became colder, which, in conjunction with increases in daily minimum temperature, caused a decrease in the daily temperature range. Trends in minimum temperatures range from 1.0 to 2.5°C per century and are largest in the Peace Region (2.0°C per century) and in the Okanagan (1.8°C per century). Trends in maximum temperatures range from 0.5 to 1.5°C per century and are largest in the Columbia Region (1.3°C per century) and in the Okanagan (1.0°C per century). Positive trends in winter maximum temperatures are significant in the Columbia Region, the Okanagan, on the South Coast, and on the north-west of the province. The Peace Region and the Okanagan show significant positive trends in spring maximum temperatures.

Annual precipitation in British Columbia increased by about 20% (Figure 5 b), which is consistent with a 5 to 35% precipitation increase across Canada that has been reported by Zhang (2000). Most of the precipitation increase in British Columbia occurred in fall, winter, and spring, with highest increases in the northern interior of British Columbia and with no trends in the south-western parts of the province (Figure 7 e, f, h).

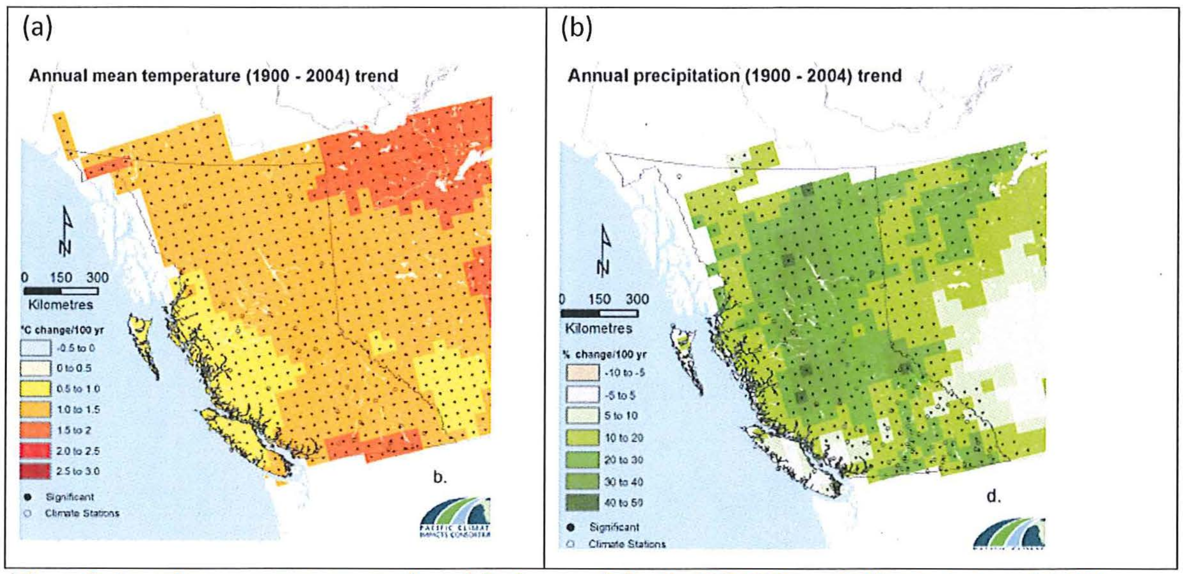

Figure 5. Annual mean temperature and precipitation trends for the 1900-2004 period (Rodenhuis et al. 2007)

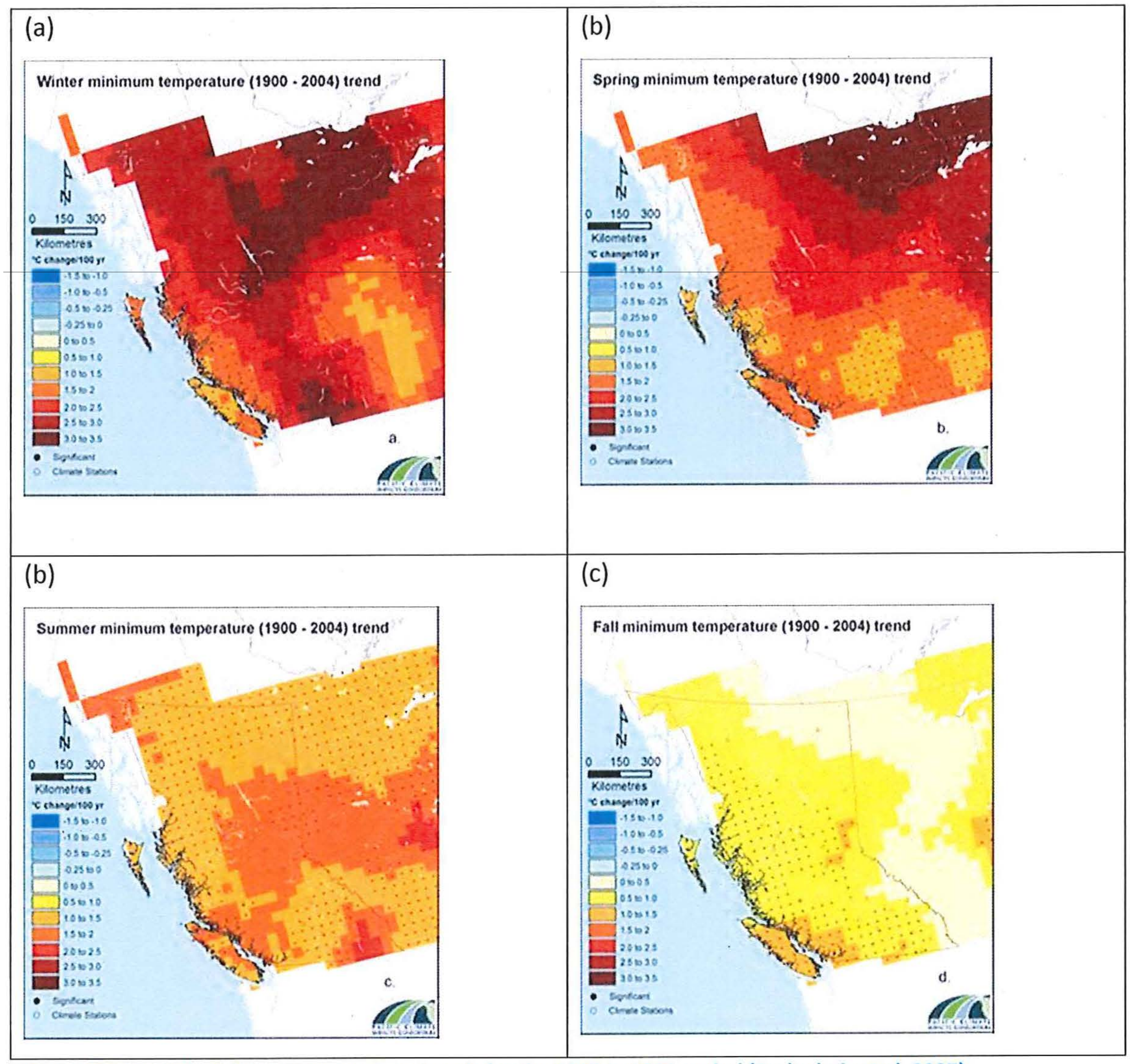

Figure 6. Seasonal minimum temperature trends for the 1900 to 2004 period (Rodenhuis et al. 2007).

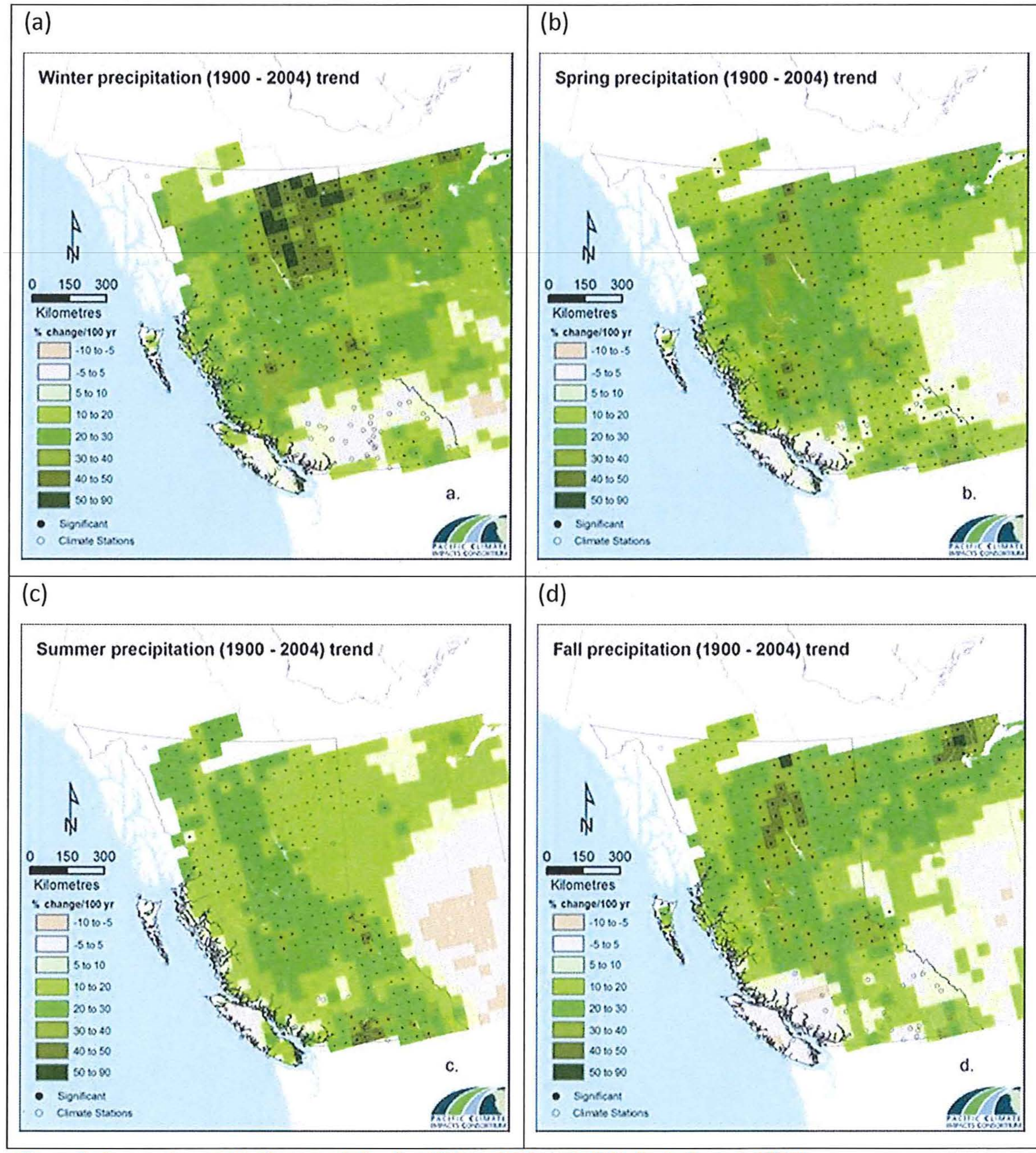

Figure 7. Seasonal precipitation trends for the 1900 to 2004 period (Rodenhuis et al. 2007).

Mountain snowpacks are an important factor in the water cycle and a large component of seasonal water storage in most of BC Hydro's watersheds. For many BC Hydro projects, basin-wide snow storage is larger than reservoir storage. A snowpack's water content is reported in millimeters of snow water equivalent (SWE). In British Columbia and in North America in general, SWE measured on April 1st is an index of the maximum seasonal snow accumulation, even though the timing of peak accumulation can vary substantially at individual measurement sites and from year to year. Since April 1st snowpack records are generally longer than for any other time of the year, trend analysis is often done with April 1st SWE data.

Peak winter snow accumulation in British Columbia experienced a substantial reduction over the 1950's and the early 21st century (Chapman 2007 and Rodenhuis et al. 2007). Chapman (2007) found that on average across the province, April 1st SWE dropped by about 18% on average between 1956 and 2005 with substantial spatial differences (Table 2). The Middle Fraser region experienced a 47% reduction, while the Peace region showed no notable changes (~4% reduction). The Columbia region showed a 20% reduction in April 1st SWE, the Kootenay region 23%, and the South Coast and Vancouver Island region showed a 17% reduction in April 1st SWE. Contrary to the overall trend, some - mostly northerly - measurement locations recorded increases in SWE.

Chapman (2007) concluded that much of the reduction in April 1st SWE over past 50 year period is related to variability in the ENSO and PDO signals. The transition to a PDO warm phase in 1976 is marked by a sharp reduction in April 1st SWE at many monitoring sites. A climate change signal can be obtained by removing the low frequency climate variability stemming from the ENSO and PDO effects from the data. After removing the ENSO and PDO effects, the province wide April 1st SWE trends become very small with a snowpack decline of about 4% on average (Table 2). In some regions, the Peace region for example, removing the ENSO and PDO effects reverses the direction of the trend. The Middle Fraser region experienced the highest non ENSO or PDO related reductions in April 1st SWE (27% reduction).

An important limitation of analysing SWE data from snow courses and snow pillows is that relationships between snow trends and elevation are difficult to establish because very little of the British Columbia snow survey network is located at the lowest and highest elevations, but biased towards 'mid-elevations.' Modeling studies suggest that the highest elevated areas, which are cold enough to be less sensitive to warming and which have historically seen increases in precipitation, follow precipitation trends rather than temperature trends and hence show positive snowpack trends from 1950 to 1997.

Table 2. Trends in April 1st Snow Water Equivalence at British Columbia long-term snow courses. Results are shown for unadjusted data and data with the effects of ENSO and PDO variability removed (Chapman, 2007).

Basin / Region	Percent Change 1956-2005					
	Unadjusted data			Adjusted data *		
	Min.	Mean	Max.	Min.	Mean	Max.
Peace	-21	-4	8	-12	7	20
Columbia	-73	-20	-2	-47	-5	10
Kootenay	-36	-23	-11	-19	-6	5
Middle Fraser	-97	-47	-13	-61	-27	3
South Coast/ Vancouver Island	-20	-17	-13	-13	-4	4
British Columbia	-97	-18	47	-61	-4	40

* PDO and ENSO signal removed

A change in glacier cover provides visually compelling evidence of the effects of climate change on the water cycle. Mountain glaciers in British Columbia lost about 11 % of their area between 1985 and 2005. Relative to the 1985 glacier cover, maritime glaciers in British Columbia lost less area than interior glaciers. However, since maritime glaciers contain more ice mass than their interior counterparts, absolute glacier volume loss is larger in the Coast Mountains than in the Columbia region and the Rocky Mountains (Schiefer et al., 2007). In the Columbia River basin the decline of glacier cover from 1986 to 2000 was approximately 16% (Moore et al., 2011). As one would expect, glaciers thinned most at low elevations. Figure 8 illustrates the retreat of the Illecillewaet Glacier at Roger's Pass (Selkirk Mountains) in the Arrow basin between 1887 and 2000.

In 2005, glaciers - ranging from large ice fields to valley and small hanging glaciers - occupied approximately 25,000 km^2 or 3% of British Columbia's surface area (Bolch et al., 2010). Glacier coverages in BC Hydro watersheds range from 0 to 19%. Watersheds with glacier coverage more than 2% of the drainage area include Lajoie (19%), Cheakamus (8%), Duncan (6%), Mica (5%), Revelstoke (5%), and Stave (3%). Obviously, the impact of glacial processes on watershed hydrology decreases from the toe of a glacier to the point where the river enters the reservoir. At the scale of watersheds operated by BC Hydro, the impact of glacier ice melt to annual inflow into most reservoirs is therefore relatively minor. However, for late summer flows even a glacier cover of 5% can significantly contribute to streamflow. In the Mica basin, a basin with 5% glacier cover, for example, the mean annual contribution of ice melt to total streamflow from 1972 to 2007 varied between 3 and 9% and averages 6%. In years with low snow accumulation and high temperatures such as 1998, glacier ice melt contributed 25% to August streamflow and 35% to September streamflow. In low glaciated basins like Mica, sensitivity of streamflow to historical changes in glacier area is low. However, as it will be shown later, the sensitivity of streamflow to future changes in glacier area is detectable with hydrological models and not negligible.

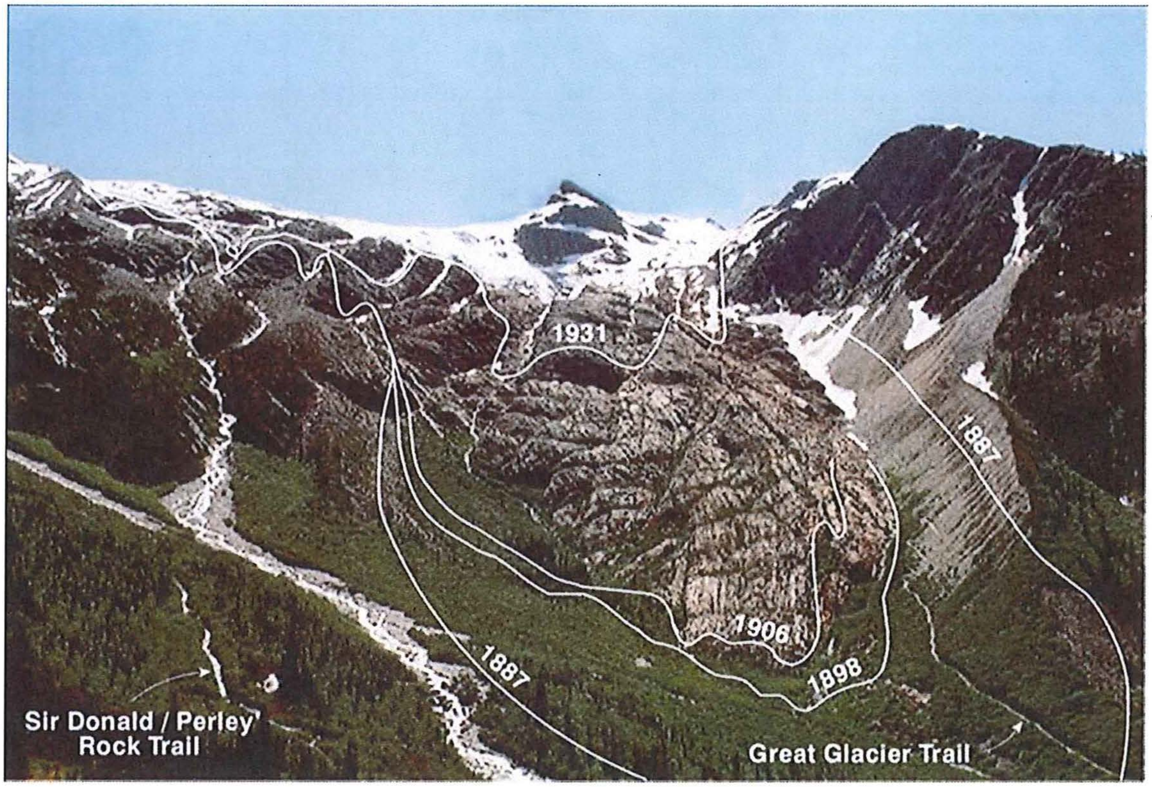

Figure 8. Extent of Illecillewaet Glacier at Roger's Pass (Selkirk Mountains) in the Arrow watershed approximately in 2000 and with lines indicating previous glacier extent. Source: Dr. Dan McCarthy, Brock University & Mas Matsushita, Parks Canada.

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Summary of historical trends in climate

Temperature

- Over the last century, mean annual temperature in British Columbia increased by about 1°C
- All parts of British Columbia got warmer
- Mean temperature increases are caused by increasing daily minimum temperatures in winter and spring ("it got less cold, rather than substantially warmer")
- The northern parts of British Columbia are experiencing the highest increase in fall and winter minimum temperatures
- Cooling was detected in daily maximum temperatures in summer and fall

Precipitation

- Over the last century, British Columbia as a whole became wetter
- Precipitation trends are not uniform during all periods of the year and across all regions
- Annual precipitation increased by about 20 % mainly due to increases in fall, winter and spring precipitation, and due to increases in northern interior British Columbia
- There are areas where precipitation decreased
- No precipitation trends are found in south-western British Columbia

Snow

- On average across the province, the April 1st SWE was 18% lower in 2005 than it was in 1956
- Most of the historical snowpack decline can be attributed to ENSO and PDO signals and not to long term climate change
- After removing the ENSO and PDO signals trends in snowpack decline are much smaller and average to a 4% reduction over British Columbia
- The Middle Fraser region experienced the highest non ENSO or PDO related reductions in April 1st SWE (27% reduction)

Glaciers

- Between 1985 and 2005 glaciers in British Columbia lost about 11 % of their area
- Relative to the 1985 glacier cover, maritime glaciers in British Columbia lost less area than interior glaciers
- Since maritime glaciers contain more ice mass than their interior counterparts, absolute glacier volume loss is larger in the Coast Mountains than in the Columbia and Rocky Mountains
- The annual contribution of glacier ice melt to reservoir inflows is small and in the range of a few percent (e.g., 3 to 9% for Mica basin)
- In years with low snow accumulation and high temperatures glacier ice can substantially contributed to late summer streamflow (e.g., 25% to August streamflow and 35% to September streamflow in 1998 in the Mica basin)

6.2 Future Changes in Climate

Future climates in the 21st Century are derived from GCM simulations driven by different emission scenarios. Future greenhouse gas emissions are difficult to project because they depend on societal development, i.e., on economic growth, on population increase, on technological change and on changes in land use. The wide range of emission scenarios reflects these uncertainties. No single GCM is perfect; each one has its strengths and weaknesses. For a given emission scenario, different GCMs will produce different climate projections due incomplete physical knowledge, model parameter uncertainty, and the extreme nonlinearity of the climate system. The range of GCM projections for a given emission scenario reflects these modelling uncertainties.

To quantify uncertainties it is important to consider several emission scenarios and GCMs. The result is a large number of future realities, each physically plausible and equally *likely*, and - ideally - bracketing the envelope of what will ultimately become reality. The selection of GCMs and emission scenarios depends on the intended application. There is no universal set of performance metrics that are optimally suited for all applications. Modelling groups usually use different rationales or methods to select the GCMs and emission scenarios that will be used for a climate change impact assessment.

With the objective of reducing computational time and easing interpretation of the results, the WC^2N and PCIC studies used a similar, multicriteria-based approach to select emission scenarios climate scenarios. GCMs were selected based on how good they reproduce global, regional and local phenomena. Poorer performers were omitted and the remaining GCM ensemble members were treated as statistically indistinguishable. This lead to the selection of 16 and 23 scenarios for the WC^2N and the PCIC study, respectively.

The selection of emission scenarios in the UW-CIG study were based on the rationale that future climate scenarios should reflect the central estimates of future climates as well as bracket the range of temperature and precipitation changes. In addition, a scenario that predicted the least change in precipitation and temperature was chosen. This approach led to six scenarios, which were labelled 'central,' 'more warming and wetter,' 'less warming and wetter,' 'more warming and drier,' 'less warming and drier,' and 'minimal change.'

The following summary of future projections of climate change is based on the analysis of future climate by PCIC (Rodenhuis et al. 2007), but also draws from the analysis of future reservoir inflows by PCIC (Werner, 2011; Schnorbus et al. 2011) and the PCIC Regional Analysis Tool (http://pacificclimate.org/tools-and-data/regional-analysis-tool).

All model projections, independent of GCM and emission scenario, are fairly consistent in the direction and magnitude of regional temperature changes and less consistent about the direction and magnitude of precipitation changes. In general, trends observed during the past century in British

Columbia will *likely* continue throughout the 21st century. The *very likely* projected warming will *likely* be accompanied by wetter conditions.

Ensemble of 23 downscaled projections from 8 GCMs runs under B1 (except for HADGEM1, for which B1 was not available), A1B and A2 project that in the 2050s (2041-2070) all parts of British Columbia will *very likely* get warmer and temperatures will rise in all four seasons relative to the 1961-1990 baseline period (Figure 9).

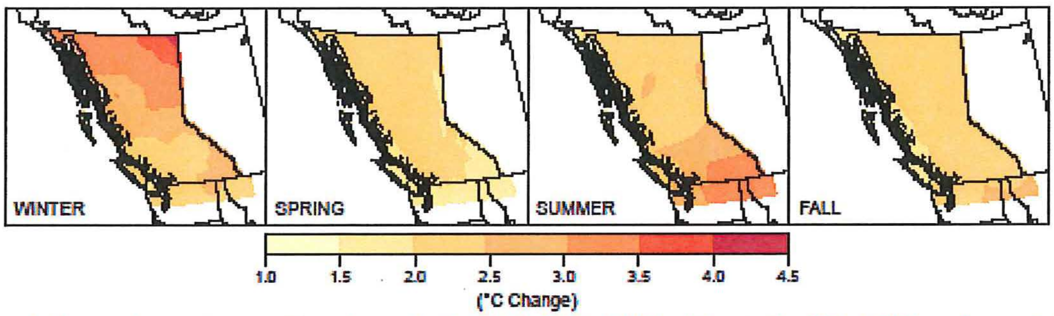

Figure 9. Seasonal mean temperature change in the 2050s (2041-2070) relative to the1961-1990 baseline period. Source: Schnorbus et al. (2011).

By the mid 2050's (2041-2070), mean annual temperature is projected to increase by 1.4 to 3.7˚C (median change is 2.3˚C) relative to 1961-1990 baseline period (Table 3). The expected warming will fall outside the range of instrumental historical variability (the historical period for which observations exist). In southern interior British Columbia, e.g. the Columbia River basin, warming will be greatest in summer (Table 4), while in north-eastern British Columbia, e.g. the Williston basin, warming will be greatest in winter. In south coastal British Columbia, e.g. the Strathcona watershed, warming will be more evenly distributed across the seasons.

Much of British Columbia will *likely* become modestly wetter (Figure 10). Ensemble projections for the 2050's show a median annual precipitation increase of 8% across British Columbia relative to 1961-1990 baseline period (Table 3). Depending on the region, the projections of annual precipitation increases range between 0 and 18 % (Table 4).

Contrary to temperature projections, the projected increase in precipitation is not expected to fall outside the range of instrumental historical variability, which suggests that precipitation changes are much more modest compared to temperature change. Precipitation increases in the southern Interior and in north-eastern and south coastal British Columbia are projected to be greatest in fall, winter and spring (Table 4).

Precipitation increases are higher for the northern and north-eastern parts of the province, where increases are also more evenly distributed across all seasons. In summer, the southern portion of the province, and particularly the southwest, will *likely* become drier (Table 4).

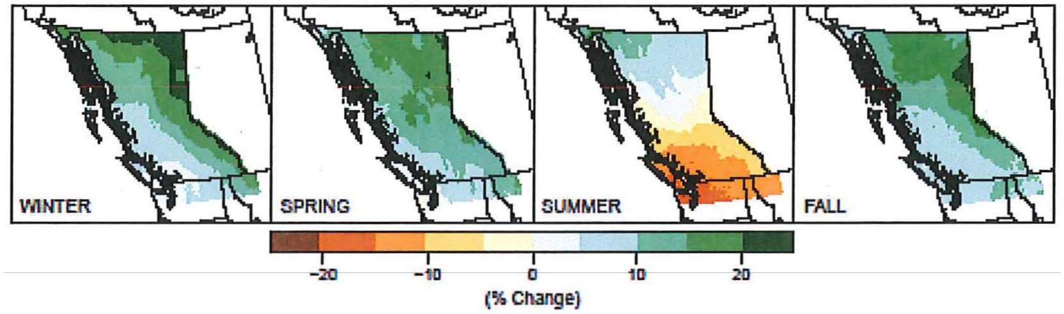

Figure 10. Seasonal mean precipitation change in the 2050s (2041-2070) relative to the 1961-1990 baseline period. Source: Schnorbus et al. (2011).

Table 3. Ensemble temperature and precipitation anomalies of the 2050s (2041-2070) relative to the 1961-1990 baseline period for British Columbia; the ensemble includes 23 downscaled projections from 8 GCMs run under B1 (except for HADGEM1, for which B1 was not available), A1B and A2. Source: Werner et al. (2011).

	Temperature Anomaly (°C)					Precipitation Anomaly (%)				
	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall	Annual
Minimum	0.6	1.1	1.4	1.3	1.4	5	0	-21	1	0
Average	2.6	2.1	2.6	2.2	2.4	13	12	-3	13	9
Median	2.7	2.1	2.5	2.1	2.3	12	13	-1	12	8
Maximum	3.6	3.2	4.4	3.9	3.7	26	19	5	27	18

Table 4. Regional ensemble average temperature and precipitation anomalies of the 2050s (2041-2070) relative to the 1961-1990 baseline period, the ensemble includes 23 downscaled projections from 8 GCMs run under B1 (except for HADGEM1, for which B1 was not available), A1B and A2. Source: Werner (2011).

	Temperature Anomaly (°C)					Precipitation Anomaly (%)				
	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall	Annual
South Coast	2	2	2.5	2.1	2.2	5	6	-14	8	4
Okanagan	2.4	2.2	3.2	2.4	2.5	7	9	-14	9	3
Columbia	2.4	2.1	3.1	2.3	2.5	13	12	-9	12	8
Fraser	2.4	2.2	2.6	2.2	2.4	11	11	-7	12	6
North Coast	2.2	2	2.1	2	2.1	9	8	-5	9	7
Northwest	2.7	2.1	2.3	2.2	2.3	15	12	8	13	12
Peace Basin	3.1	2.2	2.4	2.3	2.5	19	17	4	17	12

Summary of future trends in climate

Temperature

- By 2050 all parts of British Columbia will *very likely* become warmer
- Mean annual temperature is projected to increase by 1.4-3.7ºC relative to 1961-1990 baseline period (median change is 2.3ºC)
- The expected warming will fall outside the range of historical variability
- In the southern interior of British Columbia (e.g., the Columbia River basin) warming will be greatest in summer
- In north-eastern British Columbia (e.g., the Williston basin) warming will be greatest in winter
- In south coastal British Columbia (e.g., the Strathcona basin) warming will be evenly distributed across the seasons

Precipitation

- By 2050 much of British Columbia will *likely* become modestly wetter (median ~8 %)
- Depending on the region, the projections of annual precipitation increase range between 0 and 18 %
- The projected increase in precipitation is not expected to fall outside the range of historical variability
- Precipitation increases in the southern interior, northeastern and south coastal British Columbia are projected to be greatest in fall, winter and spring
- Precipitation in the northern and particularly northeastern parts of the province show the highest precipitation increases with increases across all seasons
- In summer, the southern portion of the province, and particularly the southwest, will *likely* become drier

7 Historical and Future Impacts of Climate Change on Reservoir Inflows

7.1 Historical Changes in Reservoir Inflows

7.1.1 Long Term Historical Changes in Streamflow

Paleo-climatological methods such as tree-ring records, changes in isotope concentrations, or changes in organic carbon, nitrogen, cellulose oxygen isotope composition etc. can be used to reconstruct long term records of streamflows, which can then be used to put instrumental records of streamflow into perspective.

Wolfe et al. (2005) reconstructed streamflows for the Peace River at the Peace-Athabasca Delta by multi proxy paleo-climatological analysis of lake sediments. They found that although regulation of the Peace River for hydroelectric power generation since 1968 has been blamed as the major reason for an extended period of drying due to a reduced frequency of ice jams, both wetter and drier conditions have persisted for decades in the recent past under natural climatic variability. Furthermore, they found that the recently observed dryness is part of a longer trend which began some 20–40 years prior to Peace River regulation.

Hart et al. (2010) applied dendro-climatological techniques to establish long term streamflow records for Chilko River, a glacier fed watershed in the Coast Mountains of British Columbia. Their findings are similar to those of Wolfe et al. (2005), i.e. recent observed streamflow variability is well within the range of long term streamflow variability. In British Columbia, discharge, PDO and ENSO have the highest influence on streamflow when in phase (Hamlet and Lettenmaier, 1999). Hart el al. (2010) confirmed that PDO teleconnections have a long-term influence on the hydroclimatic regime on Chilko River streamflow but found no significant influence of ENSO (though one ENSO index was nearly significant).

For the Columbia River at The Dalles, streamflow reconstructions based on dendro-chronological records by Gedalof et al. (2004) also found that the instrumental streamflow record is within the variability of the reconstructed record (the instrumental record captures between 65 and 78% of the variability in the flow record). There were several periods of severe low flows since 1770, the most severe one occurred during the 1840's with nearly as extreme low flows during the 1930's. Observed as well as reconstructed flows show that the period between 1950 and 1987 is anomalous because of its lack of a notable multiyear drought. A comparison of the reconstructed streamflow with paleorecords of PDO and ENSO show a significant correlation in the 20th century, but suggests only a very weak link prior to 1900.

7.1.2 Historical Changes in Reservoir Inflows at an Instrumental Time Scale

A detailed analysis of climate change signals of BC Hydro reservoir inflow was conducted by BC Hydro hydrologists (Fleming, 2010). Fleming (2010) found that historical trends in BC Hydro reservoir inflow over the 1984 to 2007 period were mostly very small. There is no significant evidence for historically declining annual total water supply in any of the basins that were analyzed (Table 5). Rather, there is some evidence for a modest historical increase in streamflow in some basins (Table 5). Despite the lack of significant trends in annual flow volumes, there is evidence for changes in the seasonality of inflow: fall-winter inflow increased at almost all basins in the study. Weaker evidence exists for a possible modest decline in late-summer flow for those basins driven primarily by melt of glacial ice and/or seasonal snowpack (Table 5). No evidence was found for historical changes in the severity of year-to-year fluctuations of annual reservoir inflow volumes, which implies that the reliability of annual water supply forecasts has not changed significantly.

Overall conclusions regarding long-term trends in water supply were found to be largely insensitive to methodological choices. That no trends in annual inflows were detected by Fleming (2010) does not imply that there are no trends. The short records length and data quality issues, combined with possibly a low-amplitude climate change signal that is superimposed on comparatively high-amplitude year-to-year fluctuations, create challenges in providing an adequately picture of long-term trends.

Table 5. Results from primary trend analysis for all months, as well as annual means and combined usable inflow, presented as linear slopes in m3/s/yr for mean volumetric flow rates, or GWh/yr for combined usable inflow. Blue and red shading indicate positive and negative water resource trends, respectively; slope values with a magnitude equal to zero within one decimal place are left uncolored. Trends with signal-to-noise ratios 0.1 or greater are outlined by a box; those with S:N > 0.20 are additionally illustrated in bold font.

REGION	PROJECT	O	N	D	J	F	M	A	M	J	J	A	S	yr
south coastal	SCA	0.7	1.9	**2.1**	1.9	-1.3	-0.1	0.3	0.8	1.1	0.8	0.0	0.2	0.7
	CMX	0.4	0.7	**0.9**	0.9	-0.7	0.1	0.4	0.4	0.4	0.3	0.0	0.1	**0.3**
	ASH	0.2	0.1	0.4	0.4	-0.6	-0.1	-0.1	0.0	0.0	0.2	0.1	0.1	0.0
	JOR	0.2	0.0	0.5	0.6	-0.3	0.4	-0.1	-0.2	0.0	0.0	0.0	0.1	0.1
	ALU	0.3	-0.1	**0.7**	0.4	-0.3	0.5	-0.1	-0.2	0.1	0.2	0.1	0.1	0.2
	CQD	0.2	-0.1	**0.7**	0.5	-0.3	0.4	0.0	-0.1	0.2	0.2	0.1	0.1	0.2
	SFL	1.0	0.0	**3.5**	2.4	-1.6	1.8	-0.1	-0.2	0.5	0.8	0.4	0.2	0.7
	WAH	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	COM	0.4	0.4	**0.9**	0.7	-0.5	0.2	0.1	-0.1	0.3	0.7	0.0	0.2	0.3
	CMS	0.2	0.4	**0.7**	0.7	-0.3	-0.1	0.0	-0.3	-0.2	-0.1	-0.5	-0.1	0.0
Bridge	BRR	0.0	0.1	0.3	0.1	-0.1	-0.1	0.0	0.1	0.9	0.9	-0.3	0.2	0.2
	LAJ	-0.3	0.0	0.1	0.1	0.1	0.0	0.1	0.3	0.7	0.7	-0.7	-0.4	0.1
Columbia	MCD	3.7	1.3	**1.8**	**1.7**	0.9	0.9	0.7	-0.1	1.1	7.3	-5.1	0.0	1.2
	REV	1.5	0.0	-0.1	0.7	-0.2	-0.1	0.1	0.9	1.7	3.4	-0.9	0.2	0.6
	ARD	2.1	0.3	1.5	1.7	0.9	1.4	-0.4	2.0	0.5	0.0	-2.0	0.1	0.7
	WGS	0.1	0.0	0.0	0.1	**0.1**	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.1
	SGR	0.5	0.2	0.2	**0.3**	0.2	0.1	-0.1	0.1	0.5	-0.3	-0.3	0.0	0.1
Kootenays	DDM	1.2	0.3	0.0	0.2	0.1	0.1	0.1	0.9	0.2	1.5	-0.6	0.9	0.4
	KLK	1.7	-0.8	2.1	3.0	1.1	3.3	-1.8	4.1	3.5	1.4	0.1	0.5	1.5
Peace	GMS	-1.6	0.5	0.2	-0.4	2.0	0.4	2.4	-3.1	22.2	-2.3	1.4	1.8	2.0
combined usable inflow	n/a	9.6	7.1	**14.6**	**14.2**	1.1	6.2	4.0	-0.8	39.7	21.2	-14.6	1.7	8.7

Summary of Historical changes in reservoir inflows

- Historical trends in annual inflows into BC Hydro reservoirs between 1984 and 2007 are very small and statistically not significant
- In some basins there is evidence for a modest historical increase in annual water supply
- Seasonality of inflow has changed
- Fall-winter inflows increased and late-summer flows declined
- Year-to-year fluctuations in annual reservoir inflow volumes have not changed

7.2 Future Changes to Reservoir Inflows

In most of the scientific literature future projections are presented separately for each emission scenario. To facilitate a study inter-comparison for the Mica river basin, flow projections in this report are either aggregated into a single probabilistic projection, or are compared based on the A1B emission scenario (comparisons of other emission scenarios can be requested from HTS). Aggregating emission scenarios into one probabilistic projection is justified by the equal likelihood of emission scenarios given by the IPCC (2007). Another justification of summarizing all emission scenarios into one probabilistic framework is that emission scenarios – at least to some extent - influence the range of possible outcomes and hence define the entire probability distribution, which forms the base for decision making. Though future projections are available up until 2100, the summary in this report focuses on reservoir inflow projections around 2050.

A prerequisite for simulating future reservoir inflows with a hydrological model is an adequate model performance. Multi-agency projections are available for Columbia and Kootenay River watersheds. BC Hydro-commissioned studies, PCIC and WC^2N, and the UW-CIG study individually assessed prediction uncertainties. What is deemed 'adequate' model performance depends on a variety of factors, most importantly the quality of forcing data (garbage in – garbage out), the quality of streamflow, i.e. reservoir inflow, data, and the type of hydroclimate. For example, in a snow dominated watersheds like the Mica basin with good quality streamflow and forcing data, a Nash-Sutcliffe efficiency (E) of greater than ~0.9 can be expected. Any E below ~0.8 in such a watershed suggests poor model performance or model structural errors. In a rain dominated watershed, even an E of 0.7 can be good. Since forcing data and reservoir inflow data for the Mica basin are of good quality, an E of ~0.9 and higher can be expected for model calibration and model testing.

The UW-CIG model calibration and testing does not meet these expectations. In all watersheds, except for Kootenay Lake (KLK), E is lower than 0.80 (Table 6), which suggests that some hydrological processes are not well simulated by the model. For the UW-CIG calibrations of the Mica basin (MCD in Table 6), E is only 0.68, whereas both PCIC and WC^2N achieve E values of 0.90 and higher. WC^2N predictions are based on an ensemble of 23 parameter sets with an E of 0.93 and 0.95 for the best parameter set for model calibration and testing, respectively. A reason for the poor model performance of the VIC model in the UW-CIG study is that this study focused on the entire Columbia River basin and hence the model had to be calibrated to a larger area. Nevertheless, because of the poorer model performance in the Upper Columbia River, it is recommended not to use the UW-CIG data for long term planning in the Upper Columbia River watersheds. Despite its poorer quality, the UW-CIG data is used in an intercomparison study for the Mica basin.

Table 6. Comparison of Nash-Sutcliffe (E) and % volume bias (%VB) for the models used PCIC, WC^2N, and UW-CIG.

	PCIC / VIC				WC^2N / HBV-EC				UW-CIG / VIC*	
	1990-94/95 calibration		1985-89 testing		2000-07 calibration		1985-99 testing		1975-89 calibration	1960-74 testing
Project	E	%VB	E	%VB	E	%VB	E	%VB	E	E
MCD	0.89	-9	0.88	-7	>0.92	<5%	>0.92	<5%	0.68**	n/a
REV	0.97	-4	0.92	-10	n/a	n/a	n/a	n/a	0.76***	0.76***
ARD	0.78	-2	0.80	-8	n/a	n/a	n/a	n/a	0.78**	n/a
DDM	0.65	-7	0.73	-8	n/a	n/a	n/a	n/a	0.48**	n/a
KLK	0.67	-7	0.72	4	n/a	n/a	n/a	n/a	0.91**	n/a
GMS	0.64	1	0.75	-11	n/a	n/a	n/a	n/a	n/a	n/a
SCA	0.72	2	0.72	6	n/a	n/a	n/a	n/a	n/a	n/a

* model performance for simulating total upstream area

** http://www.hydro.washington.edu/2860/products/sites/

*** Elsner and Hamlet 2010

7.2.1 Climate Change Impacts on Reservoir Inflow in Selected Regions

7.2.1.1 Upper Columbia Region – Study Intercomparison

The Mica dam drains an area of 20,742 km^2, with terrain elevation ranging from 579 m above sea level (a.s.l.) at the Mica dam to 3685 m a.s.l. on mountain tops. Annual precipitation averages to 1075 mm, approximately 70% of which falls as snow. Mean annual temperature is 1.9°C with monthly average values ranging from -9.4°C in January to 13.4°C in July. In 1985, glaciers covered 1268 km^2 in the Mica basin, representing 6.1% of the total basin area. Between 1985 and 2000, the glacier area decreased by 101 km^2, and an additional 80 km^2 of glacier area was lost between 2000 and 2005, thus reducing glacier cover to 5.2% of the basin area. About 50% of the basin consists of open land cover types (i.e. alpine areas, range lands, agricultural lands, recently logged areas), and about 45% of the area is forested. The climate in the Upper Columbia Region can be classified as humid-continental. Frontal air masses deposit moisture in the winter as they pass over the Columbia Mountains. Summer rainfall occurs from a combination of both local convective activity and from frontal systems. This results in more or less uniform amounts of precipitation throughout the year, with slightly higher precipitation in winter. The hydrology is characterized by a nivo-glacial regime dominated by the spring freshet. Glacier ice melt currently contributes between 3 and 9% of annual runoff. Ice melt contributions are more important in August and September, when they range up to 25% and 35% of monthly runoff, respectively.

7.2.1.1.1 Glaciers

Glaciers in the Columbia basin are currently experiencing negative mass balance and, even if the current climate were to continue without further warming, glaciers would *likely* continue to retreat for one or more decades. Future simulations with the UBC Regional Glaciation Model (UBC-RGM) reveal that glaciers in the Mica basin are projected to continue retreating under all of the future climate scenarios. Depending on the GCM and emission scenario, glacier cover in 2100 is projected to decrease by 44 to 100% of the 2000 coverage, with a mean decrease of 93%. An example of UBC-RGM simulations is given in Figure 11, which visualizes the retreat of the Athabasca glacier in the 21st century.

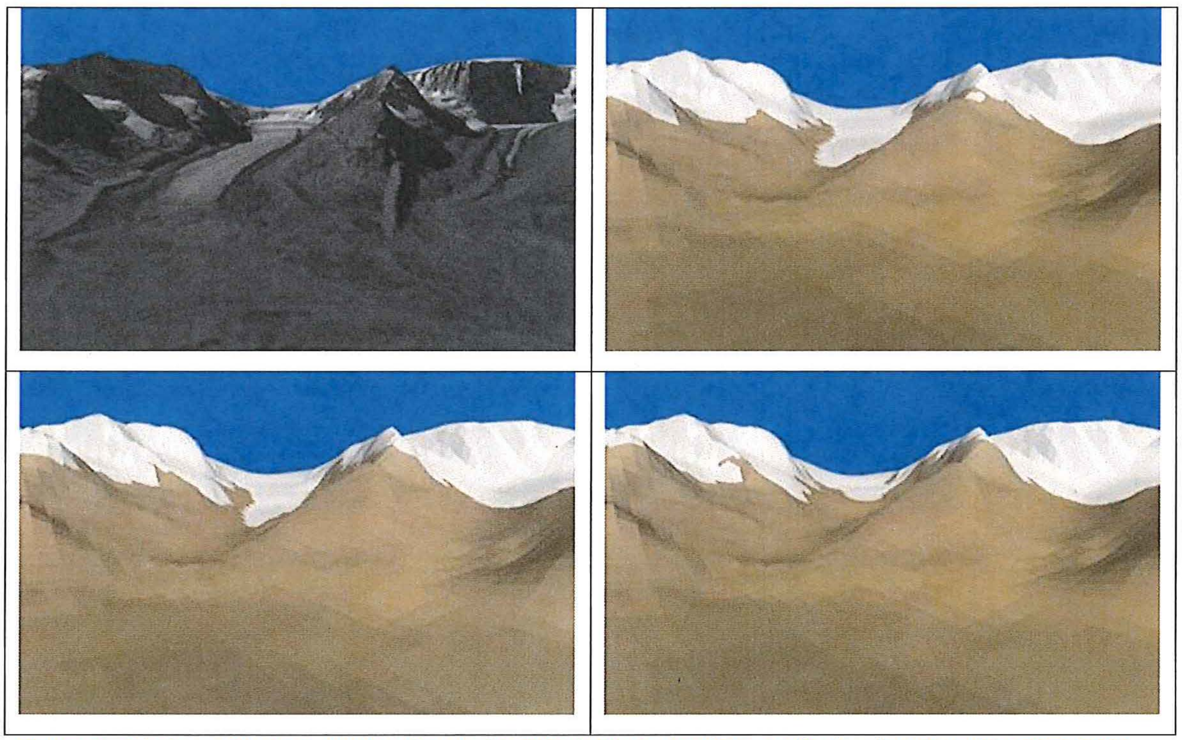

Figure 11. Athabasca Glacier coverage observed in 2001 (with the LandSat satellite) and projected for 2050, 2080 and 2100 by the CGCM3.1 GCM forced with the A1B emission scenario. Graphics: Glacier Modelling Group, Earth & Ocean Sciences, UBC.

7.2.1.1.2 Monthly Streamflow Projections

There is substantial uncertainty in the future projections, arising from (1) variations among GCMs, (2) variations among emission scenarios, (3) uncertainty inherent with the use of any geophysical model, and (4) the uncertainty in recent glacier volume change. However, the projections by PCIC, WC^2N, and UW-CIG for the Mica basin are consistent in their trend that streamflow will increase in March and April and decrease in August and September, regardless of the GCM and emission scenario selected

(Figure 12). Future warming will generate an earlier onset of spring melt and lower flows in late summer and early autumn, consistent with other studies focused on climate change impacts on streamflow in snow-dominated catchments. The uncertainties are reflected in how much the projected changes in the timing of Mica reservoir inflow differ between the studies. The WC^2N study projects a snowmelt freshet onset and summer flow recession as much as one month earlier than others (Figure 12).

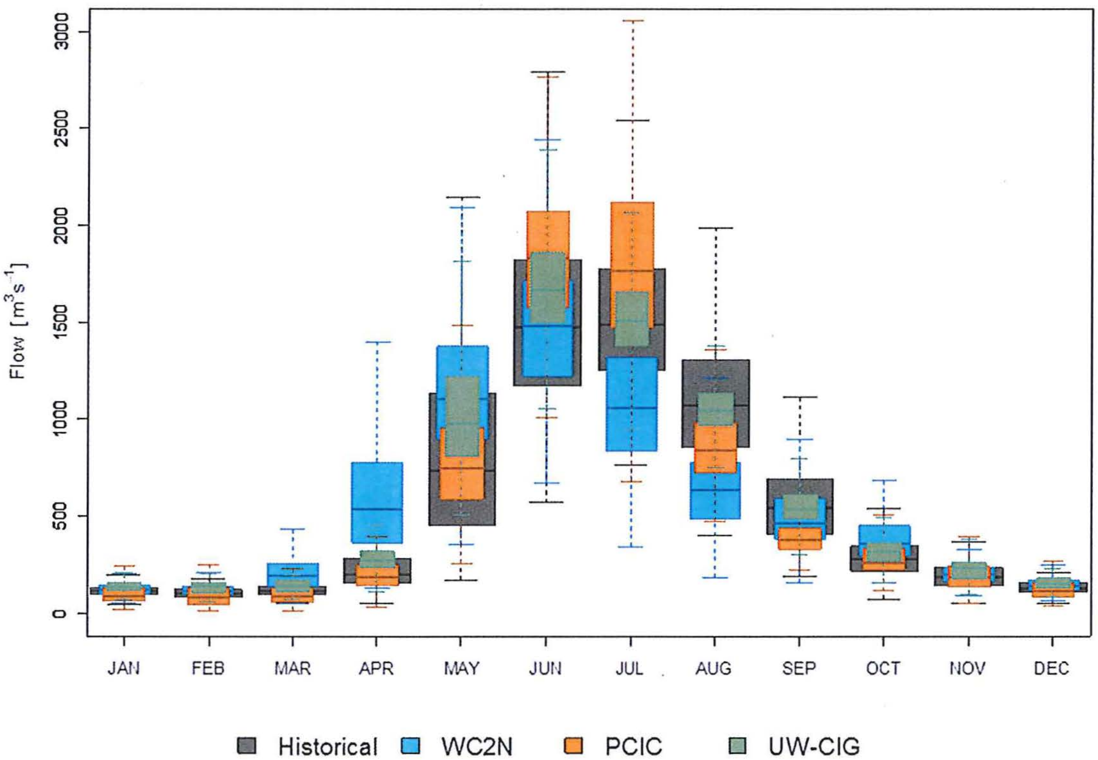

Figure 12. Example of multi-agency ensemble of Mica flow projections for the 2050s for all emission scenarios.

A direct inference of future hydrological changes from a comparison between observed data with future projections, like in Figure 1, is only possible with a perfect model. Inference of hydrological changes with an imperfect model, models in all three studies are - like all models - imperfect, can only be accomplished when each future projection is compared with its respective historical baseline. A historical baseline is derived by forcing hydrological models with simulated historical forcings, i.e. GCMs are run not only for the future but also for the historical period to provide a historical baseline of forcings. The historical GCM runs for each emission scenario are then fed into the hydrological models. Historical baselines of mean seasonal streamflow over all GCM/emission scenario combinations in the PCIC and UW-CIG study closely match the observed data whereas the WC^2N study shows some discrepancy to observed data (bold lines in Figure 13). The reason for this is that GCM forcings applied in the PCIC and UW-CIG studies are bias corrected using observations. The WC^2N study opted not to use a bias correction to maintain patterns from the raw GCM output. Despite the difference to observed data, the WC^2N baseline is well within observed variability (confirmed by resampling of several realizations from the distributions of observed values).

Future warming will generate an earlier onset of spring melt and lower flows in late summer and early autumn. Ice melt contributions to August streamflow decline under most future climate scenarios. The decrease in ice melt contributions to August streamflow exacerbates the effect of an earlier snowmelt in producing low flows in late summer.

The greatest uncertainties with future projections seem to lie in the different modelling approaches used in the PCIC, UW-CIG, and WC^2N studies. Judged from the overlap between the different emission scenarios, uncertainties in future greenhouse gas emissions are smaller than the differences between the three studies and smaller than differences between GCMs. The differences in projections between GCMs are greatest in the WC^2N study. Reasons for that are that GCM forcings were not bias corrected and that projections also include parameter uncertainty of the hydrological model.

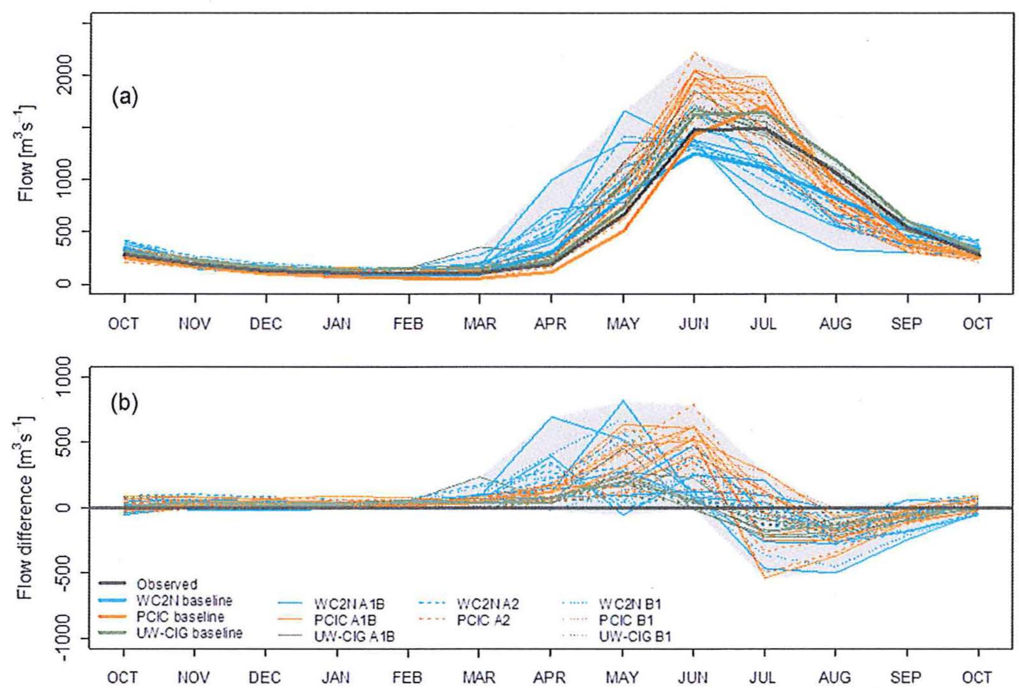

Figure 13 (a) Observed and future 2050s monthly Mica inflow and (b) flow anomalies relative to historical baseline for each study (bold lines) for all emission scenarios. Lines correspond to monthly medians for individual GCM runs under A1B, A2, or B1 emission scenarios. Flow anomalies (b) are plotted relative to the median of all historic runs for WC^2N, PCIC and UW-CIG, respectively.

7.2.1.1.3 Annual Streamflow Projections

PCIC, WC^{2}N, and UW-CIG multi GCM projections for annual water supply in the Mica basin differ in magnitude, but agree that the mean annual flow will increase in the future (Figure 14). Projected changes for different emission scenarios show substantial overlap. The WC^{2}N study projects that mean annual flow in the Mica basin will increase by 9% (1-21%). PCIC predicts higher flow increases, averaging to 18% (7-30%). UW-CIG predicts the lowest amongst the three studies with an average of 4% (-3-12%).

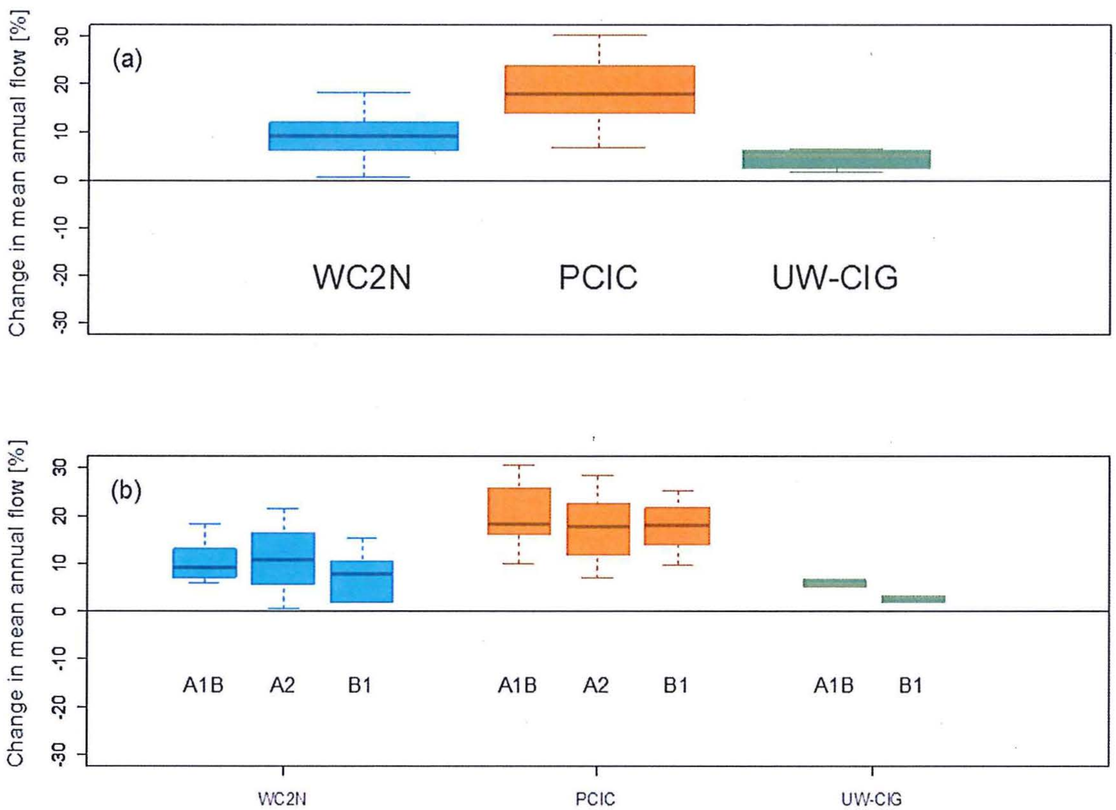

Figure 14. Projected changes in mean annual flow summarized for each study using (a) all emission scenarios and GCMs and (b) for each individual emission scenario.

Figure 15 shows how the interannual variation compares to the increasing flow trend for the A1B emission scenario. The main cause for increasing annual flow is an increase in precipitation. Different philosophies of selecting climate forcings and handling of hydrologic processes by the watershed models play a role as well. For instance, PCIC projects a decrease in evaporation, which leaves more water for runoff, while both WC^{2}N and UW-CIG predict an increase in evaporation, which reduces the amount of water available for runoff. Ice melt contributions to annual runoff decline in all future scenarios, the magnitude depends on the hydrological model, which also partially offsets projected increases in precipitation.

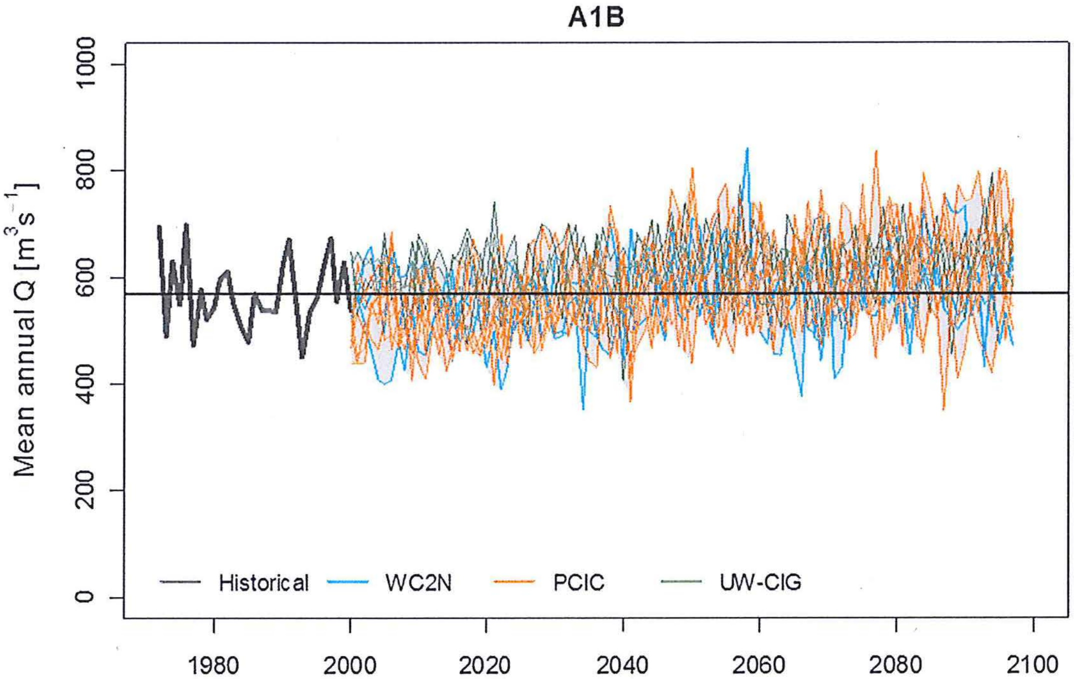

Figure 15. Multi model mean annual streamflow projections for Mica basin under the A1B emission scenario.

Figure 16 illustrates projections for August streamflow under the A1B emission scenario using GCM runs from PCIC, WC^2N, and UW-CIG studies. Projections for all three studies indicate substantial decreases in August streamflow during the 21st century. Depending on the scenario, changes between -6 and -56% are projected for the period 2050-2065 and between -13 and -69% for the period 2085-2100.

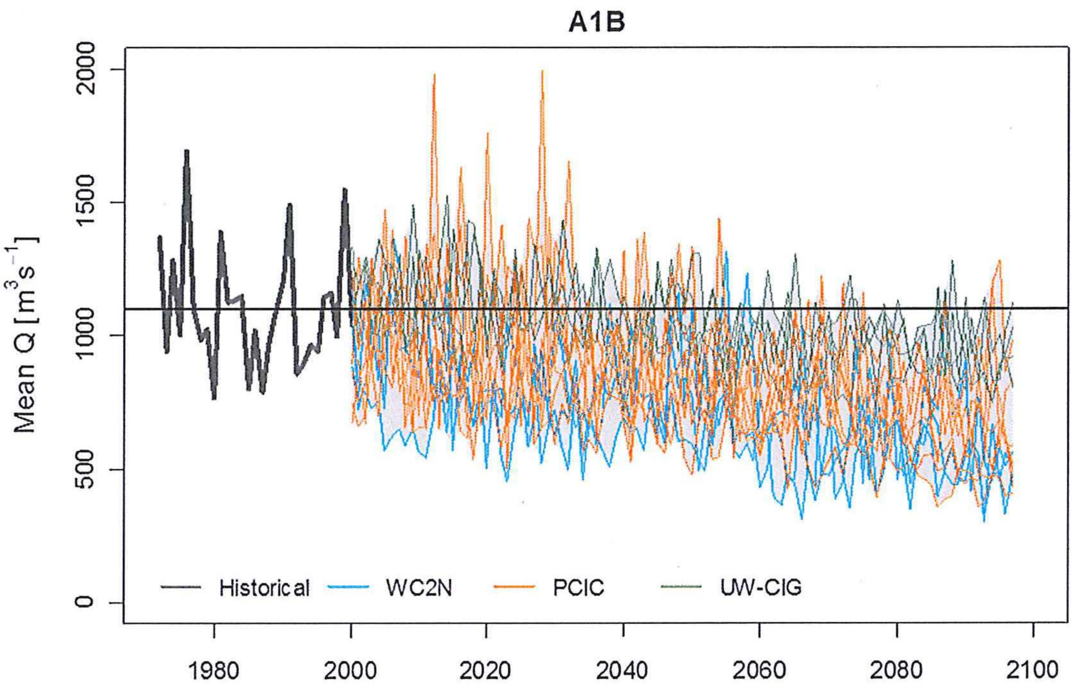

Figure 16. Multi model projections of mean August streamflow for Mica basin under the A1B emission scenario.

7.2.1.1.4 Conclusions

The PCIC, WC^2N, and UW-CIG study intercomparison for the Mica basin suggest that year-to-year variability in water supply and hydrologic modelling uncertainty will dominate prediction uncertainty in the near future. Up until the 2050s, the use of different GCMs contributes more to overall uncertainty than the different emission scenarios. Hydrologic modelling uncertainty remains a relatively large source of uncertainty at that forecast horizon. Beyond the 2050s, emission scenarios, i.e. the unknowns in future greenhouse gas emissions, become more important. Known unknowns, such as volcanic eruptions can exert a temporary effect on climate, but are difficult to predict far out in advance but could substantially alter climate forcings and consequently hydrological projections.

The narrow range of the UW-CIG uncertainty bounds is not surprising, as the UW-CIG reduced the ensemble size more than other modeling groups. WC^2N's large uncertainty bounds are the consequence of incorporating modeling uncertainty into the projections and therefore, possibly more realistic.

Summary of climate change impacts on reservoir inflow in the Columbia Region – study inter-comparison

- Depending on the GCM and emission scenario, glacier cover in 2100 will *very likley* decrease by 44% to 100% of the 2000 coverage, with a mean decrease of 93%
- Streamflow will *very likely* increase in March and April and decrease in August and September regardless of the GCM and emission scenario
- Mean annual flow will *likely* increase
- Up to 2050, GCMs contribute more to overall uncertainty than the different emission scenarios
- The level of confidence is highest for the WC^2N data and lowest for the UW-CIG data

7.2.1.2 *Peace Region*

The Peace Region is located in interior north-eastern British Columbia. The Williston basin (GMS) forms the headwaters of the Peace River system that drains into the large inland Peace-Athabasca Delta in northern Alberta. The Peace Region has a continental climate with frequent Arctic air outbreaks. Frontal systems dominate winter precipitation while local convective precipitation is characteristic for the summer. The mean annual precipitation is 838 mm, approximately 40% of which falls as snow. Monthly average temperatures range from -12.0°C in January to 12.3°C in July and average to 0.2°C for the year. The hydrology is characterized by a nival regime with the spring freshet as the dominant runoff event. Glacier ice melt contributes to less than 1% to annual runoff and hence can be considered as negligible, even in late summer.

7.2.1.2.1 Monthly Streamflow Projections

By the 2050s monthly streamflow at GMS is projected to increase throughout most of the fall, winter and spring periods (Figure 17). There is evidence for an earlier freshet onset and a shift in the peak flow from June to May. Late summer flows are projected to decline. Projected absolute changes in median monthly discharge are highest in May ranging from 202 m^3/s to 1040 m^3/s depending on the GCM and emission scenario. Declines in summer flows are greatest in July, ranging from -13 m^3/s to -1424 m^3/s.

Similar to projections for the Mica basin, there is substantial overlap between individual median runs from the three emissions scenarios, which suggests that no consistent forcing response can be distinguished for the 2050s, or, in other words, that the uncertainties in emission scenarios don't emerge from the uncertainties associated with GCM selection and from natural variation.

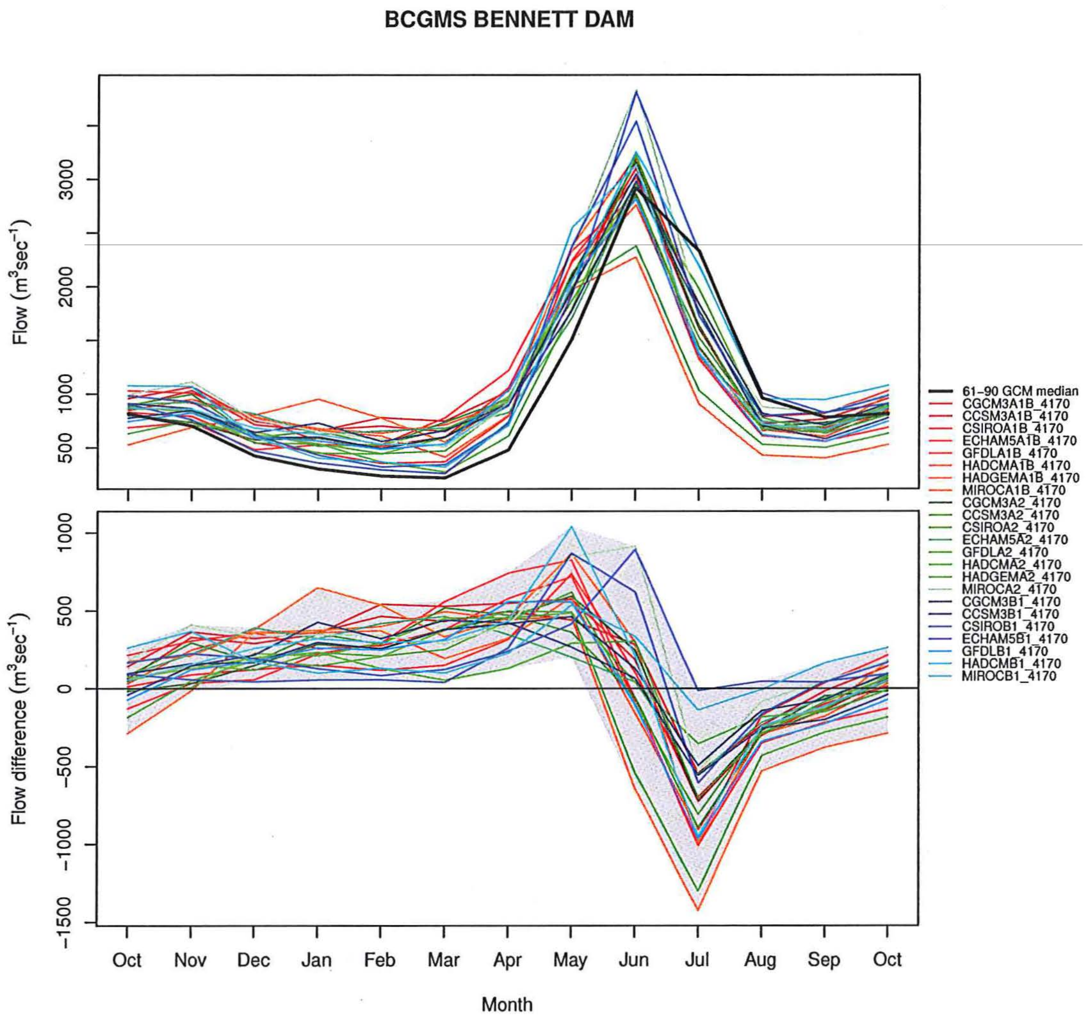

Figure 17. (a) Observed and future 2050s monthly GMS inflow and (b) flow anomalies relative to historical baseline for each study (bold lines). The historic baseline is the median of all historic runs for WC^{2}N, PCIC and UW-CIG separately. Future streamflow is shown as the monthly median for each individual GCM/ emission scenario combination. Source: PCIC (Schnorbus et al. 2011).

7.2.1.2.2 Annual Streamflow Projections

GCM runs forced with B1, A1B, and A2 emission scenarios project an increase in reservoir inflow for Williston (GMS) between 11% and 15% by the 2050s. All changes are statistically significant at the 5% level. Annual streamflow projections at the Site C dam project, Peace River above Pine (PEAPN), and downstream of Site C, Peace River at Taylor (PEACT) are similar to GMS projections with increasing annual discharge towards the 2050s. Differences between emission scenarios are marginal except for B1 based projections at PEAPN, which are larger than those projected for either A1B or A2.

Table 7. Historic and future annual discharge ensemble statistics and anomalies (%) for the Peace River project sites. Source: PCIC (Schnorbus, 2011).

Annual Discharge Statistics by Period and Emissions (m3/s)

	1961-1990	2040-2071			Relative Difference		
		B1	A1B	A2	B1	A1B	A2
			GMS				
minimum	701	783	767	717	0.12	0.09	0.02
75th	957	1063	1049	1027	0.11	0.1	0.07
median	1036	1163	1171	1146	0.12	0.13	0.11
25th	1144	1280	1292	1275	0.12	0.13	0.11
maximum	1417	1600	1618	1630	0.13	0.14	0.15
			PEAPN*				
minimum	51	52	46	47	0.02	-0.1	-0.08
75th	83	91	84	84	0.1	0.01	0.01
median	97	111	99	100	0.14	0.02	0.03
25th	117	134	116	124	0.15	-0.01	0.06
maximum	167	193	163	182	0.16	-0.02	0.09
			PEACT**				
minimum	111	130	105	109	0.17	-0.05	-0.02
75th	165	184	182	178	0.12	0.1	0.08
median	186	213	209	206	0.15	0.12	0.11
25th	208	247	241	236	0.15	0.12	0.11
maximum	270	327	325	318	0.15	0.12	0.11

*Peace River above Pine (Site C)
**Peace River at Taylor

Summary of climate change impacts on reservoir inflow in the Peace Region

- Annual streamflow at GMS will *very likely* increase
- Streamflow will *likely* increase throughout most of the fall, winter and spring
- Late summer flows are projected to decline
- There is evidence for an earlier freshet onset and a shift in the peak flow from June to May.
- Projections at the Site C dam project (Peace River above Pine), and downstream of Site C (Peace River at Taylor) are similar to GMS projections
- Differences between emission scenarios are marginal

7.2.1.3 Vancouver Island-Lower Mainland-South Coast

Campbell River at Strathcona Dam was chosen to represent climate change impacts on hydrology for the Vancouver Island, Lower Mainland, and South Coast regions. The Strathcona watershed is a small coastal watershed that drains the central Vancouver Island mountains to the Strait of Georgia and impounds the Upper Campbell Lake and the Buttle Lake Reservoir. Elevation ranges between 139 m and 2200 m. Annual precipitation in the study area is 2,960 mm and shows a distinct seasonal distribution with 78% of the precipitation falling from October to March. The streamflow exhibits a double peak, on in fall driven by rainfall runoff and one in spring driven by snowmelt. The watershed can hence be classified as a hybrid nival-pluvial regime. Glacier ice melt contributes to less than 1% to annual runoff and hence can be considered as negligible, even in late summer.

7.2.1.3.1 Monthly Streamflow Projections

By 2050, the Strathcona watershed is projected to change from a hybrid nival-pluvial regime to a pluvial (rainfall) dominated regime (Figure 18). Due less precipitation falling in the form of snow, flows from October to April will increase while the spring freshet will be substantially reduced. GCMs are consistent in predicting the highest flow increases in January and the largest flow decreases in June. The month at which half the flow volume is accumulated in an average water year will shift by two months from March to January. Changes in streamflow for the A1B runs are generally the largest in magnitude (red lines in Figure 18), particularly for changes projected during the fall and winter months.

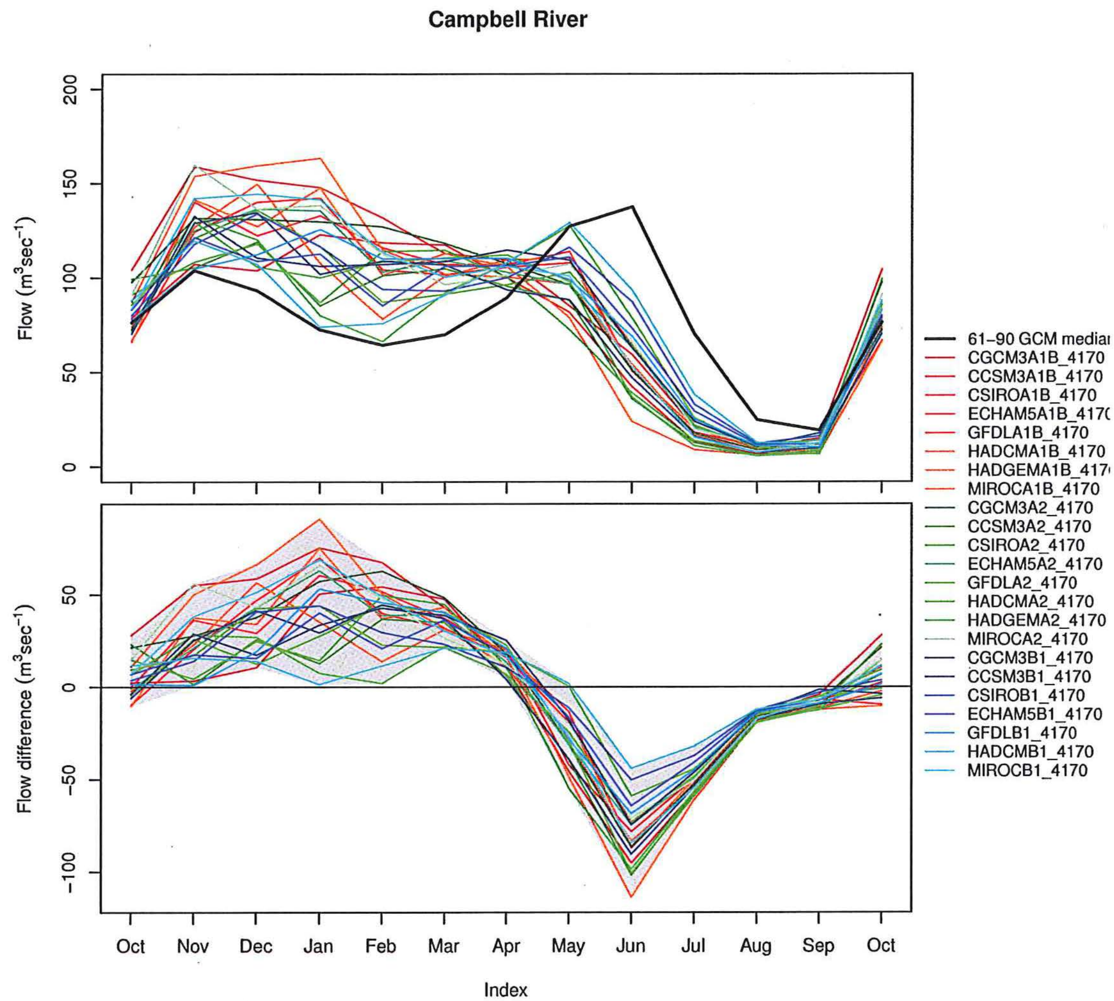

Figure 18. (a) Observed and future 2050s monthly inflow into Strathcona Dam and (b) flow anomalies relative to historical baseline for each study (bold lines). The historic baseline is the median of all historic runs for WC^2N, PCIC and UW-CIG separately. Future streamflow is shown as the monthly median for each individual GCM/ emission scenario combination. Source: PCIC (Schnorbus et al. 2011).

7.2.1.3.2 Annual Streamflow Projections

No significant changes to annual streamflow are projected. Differences between emission scenarios on annual streamflow projections are marginal. Changes to streamflow in all three scenarios, A2, B1, and A1B are in the range of only a few percent and operationally negligible.

Summary of climate change impacts on reservoir inflow for Coastal Regions

- No significant changes to annual streamflow
- The hydrological regime will *very likely* shift from a hybrid nival-pluvial regime to a pluvial (rainfall) dominated regime
- Flows from October to April will increase due to less precipitation falling as snow
- The spring freshet will be substantially reduced
- January will see the highest flow increases, June will see the largest flow decreases
- Uncertainties in emission scenarios have only a marginal effect on annual streamflow
- Changes in seasonal streamflow are largest in the A1B emission scenario

7.2.1.4 Climate Change Impacts on Water Resources of BC Hydro's Reservoirs

7.2.1.4.1 Annual Water Supply

Climate change impact projections for several of BC Hydro's watersheds suggest a *likely* modest increase in annual water availability caused by a modest increase in future precipitation (Table 8). Uncertainties in GCM model selection, parameter uncertainty in hydrological models, uncertainties in downscaling of GCM output, etc. are so large that differences in emission scenarios cannot be detected in annual streamflow projections.

There are regional differences in projections of future water supply. Modest increases in water availability are projected for watersheds in the Upper Columbia, Kootenay River, and the Williston basin (Table 8). In the Upper Columbia Region, increases in overall water supply are *likely* despite the decline in the glacier ice melt contribution to streamflow because increases in future precipitation more than offset the losses due to shrinking glaciers (Table 8). However, some models project an increase of only 10%, others as much as 26%. For the southern parts Canadian Columbia and Kootenay River basins, i.e. Whatshan, Kootenay Lake and Slocan, annual water supply will *likely* remain unchanged. For the Williston basin, some GCMs suggest that water availability will remain unchanged while other GCMs project that water supply will increase by as much as 15%. Most estimates indicate an increase of about 11%. No operationally significant changes to annual streamflow are projected for projects in the Coastal Regions (Table 8). All models have difficulties in quantifying changes to evaporation. Future projections of evaporation are further hampered by uncertainties in how vegetation might response to climate change. Across most regions potential and actual evaporation will *likely* increase due to higher temperatures and hence partly offset the increased precipitation input. A notable exception is the projected decrease in evaporation for the Mica basin by the PCIC, which causes the annual water supply to increase in addition to the increase caused by precipitation.

7.2.1.4.2 Seasonal Changes to Streamflow Regimes

Climate change will *very likely* lead to changes in seasonal streamflow. Across all regions, water availability in summer will *very likely* decline (Table 8). The hydrological processes that are responsible for shifting seasonal water availability vary between regions and can even differ between adjacent watersheds of different physiography.

Global warming has a clear impact on snow dynamics, resulting in a shift to an earlier melt season, including an earlier onset of the spring snowmelt freshet, an earlier freshet peak and an earlier recession from the freshet peak. This continues the observed trend in reservoir inflows over the past decades. Snowmelt-dominated watersheds in the southern interior, for example at Arrow or Kootenay Lake, will experience higher flows during winter and lower flows during late summer, but will *very likely* remain snowmelt-dominated (Table 8). Similarly, Williston basin will remain a hybrid snowmelt- and rainfall-dominated watershed (Table 8). Air temperature seems to be more important as a driver for snowpack dynamics in the lower elevated Columbia region, where temperatures are less below freezing, than in the higher elevated Southern Rockies region and hence makes the Columbia region more prone to seasonal changes in streamflow compared to other regions in North America (Pederson, 2011).

Glaciers are projected to continue retreating under all of the future climate scenarios. Under a warming climate, the glacier ice melt contribution to streamflow initially increases due to the extra energy input but eventually decreases as a result of glacier area reduction. Studies suggest that glaciers in British Columbia are already in the stage where glacier ice melt is on the decline (e.g. Stahl and Moore 2006). In the Mica basin, approximately 40% of glacier cover (11-80%) will disappear by 2050 and 90% (44-99%) by 2100 (Moore et al. 2011). Glaciers show a delayed response to the current climate. As a result, glaciers would continue to lose about 20% of their current area and reach a new equilibrium within 50-100 years even if the climate remained similar to today's (Stahl et al., 2008). The decrease in ice melt contributions to August streamflow will exacerbate the effect of an earlier snowmelt in producing low flows in late summer (Table 8). Current hybrid snowmelt- and glaciermelt-dominated watersheds such as the glacierized watersheds in the Columbia and Kootenay River basins will turn into snowmelt-dominated watersheds. Columbia, Kootenay River, and Williston basins could see increases in basin wide snow accumulation because of the projected increases in winter precipitation, which could increase spring flows.

The biggest changes to seasonal flow regimes can be expected for Coastal projects (Table 8). There, rainfall-runoff processes will *very likely* become dominant over snowmelt processes. Hybrid rainfall- and snowmelt-dominated watersheds will turn into rainfall-dominated watersheds. With only marginal precipitation increases, the Coastal region will see a decline of basin-wide snowpack and consequently a reduction in spring runoff.

Table 8. Seasonal and annual inflow anomalies for select BC Hydro projects for the 2050s relative to 1961-1990 normals.

REGION	PROJECT		Winter	Spring	Summer	Fall	Year	Source
south coastal	SCA	5 percentile	45%	-10%	-68%	8%	-10%	PCIC
		50 percentile	**52%**	**6%**	**-64%**	**10%**	**1%**	
		95 percentile	42%	13%	-43%	12%	8%	
Columbia	MCD	5 percentile	14%	75%	5%	-9%	10%	PCIC
		50 percentile	**53%**	**77%**	**9%**	**2%**	**17%**	
		95 percentile	104%	68%	11%	15%	24%	
	REV	5 percentile	24%	84%	-7%	-20%	2%	PCIC
		50 percentile	**91%**	**79%**	**-2%**	**-1%**	**12%**	
		95 percentile	132%	63%	4%	21%	23%	
	ARD	5 percentile	60%	54%	-14%	-16%	-1%	PCIC
		50 percentile	**111%**	**53%**	**-7%**	**-3%**	**9%**	
		95 percentile	115%	57%	0%	18%	21%	
	WGS	5 percentile	34%	22%	-57%	-29%	-14%	PCIC
		50 percentile	**92%**	**38%**	**-41%**	**-6%**	**0%**	
		95 percentile	134%	44%	-24%	15%	15%	
Kootenays	DDM	5 percentile	1%	66%	2%	-13%	6%	PCIC
		50 percentile	**29%**	**75%**	**5%**	**1%**	**12%**	
		95 percentile	104%	75%	9%	22%	22%	
	KLK	5 percentile	72%	37%	-31%	-27%	-5%	PCIC
		50 percentile	**86%**	**38%**	**-18%**	**-4%**	**6%**	
		95 percentile	101%	46%	-12%	17%	16%	
Peace	GMS	5 percentile	25%	46%	-28%	-5%	-7%	PCIC
		50 percentile	**78%**	**61%**	**-15%**	**5%**	**11%**	
		95 percentile	64%	55%	-7%	13%	19%	

*Winter: DJF, spring: MAM, summer: JJA, fall: SON

8 Conclusions

There is substantial uncertainty in the future projections arising from variations among GCMs, model parameter uncertainty, uncertainty in the downscaling of GCM output, model structural uncertainty, uncertainty in recent glacier volume change, etc. Up until the 2050s, GCMs are found to contribute more too overall uncertainty than the different emission scenarios, i.e. the unknowns in future greenhouse gas emissions. Hydrologic modelling uncertainty remains a relatively large source of uncertainty at that forecast horizon. Beyond the 2050s, emission scenarios become more important and emerge from all other uncertainties. Despite all these uncertainties, some general conclusions can be drawn from the climate change impact studies:

- Historical trends in annual reservoir inflows are small and not significant. There is some evidence for a modest historical increase in annual inflows into BC Hydro's reservoirs.
- There is evidence for historical changes in the seasonality of inflows. Fall and winter inflows have shown an increase in almost all regions; there is weaker evidence for a possible modest decline in late-summer flows for those basins driven primarily by melt of glacial ice and/or seasonal snowpack.
- For the period of inflow records (35 to 47 years, depending on the reservoir), the severity of year-to-year fluctuations in annual reservoir inflow volumes has not changed.
- Projected warming in the 21st century shows a continuation of patterns similar to those of recent decades.
- All emission scenarios project higher temperatures in all seasons in all areas of British Columbia during the 21st century that will *very likely* be larger than those observed during the 20th century.
- Precipitation projections suggest *likely* increases in winter, spring, and fall for all study areas under all scenarios.
- A modest increase in annual water availability is likely for BC Hydro's hydroelectric system.
- Annual discharge in most Upper Columbia watersheds is projected to likely increase.
- In the Columbia and Kootenay regions, late fall and winter flows will increase slightly; the onset of the snowmelt freshet will be earlier; spring and early-summer flows will be substantially higher; earlier peak flows and higher monthly peak flows can be expected; and late-summer and early-fall flows will be substantially lower.
- Annual discharge is projected to increase in the Peace region, where late-fall and winter flows will increase slightly; the snowmelt freshet will begin earlier due to higher spring temperatures; and summer flows will be lower.

- Snow processes on the South Coast will become less important to the hydrology of the watersheds; fall and winter flows will increase, with a larger fraction of precipitation falling as rain; and spring and summer flows will decrease.
- The Campbell River area will see negligible changes to annual discharges.

9 Planning Data Set Recommendations

Analogue to the CMIP3 ensemble of GCMs, flow projections provided by the individual modeling groups could theoretically be considered members of a multi-agency super-ensemble and could be given equal likelihood. Here, we decide on one planning dataset for each of the projects using expert knowledge. The criteria are hydrologic model performance, agreement with projections of other modeling groups, and agreement with hydrological changes reported in literature.

Due to the lack of explicit handling of glacier processes and the availability of an alternative data source it is recommended to not use the UW-CIG projections as planning datasets for Canadian Columbia River basins. Instead, and with the exception of Mica, planning data sets provided by PCIC should be used. For Mica, WC^2N projections are believed to be superior because the hydrologic model performance is better compared to models in the other studies, hydrological changes agree with peer reviewed literature, and glacier area change is modelled dynamically.

10 Future Tasks

The next step for BC Hydro is to feed operational and planning models with projected inflow scenarios to assess how sensitive hydroelectric power generation is to the hydrologic impacts of climate change. For instance, it has not been determined whether reservoir storage will be able to buffer projected changes in seasonal runoff timing, such as lower summer inflows. Changes in the year-to-year variability of water supply, and hence changes to the frequency and severity of hydrological droughts will also need further research.

Water availability is but one of many climate-related factors affecting hydroelectric power generation, however. Just as important are the effects of a changing climate on heating and cooling demand, on infrastructure, such as transmission and distribution lines, impacts to fisheries and habitat, as well as changes in demographics, socio-economics, and government policies, such as the BC Energy Plan and the Clean Energy Act. All these factors must be integrated to develop a useful and holistic vision of how best to adapt to a changing climate. To this goal, BC Hydro continues to work with the Pacific Climate Impacts Consortium and others to further expand our knowledge of climate change science, and has developed an Adaptation Working Group within BC Hydro to further assess and address the risks of climate change to continuing to power B.C. with clean, reliable electricity for Generations.

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