Climate Overview 2007

Hydro-climatology and Future Climate Impacts in British Columbia

Project Lead: D. Rodenhuis
Project Team: K.E. Bennett
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12 December 2007
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Executive Summary

The Intergovernmental Panel on Climate Change (IPCC) has released their Fourth Assessment Reports[1,2]. It is now unequivocal that the global climate system is warming, and the expectations are that the global annual mean temperature will rise more than 3°C this century. Continued warming and changing of precipitation patterns will have a large effect on hydrology with significant implications for the economy, infrastructure, and ecosystems of British Columbia. In order to adapt to climate change, it is important to understand historical trends and future projections in Pacific North America, and in particular, British Columbia.

The foundation for understanding the consequences of changing climate (temperature and precipitation) at a regional scale are water resources at the ground level; i.e. *hydrology*. This requires knowledge of the hydrological regime (rain, snow, ice), hydrological resources (snowpack, glaciers, reservoirs, lakes, wetlands, groundwater and soil moisture), and hydrological processes (interception, evaporation, transpiration, and streamflow). Extremely important water resources *responses* will result from climate change. Subsequently these responses will influence important economic sectors: power generation, forestry, fisheries, agriculture, mining, and their commercial derivatives.

The first half of this report presents an updated analysis of BC's historical climate trends and variability. An interpolated dataset describes the diversity of BC's climate. Established methods were applied to calculate trends for temperature and precipitation, snowpack, streamflow and lake ice. Trends in glaciers were synthesized from contemporary studies. The response of temperature, precipitation, snowpack and streamflow to climate variability, i.e. the El Niño Southern Oscillation (ENSO)[i] and the Pacific Decadal Oscillation (PDO)[ii] is also included in this report.

The second part of the report applies projections of future climate using the latest Global Climate Model (GCM) results from the IPCC Fourth Assessment at a coarse scale. The Canadian Regional Climate Model (CRCM) was also used to obtain climate projections on a regional scale, and empirical methods were used for high-definition mapping in BC. Changes to future snowpack were estimated using a new version of the CRCM. Future climate *impacts* on glaciers and streamflow were synthesized from select research publications. Examples of future hydrologic impacts, such as soil moisture, changes to growing-degree-days and the Mountain Pine Beetle infestation, were identified.

The most important results from the historical analysis and future projections of climate change are summarized:

During the past century………

- positive trends in annual daily minimum temperature +1.7°C (+1.0°C to +2.5°C per century)[iii], daily maximum temperature +0.6°C (+0.5°C to +1.5°C per century), and daily mean temperature +1.2°C (+0.5°C to +1.5°C per century) have been documented. In northern BC the trends in minimum wintertime temperature were up to +3.5°C per century. For comparison, the *global* mean temperature trend is +0.7°C (between +0.6°C and 0.9°C per century).
- trends in precipitation were also generally positive (+22% per century on average across BC) and some observations of +50% per century occurred in wintertime in the interior. However,

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[i] ENSO is a tropical Pacific phenomenon that influences weather around the world and across Canada with periodicity of 2 to 7 years and events persisting for 6 to 18 months.
[ii] PDO is a pattern of mid-latitude climate variability with phases lasting 20-30 years.
[iii] The range in brackets indicates the geographical range of significant results for BC, based on the intervals presented in the legends of Figure 2.1.1a to 2.1.1d and Figure 2.1.2 to 2.1.4, preceded by the average for BC.

there were exceptions, and some of the trends were reversed (negative) for shorter records (50 years).

- climate variability had a pronounced influence on seasonal temperature and precipitation in BC, especially in the winter and spring seasons. During the warm phase of ENSO, the temperature was higher (+0.5°C to +2.8°C) and the precipitation was somewhat less (-5%) compared to the cool phase. There was also a comparable influence of the PDO warm phase on temperature (+2.9°C) although precipitation was not significantly different. However, climate variability responses differ between the seven hydro-climatic regions of BC. The magnitude of climate variability was comparable to climatic trends over the century.

Historical hydrologic trends and variability include………

- losses of April 1st snowpack of -25% on average at BC sites and as much as -50% at a few sites over the past 50 years. For shorter record lengths, however, the variability was large and not homogeneous across the Province. In addition, ENSO influenced snowpack by -12% to +21%[iv]. The geographical complexity of snowpack in BC prevents a simple interpretation of results.
- trends in glacier volume over the 1985-1999 period, which demonstrated an annual rate of volume loss of 22.48 ± 5.53 km^3 per year from the glaciated areas of BC. These trends indicate that many glaciers are out of phase with the current climate. Currently, the Western Canadian Cryospheric Network (WC2N) is working to project the response of glaciers in Western Canada to climate change.
- changes in streamflow have occurred throughout BC, but depend on the hydro-climatic region and the streamflow regime. The timing of spring runoff has advanced (10 to 30 days) in runoff regimes dominated by snowmelt runoff. For watersheds at low elevations and southern latitudes that have lost their glacier influence, the annual mean streamflow decreased and the minimum daily average streamflow decreased. This result was consistent with the impacts of warmer temperatures in mixed snow/glacial runoff regimes.
- impacts of ENSO and PDO on the seasonal variability of streamflow. The strongest influence occurred in southern BC. The timing of the response depended on flow regime: pluvial (rain-dominated), hybrid (a mix of rain and snow), nival (snow-dominated), or nival/glacial.
- decreased duration of lake ice in the most recent records (0 to 42 days). The spring break-up of lake ice also occurred up to 10 days earlier, although one station in the north-eastern portion of the Province showed a later break-up by 2 days.
- feedbacks from changing surface groundcover that are already evident in BC forests due to the Mountain Pine Beetle infestation. The ground cover is changing and impacts to hydrology can only be estimated. Earlier peak flows, increased low flows, and increased annual runoff are expected consequences.

By the middle of this century (2050s)………..

- the average annual temperature in BC is projected using an ensemble of GCMs to be warmer by +1.7°C (+1.2°C to +2.5°C)[v] compared to the GCM baseline (1961-1990) climate, and this

[iv] Based on the geographical range of results available across BC.
[v] The ranges in brackets indicates the results from 30 GCM projections (section 4.1), preceded by the average projection.

shift is projected to occur in both winter and summer seasons. For comparison the global average temperature is projected to increase by an estimated +1.5°C by the 2050s.

- the average annual precipitation in BC is projected to increase slightly by +6% (+3% to 11%). However, most of this increase is projected to occur in the winter season, while decreases are projected to be -3% (-9% to +2%) in the summer.
- regional differences from the BC temperature and precipitation projections are evident using the Canadian RCM (CRCM). In particular, the CRCM projected winter temperature increase varies from +2.0°C to +4.2°C at most locations across BC and precipitation varies by up to 13% from the BC average projection.

Hydrologic impacts of projected climate change (2050s) include………

- a decline in snowpack was projected by the Canadian RCM of up to -55% especially in the Coastal Mountains of BC. This result is consistent with historical trends and projected changes in temperature and precipitation.
- a reduction in glacier volume over the 1985-1999 period. The annual trend was -22.48±5.53 km^3 per year from the glaciated areas of BC. This suggests that many glaciers are not in equilibrium with the current climate.
- a comprehensive hydrologic analysis of projected streamflow in BC is not available. One study of the Bridge Glacier indicated a decrease in August streamflow of -37% by the 2050s. A study of the Columbia Basin projected a reduction of flow in the dry season of (-10% to -25%), and a reduction of flow during the summer months of up to -90% by the 2050s.
- a study of the Columbia Basin projected a reduction in soil moisture by the 2040s during the summer and fall for parts of the Basin. Continental estimates of water balance are available, but experimental, and direct measurements in BC are sparse.

Uncertainties and consistencies

Estimates of trends and projections of future climate and their impacts contain numerous limitations. The lack of long records from a diverse range of representative sites is just part of the problem. Additional uncertainties arise in the use of GCM and RCM models with coarse resolution and imperfect physics. Unqualified acceptance of precise numerical values for projected temperatures, precipitation or hydrological impact variables is not warranted.

When future projections of climate out to mid-century (2050s) are made on a global scale, *regional* anomalies of hydrological components are consistent across BC and regional anomalies are often larger than global projections. However, these results are qualified by the choice of emissions scenario and the accuracy and resolution of climate projections.

Despite these limitations, there remains a certainty: throughout Pacific North America the hydrological system is changing, including the distribution of precipitation and liquid/ice regimes, the timing of streamflow and glacier runoff. A coherent picture emerges for the BC region that is consistent with global projections: rising temperatures, particularly in the winter in the north and in the summer along the coast, and these changes will have critical impacts on hydrological resources in the Province. This will challenge the current methods for water management in BC.

Next steps

With this understanding, the next steps can be visualized: monitoring of weather conditions to determine climate variability, updating future climate scenarios as new research results become available, analyzing extreme weather and hydrological events, and a thorough assessment of water resources with a hydrologic model.

For operational management of BC water resources, diagnostic use of hydrologic modelling is imperative. A suitable model must be selected, the surface conditions identified, and diagnostic studies performed. To accomplish this objective, it will be necessary to attract the broadest participation within the Pacific Climate Impacts Consortium and collaborate with other scientific facilities in Canada and the US.

Regional differences and the effect of hydrological feedbacks across Pacific North America can be identified by a high-resolution RCM. This requires the collaboration of another PCIC member (Ouranos, Montréal) and with the Canadian Centre for Climate modelling and analysis (CCCma) at the University of Victoria. The potential for increased intensity of Pacific storms needs evaluation in the context of projected climate conditions. All of this research requires investigations and analysis and collaboration from the research community that can be subsequently translated into adaptive strategies and decisions for power generation and water resources.

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[1] IPCC, 2007b. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 18 pp.

[2] IPCC, 2007a. Summary for Policymakers. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 22 pp.

Preface

This report is intended to be a brief but comprehensive survey of our current knowledge of climate variability and change in British Columbia, including the past record of historical trends and estimates of future climate scenarios. The focus is on water resources within the Provinces and States of Pacific North America[1], but does not directly address implications for water resources system operations. Our intended audience is managers at BC Hydro who are planning and allocating water resources. However, we are also aware of scientific scrutiny of our analysis from many researchers in climate and hydrology. 'Impacts' as used in this report refers to the consequence of climate change and variability on regional hydro-climatology, which has implications for subsequent impacts studies on water resource systems.

Analysis using updated data and peer-reviewed methodology has formed the foundation of our present understanding and was the basis of this work. Whenever possible, our intention was to extend and improve existing results—notably in climate trends and projections of climate in the 2050s. Consequently, we used the latest climate change scenarios from IPCC (2007), and we extended the analysis of trends to include the most recent years available, and improved the resolution when it was possible. Analysis was conducted by the staff of the Pacific Climate Impacts Consortium (PCIC) at the University of Victoria. Our original work is indicated with the PCIC logo on the graphical materials.

Coupled with this ambition to extend earlier analyses was a constraint for a concise synthesis of results. The conflict between these objectives (scope and brevity) was a challenge to resolve. First, it is difficult to acknowledge all the previous work that has been done by many scientific colleagues. Secondly, BC hydro-climatology is extremely diverse and difficult to summarize without defining multiple subregions and presenting an overwhelming number of details. Finally, this technical subject resists a simplified interpretation in a concise document.

The format of the report follows a strict formula. The report has been divided by two foci: historical hydro-climatology and future projections of regional climate change and its impacts on hydro-climatology of the Province. Results are highlighted at the beginning of each section and the methodology has been omitted from this report to achieve a concise synthesis. A separate addendum of methodology is available for interested readers. References have been included as footnotes that are listed at the end of each section. Figure and Table listings are located at the back of the report. The vision and scope of the Consortium are available at www.PacificClimate.org.

Finally, this report is a product of the Climate Overview Project, Contract No. 00023453, BC Hydro. Supplemental funding was provided by the BC Ministry of the Environment. The support of these two institutions is gratefully acknowledged.

Dave Rodenhuis, Project Leader

Katrina Bennett, Hydrologist
Arelia Werner, Hydrologist
Trevor Murdock, Climate Scientist
David Bronaugh, Programmer Analyst

[1] PCIC. 2006. Executive Summary, Climate Overview, Proposal to BC Hydro, December 2006. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 19 pp.

Acknowledgments

The Climate Overview Project was conceived at a meeting with BC Hydro and PCIC staff members just a year ago (November 2006), and we began work on the Climate Overview in early 2007. I wish to thank BC Hydro for initiating and supporting this project, and we value the additional support from the BC Ministry of Environment.

Although 95% of the graphical output in this report comes directly from our own analysis, the PCIC staff relied heavily on a foundation of recent research for methodology and to support our findings. This work is documented in the extensive references in the report. However, several scientists were exceptionally generous with advice or data, and I would like to acknowledge, especially: Allan Chapman, BC River Forecast Centre; Dan Moore, University of British Columbia; Phil Mote, University of Washington; Paul Whitfield, Environment Canada; and Xuebin Zhang, Environment Canada.

The participants of the Technical Workshop (Vancouver, 23 February 2007) contributed their time and advice at an early stage of the project. I am grateful to: Carol Cheuk, Stewart Cohen, Dan Moore, Amy Snover, and Paul Whitfield.

A number of experts have reviewed the draft report and the PCIC staff has benefited from their advice: Elaine Barrow, Sarah Boon, Allan Chapman, Stewart Cohen, Doug McCollor, Dan Moore, Phil Mote, Robin Pike, Dan Smith, Dave Spittlehouse, and Xuebin Zhang.

Despite these professional contributions and technical advice, we also have an obligation to deliver a report that is structured and documented to meet the needs of our customer, BC Hydro. Therefore, we were obliged to find a compromise on some occasions. The limitations of our report remain our responsibility, and our accomplishments rest upon the work of many other colleagues. I thank them all.

Finally, I would like to express my personal appreciation to the PCIC staff members who analyzed the data, read the papers, and wrote this report. Katrina Bennett led the process to organize a technical workshop and respond to reviewers comments. She was also responsible for climate trends and variability (section 2.1, 2.2) and the snowpack section (section 3.1). Arelia Werner had the primary responsibility for hydrologic impacts that included the analysis of past and future glaciers (section 3.2, 5.2), streamflow (section 3.3, 5.3), and lake ice (section 3.4). Trevor Murdock and David Bronaugh computed future climate projections and downscaling (section 4). Although this report was a team effort, each individual brought their special expertise and commitment to attain a final result.

Dave Rodenhuis
Lead, Climate Overview Project

The Pacific Climate Impacts Consortium
University of Victoria

December 2007

I. Introduction – Historical hydro-climate trends and variability

The basis for understanding climate variability and change is knowledge of historical climatology of temperature and precipitation. With this understanding and insight, the impacts on water resources, ecosystems, commerce, and public life can be estimated. The historical hydro-climatology records (climate and water resources) also provide a foundation that can be used to test ideas and concepts regarding the behaviour of the physical system and the potential for change in the future. This foundation allows us to properly assess the vulnerability of our dependence upon water resources in the context of potential climate change.

Several summaries have documented historical climate change in British Columbia and potential impacts in the 21st century. The impacts of climate change in BC are already apparent, and other recent surveys have characterized climate and hydrology in BC[1,2] and documented climate impacts [3,4,5]. These summaries, as well as other contemporary results, were utilized for this report and verified with independent analysis whenever there was an opportunity.

Within British Columbia (BC) a variety climatic zones exist in close proximity—both horizontally and vertically. The influences of historical climate change and variability differ across these zones and within zones. In most cases weather and hydrological observations are collected by public agencies at designated locations and times, whereas hydro-climatological information is needed on much larger spatial and temporal scales, for example in BC watersheds over a period of decades. Therefore, climate data should ideally come from consistent, well-sited, locally-representative, long-term observations that are distributed somewhat homogeneously across the Province. These conditions are seldom met and this limits analysis and results.

Regional Climate Trends

During the past century, the climate has been assumed to be nearly constant, but with annual variations. Now trends in temperature and precipitation clearly indicate that climate is changing. These changes may appear of little consequence, or even appear to be beneficial. However, *regional* climate trends, and *regional* hydrological impacts affect infrastructures, economy and daily life, and therefore the *regional* scale is where impacts occur. In this report, trends in temperature and precipitation on global and continental scales are compared to regional data sets, which have been extended and reanalyzed with peer-reviewed methodology and measures of statistical significance.

Regional Climate Variability

Trend detection can be complicated by cycles of climate variability. Climate is variable and some climate variability occurs on a regional scale. There are several measures of climate variability on BC's hydro-climate: El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are examined in this report. The distribution of these influences within the Province has been detected and described. Other indices that may illustrate climate variability in BC include the Pacific North American (PNA) pattern, and Arctic Oscillation (AO). However, the periods associated with these different mechanisms range from years to decades. Some useful terminology for climate variability is included at the end of this introduction.

Hydrologic Trends and Variability

Hydrologic impacts of historical climate change and variability also change the cryosphere, i.e. the accumulated winter snowpack and the stored water resources of mountain glaciers. Along with natural lakes, snowpack and glaciers compose a natural and valuable storage of water resources during the dry season.

Long-term trends in *snowpack* have direct implications for seasonal timing and volume of runoff. In this report, trends are updated, compared to the current period, and the statistical significance computed. The influence of ENSO and PDO are illustrated. The physical state of BC *glaciers* has changed in response to climate change and variability. Glaciers are examined through a review of existing research investigations at selected sites. *Ice-cover* on lakes or rivers has been shown to be a good proxy indicator of climate change as ice-cover reflects decadal and inter-decadal climate variation due to ENSO and PDO. The timing of the duration of lake ice was synthesized from contemporary records and analyses. Changes in *streamflow* are the most immediate and tangible hydrological impact of a changing and variable climate system. Trends and variability could be resolved only through analyses that subdivided streamflow by distinct flow regimes and by altitude.

Streamflow may be impacted by changes in ground cover occurring as a result of the Mountain Pine Beetle infestation. Climate variability and climate change may shift future streamflow response but information on impact of the Mountain Pine Beetle to BC's watersheds is limited and knowledge of industry response (i.e. salvage logging) is unknown.

<u>Limitations</u>

A full knowledge of historical climate trends and variability is a foundation for testing assertions of future climate change. Yet, the observational base of climate variables is limited—both temporally and spatially—and especially in northern areas of BC. Likewise, the cryosphere is not systematically and comprehensively observed.

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[1] Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.

[2] Eaton, B. and Moore, R.D., Ibid.Chapter 4: Regional Hydrology.

[3] MoFR, 2006. Preparing for Climate Change: Adapting to Impacts on British Columbia's Forest and Range Resources, Ministry of Forests and Range, Victoria BC.

[4] Sydneysmith, R. and Walker, I.J., 2007 in press. BC Chapter. In: D. Lemmon (Editor), The Canadian National Assessment on Climate Change. Federal Government of Canada, Toronto, ON.

[5] BC Ministry of Environment, 2007 in press. BC State of Environment Report, BC Provincial Government, Victoria, BC.

Terminology for climate variability

The primary mode of climate variability is the annual change of seasons.

Four modes of ocean-atmosphere variability relevant to British Columbia include the: El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Pacific North American Pattern (PNA), and the Arctic Oscillation (AO). These four modes are associated with different effects on BC's climate and operate at different timescales. This is an important factor when applying knowledge of these effects to water resources management and planning in BC. For example, ENSO events affect year-to-year variability, while 20th century PDO phases persist on the order of 20 to 30 years. Only ENSO and PDO are dealt with in this report.

ENSO effects are associated with anomalously warm (cool) sea water in the equatorial Pacific[1]. This warming (cooling) leads to higher (lower) sea surface temperatures, changes in sea level and storm tracks and various other impacts to hydrology and local climate in BC. The warm phase of ENSO is commonly referred to as El Niño, while the cool phase is called La Niña. ENSO responses tend to be strongest in winter and spring. A more detailed explanation of the ENSO phenomena can be found in other sources.

Two phases of the **PDO** are associated with climate in BC, a warm (positive) and a cool (negative) phase. The positive (negative) PDO phase is observed when the sea surface temperatures (SSTs) in the Central and Western North Pacific Ocean are below (above) average, while the SSTs along the west coast of North America are above (below) average.

During the positive phase of the **PNA**[2], a strong Aleutian low develops in the Northeast Pacific, while enhanced air flow is directed north along the western coast of North America and a ridge of high pressure occurs over the Rocky Mountains. During El Niño and positive PDO winters, these PNA forcings stabilize the polar jet stream and retain cold arctic air, maintaining warmer temperatures through winter months in Pacific North America. Positive PNA has been linked to warmer winter time temperatures. Precipitation impacts are more variable, and reduced snowpack levels have been observed during this phase.

The **AO** is associated with changes in the winter polar jet stream, which can cause abnormally low temperatures in some parts of the Province. The AO influences glacially-fed streamflow systems in northern BC[3].

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[1] Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[2] Ibid.
[3] Fleming, S., Moore, R.D. and Clarke, G.K.C., 2006. Glacier-mediated streamflow teleconnections to the Arctic Oscillation. International Journal of Climatology, 26: 619–636.

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1. Hydro-climatology

1.1. Temperature and precipitation

It is important that the hydro-climatology of BC is defined to place past trends and future projections in the context of average conditions and variability. In this report, BC was divided into regions which have similar hydro-climatic characteristics. An interpolated dataset representative of BC's complex climatic diversity was applied to examine the hydro-climatology within regions. Runoff regimes were also described.

Results

- BC has a diverse climatology because of its geographical exposure to the Pacific Ocean, the North American landmass, and topography (**Figure 1.1.1, 1.1.2**).
- Historical observations are essential for analysis of past climate. Currently, little is known about colder regions in BC as most observation stations are either located in the south or below 200 m elevation (**Figure 1.1.1, 1.1.2, 1.1.4a**). Areas above 1000 m are not well represented (**Figure 1.1.4a**).
- The transformation from site-specific historical weather and hydrological observations into an interpolated dataset uses PRISM[i,1] methodology. PRISM data was selected to display climatological data because it accounts for topographic influences and produces a high-resolution mapping.
- Seven different regions are identified (**Figure 1.1.3**) as a means of classifying the hydro-climate system. The zero-degree isotherm (**Figure 1.1.1, 1.1.2**) is especially sensitive to climatic change and examining the movement of this line can provide insight into the affect of climate change on the hydro-climatology of BC (section 3.3, 4.3).
- There are four idealized types of runoff typically represented in BC: *pluvial, hybrid, nival, and nival-glacial* (**Figure 1.1.5**). The timing of peak flows and low flows is different in each runoff system. The effect of climate change can modify both the amount of total annual runoff and its seasonal timing. Climate variability contributes additional uncertainty into possible changes in timing and amount of flow.

Discussion

Diverse spatial temperature and precipitation patterns across BC demonstrate BC's complex climatology. Annual mean temperatures in coastal areas are the highest on average ranging from 5^{o}C to 10^{o}C (**Figure 1.1.1**). Away from the coast, annual mean temperatures in the southern interior of the Province range from 0 ^{o}C to 5^{o}C. Parts of the Fraser Plateau and Okanagan have high annual mean temperatures due to extremely high summer temperatures. The northern parts of the Province and high elevations in the Coastal and Rocky Mountains have low annual mean temperatures that reach -15^{o}C is some places, but generally range from -5^{o}C to 0^{o}C.

In the North and South Coast regions precipitation ranges from 1,500 mm up to approximately 5,000 mm per year at a few locations (**Figure 1.1.2**). Precipitation amounts are lower between the Coastal and Rocky Mountains, in the Fraser Plateau and Okanagan, ranging from trace amounts to 1,400 mm per year. Large precipitation gradients (up to 2,050 mm of precipitation per year) exist in the Rocky Mountains, Columbia Basin and part of the north-eastern Fraser Plateau.

BC's climate is primarily controlled by mountain ranges that run north-south that interact with weather systems originating in the Pacific Ocean and influence the movement of storm tracks across the Province[2]. However, topography, distance from the coast, and elevation all combine to drive climate and weather patterns in BC. Climate variability in BC is also affected by variability in sea surface temperatures and atmospheric circulation patterns of the Pacific Ocean[3]. These teleconnections are

[i] PRISM - Parameter-elevation Regressions on Independent Slopes Model.

presented and discussed in more detail in other sections of the report (introduction I, section 2.2). The synoptic[ii] climatology of BC is an important consideration with regard to BC's hydro-climatology. Thirteen dominant circulation types have been described for BC[4]. This classification system provides an intuitive framework for understanding the influence of large-scale teleconnections on the surface climate of BC[5].

Observational Networks and Spatial Interpolation

Understanding hydro-climatology in BC relies in part on having an adequate observational network. However, the network of climate stations in BC is ≤10% smaller than the World Meteorological Organization's minimum recommended size to adequately observe weather information[6]. The number of hydrometric stations in BC is also inadequate to represent the variable hydrologic regimes present within BC, which are required for engineering design, flood warning or avoidance, and sustainable resource management [7]. Most observation stations are located in the south and information is particularly scarce in non-urban areas, small watersheds and in the northern cold regions of BC (**Figure 1.1.1, 1.1.2, 1.1.4a**). Additionally, most stations are situated at elevations below 200 m, whereas high elevation areas[8] above 1000 m are not well represented (**Figure 1.1.4a**). The current observational network presents a barrier to evaluating changes in temperature, precipitation, glacier cover, snowpack, and streamflow in the Province.

The observational networks provide station-based estimates of air temperature and precipitation, and interpolation of these point data is important to present information on these variables for all of BC. However, interpolating air temperatures and precipitation, given the current observation network is challenging due to the highly variable density and biased distribution of the stations. PRISM is potentially more sophisticated than other methods of interpolation. PRISM applies a digital elevation model (DEM) to incorporate elevation and slope. PRISM also incorporates meterological and climatological expert knowledge; therefore it is not purely a statistical interpretation[9] (**Figure 1.1.4b**). PRISM was used in this report to document BC's historical climatology, i.e. air temperature and precipitation (**Figure 1.1.1, 1.1.2**).

The success of spatial interpolation techniques in representing daily air temperature was explored recently for BC[10]. Specified lapse rates were found to be insufficient to account for the large variability in daily lapse rates in winter[11]. Methods that computed lapse rates from local control points performed poorly when there were a small number of high elevation data sites[12]. Although PRISM uses control points it represents the atmosphere with two-layers and uses a topographic index to better represent cold air drainage[13]. Even with further understanding of the effect of topography and synoptic patterns on temperature patterns an appropriate observation network that includes high-elevation stations is indispensable for creating a representative spatial interpolation of climate variables[14].

Classification of BC's Hydro-Climate

There are several different classification schemas that have been developed to divide the Province into meaningful zones based on climate, vegetation, or soils[15,16,17]. However, these schemas were either not focused on hydro-climatic factors or divided the Province into a high number of areas that were not tractable for exploring within this report. Hence, for this report the Province has been divided into seven hydro-climate regions (**Figure 1.1.3**). These regions reflect the areas where similar patterns of air temperature, precipitation and hydrology occur and provide a conceptual framework within which the diverse hydro-climate of the Province can been more easily discussed. The following describes these seven regions and provides background on why they were selected.

The coastal regions of BC situated near to the Pacific Ocean have mountainous terrain and are thus affected by similar storm patterns and orographic uplift. The southern coastal region contains the two

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[ii] Synoptic climatology is the study of climate from the perspective of atmospheric circulation, with emphasis on the connections between circulation patterns and climatic differences.

largest population centres in BC, Greater Vancouver and Greater Victoria. Hence, water quality, quantity and extreme events strongly impact the residents of these districts[18].

The interior regions of BC tend to be drier than the coastal regions and therefore may have a different response to climate change. The Fraser Plateau and Interior Plateau encompass the Fraser and Nechako River basins. Both basins are situated at high elevations in the rain shadow of the Coast Mountains and to the west of the Rocky Mountains. The Okanagan region, a focal area for recent research on climate change and hydrology, is already facing water shortages owing to large demands on the resource from agricultural requirements and recent rapid population growth[19,20]. Located adjacent to the Okanagan, the Columbia Basin has the potential to be strongly affected by climate change owing to its southern latitude combined with a reliance on snow and glaciers, which have been declining in recent years[21]. The Columbia River Treaty (a bilateral agreement between Canada and the US) is up for re-negotiation starting in 2014 and necessitates comprehensive understanding of impacts of climate change to water resources in the Columbia.

In the north of the Province, the northwest encloses the Northern Coast Mountains, the Rocky Mountains and the Stikine Plateau which include the Skeena, Stikine, and Taku River drainage basins. In the northeastern portion of the Province the Peace Basin region includes the Liard and Peace River drainages and has a unique hydro-climatic regime with a large fraction of rainfall taking place in summer.

Another means of classifying the Province is to use the freezing level as determined by elevation, aspect or latitude to distinguish snow-dominated regions from rain-dominated regions (**Figure 1.1.2**). In this report (section 4.3), the zero-degree isotherm is used to differentiate zones either above or below the isotherm. Areas adjacent to the line are sensitive to climate change because they lie in the transition zone between rain and snow. As the climate adjusts, this line will shift. Examining the movement of this line can provide insight into the affect of climate change on the hydro-climatology of BC[22].

Classification of Runoff Regimes

Classification of seasonal runoff regimes has recently been carried out for BC[23] and in the past was carried out specifically for the Georgia[24] and the Fraser Basins[25]. Runoff was classified into one of four categories: rain-fall dominated (pluvial), a mixture of rain-fall and snow-melt (hybrid), snow-melt dominated (nival), and snow-melt combined with glacier-melt (nival/glacial) (**Figure 1.1.5**). Due to lower temperatures in high latitudes and altitudes, areas outside the Georgia Basin are likely to have either nival or nival/glacial runoff regimes. However, it has been shown that some areas display unique characteristics such as having summer peak flows resulting from summer rains[26]. Yet, classifying rivers within these regimes helps to identify how they are vulnerable in the face of climate change and allows results to be grouped in a way that facilitates discussion.

The timing of peak and low flows is different in each regime. *Pluvial* tends to peak in November and December, with lowest flows occurring in July and August. *Hybrid* can have high flows from October to January and then again in April to June and have low flows in July and August. The proportion of rainfall versus snow-melt in the runoff of the hybrid regime is determined by temperature. Moving inland from the coast, or northwards up the coast, increases the predominance of snow-melt, as would increases in the mean basin elevation. *Nival* tends to peak in May, June, or July, and has lowest flows in the winter months of December to March when incoming precipitation is stored as snow. *Nival/glacial* has high flows that extend from May to August or September[27]. Again, from December to March, flows are low as precipitation is stored as snowpack**.**

Another approach for classification of BC's runoff zones is to use cluster analysis, which would group streams based on those which have similar data structures[28]. The similarity of the data structures would be defined by how the data sets are partitioned into clusters such that each cluster shares a common trait. The classification of runoff zones would be helpful for identifying areas susceptible to climate change and could help to estimate streamflow changes. Understanding runoff zones could assist with planning and management of water resources, predicated upon understanding the timing and magnitude of flows. Altered hydrologic regimes could then be managed or re-engineered.

Uncertainties and Limitations

Due to the limited observational network in BC, it is challenging to create high quality interpolated datasets. In many cases, interpolated datasets are used without evaluation of the data upon which they are based or without knowledge of the strengths and limitations of the interpolation method they were constructed with. Yet, without these interpolated datasets little could be said about changes to climate and hydrology in areas of BC where observations are sparse and changes could be severe (i.e. northern BC). Additionally, gridded datasets such as CANGRID provide an avenue for visualizing the spatial distribution of changes in parameters such as temperature and precipitation. These visualizations can be more easily compared to future projections. Conclusions drawn from application of interpolated datasets such as PRISM (applied in this report) are presented in the context of these limitations.

Short record lengths and extended periods of missing data can also hamper the investigation of the influence of climate change and variability on the hydro-climatology of BC. Often, the influence of climate variability cannot be distinguished from that of climate change because some modes of climate variability such as the Pacific Decadal Oscillation (PDO) operate on multi-decadal time scales. Therefore, a considerably long record is required to adequately distinguish between trends created by the PDO switch from one phase to another (cool to warm) from trends occurring due to climate change.

A regional assessment of hydro-climatic zones has been attempted using different methods[29,30], but consensus on the approach and the subsequent division of BC into specific hydro-climate regions has not been reached. This is due in part to the limited observational data on which to base decisions. However, this exercise would assist scientists and planners to identify regions of vulnerability based on the hydro-climate. In terms of climate change, identifying potentially vulnerable areas in the Province would better prepare communities for the changes that may occur.

The regions defined here were based on an amalgamation of BC watersheds[31] and the Hydrologic Zones of BC[32]. Twenty-seven hydrologic zones are defined in the Hydrologic Zones of BC, which would be unmanageable in a report of this size. Therefore, a somewhat arbitrary approach was applied to combine the watersheds with the hydrologic zones and to arrive at a reasonable number of regions. As such, these regions should not be seen as a scientifically based classification as the response to climate variability and change may not always uniform within these regions.

Gaps

- The hydrometric network in BC has been downsized since the 1990s. The hydrometric network does not meet WMO standards.
- The hydro-climatic characterization of BC applied in this report has not been made on the basis of scientific consensus.
- Classification of the entire Province by runoff regimes is not currently available.

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[1] Daly, C., Neilson, R.P. and Phillips, D.L., 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology, 33: 140-158.

[2] Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.

[3] Ibid.

[4] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.

[5] Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.

[6] Miles, M., and Associates, 2003. British Columbia's Climate Related Observation Networks: An Adequacy Review. Report to the Ministry of Environment, Victoria, BC.
[7] Azar, J., Sellars, D. and Schroeter, D., 2003. Report for the British Columbia Ministry of Sustainable Resource Development. Hydrometric Business Review: 64pp.
[8] Miles, M., and Associates, 2003. British Columbia's Climate Related Observation Networks: An Adequacy Review. Report to the Ministry of Environment, Victoria, BC.
[9] Daly, C., 2006. Guidelines for assessing the suitability of spatial climate data sets. International Journal of Climatology(26): 707-721.
[10] Stahl, K., Moore, R.D., Floyer, J.A., Asplin, M.G. and McKendry, I.G., 2006a. Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. Agricultural and Forest Meteorology, 139: 224-236.
[11] Ibid.
[12] Ibid.
[13] Daly, C., 2006. Guidelines for assessing the suitability of spatial climate data sets. International Journal of Climatology(26): 707-721.
[14] Stahl, K., Moore, R.D., Floyer, J.A., Asplin, M.G. and McKendry, I.G., 2006a. Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. Agricultural and Forest Meteorology, 139: 224-236.
[15] Phillips, D., 1980. The Climates of Canada, Supply and Services Canada, Ottawa.
[16] Valentine, K.W.G., Sprout, P.N., Baker, T.E. and Lavkulich, L.M., 1978. The Soil Landscapes of British Columbia, BC Ministry of Environment, Resource Analysis Branch, Victoria BC.
[17] Chilton, R.H., 1981. A summary of climate regimes of British Columbia, BC Ministry of Environment, Victoria, BC.
[18] Jakob, M., McKendry, I. and Lee, R., 2003. Long-term changes in rainfall intensity in Vancouver, British Columbia. Canadian Water Resources Journal, 28(4): 587-604.
[19] Cohen, S. et al., 2006. Learning with local help: Expanding the dialogue on climate change and water management in the Okanagan Region, British Columbia, Canada. Climatic Change, 75: 331–358.
[20] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[21] Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.
[22] Bonsal, B.R. and Prowse, T.D., 2003. Trends and variability in spring and autumn 0 °C isotherm dates over Canada. Climatic Change, 57(3): 341-358.
[23] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[24] Wade, N.L., Martin, J. and Whitfield, P.H., 2001. Hydrologic and climatic zonation of Georgia Basin, British Columbia. Canadian Water Resources Journal, 26: 43-70.
[25] Moore, R.D., 1991. Hydrology and water supply in the Fraser River basin. In: A.H.J. Dorcey and J.R. Griggs (Editors), Water in Sustainable Development: Exploring our Common Future in the Fraser River Basin. Westwater Research Centre, UBC, Vancouver, BC, pp. 21-40.
[26] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[27] Ibid.
[28] Whitfield, P.H. and Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25: 19-65.
[29] Wade, N.L., Martin, J. and Whitfield, P.H., 2001. Hydrologic and climatic zonation of Georgia Basin, British Columbia. Canadian Water Resources Journal, 26: 43-70.
[30] Moore, R.D., 1991. Hydrology and water supply in the Fraser River basin. In: A.H.J. Dorcey and J.R. Griggs (Editors), Water in Sustainable Development: Exploring our Common Future in the Fraser River Basin. Westwater Research Centre, UBC, Vancouver, BC, pp. 21-40.
[31] MoE. 2005. BC Watersheds Atlas. Ecosystems Branch, BC Ministry of the Environment.
[32] MoE. 2004. Hydrologic Zones of BC. Resource Information Branch, BCMinistry of the Environment.

Figures

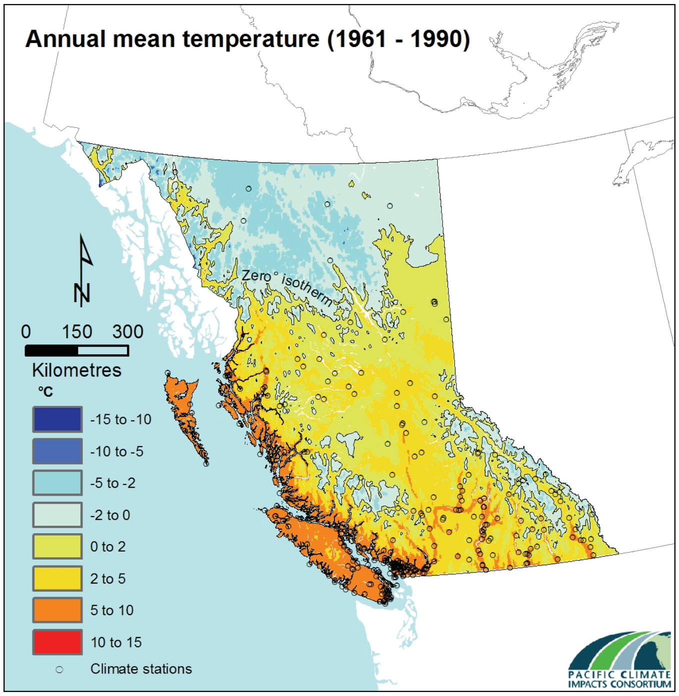

Figure 1.1.1 – Annual mean temperature (1961-1990) climatology. The zero-degree isotherm line is indicated by the dashed line. Source: PRISM data with Meteorological Service of Canada, Adjusted Historical Canadian Climate Data climate station locations.

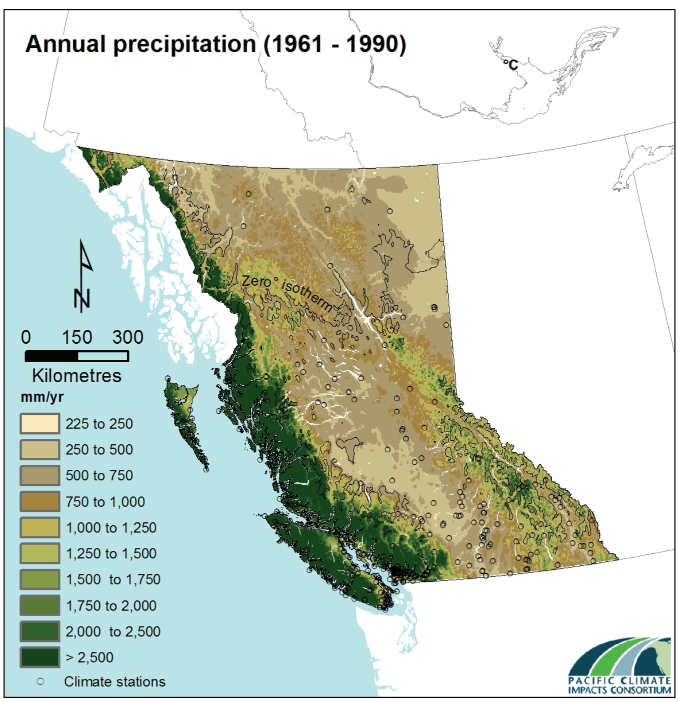

Figure 1.1.2 – Annual precipitation (1961-1990) climatology. The zero-degree isotherm line is indicated by the dashed line. Source: PRISM data with Meteorological Service of Canada, Adjusted Historical Canadian Climate Data climate station locations.

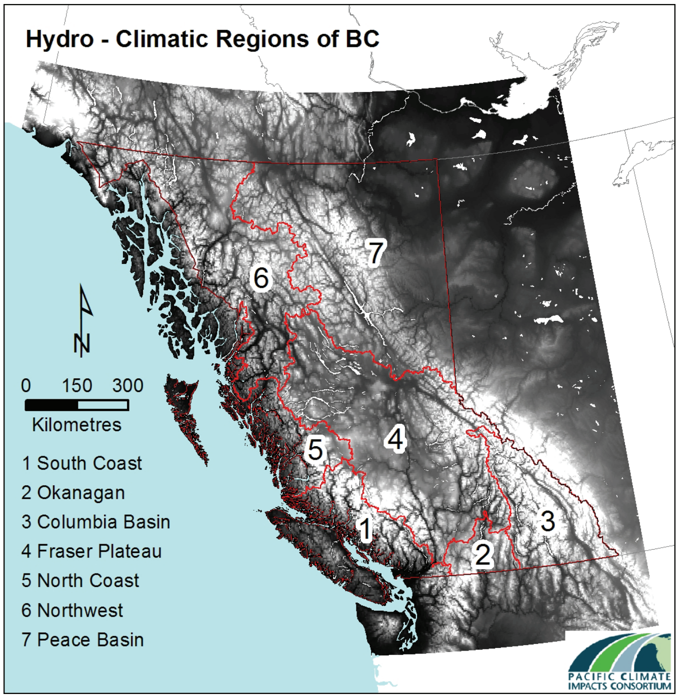

Figure 1.1.3 – Hydro-climatic regions used for this report. Source: PRISM elevation.

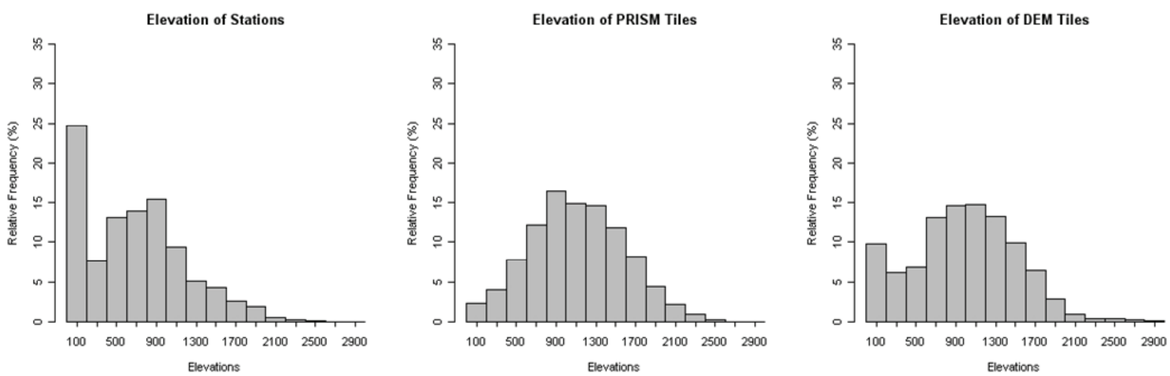

Figure 1.1.4 – Elevation of stations are illustrated as a) relative frequency distribution of observing stations, b) relative frequency distribution of PRISM tiles, and c) relative frequency distribution of topography of BC. Source: PRISM data with Meteorological Service of Canada, Adjusted Historical Canadian Climate Data climate station locations, and Canada3D digital elevation model (DEM) produced by the Canadian Forestry Service - Ontario region.

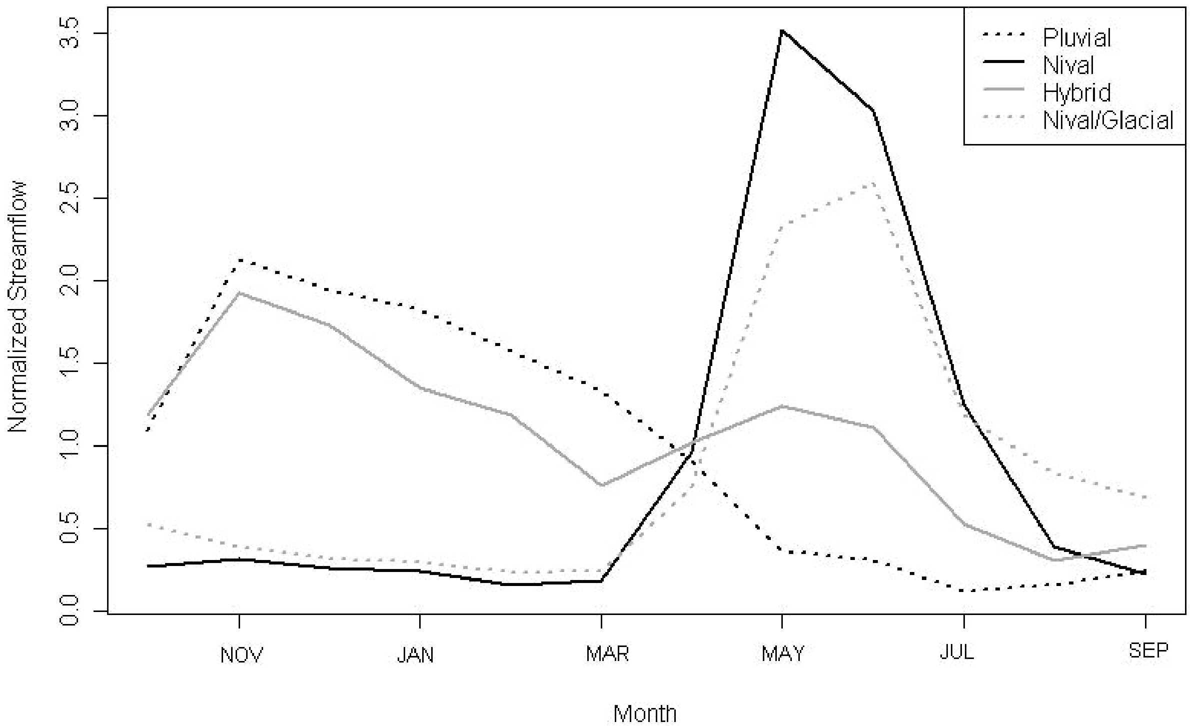

Figure 1.1.5 – Hydrological zones (pluvial, nival, hybrid, and nival/glacial). Normalized streamflow is shown on the y-axis (unitless) and months are shown on the x-axis. Source: RHBN Hydrometric data.

2. Past climate trends and variability

2.1. High resolution trends in temperature and precipitation

Trends in temperature and precipitation over the past century are important indicators of climate change. In this report, high-resolution (50 km) gridded temperature and precipitation data were used to calculate trends across BC using the latest information available (1900-2004).

Results

- Positive trends of annual *minimum* temperatures[i] were statistically significant +1.7°C (+1.0°C to +2.5°C) [ii] in BC over the past century (**Figure 2.1.1a**). However, the trends in annual *maximum* temperature during the period were lower +0.6°C (+0.5°C to +1.5°C per century, **Figure 2.1.1c**). Thus, the historical trends show that BC has been getting less cold, rather than substantially warmer[1,2].
- However, for ecologically sensitive or vulnerable sites, even small changes in annual *maximum* temperatures may have large impacts. In the Okanagan region and in the Columbia Basin, annual *maximum* temperature increased significantly (+1.3°C per century and +1.0°C per century, respectively, **Figure 2.1.1c**).
- *Seasonal* trends of *minimum* temperature were detected principally in the winter and spring seasons with increases as much as +3.5°C per century in northern BC (**Figure 2.1.2a, b**).
- *Seasonal* trends of *maximum* temperatures were significant but negative in the summer, with decreases up to -1.5°C per century. In the fall, the trends follow a similar pattern, although results are not significant (**Figure 2.1.3c, d)**.
- Trends in annual precipitation during the century were primarily positive (+22% per century) but vary spatially across BC. The largest trend occurred in the interior of BC (up to +50% per century, **Figure 2.1.1d**), where small absolute increases are a large percentage relative to the total amount of precipitation (mm).
- The *seasonal* trends indicate an increase in precipitation of +50% over the century compared to the historical climatology in the winter and spring over most of BC, especially in the northern interior (**Figure 2.1.4a, b**). Some exceptions occurred (negative or undetectable trends) in southwest BC, although these results were not statistically significant.
- These trends in precipitation over the past century were influenced by the dry years of the 1930s[3]. For example, the last half-century trends in precipitation are *negative* in the interior of BC, especially in winter (section 3.1)[4].
- All temperature and precipitation results (high-resolution, updated trends) in BC are generally consistent with previously published results for Canada. These trends are consistent, but larger than trends for North America.
- Trends in extreme events (precipitation) were not analyzed, although there is some evidence of increased intensity in Canada and North America[5].

Discussion

This section updates previous work developed at a 200 km scale for all of Canada and utilizing although at a finer scale (50 km) CANGRID data[6]. The 50 km scale is an appropriate resolution for a regional survey of historic trends, especially considering the Province's variable topography and hydro-climatology (section 1). The refined scale also allows for regional planners and communities to identify

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[i] Minimum and maximum temperatures are observed on a daily basis. Annual and seasonal temperatures were calculated from mean monthly values and summarized. Winter is December to February, spring is March to May, summer is June to August, and fall is September to November.

[ii] The range in brackets indicates the geographical range of significant results for BC, based on the intervals presented in the legends of Figure 2.1.1a to 2.1.1d and Figure 2.1.2 to 2.1.4, preceded by the average for BC.

trends in their region. For example, Metro Vancouver and the Capital Regional District (Victoria) fall into the same grid cell at the 200 km scale of analysis, with an annual total precipitation trend of +11%. The 50 km level work reveals that Metro Vancouver and surrounding region have an annual total precipitation trend of +10% while the CRD's trend is +18%. Knowledge of these differences may prove valuable to regional districts, businesses and provincial bodies implementing planning measures at the local level.

Temperature trends were observed to vary spatially across the Province (**Figure 2.1.1**). In general, trends in minimum temperature ranged from 1.7°C (+1.0°C to +2.5°C per century) and were largest in the Peace Basin (+2.0°C per century) and the Okanagan Basin (+1.8°C per century). Maximum temperature trends ranged from +0.5°C to +1.5°C per century (+0.6°C per century on average across BC), and increased significantly in the Columbia Basin (+1.3°C/century) and the Okanagan (+1.0°C per century).

Significant trends are not occurring in all areas of the Province nor across all variables. Recent research on trend analysis points out that significance measures do not necessarily reflect uncertainty in results[7]. Results, regardless of significance, can indicate a valid trend and non-significant trend results should not be disregarded entirely[8].

Seminal research on Canadian climate trends from 1900-1998 for southern Canada (south of 60°N) illustrate a statistically significant positive trend in annual mean temperatures of +0.9°C, as the anomaly relative to the 1961-1990 average, over the 99-year period[9]. The IPCC[10] reported trends for land surface average temperature over North America on the range of 0.72°C (±0.26°C)[11] to 0.89°C (±0.25°C)°C[12] (period of 1901-2005). In BC, annual mean temperatures have increased up to 2.0°C over the century (**Figure 2.1.1b**). Findings as presented in this report concur with these results even though the periods of analysis are slightly different.

The most strong and significant seasonal temperature trends in Canada occurred in the *minimum* temperature records during winter and spring in the western parts of the country (BC)[13]. Seasonal analysis of temperature supports this finding, with the greatest increases occurring in northern BC (3.5°C per century, **Figure 2.1.2a**). As minimum temperature increased to a greater degree than maximum temperature, a declining diurnal temperature range can be inferred[14,15]. The reason for the difference is not fully understood, and trend results for different time scales (i.e. 50 years) show that average maximum temperatures in the most recent 50 years are also increasing at a comparable rate to minimum temperatures[16]. There is also evidence that in the future, average maximum temperatures will change just as much, if not more, than minimum temperatures (section 4).

Maximum temperature changes have occurred in some of the most the sensitive regions of the Province. A significant and positive winter *maximum* temperature trend occurred in southern BC (+1.6°C per century, South Coast, Okanagan and the Columbia Basin) and the Northwest (+2°C per century) of the Province, and in spring in the Peace Basin and the Okanagan. The Okanagan, where maximum temperature increased by +1.9°C per century, is currently dealing with water shortages and water quality issues[17]. Meanwhile, in the north, increased maximum temperatures may have shifted snowmelt dates, which could lead to increased occurrence of mid-winter melt events ice-jams and flooding (section 3.3).

Maximum temperature changes in the summer have decreased significantly in *summer* on the central and northern coast and in the *fall* through most of northern BC (although not significantly). Station data has been examined to determine extreme temperature changes across Canada and the results support this finding[18]. A cooling trend of maximum temperatures in summer and fall may reduce the diurnal temperature range and affect evaporation feedback mechanisms, which could have implications for low flow periods (section 3.3).

Annual total relative precipitation (1900-1998) has increased by +12% across Canada, while results from this study (1900-2004) indicate precipitation increased by +22% on average across BC[19]. The plateau and valley regions of BC, where small absolute increases are a large percentage relative to the total amount of precipitation (mm), experienced the greatest relative precipitation increases (up to +50% per century, **Figure 2.1.1d**). A station-based seasonal analysis of precipitation trends echoes BC-specific findings that winter and spring precipitation increases are most significant and strong of all seasons[20]. Precipitation increased (at most stations) strongly during the months of April to July[21]. Trends occurring in BC are reflective of a broader-scale trend toward increased precipitation occurring within the Pacific Northwest as a whole. Some exceptions existed in southwest BC, where a negative precipitation trend was observed, although results were not statistically significant.

Station-based trend analysis differs from the methodology undertaken to evaluate trends for BC. This report applies gridded data based on an adjusted homogenized data set[22]. Interpolated (gridded) data introduce less noise than station data and results in smoothed fields suitable for broad-scale measurement of data such as long-term trends[23]. The use of gridded data over station data also enabled trend evaluation across all regions of the Province, even in locations where stations were sparse (such as in the north, **Figure 2.1.1a to Figure 2.1.1d**). Although there are few stations, the topography is far less complex in the north versus the southern regions of BC, which may reduce uncertainty related to the sparseness of the monitoring network.

Decadal analysis with respect to trends is an important consideration. Positive temperature trends occurring over the past century can be mostly attributed to the changes that occurred before the 1940s and after the mid-1970s[24]. Changes in solar radiation as a consequence of increased cloud cover prior to the 1950s may have played a role in lower daily temperature ranges that occurred during this period of the record[25]. Likewise increased annual total precipitation occurred between the 1920s and the 1970s[26]. Therefore precipitation trends are particularly strong because the very dry years are influence the entire 20th-century trend analysis. Precipitation trends in the past 50 years, for example, are negative in the interior of BC, especially in the winter[27]. Clustering and analysis of shorter duration station records are other approaches that provide insight into recent decadal changes in temperature and precipitation trends across Canada and for BC[28, 29, 30].

Trends in extreme events are also an important consideration as extremes in both temperatures and precipitation can have severe impacts to BC communities and infrastructure. In Southwestern Canada, heavy rainfall[31] trends were significant and positive (+0% to +7%) in May-June-July over the second part of the century (1950-1995) [32]. This finding was also noted in terms of increasing areas affected by extreme dry and extreme wet summer conditions[33]. However, no trend was observed in intensity or frequency of heavy precipitation events over the 1900-1998 period [34].

Uncertainties and Limitations

The approach used to create the 50 km scale trends was based on a well-established methodology and hence the results are updated at a finer scale, but closely reflect the broad-level 200 km findings[35]. However, the gains from re-generating this data set at the 50 km resolution may be offset by the losses in smoothing. Smoothing at the 200 km scale was noted[36] to be appropriate for analysis of trends and detection of change in long-term time series data of temperature and precipitation. Additionally, the finer scale of analysis (50 km) may result in new errors that have yet to be assessed. The error bounds established and applied at the 200 km scale may not be applicable to the 50 km resolution[37] and careful error-checking against station data is warranted to determine the error bounds at the 50 km resolution.

The CANGRID data set has not been analysed for trends within varying time-steps[38]. An 11-day or 5-day time-scale could yield more sensitive results than the current trend analysis. A finer temporal scale may also be more relevant to planners in BC.

A point of clarification also is required with regard to *mean* temperature results. Annual *mean* temperature measures were calculated for this study, but seasonal results not shown. This is because the signals observed within the seasonal minimum and maximum temperature fields are generally more relevant to planning initiatives. For example, long-term changes in winter minimum temperatures influence hydrology and climate and can impact streamflow or snowpack conditions (section 3).

Gaps

- Warming over the century results in larger changes in minimum temperatures compared to maximum temperatures and this results in a decline in the daily temperature range[39]. However, this effect may be linked more closely with cloud cover amounts that occurred in the first half of the 20th century[40]. The link between changes in minimum (night time) temperatures and cloud cover is not understood at this time[41].

- Annual precipitation increases over the past century occurred in the first two thirds of the record, primarily during the 1920s to 1970s[42]. Decadal analysis may yield important information in terms of the timing of precipitation declines, differentiating what occurred over the past century from the most recent decades and forging a link to future precipitation projections.
- Analysis of trends in areas affected by extreme dry and extreme wet increased during the summer for the second half of the century[43]. Hence there was a concurrent increase in the area of land where extreme wet conditions occurred, while the extent of extreme dry areas also increased. This observation is possibly indicative of an enhanced hydrologic cycle[44,45].
- Trend detection for extremes (number of wet days, number of dry days, spatial extent of dry and wet areas, rainfall intensity, and frequency of high rainfall events) should be more carefully examined for British Columbia[46].
- Trends in synoptic climatology types[47] for BC would be valuable to determine if changes that have occurred are related to the synoptic weather and teleconnection (section 2.2) patterns that drive climate in BC.
- Temperature and precipitation processes operate within different spatial and temporal domains through separate processes, and thus analysis of temperature and precipitation trends must incorporate this. For example, 11-day periods for temperature may be appropriate; however, precipitation trends could be detectable at finer temporal scales, such as 5-day events[48].
- A BC-focused trend analysis of extreme events (number of wet days, number of dry days, spatial extent of dry and wet areas, rainfall intensity[49], and frequency of high rainfall events) may help to quantify the extent that flooding events, ice-jams, rain-on-snow (mid-winter warming) events, and storm surges are increasing, as noted by BC's Provincial Emergency Program[50].
- Further insight into changes in precipitation could be gained from trend analysis that separates precipitation into rainfall and snowfall components[51].
- Utmost caution is recommended when selecting a measure of significance because different types of trend tests may be successful at detecting significance in hydrologic and climate parameters[52]. Non-significant results can still be valid, especially in poorly-understood systems, and should not be completely disregarded[53].

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[1] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[2] Bonsal, B.R., Zhang, X., Vincent, L.A. and Hogg, W.D., 2001b. Characteristics of daily and extreme temperatures over Canada. Journal of Climate, 14: 1959-1976.
[3] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[4] Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
[5] Zhang, X., Hogg, W.D. and Mekis, É., 2001b. Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate, 2001(14): 1923-1936.d
[6] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[7] Cohn, T.A. and Lins, H.F., 2005. Nature's style: Naturally trendy. Geophyscial Research Letters, 32: L23402, doi:10.1029/2005GK024476.
[8] Ibid.
[9] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[10] IPCC, 2007b. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 18 pp.

[11] Smith, T.M. and Reynolds, R.W., 2005. A global merged land and sea surface temperature reconstruction based on historical observations (1880–1997). Journal of Climate, 18: 2021–2036.
[12] Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B. and Jones, P.D., 2006. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. Journal of Geophysical Research, 111, D12106, doi:10.1029/2005JD006548.
[13] Bonsal, B.R., Zhang, X., Vincent, L.A. and Hogg, W.D., 2001b. Characteristics of daily and extreme temperatures over Canada. Journal of Climate, 14: 1959-1976.
[14] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[15] Bonsal, B.R., Shabbar, A. and Higuchi, K., 2001a. Impacts of low frequency variability modes on Canadian winter temperature. International Journal of Climatology 21: 95-108.
[16] Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
[17] Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.
[18] Bonsal, B.R., Zhang, X., Vincent, L.A. and Hogg, W.D., 2001b. Characteristics of daily and extreme temperatures over Canada. Journal of Climate, 14: 1959-1976.
[19] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[20] Mote, P.W., 2003a. Twentieth-century fluctuation and trends in temperature, precipitation, and mountain snowpack in the Georgia Basin-Puget Sound region, Canada. Water Resources Journal, 28(4): 567-585.
[21] Ibid.
[22] Mekis, E. and Hogg, W.D., 1999: . Rehabilitation and analysis of Canadian daily precipitation time series. Atmosphere-Ocean(37): 53-85.
[23] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[24] Ibid.
[25] Henderson-Sellers, A., 1989. Continental cloudiness changes this century. GeoJournal, 27(3): 255-262.
[26] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[27] Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
[28] Whitfield, P.H. and Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25: 19-65.
[29] Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
[30] Whitfield, P.H., 2001. Linked hydrologic and climate variations in British Columbia and Yukon. Environmental Monitoring and Assessment, 67: 217-238.
[31] See Stone et al. (2000) for a description of heavy precipitation
[32] Stone, D.A., Weaver, A.J. and Zwiers, F.W., 2000. Trends in canadian precipitation intensity. Atmosphere-Ocean, 38(2): 321-347.
[33] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[34] Zhang, X., Hogg, W.D. and Mekis, É., 2001b. Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate, 2001(14): 1923-1936.d
[35] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[36] Ibid.
[37] Ibid.
[38] Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
[39] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[40] Henderson-Sellers, A., 1989. Continental cloudiness changes this century. GeoJournal, 27(3): 255-262.

[41] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[42] Ibid.
[43] Ibid.
[44] Ibid.
[45] Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology, 319: 83-95.
[46] Stone, D.A., Weaver, A.J. and Zwiers, F.W., 2000. Trends in canadian precipitation intensity. Atmosphere-Ocean, 38(2): 321-347.
[47] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
[48] Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
[49] Stone, D.A., Weaver, A.J. and Zwiers, F.W., 2000. Trends in canadian precipitation intensity. Atmosphere-Ocean, 38(2): 321-347.
[50] Whyte, J., 2006. Extreme weather impacts on PEP and Public Safety. CWRA Conference Proceedings, CWRA Conference, Victoria, BC.
[51] Knowles, N., Dettinger, M., and Cayan, D., 2006. Trends in snowfall versus rainfall for the Western United States. Journal of Climate, 19(18): 4545-4559.
[52] Cohn, T.A. and Lins, H.F., 2005. Nature's style: Naturally trendy. Geophyscial Research Letters, 32: L23402, doi:10.1029/2005GK024476.
[53] Ibid.

Figures

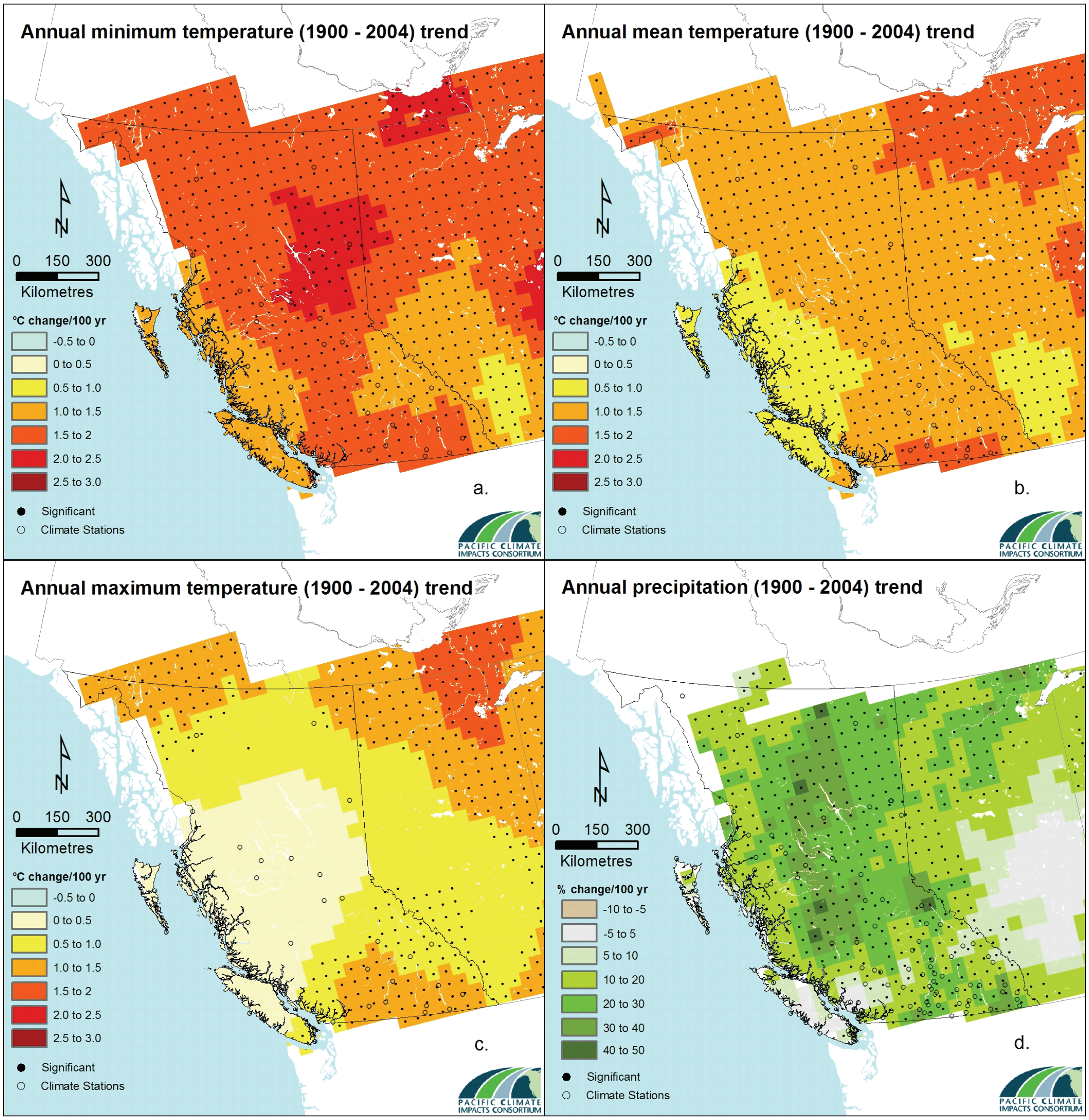

Figure 2.1.1 – Annual trends in (a) minimum, (b) mean, (c) maximum temperature and (d) precipitation for British Columbia. Results are based on 1900 to 2004 data and calculated as degree Celsius change per century. Black solid circles indicate statistically significant results (95% confidence level). Open circles show the location of Adjusted Historical Canadian Climate Station sites (AHCCD). Source: CANGRID (50 km) data; adapted from Zhang et al. 2000.

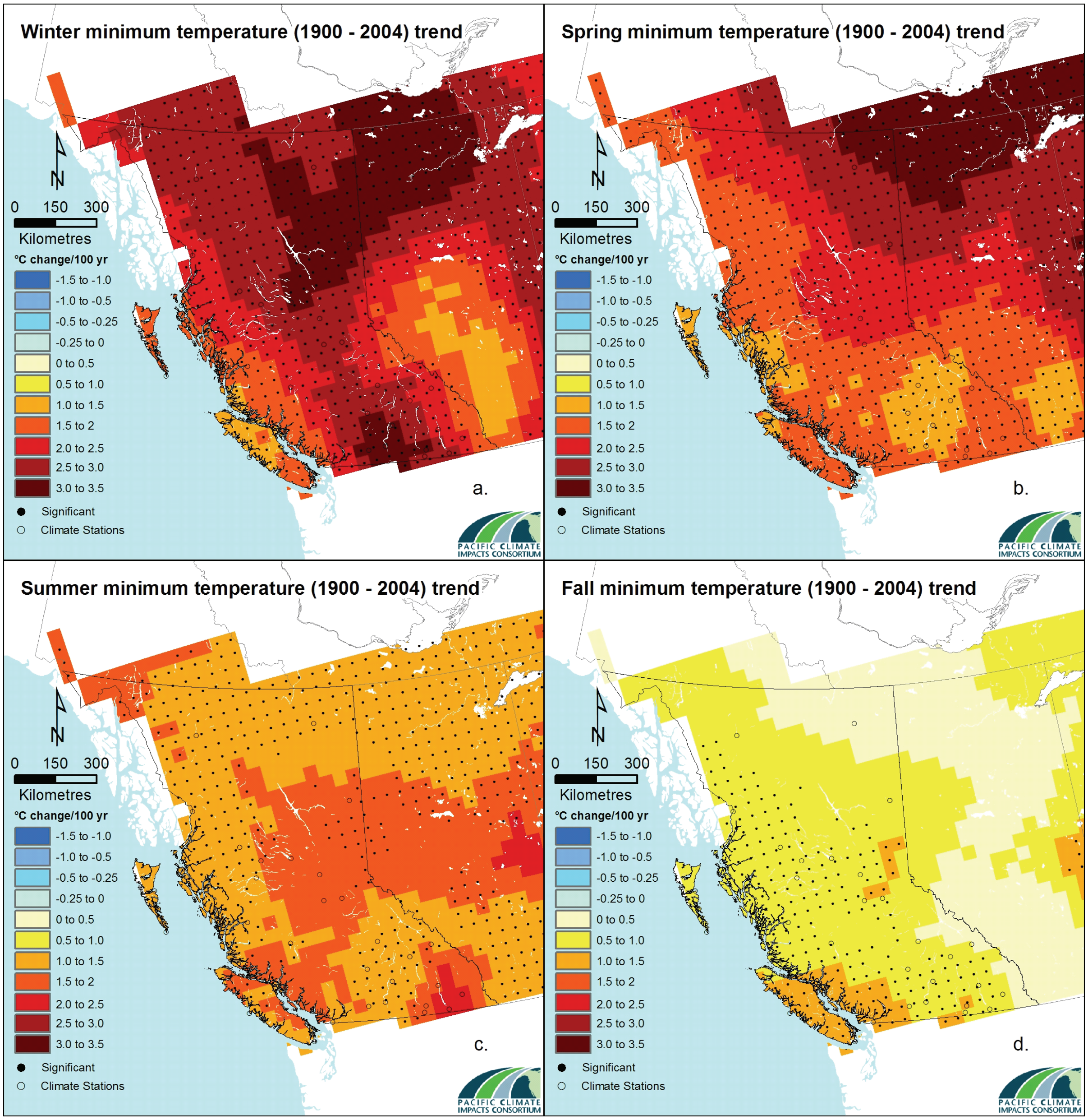

Figure 2.1.2 – Seasonal trends in minimum temperature (a) winter, (b) spring, (c) summer and (d) fall for British Columbia. Results are based on 1900 to 2004 data and calculated as degree Celsius change per century. Black solid circles indicate statistically significant results (95% confidence level). Open circles show the location of Adjusted Historical Canadian Climate Station sites (AHCCD). Source: CANGRID (50 km) data; adapted from Zhang et al. 2000.

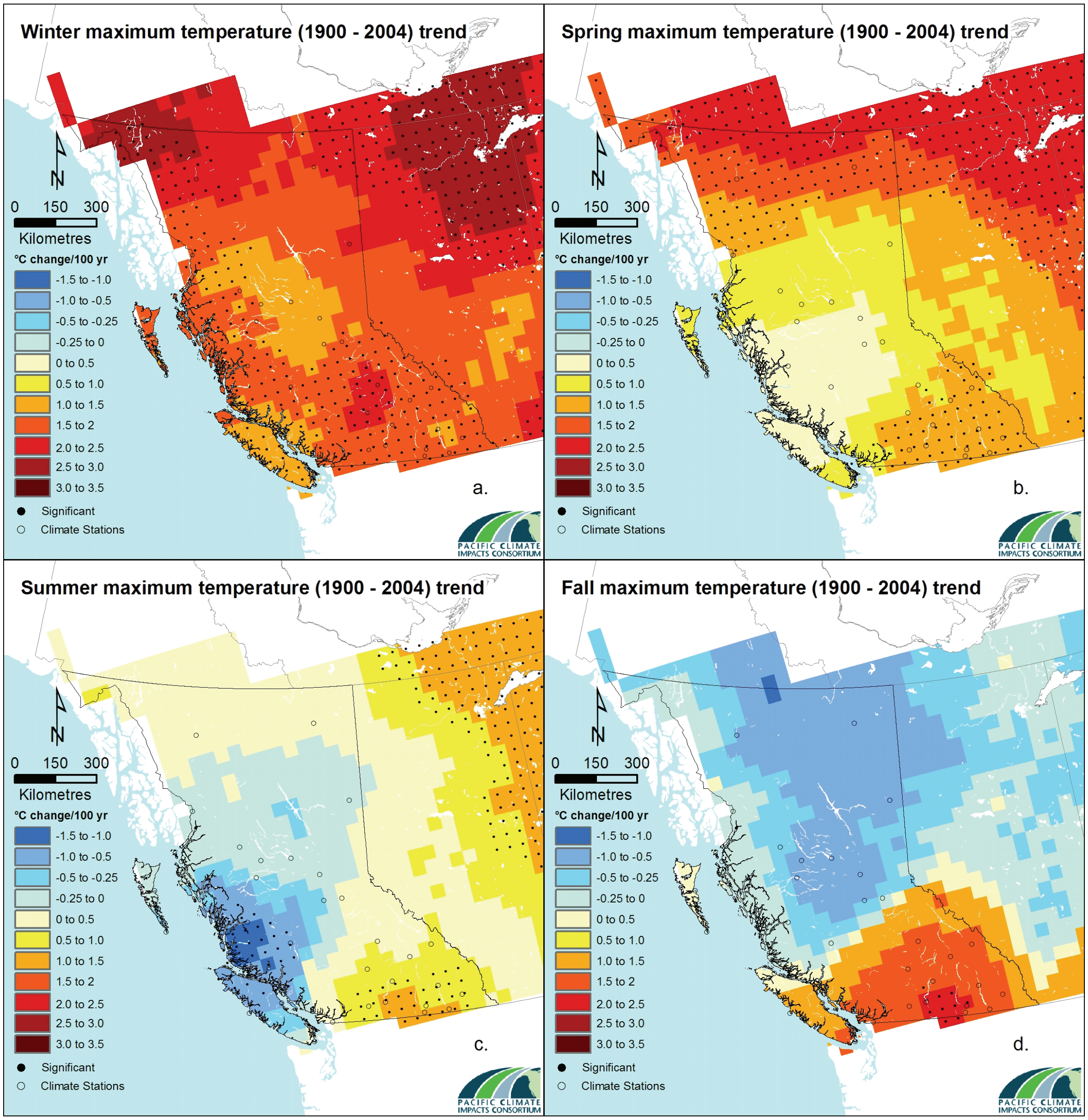

Figure 2.1.3 – Seasonal trends in maximum temperature (a) winter, (b) spring, (c) summer and (d) fall for British Columbia. Results are based on 1900 to 2004 data and calculated as degree Celsius change per century. Black solid circles indicate statistically significant results (95% confidence level). Open circles show the location of Adjusted Historical Canadian Climate Station sites (AHCCD). Source: CANGRID (50 km) data; adapted from Zhang et al. 2000.

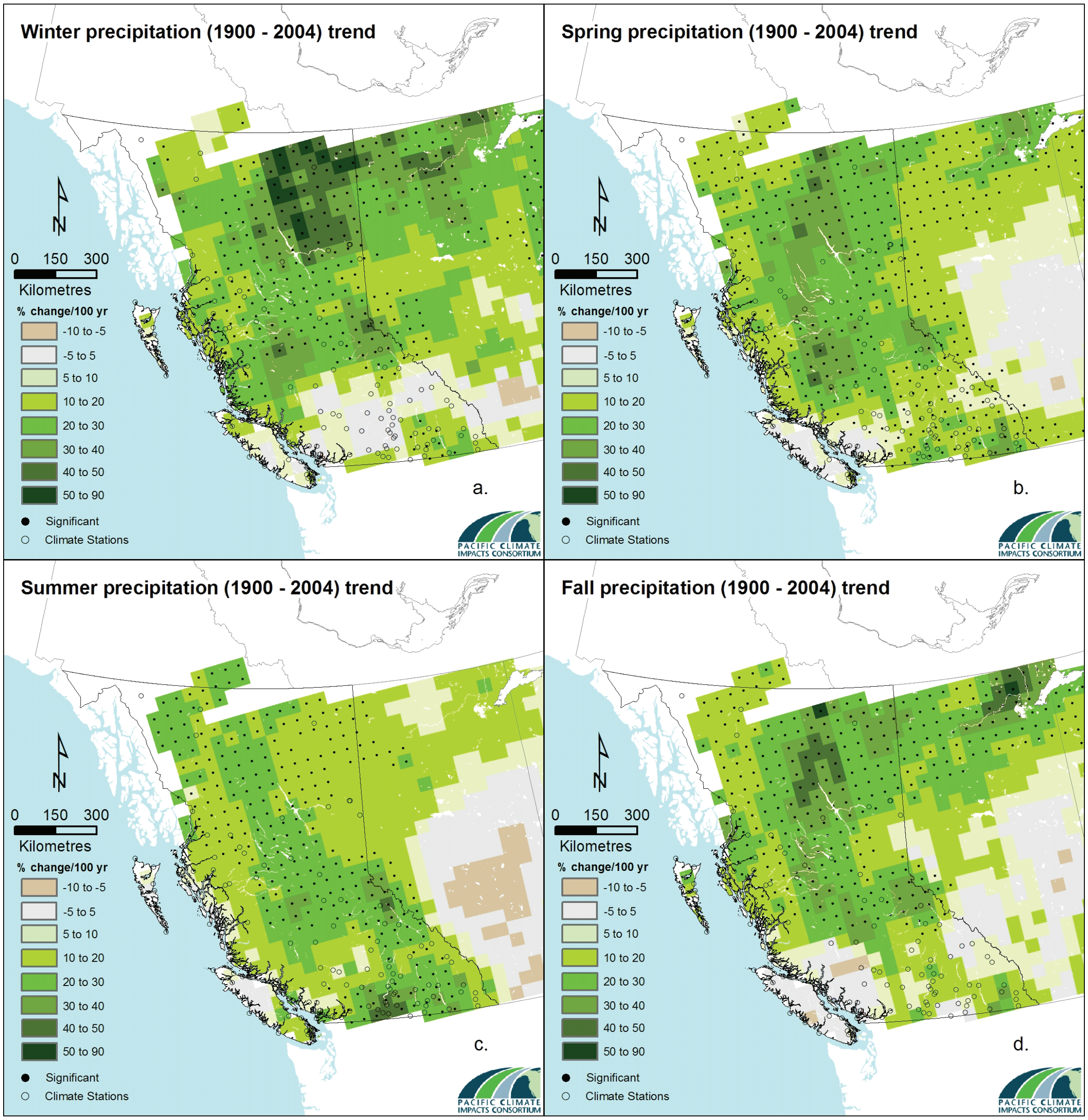

Figure 2.1.4 – Seasonal trends in precipitation (a) winter, (b) spring, (c) summer and (d) fall for British Columbia. Results are based on 1900 to 2004 data and calculated as degree Celsius change per century. Black solid circles indicate statistically significant results (95% confidence level). Open circles show the location of Adjusted Historical Canadian Climate Station sites (AHCCD). Source: CANGRID (50 km) data; adapted from Zhang et al. 2000.

2.2. Climate variability

This section of the report presents the temperature and precipitation pattern associated with two modes of climate variability – ENSO and PDO – observable in BC. ENSO and PDO impacts on temperature and precipitation across BC were calculated using an up-to-date (1900-2004) gridded data set. Section 3.1 and 3.2 include a discussion of the impacts of these atmospheric modes on snowpack and streamflow. ENSO and PDO are described in the terminology box of the Introduction (I) to this report.

Results

- During the warm phase of ENSO, *temperature* in BC was significantly higher (+0.5°C to +2.8°C[i]) from December through June compared to the response during the negative phase (**Figure 2.2.1**). Likewise a significant temperature response (up to +2.9°C in some locations) was observed during the positive phase of PDO compared to the negative phase (**Figure 2.2.1**). Temperature responses to ENSO and PDO are consistent across all 7 regions of BC for most of the year. However, there are exceptions to these results.
- During the warm phase of ENSO, the monthly averaged *precipitation* (October to March) in BC was somewhat less (decreased 5%) compared to the response during the cool phase (**Figure 2.2.2**). During the positive phase of the PDO, the monthly averaged precipitation (October to March) was not significantly different (**Figure 2.2.2**). But there are important exceptions in some regions, particularly in BC's North Coast and Northwest regions, where the October to March positive PDO signal was opposite to the rest of the Province.
- On a *seasonal* basis, ENSO and PDO influences on *temperature* were strongest and more spatially variable in winter (**Figure 2.2.3**). ENSO influence on *precipitation* was strong in winter (**Figure 2.2.4**) and the PDO influence on precipitation was strong in spring (**Figure 2.2.5**). The precipitation patterns were variable across BC.
- The impacts of ENSO and PDO reinforce each other depending on the phase (not shown), and this may increase the likelihood of extreme weather events (section 3.1, 3.3).
- Seasonal climate variability on the scale of years and decades may cause changes in temperature and precipitation of the same magnitude or greater than changes in historical, long-term seasonal trends (**Figure 2.1.2 to 2.1.4, 2.2.3 to 2.2.5**). For example, El Niño winter mean temperatures are +2.0°C (**Figure 2.2.4, Table 2.2.1**) warmer than the 20th century trends in BC winter mean temperature (+2.1°C per century).

Discussion

The impact of ENSO on climate in Canada is well-documented[1,2], but much less is understood about the PDO, which was identified in the mid-1990s[3,4]. Therefore, the question remains whether the range and scale of effects observed in instrumental records is representative. It appears that these impacts have occurred for much longer than the instrumental records can demonstrate[5,6,7]. Therefore, BC's record may show only a part of the potential range of climate variability.

The climate variability related to ENSO and PDO in BC as shown in this report has also been documented by other researchers using different proxies to infer variability and shifts. Within BC, effects of ENSO, PDO, PNA and AO on climate and hydrology have been well documented[8,9,10,11,12,13,14,15.] For example, a bootstrapped, month-by-month approach examined four stations located within the Georgia Basin for significant differences between composites of El Niño versus La Niña, El Niño versus neutral, La Niña versus neutral and PDO warm versus PDO cool[16]. This work illustrated how significance testing can be applied to identify results that are statistically different from each other (i.e. El Niño versus La Niña) or a baseline (ENSO neutral conditions).

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[i] This number represents the geographical range of the data.

ENSO temperature responses in the South Coast region are reasonably consistent with previously published research that reported results from stations within the Georgia Basin[17]. ENSO response was slightly shorter-lived compared to the PDO response[18], El Niño temperatures were significantly warmer compared to La Niña temperatures during December through June (+0.5°C to +2.9°C[ii]) whereas warm PDO was significantly warmer than cool PDO during January through August (**Figure 2.2.1,** up to +2.9°C in some locations). Spatial responses in ENSO and PDO temperature are distinct in that the signal is quite clearly defined for different areas of the Province (**Figure 2.2.3**). The north central (Fraser Plateau) and the Peace Basin are most strongly affected by ENSO temperature response, while PDO response is more consistent across BC (**Figure 2.2.3a, c**).

El Niño precipitation responses were generally drier during the October to March water year (decreased 5%) and wetter in the summer and fall periods compared to La Niña (**Figure 2.2.2**). The PDO precipitation response was more varied, tending towards increased precipitation throughout the year during warm events. However, there was only one location (Northwest) where statistically significant results were observed in the PDO response.

Spatial responses in precipitation patterns in BC are strongly affected by topography and distance from the coast, therefore precipitation responses are mixed across the Province. Hence, valleys and mountain ranges influenced the response and created the pattern observed (**Figure 2.2.4 to 2.2.5**). During El Niño winters, the Province is generally drier, with the exception of northern Vancouver Island, Haida Gwaii and parts of the south coast, which display an opposite (wet) signal (**Figure 2.2.4a**). Most of the Province is wetter during La Niña winters (**Figure 2.2.4c**). During spring, the El Niño (La Niña) response is weaker than in winter and reversed, with drier (wetter) conditions throughout most of BC (**Figure 2.2.4b, d**). Warm (cool) PDO conditions during winter generally exhibit the same pattern as El Niño (La Niña) winter but signals are weaker (**Figure 2.2.5a, c**). During spring, the PDO warm (cool) precipitation response is strong and wide spread over the Province (**Figure 2.2.5b, d**).

The interaction of PDO and ENSO can amplify responses in a particular region[19,20]. For example, results from Southwestern BC[21] illustrate that in-phase La Niña/cool PDO precipitation is +19% to +25% higher than during non-ENSO and out-of-phase (PDO) years, and +39% greater than during in-phase El Niño/warm PDO years[22]. During these in-phase periods, ENSO and PDO reinforce each other and hence there may also be increased likelihood of extreme weather events.

Climate variability and the underlying weather patterns may be illustrated by synoptic typing that is associated with weather in BC. Five to six weather types occurring within BC are significantly affected by interannual climate variation[23]. For example, the frequency of a cool-and-wet weather type (Type 3) is significantly increased during negative PDO and PNA winters. Concurrently, another type (Type 13) shows the opposite pattern, which creates a negative feedback response and hence a stronger precipitation anomaly in the interior of BC and weaker precipitation anomaly along the northern coast. These findings help to explain why increased precipitation occurred during positive PDO phases on the northern coast, while the Fraser Plateau and the South Coast were drier (**Figure 2.2.5a**). Another key finding is related to within-type variability associated with teleconnection patterns, which has important consequences for statistical downscaling techniques for regional climate projections (section 4.3) [24].

Understanding how climate variability affects BC hydro-climatology (temperature and precipitation) is important for two reasons: the temporal and spatial extents of climate variability provide context to determine the relative importance of projected, future climate changes; and it may provide an important analogue to future climate change that could operate within the ranges of already-observed climate variability. The impact of climate variability on the Canadian economy may cost between two and five billion dollars[25], an expense that could potentially be offset with advance knowledge of the range of expected impacts[26].

Further, the importance of these short-term and locally driven modulations of climate must be clearly understood within the context of broad-scale climate change. A shift to a negative PDO state, in future years, could present a cooling effect that, in some locations, could operate to temporarily "reverse"

[ii] This number represents the range in the data. Numbers revised in 2009.

climate change. However, a return to a negative PDO phase must be differentiated from a reversal in the global warming trends. Future climate change projections will be superimposed on this variability. Future climate change may also influence variability as well as changing average climate. Detection and attribution of source of impacts is very difficult given the complex relationship between climate variability and climate change.

Uncertainties and Limitations

The current status of the PDO is under debate in the scientific literature. Some researchers promote the theory that the PDO has evolved into a new regime[27,28] that is not indicative of the 30+ year phases which were experienced prior to 1998[29]. Knowledge of the PDO phase is important for planning, especially if the PDO mechanism has changed to a new regime.

Gaps

- The spatial variability of ENSO and PDO response in BC has not been tested using statistical significance measures (i.e. using gridded data sets).
- Testing the differences between ENSO and PDO impacts on a seasonal basis using statistical techniques has not been produced for all of BC.
- A test of different composites of ENSO would be useful to determine which composite has the greatest influence on climate variability in BC[30,31, 32].
- Detailed analysis on extremes and how these relate to climate variability is not available for BC at this time.

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[1] Shabbar, A., 1996. The impact of El Nino-Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean, 34(2): 401-416.
[2] Shabbar, A., Bonsal, B. and Khandekar, M., 1997. Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate, 10: 3016 - 3026.
[3] Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78: 1069-1079.
[4] Zhang, Y., Wallace, J.M. and Battisti, D.S., 1997. ENSO-like interdecadal variability:1900–93. Journal of Climate, 10: 1004–1020.
[5] Biondi, F., Gershunov, A. and Cayan, D.R., 2001. North Pacific decadal climate variability since 1661. Ibid., 14: 5-10.
[6] Gedalof, Z. and Smith, D.J., 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophysical Research Letters, 28: 1515 - 1518.
[7] Donders, T.H., Wagner, F., Dilcher, D.L. and Visscher, H., 2005. Mid- to late-Holocene El Nino-Southern Oscillation dynamics reflected in the subtropical terrestrial realm. Proceedings of the National Academy of Sciences, 102(31): 10904 - 10908.
[8] Moore, R.D. and McKendry, I.G., 1996. Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. Water Resources Research, 32(3): 623-632.
[9] Bitz, C.M. and Battisti, D.S., 1999. Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska. Journal of Climate, 12: 3181 - 3196.
[10] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[11] Kiffney, P.M., Bull, J.P. and Feller, M.C., 2002. Climatic and hydrologic variability in a coastal watershed of Southwestern British Columbia. Journa of the American Water Resources Association, 38(5): 1437 - 1451.
[12] Gobena, A.K. and Gan, T.Y., 2006. Low-frequency variability in Southwestern Canadian stream flow: Links with large-scale climate anomalies. International Journal of Climatology, 26: 1843 - 1869.
[13] Stahl, K., Moore, R.D. and McKendry, I.G., Ibid.The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. (4): 541-560.
[14] Fleming, S., Moore, R.D. and Clarke, G.K.C., Ibid.Glacier-mediated streamflow teleconnections to the Arctic Oscillation. 619–636.

[15] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[16] Ibid.
[17] Ibid.
[18] Ibid.
[19] Storlazzi, C.D., Willis, C.M. and Griggs, G.B., 2000. Comparative impacts of the 1982-3 and 1997-8 El Niño winters on the central California coast. Journal of Coastal Research 16(1022-1036).
[20] Gershunov, A. and Barnett, T.P., 1998. Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society, 79(12): 2715-2725.
[21] the Malcolm Knapp Research Forest
[22] Kiffney, P.M., Bull, J.P. and Feller, M.C., 2002. Climatic and hydrologic variability in a coastal watershed of Southwestern British Columbia. Journa of the American Water Resources Association, 38(5): 1437 - 1451.
[23] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
[24] Ibid.
[25] Shabbar, A., 2006. The impact of El Nino-Southern Oscillation on the Canadian climate. Advances in Geosciences, 6: 149-153.
[26] Hamlet, A.F., 2003. The role of transboundary agreements in the Columbia River Basin: An integrated assessment in the context of historical development, climate, and evolving water policy. In: H. Diaz and B. Morehouse (Editors), Climate, Water and Transboundary Challenges in the Americas. Kluwer Press, Boston, pp. 263-289.
[27] Bond, N.A., Overland, J.E., Spillane, M. and Stabeno, P., 2003. Recent shifts in the state of the North Pacific. Geophysical Research Letters, 30(23): 2183, doi: 10,1029/2003GL018597.
[28] Peterson, W.T. and Schwing, F.B., 2003. A new climate regime in northeast pacific ecosystems. Geophyscial Research Letters, 30(17): 1896, doi: 10.1029/2003GL017528.
[29] Mantua, N.J. and Hare, S.R., 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47: 103–145.
[30] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[31] Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
[32] Kiffney, P.M., Bull, J.P. and Feller, M.C., 2002. Climatic and hydrologic variability in a coastal watershed of Southwestern British Columbia. Journa of the American Water Resources Association, 38(5): 1437 - 1451.

Figures and Tables

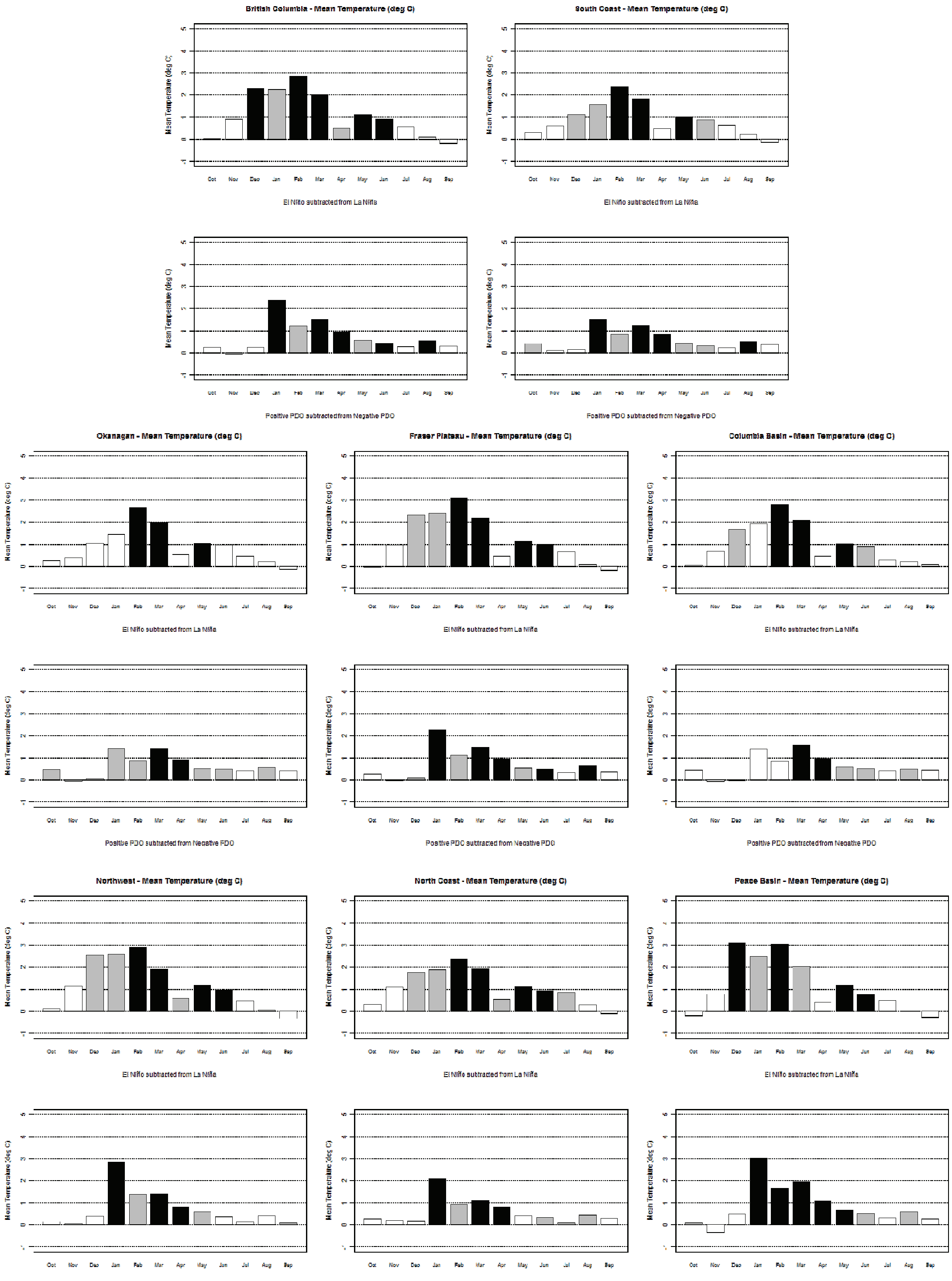

Figure 2.2.1 revised March 2009 - Differences in mean temperature (°C, 1900-2007) between El Niño subtracted from La Niña, and mean temperature (°C, 1900-1998) positive PDO phase subtracted from negative PDO phase across the seven different regions of BC and for all of British Columbia for each month (October to September, x-axis). Statistical significance is indicated by gray (95%) or black (99%) shading. Source: CANGRID (50 km) 2007 data, CIG 2006.

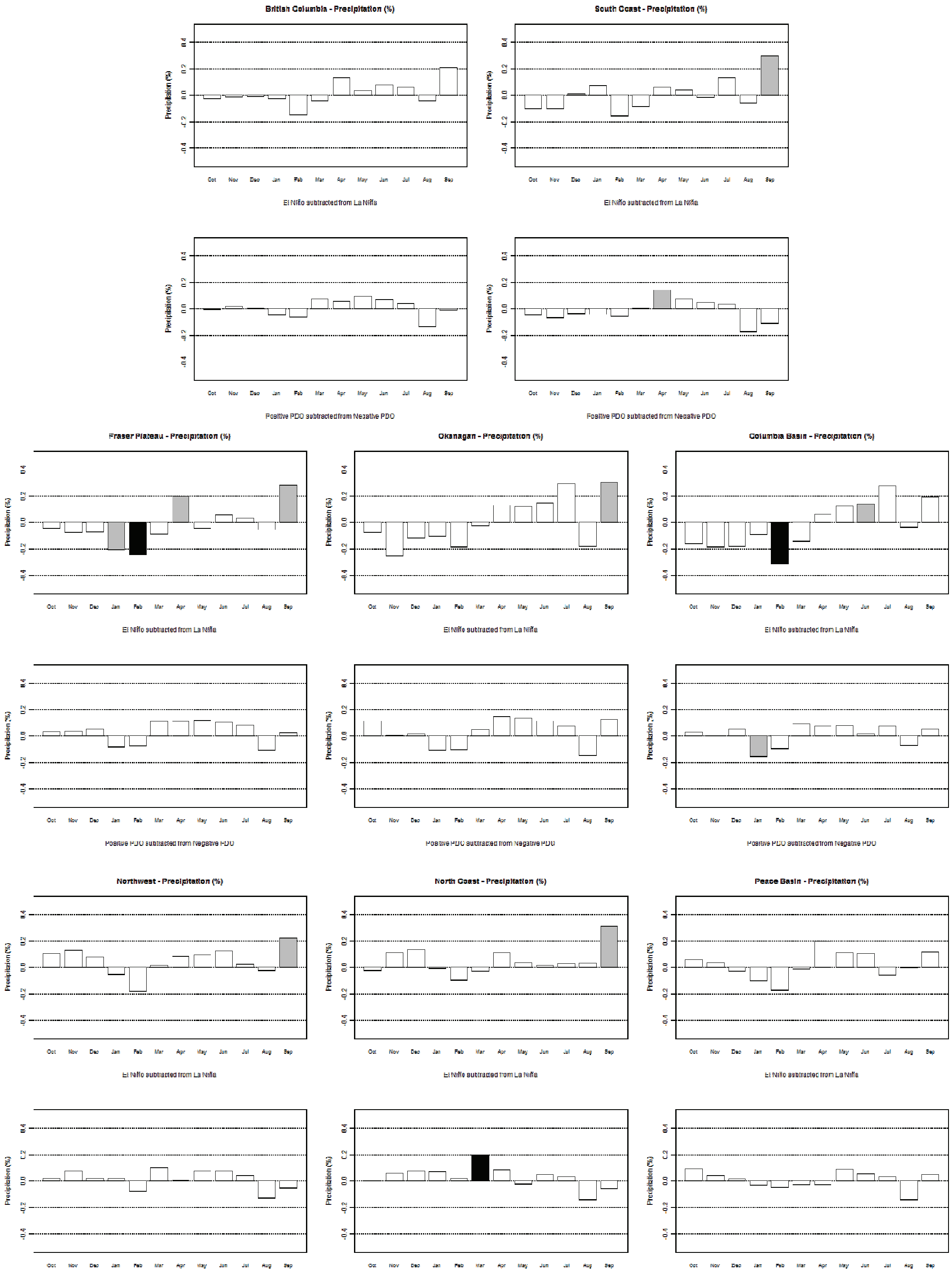

Figure 2.2.2 revised March 2009 - **Differences in precipitation (1900-2007) El Niño subtracted from La Niña precipitation and precipitation (1900-1998) positive PDO phase subtracted from negative PDO phase, shown as a percentage of the 1961 – 1990 climatology. Results illustrated for the seven different regions of BC and for all of British Columbia for each month (October to September, x-axis).. Statistical significance is indicated by gray (95%) or black (99%) shading. Source: CANGRID 2007 (50 km) data, CIG 2006.**

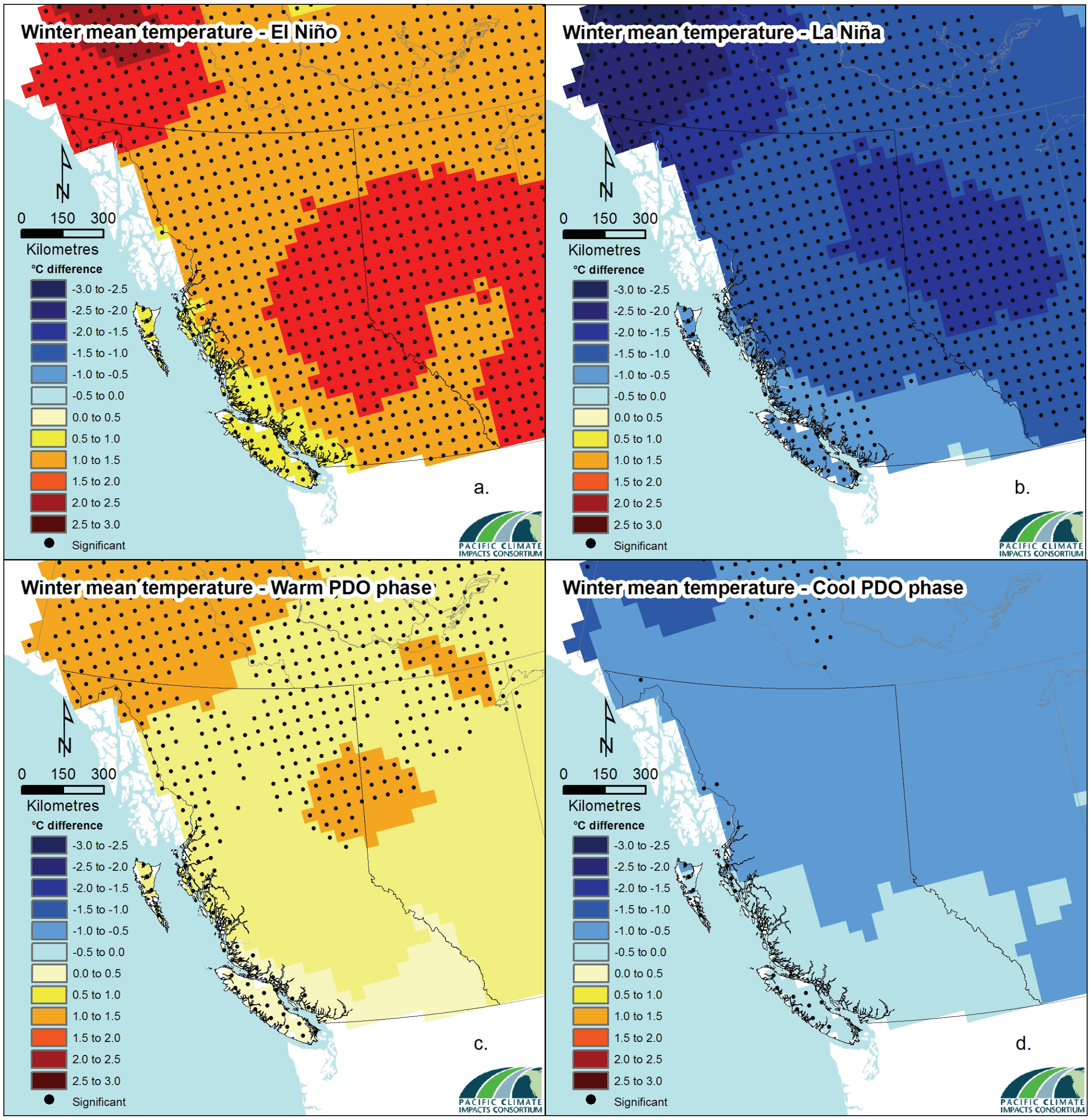

Figure 2.2.3 updated March 2009 - Seasonal climate variability for mean temperature (a) El Niño winter, (b) La Niña winter, (c) warm PDO winter and (d) cool PDO winter for British Columbia. Results are composites from the 1900 – 2007 (ENSO) and 1900 – 1998 (PDO) and calculated as degree Celsius differences from the long-term average. Black solid circles indicate statistically significant results (95 % confidence level) compared to normal. Source: CANGRID (50 km) data.

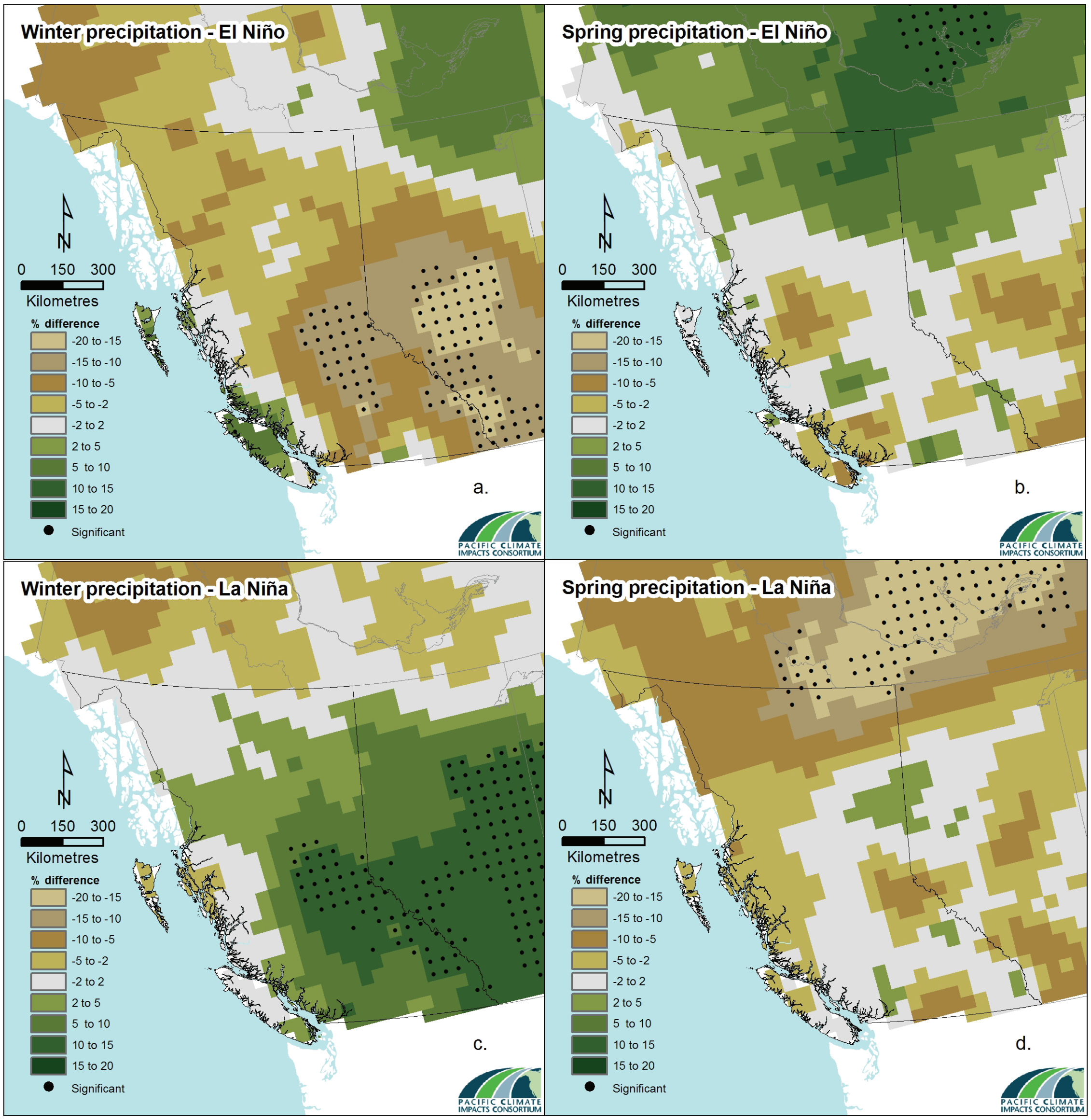

Figure 2.2.4 revised March 2009 - Seasonal climate variability for precipitation (a) El Niño winter, (b) El Niño spring, (c) La Niña winter and (d) La Niña spring for British Columbia. Results are based on 1900 to 2007 (ENSO) and calculated as a difference from the long-term average, percent of the 1961 – 1990 climatology. Source: CANGRID (50 km) data.

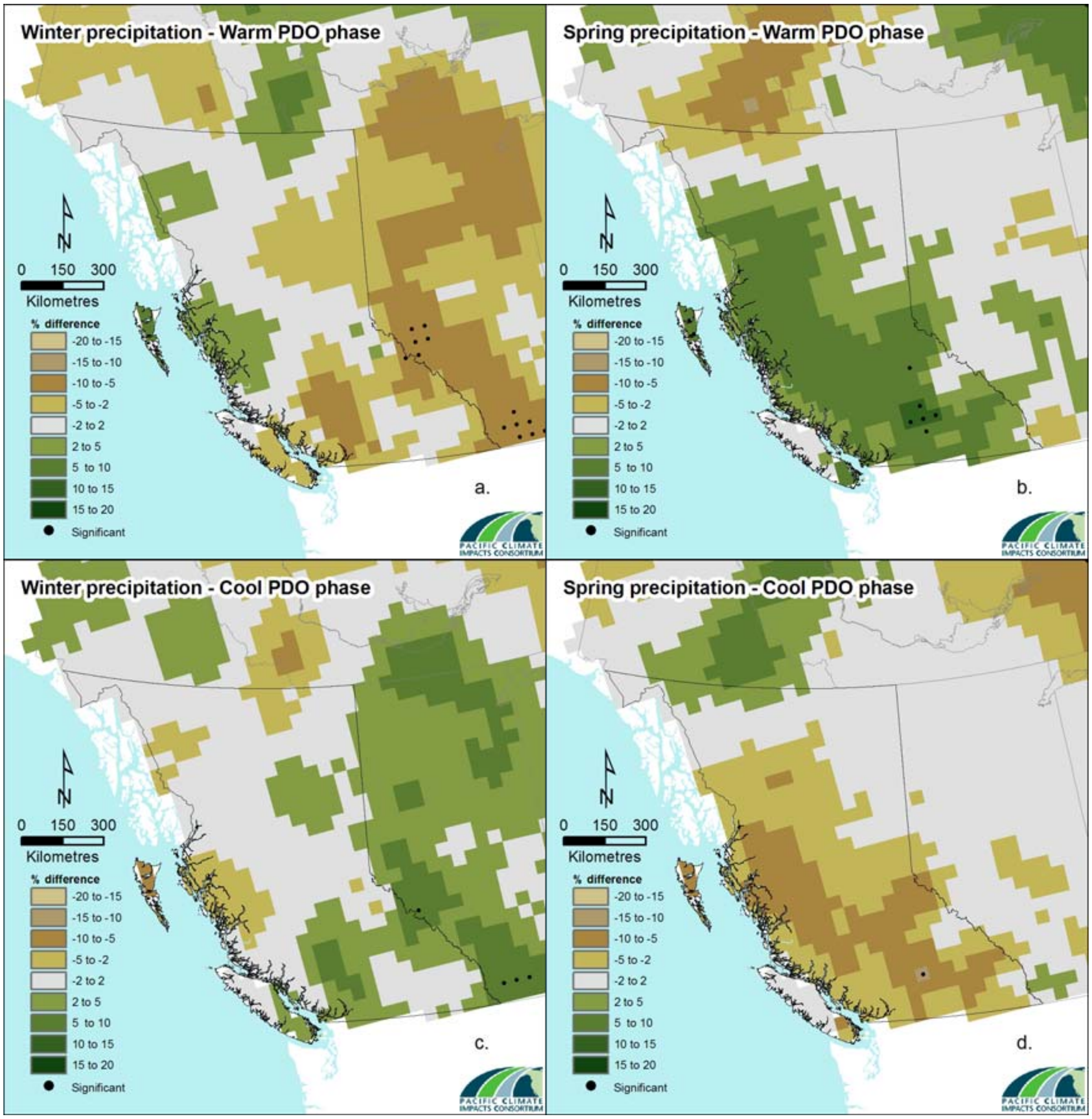

Figure 2.2.5 revised March 2009 - Seasonal climate variability for precipitation (a) warm PDO phase winter, (b) warm PDO phase spring, (c) cool PDO phase winter and (d) cool PDO phase spring for British Columbia. Results are based on 1900 to 1998 (PDO) and calculated as a difference from the long-term average, percent of the 1961 – 1990 climatology. Source: CANGRID (50 km) data.

Table 2.2.1 revised March 2009 - Seasonal mean temperature (°C difference from the long-term average) and precipitation (% difference of the 1961-1990 climatology from the long-term average) for four teleconnections (El Niño, La Niña, Warm PDO, and Cool PDO). Results are composites from the 1900 – 2007 (ENSO) and 1900 – 1998 (PDO). Italicized values are mapped for BC (see Figure 2.2.3 to 2.2.5). Source: CANGRID (50 km) data.

Teleconnection		Temperature (°C)				Precipitation (%)			
		Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
El Niño	Min	*-0.3*	-0.4	-0.2	-0.4	*-19*	*-12*	-20	-12
	25th Percentile	*0.6*	0.2	0.1	-0.2	*-4*	*-2*	-3	-2
	Median	*1.0*	0.5	0.1	-0.1	*1*	*2*	1	1
	Mean	*1.0*	0.5	0.2	0.0	*0*	*2*	0	0
	75th Percentile	1.4	0.7	0.2	0.1	*4*	*6*	3	3
	Max	*2.3*	1.2	0.7	0.6	*16*	*25*	14	11
La Niña	Min	*-2.6*	-0.8	-0.5	-0.4	*-23*	*-27*	-18	-12
	25th Percentile	*-1.3*	-0.5	-0.2	-0.1	*-2*	*-7*	-4	-3
	Median	*-0.8*	-0.3	-0.1	0.0	*2*	*-2*	-1	-1
	Mean	*-0.8*	-0.3	-0.1	0.1	*2*	*-3*	-1	-2
	75th Percentile	*-0.3*	-0.1	0.0	0.3	*6*	*1*	2	1
	Max	*0.2*	0.4	0.2	0.7	*28*	*18*	12	14
Warm PDO	Min	*-0.6*	-0.2	-0.2	-0.4	*-12*	*-10*	-8	-7
	25th Percentile	*0.1*	0.2	0.1	-0.2	*-2*	*0*	-1	2
	Median	*0.5*	0.5	0.2	-0.1	*1*	*3*	1	3
	Mean	*0.4*	0.4	0.2	-0.1	*3*	*4*	1	4
	75th Percentile	*0.8*	0.6	0.3	0.0	*6*	*7*	3	5
	Max	*1.4*	1.0	0.4	0.2	*33*	*31*	16	17
Cool PDO	Min	*-1.5*	-0.8	-0.3	-0.2	*-35*	*-26*	-14	-15
	25th Percentile	*-0.7*	-0.5	-0.2	0.0	*-5*	*-7*	-3	-5
	Median	*-0.4*	-0.4	-0.2	0.1	*-1*	*-2*	-1	-3
	Mean	*-0.3*	-0.3	-0.1	0.1	*-3*	*-4*	-1	-3
	75th Percentile	*-0.1*	-0.2	-0.1	0.1	*2*	*0*	1	-1
	Max	*0.7*	0.3	0.2	0.3	*10*	*9*	6	6

3. Hydrological trends and variability

3.1. Snowpack

Snowmelt runoff contributes 50 to 80% of the total flow[1] in nival basins (section 3.3); therefore it is an important hydrologic variable for recharge and sustenance of baseflow conditions[2]. This analysis extends previous efforts to examine a comprehensive snowpack dataset from northern and southern BC, updates trend analysis on snowpack to 2007, and highlights historical variability in snowpack over the past century.

Results

- An analysis of *long-term trends* (> 50 years) in April 1st snowpack can only be achieved in southern BC since most of the Province does not have historical data extending back more than 50 years.
- Long-term (1951 – 2007) average *relative*[i] April 1st snowpack trends were -25% (**Figure 3.1.1a**) in BC. Trends were negative at all stations and most were statistically significant within the four regions for which data was available. At a few stations, relative decreases in snowpack of up to 50%[ii] occurred during the same period.
- The analysis of snowpack trends during the *baseline period* (1961-1990; 30 years) includes additional observational stations (**Figure 3.1.1b**). The trends in snowpack were larger and consistent with snowpack trends from the *long-term record* (1951 – 2007). However, significant relative increases in snowpack up to +80% occurred at one northern station.
- The trends during the *current period* (1978-2007; 30 years) are computed from many stations in northern BC and across the Province. In this period, a mixture of both positive and negative trends occurred, and most of the trends were not statistically significant (**Figure 3.1.1c**). Even in southern BC, these results neither confirm nor contradict the positive trend obtained from the long-term and the baseline periods.
- The complexity of recent (30 years) changes in snowpack trends was the result of several influences including a denser network of snowpack survey stations available for analysis, variable precipitation (section 2.2), elevation effects and a short record of observations for the 1978 – 2007 period.
- During the warm (cool) phase of ENSO, a decrease (increase) in snowpack occurred (**Figure 3.1.2a, b,** an average of -11% and +21% and for warm and cool phases, respectively). In southern BC, the magnitude of ENSO response was weaker than the trends in historical snowpack. Generally, ENSO responses in the northern part of the Province were weaker.
- The response to PDO phases is similar to the response to ENSO phases in southern BC snowpack (average -1% and +14% for positive and negative phases, respectively). In the northern parts of the Province, cool PDO responses appear reversed (**Figure 3.1.2c, d**).

Discussion

Trends

Trends in April 1st snow water equivalent documented in this section were consistent with research on long-term SWE trends[3,4,5,6]. This analysis improves on previous publications, which have been based on studies focused on Western Washington[7] (including results for southern BC) or on broad-scale regions that encompass BC but are not focused on BC[8,9,10]. Specifically, BC's northern regions have not been extensively documented due to a limited observational network and short record lengths and therefore the

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[i] Relative percentage is calculated as a percent of the initial trend condition at the first year of record (Mote et al. 2005).

[ii] Over the period of 57 years

most recent period (1978 – 2007) was included in this analysis to addresses this concern. Trends have been updated (2007) to include the period for which IPCC researchers[11] have documented as having the most strong and significant climate change impacts, especially with regard to temperature[12].

Results for the 1951-2007 period were comparable with other observations noting the decline in SWE trend occurring in many regions including the Georgia Basin[13] (>30% decrease), across the Pacific Northwest[14] (> 40% decrease in the Cascades) and throughout Western North America[15] (> 50% decrease), respectively. Declines in SWE occurred frequently at elevations below about 1800m ranging from 20-50% (average 25% decrease) at most stations in BC[16,17]. Longer term trend analysis based on modelling illustrates that snowpack trends over the whole century are similar to trends in the recent past (since the 1950s)[18].

Across southern BC, significant negative trends (-23% on average) were observed at stations located within mountainous regions during the 1961-1990 period. However, in the northwest corner of BC a station located near the town of Atlin exhibited significant positive trends in SWE (+80%). The North Coast, Northwest or the Peace Basin regions of the Province have few snowpack observation stations in the 1961-1990 period suitable for trend analysis. Therefore, the Atlin station could represent an anomaly. This station will be discussed in more detail in subsequent paragraphs.

Across the Province, increasing and decreasing SWE trends were observed for the most recent period (1978-2007). On the South Coast, SWE increased over the period (+34% on average), but none of these results were significant. Through the Okanagan region, the response was mixed – about 40% of the stations showed increasing trends (i.e. Trout Creek, increase of +35%), while only 15% of stations showed decreasing trends (i.e. Vaseux Creek, decrease of -45%). The Columbia Basin had a mixed snowpack trend signal as well, although most trends were weak (+1.7% on average). Trends in the Fraser Basin increased (+51% SWE, on average), while 23% of stations showed decreasing trends whereas 26% of stations observed had no trend[iii]. Through the northern stations (Peace Basin, northern Fraser Basin and the Northwest), increases and decreases in SWE were noted. The Atlin station (Log Cabin) exhibited an increased trend (+29%) during this period, although the trend was not statistically significant.

SWE trends in BC are likely correlated with station temperature and precipitation trends. The influences of temperature and precipitation on snowpack response has been documented by other researchers and the effects of temperature and precipitation separated[19,20]. In general, positive trends in temperature have overwhelmed any increases in SWE occurring as a result of increased precipitation (section 2.1), leading to an overall decline in SWE across the Pacific Northwest and Western North America[21].

High elevation stations, however, tend to be some of the coldest areas for most of the winter season and therefore they are less sensitive to changes in temperature compared to mid-elevation stations. For this reason, high elevation stations may experience fewer mid-winter melt events[22]. Hence, in high-elevation regions such as Rocky Mountains, trends depended mainly on the changes in precipitation. In the interior of BC, decreases in precipitation have been documented over the past 50 years, which also may have effected declining snowpack [23]. The relationship between temperature and precipitation at BC snowpack observation stations requires further analysis.

The impact of elevation on snowpack changes[24] appear to be reflected most clearly in the 1978-2007 SWE trends. In BC, stations which exhibited increasing trends (+24% on average) in snowpack showed a decreasing trend with increasing elevation ($r^2 = 0.21$, $p < 0.001$, ~1400 m). However, stations that exhibit negative SWE trends (-22% on average) had a weaker relationship between SWE trend and elevation ($r^2 = 0.11$, $p < 0.05$, ~1200m) that also decreased with increasing elevation. In summary, small trends (in either direction) are found at higher elevations and larger trends occurred at lower elevations (in either direction) in BC. The differences in trends across BC occurring in the most recent period (1978 – 2007) is likely due to the increased number of observation stations that occur at different elevations, latitudes, and distances from the coast (section 1). More research is required to understand the changes in snowpack trends occurring in the 1978 – 2007 period.

[iii] No trend refers to SWE trends ±5% or less.

Snowfall that occurred in the Atlin region (Log Cabin station) has increased in part due to changes in historical air temperatures and precipitation over the past century, especially in seasons when temperatures were below freezing (winter, section 2.1). Further research on changes to precipitation patterns and shifts in teleconnections is required to understand whether this response is correlated with responses at other northern stations or outside of BC (Yukon, NWT, Alaska and northern Alberta) and to hypothesize why increased snowpack occurred.

Climate Variability

El Niño influenced BC SWE trends more-or-less uniformly across the Province. In general, El Niño years exhibited lower average SWE (11% decrease) compared to average long-term conditions (1935-2005). However, northern Vancouver Island SWE appears to have increased during El Niño years. During La Niña years, the opposite effect occurred across BC - SWE increased 21% on average across BC. Increases were larger on the South Coast, Okanagan and in the lower Fraser Basin regions.

During the PDO warm phase, average SWE was 8% lower than the average long-term conditions (1935-2005), and responded similarly to El Niño signals. The PDO warm phase signal was weak in the north of BC and strongest in the South Coast and the Okanagan. SWE was higher (14%) on average during PDO cool (negative) phase years. In this case northern BC responded in the opposite direction to the southern BC stations; SWE was 9% lower in northern BC during the PDO cool phase.

Interannual variations in SWE have been examined by other researchers and findings support results reported in this section. The effects of interannual variability on snow in the Columbia Basin were examined and most of the impact on SWE resulted from high PNA, La Niña, El Niño and low PNA[25]. The PNA pattern and SWE in BC and Western North America was documented to affect SWE by increasing (decreasing) SWE in years of strong (weak) response[26,27]. However, the PNA can only account for part of the variability in SWE observed. The remaining influence is predominantly owing to temperature increases observed in the past century that are largely unrelated to climate variability and may be affected by human impact on the climate[28].

Changes in global temperatures can shift atmospheric circulation and alter synoptic weather patterns and the processes driving snow accumulation and ablation. SWE may be more responsive to the incoming Pacific storm events versus shifts in mean climate[29], hence, it may be more difficult to correlate changes in SWE directly with shifts in temperature and precipitation at nearby climate stations[30]. Rather, changes in snow may be more closely linked to changes in synoptic weather patterns[31]. For example, a change in synoptic-scale circulation involving deepening of the Aleutian low was observed to be associated with lighter-than-average snowpack conditions across BC[32].

Uncertainties and Limitations

Trends in SWE for BC are hampered by short records with incomplete/missing data. There are two issues with the missing data. The first issue is length of record at each station, the second is the difference in terms of missing data values throughout the record. Many stations in BC began in the 1950s or later. However, some stations (e.g. Grouse Mountain) have a long record (1935-present).

Truncating the data sets such that records are mostly complete and do not start or stop with multiple years of missing data requires that many stations be dropped from the analysis. There are approximately 250 stations in BC, however, for the periods analysed the maximum number of usable records is 136. Over the 1951-2007 period records were limited (only 25 stations were used for analysis) due to data availability and quality.

The other concern with SWE data is with regards to stations or missing data values. In some years, stations were not monitored and these occurred randomly through the data set. Stations with more than 20% of their record missing were discarded. Some researchers are beginning to infill data sets with values predicted from correlated adjacent stations[33]. The quantitative influence of missing values on this trend analysis has yet to be assessed. However, a test of trends using infilled data resulted in differences between -10% to +22% of the non-infilled trend. One other type of error includes snowpack observation errors. Snowpack measurements are hampered by problems such as gauge undercatch and rely on accurate model calculations to convert snow depth to snow water equivalent[34].

Trends must be presented without bias in terms of their latitudinal and elevational gradients. SWE stations are scattered across the Province but tend to be most abundant spatially in southern BC. Another issue which is not immediately apparent is that the BC snow network is located primarily between the elevations of 1200 and 1700 m[iv]. As discussed and presented by other researchers, elevation exerts a strong influence on trend[35]; however, in BC regional variations in snow course elevations may exert a confounding signal on the relationships between trends and elevation[36].

There is some debate as to how warming decreases snowpack. Recent research illustrates that it is not so much that more precipitation is falling as rain but that the sensible heat flux is increasing during winter, as in the case for increased trends in snow ablation at stations across North America[37]. Melt events may be playing a large role in end-of-season snowpack[38]. An alternate study points to the importance of rain-to-snow ratios and increasing rainfall trends across the United States[39].

Gaps

- A Western North America wide (beyond the bounds of BC to Yukon, NWT, Alberta and Washington, Oregon and Idaho) analysis of SWE trends is not available.
- The impact of changes in climate on SWE trends in BC is not well understood, especially in the northern regions of BC.
- Correlation analysis is being undertaken by other researchers to infill missing data, but no such information is available for stations across BC.
- Integrated analysis of snowpack trends and streamflow trends in BC has not been conducted.
- Statistical analysis (i.e. comparing the response of SWE to ENSO and PDO) may provide greater insight on the SWE response to climate variability.
- Up-to-date research on alternate teleconnection patterns (PNA or AO) and the impact of these patterns on BC SWE is limited.
- Synoptic climatology in BC and the influence on SWE trend is not well understood.

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[1] Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2004. Changes in snowmelt runoff timing in Western North America under a 'business as usual' climate change scenario. Climate Change, 62: 217-232.
[2] McCabe, G.J. and Clark, M.P., 2005. Trends and variability in snowmelt runoff in the Western United States. Journal of Hydrometeorology, 6: 476 - 482.
[3] Mote, P.W., 2003a. Twentieth-century fluctuation and trends in temperature, precipitation, and mountain snowpack in the Georgia Basin-Puget Sound region, Canada. Water Resources Journal, 28(4): 567-585.
[4] Mote, P.W., 2003b. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters, 30(12): 1601, 3-1 to 3-4.
[5] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[6] Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in Western North America. American Meterological Society, 19: 6209 - 6220.
[7] Mote, P.W., 2003a. Twentieth-century fluctuation and trends in temperature, precipitation, and mountain snowpack in the Georgia Basin-Puget Sound region, Canada. Water Resources Journal, 28(4): 567-585.
[8] Brown, R.D., 2000. Northern hemisphere snow cover variability and change, 1915 – 97. American Meteorological Society: 2339 – 2335.
[9] Groisman, P.Y., Karl, T.R., Knight, R.W. and Stenchikov, G.L., 1994. Changes in snow cover, temperature, and radiative heat balance over the Northern Hemisphere. Journal of Climate, 7: 1633-1656.
[10] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.

[iv] First and third quartiles

[11] IPCC, 2007b. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 18 pp.
[12] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[13] Mote, P.W., 2003a. Twentieth-century fluctuation and trends in temperature, precipitation, and mountain snowpack in the Georgia Basin-Puget Sound region, Canada. Water Resources Journal, 28(4): 567-585.
[14] Mote, P.W., 2003b. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters, 30(12): 1601, 3-1 to 3-4.
[15] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[16] Mote, P.W., 2003b. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters, 30(12): 1601, 3-1 to 3-4.
[17] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[18] Hamlet, A.F., Mote, P.W., Clark, M.P. and Lettenmaier, D.P., 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. Journal of Climate, 18(21): 4545-4561.
[19] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[20] Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in Western North America. American Meterological Society, 19: 6209 - 6220.
[21] Ibid.
[22] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[23] Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
[24] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[25] Hsieh, W.W, and Tang, B. 2001. Interannual variability of accumulated snow in the Columbia basin, British Columbia. Water Resources Research. 37 (6): 1753–1759.
[26] Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in Western North America. American Meterological Society, 19: 6209 - 6220.
[27] Moore, R.D. and McKendry, I.G., 1996. Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. Water Resources Research, 32(3): 623-632.
[28] Karoly, D.J. and Wu, Q., 2005. Detection of regional surface temperature trends. Journal of Climate, Letters, 18: 4337-4343.
[29] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[30] Ibid.
[31] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
[32] Moore, R.D. and McKendry, I.G., 1996. Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. Water Resources Research, 32(3): 623-632.
[33] Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in Western North America. American Meterological Society, 19: 6209 - 6220.
[34] Goodison, B.E., 1978. Accuracy of Canadian snow gauge measurements. American Meteorological Society, 17: 1542-1548.
[35] Mote, P.W., A.F. Hamlet, and E.P. Salathé., 2007 in press. Has spring snowpack declined in the Washington Cascades? Hydrology and Earth System Sciences Discussions, 4: 2073-2110.
[36] Moore, R.D., 1991. Hydrology and water supply in the Fraser River basin. In: A.H.J. Dorcey and J.R. Griggs (Editors), Water in Sustainable Development: Exploring our Common Future in the Fraser River Basin. Westwater Research Centre, UBC, Vancouver, BC, pp. 21-40.
[37] Dyer, J.L. and Mote, T.L., 2007. Trends in snow ablation over North America. International Journal of Climatology, 27: 739-748.

[38] Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
[39] Knowles, N., Dettinger, M., and Cayan, D., 2006. Trends in snowfall versus rainfall for the Western United States. Journal of Climate, 19(18): 4545-4559.

Figures

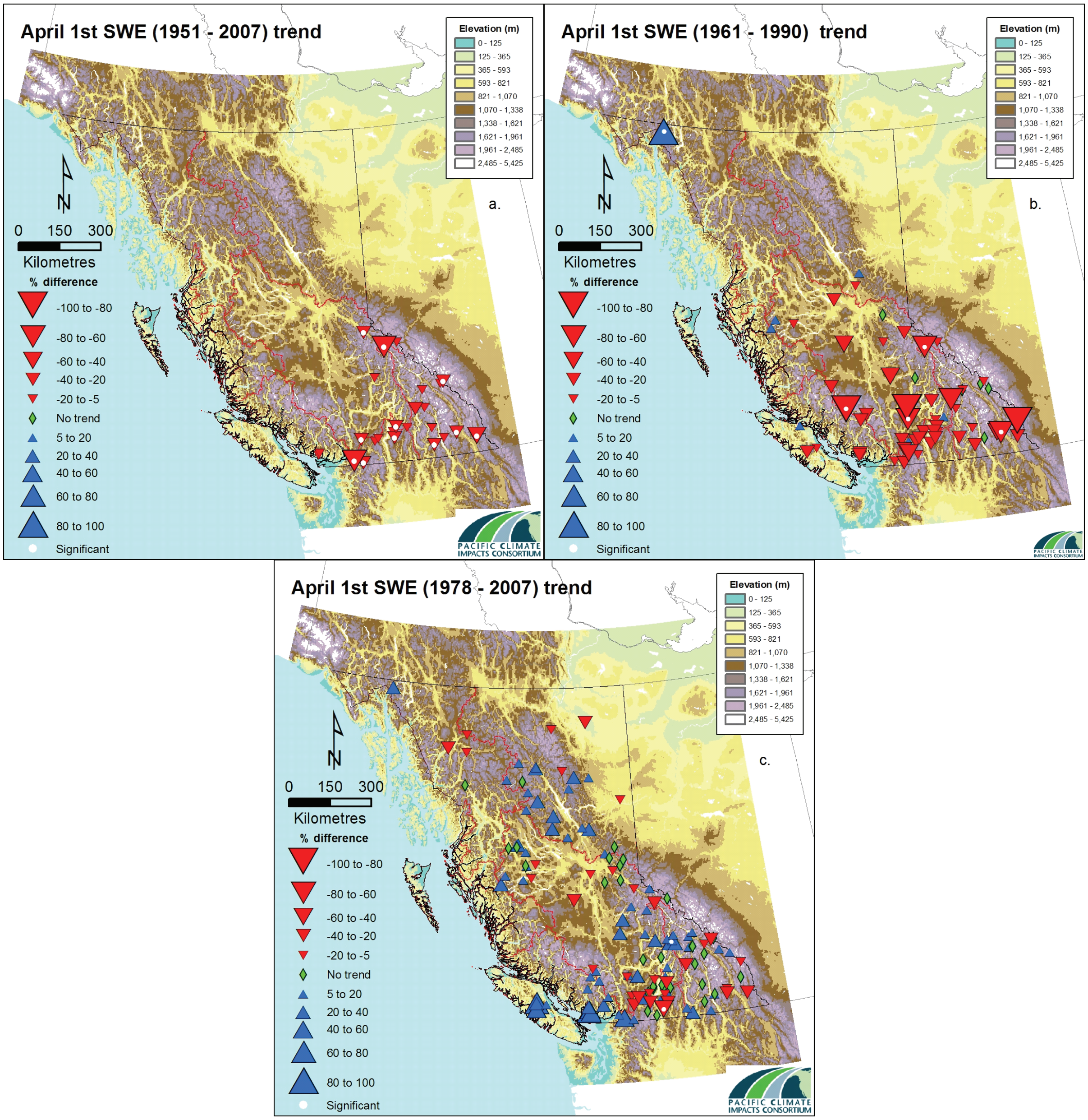

Figure 3.1.1 – Estimated trends in snow water equivalent (SWE % difference from the long-term average, relative to the initial trend condition at the first year of record over the specific periods: (a) 1951-2007, (b)1961-1990, and (c) 1978-2007. Downward (red) triangles indicate decreasing trend, upward (blue) triangles indicate increasing trend. Green diamonds indicate no change. Triangles are sized according to trend magnitude. White dots show significance (95% of greater). Elevation (m) for BC is illustrated by the colour ramp in the upper right corner of the map. Source: RFC-BC, 2007 data; Zhang et al. 2000.

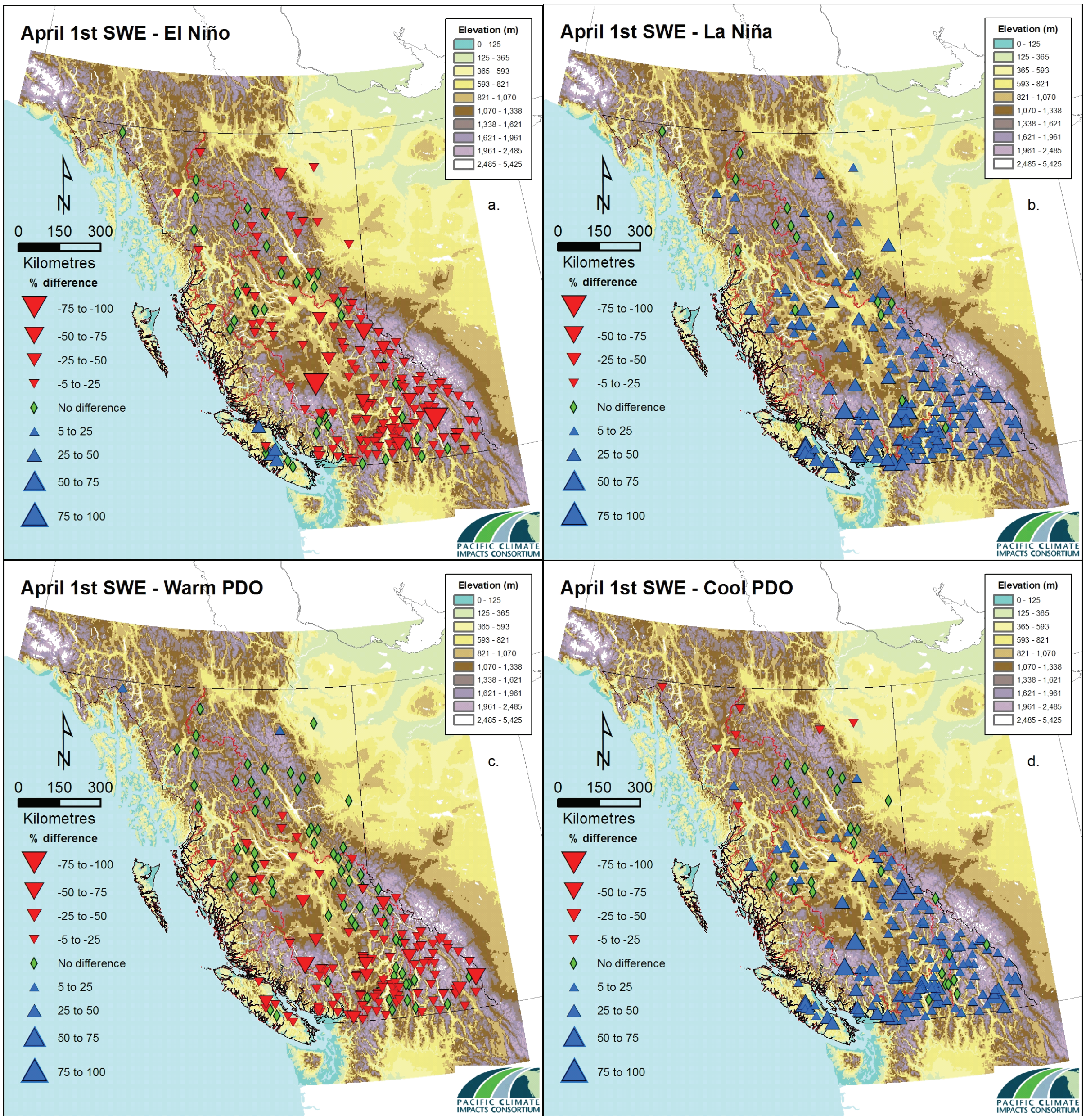

Figure 3.1.2 - Influence of teleconnections on snow water equivalent (SWE), shown as a percent difference from the long-term average for ENSO (1940-2005) and PDO (1940-2005). Results are shown for (a) El Niño, (b) La Niña, (c) warm PDO phase and (d) cool PDO phase for British Columbia. Downward (red) triangles indicate decreasing influence, upward (blue) triangles indicate increasing influence. Green diamonds indicate no change. Triangles are sized according to magnitude of difference. Elevation (m) for BC is illustrated by the colour ramp in the upper right corner of the map. Source: RFC-BC data; Zhang et al. 2000.

3.2. Glaciers

Glaciers act as natural reservoirs that store water over the winter season and release it during the summer, a process that sustains ecosystems and supplements power generation. Glaciers are also sensitive indicators of climate change. The following provides a synthesis of what is known about glaciers in BC based on recent studies.

Results

- Glaciers cover 30,000 km^2 or 3% of the area of BC[i] (**Figure 3.2.1).** Glaciated basins in BC showed a statistically significant *decrease* in August streamflow from 1976 to 1996[1]. Since decreases in streamflow resulting from changes in glacier contributions are usually preceded by *increased* streamflow, current glacier conditions appear to be in an advanced state of change.
- In a study conducted the Columbia River, glacier-melt supplied 10 to 30% of the annual flow, and up to 50% of the late summer flow (based on flows at the Dalles, Oregon)[2,3].
- In BC, only a few individual glaciers have been monitored over multiple decades[4]. A case study of the historical record from Place Glacier shows decreasing accumulation in the winter season, and increasing melt in the summer season (**Figure 3.2.2**) [5]. These changes indicate that the glacier is out of equilibrium with the current climate[6]. A new equilibrium can only be reached with a large reduction in glacier area and a withdrawal of the glacier terminus[7].
- The net mass balance of glaciers in Western North America tends to be positively correlated with winter precipitation and negatively correlated with summer temperature[8,9]. A change of mass balance on the Place Glacier occurred after the mid-1970s when the Pacific Decadal Oscillation (PDO) shifted to its warm phase, leading to decreased snow in winter and increased spring and summer temperature (**Figure 3.2.2**).
- Volume loss of BC glaciers over the 1985-1999 period was quantified using radar and digital terrain models from aerial photography[10]. Using this method, volume loss from all of the glaciers was found to be occurring at a rate of 22.48±5.53 km^3 per year [11]. These observations should be taken as a powerful warning of a negative trend in BC.

Discussion

Glaciers are an important water resource in BC. Covering an area of 30,000 km^2 and 48% of BC's gauged systems[ii] (**Figure 3.2.1**) glacier-melt moderates inter-annual variability in streamflow and helps to maintain higher runoff volume in times of extreme warm and dry conditions[12]. Glacier-melt also supports ecosystem functions by maintaining cooler water temperatures. In the Columbia Basin, glacier-melt was found to supply 10 to 30% of the annual flow and up to 50% of the late summer flow in a 1986 study (based on flows at the Dalles, Oregon)[13,14]. However, a large majority of streams in glaciated basins in BC showed a statistically significant decrease in August streamflow during 1976 to 1996, which suggests that these glaciers are in the later stages of recession where melt-water has decreased as a result of decreased area[15].

Since the end of the Little Ice Age, glaciers have been receding at many locations globally[16,17,18]. Records since 1960 show broad agreement on the evolution of global glacier mass balance (the measured difference between accumulation of snow and ice in winter and loss of snow and ice by ablation in summer)[19]. Around 1970, the global mass balance of glaciers was close to zero and has continued to decline to a negative state[20]. The observed decline in glaciers echoes other studies which have found that most alpine glaciers have undergone accelerated mass loss and terminal retreat in recent decades[21].

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[i] This approximation is based on an areal inventory completed in 1996.
[ii] Based on Water Survey of Canada's hydrometric network of 236 gauging stations with 10 or more years of record, no gaps of more than 6 consecutive years, natural flow conditions, and available land cover data.

Glacial recession can be attributed to both climate change and variability, the effects of which may reinforce each other. For example, recession of many glaciers increased during the 1977 to 1998 warm PDO period[22] when some of the warmest global temperatures were recorded.

In BC, glaciers have been receding in recent decades across most of the Province. Due to the lack of annual mass balance data, innovative means have been applied to determine the recent volume loss of glaciers[23]. Radar, LandSat imagery, digital terrain models, and aerial photography have been employed to investigate volume loss in multiple studies. One such study subdivided the glaciated mountain ranges in BC into ten regions and investigated changes in glaciers from 1985 to 1999[24]. After bias correction, the thinning rate for BC glaciers was found to be -0.78±0.19 m per year for this period, which yields an annual volume loss of 22.48±5.53 km^3 per year. Rates of thinning varied from -0.53±0.13 m per year to -0.89±0.23 m per year by region. Coastal ranges (north and south) lost the largest fraction of ice, low elevations showed the most thinning, and rates of thinning declined with altitude[25]. In another study, net changes in the combined glacier volume from the Columbia and Rocky Mountains (1952-2001), and Coast Mountains (1965-2002) was negative (estimated volume loss over the whole region of 13±3 km^3 over the study period)[26]. The area of glaciers in the Coast, Columbia, and Rocky Mountains decreased by 120±10 km^2 (-5%), 20 km^2 (-5%), and 6 km^2 (-15%), respectively for the same time periods.

Accelerated thinning rates have been reported for the northern Coast Mountains versus other regions[27,28]. This accelerated glacier mass wastage was correlated to increased summer temperatures in coastal regions[29]. The strength of this association is likely related to most near-coastal glaciers being at low elevations with frontal parts near sea level where increases in air temperature may have an enhanced effect on the melting of snow and ice[30]. In the Canadian Cordillera, the retreat of glaciers within the Coast Mountains accounted for approximately 90% of the total ice wastage, while the majority of the remaining loss was due to the retreat of glaciers in the Columbia Mountains. Thus, absolute changes were greater in the Coast Mountains than in the remaining areas in the study area[31]. One exception to this pattern was found at the Taku Glacier in Alaska, U.S.A. This glacier drains from the Juneau Ice Field and is one of the few glaciers that advanced over the last century (7 m since 1890)[32]. The cause of the Taku Glacier advance has been addressed in several articles and is primarily related to a large calving retreat in the last few decades, which lead to a positive imbalance and hence, glacier advancement and growth[33].

Monitoring of glacier mass balance has been conducted for roughly 20 glaciers in BC, but only two were still monitored at the time of writing; Place Glacier and Helm Glacier (**Figure 3.2.1**)[34]. At Place Glacier, precipitation and temperature changes have thrust the glacier out-of-phase with the current climate[35]. Equilibrium, where accumulation is equal to ablation, can only be achieved if the area of Place Glacier shrinks to less than 2 km^2 and the terminus moves up to 2060 m.[36] Helm Glacier is also receding[37]. The Illecillewaet Glacier (south eastern BC) and Peyto Glacier (on the Alberta side of the Rockies) are located in the interior and are not influenced by coastal effects. However, the Illecillewaet Glacier retreated more than 1000 m from 1887-1962, but advanced 100 m between 1962 and 1984[38] before resuming its retreat in 1984[39]. Peyto Glacier has shown similar trends to Place Glacier, which suggests that declining trends are far reaching[40].

Trends in glacier mass balance are similar south of the BC border. In 1971, the North Cascade Glacier Climate Project (NCGCP) surveyed more than 700 glaciers covering 250 km^2 within the North Cascade region[41]. All 47 of the observed glaciers retreated during the 1984-2006 period[42]. The annual mean balance (1984-2006) of 10 glaciers selected for more detailed study indicated glacial decline of 0.54 m per year and a cumulative net loss in mass balance of 12.38 m, which is equivalent to at least 14 m of thickness loss[43]. The loss of mass ranged from 20% to 40% of total glacier volume, a rate of retreat insufficient for re-equilibrium[44]. All of the glaciers had similar responses in spite of the regional variations in influence on glacier mass balance such as aspect, elevation, and location with respect to prevailing winds[45]. Similarly, in Glacier National Park, Montana over two-thirds of the 150 glaciers surveyed in 1850 had disappeared by 1980 and the remaining glaciers were greatly reduced in area and volume[46, 47].

The net mass balance of glaciers in Western North America tends to be positively correlated with winter precipitation and negatively correlated with summer temperature[48,49]. The high correlation between air temperature and glacier recession is partially a result of air temperature being representative of energy released from the atmosphere in the form of longwave radiation, which is the most important heat source for melt[50]. Secondary and tertiary heat sources such as shortwave radiation and sensible heat fluxes are also correlated to air temperature[51]. Although precipitation increased across most of the Province in most seasons over the 1900 to 2004 period, no trend was found annually for the southwest of BC, nor was a trend found in fall or winter for the southern half of the Province (section 2.1). Furthermore, in spite of increases in precipitation, a 25% decrease in snow water equivalent was found across the Province for the 1951 to 2007 period (section 3.1). Summer-minimum temperatures increased by 1 ^{o}C to 2.5 ^{o}C during the 1900 to 2004 period (section 2.1). However, summer-maximum temperatures decreased in Southwestern and Interior BC by up to 1.5 ^{o}C and increased by up to 2.5 ^{o}C in areas like the Columbia Basin during the 1900 to 2004 period (section 2.1).

Average annual temperature and minimum spring temperature were also identified as influences on the observed distribution of glaciers in the Rocky Mountains[52]. Air temperature increased across most of the Province over the 1900 to 2004 period (section 2.1). Increases were greatest for minimum air temperatures, especially in winter and spring, increasing by up to 3.5 ^{o}C in some places (section 2.1). The high correlation between air temperature and glacier recession is also related to the influence of air temperature on precipitation form. An increase in air temperature can result in an increased ratio of precipitation falling as rain versus snow[53], which may decrease the amount of snow adding to the accumulation of glaciers. Additionally, older snow has lower reflective properties or albedo than new snow. Therefore, low-albedo snow does not reflect incoming energy from the sun to reduce glacier melt. Thus, trends in precipitation, air temperature and snowpack found in section 2.1 and section 3.1 provide reasonable causes for the observed glacier recession documented for BC.

At Place Glacier, the mass balance of the glacier has responded primarily to the PDO signal (**Figure 3.2.2)**. At the start of the warm PDO phase, there was a step change in the mass balance to less accumulation and more recession in the summer[54]. The glacier's winter and net balances were found to be negatively correlated with the PDO, primarily via changes to winter precipitation associated with the PDO[55]. The summer balance was positively correlated with summer temperature, which enhanced the effects of changes in winter balance on net balance, but was not correlated with ENSO or PDO[56]. Thinning and retreat of the glaciers in Garibaldi Park, where Place Glacier is located, occurred during two intervals, one between about 1930 and 1960 and another starting in the late 1970s and continuing to present[57]. However, glacial response to changes in climate can vary from glacier to glacier by as much as decades.

Uncertainties and Limitations

The study of changes in glacial volume and area in BC are hindered by the lack of spatial coverage and low frequency of air photos, radar, and laser altimetry for BC and errors within the available datasets[58]. Digital elevation models used in this work have inherent errors that must be corrected to guarantee the accuracy of results. Digitizing the surface area of glaciers depends on how accurately the margins of individual glaciers can be identified, which depends on the resolution of the image, the snow conditions and the contrast between the ice and adjacent terrain. Also, poor photographic contrasts, which are estimated as the reported vertical errors for the Terrain Resource Information Management (TRIM) and National Topographic Database (NTDB) data, also add errors to the estimates of accumulation. Finally, the parameters chosen for the volume-area scaling relationship can contribute error.

Mass balance studies can incur error during manual measurement and analysis. Measurements of annual mass balance of a single glacier are said to be ±200 kg/m^2 per year [59]. The majority of this uncertainty comes from the natural horizontal variability inherent across the surface of the glacier, which can not be evaluated using point measurements at single elevation bands[60]. Additionally, most studies only measure the surface balance of the glacier, although internal accumulation could be taking place[61].

Glacier mass balance observations tend to be limited spatially and often are not maintained consistently over time. Therefore, global glacier datasets tend to fluctuate continually, such that the common record between the more than 300 measured glaciers is only one year. In BC, trends in glacier mass balance are based on limited observational data that do not cover all of the different regions. Study sites tend to be selected based on which glaciers are most easily accessible and safe. Therefore, most monitored glaciers are at lower elevations. Hence, findings are biased towards these selected glaciers and cannot be said to be representative of glacial trends in all areas.

Finally, few studies distinguish the influence of modes of climate variability on glacier trends from those created for climate change. This distinction could be valuable for future projections of glacier change. The work of the Western Canadian Cryospheric Network (WC^2N) could provide scientists with a means of understanding the relation of glacier fluctuation to climate variability[62]. Local scale studies from representative regions will be used to document the influence of climate controls on glacier mass balance, and these controls will be related to regional and broader scale climate dynamics[63].

Gaps

- Climate variability (such as ENSO, PDO, and PNA) and their influence on glaciers is not fully understood[64].
- Local scale studies from representative regions have not been conducted to document the influence of climate controls on glacier mass balance.
- Climate (e.g. temperature and precipitation) identified at the local scale of glaciers has not been related to regional synoptics and large scale teleconnections[65].
- Advances in numerical algorithms and computing resources and their ability to drive dynamic region-scale glacier models using meteorological forcings of local to hemispheric data have not been fully explored[66].

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[1] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
[2] Menounos, B. and Wheate, R., 2007. State and fate of Western Canadian glaciers, Conference, Ministry of the Environment, Victoria, BC.
[3] Brugman, M.M., Raistrick, P. and Pietroniro, A., 1997. Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon (Chapter 6). Environment Canada and BC Ministry of Environment, Lands, and Parks.
[4] Dyurgerov, M.B. and Meier, M.F., 2005. Glaciers and the Change Earth System: A 2004 Snapshot, Institute of Arctic and Alpine Research, University of Colorado, Boulder.
[5] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[6] Ibid.
[7] Ibid.
[8] Koch, J., Menounos, B., Clague, J.J. and Osborn, G.D., 2004. Environmental changes in Garabaldi Provincial Park, southern Coast Mountains, British Columbia. Geoscience Canada, 31(3): 127-135.
[9] Dyurgerov, M.B. and McCabe, G.J., 2006. Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. Arctic, Antarctic, and Alpine Research, 38(2): 190-197.
[10] Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.
[11] Ibid.
[12] Debeer, C.M. and Sharp, M.J., 2007. Recent changes in glacier area and volume within the southern Canadian Cordillera. Annals of Glaciology, 46: 215-221.
[13] Menounos, B. and Wheate, R., 2007. State and fate of Western Canadian glaciers, Conference, Ministry of the Environment, Victoria, BC.
[14] Brugman, M.M., Raistrick, P. and Pietroniro, A., 1997. Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon (Chapter 6). Environment Canada and BC Ministry of Environment, Lands, and Parks.

[15] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
[16] Luckman, B.H., Harding, K.A. and Hamilton, J.P., 1987. Recent glacier advances in the Premier Range, British Columbia. Journal of Earth Sciences, 24: 1149-1161.
[17] Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F. and Ohmura, A., 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961-2004. Geophysical Research Letters, 33(L19501): 1-5.
[18] Dyurgerov, M.B. and McCabe, G.J., 2006. Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. Arctic, Antarctic, and Alpine Research, 38(2): 190-197.
[19] Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F. and Ohmura, A., 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961-2004. Geophysical Research Letters, 33(L19501): 1-5.
[20] Ibid.
[21] Debeer, C.M. and Sharp, M.J., 2007. Recent changes in glacier area and volume within the southern Canadian Cordillera. Annals of Glaciology, 46: 215-221.
[22] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[23] Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.
[24] Ibid.
[25]Ibid.
[26] Debeer, C.M. and Sharp, M.J., 2007. Recent changes in glacier area and volume within the southern Canadian Cordillera. Annals of Glaciology, 46: 215-221.
[27]Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.
[28] Larsen, C.F., Motyka, R.J., Arendt, A.A., Echelmeyer, K.A. and Giessler, P.E., 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research, 112(F01007): 1-11.
[29] Dyurgerov, M.B. and McCabe, G.J., 2006. Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. Arctic, Antarctic, and Alpine Research, 38(2): 190-197.
[30] Ibid.
[31] Debeer, C.M. and Sharp, M.J., 2007. Recent changes in glacier area and volume within the southern Canadian Cordillera. Annals of Glaciology, 46: 215-221.
[32] Larsen, C.F., Motyka, R.J., Arendt, A.A., Echelmeyer, K.A. and Giessler, P.E., 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research, 112(F01007): 1-11.
[33] Ibid.
[34] Miles, M., and Associates, 2003. British Columbia's Climate Related Observation Networks: An Adequacy Review. Report to the Ministry of Environment, Victoria, BC.
[35] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[36] Moore, R.D., 2007. Introduction to Glacier Hydrology, Climate Change and Low Flows - Influence of Glaciers and Groundwater, Vancouver, BC.
[37] Dyurgerov, M.B. and Meier, M.F., 2005. Glaciers and the Change Earth System: A 2004 Snapshot, Institute of Arctic and Alpine Research, University of Colorado, Boulder.
[38] Champoux, A. and Ommanney, C.S.L., 1986. Evolution of the Illecillewaet Glacier, Glacier National Park, B.C. using historical data, aerial photography, and satellite image analysis. Annals of Glaciology, 8: 31-33.
[39] Sidjack, R.W. and Wheate, R.D., 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elvation data. International Journal of Remote Sensing, 20(2): 273-284.
[40] Dyurgerov, M.B. and Meier, M.F., 2005. Glaciers and the Change Earth System: A 2004 Snapshot, Institute of Arctic and Alpine Research, University of Colorado, Boulder.
[41] Post, A., Richardson, D., Tangbor, W.V. and Rosselot, F.L., 1971. Inventory of glaciers in the North Cascades, Washington. In: USGS (Editor). Prof. Paper.
[42] Pelto, M.S., 2007. Glacier annual balance measurement, prediction, forecasting and climate correlations, North Cascades, Washington 1984-2006. The Cryosphere Discussion, 1: 17-39.
[43] Ibid.
[44] Ibid.

[45] Ibid.
[46] Hall, M.H.P. and Fagre, D.B., February 2003. Modeled Climate-Induced Glacier Change in Glacier National Park, 1850-2100. BioScience, 53(2): 131-140.
[47] Carrar, P.E. and McGimsey, R.G., 1981. The late-neoglacial histories of the Agassiz and Jackson Glaciers, Glacier National Park, Montana. Arctic and Alpine Research, 13: 183-196.
[48] Koch, J., Menounos, B., Clague, J.J. and Osborn, G.D., 2004. Environmental changes in Garabaldi Provincial Park, southern Coast Mountains, British Columbia. Geoscience Canada, 31(3): 127-135.
[49] Dyurgerov, M.B. and McCabe, G.J., 2006. Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. Arctic, Antarctic, and Alpine Research, 38(2): 190-197.
[50] Ohmura, A., 2001. Physical basis for temperature/melt-index method. Journal of Applied Meteorology, 40: 753-761.
[51] Ibid.
[52] Shea, J.M., Marshall, S.J. and Livingston, J.M., 2004. Glacier distributions and climate in the Canadian Rockies. Arctic, Antarctic, and Alpine Research, 36(2): 272-279.
[53] Knowles, N., Dettinger, M., and Cayan, D., 2006. Trends in snowfall versus rainfall for the Western United States. Journal of Climate, 19(18): 4545-4559.
[54] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[55] Ibid.
[56] Ibid.
[57] Koch, J., Menounos, B., Clague, J.J. and Osborn, G.D., 2004. Environmental changes in Garabaldi Provincial Park, southern Coast Mountains, British Columbia. Geoscience Canada, 31(3): 127-135.
[58] Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.
[59] Cogley, J.G., 2005. Mass and energy balances of glaciers and ice sheets, in Encyclopedia of Hydrological Science, vol. 4, edited by M.G. Anderson, John Wiley, Hoboken, New Jersey, pp. 2555-2573.
[60] Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F. and Ohmura, A., 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961-2004. Geophysical Research Letters, 33(L19501): 1-5.
[61] Ibid.
[62] Menounos, B., 2006. Proposal: Western Canadian Cryospheric Network.
[63] Ibid.
[64] Ibid.
[65] Ibid.
[66] Ibid.

Figures

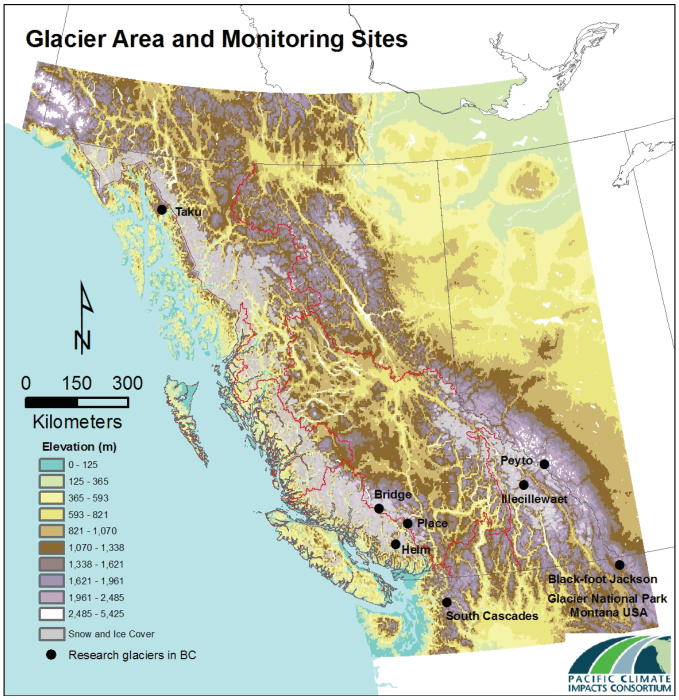

Figure 3.2.1 – Glacier area and monitoring sites in BC. Source: 1990s Baseline Thematic Mapping data.

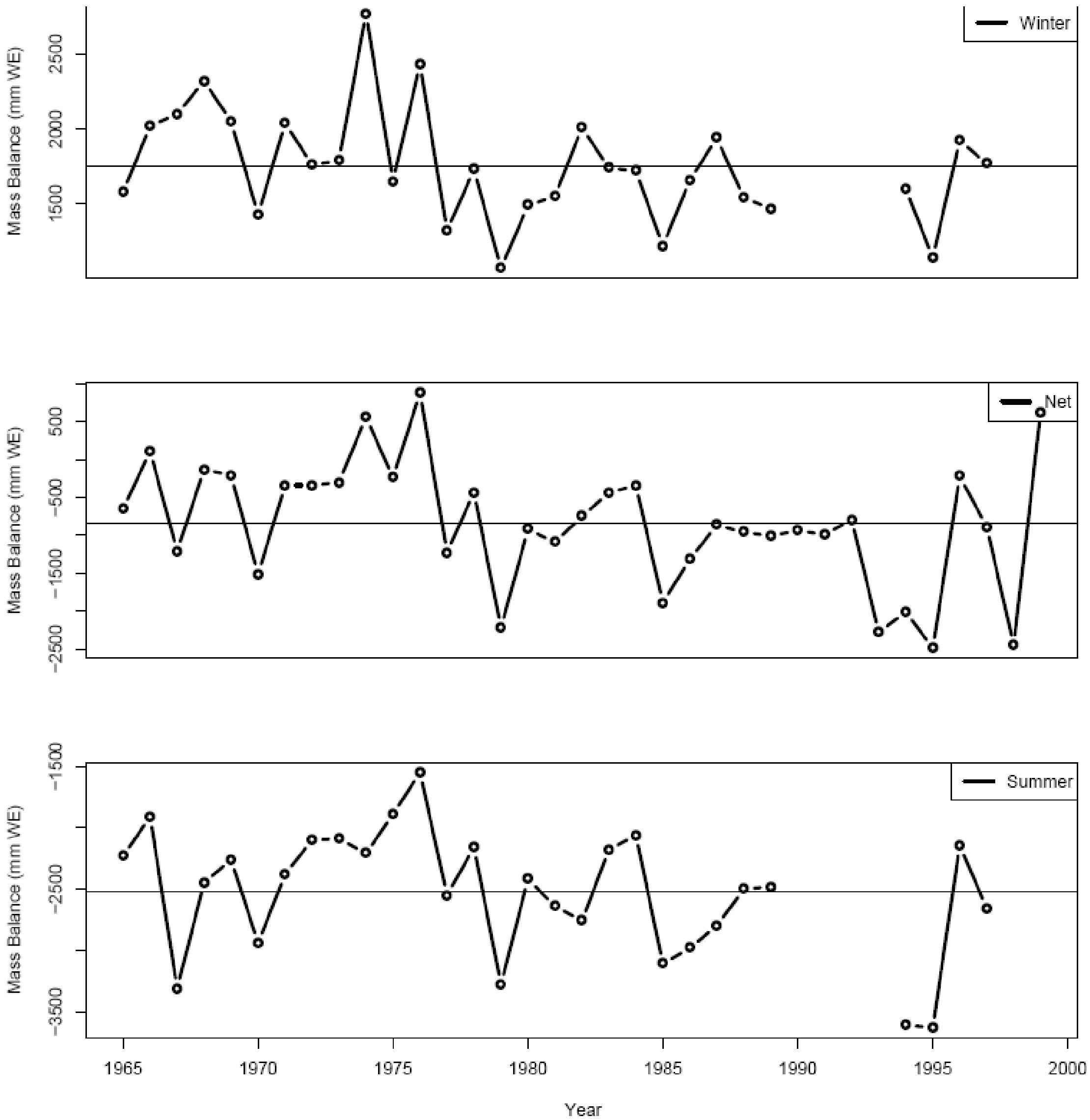

Figure 3.2.2 - Mass Balance (mm, WE stands for water equivalent). Source: Adapted from Moore and Demuth 2001[1].

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[1] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.

3.3. Streamflow

Streamflow is a source of water supply for domestic use, agriculture, and energy production and is also a potential threat in the form of floods or bank erosion. In this report, an analysis of trends in minimum and maximum daily flow, and annual mean flow is updated to 1976-2005 and compared to other work[1]. A composite analysis of the influence of PDO and ENSO on streamflow is extended across all of BC. In general, overall availability of water supply is affected by mean flows, maximum flows reflect risk of floods, and minimum flows have implications for water allocation in the dry season.

Results

Trends

- The streamflow observation network in BC is limited, especially in the northern regions of the Province (**Figure 3.3.1d**). Where hydrometric stations do exist, many records do not start until the 1970s. The current streamflow observation network and record length are inadequate for a full investigation of the historical influence of climate change and variability across the Province[2].
- Trends in streamflow over the last 30 years were not uniform across the hydro-climatic regions (section 1), but were more coherent within runoff regimes (i.e. pluvial, hybrid, nival and nival/glacial).
- In *pluvial* regimes on the South Coast (13% of all stations) streamflow decreased, including annual mean (-14% to -15%), average daily minimum (-62% to -7%) and average daily maximum (-37% to -1%), with one exception (North Alouette River)[i].
- On the North Coast, the Yakoun River (a *pluvial* regime) trends increased for annual mean streamflow (+2%), minimum (+80%) and maximum streamflow (3%).
- In *hybrid* regimes on the South Coast (8% of all stations) annual mean streamflow increased (1% to 42%), minimum streamflow decreased (-20% to -7%) and responses in maximum streamflow were mixed (-8% to +23%).
- In *nival* regimes in the Okanagan (10% of all stations analysed) annual mean streamflow decreased (-14% to -7%), maximum streamflow decreased (-28% to -18%), and minimum streamflow increased (+10% to +50%), with the exception of Whiteman Creek (**Figure 3.3.1a, b, c**). In *nival* regimes in the Columbia Basin (5% of all stations analysed) annual mean streamflow increased (+7% to +33%), maximum streamflow increased (+12% to +23%), and minimum streamflow decreased (-2% to -25%). *Nival* regimes in the Fraser Plateau and Peace Basin (5% of all stations) responded oppositely.
- *Nival/glacial* regimes make up the largest subset of the stations evaluated in this study (46%). This runoff regime was found in all the regions except for the Okanagan. Coherent streamflow trends were discovered for *nival/glacial* watersheds that had similar percentage glacier cover, mean basin elevation, latitude, and proximity to the coast. Generally, watersheds with less glacier cover showed decreases in annual mean, minimum and maximum streamflow. Some exceptions were found in the Peace Basin and interior regions of the Province where minimum streamflow increased (**Figure 3.3.1a, b, c**). In *nival/glacial* regimes that had more glacier cover and higher mean basin elevation, annual mean and maximum streamflow increased, while minimum streamflow decreased.
- For Pacific North America, annual streamflow has advanced (10-30) days in *nival* basins over the 1948-2002 period, as measured by changes in the streamflow centre of mass.

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[i] Percentages are calculated by dividing the trend (m^3/s per day for average daily minimum and maximum streamflow, and m^3 per year for annual mean streamflow) over the 30 year period by the intercept of the trend. The range, as indicated in brackets, is determined from the variability of streamflow stations analysed. Average daily minimum and maximum streamflow herein referred to as minimum and maximum streamflow.

Climate Variability

- Streamflow in *pluvial* regimes on the South Coast streamflow decreased significantly from May to August in El Niño years as compared to La Niña years (**Figure 3.3.2a**). Some of the *pluvial* regimes transitioned into *hybrid* regimes in La Niña years (**Figure 3.3.2b**), due to lower temperatures, increased precipitation and increased snowpack (section 2.2). The *pluvial* regime on the North Coast did not respond to ENSO (**Figure 3.3.2c**).
- *Nival* regimes are primarily located in the Okanagan. In this region, differences between ENSO phases were especially strong (**Figure 3.3.3a, b**). Streamflow in rivers in this region increased from May to August during La Niña years when compared to El Niño years (**Figure 3.3.3a**). This effect was also observed from November to February in the Similkameen River (**Figure 3.3.3b**) making this river somewhat more hybrid than nival.
- In *nival/glacial* regimes in the *southern regions* of the Province (the Columbia and the southern part of the Fraser Plateau) streamflow decreased significantly in El Niño years during June through September for both regions and also during November through February in the Columbia (**Figure 3.3.4a, b**).
- In contrast, in *nival/glacial* regimes in the *northern regions* of the Province (Northwest, Peace Basin, and the northern reaches of the Fraser Plateau and Columbia) no differences in streamflow were detected between ENSO phases (**Figure 3.3.5a, b**).
- During PDO events, the start of the spring-summer freshet was delayed and higher flows occurred during the cool PDO phase (South Coast, Okanagan, Peace Basin, Fraser Plateau, and Columbia regions) for selected *nival* and *nival/glacial* rivers (**Figure 3.3.6a to 3.3.6d**). These results are broadly consistent with the PDO response in temperature and precipitation that affects the accumulation of snow during winter and subsequent melting in spring (section 2.2).
- Unique responses to PDO occurred at Sikanni River in the Peace Basin. Streamflow decreased during the snowmelt period in the cool PDO phase (**Figure 3.3.7a**). In the Fraser Plateau, Stellako River streamflow increased significantly during cool PDO phases (**Figure 3.3.7b**). PDO influences were not tested in the Northwest and North Coast due to insufficient data.

Discussion

Trends

This analysis calculates trends for the most recent 30 year period, 1976-2005 (**Figure 3.3.1a to 3.3.1c**), and compares these results with previous work[3]. Annual mean, minimum and maximum streamflow were investigated. Province-wide results are examined in contrast to Canada-wide findings[4] and then within different runoff regimes.

In general, annual mean streamflow decreased in the southern parts of the Province, increased in the central and Fraser Plateau regions, and decreased in the Northwestern areas. The decreased trends in streamflow in the southern parts of the Province are similar to trends found by other researchers[5]. Streamflow decreases in southern BC may have occurred due to positive trends in temperature that increase potential evaporation, concurrent with small changes in precipitation[6].

In *pluvial* regimes on the South Coast (13% of all stations) trends for annual mean (-14% to -15%), minimum (-62% to -7%) and maximum (-37% to -1%) streamflow decreased, with one exception (North Alouette River). Decreased minimum streamflow is likely a result of an extended low-flow period between spring and fall rains, consistent with results from previous findings[7].

Decreased maximum streamflow in *pluvial* regions may be related to decreased winter precipitation, which occurred in these regimes during the peak flow season (November to December)[8]. Winter precipitation decreased at Agassiz, Vancouver Airport, Victoria Airport, and Comox Airport for the 1950-2001 period[9]. Decreased annual mean streamflow could be related to increased evaporation that occurred in conjunction with increased temperature and small decreases in precipitation in the South Coast region.

The Yakoun River in Haida Gwaii is a North Coast *pluvial* regime. This archipelago is located on the far outer reaches of the Pacific Ocean and therefore is the most coastally exposed river system examined in this report. At Yakoun River, increased trends in annual mean (+2%), minimum (+80%) and maximum streamflow (+3%) were observed. Increased precipitation trends in this region could have influenced increased river flow in this region (section 2).

In *hybrid* regimes on the South Coast (8% of all stations) annual mean streamflow increased (+1% to +42%) and minimum streamflow decreased (-20% to -7%), while responses in maximum streamflow were mixed (-8% to +23%). Hybrid systems are possibly becoming more pluvial as less precipitation is falling as snow under warmer conditions. With less snow, there are potentially less rain-on-snow events, which may in some circumstances lead to extreme events such as flooding, landslides, and mass movement/wasting[10].

In *nival* regimes in the Okanagan (10% of all stations) annual mean streamflow decreased (-14% to -7%), maximum streamflow decreased (-28% to -18%), and minimum streamflow increased (+10% to +50%). Whiteman Creek was the only exception to this (**Figure 3.3.1a to 3.3.1c**). Pennask Creek in the Fraser Plateau has trends similar to most Okanagan streams. *Nival* regimes in the Columbia (5% of all stations) exhibit increases in annual mean streamflow (+7% to +33%) and maximum streamflow (+12% to +23%), while minimum streamflow decreased (-25% to -2%). *Nival* regimes in the Peace Basin (2.5% of all stations) had an opposite response to those in the Okanagan and Fraser Plateau.

In areas such as the Okanagan, more precipitation has fallen as rain than snow and snowpack declined (section 2.1, 3.1), which resulted in a decreased spring-melt freshet. The spring-melt freshet takes place in May or June and is the time when maximum daily streamflow occurs[11]. Increased temperatures may have resulted in the intensification of the water cycle causing increased evaporation and promoting more convective precipitation[12]. Similarly, increases in maximum streamflow and annual mean streamflow in the Peace could be reflective of increased summer precipitation (section 2) in this region as maximums may occur during summer precipitation events as opposed to spring-melt events[13].

Whiteman Creek, located in the Okanagan, had an opposite response to others in the region. Whiteman Creek is the farthest north in the basin and has the smallest drainage area. The opposing direction of trend in annual mean streamflow and minimum and maximum streamflow could be attributed to its northern location.

In the Columbia Basin, *nival* regimes exhibited increased mean and maximum streamflow owing to elevational effects. These watersheds are situated in the Rocky Mountains and have a mean basin elevation of nearly 1600 m, where higher snow accumulation tends to occur (section 3.1). Additionally, this region does not experience strong convective precipitation in the summer (as is the case in the Okanagan), hence earlier snowmelt runoff led to decreased streamflow in the low-flow seasons (minimum streamflow).

Another streamflow response is the advanced onset of spring-melt by 10-30 days over the 1948-2002 period in the majority of nival regimes across Western North America[14]. Although there is considerable inter-annual variability, observed trends are large and showed remarkable regional coherence but were not significant in all cases. The early snowmelt resulted in decreased late season streamflow and a prolonged summer drought period[15,16,17].

Nival/glacial regimes make up the largest subset of the streamflow evaluated in this study (46% of all stations). *Nival/glacial* runoff regimes were found within all regions except the Okanagan. Coherent trends were found in *nival/glacial* watersheds that had similar percentage glacier cover, mean basin elevation, latitude, and proximity to the coast. The spatial distribution of regime types throughout BC is determined primarily by the elevation of a drainage basin and the distance of the drainage basin from the coast[18]. Regime types are influenced to a lesser degree by latitude[19]. The shape of hydrographs in *nival* regimes is a function of several factors, including altitude, latitude, aspect, vegetation, temperature, and the type and temporal distribution of precipitation[20].

Generally, watersheds with lower percentage glacier cover showed decreases in annual mean, minimum and maximum streamflow. These results support other findings that show minimum flows are decreasing as glacier cover reduces with warmer temperatures[21]. Warming has led to less snow accumulation, more evaporation and more sublimation, which has contributed to the reduction of mean and maximum streamflow. Exceptions were found in the Peace Basin and Fraser Plateau regions where minimum streamflow increased for some basins (**Figure 3.3.1a to 3.3.1c**). There is a possibility that this could be related to increases in summer precipitation in these areas (section 2.1).

In *nival/glacial* regimes that had a higher percentage of glacier cover and had higher mean basin elevation, annual mean and maximum streamflow increased, while minimum streamflow decreased. At these higher elevation basins temperatures were still sufficiently cool that snowpack could have accumulated, and evaporation and sublimation may not have increased at a rate that was greater than increases in precipitation.

Minimum flows could have reduced due to the increased albedo of glaciers covered with snow[22]. Changes to summer precipitation patterns could have also contributed to reductions in minimum flows.

Climate Variability

This analysis extends previous work to all of BC to investigate the influence of ENSO and PDO on runoff regimes and to decipher any possible spatial responses to these teleconnection patterns[23]. The same time periods were addressed to ensure compatibility of these results. The response of streamflow to ENSO and PDO will be discussed by runoff regime.

Strictly *nival* regimes are primarily located in the Okanagan. A strong influence of ENSO on *nival* regimes in the Okanagan from May to August was observed, where streamflow increased during La Niña years over El Niño years (**Figure 3.3.2a**). In effect these *nival* regimes became more like hybrid regimes, likely as a result of rainfall inputs during winter. The observed peak was increased during wet La Niña years with increased flow from May to July (**Figure 3.3.2.b**). The stark contrast in streamflow response between the two ENSO phases may be attributed to the modulating effect of ENSO on snowpack accumulation (section 3.1). The *nival* regimes located in the Northwest and Peace Basin did not show significant differences between ENSO phases (**Figure 3.3.2c, d**).

May to August streamflow in *pluvial* regimes on the South Coast decreased significantly in El Niño years compared to La Niña years (**Figure 3.3.3a**). The transition from winter freshet to summer low-flow conditions takes place primarily from May to June in *pluvial* regimes. Increased streamflow in La Niña years during the winter months occurred as well. However, these differences were not statistically significant. The timing of ENSO responses between catchments may differ because of the unique morphology and elevation gradients of each catchment, which alter storage effects[24].

Results in this section echo those from the study which the analysis was modeled after[25] and can be explained by associated changes in temperature and precipitation during these phases in this region[26]. The increased frequency of southwesterly airflow that advects warm, moist air into this region during El Niño winters contributed to these changes in temperature and precipitation[27].

Some of the streams classed as *pluvial* regimes were reclassified during the La Niña years into *hybrid* regimes due to a distinguishable spring-summer nival component. During La Niña years (**Figure 3.3.3b**), lower temperatures, increased precipitation and greater snowpack (section 2.2) led to increased peak flows in November from winter rainfall and a smaller peak in the spring or early summer. In contrast, El Niño years showed a single winter rainfall peak. Differences were large and statistically significant in April through June and November (**Figure 3.3.3b**). This finding may have implications for water planning practices. Note that previous researchers have defined these systems as nival-supported pluvial regimes and described the phase transitions of the precipitation associated with the different phases of ENSO[28].

The Yakoun River is a *pluvial* regime on the North Coast, where the response to ENSO was not statistically significant (**Figure 3.3.3c**). There appears to be more flow in the Yakoun during El Niño years over La Niña or ENSO Neutral years. This is opposite to the signal in the South Coast. Other studies have shown slight increases (decreases) in precipitation during El Niño (La Niña) years in this area[29]. However, this response seems to be anomalous when compared to other stations in the region. Therefore, this station should be investigated further to see if local effects are at play. It is possible that there is high variability in precipitation and streamflow in this region due to the variability in storm tracks at this latitude[30].

The influence of ENSO on *nival/glacial* regimes is variable between catchments and complex due to multiple contributing factors[31]. The responses were broken down into two groups, south versus north. In the southern regions of the Province (the Columbia Basin and the southern Fraser Plateau) streamflow decreased significantly in El Niño years during June through September for both regions and during November through February in the Columbia Basin only (**Figure 3.3.4a, b**). In contrast, in the northern regions of the Province (the northern reaches of the Fraser Plateau and Columbia Basin) no differences in streamflow were detected between ENSO phases in *nival/glacial* regimes (**Figure 3.3.5a, b**). This can again be attributed to the stronger influence of ENSO on the southern reaches of the Province (section 2.2).

The analysis of PDO response to the four different runoff regimes was restricted to fewer stations than the analysis for ENSO because only stations with longer records could be used. Based on the available records, one key result was identified. The start of the spring-summer freshet was delayed and higher flows occurred during the cool PDO phase (South Coast, Okanagan, Peace Basin, Fraser Plateau, and Columbia

Basin regions) for select *nival* and *nival/glacial* rivers (**Figure 3.3.6a to 3.3.6d**). These results are broadly consistent with the PDO response in temperature and precipitation that affects the accumulation of snow during winter and subsequent melting in spring (section 2.2, 3.1).

Unique responses to PDO occurred at Sikanni River, in the Peace Basin, where streamflow during the snowmelt period declined in the cool PDO phase (**Figure 3.3.7a**). At the Stellako River in the Fraser Plateau, streamflow increased during cool PDO phases (**Figure 3.3.7b**). It is beyond the scope of this report to investigate the cause of these responses. PDO influences were not tested in the Northwest and North Coast regions due to data limitations.

These findings show the importance of modulating effects of ENSO and PDO phases on streamflow that should be considered for the purposes of planning and management. Hydroelectric power generation (i.e. run-of-river) may consider the influence of these impacts before setting policy as generation capacity could be strongly influenced by specific climate variations. Additionally, fisheries could be affected by changes in response to climate variability, such as streamflow timing[32].

Mountain Pine Beetle effects on BC streamflow

Large-scale change to land surface cover in BC watersheds as a result the expansion of the mountain pine beetle may lead to alterations in streamflow patterns and stream ecology. The mountain pine beetle (MPB) infestation is the largest recorded outbreak in BC's history; more than 8.7 million hectares (mid-2000s estimates) of pine forests in BC[33] are currently infested with the MPB. For example, upstream of the Chilcotin River, ten of the most severely affected watersheds have greater than 50% of their land surface affected by moderate, severe and very severe MPB infestation levels (analysis not shown). Impacts to hydrology and freshwater ecology in the Fraser Plateau region could negatively impact communities and economies if assessment and planning measures are not implemented.

The hydrologic influence of the MPB has been the focus of only a limited number of publications[34]. The lack of information on the effects of a wide-spread outbreak on hydrology is the greatest limitation in this research area. MPB-related changes to hydrology have been surmised from studies that were not intended to illustrate MPB effects, but were originally intended as forest harvesting studies[35] or were focused on areas outside of BC[36,37,38,39,40,41]. For example, a recent literature review on hydrologic impacts of MPB discusses the impacts of MPB on hydrology using the alternate research available[42].

MPB may affect the hydrology of forested watersheds[43], including increases in annual water yield, increases in late summer and fall low flows and increases (or no change) in peak flow. Additionally, a shift in timing of peak flows may occur earlier in the season. Recent work indicates that ablation rates and snow accumulation in MPB affected stands will also change[44].

One of the pressing issues in the study of hydrologic impacts of the MPB infestation is the cumulative effects of MPB in conjunction with future climate conditions[45] or other land cover changes, such as forest fires or logging, which will also influence hydrology. Climate change has been discussed as a cause for the recent outbreaks of MPB[46,47], but no recent literature examines the combined feedback effects of climate change and MPB on hydrology (section 5.3). However, these cumulative impacts are likely complex, and impact studies must include consideration of management practices within MPB-infested forests. For example, salvage-logging efforts could exacerbate sedimentation and landslides depending on the type of logging and stand clearing practices[48], which could lead to increased impacts on the hydrology in MPB affected stands.

Uncertainties and Limitations

Trends in streamflow over the last 30 years were not uniform within hydro-climatic regions as defined by an amalgamation of the BC watersheds[49] and the Hydrologic Zones of BC[50]. Because of this, trends could not be described by regions and were often more coherent within groups of similar glacier cover, elevation, latitude, and proximity to the coast than region. Responses were especially diverse across the Fraser Plateau, likely because of the large latitudinal expanse of this region. Furthermore, many of the regions did not have enough observation stations to adequately represent the diversity of the hydrology within a given region.

This was especially true in the northern areas of the Province where if stations do exist, many records do not start until the 1970s (**Figure 3.3.1a**).

The analysis of trends in minimum and maximum flow was based on average daily values, which created room for potential error in the interpretation of results. Firstly, different runoff regimes generally have minimum and maximum flow at different times in the year. Pluvial regimes generally have low flow in the summer where as nival regimes generally have low flows in the winter[51]. Secondly, there is potential for the daily low value to occur at times outside of the common low flow period. As applied in this study, this analysis provided no information about the season in which the minimum of maximum flow took place. Thus, the trends would not necessarily have reflected a change in the magnitude of flow for a specific period. One solution would be to use seven consecutive days of low flows to get a better sense of changes in low-flow periods and to eventually better allocate limited water supply[52].

Comparison of streamflow results to trends in temperature, precipitation, and snowpack results was hindered by the lack of overlapping periods. Trends in streamflow were investigated for the latest 30 year period 1976-2005 to update a previous study[53] and to allow the analysis of the largest number of stations. However, this period is not directly comparable with other trend estimates in this report such as with snowpack or temperature and precipitation. Trends in snowpack were carried out for 1950-2007 (section 3.1). Temperature and precipitation were analyzed from 1900-2004 (section 2.2). Thus, some generalizations had to be made to compare the different variables.

Over the 1976-2005 study period the warm PDO (1977-1998) likely influenced trends in streamflow. Other researchers[54] have worked to separate the influence of natural variability from that of climate change, but efforts were not made to do so here. Furthermore, the investigation of the influence of climate variability on streamflow did not include bootstrapped statistical significance testing of composites, as in a previous study that this analysis was modeled after[55]. However, the Mann-Whitney U test is robust to non-parametric conditions[56] and was shown to produce similar results in terms of statistical significance to those produced with the bootstrapping technique.

Gaps

- Trends in monthly mean streamflow, the 10th through to the 90th percentiles of daily mean streamflow, the start date of the spring freshet season, date of annual maximum daily streamflow, centroid of annual streamflow, date of river ice freeze-up, date of spring ice break-up, and duration of ice cover have been examined in other work[57]. All of these are meaningful indices that may reveal important information on streamflow changes.
- A field significance test would provide a statistical check of the coherence of the trends across the Province.
- The Arctic Oscillation (AO) likely has similar influence on streamflow in the northern regions of the Province to that of ENSO and PDO. However, individual streams have not been investigated for their response to the AO, nor has the regional influence been quantified.
- Drainage basins in BC exhibit a mixture of flood generating mechanisms. Each runoff type has been shown to respond differently to ENSO and PDO and hence these mechanisms would be affected by these patterns. These responses need to be integrated and summarized for incorporation into flood frequency analysis.

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[1] Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.
[2] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[3] Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.
[4] Ibid.
[5] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[6] Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.

[7] Whitfield, P.H. and Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25: 19-65.
[8] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[9] http://www.ecoinfo.ec.gc.ca/env_ind/region/climate/climate_data_e.cfm#dataset
[10] van Heeswijk, Marijke, Kimball, J.S., and Marks, Danny, 1996, Simulation of water available for runoff in clearcut forest openings during rain-on-snow events in the Western Cascade Range of Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 95-4219, 67 pp.
[11] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[12] Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology, 319: 83-95.
[13] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[14] Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate, 18: 1136-1155.
[15] Leith, R.M. and Whitfield, P.H., 1998. Evidence of climate change effects on the hydrology of streams in South-Central B.C. Canadian Water Resources Journal 23: 219-230.
[16] Whitfield, P.H. and Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Ibid., 25: 19-65.
[17] Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate, 18: 1136-1155.
Where is 28??
[18] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[19] Ibid.
[20] Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate, 18: 1136-1155.
[21] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
[22] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
[23] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Ibid., 21(24): 3264-3287.
[24] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[25] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[26] Shabbar, A., 1996. The impact of El Nino-Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean, 34(2): 401-416.
[27] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
[28] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[29] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
[30] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[31] Fleming, S., Moore, R.D. and Clarke, G.K.C., 2006. Glacier-mediated streamflow teleconnections to the Arctic Oscillation. International Journal of Climatology, 26: 619–636.

[32] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[33] BC-MoFR. (2006). Mountain Pine Beetle Action Plan 2006 – 2014. BC Ministry of Forests and Range. Victoria, BC. 21pp.
[34] Uunila, L., Guy, B. and Pike, R., 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: Key questions and current knowledge. Extended Abtract. BC Journal of Ecosystems and Management, 7(2): 37-39.
[35] Cheng, J.D., 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in Southern British Columbia, Canada. Water Resources Research, 25: 449-456.
[36] Love, L.D., 1955. The effect on stream flow of the killing of spruce and pine by the Engleman spruce beetle. Transaction of the American Geophysical Union, 36: 113-118.
[37] Bethlahmy, N., 1974. More streamflow after a bark beetle epidemic. Journal of Hydrology, 23: 185-189, Bethlahmy, N., 1975. A Colorado episode: Beetle epidemic, ghost forests, more streamflow. Northwest Science, 49: 95-105.
[38] Bethlahmy, N. (1975) A Colorado episode: beetle epidemic, ghost forests, more streamflow. Northwest Science 49, 95-105.
[39] Potts, D.F., 1984. Hydrologic impacts of large-scale mountain pine beetle (*Dendroctonus Ponderosae* Hopkins) epidemic. Water Resources Research, 20: 373-377.
[40] Troendle, C.A. and Nankervis, J.E., 2000. Estimating additional water yield from changes in management of national forests in the North Platte Basin, Platte River Office Bureau of Reclamation, Lakewood CO.
[41] Ladekarl, U.L., Normberg, P., Rasmussen, K.R., Nielsen, K.E. and Hansen, B., 2001. Effects of a heather beetle attack on soil moisture and water balance at a Danish heathland. Plant and Soil, 239: 147-158.
[42] Hélie, J.F., Peters, D.L., Tattrie, K.R. and Gibson, J.J., 2005. Review and synthesis of potential hydrologic impacts of mountain pine beetle and related harvesting activities in British Columbia: Mountain Pine Beetle Initiative Working Paper 2005-23. Natural Resources Canada, Canadian Forest Service, Victoria BC.
[43] Uunila, L., Guy, B. and Pike, R., 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: Key questions and current knowledge. Extended Abtract. BC Journal of Ecosystems and Management, 7(2): 37-39.
[44] Boon, S., 2007 in press. Snow accumulation and ablation in a beetle-killed pine stand in Northern Interior British Columbia. BC Journal of Ecosystem Management.
[45] See Doyle 2006 for a note on the subject of climate change and streamflow in MPB-related hydrologic studies
[46] Stahl, K., Moore, R.D. and McKendry, I.G., 2006b. Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. Climate Research, 32: 13-23.
[47] Carroll, A.L. et al., 2006. Impacts of climate change on range expansion by the mountain pine beetle, Natural Resources Canada, Canadian Forest Service, Victoria.
[48] FORREX. (2007) Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary Results of Research from BC and Alberta. Kelowna, BC.
[49] Ecosystems Branch (MOE), 2005. BC Watershed Atlas. http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?from=advancedsearch&edit=true&showall=showall&recordSet=ISO19115&recordUID=4434
[50] Resource Information Branch (MOE), 2004. Hydrologic Zones of British Columbia. http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?from=datacustodians&edit=true&showall=showall&recordSet=ISO19115&recordUID=5330
[51] Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[52] Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
[53] Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.
[54] Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate, 18: 1136-1155.
[55] Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
[56] Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
[57] Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.

Figures

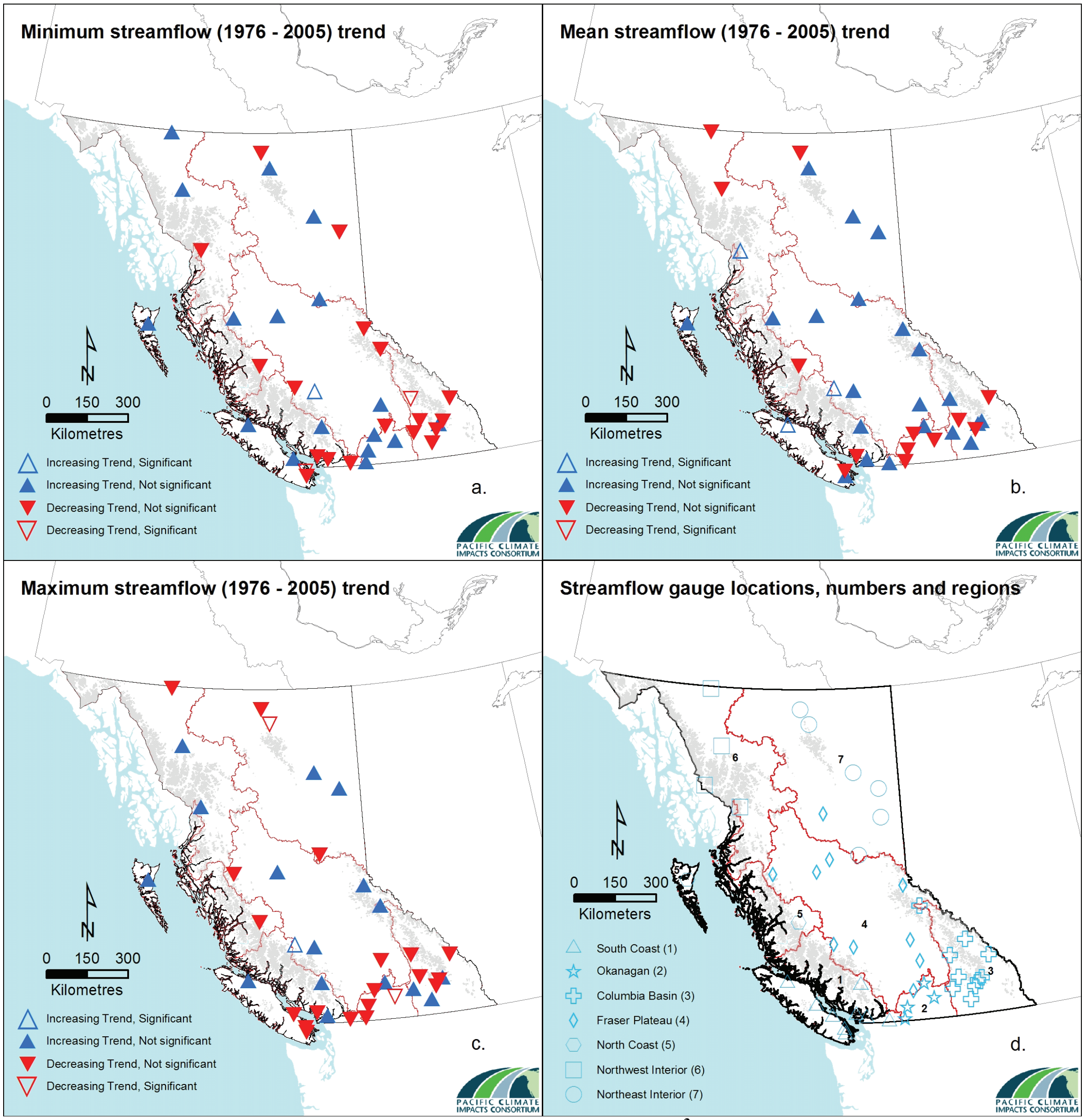

Figure 3.3.1 – a) Annual minimum streamflow 1976-2005 trend (m^3/s per day) b) annual mean streamflow 1976-2005 trend (m^3/s per day), c) annual maximum streamflow 1976-2005 trend (m^3/s per day) and d) streamflow gauge locations, numbers, and regions. Grey areas indicate snow and glacier cover zones. Source: RHBN data, Baseline Thematic Mapping (BTM).

ENSO

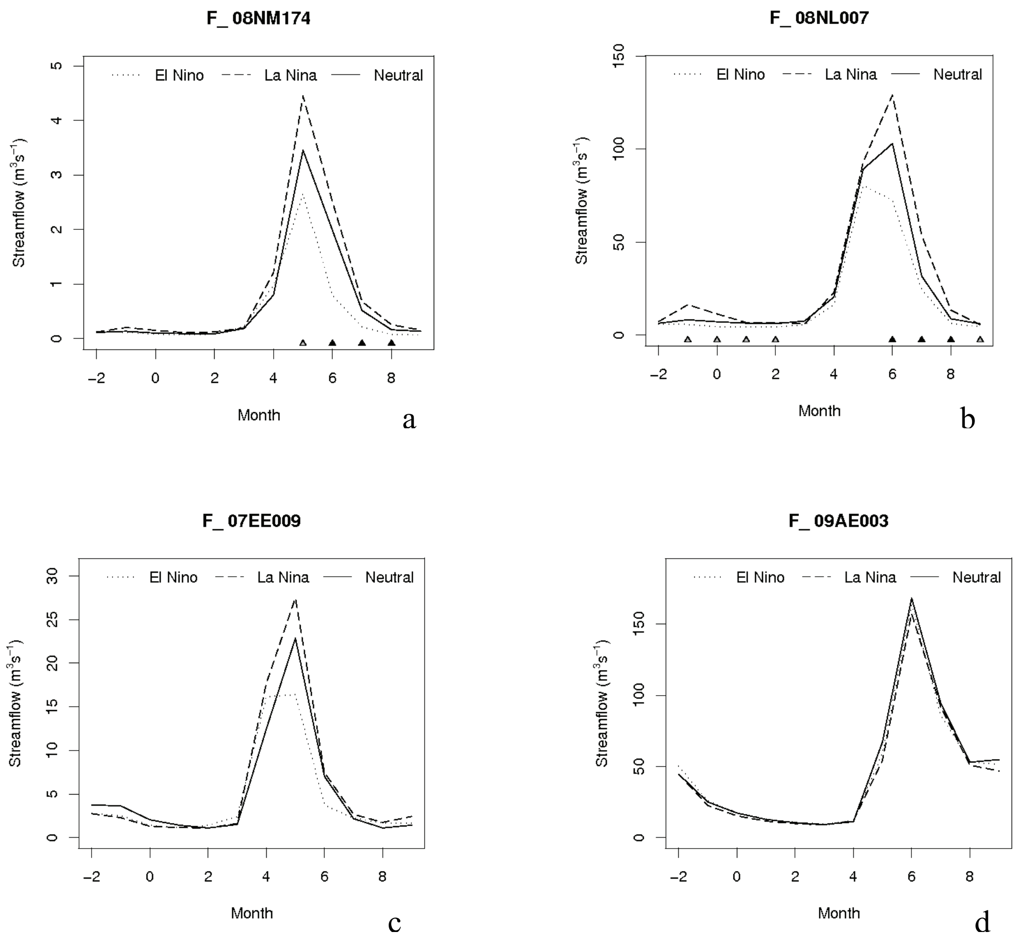

Figure 3.3.2 – Composite analysis results for ENSO on seasonal pattern of mean monthly streamflow (m^3/s) for the a) West Kettle River – Okanagan (nival), b) Similkameen River (at Princeton) – Okanagan (nival/hybrid), c) Chuchinka Creek - Peace Basin (hybrid), and d) Swift River - Northwest (nival). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the El Niño, La Niña, or Neutral years and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

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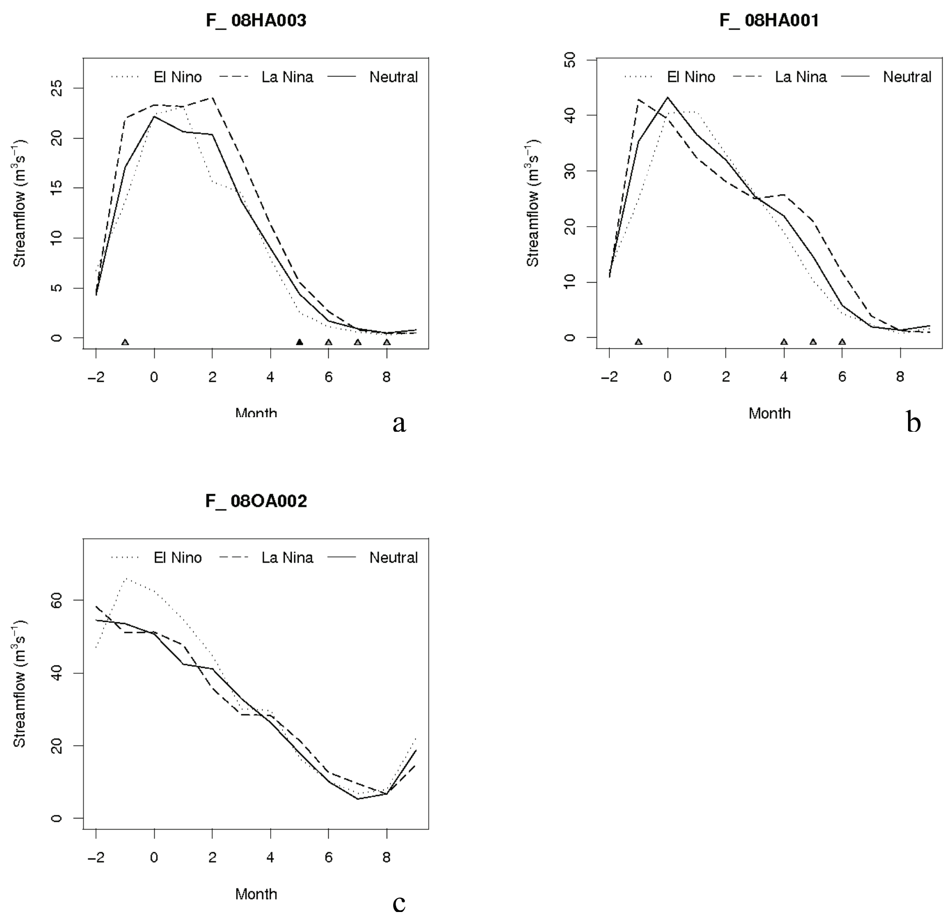

Figure 3.3.3 – Composite analysis results for ENSO on seasonal pattern of mean monthly streamflow (m^3/s) for the South Coast a) Koksilah River (pluvial), b) Chemainus River (nival-supported pluvial), and on the North Coast c) Yakoun River (pluvial). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the El Niño, La Niña, or Neutral years and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

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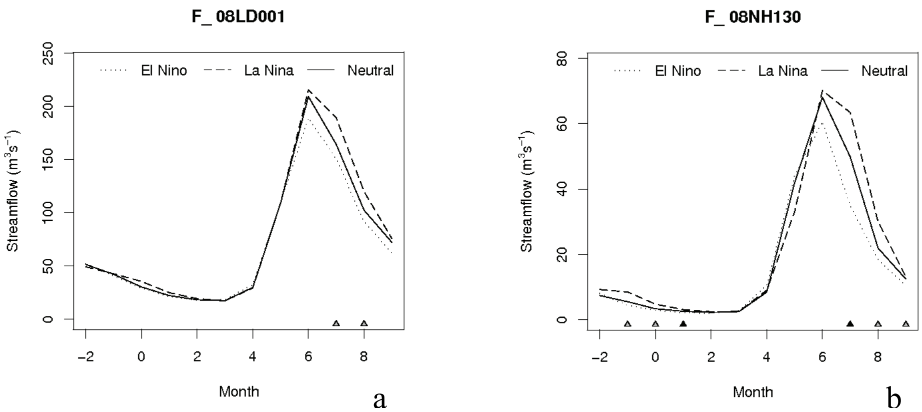

Figure 3.3.4 – Composite analysis results for ENSO on seasonal pattern of mean monthly streamflow (m^3/s) a) Adams River - Interior (nival/glacial), and b) Fry Creek - Columbia (nival-glacial). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the El Niño, La Niña, or Neutral years and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

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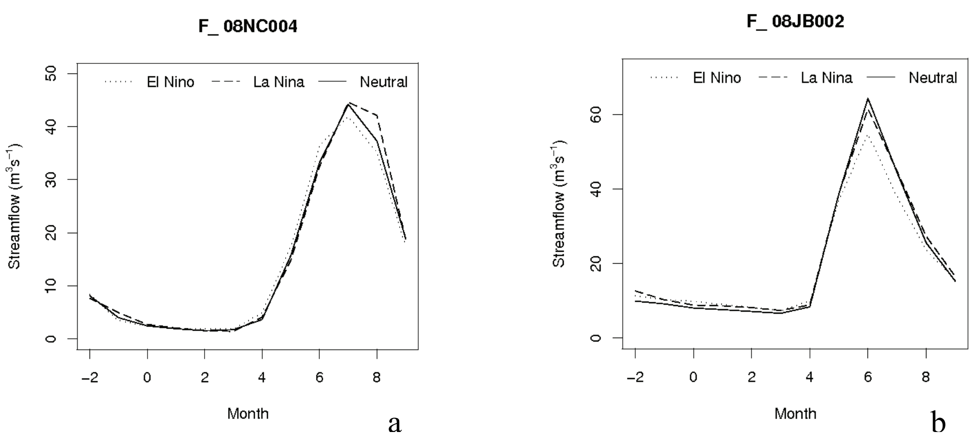


Figure 3.3.5 – Composite analysis results for ENSO on seasonal pattern of mean monthly streamflow (m3/s) a) Canoe River - Columbia (nival/glacial), and b) the Stellako River – Interior (nival/glacial). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the El Niño, La Niña, or Neutral years and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

PDO

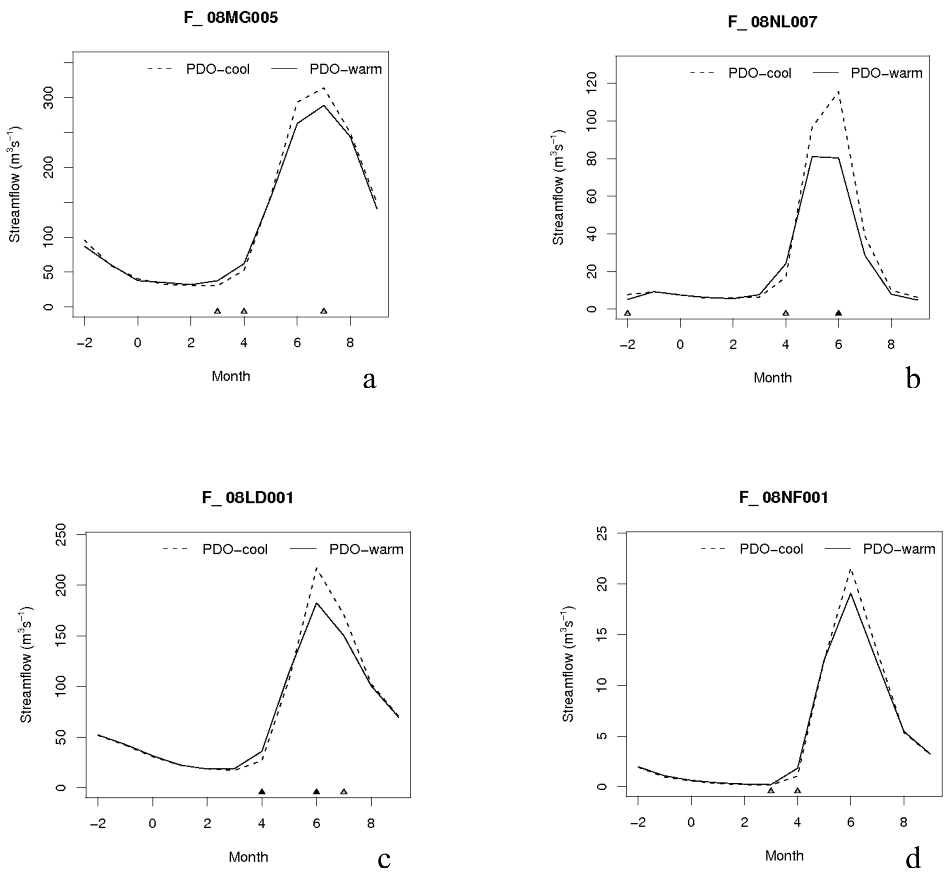
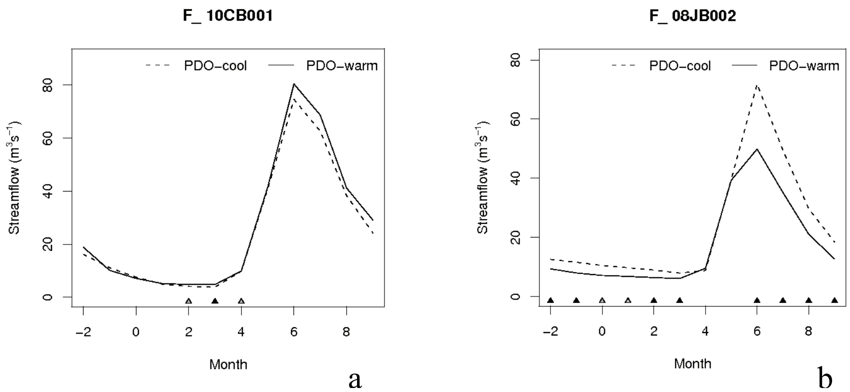


Figure 3.3.6 – Composite analysis results for PDO on seasonal pattern of mean monthly streamflow (m^3/s) a) Lillooet River - South Coast (nival/glacial), b) Similkameen River - Okanagan (nival/hybrid), c) Adams River – Interior (nival/glacial), and d) Kootney River – Columbia (nival/glacial). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the PDO cool and PDO warm phases and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

PDO



a b

Figure 3.3.7 – Composite analysis results for PDO on seasonal pattern of mean monthly streamflow (m^3/s) a) Sikanni Chief – Peace Basin (nival) and b) Stellako River – Interior (nival/glacial). The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. The y-axis shows average streamflow (m^3/s) for a given month for the PDO cool and PDO warm phases and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: RHBN data, PCIC.

3.4. Lake Ice

Trends in freeze-up, break-up, and duration of lake ice cover are a good proxy indicator of climate variability and change. This study investigates trends in lake ice cover for the most recent 30 year period 1976-2005 and compares trends from that period to those for the 1966-1995 period. New sites were evaluated that had not been previously investigated in BC.

Results

- Lake and river ice are an excellent indicator of climate change, especially because decadal and inter-decadal variation due to PDO and ENSO are integrated in melt response (break-up, freeze up and ice duration). Trends in lake ice cover were computed for 1976-2005 to provide updated results for the most recent 30 year period and trends for 1966-1995 were included to compare to a national[1] study.
- For both time periods, *break-up* occurred earlier. During 1966-1995 *break-up* occurred 5 to 40 days earlier and for 1976-2005 break-up occurred 3 to 10 days earlier (**Figure 3.4.1a, b**). Half of these trends are significant at the 90% confidence interval based on these two periods. *Break-up* trends at Charlie Lake switched from earlier *break-up* (significant at 90% level) in 1966-1995 to later *break-up* (not significant at 90% level) in 1976-2000.
- Lake ice *duration* was shorter by 0 to 48 days for 1966-1995 and 0 to 42 days for 1976-2005 (**Figure 3.4.2a, b**). These trends were spatially coherent and 20% of the stations had significant trends.
- The more recent 1976-2005 period shows spatial coherence of trends towards later *freeze-up* by 7 to 40 days. Trends at two of the three stations were statistically significant. This is consistent with recent warmer temperatures that delayed the onset of *freeze-up* across BC. Trends in *freeze-up dates* for the 1966-1995 period were spatially variable which is in agreement with other studies. Factors such as wind may influence *freeze-up* causing results to be less clear than break-up results (**Figure 3.4.3a, b**).
- The change in lake ice in the 1976-2005 period reflects the enhanced spring and winter warming that occurred in BC during the 20th century, and signals potential increases in lake evaporation and disruption to ecosystems[2].

Discussion

Trends in *break-up* dates for the 1966-1995 period were consistently negative and statistically significant indicating that *break-up* occurred earlier for this period (**Figure 3.4.1a, b**), as found by other researchers[3]. Over the 1976-2005 period, *break-up* took place from 3 to 10 days earlier based on data from Tie, Williams, Loon, Nukko, and Heffley Lakes. Trends at Williams Lake and Loon Lake were statistically significant at the 90% confidence level. Charlie Lake was the one exception, where break-up took place 3 days later.

Loon and Heffley Lakes were analysed in both the 1966-1995 and 1976-2005 periods. *Break-up* dates advanced by 18 and 40 days in the 1966-1995 period, and by 4 and 10 days in the 1976-2005 period at Loon and Heffley Lake, respectively. These lakes are the most southern and would therefore have larger trends owing to larger increases in spring temperatures occurring in the southern parts of BC[4].

Trends in lake-ice *duration* for the 1966-1995 period and the 1976-2005 period were consistently negative indicating that the *duration* of ice cover has become shorter (**Figure 3.4.2a, b, c**). The range of decrease in the number of days of ice *duration* was from 0 to 48 days for 1966-1995 and 0 to 42 for 1976-2005, 50% of the stations in 1976-2005 showed significant trends. Again, the largest decreases in duration occurred at the lakes which are farthest south, Loon and Heffley Lake, for both periods.

Trends in *freeze-up* dates in the 1966-1995 period included Charlie, Dease, Heffley, Loon, Nukko, Kathryn and Williams Lakes. Results showed that just over half of the lakes had later *freeze-up* dates and only Dease, William and Nukko Lakes had earlier *freeze-up* dates (**Figure 3.4.3b**). Dease Lake is located the farthest northwest and William and Nukko Lake are located in the central part of the Province. Over the 1976-2005 period, *freeze-up* took place from 7 to 40 days later based on data from Loon, Nukko, and Heffley Lakes (**Figure 3.4.3c**). The change in lake ice in the 1976-2005 period reflects the enhanced spring and winter warming that occurred in BC during the 20th century, and signals potential increases in lake evaporation and potential disruption to ecosystems[5].

A particularly strong trend in *break-up* dates has been found in Western Canada in comparison to the rest of Canada[6]. The results for *freeze-up* across different time periods and at different sites are not as consistent as those for *break-up* and lake ice *duration*[7]. Other studies have shown that although there is a clear trend towards earlier *break-up* dates, *freeze-up* dates are more complex and trends are not spatially consistent[8]. These alternate results reinforced findings documented in this report.

Due to data limitations, the same lakes are not represented in all time periods. This limits the comparison of trends from one period to another. However, Charlie, Nukko, and Williams Lakes were represented in all periods and therefore results at these lake sites can be compared across periods. The changes in lake ice *break-up* suggest that stronger trends occurred during the 1966-1995 period than during the 1976-2005 period. The 1966-1995 period started in a cool PDO phase and did not switch to a warm phase until 1977[9]. In the 1976-2005 period the majority of the years were in the warm PDO phase (up to 1998, section 2.1). Also, some of the warmest temperatures on record occurred in the 1990s which can be attributed to the PDO warm phase, El Niño events, and climate change.

Although PDO phases likely had a strong influence on the trends in these periods there are other factors. Air temperature was found to be the strongest indicator of lake ice cover in one study[10]. However, freeze-up, break-up, and duration of lake ice was also found to be somewhat dependent on dew point, solar radiation, wind speed, and snowfall[11]. These factors could help to explain the different trends in lake ice in the different regions. For example, the trend at Charlie Lake over this period may be reflective of increases in snowfall in the region that would have contributed to ice cover persisting longer on lake surfaces in this region than in others (section 3.1).

Two additional lakes were investigated in this study that had not been before: Tie and Loon Lakes. Tie Lake is located farther south than any of the other lakes and it displays trends toward earlier *break-up* (**Figure 3.4.1c**). Loon Lake is located close to Heffley Lake in the Fraser Plateau and has trends that are similar to those from Heffley, which are larger and significant (**Figure 3.4.1, 3.4.2, 3.4.3**). Trends for Williams and Nukko Lake, which are also within the Fraser Plateau, also show earlier *break-up*.

Uncertainties and Limitations

Although the lakes analysed here had been examined in previous research[12], results were slightly different. These differences demonstrated the impact of not having consistent guidelines for data collection procedures. For example, one observer may view the lake from a different side of the lake than another and hence might have recorded the lake ice break-up earlier than an observer at another site. Efforts should be made to align techniques to allow the amalgamation of datasets and continuity of trend results.

The number of lakes which have data on ice cover is limited and the results presented here are not representative of trends for all lakes in BC or for regions in which lakes are situated.

Gaps

- Trends in lake and river ice have not been linked to trends in phenology (i.e. the emergence of leaves, the first appearance of migratory birds) and other indicators of climate change.
- There are other non-thermal effects that influence lake ice break-up and freeze-up (such as wind) that were not explored here.
- A better understanding of how changes to lake ice cover result from climate change could be tested using the relationship of synoptic patterns to trends in break-up/freeze-up events. The influence of climatic and hydrologic forcing mechanisms (i.e. drainage area) on break-up/freeze-up response could also provide more information.

- Synthetic Aperture Radar (SAR), such as Advanced Synthetic Aperture Radar (ASAR) and optical Advanced Along-Track Radiometer (AATSR) data from the Environmental Satellite (ENVISAT) are also being used to map freeze-up and break-up dates over large areas of Canada, but have not been tested against all available monitoring data.

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[1] Duguay, C.R. et al., 2006. Recent trends in Canadian lake ice cover. Hydrological Processes, 20: 781-801.
[2] Ibid.
[3] Ibid.
[4] Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
[5] Duguay, C.R. et al., 2006. Recent trends in Canadian lake ice cover. Hydrological Processes, 20: 781-801.
[6] Ibid.
[7] Ibid.
[8] http://www.ec.gc.ca/climate/CCAF-FACC/Science/nat2002/terrestrial_e.htm
[9] Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78: 1069-1079.
[10] Gao, S. and Stefan, H.G., 2004. Potential climate change effects on ice covers of five freshwater lakes. Journal of Hydrologic Engineering, May/June(226-234).
[11] Ibid.
[12] Duguay, C.R. et al., 2006. Recent trends in Canadian lake ice cover. Hydrological Processes, 20: 781-801.

Figures

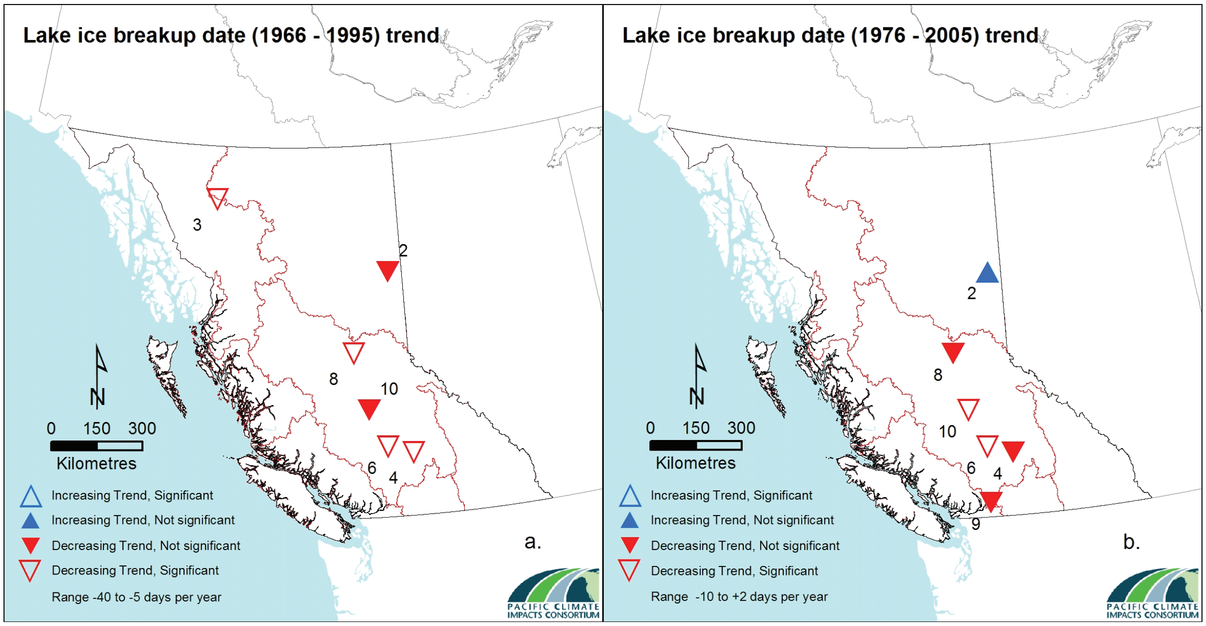

Figure 3.4.1 – Trends in break-up dates across BC for two periods a) 1966-95, and b) 1976-05. Triangles pointing up indicate later break-up dates and those pointing down indicate earlier break-up dates (1-Alta Lake, 2-Charlie Lake, 3-Dease Lake, 4-Heffley Lake, 5-Kathryn Lake, 6- Loon Lake, 7-Tie Lake, 8-Nukko Lake, 9-, and 10-Williams Lake). Open triangles denote trend is significant (95%) and closed triangles denote trend is not significant. Source: BC Lake Stewardship Society data.

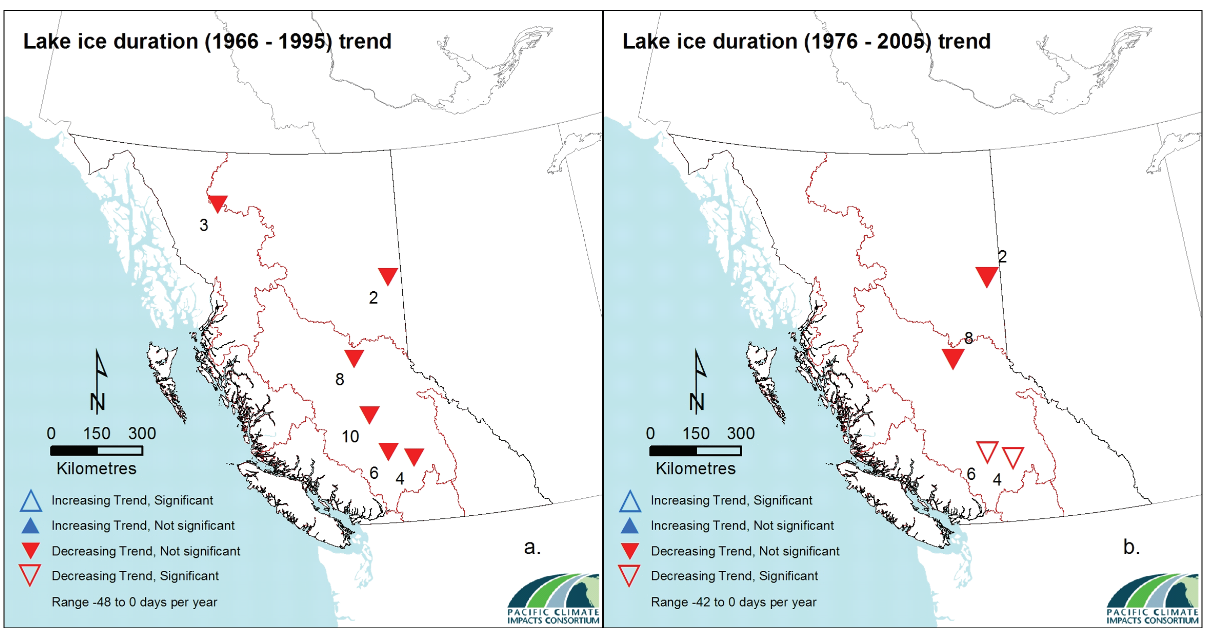

Figure 3.4.2 – Trends in duration of ice cover across BC for two periods a) 1966-95, and b) 1976-05. Triangles pointing up indicate longer duration and those pointing down indicate shorter duration. (1-Alta Lake, 2-Charlie Lake, 3-Dease Lake, 4-Heffley Lake, 5-Kathryn Lake, 6- Loon Lake, 7-Tie Lake, 8-Nukko Lake, 9-, and 10-Williams Lake). Open triangles denote trend is significant (95%) and closed triangles denote trend is not significant. Source: BC Lake Stewardship Society data.

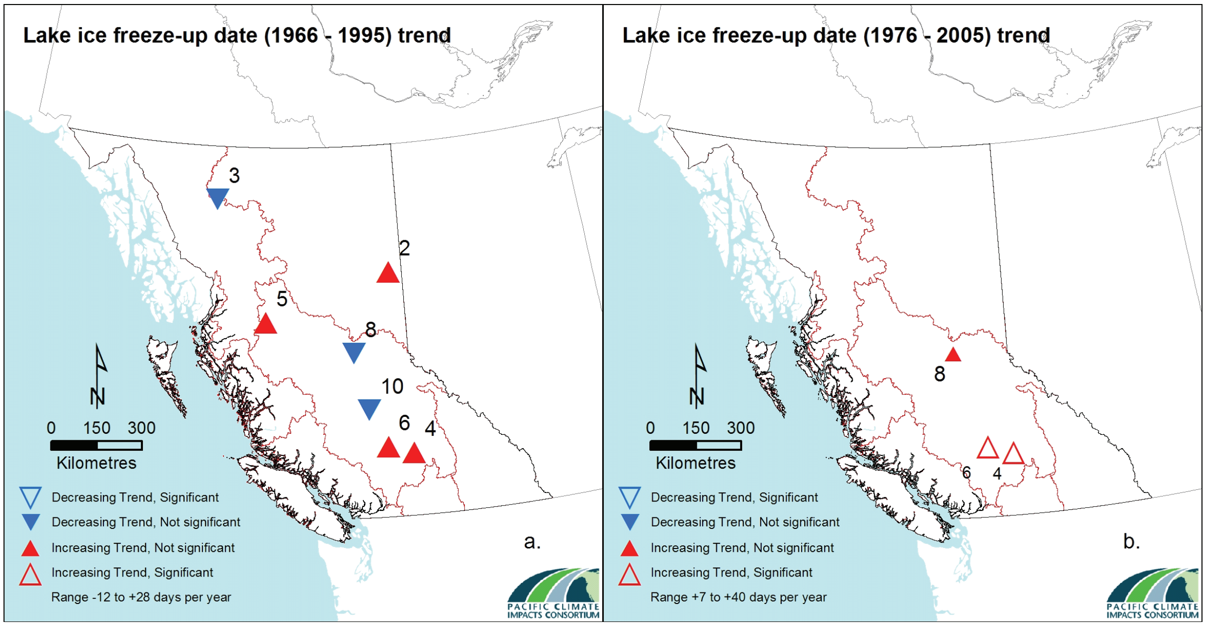

Figure 3.4.3 – Trends in freeze-up dates across BC for two periods a) 1966-95, and b) 1976-05. Triangles pointing up indicate later freeze-up dates and those pointing down indicate earlier freeze-up. (1-Alta Lake, 2-Charlie Lake, 3-Dease Lake, 4-Heffley Lake, 5-Kathryn Lake, 6- Loon Lake, 7-Tie Lake, 8-Nukko Lake, 9-, and 10-Williams Lake). Open triangles denote trend is significant (95%) and closed triangles denote trend is not significant. Source: BC Lake Stewardship Society data.

II. Introduction – Future climate change, impacts, and feedbacks (2050s)

Climate Change Projections from GCMs

Projections of future climate change and its impacts over the coming century are based on global climate models (GCMs). GCMs are numerical models that simulate global climate and are driven by the difference between incoming solar radiation and infrared cooling of the earth system. Infrared cooling is controlled by clouds, atmospheric turbidity, and by small concentrations of greenhouse gases (GHG) in the atmosphere, principally carbon dioxide. The imbalance in net radiation drives the climate model (as it does the real climate system) towards a different climate. The concentrations of GHGs are determined by both natural processes and human activities, and the latter depends on assumptions about population growth, future economic activity, and mitigation policy decisions - specified as *emissions scenarios*.

Three SRES[i] marker emissions scenarios are commonly used: A2 most closely describes an extension of current emissions in an uncoordinated (heterogeneous) world economy and would result in a temperature change of +3.4°C by the end of the century. B1 refers to a more adaptive global society and would result in a temperature change of +1.8°C. A1B refers to a balance of energy decisions which would result in intermediate levels of emissions[1].

Even with identical emissions scenarios, each GCM produces somewhat different results. However, useful information about the future climate may be obtained using an ensemble of climate projections. For this report, ensembles of projections are obtained from 15 recent GCMs, including the following from Canada, the United Kingdom, and the United States as listed below:

- CCCma CGCM3 – Canadian Global Climate Model version 3 (Canadian Climate Centre for Modeling and Analysis, University of Victoria, BC)
- UKMO HadCM3 – Hadley Climate Model version 3, (UK Met Office, United Kingdom)
- NCAR CCSM – Community Climate System Model (National Center for Atmospheric Research, Boulder, Colorado)
- GFDL CM2.x – Geophysical Fluid Dynamics Laboratory Coupled Model versions 2.0 and 2.1 (National Oceanic and Atmospheric Administration, Princeton, New Jersey)

In this report, an ensemble of GCM projections has been used to estimate the future climate in mid-century (2050s), and to quantify the magnitude and relative amount of uncertainty in temperature and precipitation. These projections have been averaged over several decades (2041-2070) to eliminate short term climate variability and are compared to historical variability.

Downscaling Methods

The spatial resolution of GCMs is limited, and they are designed for global and continental scales. Therefore, some sort of downscaling methodology is needed to place future climate projections on a regional spatial scale where specific problems are addressed, commercial decisions are made, and regional planning occurs.

Two methods of downscaling climate projections are shown: dynamical downscaling using a Regional Climate Model (RCM) and empirical downscaling using high-definition climatology. Dynamical downscaling provides physically consistent regional projections at a 45 km resolution. Empirical downscaling uses detailed climatology to display high definition projected temperature and precipitation that can be compared directly to the historical climatology. Both downscaling methods depend on GCM projections. Although a comprehensive range of uncertainty is not available for downscaled results, GCM uncertainty is a useful guideline.

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[i] By the end of the 21st century the CO_2 equivalent global greenhouse gas concentrations is roughly 600 ppm, 850 ppm, and 1250 ppm for B1, A1B, and A2, respectively.

An example of a high definition downscaling application is estimates of growing degree days (GDDs). Growing degree days depend on temperature and future projections of changes to GDDs for rates of evaporation and transpiration, as well as for agricultural production. These changes in evaporation from landscapes will have subsequent impacts on streamflow conditions in BC.

Hydrologic Impacts and Feedbacks of Climate Change

Climate change will have impacts on the entire hydrological system. In particular, climate change will influence temperature, evaporation, and soil moisture as well as the timing, amount, and form of precipitation. During the cold seasons of the year, temperature affects the balance between cryospheric regimes (which are long-term storage) and rainfall (which results in a short-term response in streamflow). Projected changes in temperature are especially critical for BC water resources because temperature controls the storage of snowfall in the wet/cold season for subsequent use in the dry/warm season. The temporal and spatial location of the zero-degree-isotherm generally illustrates this influence.

Projected changes in annual precipitation are small and somewhat uncertain, but fractionally large in climatologically dry regions. Small changes in precipitation may have less impact than transition from snow to rain which may cause complex changes in cryospheric regimes (glaciers, snowpack, lake ice) that lead to subsequent changes in operation of reservoirs and in the seasonal shifts in timing of streamflow.

Snowpack is a critical seasonal resource that is renewed each year at high elevations, but is utilized throughout the region during most of the year after transformation in reservoirs, streamflow, and ground water. In this report, an estimate of future snowpack in the 2050s is investigated with the RCM.

Glaciers also contribute to water resources, but their influence extends from seasons to decades. During the late summer when rivers typically experience low flows and ecological requirements are high, glacier runoff may be a large fraction of the streamflow. However, knowledge of the scope and location of climate impacts on glaciers is limited. Results of current research have been synthesized in this report.

Streamflow projections in complex topography are difficult to compute precisely with either the GCM or RCM. This topic is the domain of a hydrological model that is forced by a future projection of temperature and precipitation. Several modeling studies have been conducted in BC, for example, in the Columbia, Okanagan, and Fraser Basins.

Soil moisture acts as a water reserve for vegetation and agriculture. It integrates inputs from rain, snowmelt, and losses due to evaporation, transpiration, interception, surface runoff, and drainage (base flow). Surface evaporation is a critical hydrological feedback from the earth's surface into the atmosphere that has, itself, been modified by global climate change. Evaporation depends in part on conditions of soil moisture, solar radiation, and ground cover. Each process influences soil moisture with a different temporal signature and affects the timing of streamflow parameters. Finally, changes in soil moisture determine the fraction of precipitation and snowmelt that is released to streams as runoff.

Some local measurements of soil moisture have been made in BC, but projections for the 2050s require a comprehensive hydrologic model that would determine impacts on agriculture and forestry, and feedbacks within the hydrologic system. Current projections of changes in soil moisture have been made only for the Columbia Basin.

Limitations

Projections of future climate from dynamic climate models (GCMs and RCMs) are limited by imperfect physics that are implicit in model approximations. Although models are able to quantitatively project temperature changes, the limit of coarse resolution requires empirical downscaling and that introduces additional uncertainties. Projections of precipitation are less certain due to the difficulty in representing mesoscale dynamics and microphysical processes. Moreover, atmospheric models distribute precipitation into surface water regimes, but are not redistributed within the physical watershed and streamflow, except in a bulk sense.

Future climate impacts on water resources are large and important, but many details are missing. Knowledge of future climate projections within BC or Pacific North America requires a Regional Climate model and a comparative hydrologic model.

[1] A more complete description of emissions scenarios comes from IPCC (2000), Special Report on Emissions Scenarios (SRES): http://www.grida.no/climate/ipcc/emission/

4. Future climate change projections

4.0. Future climate change terminology and conventions

The use of information about future climate for planning, decision-making, and policy is a relatively new practice. The terminology and conventions used to describe information about future climate has been guided largely by a recent synthesis document on the use of global change scenarios[1].

A distinguishing feature of all climate projection methods is the representation of topography (**Figure 4.0.1**). Presentation of results at higher resolution (with more precision) is appealing, but implies neither increased accuracy nor reliability. Single high resolution projections should not be used without also considering the range of projections from multiple GCMs.

Section 4 as a whole provides a scenario of future climate change in BC, with each section providing complementary information. Section 4.1 shows the range of future climate projections and quantifies the associated uncertainty. Section 4.2 contains a physically consistent high-resolution climate projection, but only for one of the many possibilities shown in section 4.1. Finally, section 4.3 shows the future climate at a resolution that is comparable to a high definition interpolation of BC's historical climate.

Terminology for section 4

Global Climate Model (**GCM**) – a numerical model that simulates global climate.

Regional Climate Model (**RCM**) – a numerical model that is forced by boundary conditions obtained from a GCM, and simulates climate at a higher resolution over a limited area (such as North America).

Emissions scenario is an estimation of greenhouse gas concentrations during the 21st century based on socio-economic assumptions.

Projection refers to the result from a single GCM or RCM following a given emissions scenario.

Run is used to distinguish projections from a given GCM following the same emissions scenario. (Runs differ only by initial conditions.)

The model **baseline** climate from a GCM or RCM is the average simulated climate for the 30-year period using 1961-1990 greenhouse gas concentrations.

Anomalies are projected changes in future climate expressed as a difference from the model baseline.

Ensemble refers to a collection of GCM projections. The terms *climate scenario* (and *climate change scenario* where the anomaly from the model baseline is taken) are also applicable to the ensemble of projections.

AR4 refers to the IPCC Fourth Assessment Report.

Conventions for section 4

Seasonal projections are shown only for **winter** (December-January-February) and summer (June-July-August). Results are not shown for spring and fall.

Unless otherwise stated, **anomalies** have been averaged in time for the 2050s (2041-2070) difference from 1961-1990 model baseline and in space for all grid boxes within BC. The 1961-1990 period is chosen because most decision making is adapted to this historical period. A portion of the projected climate change from 1961-1990 to the 2050s has already occurred in the record of the past decades (**Table 4.1.5b**).

Unless otherwise stated, **ensemble results** are based on one projection following each of the B1 and A2 emissions scenarios from 15 GCMs (30 projections total). Where indicated, smaller ensembles are used to estimate uncertainty, to compare to sub-continental and global projections (**Table 4.1.3**, **4.1.4a**), or to examine consistency between different runs from the same GCM and emissions scenario (**Table 4.1.2**).

The **range** of GCM projections reported in section 4.1 is derived from an ensemble of projections including 15 GCMs each following one or more of the A2, A1B and B1 emissions scenarios. The range is expressed using the 10^{th} and 90^{th} percentiles (range explained by 80% of projections) in brackets.

The **geographical range** reported in section 4.2 is derived from the single RCM projection at 624 grid boxes within BC. In this case, the range illustrates how RCM anomalies vary across the Province. Although illustrating a different concept, this range is also expressed using the 10^{th} and 90^{th} percentiles (range explained by 80% of grid boxes) in brackets.

Temperature is used to refer to **mean** temperature: the average of nighttime lows (minimum temperatures) and daytime highs (maximum temperature).

Precipitation anomalies are reported as a percentage of the model baseline value. Precipitation projections are described as **wetter** or as **drier** by the 2050s than baseline, even though precipitation includes snow as well as rain (technically the projected anomalies are *increases* and *decreases* from the baseline).

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[1] Parson, Burkett, Fisher-Vanden, Keith, Mearns, Pitcher, Rosenzweig, and Webster 2007. Global Change Scenarios: Their development and use. Synthesis and Assessment Product 2.1b. Washington, DC: US Climate Science Program.

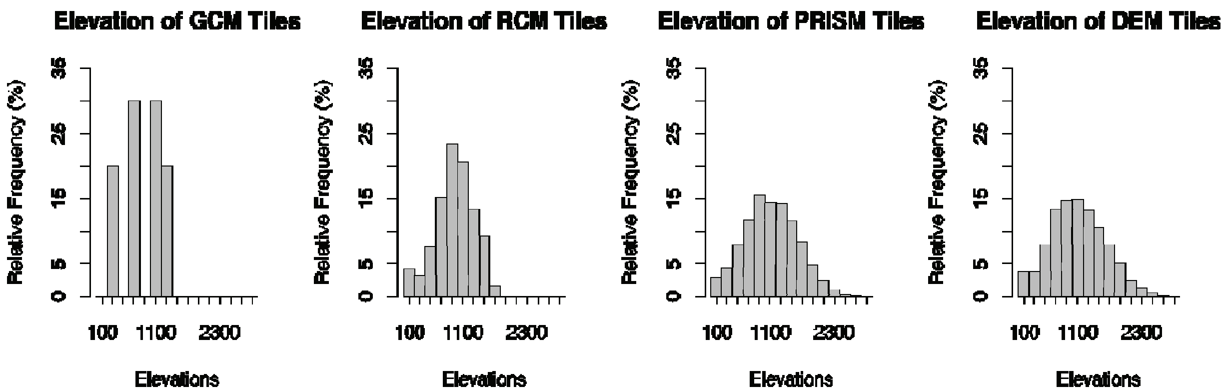

Figure 4.0.1 – Elevation as represented by (a) GCM (CGCM3), (b) RCM (CRCM4), (c) PRISM, and (d) Digital Elevation Model. Source: (a) Environment Canada, (b) Ouranos Consortium, (c) Oregon State University, (d) Canada3D digital elevation model (DEM) produced by the Canadian Forestry Service, Ontario region (NAD83).

4.1. GCM projections

GCM projections of future climate conditions are the starting point for high-resolution downscaling shown in later sections. An ensemble of projections (collection of results from several GCMs) provides a range of plausible future climate conditions. The ensemble compiled for use in this section uses the latest projections prepared for the IPCC Fourth Assessment (AR4). This is the first publication of AR4 results applied to BC.

Throughout section 4.1, unless otherwise indicated: (i) the ensemble includes 15 GCMs with one projection following each of the A2 and B1 emissions scenarios (30 projections total), (ii) anomalies have been averaged in time for 2050s (difference between the 2041-2070 from 1961-1990 model baseline) and in space for all grid boxes within BC, and (iii) ranges in brackets following anomalies are the 10th to 90th percentiles from the ensemble. See information boxes in section 4.0 for conventions and definitions.

Results

- By the middle of the 21st century (2050s) annual temperature and precipitation for BC are estimated to be +1.7°C (+1.2°C to +2.5°C) warmer and +6% (+3% to +11%) wetter than the 1961 – 1990 baseline (**Figure 4.1.1**).
- Projected *winter* and *summer* season temperatures in the 2050s are +1.9°C (+0.5°C to +2.7°C) and +1.8°C (+1.2°C to +2.7°C) warmer than the baseline, respectively (**Table 4.1.1**). The winter precipitation projection is +7% wetter (-2% drier to +15% wetter) than the baseline. The winter ensemble average is similar to annual but the wider range indicates more uncertainty. Summer precipitation is -3% drier (-9% drier to +2% wetter) than the baseline.
- A *single* projection from the Canadian model (CGCM3; **Figure 4.1.2**) following the A2 emissions scenario is +2.6°C warmer and +14% wetter than the baseline for BC in the 2050s. These results are compared to four other CGCM3 projections following A2, and to the ensemble of projections from 15 GCMs (**Figure 4.1.1, Table 4.1.2**).
- An estimate of *uncertainty* in BC projections in the 2050s from different GCMs is 1.3°C for temperature and 10% of the baseline for precipitation (**Table 4.1.3**). This uncertainty is less than the ensemble average anomaly for temperature (+1.7°C) but not for precipitation (+6%). Thus, there is more confidence in the ensemble average projection for temperature than for precipitation.
- An estimate of *uncertainty* in BC temperature projections from different emissions scenarios is 0.3°C in the 2050s and 1.2°C in the 2080s (**Table 4.1.3**). The influence of emissions scenario is relatively small compared to GCM uncertainty in the 2050s, but it increases by the 2080s.
- By the end of the 21st century (2080s), BC's annual temperature is projected to be +2.8°C (+1.5°C to +4.0°C) warmer than the baseline (**Figure 4.1.3, Table 4.1.4**). This projection is comparable to the range between the warmest and coldest years of the 20th century (+3.1°C[i]). However, the projected change in precipitation is +10% (+6% to +17%) wetter and is well within the range of observed historical precipitation variability (38%).

Discussion

GCMs are the fundamental tools for understanding future climate change. The availability of many GCM projections allows for construction of an ensemble that can be used to provide estimates of plausible climate change as well as to quantitatively estimate uncertainty. The range of projections from an ensemble can thus be used to develop scenarios for decision making and planning[1].

The ensemble of GCM projections is used in several ways. First, temperature and precipitation anomalies averaged over BC are shown as a time series for the 21st century. Then, detailed projections are provided, including seasonal and regional results, for the average of the 2050s. Next, the limitations of using a single GCM projection are demonstrated and the uncertainty that may be attributed to GCMs is

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[i] Indicated by ±two standard deviations from the 1895-2003 historical average (~96% of all years).

determined. In addition to the 2050s, results for the 2080s (2070-2100) are presented in order to illustrate the climate change response to different emissions scenarios. Finally, a comparison of BC anomalies to sub-continental and global projections is followed by discussion of 21st century BC climate change in the context of historical variability.

Climate change projections for BC (2050s)

Figure 4.1.1 shows projected climate change anomalies for BC smoothed (using the LOESS technique)[2] in time over the 21st century. Smoothing improves legibility of the figure and suppresses inter-decadal and year-to-year variability. Displaying the projected anomalies removes individual model systematic bias. Projections are not directly comparable to the historical variations shown in black, included for comparison to magnitude of future change. Future climate change will consist of projected changes to the average superimposed with future climate variability. However, historical climate variability in BC is large, as shown in **Figure 4.1.1** by the 20th century observations and in section 2.2. Therefore periods of cooler temperature may occur within the context of projected warming.

The 2050s ensemble average temperature projections are +1.7°C (+1.2°C to +2.5°C) warmer and +6% (+3% to +11%) wetter than the baseline averaged over BC (**Figure 4.1.1, Table 4.1.1a**). Seasonal and regional projections differ from the annual anomalies in many cases (**Table 4.1.1a**, **b**).

The ensemble average winter and summer temperature projections are +1.9°C (+0.5°C to +2.7°C) and +1.8°C (+1.2°C to +2.7°C) warmer than the baseline, respectively. Although similar to the annual anomaly, the range is larger for winter. This implies more uncertainty in the magnitude of the winter temperature response.

The ensemble winter and summer precipitation projections are +7% wetter (-2% drier to +15% wetter) and -3% drier (-9% drier to +2% wetter) than the baseline, respectively. The winter ensemble average is similar to annual but has a larger range, indicating more uncertainty than in the annual projection. Conversely, by the 2050s most GCMs in the ensemble project drier summers on average across BC. Unlike the annual precipitation projection, the seasonal ranges include both increases and decreases in projected precipitation.

The *annual* precipitation anomaly is consistent across the regions of BC (**Table 4.1.1b**); however, the ensemble average summer precipitation projections vary considerably across the Province (-13% drier in Southern BC and Vancouver Island to +4% wetter in the North West Interior). Annual and seasonal temperature anomalies are also consistent across these regions, although there are differences of as much as -0.4°C cooler to +0.8°C warmer than the BC average in some cases. These regional results use a small number of low-resolution GCM grid boxes, and are shown only to illustrate the magnitude of the ensemble's differences in projected climate change within smaller regions. See subsequent sections for results of dynamical and empirical downscaling that distribute GCM projections within the region (**Figure 4.2.1, 4.3.1**).

About the ensemble

The results in this section are based on an ensemble of 30 projections that were prepared for the recently released IPCC Fourth Assessment Report (AR4). An ensemble based on projections prepared for the previous IPCC Third Assessment Report (TAR) has also been used extensively and published widely[ii]. The TAR ensemble 2050s projection for BC is +2.3°C (+1.7°C to +3.4°C)[iii] warmer than the baseline, consistent with results published for all of Canada using a similar ensemble[3]. The AR4 ensemble used in this report exhibits a smaller projected temperature increase than the TAR ensemble and a smaller range.

[ii] Data from the TAR ensemble were originally available from www.cics.uvic.ca/scenarios and subsequently from www.ccsn.ca and www.PacificClimate.org/tools.

[iii] Range from analysis by PCIC of TAR ensemble using data from http://www.PacificClimate.org/tools/ with BC region selected and settings of threshold=0.5 and fringe=0.

Differences between the results arise from several improvements in the AR4 ensemble. The number of GCMs is evenly represented in the AR4 ensemble and more GCMs are included: 2 projections from each of 15 GCMs rather than a variable number (2 to 7) of projections from each of 7 GCMs in the TAR ensemble. The number of emissions scenarios in the AR4 ensemble is even: B1 and A2 each have 15 projections. In order to have an adequate number of projections, the TAR ensemble included an uneven representation of emissions scenarios: B1 (3), A1T (1), B2 (10), A1B (2), A2 (11), and A1FI (2). Finally, the AR4 ensemble includes the most recent versions of GCMs (e.g. version 3 of the Canadian GCM rather than version 2 in the TAR ensemble).

Although a comprehensive comparison of the differences between the ensembles has not been conducted, initial analysis (not shown) suggests that the smaller anomaly from the AR4 ensemble is mainly due to the presence of more projections with higher emissions in the TAR ensemble, rather than the presence of additional and updated versions of GCMs. For example, the 2050s anomalies for BC are +2.4°C warmer than the baseline for CGCM2 and 2.3°C warmer than the baseline for the newer version CGCM3[iv].

Comprehensive analysis of the full set of 140 projections prepared for AR4 has not been completed. Preliminary analysis (not shown) suggests that the range of seasonal precipitation projections is likely to increase with the addition of more projections to the ensemble. The 30-projection ensemble appears representative of the full set for 2050s annual temperature, seasonal temperature, and annual precipitation projections for BC. For example, an additional 15 projections (from the same GCMs) following the A1B emissions scenario makes almost no difference to the ensemble averages or the range of annual or seasonal temperature projections (**Table 4.1.3**).

Single GCM projection

In addition to the ensemble, a single projection from CGCM3 following the A2 emissions scenario is examined because it is used as the basis for most of the downscaling shown throughout section 4 and section 5 of this report. The limitations of using a single projection (as in section 4.2) are illustrated below by comparing results to other runs from the same model and to the ensemble of GCM projections. Thus, when using a single GCM projection, it is particularly important to consider the ensemble range and uncertainty as presented in this section.

Projections from five runs are available from the CGCM3 model following A2. The only difference between the runs is the GCM initial conditions. Results are generally consistent, with the exception of run 5 winter (**Table 4.1.2**). Excluding run 5, there is a range of at most 0.5°C and 5% for annual winter and summer results. The run 5 winter, however, has a temperature anomaly +1.0°C greater than the coolest run and a precipitation anomaly more than double the smallest increase.

The CGCM3 2050s projection for run 4 following the A2 scenario is used as boundary conditions for downscaling in subsequent sections of this report. This projection is 2.6°C warmer and 14% wetter than the baseline for BC (**Figure 4.1.2**). These anomalies are larger than both the ensemble average and the upper range based on the 90th percentiles of ensemble projections (compare run 4 in **Table 4.1.2** with *B1, A2* and with A2 in **Table 4.1.3a**).

Considerable warming is projected by the entire ensemble, whereas both the magnitude and even the sign of precipitation are relatively less certain (**Figure 4.1.1, Table 4.1.1a**). These results suggest that the downscaled results in subsequent sections are on the warmer and wetter side of the ensemble of projections for BC.

Uncertainty from GCMs and emissions scenarios

The ranges of projected future climate reported in this section include uncertainties in both GCMs and emissions scenarios. The portion of uncertainty attributable to GCMs arises from differences in the way GCMs represent the climate. The portion of uncertainty attributable to emissions scenarios arises because

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[iv] Average of all available runs following A2 from CGCM2 (3 runs) and CGCM3 (5 runs).

future technological developments and economic, social, and policy choices that influence greenhouse gas emissions are unknown. Ensembles of projections following the B1, A1B and A2 emissions scenarios are used below to estimate the amount of uncertainty present in GCMs and to illustrate the effects of reducing greenhouse gas emissions using differences in projections averaged over BC. These estimates do not account for possible systematic biases present in the GCMs and emissions scenarios.

GCM uncertainty is larger than the difference between emissions scenarios in the 2050s projections for BC. For example, GCM uncertainty[v] is 1.3°C for temperature and 10% of the baseline for precipitation but the A2 ensemble average is only 0.3°C warmer[vi] than B1. The GCM uncertainty is smaller than the projected ensemble average anomaly for temperature (+1.7°C) but larger than the projected ensemble average anomaly for precipitation (+6%). There is therefore more confidence in temperature than precipitation with regard to the ensemble average projection, because the response is larger than the uncertainty (**Table 4.1.3**).

The increased warming by the 2050s for the A2 emissions scenario compared to B1, although small, is consistent with larger emissions prescribed in A2. The 2080s anomalies show the impact on BC climate of different emissions policy options. For example, the 2080s ensemble average projection for BC is +1.2°C[vi] warmer and +3.5% wetter for A2 than B1 (**Table 4.1.3**).

To further illustrate the effect of emissions scenarios, ensemble average temperature anomalies following each of three emissions scenarios are expressed as ratios. By the 2050s, the ratios of projected (B1 : A1B : A2) warming for BC are (1 : 1.25 : 1.15). By the 2080s, they increase to (1 : 1.37 : 1.55). For example, in BC the 2080s warming following A2 is 55% larger than following B1.

Comparison to regional and global warming

Other climate change projections[4] for the US Pacific Northwest (PNW) use an ensemble similar to the AR4 (A2, B1) ensemble used in this section. Results from each ensemble for the US PNW (not shown) are consistent with each other. For the 2040s over the US PNW region, CGCM3 is wetter than most GCMs[5] (as it is for 2050s BC) and the temperature projection is close to the ensemble average (unlike the 2050s BC projection which is warmer than most projections).

The 2050s ensemble average projection for BC (+1.7°C) is similar to the global estimate (+1.5°C)[vii], although these results are not directly comparable due to differences in ensembles and time periods. IPCC estimates of warming focus on the end of the 21st century, specifically the 2090s following the A1B emissions scenario (**Table 4.1.4a**). Warming projected for BC is similar to projections for the larger Western North America region. Furthermore, the ratios of (B1 : A1B : A2) 2090s warming for BC of (1 : 1.46 : 1.71) are very consistent with the global ratios of (1 : 1.45 : 1.70)[6].

The IPCC also reports that by the end of the 21st century in North America: (i) the annual mean temperature change is likely to exceed global changes, (ii) seasonal changes are likely to be largest in the winter in the north, (ii) annual precipitation is very likely to increase in Canada, and (iv) winter and spring precipitation are likely to increase but summer precipitation to decrease in southern Canada[7]. The ensemble of GCM projections in this section is generally consistent with these results.

Finally, Western North America projections following A1B show a time of 15 years for annual temperature and 70 years for annual precipitation in order for the anomaly to become statistically discernable from the baseline[8]. This indicates the time for the impact of climate change to become relatively large in comparison to the historical variability and is consistent with **Figure 4.1.3**, which shows that projected changes to temperature are relatively larger in comparison to historical variability than precipitation projections.

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[v] Based on the difference between the 10th and 90th percentiles for BC from the ensemble of 15 GCM projections following the A2 emissions scenario only.

[vi] Based on the difference between the ensemble averages for BC from the ensemble of 15 GCM projections following A2 and the ensemble of 15 GCM projections following B1.

[vii] Average of IPCC multi-model ensemble projections for B1 (1.29°C) and A2 (1.65°C) for the (2046-2065) anomaly from (1980-1999) model baseline.

Comparison to historical variability

Projected climate change in BC for the 21st century is shown using ensemble ranges for the 2020s, 2050s, and 2080s and the historical variability during the 20th century in **Figure 4.1.3**. Historical variability (horizontal blue bar) represents the difference between the warmest (wettest) years and the coldest (driest) years of the 20th century[viii]. Note that the ranges for the future periods are shown as the changes to the average (vertical blue bar), but that in future, climate variability will also take place and will be superimposed on projected changes.

The 2080s projected temperature for BC, +2.8°C (+1.5°C to +4.0°C) warmer than the baseline (**Table 4.1.4b**) is considerably warmer than the 2050s anomalies (**Table 4.1.1a**). The +2.8°C ensemble average projection is close to 20th century historical variability in BC (3.1°C). Therefore, projected annual temperature by the 2080s for an *average* year is warmer than all but the very *warmest* years in the historical record. Indeed, the projected 2080s climate is warmer than any climate that has existed in BC for several thousands of years[9].

The 2080s projected precipitation for BC is +10% (+6% to +17%) wetter than the baseline (**Table 4.1.4b**), which is within the range of observed historical precipitation variability (38%). Nevertheless, even small changes of annual precipitation could result in significant hydrological impacts when combined with projected warming and seasonal shifts in precipitation (section 5).

Uncertainties and Limitations

All GCMs suffer from limitations in their ability to simulate the baseline climate[10] (**Table 4.1.5**), which means that for most purposes, anomalies from the GCM baseline are considered more robust than the actual simulated climate itself because of the removal of systematic bias (over or underestimation present in both time periods). Thus, in order to describe the future climate, anomalies computed from GCM projections must be applied to historical observations of the baseline climate.

GCM projections may vary considerably over short periods of time or over a small number of grid boxes, even when the model baselines are removed. GCMs are designed to represent the average statistics of global climate, which has several implications:

- A given year in a GCM simulation is not directly comparable to the same historical year or the same year in another climate model.
- It is important to use results from as many GCMs as possible. Scatterplots such as those available at www.PacificClimate.org may be used to select GCMs with different impacts in the region of interest.
- Projected results should be averaged over many grid boxes (i.e. sub-continental or larger).
- Although statistics of daily GCM projections may be compared with the baseline, daily GCM results should not be used as simulations of day-to-day weather in impacts studies.

GCM results shown in this report are only changes to average quantities, and extremes have not been presented. However, practical decisions require information about occurrence of extremes. Analysis of probabilities of extremes on a continental scale shows a return period of only 7-10 years by the 2050s[ix] for what, in the 1990s, was a 20-year precipitation event[11]. This increase in extreme precipitation is larger than the projected global result (11.5 years return period).

In addition, the impacts described here have been provided without an investigation of the meteorological conditions simulated by GCMs that accompany them. As climate change occurs in BC, systematic changes to the storm track of westerly winds that determine much of BC's weather are expected: IPCC AR4 projections generally feature a more intense Aleutian low shifted to the north[12]. The Canadian GCM appears to have a modest capability to reproduce weather patterns in the region and this could be examined in more detail[13].

[viii] As indicated by ±two standard deviations from the 1895-2003 historical average (~96% of all years).

[ix] 2050s in this case indicates 2046-2065 average

Finally, GCM uncertainties are considerable. The range of projections available from an ensemble of multiple GCMs provides useful information about this uncertainty. As climate models are improved, the level of uncertainty is reduced. However, uncertainty will always remain because the climate system is inherently non-linear.

Gaps

- For impacts analysis, improvements to GCM simulated baseline climates and inclusion of land-surface and greenhouse gas feedbacks are required.
- A very large number of projections are needed to determine regional probabilistic scenarios of changes to average quantities, extreme events[14], and of uncertainty.
- Improved relevance to decision making requires analysis of seasonal results as well as other variables beyond temperature and precipitation.
- An investigation of systematic changes to frequency of occurrence of weather patterns[15] is required to provide an in-depth understanding of projected impacts.
- Improved projections of impacts may be found by development of Earth System Climate Models (ESCMs). These models generally have a simplified representation of some parts of the climate system but do contain some climate components that allow impacts to be simulated directly. ESCMs are also useful when a large number of simulations are needed, because their computing requirements are often relatively modest.

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[1] Carter, T.R., Hulme, M. and Lal, M., 1999. Guidelines on the use of scenario data for climate impact and adaptation assessment, Task Group on Scenarios for Climate Impact Assessment, Intergovernmental Panel on Climate Change.
[2] Cleveland, W.S. 1979. Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association, 74: 368.
[3] Barrow E., Maxwell, B. and Gachon, P. (Editors), 2004. Climate Variability and Change in Canada: Past, Present and Future, ACSD Science Assessment Series No. 2. Meteorological Service of Canada, Environment Canada, Toronto, ON, 114 pp.
[4] Mote, P., Salathe, E. and Peacock, C., 2005a. Scenarios of future climate for the Pacific Northwest, Climate Impacts Group Report, University of Washington.
[5] Salathe, E.P., Mote, P.W. and Wiley, M.W., in press (2007). Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest. International Journal of Climatology.
[6] Christensen, J.H. et al., 2007. Regional Climate Projections. In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
[7] Ibid.
[8] Ibid.
[9] Hebda, R.J., 1995. British Columbia vegetation and climate history with focus on 6 KA BP. . Geographie Physique et Quaternaire, 49: 55-79.
[10] Bonsal, B., Prowse, T. and Pietroniro, A., 2002. An assessment of Global Climate Model-simulated climate for the Western Cordillera of Canada (1961-90). Hydrological Processes, 17(18): 3703 – 3716.
[11] Kharin, V.V., Zwiers, F.W., Zhang, X. and Hegerl, G.C., 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of Global Coupled Model simulations. Journal of Climate, 20: 1419-1444.
[12] Christensen, J.H. et al., 2007. Regional Climate Projections. In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
[13] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.

[14] Goodess, C.M., Osborn, T.J. and Hulme, M., 2003. The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events, Tyndall Centre for Climate Change Research, Norwich, UK.

[15] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.

Figures and Tables

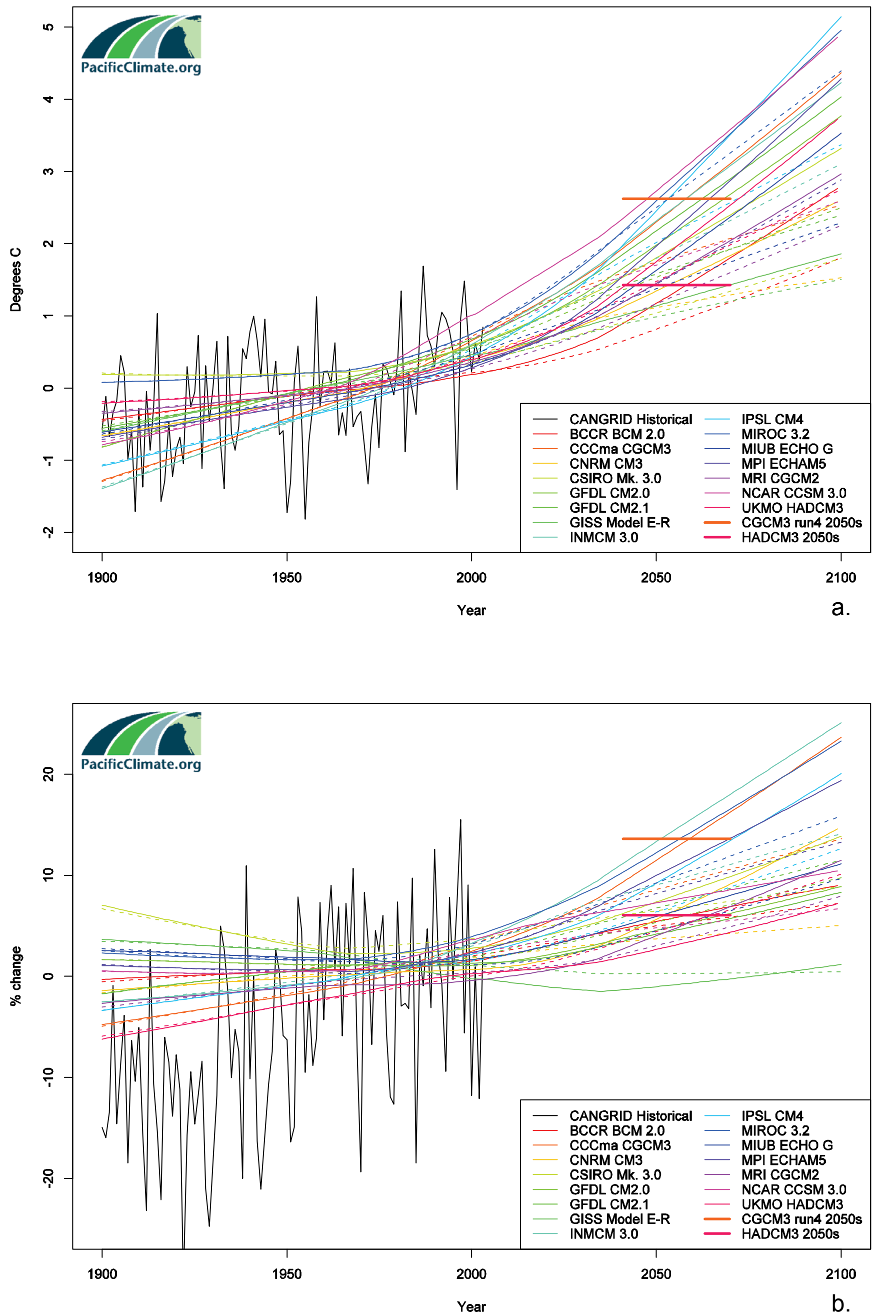

Figure 4.1.1 – Time series (1900-2100) of Global Climate Model (BC average) anomalies from ensemble (15 GCMs following each of B1 and A2) (a) annual mean temperature (b) annual precipitation. Results are smoothed in time using LOESS[1]. CANGRID historical data (black line) is shown for comparison to (1961-1990) bias-corrected GCM results. Thick horizontal lines show 2050s (2041-2070) averages for CGCM3 A2 (run 4) and HadCM2 B1. GCM projections follow A2 (solid) and B1 (dashed) lines. Source: Lawrence Livermore National Laboratory (LLNL) data prepared for IPCC AR4 by several international climate modelling centres.

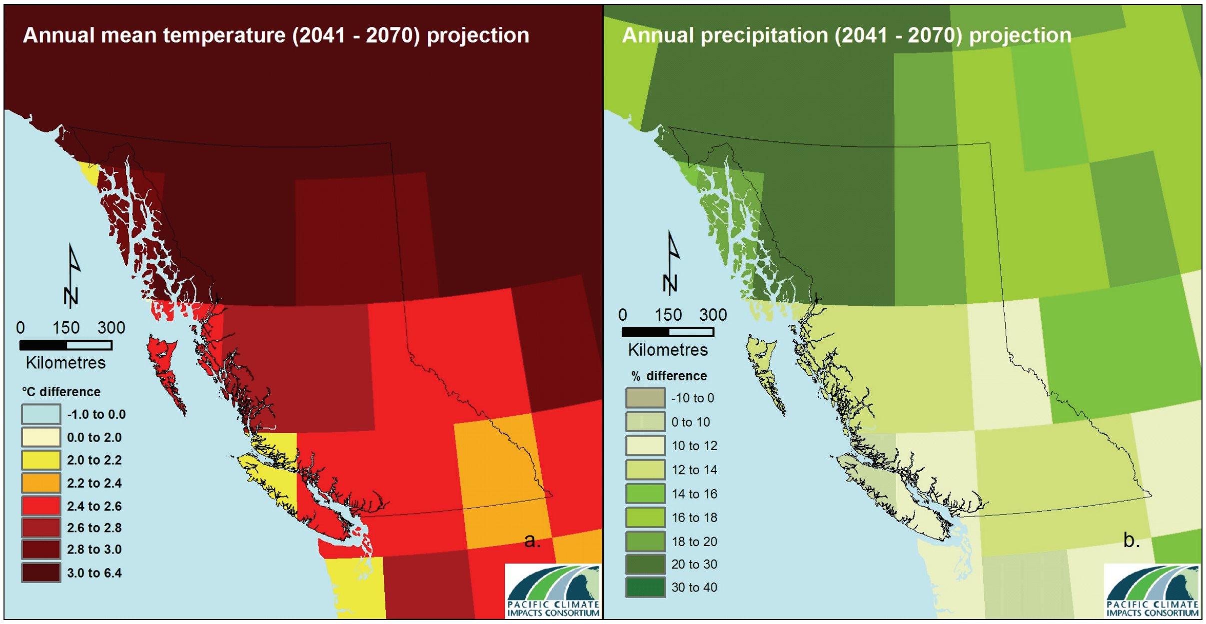

Figure 4.1.2 –2050s (2041-2070) climate projections from CGCM3 following A2 emissions scenario for (a) annual mean temperature, and (b) annual precipitation. Source: LLNL (IPCC AR4) data.

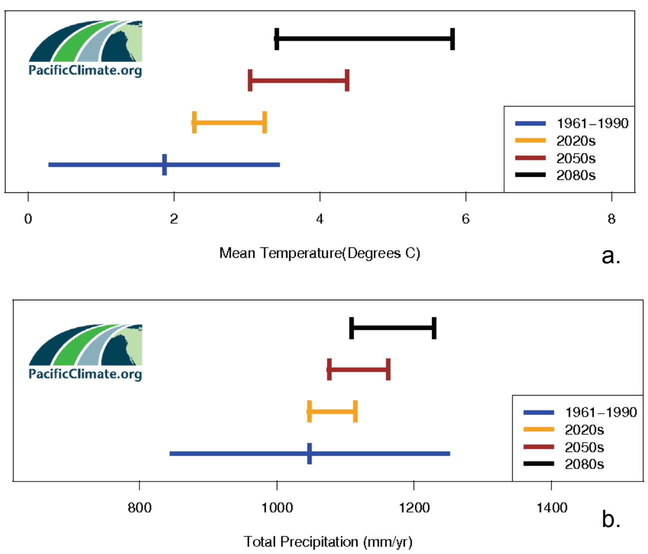

Figure 4.1.3 – Range of Global Climate Model (BC average) anomalies (2020s, 2050s, and 2080s) from ensemble (15 GCMs following each of B1 and A2) (a) annual mean temperature (b) annual precipitation. The vertical and horizontal blue lines show BC (1961-1990) climatology and (1895-2003) variability (two standard deviations over the historical period), respectively. The area between each bar represents range in BC average anomaly only (future variability not shown). Source: based on similar figure for US PNW by University of Washington[2]; modified for BC using LLNL (IPCC AR4) data.

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[1] Cleveland, W.S. 1979. Robust locally weighted regression and smoothing scatterplots, Journal of the American Statistical Association 74: 368.
[2] Kay, J., J. Casola, and A. Snover, A. Regional climate change primer, Climate Impacts Group, University of Washington. 1 pp.

Measure (from ensemble)	Temperature anomaly (°C)			Precipitation anomaly (%)		
	Winter	Summer	Annual	Winter	Summer	Annual
10th percentile	0.5	1.2	1.2	-2	-9	3
Average	***1.9***	***1.8***	***1.7***	***7***	***-3***	***6***
Median	1.9	1.8	1.7	8	-1	6
90th Percentile	2.7	2.7	2.5	15	2	11

Table 4.1.1a – BC 2050s (2041-2070) ensemble average anomalies from the 1961-1990 baseline (15 GCMs following each of B1 and A2). Source: LLNL (IPCC AR4) data.

Region	Temperature anomaly (°C)			Precipitation anomaly (%)		
	Winter	Summer	Annual	Winter	Summer	Annual
Columbia Basin	1.8	2.4	1.9	7	-8	4
Peace Basin	1.9	2.0	1.8	8	-4	7
North Coast	1.5	1.4	1.4	6	-8	6
North East Interior	2.4	1.8	1.9	9	3	7
Northwest	2.0	1.8	1.8	10	4	8
Okanagan	2.0	2.6	2.1	5	-8	5
South Coast	1.5	1.7	1.5	6	-13	6
BC	***1.9***	***1.8***	***1.7***	***7***	***-3***	***6***

Table 4.1.1b – Regional 2050s (2041-2070) ensemble average anomalies from the 1961-1990 baseline (15 GCMs following each of B1 and A2). See Figure 1.1.1 for region locations. Source: LLNL (IPCC AR4) data.

Projection (run #)	Temperature anomaly (°C)			Precipitation anomaly (%)		
	Winter	Summer	Annual	Winter	Summer	Annual
1	3.0	2.0	2.3	15	2	11
2	3.1	2.5	2.5	17	7	15
3	3.1	2.3	2.3	13	6	15
4	***3.2***	***2.2***	***2.6***	***15***	***6***	***14***
5	4.0	2.2	2.5	29	3	16
Average	3.3	2.2	2.4	18	5	14
Run 1-4 range (max-min)	0.2	0.5	0.3	4	5	4
Range (max-min)	1.0	0.5	0.3	16	5	5

Table 4.1.2 – BC 2050s (2041-2070) anomalies from the 1961-1990 baseline for 5 CGCM3 runs following A2. Run 1 is used in ensembles (section 4.1). Run 4 is used for single GCM results in section 4.1 and to force downscaling results (section 4.2, 4.3). Source: LLNL (IPCC AR4) data.

Emissions Scenario	Min	10th percentile	25th percentile	Average	50th percentile (median)	75th percentile	90th percentile	Max
B1	0.6	1.2	1.3	1.6	1.6	1.8	2.1	2.9
A1B	1.3	1.3	1.5	2.0	2.1	2.5	2.8	3.1
A2	1.0	1.2	1.5	1.9	1.9	2.3	2.5	2.6
B1,A2	***0.6***	***1.2***	***1.4***	***1.7***	***1.7***	***2.0***	***2.5***	***2.9***
B1,A1B,A2	0.6	1.3	1.4	1.8	1.8	2.2	2.6	3.1

Table 4.1.3a – BC 2050s (2041-2070) annual temperature anomalies (°C) from the 1961-1990 baseline. Range from 15 GCMs for each of 1, 2, or 3 emissions scenarios. Min = minimum, max = maximum. Source: LLNL (IPCC AR4) data.

Emissions Scenario	Min	10th percentile	25th percentile	Average	50th percentile (median)	75th percentile	90th percentile	Max
B1	1.3	1.4	1.8	2.2	2.0	2.5	2.8	3.9
A1B	1.4	2.0	2.5	3.0	3.2	3.4	3.9	4.6
A2	1.5	2.5	2.8	3.4	3.4	3.8	4.5	4.5
B1,A2	***1.3***	***1.5***	***2.0***	***2.8***	***2.6***	***3.6***	***4.0***	***4.5***
B1,A1B,A2	1.3	1.6	2.1	2.8	2.8	3.4	4.0	4.6

Table 4.1.3b – BC 2080s (2071-2100) annual temperature anomalies (°C) from the 1961-1990 baseline. Range from 15 GCMs for each of 1, 2, or 3 emissions scenarios. Min = minimum, max = maximum. Source: LLNL (IPCC AR4) data.

Geo-graphical Area	Min	10th percentile	25th percentile	Average	50th percentile (median)	75th percentile	90th percentile	Max
BC	1.4	2.0	2.5	3.0	3.0	3.5	4.0	4.8
Western North America	2.1	n/a	2.9	n/a	3.4	4.1	n/a	5.7
Globe	n/a	n/a	1.7	n/a	n/a	4.4	n/a	n/a

Table 4.1.4a – BC, Western North America and Global (2090-2099) annual temperature anomalies (°C) from the 1980-1999 baseline following A1B. BC range based on ensemble of 15 GCMs, regional and global range based on ensemble of 21 GCMs and other models. Min = minimum, max = maximum. Source: LLNL (IPCC AR4) data (BC range), IPCC AR4 Working Group 1 Technical Report Chapters 10 and 11 (global and regional ranges).

Measure (from ensemble)	Temperature anomaly (°C)			Precipitation anomaly (%)		
	Winter	Summer	Annual	Winter	Summer	Annual
10th percentile	1.5	1.7	1.5	4	-13	6
Average	***3.0***	***2.9***	***2.8***	***13***	***-3***	***10***
Median	2.8	2.9	2.6	12	0	9
90th percentile	4.9	4.5	4.0	22	5	17

Table 4.1.4b – BC 2080s (2071-2100) ensemble average anomalies from the 1961-1990 baseline (15 GCMs following each of B1 and A2). Source: LLNL (IPCC AR4) data.

Time period	Ensemble average temperature (°C)			Ensemble average precipitation (mm)		
	Winter	Summer	Annual	Winter	Summer	Annual
1961-1990	-6.9	10.3	1.4	409	227	1320
1980-1999	-6.6	10.4	1.6	414	228	1337
2041-2070	-5.0	12.1	3.1	439	222	1404
2071-2100	-3.9	13.1	4.1	460	220	1456
2090-2099	-3.6	13.4	4.4	464	220	1474

Table 4.1.5a – Ensemble average (15 GCMs following each of B1 and A2) temperature and precipitation for several time periods. Averaged over BC. Source: LLNL (IPCC AR4) data.

Time period	Observed temperature (°C)			Observed precipitation (mm)		
	Winter	Summer	Annual	Winter	Summer	Annual
1961-1990	-8.8	12.1	1.9	330	196	1048
1980-1999	-7.9	12.3	2.4	325	208	1064

Table 4.1.5b – Observed average temperature and precipitation for two time periods. Averaged over BC. Source: Environment Canada data (CANGRID).

4.2. RCM projections

Dynamical downscaling with an RCM introduces a more realistic representation of elevation and land surface characteristics to GCM projections (**Figure 4.0.1**). Projections from the latest version of the Canadian Regional Climate Model (CRCM4[i]) are presented for BC and surrounding areas at higher resolution (45 km) than the GCM projection (approximately 350 km)[1]. In addition to average projected anomalies over BC, a *geographical* range was computed to show how RCM projections vary across BC. This is the first publication of CRCM4 results for BC.

Throughout section 4.2, unless otherwise indicated: (i) anomalies have been averaged in time for 2050s (2041-2070 difference from model 1961-1990 baseline) and in space for all grid boxes within BC, and (ii) ranges in brackets following anomalies are the 10th to 90th percentiles for multiple grid boxes within BC. This range illustrates how much projected anomalies vary throughout BC for the single RCM projection. Therefore the geographical range illustrates a different result than the ensemble range from multiple GCMs (section 4.1). See information boxes in section 4 for conventions and definitions.

Results

- A single projection of annual temperature and precipitation in the 2050s from the Canadian RCM following the A2 emissions scenario is +2.6°C warmer and +13% wetter than the baseline for BC[ii]. Projected warming is greater in the central interior, over the Rocky Mountains, and in the north (**Figure 4.2.1a**). Central BC and the north show the largest relative increases in precipitation.
- *Winter* and *summer* projections of *temperature* are +3.3°C and +2.3°C warmer than the baseline. In particular, winter warming is greater than summer warming at most locations in central and northern BC (**Figure 4.2.2**). Relative to the rest of BC, summer warming is greatest over most of the Coast Mountains.
- *Winter* and *summer* projections of *precipitation* are +14% and +10% wetter than the baseline. The winter anomaly is slightly wetter than the summer anomaly at most locations, and the summer projection is drier than the baseline at several locations in the eastern Rockies and South Coast, and Washington State (**Figure 4.2.3**).
- The *uncertainty* in an RCM projection depends in part upon selection of a single forcing GCM and emissions scenario. The RCM may reduce some sources of bias and errors compared to its forcing GCM and introduce new ones. In place of an estimate of RCM uncertainty, the estimate of GCM uncertainty for the A2 emissions scenario may be used (1.3°C for temperature and 10% of the baseline for precipitation).

Discussion

Dynamical downscaling using a Regional Climate Model improves the representation of elevation (**Figure 4.0.1**) and also includes physical and dynamical processes as well as land surface characteristics at a higher resolution. RCMs provide the most physically consistent form of downscaling.

Like GCMs, RCMs include significant sources of uncertainty. Fewer RCM runs are available than GCM runs, partly because of the larger computational demands of RCMs. This section presents results from a single RCM. It is preferable to perform analysis of future climate with multiple projections. Additional RCM projections exist for BC and an ensemble of RCM results for BC is in preparation.

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[i] The Canadian Regional Climate Model version 4.1.1 (CRCM4) was developed by the Ouranos Consortium in collaboration with the Canadian Centre for Climate Modelling and Analysis (Environment Canada). CRCM4 data were provided by the Ouranos Climate Simulations Team for runs 'acs' and 'act' forced with CGCM3 following the A2 emissions scenario run 4.

[ii] Ensemble average anomalies from CRCM4 have been averaged in time for the 2050s (2041-2070 difference from 1961-1990 model baseline) and in space for all grid boxes within BC.

Cautious interpretation and consideration of uncertainty (estimated using the ensemble of GCMs in section 4.1) is discussed below.

The RCM projection used in this section is forced by boundary conditions at the edges of its domain (North America) by the approximately 350 km resolution projection from the Canadian Global Climate Model (CGCM3[iii]) following the A2 emissions scenario (run 4). Comparison of **Figure 4.2.1** to **Figure 4.1.2** illustrates the influence of higher resolution.

The RCM 2050s BC annual temperature anomaly is +2.6°C (+2.0°C to +3.0°C) warmer than the baseline (**Figure 4.2.1a**). In general, warm anomalies become progressively larger from the south to the north and inland compared to the coast. Thus the largest anomalies are generally in the northern areas that are exposed to a continental influence. The Northwest and the Alaskan panhandle, however, exhibit warmer anomalies than areas east of the coast. Projected anomalies over the southern Rockies are also warmer than the surrounding areas. The RCM projection exhibits considerably more geographical variability in the anomalies than the forcing GCM projection (**Figure 4.1.2a**).

The RCM 2050s annual precipitation anomaly is +13% (+9% to +20%) wetter than the baseline (**Figure 4.2.1**). Although interpretation of the precipitation anomalies at specific locations requires careful consideration of uncertainty as described below, a pattern is apparent of wetter projections for the Northwest, North Coast, Peace Basin, Fraser Plateau, and Okanagan. The regional differences in precipitation between the RCM (**Figure 4.2.1b, 4.2.3**) and the GCM (**Figure 4.1.2b**) are consistent with the improved representation of mountain ranges in the RCM. For example, the RCM accurately depicts how the prevailing westerly winds in BC deposit precipitation on the leeward sides of mountains.

The geographical range (of individual grid box anomalies across BC) is +3.3°C (+2.0°C to +4.2°C) warmer in winter and +2.3°C (+1.8°C to +2.8°C) warmer than the baseline in summer. The seasonal maps (**Figure 4.2.2**) are less detailed than the annual maps (**Figure 4.2.1a**), in part because the legends of the seasonal maps have larger intervals in order to show the large warming projected for winter. Progressively warmer winter temperature anomalies are apparent from south to north, similar to the annual temperature. Summer temperature anomalies range from +2°C to +3°C for almost the entire region, except for parts of the Coastal Mountains, which exhibit warmer summer anomalies.

Winter precipitation projections are +14% (+7% to +27%) wetter than the baseline and summer precipitation projections are +10% (+3% to +21%) wetter than the baseline (**Figure 4.2.3**). Winter precipitation projections follow a very similar pattern to the annual precipitation projections (**Figure 4.2.1b**), as expected in BC where much of the annual precipitation arrives in the winter. Drier summers are projected in the eastern Columbia Basin, Alberta Rocky Mountains, and much of Washington State (**Figure 4.2.3b**).

The regional patterns and differences in annual and seasonal projections discussed above may be considered more robust than those from the GCM itself (**Figure 4.1.2**). In addition, the 1961-1990 baseline climate for BC is better simulated by the RCM than the GCM (not shown). In general, an RCM better represents the snow-albedo feedback[iv] compared to its forcing GCM, which can result in warmer RCM projections[2]. In this case, the annual RCM anomalies are identical for temperature and within 1% for precipitation (**Table 4.2.1**) compared to the forcing GCM projection.

In the absence of an analysis using an ensemble of results from multiple RCM projections, it is important to compare the RCM projections to the ensemble of GCM results and to estimates of uncertainty. The RCM 2050s projections are +0.8°C warmer and +7% wetter than the ensemble average of 30 GCM projections over BC (**Table 4.2.1**). The difference between the RCM and the ensemble average is primarily due to the differences in the forcing GCM compared to the ensemble average (section 4.1).

Comparison of the estimates of GCM uncertainty (+1.3°C and +10%; section 4.1) to the projected RCM anomalies shows that although GCM uncertainty could shift temperature anomalies in **Figure**

[iii] The Canadian Global Climate Model version 3 (CGCM3) was developed by the Canadian Centre for Climate Modelling and Analysis (Environment Canada).

[iv] Warming feedback at high elevation locations that lose snow cover and absorb more heat

4.2.1a and **4.2.2** by almost a full category, all projections for 2050s are warming (**Figure 4.1.1**). However, many of the precipitation anomalies are less than +10% (**Figure 4.2.1b**, **4.2.3**), and equal to or less than the 2050s GCM projections' uncertainty. In locations where the projected anomaly is close to the uncertainty, the direction of change (wetter or drier) is relatively uncertain. For example, this is the case in the South Coast and Columbia Basin regions for annual, winter and summer precipitation as well as the Okanagan and Peace Basin for summer precipitation.

Furthermore, the amount of precipitation that occurs in BC is largely dependent on Pacific storm tracks[3]. There is some evidence that Pacific storm tracks have not always behaved such as they have in the recent past. Paleo-climate evidence (since 1750) for southeastern BC suggests that the historical climatology for summer precipitation in this region may have a wet bias[4]. The RCM projections are also wetter than the ensemble range, therefore increased periods of summer drought may be more likely than indicated by the small (and mostly wetter than baseline) RCM projected summer precipitation anomalies.

Some RCMs project changes to temperature and precipitation extremes in the US Pacific Northwest[5]. Results include more frequent occurrences of extreme heat, less frequent extreme cold, and increased extreme winter precipitation (even despite decreased mean precipitation in some cases), increased rain-on-snow events, and more severe flooding[6].

Uncertainties and Limitations

In general, RCM projections have not been extensively compared to those from GCMs and other RCMs, partly due to the relatively higher computational costs involved in running RCMs. One initiative, NARCCAP, is underway to generate an ensemble of RCM results forced by different GCMs for North America[7]. Comparisons of RCM results to each other, to GCM projections and to observations have been completed for CRCM3[8,9] (as described in Uncertainties and Limitations, section 5.1). However, the CRCM version used here (4.1.1) has yet to be documented in the peer-reviewed literature and results may be different between this version and those published using version 3.6 and 3.7[10].

The major difference between CRCM4 and older versions is that it incorporates land surface cover, but other improvements have also been made. The land surface scheme (CLASS) is expected to improve surface exchanges of heat, moisture and momentum in particular. However, seasonal maps, BC average anomalies, and ranges shown in this report are all qualitatively consistent with temperature and precipitation projections from previous versions of the Canadian RCM[11]. Temperature anomalies are also of the same order as projections for the Western US of approximately +1°C to +4°C from four other RCMs[v,12].

In general, RCMs show several improvements over the use of GCMs alone[13,14,15]. However, even the resolution of CRCM4, which is a significant improvement on CGCM3 resolution (**Figure 4.0.1**), has been shown to represent the topography in BC too coarsely to fully capture the rainshadow effects that dominate precipitation patterns for impacts analysis, as illustrated by the low projected baseline Fraser River flow[16]. A 10 km resolution version of the Canadian RCM under development by Ouranos Consortium is expected to improve this result.

A comparison of projections from four RCMs over the Western United States found that differences in results between the RCMs were slightly larger than the level of uncertainty in observational estimates. The level of uncertainty was large enough to call into question the value of an individual projection for decision making[17].

Gaps

- Improved relevance to decision making requires analysis of regional and seasonal results as well as other variables beyond temperature and precipitation.
- Determining changes to frequency of occurrence of extremes and extreme events for the Pacific North America region requires comparison of RCM dynamical downscaling results to statistical downscaling of extremes[18,19,20].

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[v] From four RCMs driven by different GCMs and CO_2 forcing of 1.36-1.8 times present-day concentrations.

- An investigation of systematic changes to frequency of occurrence of weather patterns[21] is required in order to provide a more thorough understanding of projected impacts.
- RCM uncertainty is poorly understood due to the lack of extensive comparison to results for multiple experiments from other RCMs[22] and to other downscaling methods (section 4.3).

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[1] Caya, D. and Laprise, R., 1999. A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. Monthly Weather Review, 127: 341-362.
[2] Duffy, P.B. et al., 2006. Simulations of present and future climates in the Western United States with four nested Regional Climate Models. Journal of Climate, 19(6): 873–895.
[3] Palmer, T.N., 1999. A nonlinear dynamical perspective on climate prediction. Ibid., 12: 575-591.
[4] Gedalof, Z., Peterson, D.L. and Mantua, N.J., 2004. Columbia River flow and drought since 1750. Journal of the American Water Resources Association, 40: 1579-1592.
[5] Christensen, J.H. et al., 2007. Regional Climate Projections. In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
[6] Ibid.
[7] Gutowski, W., 2005. The North American Regional Climate Change Assessment Program (NARCCAP): A multiple AOGCM and RCM climate scenario project over North America. Geophysical Research Abstracts 7: 05975.
[8] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[9] de Elia, R. et al., submitted (2006). Evaluation of uncertainties in the CRCM-simulated North American climate: nesting-related issues. Climate Dynamics.
[10] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[11] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[12] Duffy, P.B. et al., Ibid.Simulations of present and future climates in the Western United States with four nested Regional Climate Models. (6): 873–895.
[13] Hanson, C.E., Palutikof, J.P., Dlugolecki, A. and Giannakopoulos, C., 2006. Bridging the gap between science and the stakeholder: The case of climate change research. Climate Research, 31(1): 121-133.
[14] Duffy, P.B. et al., 2006. Simulations of present and future climates in the Western United States with four nested Regional Climate Models. Journal of Climate, 19(6): 873–895.
[15] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[16] Ibid.
[17] Duffy, P.B. et al., 2006. Simulations of present and future climates in the Western United States with four nested Regional Climate Models. Journal of Climate, 19(6): 873–895.
[18] Gachon, P. et al., 2005. A first evaluation of the strength and weaknesses of statistical downscaling methods for simulating extremes over various regions of Eastern Canada.
[19] Goodess, C.M., Frei, C. and Schmidli, J., 2005. Temperature and precipitation extremes at the station and climate model grid-point scales: Some lessons learnt from the statistical and dynamical approaches to downscaling used in the STARDEX project. Geophysical Research Abstracts, 7: 03758.
[20] Nguyen V.T.V., T.D. Nguyen, and P. Gachon. 2006. On the linkage of large-scale climate variability with local characteristics of daily precipitation and temperature extremes: an evaluation of statistical downscaling methods. Advances in Geosciences, 4(16), 1-9.
[21] Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
[22] Gutowski, W., 2005. The North American Regional Climate Change Assessment Program (NARCCAP): A multiple AOGCM and RCM climate scenario project over North America. Geophysical Research Abstracts 7: 05975.

Figures and Tables

Model	Temperature anomaly (°C)			Precipitation anomaly (%)		
	Winter	Summer	Annual	Winter	Summer	Annual
GCM ensemble average for *A2 and B1 emissions scenarios combined*	1.9	1.8	1.7	7	-3	6
GCM ensemble average for *A2 emissions scenarios only*	2.0	2.0	1.9	7	-4	6
CGCM3 following *A2*, run 1	3.0	2.0	2.3	15	2	11
CGCM3 following *A2*, run 4	3.2	2.2	2.6	15	6	14
RCM (forced by *CGCM3* following *A2*, *run 4*)	3.3	2.3	2.6	14	10	13

Table 4.2.1 – BC average 2050s anomalies from the baseline – comparison of GCMs and RCM. Source: LLNL (IPCC AR4) data, Ouranos Consortium Climate Simulations Team data.

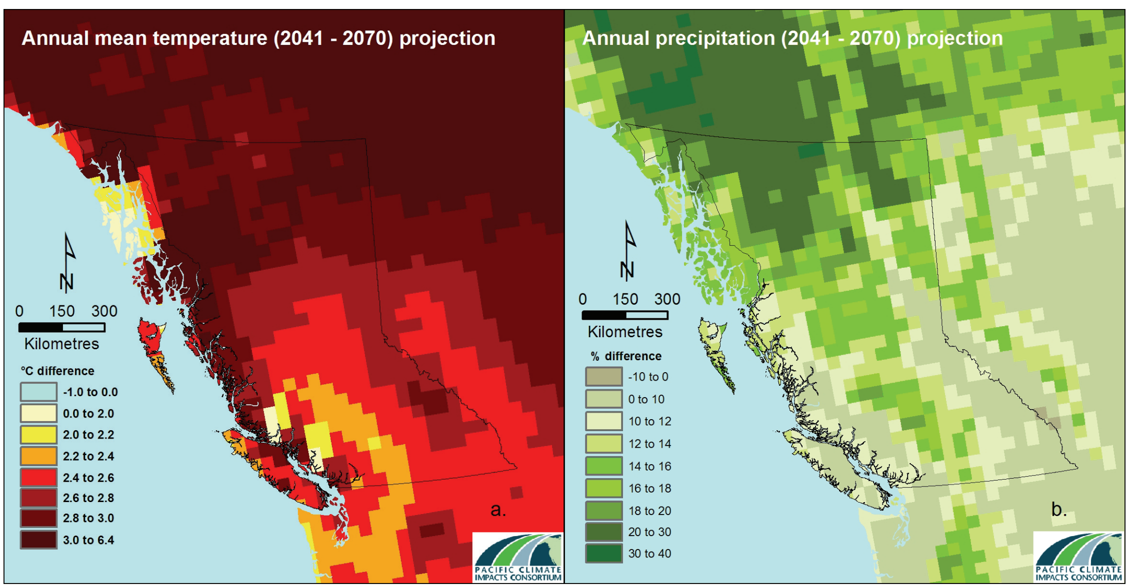

Figure 4.2.1 revised 2009 – 2050s (2041-2070) climate anomaly projections from CRCM4 forced with CGCM3 and A2 emissions scenario (a) annual mean temperature, and (b) annual precipitation. Source: Ouranos Consortium data.

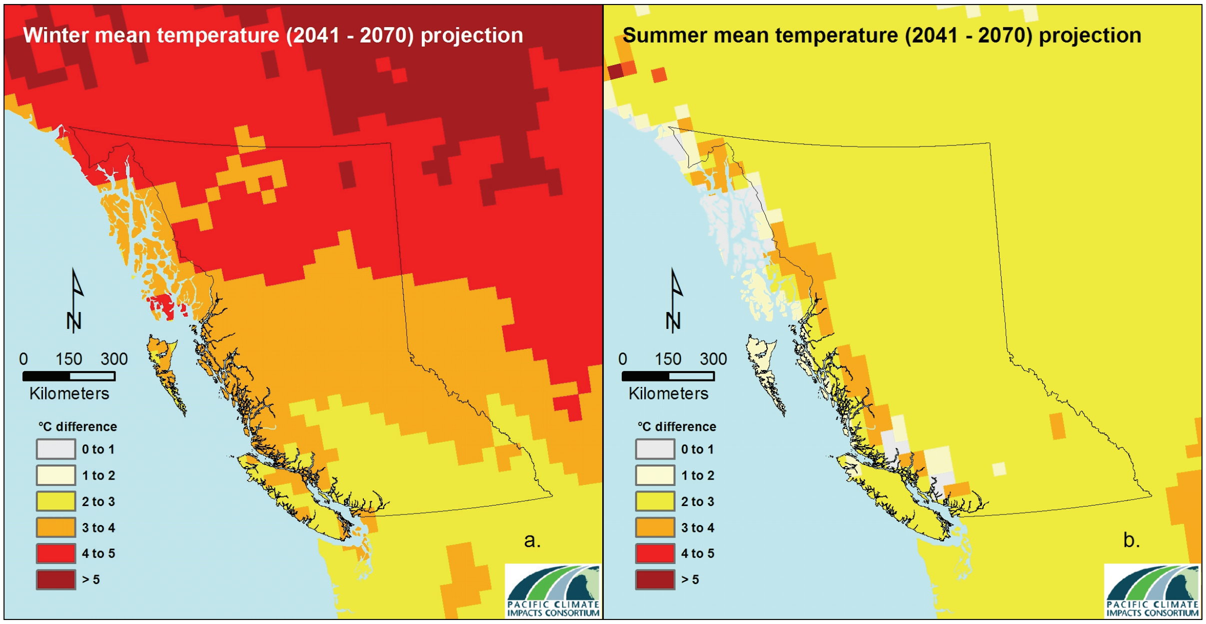

Figure 4.2.2 – BC 2050s (2041-2070) climate anomaly projections from CRCM4 forced with CGCM3 and A2 emissions scenario (a) winter mean temperature, and (b) summer mean temperature. Source: Ouranos Consortium data.

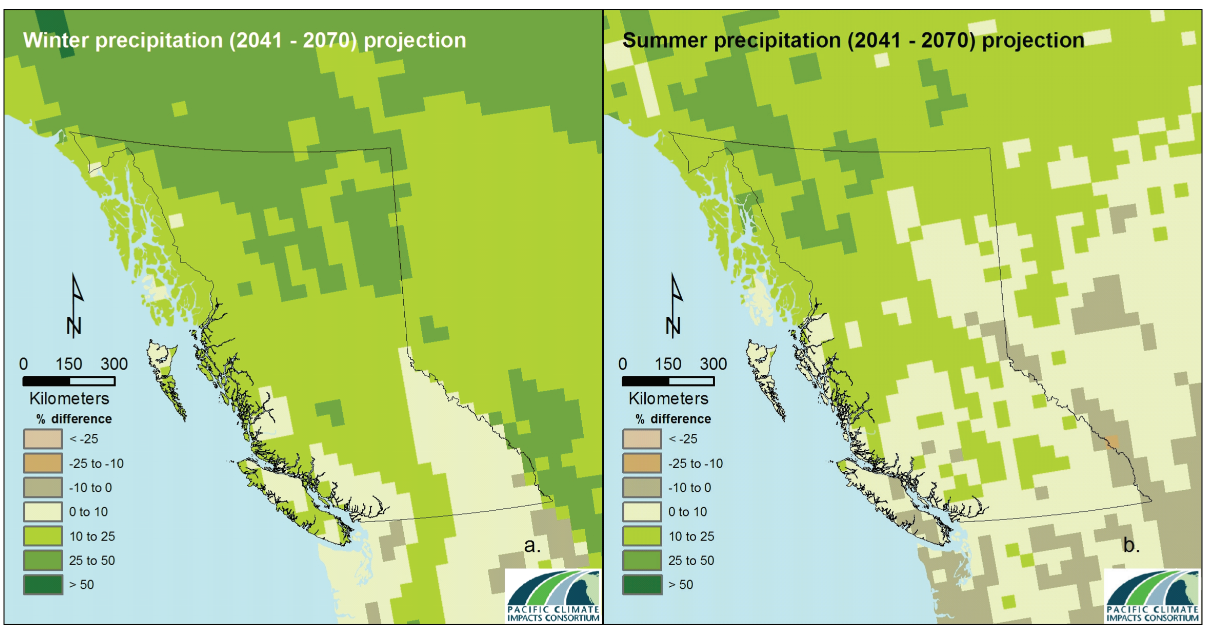

Figure 4.2.3 – BC 2050s (2041-2070) climate anomaly projections from CRCM4 forced with CGCM3 and A2 emissions scenario (a) winter precipitation, and (b) summer precipitation. Source: Ouranos Consortium data.

4.3. High definition climate projections

Future climate projections at high-resolution are needed to determine biological, physical, and socio-economic impacts[1] for informed decision making. Because of BC's complex topography, elevation has a large influence on local climate. Thus, spatial downscaling is particularly useful. High-resolution climate projections (4 km) were produced using empirical downscaling of a projection from the Canadian model (CGCM3) following the A2 emissions scenario by modifying the *ClimateBC*[2] downscaling tool. This is the first time that empirical downscaling has been conducted for BC using IPCC AR4 global climate model projections.

Results

- A high-definition projection of annual temperature in the 2050s illustrates warming compared to the 1961-1990 climatology (**Figure 1.1.1**, **4.3.1a**). This projection is derived from the Canadian GCM following the A2 emissions scenario. By the 2050s, the zero-degree isotherm is confined to higher elevations and smaller areas in the Rocky and Coast mountain ranges and it no longer remains in coastal and eastern areas of northern BC.
- Downscaled annual *precipitation* appears very similar to the 1961-1990 climatology (**Figure 1.1.2**, **4.3.1b**). However, maps of *total* precipitation mask percentage changes in the context of large geographical variability in the 1961-1990 precipitation climatology. In addition, GCM anomalies for *annual* precipitation are modest (**Figure 4.1.2**), particularly in comparison to historical variability (**Figure 4.1.3**). Nevertheless, even small changes of annual precipitation can have significant hydrological impacts in combination with projected warming and seasonal shifts in precipitation (section 5).
- The *precision* of the high-definition results may be misleading unless inherent uncertainty in *accuracy* is also recognized. Estimates of GCM uncertainty may be used in place of estimates of high-resolution downscaling uncertainty (1.3°C for temperature and 10% of the baseline for precipitation – section 4.1). A different single GCM and emissions scenario (HadCM3 and B1) also demonstrates noticeable differences in downscaled 2050s temperature (**Figure 4.3.2a**).

Discussion

The detailed topography of BC, absent at GCM and even RCM scales, becomes apparent at this scale (4 km) and is required for most decision making. However, these results are only useful as an illustration of a plausible future climate projection.

Before presenting empirical downscaling results, it should be noted that the finest scale of downscaling uses local (point) methods combined with historical climate station observations. Point downscaling is often the most relevant to decision making; the methods are relatively simple, can be applied to a range of projections, and may provide information on changes in extreme values. Point downscaling methods include statistical regression[3], weather generators, and a novel approach being developed in BC that combines the strengths of different methods (TreeGen)[4]. Results from point downscaling applications have only been applied at a few locations in BC and are not presented in this report.

Empirical downscaling uses elevation and aspect to adjust GCM projections. Elevation and aspect have an important influence on the local climatology throughout BC (section 1). Therefore, empirical downscaling has been used widely, for example it has been used in educational kiosks as part of the permanent climate change exhibit in the Royal BC Museum[5] and forms the basis for the *ClimateBC* downscaling tool, which itself has been used to study impacts such as ecosystem classifications and tree species in BC[6].

The *ClimateBC* downscaling tool was used in this report to produce the 2050s projections (**Figure 4.3.1, 4.3.2**). Smoothed low-resolution GCM climate anomalies are applied to the PRISM[i] high-resolution (4 km) 1961-1990 climatology[7]. Unlike the climate anomaly projections in section 4.1 and 4.2, these maps show temperature and precipitation in absolute terms, rather than anomalies. The advantage of this method is that it utilized the high-resolution representation of the historical climatology.

The individual high-resolution temperature projection using CGCM3 following the A2 emissions scenario is shown in **Figure 4.3.1a**. The changes between the historical temperature (1961-1990 climatology) and the projected future temperature can be illustrated at high-resolution using a line of constant temperature (an isotherm). The zero-degree isotherm, described and shown earlier in the report (section 1), is also shown for the future projections (**Figure 4.3.1, 4.3.2**). The 2050s zero-degree isotherm remains only at higher elevations (and is almost gone) in the mountain ranges of the South Coast and Columbia Basin. The 2050s zero-degree isotherm also remains only at higher elevations in the Northwest, while in the eastern portion of the Peace Basin the 2050s zero-degree isotherm is almost absent.

As presented in section 1, there is a large geographical contrast in annual precipitation throughout BC, even over small distances (**Figure 1.1.2**). Thus, the precipitation maps created using two different GCMs appear virtually identical to each other and to the historical climatology (**Figure 1.1.2, 4.3.1b**, **4.3.2b**). This comparison masks projected 2050s relative (percent) changes to annual precipitation.

Annually, BC's projected average annual precipitation increase from CGCM3 following A2 is +14%, only slightly larger than GCM precipitation uncertainty of 10% (section 4.1). In the eastern portion of the Peace Basin, however, the percent annual precipitation increases are larger (**Figure 4.1.2b**), and a wetter 2050s is noticeable there (**Figure 4.3.1b**).

Seasonal changes to precipitation as percent anomalies during winter and summer can differ considerably from annual (**Table 4.1.1b**). Other researchers have used a downscaled seasonal projection from CGCM2 following the A2 emissions scenario to show that October to March precipitation is projected to decrease in the southern half of BC while increased precipitation is projected for October to March in northern BC and for April to September Province-wide[8].

These results demonstrate the value of empirical downscaling, but must be used with caution since they are from an individual projection. Although comprehensive quantitative estimates of uncertainty are not available for these high-resolution maps, there are two ways of examining the uncertainty in these projections.

First, downscaled maps were generated from the HadCM3[ii] climate model following the B1 emissions scenario (**Figure 4.3.2**). These maps show differences from CGCM3 following the A2 emissions scenario (**Figure 4.3.1**). Comparison of downscaled temperature projections shows visible temperature differences at many locations across all regions of BC (**Figure 4.3.1a, 4.3.2a**). At a given location the change is different by up to a full category (see legend). Although annual total precipitation projections between the two do not *appear* to vary considerably, this result does not suggest confidence in precipitation projections. Rather, it indicates that the magnitude of the annual precipitation projections is small *in comparison to* the geographical variability of precipitation (as discussed above). Furthermore, the possible effect of even small changes in amount of precipitation, when combined with changes to timing and temperature could have significant impacts on snowfall and streamflow (section 5).

Additionally, estimates of GCM uncertainty may be obtained from the ensemble range of 15 GCMs following the A2 emissions scenario (section 4.1). The uncertainties for 2050s BC are 1.3°C for temperature and 10% for precipitation. These estimates are only indicative of the magnitude of uncertainty. They are not "error bars" for individual anomalies, which would be estimated using sensitivity analysis or probabilistic methods with a very large number of projections.

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[i] Parameter-elevation Regressions on Independent Slopes Model

[ii] United Kingdom's Hadley Centre for Climate Prediction and Research version 3

Applying High Definition Projections: Growing Degree Days

High definition projections of temperature can be converted directly into growing-degree-days (GDDs). The number of growing degree days (GDDs) has implications for agricultural production and for rates of evaporation and transpiration[9]. To obtain estimates of GDDs for BC, ClimateBC was employed to create a (4 km) projection of GDDs (5°C base) using the same CGCM3 projection (A2, run 4) used to force the RCM (section 4.2) and the high-definition temperature and precipitation projections in this section (**Figure 4.3.1**)[10].

In many areas of BC, an annual mean increase of 500 GDDs above the 1961-1990 baseline is projected (**Figure 4.3.3**). **Figure 4.3.4** shows projected GDDs in the Okanagan by the 2050s of 2500-3000, which is a +25% increase from the 1961-1990 period. Other researchers found a 51% increase in GDDs for the 2080s was estimated for the Okanagan basin at the Kelowna Airport, based on results from three runs of the CGCM1 model following the IS92a emissions scenario[11]. These estimates are roughly consistent with each other given that the projected temperature increase (+2.5°C) by the 2080s is larger than the projected increase (+1.7°C) for the 2050s (section 4).

GDDs projections to the 2050s illustrate potentially increased opportunities for crops (assuming water availability and soil suitability). Projected GDDs indicate possible expansion of growing conditions of the Fraser and Okanagan valleys into central BC and the Peace Basin. For example, projected 2050s GDDs in the Peace Basin are sufficient to grow canola, which ripens after 1041 accumulated GDDs[12]. Projected 2050s GDDs in the Fraser Valley are 2500-3000 (**Figure 4.3.4**). An increased survival rate of pests could also complicate future growing conditions for some crops[13].

The Okanagan Valley is one of only two areas in Canada that can sustain tender fruit and grape production[14] owing to mild winters with high snowfall, mild spring time temperatures, and long hot summers[15]. The Okanagan is already stressed for water supply to irrigate these crops[16], and precipitation in these areas is not projected to increase (section 4). Therefore an increase in growing season, land base or crop variety may be limited by the water supply. However, plant stomatal response to increased temperatures could lead to reduced transpiration and crop water requirements might be lower in future climates[17]. Regardless, irrigation requirements will change (timing and quantity) and considering these changes will be important to ensure water supply for crops.

Finally, a change in GDDs and therefore groundcover may also have important feedbacks to the physical climate system by changing the heat and moisture feedback at the surface and the water balance via plant transpiration and growth.

Uncertainties and Limitations

The precision of the high-definition results is misleading unless uncertainty from the coarse resolution GCM is taken into account. The GCM itself crudely represents BC's mountain ranges (**Figure 4.0.1**). Comparing **Figure 4.1.2** to **4.2.1** shows that the GCM anomalies considerably underestimate regional variability. Therefore, the value of an individual high-resolution projection on its own for decision-making is marginal. However, projections in this section illustrate the importance of local climatology and should be used in conjunction with results of the preceding sections. The RCM results show the regional distribution of 2050s climate change (section 4.2), and ensemble results (section 4.1) show the range of projected changes for BC using different GCMs and emissions scenarios.

Computation of high-resolution projections using different GCMs and emissions scenarios will provide different results. For example, high definition downscaled projections from an ensemble of GCM projections prepared for the IPCC Third Assessment (see section 4.1 for a description of this TAR ensemble) show a range of projections for temperature, precipitation, and selected impacts by using 10th percentile, median, and 90th percentile impacts[18].

Empirical downscaling also relies on historical station data that is sparse in some locations (section 1). This method can be used only for changes in average conditions[19] and historical relationships of climate parameters to elevation and aspect must be assumed constant in time. Finally, the process of empirical downscaling can reduce physical consistency between the parameters.

Gaps

- Downscaling of additional GCM projections are needed to illustrate uncertainty.
- Improved relevance to decision making requires analysis of seasonal results as well as variables beyond temperature and precipitation.
- Comprehensive comparisons of downscaling results to assess the relative strengths and weaknesses of different downscaling methods in Pacific North America have not been made.
- Combined methods have not been investigated, such as hydrological models forced by GCMs and empirical downscaling from RCMs.

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[1] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[2] Wang, T.L., Hamann, A., Spittlehouse, D.L. and Aitken, S.N., 2006. Development of scale-free climate data for Western Canada for use in resource management. International Journal of Climatology, 26: 383-397.
[3] Wilby R.L., C.W. Dawson, and E.M. Barrow. 2002. SDSM - a decision support tool for the assessment of regional climate change impacts, Environmental Modelling and Software, 17(2): 145-157.
[4] Cannon, A.J., in press (2007). Nonlinear Analog Predictor Analysis: a coupled neural network/analog model for climate downscaling. Neural Networks.
[5] Murdock, T.Q., R. Hebda, I.J. O'Connell. In prep (2007). High-resolution climatology downscaling for BC
[6] Hamann, A. and T. Wang. 2006, Potential effects of climate change on ecosystem and tree species distribution in British Columbia, Ecology, 87(11): 2773-2786.
[7] Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate, Climate Research, 22: 99-113.
[8] Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
[9] Bonsal, B.R., Zhang, X., Vincent, L.A. and Hogg, W.D., 2001b. Characteristics of daily and extreme temperatures over Canada. Journal of Climate, 14: 1959-1976.
[10] Wang, T.L., Hamann, A., Spittlehouse, D.L. and Aitken, S.N., 2006. Development of scale-free climate data for Western Canada for use in resource management. International Journal of Climatology, 26: 383-397.
[11] Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.
[12] Canola Development and Growing Degree Days (GDD) http://ndawn.ndsu.nodak.edu/help.html?topic=canolagdd-info North Dakota State University Accessed on May 16, 2007
[13] Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.
[14] Ibid.
[15] Ibid.
[16] Ibid.
[17] Shuttleworth, W.J., 2007. Putting the "vap" into evaporation. Hydrological Earth System Sciences, 11: 210-244.
[18] http://www.pacificclimate.org/impacts/rbcmuseum/
[19] Evans and Schreider. 2002. Hydrological Impacts of Climate Change on Inflows to Perth, Australia, Climatic Change, 55(3): 361-393.

Figures

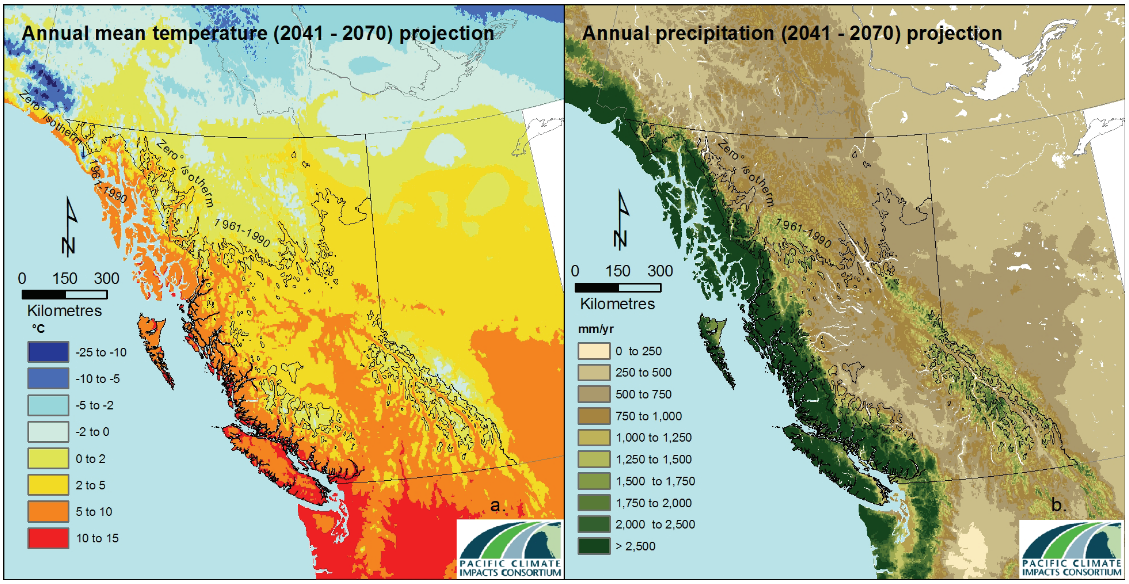

Figure 4.3.1 revised 2009 – 2050s (2041-2070) high-resolution climate projections using PRISM climatology delta-method using CGCM3 A2 emissions scenario (a) annual mean temperature, (b) annual precipitation. Source: LLNL (IPCC AR4) data, ClimateBC.

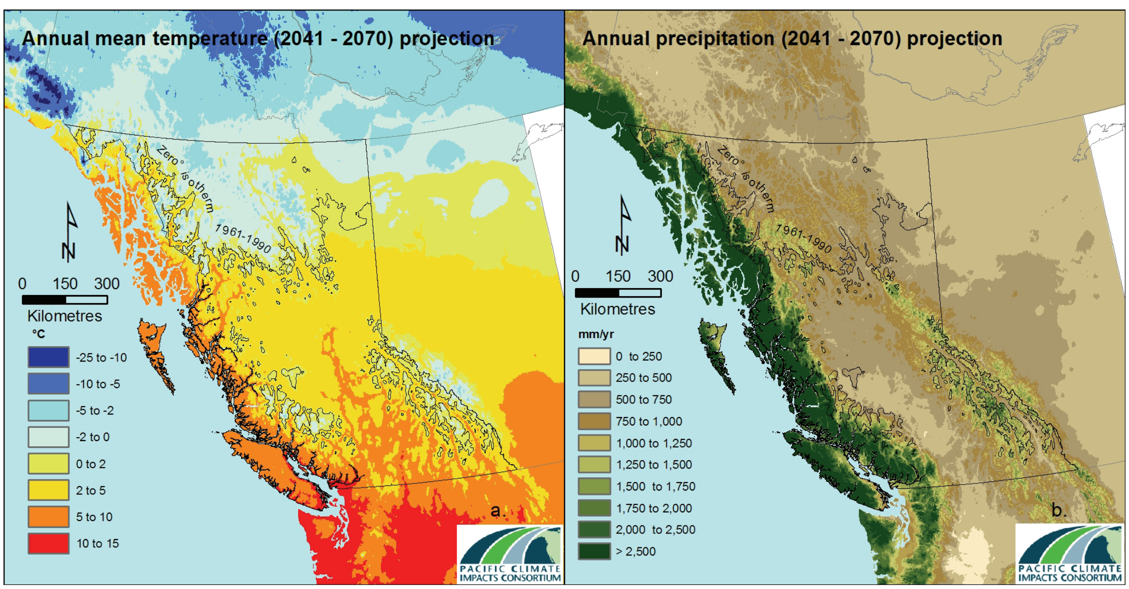

Figure 4.3.2 revised 2009 – 2050s (2041-2070) high-resolution climate projections using PRISM climatology delta-method using HadCM3 B1 emissions scenario (a) annual mean temperature, (b) annual precipitation. Source: LLNL (IPCC AR4) data, ClimateBC.

Figures: Growing Degree Days

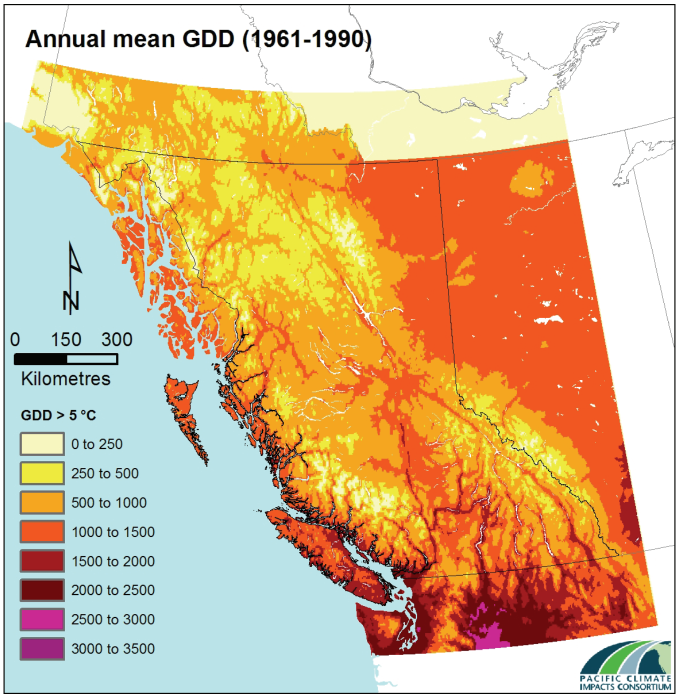

Figure 4.3.3 – 1961 – 1990 climatology of mean annual growing degree days (GDD) that are greater than 5°C using PRISM climatology. Source: PRISM data.

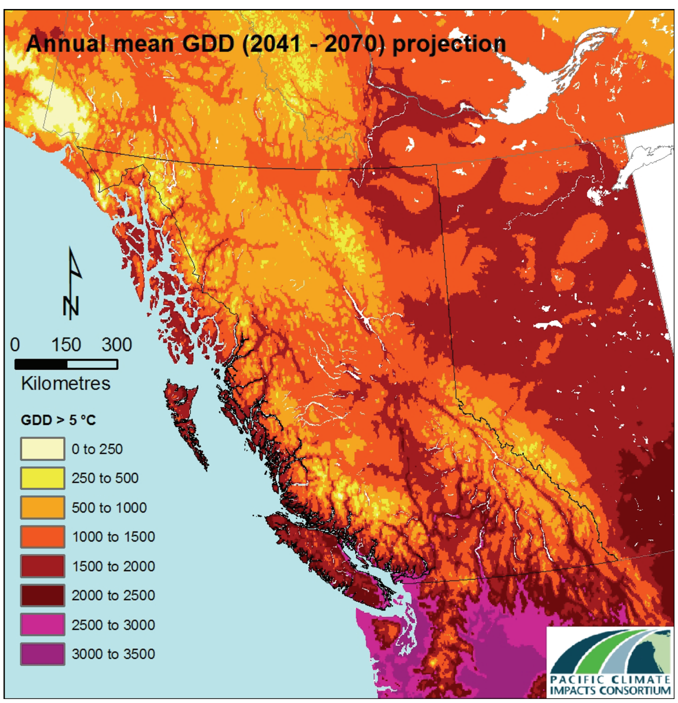

Figure 4.3.4 revised 2009 – 2050s (2041- 2070) high-resolution climate projection of mean annual growing degree days using downscaled temperature with PRISM climatology delta method with CGCM3 following A2 emissions scenario. Source: LLNL (IPCC AR4) data, ClimateBC.

5. Future climate – Hydrologic impacts

5.1. Response – Snowpack

Snowpack is a critical resource; it retains fresh water during winter and supplies streamflow to soils, lakes, and reservoirs during summer low-flow periods. Projected future changes to snowpack are presented for BC in this section. This is the first publication of future snowpack from version 4 of the Canadian Regional Climate Model (CRCM4) results for this region.

Results

- The Canadian Regional Climate Model (CRCM4[i]) projections of spring snowpack[ii] for BC show a decline by the 2050s (-200 kg/m^2, **Figure 5.1.1**). The effect is pronounced in the Coastal Mountain ranges (-500 kg/m^2).
- Relative changes in CRCM4 projections of spring snowpack (%) indicate declines (-18%) across most regions of BC (**Figure 5.1.2**), most notably along the North and South Coast (-56% and -54%. This result is roughly consistent with historical trends in spring snowpack (section 3.1) and projected temperature increases (section 4), however, some exceptions exist.
- A single estimate by one RCM is not sufficient to confidently determine projected future changes to snowpack. However, the results demonstrate that a combination of approaches (GCMs, statistical downscaling and multiple RCMs) are needed to provide reliable future estimates of changes to snowpack in BC.

Discussion

Spring snowpack is projected to decline by the Canadian Regional Climate Model (CRCM4) in various areas of the Province (on average -200 kg/m^2). Most notably in the South and North coastal regions declines are greater than -500 kg/m^2 and at high-elevation sites along the South Coast declines are greater than -1000 kg/m^2 (**Figure 5.1.1**). Relative changes in spring snow water equivalent are shown as a percentage difference between the CRCM4 1961-1990 baseline and the 2050s (2041-2070) projection (**Figure 5.1.2**). Percentage declines in spring snowpack are most prevalent along the North and South Coast (-56% and -54%, respectively).

Most of the largest decreases in snowpack occur in the mountainous regions of BC, but declines tend to be greater in the Coastal Mountains versus the Rocky Mountains. Some of these differences could be due to elevation, as the Rocky Mountain ranges are higher than the coast and changes in temperature at higher elevations are less than for lower-elevation sites around the Province (section 1, 2). Orographic effects may also be greater in the Rocky Mountain ranges compared to the Coast Mountains. Changes in snowpack in some parts of the Province are discussed in more detail below.

The projected declines in BC snowpack are consistent with other research findings. Localized 2050s decreases in the mountain ranges are projected by other researchers for the winter (December-January-February)[1]. Reductions in snow water equivalent were noted in the Fraser Basin, although model errors could account for a portion of the reduction[2]. The projected decreases were primarily caused by the change in snow-to-rain ratios occurring through December, which delayed snowfall into the later winter months and reduced annual snow water equivalent[3].

Projected CRCM4 precipitation was also shown to be higher on average than ensemble GCM results (section 4.1, **Table 4.2.1**). The spring CRCM4 precipitation estimates are similarly high in comparison to

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[i] The Canadian Regional Climate Model version 4.1.1 (CRCM4) was developed by the Ouranos Consortium in collaboration with the Canadian Centre for Climate Modelling and Analysis (Environment Canada). CRCM4 data were provided by the Ouranos Climate Simulations Team for runs 'acs' and 'act' forced with CGCM3 following the A2 emissions scenario run 4.

[ii] Provided as kg/m^2 difference (from the 1961 – 1990 baseline), which is almost equivalent to mm (SWE) as presented in section 3.1, assuming a 10:1 snow water equivalent ratio.

GCM results (not shown). An analysis of the relative influence of future temperature, snowfall, and rainfall changes on the projected snowpack decreases for BC has not been undertaken.

Increases in spring snowpack (+12%) are projected for the north. Although these increases are not directly comparable with the Arctic Climate Impact Assessment projection (2041-2060) of snow cover (extent) over the Northern Hemisphere[4] or the IPCC AR4[5] projections from CGCM3, the difference is consistent with the wetter CRCM4 precipitation projection (7% wetter than the ensemble average of 30 GCM projections) over BC (section 4.2, **Table 4.2.1**).

Changes to snow water equivalent in the Columbia Basin were examined using a hydrologic model (VIC, section 5.2)[6]. The modelled results illustrate significant declines in Columbia Basin snowpack by the 2050s associated with projected warming rather than changes in precipitation volume[7]. The observed reduction in spring snow lowers effective basin storage that can jeopardize the consistent supply of summer streamflow during the summer low-flow period. Reductions are due to mid-winter melting events and the reduction of precipitation falling as snow[8].

Uncertainties and Limitations

Despite recent improvements in RCM predictive capability, there is still uncertainty associated with these estimates. RCMs provide a useful comparative tool to use in conjunction with other methods of estimating future changes in snowpack and snow water equivalent. Reliable snowpack projections may be obtained by using a combination of statistical downscaling techniques, satellite measurements, and corroboration with GCM projections to obtain information on snowpack changes and compare these alternate projections with outcomes from multiple RCMs (section 4.1, 4.2).

Previous publications documenting CRCM developments primarily apply comparisons between the CRCM3 model projections and observed data sets to test the reliability of the results. For example, the differences between the CRCM3 as compared to the CRU time series[9] gridded observations for the 1961-1990 climatology were analysed[10] and CRCM3 strengths and weaknesses were presented, which have important implications for projected snowpack. Note, however, as discussed in section 4.2, previous publications[11,12] have documented CRCM3 forced by CGCM2, while this report focuses on the CRCM4 results forced by CGCM3.

A warm temperature bias (4°C to 6°C) was noted over the DJF season[13], which could have implications in snow-covered regions, such as BC's Fraser Plateau or the Peace Basin. Meanwhile, a cold bias (2°C to 3°C) occurred north of 60°, possibly due to the limited observational network in this region of Canada[14]. The distribution of winter precipitation was captured within large-scale features, for example, maximum precipitation along the west coast (although shifted slightly north) and in the Rocky Mountains east of the Okanagan. However, excess precipitation was simulated inland of the Coast Mountains[15]. The over-prediction of precipitation for the Western Cordillera region reflects model bias towards excess precipitation in the interior valleys and plateaus of southern BC, which indicates a limitation in model topography that does not reproduce the rain shadow effect[16].

Future changes in SWE were examined in the Fraser and Mackenzie basins[17]. Version 3.7 of the CRCM, when cross-compared to SWE observations[18], tended to over estimate snow water equivalent for the Fraser, Mackenzie and the Yukon basins[19]. This result was influenced by a cold bias occurring during late-fall and early winter. The primarily cause of this bias was a new radiation scheme applied in version 3.7, which increased atmospheric absorption hence, led to projection of a colder surface[20].

Snowpack is a difficult variable to measure for other reasons than those detailed above. As the projected changes to snowpack rely on both temperature and precipitation, a great deal of uncertainty is associated with estimates. Reliable future projections of snowpack may be best obtained from a combination of different techniques, as suggested above (see also section 4 for more details with regards to GCMs). Additionally, snowpack measurements (observed) are hampered by challenges such as gauge undercatch[21], and rely on accurate model calculations to convert snow depth to snow water equivalent. Hence future projections have few reliable historical observations for proper comparison or error-checking (section 3.1).

Gaps

- There is no peer-reviewed literature that describes CRCM4 results for snowpack projections within BC regions or at for BC as a whole.
- Testing of the RCM often relies on use of data such as the CRU TS 2.0. Because the CRU TS 2.0 data is based on the observational network, there may be flaws in the use of this data to estimate RCM errors. For example, the CRU does not take into account known biases in precipitation measurements, such as wind-induced gauge undercatch of snow. Correcting this can result in a more favorable comparison during the winter in northern regions of Canada[22]. Comparisons of RCM performance in BC may benefit from the application of alternate data, or a corrected version of the CRU time series[23,24].
- Historical trends in snow water equivalent and future projections of snow water equivalent using the RCM or other means (e.g. GCMs, statistical downscaling techniques) are needed.

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[1] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[2] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[3] Ibid.
[4] ACIA, 2005. Chapter 6: Cryosphere and Hydrology. In: J.E. Walsh (Editor), The Artic Climate Impact Assessment. . Cambridge University Press, pp. 1042 p.
[5] Christensen, J.H. et al., 2007. Regional Climate Projections. In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.
[6] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.
[7] Ibid.
[8] Ibid.
[9] Mitchell, T.D. and Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology, 25(6): 693 - 712.
[10] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[11] Ibid.
[12] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[13] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[14] New, M., Hulme, M. and Jones, P., 1999. Representing twentieth-century space–time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. Ibid., 12(3): 829–856.
[15] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Ibid., 19: 3112 - 3132.
[16] Laprise, R., Caya, D., Frigon, A. and Paquin, D., 2003. Current and pertubed climate as simulated by the second-generation Canadian Regional Climate Model over Northwestern North America. Climate Dynamics, 21: 405-421.
[17] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[18] Brown et al. 2003
[19] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.
[20] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[21] Goodison, B.E., 1978. Accuracy of Canadian snow gauge measurements. American Meteorological Society, 17: 1542-1548.
[22] Adam, J. and Lettenmaier, D.P., 2003. Adjustment of global gridded precipitation for systematic bias. Journal of Geophysical Research, 108(9): 4257, doi:10.1029/2002JD002499.

[23] Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
[24] Mitchell, T.D. and Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology, 25(6): 693 - 712.

Figures

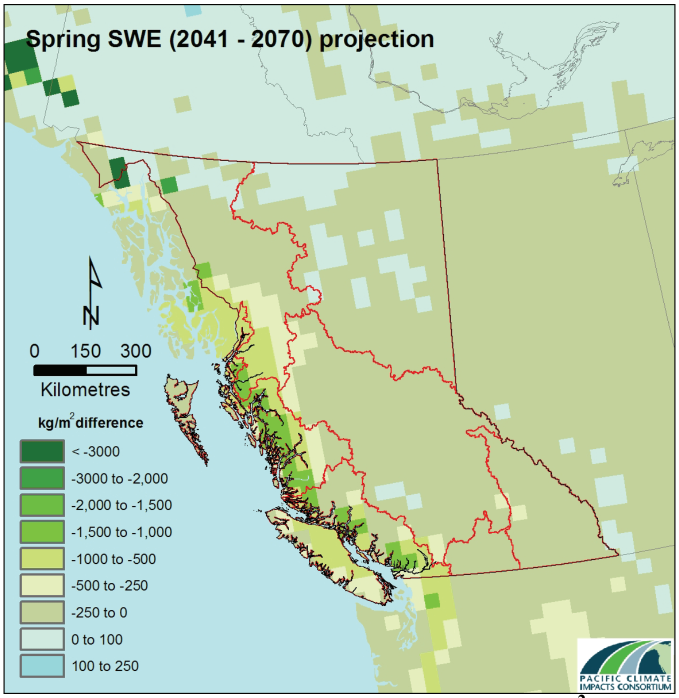

Figure 5.1.1 – Spring snow water equivalent (kg/m^2) projection for the 2050s (2041-2070) as an anomaly from the 1961-1990 baseline. Red lines illustrate the seven regions of BC. Spring includes the months of March, April and May. Source: Ouranos Consortium data.

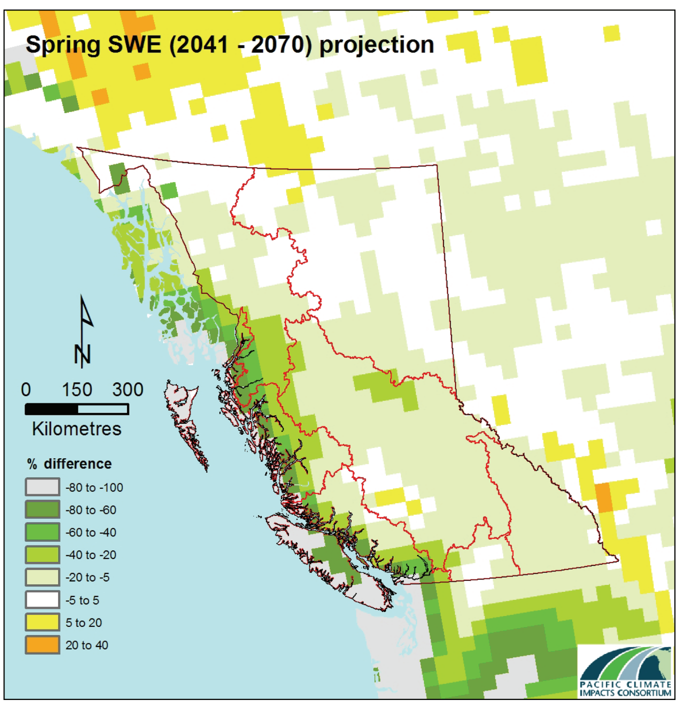

Figure 5.1.2 – Spring snow water equivalent projection for the 2050s (2041-2070) as percent difference from the 1961-1990 baseline. Red lines illustrate the seven regions of BC. No change is shown in white (±5%). Spring includes the months of March, April and May. Source: Ouranos Consortium data.

5.2. Response – Glaciers

Glaciers provide streamflow during summer low-flow periods and maintain important ecosystem functions. However, glaciers are receding in response to climate variability and change (section 3.2). This section provides a synthesis of the studies which project future response of glaciers to climate variability and climate change.

Results

- The projections for loss of glacier mass due to global warming are established on a world wide basis[1]. Within BC, however, there are only a limited number of studies that project future conditions of glaciers. In many cases, BC glaciers are not in equilibrium even with the *current* climate and are retreating (section 3.2).
- Glaciers in BC and Pacific North America at low latitudes and elevation are retreating due to both increased temperatures in the summer season and changes in precipitation (from snow to rain) in the winter season.
- The most critical parameter for determining the equilibrium state of glaciers is temperature[2]. *Historical trends* of temperature (section 2.1) were positive (warming), especially in the winter season (up to 2.5°C) in northern BC. *Projections* of temperature from the RCM (section 4.2) are large (2.0 to 3.5°C) by mid century and are consistent with the current trends.
- The glaciers in BC are at risk and require monitoring and further analysis. Bridge Glacier, covers the largest fraction of watershed area in BC and has been quantitatively modeled. Projections for the 2050s (**Figure 5.2.1**) show substantial reductions of the area of the Bridge glacier by up to 20% even without further warming of the current climate.
- The projected decline of glaciers in southern BC is corroborated by studies of other glaciers to the southeast (outside of BC) in the Blackfoot-Jackson Glacier Basin in Glacier National Park, Montana where glacier area is projected to contract to be entirely zero by 2030.

Discussion

According to the IPCC Technical Summary for the Fourth Assessment Report, global glacier loss will continue throughout the 21st century because increased melt rates will exceed supplements from increased snowfall[3]. Glaciers in BC appear to be following this trend. For example, the Place and Illecillewaet glaciers have both retreated[4,5]. Projections of future glacier response to climate change in BC are limited in number and therefore results from studies conducted in close proximity to BC will be discussed here in addition to those from BC.

Glacial retreat in southern BC and the Rocky Mountains may be catastrophic given the projected increases in air temperature and prevalence of precipitation falling as rain rather than snow[6]. For example, the Bridge Glacier has the highest percentage of glacier cover by area out of any watershed in the Province. The semi-distributed HBV model was coupled with a glacier response model to investigate the sensitivity of streamflow to changes in glacier cover for the Bridge River Basin[7]. Marked reductions in glacier area and summer streamflow were observed even under the assumption of a continuation of the present climate (**Figure 5.2.1**). These trends were stronger for the warming scenarios downscaled from GCM simulations (transient scenarios downscaled from CGCM3) following B1 and B2. These results suggest that for most of BC the phase of increased streamflow that generally follows climate warming[8] has passed and continued reduction in glacier area will lead to decreased streamflow[9].

Located outside of BC, but within the Rocky Mountains, the Blackfoot-Jackson Glacier Basin, in Glacier National Park, Montana, USA, was modelled by Hall and Fagre (2003)[10]. A simulation model was used to investigate two scenarios i) a carbon dioxide-doubling scenario where air temperature increased by 3.3°C and winter precipitation increased by 5% to 10% over the 1990-2100 period; and ii) a linear temperature-extrapolation scenario where future temperatures for 1990-2100 were based on linear extrapolation of the global warming trend from 1850 to 1980 to portray the gradual emergence from the Little Ice Age.

Glacial loss under the first scenario melted at a rate of 1.50 km^2 per decade resulting in the glacier area receding to zero by 2030. The increase in precipitation did not serve to offset the effects of the increased air temperature on melt rates. In the second scenario, the melt was 0.21 km^2 per decade and the glacier area did not recede to zero until 2277. This suggests that these glaciers are not out of equilibrium with the current climate (in contrast to Bridge Glacier). In these two studies, the sites are located at distinctly different locations (latitude and distance from the ocean) which could be the reason for different results. However, differences in the climate baselines and scenarios used in each study could also cause different results.

Uncertainties and Limitations

There many weaknesses in the present glacier monitoring network which complicates the science of projecting future glacial response. The North Coast, Northwest, Peace Basin, and Interior regions of BC are virtually unrepresented. Also, monitoring programs do not exist in the majority of the areas where changes to glacier cover will have major consequences, such as on important salmon spawning rivers or in hydro-electric producing basins. As a result, not enough is known about regional mass balance trends[11]. Generally, the amount of data on existing glaciers and their rate of change over the past is limited, which prevents robust analysis of trends in glacier mass balance or clear linkages between these trends and climate variability and climate change from being identified across the Province.

Methods for projecting future glacier mass balance are being developed within the Western Canadian Cryospheric Network (WC^2N). The Regional Atmosphere Modeling System (RAMS) mesoscale model is being used to downscale temperature and precipitation, and Bayesian Empirical Orthogonal Function (EOF) analysis of temperature and precipitation fields are being carried out to develop input for glacier mass balance models. The North American Regional Reanalysis (NARR) data and a linear orographic precipitation model are also being explored as a potential avenue to downscale rain. These techniques are in development, but will be invaluable in projecting glacier response.

Although the approach used to project future glacier response for the Bridge Glacier[12] is at the forefront of the science in this field, the downscaling methods applied in this report utilized only one GCM model. Employing more than one model would better define the range of GCM uncertainty (section 4.1).

The results for the Blackfoot-Jackson Glacier Basin, in Glacier National Park, Montana, USA[13] were based on the estimated change in global air temperature and precipitation and were not downscaled. Changes in air temperature over the past for Glacier National Park were demonstrated to have increased at a rate exceeding those of the global average and of those for other alpine regions. However, this influence was not incorporated into future temperature projections for the region. Relationships between trends in regional and global precipitation were also not tested.

Gaps

- Modelling efforts in BC are spatially limited and different regions in BC have not been adequately represented.
- Due to the presence of more than 10,000 glaciers in Western Canada, projected changes cannot be made with fully dynamic glaciological models for all glaciers, although these models may serve well for projecting changes at individual glaciers. Conversely, the complex topography of Western Canada imposes challenges for modelling changes in glacier cover at a regional-scale[14].
- Coupling of atmospheric and glacial models is still under development in BC and no studies up to this point have been forced with an ensemble of GCMs (section 4).
- Atmospheric flow indices provide an objective measure of upper-air conditions that are readily transferable to any location. Flow indices have been found to be strong predictors of mass balance[15]. Additionally, atmospheric flow indices capture surface weather better in the mountains

within both reanalysis and global climate model projections, as observed at the Peyto glacier in the Canadian Rockies[16]. However, the link between atmospheric flow indices and glacier mass balance values has not been applied in projections of future glacier response to date[17].

- Satellite or LiDAR surveys have been under utilized in glacial modelling. The use of LiDAR surveys could compensate for the sparse glacier monitoring network.

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[1] Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Brugman, M.M., Raistrick, P. and Pietroniro, A., 1998. Chapter 6 - Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon.

[3] Solomon, S. et al., 2007. Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[4] Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.

[5] Sidjack, R.W. and Wheate, R.D., 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elvation data. International Journal of Remote Sensing, 20(2): 273-284.

[6] Brugman, M.M., Raistrick, P. and Pietroniro, A., 1998. Chapter 6 - Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon.

[7] Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., submitted. Coupling modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.

[8] Singh, P., and N. Kumar, 1997. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff-dominated Himalayan river. Journal of Hydrology, 193: 316-350.

[9] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.

[10] Hall, M.H.P. and Fagre, D.B., February 2003. Modeled Climate-Induced Glacier Change in Glacier National Park, 1850-2100. BioScience, 53(2): 131-140.

[11] Brugman, M.M., Raistrick, P. and Pietroniro, A., 1998. Chapter 6 - Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon.

[12] Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., 2007 in press. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.

[13] Hall, M.H.P. and Fagre, D.B., February 2003. Modeled Climate-Induced Glacier Change in Glacier National Park, 1850-2100. BioScience, 53(2): 131-140.

[14] Menounos, B. Glacier extent in Western Canada: State of knowledge and future challenges. Presented at: Predicting in Ungauged Basins workshop, Manning Park.

[15] Shea, J.M. and Marshall, S.J., 2007. Atmospheric flow indices, regional climate, and glacier mass balance in the Canadian Rocky Mountains. International Journal of Climatology, 27: 233-247.

[16] Ibid.

[17] Ibid.

Figures

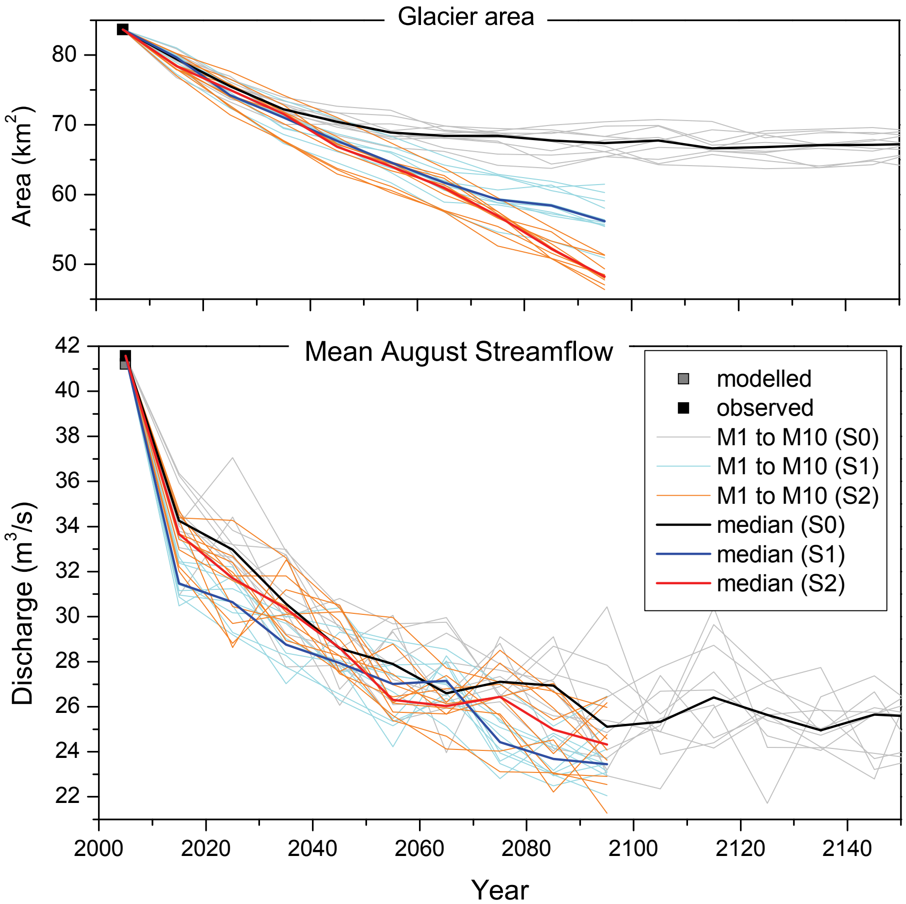

Figure 5.2.1 – Development of glacier area (upper panel) and decadal mean August streamflow (lower panel) 10 realizations (M1 to M10) and the median of scenarios S0 (present day), S1 (SRES B1), and S2 (SRES B2). Source: modified from Stahl et al., in review.

5.3. Response – Streamflow

Understanding the changes in timing and magnitude of streamflow and the probability of extreme events is highly valuable to engineers and planners. This section provides a synthesis of the results from studies of projected future streamflow across BC.

Results

- In spite of its importance for water resources, a comprehensive study of projected BC streamflow is not available. However, several independent studies have been made for major basins and individual watersheds. These studies (**Table 5.3.1**) corroborate concerns that the influence of future regional projections of warmer temperatures, uncertain precipitation and a reduction in snowpack and glaciers will adversely affect both the timing and the volume of projected stream flow[1,2,3].
- Projected changes promote the shift of streams from *nival* to *hybrid* and *hybrid* to *pluvial*. *Pluvial* systems would have increased potential for winter floods, but dry season droughts in all regime types become more prominent[4].
- A comprehensive study of the Columbia Basin provided visual examples of projected changes to streamflow for the second half of the 21st century (**Figure 5.3.1**)[5]. Simulations for a ten year mean of annual runoff volumes centered around 2045 range from 85% to 110% of the base case. Peak streamflow is projected to occur earlier in the month. Subsequently, streamflow volumes for the April-September period (dry season) are predicted to decrease to 75% to 90% of the base case[6]. Such a scenario has important implications for water management. One particular hydrologic study which focused on glacier dynamics showed that August streamflow in the Bridge River basin is projected to decrease by -37% by the year 2050[7].
- An understanding of future projections of streamflow is driven by global climate variability and change, but also depends on complex local and regional conditions that modulate the process of melting, freezing, evaporation, soil moisture and runoff. This is the domain of the macro-scale gridded hydrological models, a valuable tool for obtaining quantitative information that will support adaptation to climate change and a mechanism for synthesizing findings from independent observational watershed studies.

Discussion

The results from all studies of future streamflow for BC are summarized in **Table 5.3.1**. Most of these modelling studies have focused on *nival* systems. Other regimes, such as *nival/glacial*, play a key role in agriculture, fisheries, and water supply and their responses are likely to be more complex[8] and more challenging to model. Factors which contribute to the complexity of modelling all types of runoff regimes include the increased importance of accounting for evaporation and soil moisture (see Box 5.3.1) with future warming, and the multiple sources of streamflow that have to be accounted for (i.e. glacier-melt and groundwater).

Projected changes to annual and seasonal streamflow volumes and timing are similar across models and approaches[9]. All models and approaches that deal with nival systems predict an earlier onset of the spring freshet or peak flows compared to the base case. Projected changes to the magnitude of flow include increased winter and decreased summer and fall streamflow, along with a diminished spring freshet volume[10]. Warmer winter temperatures will cause more precipitation to fall as rain rather than snow, resulting in increased winter runoff and decreased snowpack accumulation and a tendency towards more *pluvial* streamflow regimes (section 4)[11,12]. Reductions to spring peaks will occur primarily from reductions in snowpack and from warmer temperatures causing an earlier spring melt (section 5.1).

The changes to the flood and low-flow volume producing mechanisms are different for *pluvial* and *nival* systems[13]. *Pluvial* watersheds are expected to have increased flood magnitude and frequency[14,15]. This response is primarily driven by warmer, wetter winters (section 4.1, 4.2)[16]. A decrease in the number and magnitude of flood events is predicted for many *nival* watersheds, particularly those in the semi-arid interior regions[17,18]. This decrease is driven by the spring melt taking place earlier. Drier summers in combination with year-round warming are projected to increase water shortages in both *pluvial* and *nival* rivers because of changes in rainfall timing and amounts, projected smaller snowpack and increased evaporation[19]. Also an increase in the time elapsed between snowmelt and fall rain is projected, which will extend the dry-season low-flow period. Pluvial regimes have been shown to have noticeably longer dry seasons as a result of changes in temperature and precipitation inputs. Because of this pluvial systems are considered sensitive to climate change[20].

Soil moisture in BC

Soil moisture is an important element of the water balance, a key determinant of precipitation versus runoff ratios and is often used to set the initial moisture conditions in models. Soil moisture plays an important role in the exchange of moisture and energy between the atmosphere and the land surface[21], but estimates of this variable are dependent on many factors including water availability, exposure, and meteorological variables (wind speed, humidity, cloudiness, and solar insolation). Aside from rare point measurements, the contribution of soil moisture to the water balance cannot be estimated without a hydrological model. There is little information or data available in BC on soil moisture, even though it is highly important for water management.

The impacts of climate change on *future* soil moisture projected to the 2020s and 2040s for BC was estimated from a recent study of the BC section of the Columbia Basin[22]. Soil moisture is projected to increase during the spring season in response to earlier melting of the snowpack. However, during the summer and fall seasons, future climate scenarios project increased temperatures, which imply increased evaporation rates from soil in the absence of summertime precipitation. Increases in evaporation will occur when summer days are longer, cloud cover is decreased, precipitation is low, and air temperatures are high[23]. Evaporation and transpiration is dependent on the Vapour Pressure Deficit (VPD), which is proportional to temperature and inversely proportional to humidity[24]. As the VPD increases so does evaporation. However, plants could respond to increased temperature and changes to humidity by reducing transpiration[25].

The timing of the seasonal recharge of soil moisture in future decades in BC will be largely controlled by temperature trends, assuming an adequate supply of snowpack and rain at the beginning of the year. Recharge timing is dependent on the runoff regime of an area. Soils are generally driest in *pluvial* systems before the beginning of the rainy season, which occurs in October in most locations in BC. Precipitation and cooler temperatures that occur during the fall and winter in these systems allow water to accumulate in the soil. For *nival* systems, snowmelt during the spring or early summer can replenish soil moisture. The projections of soil moisture in the Columbia Basin show that in *nival* and *hybrid* watersheds projected increasing temperatures will result in reduced snowpack and the earlier onset of snowmelt that enhances soil moisture recharge in spring. However, the direction of change of soil moisture in summer and fall is more difficult to predict because changes in solar radiation, wind speed, precipitation, humidity, temperature, evaporation and transpiration are all contributing factors. Therefore, increased temperatures in nival and hybrid systems can alter seasonal cycles of soil moisture depletion and recharge, but more research is needed[26].

Glaciers play a major role in determining low-flows for 48% of the monitored rivers in BC[27]. One study explored future streamflow response to glacier change and projected that August streamflow in the Bridge River Basin will decrease by 37% by 2050[28]. Another study in the Illecillewaet watershed projected that despite a 26% decrease in future glacial runoff (due to a 33% reduction in glacier area), the total percentage runoff contribution would remain relatively unchanged[29]. During low-flow periods at the Illecillewaet, increased contributions from groundwater would compensate for losses in flow from other sources[30]. The influence of groundwater and glacier melt on low-flows requires further study[31].

Projected changes for five sites in the Canadian portion of the Columbia Basin for the 2020s and 2040s were studied (**Figure 5.3.1a to 5.3.1e**) by the Climate Impacts Group at the University of

Washington using the Variable Infiltration Capacity (VIC) model[32]. Mica is the farthest north of all the gauges followed by Revelstoke, Duncan, Corra Linn, and Keenleyside, which is the farthest south (**Figure 5.3.1a to 5.3.1e**). These watersheds are located in the northern headwater of the Columbia River, which are projected to have slower reactions to climate change than watersheds at moderate elevations located further south. All stations show earlier onset of the spring melt and higher peak magnitudes for the 2020s and 2040s than for the base case.

Corra Linn (**Figure 5.3.1d**) has some of the largest deficits in July, August, and September even though it is not the furthest south. Characteristics, such as vegetation and topography, increase the response of the Corra Linn basin to changing climate compared to other watersheds. However, in this study the influence of glacier cover on streamflow changes was not investigated even though many of the watersheds in the Columbia Basin are known to have glaciers (section 3.2). Hence, the response of the streamflow to changes in glaciers could be a causal factor in the different responses between watersheds in the Columbia Basin, such as the Corra Linn.

Uncertainties and Limitations

The main impediments in streamflow projection are related to challenges with projecting future precipitation and temperature (section 4). GCM projections play a large role in the hydrological model outcomes[33]. Most studies summarized here applied GCM results from only one grid box, rather than averaging multiple nearby grid boxes (section 4). However, this approach is limited because the variability across GCM models is diverse and resolution is coarse (Introduction II).

Uncertainties in future precipitation amounts are greater than those for temperature estimates (section 4.1). However, changes in the form of winter precipitation are dependent on temperature estimates, which make projected changes to the form of precipitation relatively robust. Due to the uncertain nature of changes in precipitation amounts there is a potential for changes in precipitation to exacerbate or ameliorate the effects of regional warming (section 4.1). For example, an increase in temperature in combination with a decrease in winter precipitation could result in drought, but an increase in winter precipitation might maintain current conditions[34]. However, the projected decline in winter snowpack and subsequent decrease in summer streamflow is more probable because both snowpack and streamflow are known to depend more heavily on the temperature response (section 3.1, 3.3).

Characterizing uncertainty in future projections of streamflow requires results from an ensemble of models[35]. The difference between projected warming and projected precipitation signals was small between ensembles, but large differences and high uncertainty were noted in hydrologic response. Uncertainty for flooding events was also high; models reproduced central tendency measures well, but were biased in their ability to produce extremes[36].

Relating global climate projections to the regional scale is problematic because models that integrate GCM results are often suited to continental scale studies. However, hydrologically robust downscaling techniques are often limited in projecting reasonable values at regional scales and through time.

Additionally, many facets of streamflow modelling have not been fully explored or addressed using future projections. Conceptual models represent landscape features (e.g. vegetation cover) as steady-state. Therefore potential future climate change in combination with changing land cover and streamflow has yet to be addressed by hydrologic modellers.

Modelling the future response of different types of streamflow regimes (section 3.3) is limited, For example, there are only a few studies of glacier influence on future streamflow and existing research is not transferable across watersheds[37,38]. Finally, the influence of climate change on climate variability has not been investigated[39] with regards to impacts on future streamflow conditions.

Gaps

- Many of the findings reported are based on limited sites in BC. Outside of these areas little research has been done.

- Work on hybrid, pluvial, and nival/glacial regimes in BC is limited in comparison to nival regimes. Hybrid systems in the Georgia Basin, for example, are generally smaller coastal watersheds and have been identified as some of the most sensitive to climate change[40,41].
- The HBV-EC model that was used to assess the Bridge River system has been applied in other glacial regimes in BC (Canoe, Illecillewaet, and Goldstream Rivers)[42]. However, the model was not run in combination with a modern up-to-date downscaling approach such as Tree-Gen, which could provide more accurate and fine resolution results[43].
- Data from BC Hydro's hydrologic modelling at 20 sites across BC is not shared widely within the scientific community.
- A regional scale comparison of several hydrological models, with various emission scenarios, has not been conducted. A regional scale ensemble approach to hydrologic modelling would provide a holistic estimate of the range of responses that can be expected[44]. Model bias (section 4) and uncertainty estimates are available using ensemble approaches. In addition, the response of streamflow to ENSO and PDO may be observable using this approach[45,46].
- Future projections of streamflow rely on hydrologic models that are suited to a given runoff regime. A projected result of climate change is that runoff regimes may shift, as they have in the past (section 3.3). However, the ability of the available hydrologic models to adapt to transiting runoff regimes has not been documented.
- Regional Climate Models (RCMs) (e.g. 45 km) are too coarse to accurately represent hydrological processes. However, improper representation of important land-atmosphere feedbacks, such as snow-albedo feedbacks, is often the result of direct input of RCM data into offline hydrologic models[47]. This occurs due to a mismatch in spatial resolution and land surface parameterizations between the RCM and offline hydrologic models[48].

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[1] Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.
[2] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[3] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2004. Climate change implications on flood response of a mountainous watershed. Water, Air, and Soil Pollution: Focus, 4: 331-347.
[4] Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.
[5] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.
[6] Hamlet, A.F. and Lettenmaier, D.P., 1999a. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. Journal of Water Resources Planning and Management, 125(6): 333-341.
[7] Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., in press. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.
[8] Fleming, S., Moore, R.D. and Clarke, G.K.C., 2006. Glacier-mediated streamflow teleconnections to the Arctic Oscillation. International Journal of Climatology, 26: 619–636.
[9] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[10] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.
[11] Ibid.
[12] Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.
[13] Loukas, A., Lampros, V. and Dalezios, N.R., 2002a. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259: 163-188.
[14] Loukas, A., Vasiliades, L. and Dalezios, N.R., Ibid.
[15] Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.

[16] Parson, E.A. et al., 2001b. Chapter 9: Potential Consequences of Climate Variability and Change for the Pacific Northwest. In: National Assessment Synthesis Team (Editor), Climate Change Impacts on the United States The Potential Consequences of Climate Variability and Change. US Global Change Research Program.
[17] Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.
[18] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2002b. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259: 163-188.
[19] Parson, E.A. et al., 2001a. Chapter 9 - Potential Consequences of Climate Variability and Change for the Pacific Northwest.
[20] Whitfield, P.H. and Taylor, E., 1998. Apparent Recent Changes in Hydrology and Climate of Coastal British Columbia. In: Y. Alila (Editor), Mountains to Sea: Human Interaction with the Hydrologic Cycle. Proceedings of 51st Annual Canadian Water Resources Conference, pp. 22-29.
[21] Nijssen, B., Schnur, R. and Lettenmaier, D.P., 2001. Global retrospective estimation of soil moisture using the Variable Infiltration Capactiey land surface model, 1980-93. Journal of Climate, 14: 1790-1808.
[22] http://www.cses.washington.edu/cig/pnwc/clvariability.shtml
[23] Casola, J.H. et al., 2005. Climate Impacts on Washington's Hydropower, Water Supply, Forests, Fish, and Agriculture., by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle), A report prepared for King County (Washington).
[24] Shuttleworth, W.J., 1993. (editor) Chapter 4: Evaporation, Handbook of Hydrology. DR Maidment, McGraw-Hill New York. pp. 4.1-4.53.
[25] Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability. 4.3.3. Evaporation
[26] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.
[27] Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
[28] Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., 2007 in press. Coupled modelling of glacier and streamflow response to future climate scenarios. Ibid.
[29] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2004. Climate change implications on flood response of a mountainous watershed. Water, Air, and Soil Pollution: Focus, 4: 331-347.
[30] Ibid.
[31] Stahl, K. Climate Change and Low Flows: Influence of Glaciers and Groundwater. March 12, 2007. Vancouver, BC.
[32] http://www.cses.washington.edu/cig/fpt/ccstreamflowtool/sft.shtml
[33] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[34] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.
[35] Leung, L.R. and Qian, Y., 2003. Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century. Canadian Water Resources Journal, 28(4): 605-631.
[36] Ibid.
[37] Fleming, S. and Clark, G.K.C., 2005. Attenuation of high-frequency interannual streamflow variability by watershed glacial cover. ASCE Journal of Hydraulic Engineering, 131(7): 615-618.
[38] Fleming, S.W., 2005. Comparative analysis of glacial and nival streamflow regimes with implications for lotic habitat quantity and fish species richness. River Research and Applications, 21: 363-379.
[39] Hamlet, A.F., 2001. Effects of climate change on water resources in the Pacific Northwest: Impacts and policy implications, Climate Impacts Group, University of Washington, Seattle, Skamania, Washington.
[40] Whitfield, P.H. and Taylor, E., 1998. Apparent Recent Changes in Hydrology and Climate of Coastal British Columbia. In: Y. Alila (Editor), Mountains to Sea: Human Interaction with the Hydrologic Cycle. Proceedings of 51st Annual Canadian Water Resources Conference, pp. 22-29.
[41] Leung, L.R. and Qian, Y., 2003. Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century. Canadian Water Resources Journal, 28(4): 605-631.
[42] Pers. Comm. Hutchinson, D. 2007.

[43] Cannon, A.J., In press. Nonlinear analog predictor analysis: a coupled neural network/analog model for climate downscaling. Neural Networks.
[44] Parson, E.A. et al., 2001a. Chapter 9 - Potential Consequences of Climate Variability and Change for the Pacific Northwest.
[45] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
[46] Parson, E.A. et al., 2001a. Chapter 9 - Potential Consequences of Climate Variability and Change for the Pacific Northwest.
[47] Leung, L.R. and Qian, Y., 2003. Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century. Canadian Water Resources Journal, 28(4): 605-631.
[48] Ibid.

Figures and Tables

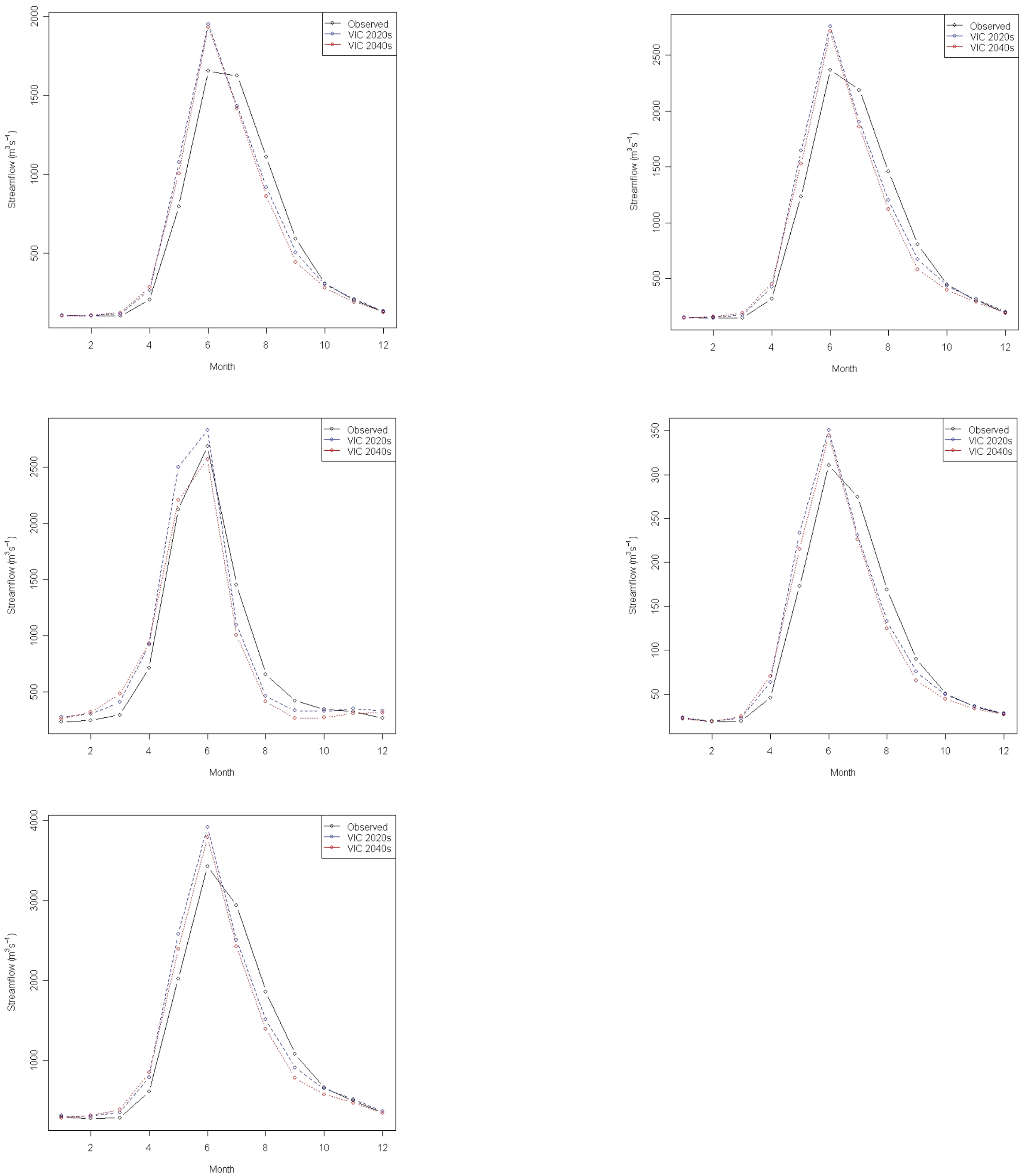

Figure 5.3.1 – a) Mica, b) Revelstoke, c) Duncan, d) Corra Linn, and e) Keenleyside Variable Infiltration Capacity (VIC) model projections for 2020s and 2040s, compared to the observed. The y-axis shows average streamflow (m^3/s) for a given month and the x-axis gives the numeric month (i.e. -2 = October, 0 = December, 8 = August). Source: Climate Impacts Group the University of Washington, USA.

Table 5.3.1 – Research studies ongoing in BC on streamflow. Source: Adapted from Merritt et al. 2006[1].

Region	Source	Study Site	Hydrologic Model	GCM Scenario[i]	Downscaling Technique	Hydrology Scenarios	Changes to streamflow
South Coast	Loukas et al. 2002[2]	Upper Campbell Creek (1194 km^2)	UBC Watershed Model	Canadian Global Climate Model (CGCM-A1): Transient simulation with observed increases CO^2 concentrations from 1990 to 1995 and assumed 1% increase annually until 2100	Delta method	Present climate: (1970-1990)	Wetter and warmer climate with an increase in overall flood magnitude and frequency of occurrence[3].
South Coast	Whitfield et al. 2002[4]	Six watersheds within the Canadian portion of the Georgia Basin (approximately 50,000 km^2)	UBC Watershed Model	CGCM1: IS92a[ii] greenhouse gas plus aerosols	Analogue Downscaling Technique	Present climate: (1973-1993) Future climate: 2020s (2013-2033), 2050s (2043-2063), 2080s (2073-2093)	Increased winter flows in pluvial streams, increasingly early onset of the spring freshet in nival streams, and a tendency for hybrid streams to become dominantly pluvial.
South Coast	Leung et al. 2003[5]	Georgia Basin/ Puget Sound	Oregon State University Land Surface Model (OSULSM) implemented in the Fifth Generation Penn State/ National Centre for Atmospheric Research (NCAR)	NCAR/Department of Energy (DOE) Parallel Climate Model (PCM)	Regional Climate Model	Current climate: (1995-2015) Future climate: (2040-2060)	Small transient watersheds have a higher likelihood of winter flooding, precipitation falling as rain, and reduced streamflow in summer. Large changes to monthly total runoff above 99th percentile for October-May, and December flood volume are 60% above maximum monthly flood volume of control climate.

[i] For background on GCMs and scenarios, refer to www.PacificClimate.org/faq/
[ii] Employs observed CO^2 levels until 1990 followed by a 1% increase in CO^2 and aerosols thereafter.

			Mesoscale model (MM5)				
Fraser River	Morrison et al. 2002[6]	Fraser River basin (217,000 km^2)	UBC Watershed Model	CGCM1 Hadley Climate Model (HadCM2)	Statistical climate inversion	Present climate: (1961-1990) Future climate: 2020s (2010-2039), 2050s (2040-2069), 2080s (2070-2099)	Modest average flow increase in the 2080's with a decrease in the average peak flow. General shift to earlier peak in the hydrograph (approx. 24 days).
Fraser River	Sushama et al. 2006[7]	Fraser River basin above Port Mann (232,000 km^2)	Canadian Regional Climate Model (CRCM)	CGCM2-A2 standard, CGCM2 - A2 updated, and CGCM2-IS92 standard	CRCM (dynamical downscaling)	Present climate: (1961-1990) Future climate: (2041-2070)	A significant decrease in SWE as less precipitation falls as snow. Runoff is higher during late-fall and early-winter. Spring peaks are attenuated and occur earlier. Increased variability in the number of days with low-flows. Increased low flows in fall.
Columbia	Loukas et al. 2004[8]	Illicillewaet Basin (1150 km^2)	UBC Watershed Model	CGCM-A1: Transient simulation with observed increases CO^2 concentrations from 1990 to 1995 and assumed 1% increase annually until 2100	Delta method	Future climate: (2080-2100)	Basin wetter and warmer climate with a decrease in the number and magnitude of peak flows and flood events[9,10].
Columbia	Hamlet and Lettenmaier 1999[11]	Columbia Basin (381,000 km^2)	VIC Model at $1/8^{th}$ degree or 12 km by 12 km (144 km^2)	CGCM, CGCM1, HadCM2, European Climate Model (ECHAM4)	Decadal mean temperature and precipitation changes were used to perturb historical records	Future climate: 2025, 2045, and 2095	Significant increase in winter runoff volumes due to increased winter precipitation and warmer winter temperatures, with resulting reductions in snowpack.

Okanagan	Merritt et al. 2006[12]	Okanagan Basin (8000 km^2)	UBC Watershed Model	CGCM2, Australian Commonwealth Scientific and Industrial Research Organization (CSIROMk2), HadCM3, both high emission (A2) and low emission (B2) scenarios	Delta method	Future climate 2020s (2010-2039), 2050s (2040-2069), 2080s (2070-2099)	Earlier onset of spring snowmelt, more rainfall dominated hydrographs and reductions in the annual and spring flow volumes in the 2050s and 2080s. Longer low flow period.
Okanagan	Cohen and Kulkarni 2001[13]	Six sub-watersheds of the Okanagan Basin	HBV	CGCM1: three ensemble runs with different initial conditions, IS92a scenario ECHAM–IS92a scenario HadCM2-IS92a scenario	Meteorological Services of Canada, Analogue Downscaling Technique	Present climate: (1961-1990) Future climate: 2020s (2010-2039), 2050s (2040-2069), 2080s (2070-2099)	Earlier onset of spring peak flows (up to 6 weeks) with reduced magnitude of peak flows.
Peace	Toth et al. 2006[14]	Peace River at Peace River (186, 000 km^2)	WATFLOOD	CGCM, CSIRO, ECHAM, Geophysics Fluid Dynamics Laboratory model (GFDL), HADCM2, NCAR, (Japanese Centre for Climate Research Studies (CCSR)	Delta method	Present climate: (1961-1990), Future climate: (2040-	Higher elevations of Peace River system may experience increased evaporative flux that compensates for higher precipitation and results in only slight increases in streamflow. Degree and direction depends on climate change scenario.
Coast	Stahl et al., 2006[15]	Bridge River Basin (152 km^2)	HBV	CGCM3 SRES (A2 and B2)	Repeated 1995-2004 climate data for 20 consecutive 10-year periods.	Calibrated for 1985-1994 and validated for 1995-2004	Even with no further climate change, because the glaciers are out of balance with the current climate there will be a 40% reduction in August streamflow by 2050.

Other	Clair et al. 1998[16]	*Montane Cordillera ecozone rivers:* Salmon, Thompson, Fraser at Hope, Columbia at Birchbank, Columbia at international boundary, Kootenay, Elk, Similkameen, Okanagan, Howell Creek *Pacific Maritime ecozone rivers:* Skeena, Quinsam	An artificial neural network (ANN) model	CGCM2 : times two CO_2 scenario	An artificial neural network (ANN) model	N/A	Predicted increases in total runoff for the Pacific and Montane Cordillera ecozones. An earlier onset of the spring melt was predicted along with increased winter and early spring flows in these two ecozones.

[1] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.

[2] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2002b. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Ibid., 259: 163-188.

[3] Ibid.

[4] Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.

[5] Leung, L.R. and Qian, Y., 2003. Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century. Canadian Water Resources Journal, 28(4): 605-631.

[6] Morrison, J., Quick, M.C. and Foreman, M.G.G., 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology, 263: 230-244.

[7] Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.

[8] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2004. Climate change implications on flood response of a mountainous watershed. Water, Air, and Soil Pollution: Focus, 4: 331-347.

[9] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2002b. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259: 163-188.

[10] Loukas, A., Vasiliades, L. and Dalezios, N.R., 2004. Climate change implications on flood response of a mountainous watershed. Water, Air, and Soil Pollution: Focus, 4: 331-347.

[11] Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.

[12] Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.

[13] Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.

[14] Toth, B., Pietroniro, A., Conly, F.M. and Kouwen, N., 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: I - hydrological model application. Hydrological Processes, 20: 4197-4214.

[15] Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., submitted. Coupling modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.

[16] Clair, T.A., Ehrmann, J. and Higuchi, K., 1998. Changes to the runoff of Canadian ecozones under a doubled CO2 atmosphere. Canadian Journal of Fisheries and Aquatic Science, 55: 2464-2477.

6. Conclusions and next steps

The results of this report document that the climate in BC is already changing, and several hydrological resources are projected to be at risk in the future. Warming trends across BC are consistent with global trends but larger. Precipitation trends are also generally positive, but spatially variable across the Province. However, in the most recent periods (the last 50 years), some precipitation trends are negative. Superimposed on these climate trends, ENSO and PDO variability produces changes of a similar magnitude to historical trends over the past century. Hydrologic impacts of a changing climate include significant decreases in snowpack, retreating glaciers, changes to streamflow timing and magnitude, and earlier lake ice break-up along with shorter lake ice duration. The regional climatic and hydrologic response to ENSO and PDO phases can be quite variable across BC.

Projected climate (2050s) for BC from an ensemble of GCMs is warmer than current conditions with fractional increases in precipitation; the CRCM projection provides additional high-resolution regional detail. Spring snowpack and glaciers in southern BC and the Rocky Mountains are projected to decline by the 2050s, except those located at high elevations. Streamflow in nival or nival-glacier regimes is also projected to decrease. Important changes in projected surface conditions will also change the soil moisture and evaporation feedbacks to the climate system, but quantitative estimates are not available.

What should be done by responsible government and industry in the face of challenges and uncertainty? These results have documented climate changes that are already occurring. There is no longer a question about the *existence* of global climate change, and regardless of any future control of carbon dioxide emissions, questions must now address the timing, magnitude, and unexpected consequences of climate change. Furthermore, if adaptive actions are to be considered, what are the consequences and the costs? In order to improve the detail and quality of climatic and hydrologic information, so as to better support higher-order impacts and adaptation assessment of water resources systems, the following are needed:

- a commitment to monitor the climate system in Pacific North America
- updating future scenarios with new research results as they become apparent
- analysis of extreme weather and hydrologic events
- a thorough analysis of current and projected water resources

With this in mind, each section of this report has also presented the limitations of the analysis, and identified gaps in knowledge. The contents of this report were screened for major topics, opportunities, or analytic tools that are needed to take the next step:

- the observational network of climate and hydrological sites
- analysis of precipitation, snowpack, and hydrographs
- satellite observational resources
- statistics of extreme weather events
- climate variability (ENSO, PDO, AO) and seasonal climate forecasting
- glacier inventory and modeling
- Regional Climate Models (RCMs)
- diagnostic hydrological models, that include parameters of soil moisture, ground cover and evaporation and transpiration feedbacks
- empirical (statistical) downscaling

Among these topics, several deserve special consideration:

- *Development of a comprehensive Diagnostic Hydrologic Model*

The value of hydrologic modeling has already been demonstrated for the Columbia River watershed using the VIC[i] hydrologic model. This model allows a common framework to evaluate all hydrologic components: precipitation, temperature, snowpack, glacier resources, soil moisture, ground water, ground cover, streamflow, and evaporation and transpiration. First, the model would be adapted to BC watersheds. Subsequently, diagnostic studies could assess the hydrologic impact of climate variability and change, as well as the consequences of feedback mechanisms.

- *Diagnostic studies of projections from a Regional Climate Model (RCM)*

The diverse topography and climatology of British Columbia require an RCM at sufficient resolution to match important watersheds with the dimensions of the hydrological model. This work requires the substantial physical and intellectual resources of national laboratories. Fortunately, collaboration with Ouranos, Montréal, and national laboratories at the University of Victoria, bring access to these model results. The output from these models is of great value for diagnostic studies of the climate and hydrological processes.

- *Analysis and projections of extreme weather events (Pacific storms)*

In addition to changes in temperature and precipitation, global climate change has the potential to increase the intensity of Pacific storms. Increasing sea surface temperatures of the Pacific Ocean and changes in climate variability can also contribute to this effect. The Province lies directly in the path of Pacific storms, and changes in intensity are an important concern for hydro-climatology and water management in the future.

[i] VIC, Variable Infiltration Capacity model

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ACIA, 2005. Chapter 6: Cryosphere and Hydrology. In: J.E. Walsh (Editor), The Artic Climate Impact Assessment. . Cambridge University Press, pp. 1042 p.

Adam, J. and Lettenmaier, D.P., 2003. Adjustment of global gridded precipitation for systematic bias. Journal of Geophysical Research, 108(9): 4257, doi:10.1029/2002JD002499.

Azar, J., Sellars, D. and Schroeter, D., 2003. Report for the British Columbia Ministry of Sustainable Resource Development. Hydrometric Business Review: 64pp.

Barrow E., Maxwell, B. and Gachon, P. (Editors), 2004. Climate Variability and Change in Canada: Past, Present and Future, ACSD Science Assessment Series No. 2. Meteorological Service of Canada, Environment Canada, Toronto, ON, 114 pp.

BC Ministry of Environment, 2007 in press. BC State of Environment Report, BC Provincial Government, Victoria, BC.

Bethlahmy, N., 1974. More streamflow after a bark beetle epidemic. Journal of Hydrology, 23: 185-189.

Bethlahmy, N., 1975. A Colorado episode: Beetle epidemic, ghost forests, more streamflow. Northwest Science, 49: 95-105.

Biondi, F., Gershunov, A. and Cayan, D.R., 2001. North Pacific decadal climate variability since 1661. Journal of Climate, 14: 5-10.

Bitz, C.M. and Battisti, D.S., 1999. Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska. Journal of Climate, 12: 3181 - 3196.

Bond, N.A., Overland, J.E., Spillane, M. and Stabeno, P., 2003. Recent shifts in the state of the North Pacific. Geophysical Research Letters, 30(23): 2183, doi: 10,1029/2003GL018597.

Bonsal, B., Prowse, T. and Pietroniro, A., 2002. An assessment of Global Climate Model-simulated climate for the Western Cordillera of Canada (1961-90). Hydrological Processes, 17(18): 3703 – 3716.

Bonsal, B.R. and Prowse, T.D., 2003. Trends and variability in spring and autumn 0 °C isotherm dates over Canada. Climatic Change, 57(3): 341-358.

Bonsal, B.R., Shabbar, A. and Higuchi, K., 2001a. Impacts of low frequency variability modes on Canadian winter temperature. International Journal of Climatology 21: 95-108.

Bonsal, B.R., Zhang, X., Vincent, L.A. and Hogg, W.D., 2001b. Characteristics of daily and extreme temperatures over Canada. Journal of Climate, 14: 1959-1976.

Boon, S., 2007 in press. Snow accumulation and ablation in a beetle-killed pine stand in Northern Interior British Columbia. BC Journal of Ecosystem Management.

Brohan, P., Kennedy, J.J., Harris, I., Tett, S.F.B. and Jones, P.D., 2006. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. Journal of Geophysical Research, 111, D12106, doi:10.1029/2005JD006548.

Brown, R.D., 2000. Northern hemisphere snow cover variability and change, 1915 – 97. American Meteorological Society: 2339 – 2335.

Brugman, M.M., Raistrick, P. and Pietroniro, A., 1998. Chapter 6 - Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon.

Brugman, M.M., Raistrick, P. and Pietroniro, A., 1997. Glacier related impacts of doubling atmospheric carbon dioxide concentration on British Columbia and Yukon (Chapter 6). Environment Canada and BC Ministry of Environment, Lands, and Parks.

Carrar, P.E. and McGimsey, R.G., 1981. The late-neoglacial histories of the Agassiz and Jackson Glaciers, Glacier National Park, Montana. Arctic and Alpine Research, 13: 183-196.

Carroll, A.L. et al., 2006. Impacts of climate change on range expansion by the mountain pine beetle, Natural Resources Canada, Canadian Forest Service, Victoria.

Carter, T.R., Hulme, M. and Lal, M., 1999. Guidelines on the use of scenario data for climate impact and adaptation assessment, Task Group on Scenarios for Climate Impact Assessment, Intergovernmental Panel on Climate Change.

Casola, J.H. et al., 2005. Climate Impacts on Washington's Hydropower, Water Supply, Forests, Fish, and Agriculture., by the Climate Impacts Group (Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle), A report prepared for King County (Washington).

Caya, D. and Laprise, R., 1999. A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. Monthly Weather Review, 127: 341-362.

Champoux, A. and Ommanney, C.S.L., 1986. Evolution of the Illecillewaet Glacier, Glacier National Park, B.C. using historical data, aerial photography, and satellite image analysis. Annals of Glaciology, 8: 31-33.

Cheng, J.D., 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in Southern British Columbia, Canada. Water Resources Research, 25: 449-456.

Chilton, R.H., 1981. A summary of climate regimes of British Columbia, BC Ministry of Environment, Victoria, BC.

Christensen, J.H. et al., 2007. Regional Climate Projections. In: S. Solomon et al. (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge United Kingdom and New York, NY, USA.

Clair, T.A., Ehrmann, J. and Higuchi, K., 1998. Changes to the runoff of Canadian ecozones under a doubled CO2 atmosphere. Canadian Journal of Fisheries and Aquatic Science, 55: 2464-2477.

Cohen, S. and Kulkarni, T., 2001. Water Management & Climate Change in the Okanagan Basin, Environment Canada/University of British Columbia, Vancouver BC.

Cohen, S. et al., 2006. Learning with local help: Expanding the dialogue on climate change and water management in the Okanagan Region, British Columbia, Canada. Climatic Change, 75: 331–358.

Cohn, T.A. and Lins, H.F., 2005. Nature's style: Naturally trendy. Geophyscial Research Letters, 32: L23402, doi:10.1029/2005GK024476.

Daly, C., 2006. Guidelines for assessing the suitability of spatial climate data sets. International Journal of Climatology(26): 707-721.

Daly, C., Neilson, R.P. and Phillips, D.L., 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology, 33: 140-158.

de Elia, R. et al., submitted (2006). Evaluation of uncertainties in the CRCM-simulated North American climate: nesting-related issues. Climate Dynamics.

Debeer, C.M. and Sharp, M.J., 2007. Recent changes in glacier area and volume within the southern Canadian Cordillera. Annals of Glaciology, 46: 215-221.

Donders, T.H., Wagner, F., Dilcher, D.L. and Visscher, H., 2005. Mid- to late-Holocene El Nino-Southern Oscillation dynamics reflected in the subtropical terrestrial realm. Proceedings of the National Academy of Sciences, 102(31): 10904 - 10908.

Duffy, P.B. et al., 2006. Simulations of present and future climates in the Western United States with four nested Regional Climate Models. Journal of Climate, 19(6): 873–895.

Duguay, C.R. et al., 2006. Recent trends in Canadian lake ice cover. Hydrological Processes, 20: 781-801.

Dyer, J.L. and Mote, T.L., 2007. Trends in snow ablation over North America. International Journal of Climatology, 27: 739-748.

Dyurgerov, M.B. and McCabe, G.J., 2006. Associations between accelerated glacier mass wastage and increased summer temperature in coastal regions. Arctic, Antarctic, and Alpine Research, 38(2): 190-197.

Dyurgerov, M.B. and Meier, M.F., 2005. Glaciers and the Change Earth System: A 2004 Snapshot, Institute of Arctic and Alpine Research, University of Colorado, Boulder.

Eaton, B. and Moore, R.D., 2007 in press. Chapter 4: Regional Hydrology. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.

Environment Canada, 2005. Environmental Indicators: Temperature and Precipitation. Environment Canada, Pacific and Yukon Region.
Fleming, S. and Clark, G.K.C., 2005. Attenuation of high-frequency interannual streamflow variability by watershed glacial cover. ASCE Journal of Hydraulic Engineering, 131(7): 615-618.
Fleming, S., Moore, R.D. and Clarke, G.K.C., 2006. Glacier-mediated streamflow teleconnections to the Arctic Oscillation. International Journal of Climatology, 26: 619–636.
Fleming, S.W., 2005. Comparative analysis of glacial and nival streamflow regimes with implications for lotic habitat quantity and fish species richness. River Research and Applications, 21: 363-379.
Fleming, S.W., Whitfield, P.H., Moore, R.D. and Quilty, E.J., 2007. Regime-dependent streamflow sensitivities to Pacific climate modes cross the Georgia–Puget transboundary ecoregion. Hydrological Processes, 21(24): 3264-3287.
Gachon, P. et al., 2005. A first evaluation of the strength and weaknesses of statistical downscaling methods for simulating extremes over various regions of Eastern Canada.
Gao, S. and Stefan, H.G., 2004. Potential climate change effects on ice covers of five freshwater lakes. Journal of Hydrologic Engineering, May/June(226-234).
Gedalof, Z., Peterson, D.L. and Mantua, N.J., 2004. Columbia River flow and drought since 1750. Journal of the American Water Resources Association, 40: 1579-1592.
Gedalof, Z. and Smith, D.J., 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophysical Research Letters, 28: 1515 - 1518.
Gershunov, A. and Barnett, T.P., 1998. Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society, 79(12): 2715-2725.
Gobena, A.K. and Gan, T.Y., 2006. Low-frequency variability in Southwestern Canadian stream flow: Links with large-scale climate anomalies. International Journal of Climatology, 26: 1843 - 1869.
Goodess, C.M., Frei, C. and Schmidli, J., 2005. Temperature and precipitation extremes at the station and climate model grid-point scales: Some lessons learnt from the statistical and dynamical approaches to downscaling used in the STARDEX project. Geophysical Research Abstracts, 7: 03758.
Goodess, C.M., Osborn, T.J. and Hulme, M., 2003. The identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events, Tyndall Centre for Climate Change Research, Norwich, UK.
Goodison, B.E., 1978. Accuracy of Canadian snow gauge measurements. American Meteorological Society, 17: 1542-1548.
Groisman, P.Y., Karl, T.R., Knight, R.W. and Stenchikov, G.L., 1994. Changes in snow cover, temperature, and radiative heat balance over the Northern Hemisphere. Journal of Climate, 7: 1633-1656.
Gutowski, W., 2005. The North American Regional Climate Change Assessment Program (NARCCAP): A multiple AOGCM and RCM climate scenario project over North America. Geophysical Research Abstracts 7: 05975.
Hall, M.H.P. and Fagre, D.B., February 2003. Modeled Climate-Induced Glacier Change in Glacier National Park, 1850-2100. BioScience, 53(2): 131-140.
Hamlet, A.F., 2001. Effects of climate change on water resources in the Pacific Northwest: Impacts and policy implications, Climate Impacts Group, University of Washington, Seattle, Skamania, Washington.
Hamlet, A.F., 2003. The role of transboundary agreements in the Columbia River Basin: An integrated assessment in the context of historical development, climate, and evolving water policy. In: H. Diaz and B. Morehouse (Editors), Climate, Water and Transboundary Challenges in the Americas. Kluwer Press, Boston, pp. 263-289.
Hamlet, A.F. and Lettenmaier, D.P., 1999a. Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals. Journal of Water Resources Planning and Management, 125(6): 333-341.

Hamlet, A.F. and Lettenmaier, D.P., 1999b. Effects of climate change on hydrology and water resources in the Columbia River Basin. Journal of the American Water Resources Association, 35(6): 1597-1623.

Hamlet, A.F., Mote, P.W., Clark, M.P. and Lettenmaier, D.P., 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. Journal of Climate, 18(21): 4545-4561.

Hanson, C.E., Palutikof, J.P., Dlugolecki, A. and Giannakopoulos, C., 2006. Bridging the gap between science and the stakeholder: The case of climate change research. Climate Research, 31(1): 121-133.

Hebda, R.J., 1995. British Columbia vegetation and climate history with focus on 6 KA BP. . Geographie Physique et Quaternaire, 49: 55-79.

Hélie, J.F., Peters, D.L., Tattrie, K.R. and Gibson, J.J., 2005. Review and synthesis of potential hydrologic impacts of mountain pine beetle and related harvesting activities in British Columbia: Mountain Pine Beetle Initiative Working Paper 2005-23. Natural Resources Canada, Canadian Forest Service, Victoria BC.

Henderson-Sellers, A., 1989. Continental cloudiness changes this century. GeoJournal, 27(3): 255-262.

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology, 319: 83-95.

IPCC, 2007a. Summary for Policymakers. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 22 pp.

IPCC, 2007b. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 18 pp.

Jakob, M., McKendry, I. and Lee, R., 2003. Long-term changes in rainfall intensity in Vancouver, British Columbia. Canadian Water Resources Journal, 28(4): 587-604.

Karoly, D.J. and Wu, Q., 2005. Detection of regional surface temperature trends. Journal of Climate, Letters, 18: 4337-4343.

Kaser, G., Cogley, J.G., Dyurgerov, M.B., Meier, M.F. and Ohmura, A., 2006. Mass balance of glaciers and ice caps: Consensus estimates for 1961-2004. Geophysical Research Letters, 33(L19501): 1-5.

Kharin, V.V., Zwiers, F.W., Zhang, X. and Hegerl, G.C., 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of Global Coupled Model simulations. Journal of Climate, 20: 1419-1444.

Kiffney, P.M., Bull, J.P. and Feller, M.C., 2002. Climatic and hydrologic variability in a coastal watershed of Southwestern British Columbia. Journa of the American Water Resources Association, 38(5): 1437 - 1451.

Knowles, N., Dettinger, M., and Cayan, D., 2006. Trends in snowfall versus rainfall for the Western United States. Journal of Climate, 19(18): 4545-4559.

Koch, J., Menounos, B., Clague, J.J. and Osborn, G.D., 2004. Environmental changes in Garabaldi Provincial Park, southern Coast Mountains, British Columbia. Geoscience Canada, 31(3): 127-135.

Ladekarl, U.L., Normberg, P., Rasmussen, K.R., Nielsen, K.E. and Hansen, B., 2001. Effects of a heather beetle attack on soil moisture and water balance at a Danish heathland. Plant and Soil, 239: 147-158.

Laprise, R., Caya, D., Frigon, A. and Paquin, D., 2003. Current and pertubed climate as simulated by the second-generation Canadian Regional Climate Model over Northwestern North America. Climate Dynamics, 21: 405-421.

Larsen, C.F., Motyka, R.J., Arendt, A.A., Echelmeyer, K.A. and Giessler, P.E., 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research, 112(F01007): 1-11.
Leith, R.M. and Whitfield, P.H., 1998. Evidence of climate change effects on the hydrology of streams in South-Central B.C. Canadian Water Resources Journal 23: 219-230.
Leung, L.R. and Qian, Y., 2003. Changes in Seasonal and Extreme Hydrologic Conditions of the Georgia Basin/Puget Sound in an Ensemble Regional Climate Simulation for the Mid-Century. Canadian Water Resources Journal, 28(4): 605-631.
Loukas, A., Lampros, V. and Dalezios, N.R., 2002a. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259: 163-188.
Loukas, A., Vasiliades, L. and Dalezios, N.R., 2002b. Potential climate change impacts on flood producing mechanisms in southern British Columbia, Canada using the CGCMA1 simulation results. Journal of Hydrology, 259: 163-188.
Loukas, A., Vasiliades, L. and Dalezios, N.R., 2004. Climate change implications on flood response of a mountainous watershed. Water, Air, and Soil Pollution: Focus, 4: 331-347.
Love, L.D., 1955. The effect on stream flow of the killing of spruce and pine by the Engleman spruce beetle. Transaction of the American Geophysical Union, 36: 113-118.
Luckman, B.H., Harding, K.A. and Hamilton, J.P., 1987. Recent glacier advances in the Premier Range, British Columbia. Journal of Earth Sciences, 24: 1149-1161.
Mantua, N.J. and Hare, S.R., 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47: 103–145.
Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78: 1069-1079.
McCabe, G.J. and Clark, M.P., 2005. Trends and variability in snowmelt runoff in the Western United States. Journal of Hydrometeorology, 6: 476 - 482.
Mekis, E. and Hogg, W.D., 1999: . Rehabilitation and analysis of Canadian daily precipitation time series. Atmosphere-Ocean(37): 53-85.
Menounos, B., 2006. Proposal: Western Canadian Cryospheric Network.
Menounos, B. and Wheate, R., 2007. State and fate of Western Canadian glaciers, Conference, Ministry of the Environment, Victoria, BC.
Merritt, W.S. et al., 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology, 326: 79-108.
Miles, M., and Associates, 2003. British Columbia's Climate Related Observation Networks: An Adequacy Review. Report to the Ministry of Environment, Victoria, BC.
Mitchell, T.D. and Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. International Journal of Climatology, 25(6): 693 - 712.
MoFR, 2006. Preparing for Climate Change: Adapting to Impacts on British Columbia's Forest and Range Resources, Ministry of Forests and Range, Victoria BC.
Moore, R.D., 1991. Hydrology and water supply in the Fraser River basin. In: A.H.J. Dorcey and J.R. Griggs (Editors), Water in Sustainable Development: Exploring our Common Future in the Fraser River Basin. Westwater Research Centre, UBC, Vancouver, BC, pp. 21-40.
Moore, R.D., 2007. Introduction to Glacier Hydrology, Climate Change and Low Flows - Influence of Glaciers and Groundwater, Vancouver, BC.
Moore, R.D. and Demuth, M.N., 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. Hydrological Processes, 15: 3473-3486.
Moore, R.D. and McKendry, I.G., 1996. Spring snowpack anomaly patterns and winter climatic variability, British Columbia, Canada. Water Resources Research, 32(3): 623-632.

Moore, R.D., Spittlehouse, D.L., Whitfield, P.H. and Stahl, K., 2007 in press. Chapter 3: Weather and Climate. In: R.G. Pike, and others (Editor), Compendium of Forest Hydrology and Geomorphology in British Columbia. BC Ministry of Forests and Range, Research Branch, Victoria, BC and FORREX Forest Research Extension Partnership, Kamloops, BC.
Morrison, J., Quick, M.C. and Foreman, M.G.G., 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology, 263: 230-244.
Mote, P., Salathe, E. and Peacock, C., 2005a. Scenarios of future climate for the Pacific Northwest, Climate Impacts Group Report, University of Washington.
Mote, P.W., 2003a. Twentieth-century fluctuation and trends in temperature, precipitation, and mountain snowpack in the Georgia Basin-Puget Sound region, Canada. Water Resources Journal, 28(4): 567-585.
Mote, P.W., 2003b. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters, 30(12): 1601, 3-1 to 3-4.
Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in Western North America. American Meterological Society, 19: 6209 - 6220.
Mote, P.W., A.F. Hamlet, and E.P. Salathé., 2007 in press. Has spring snowpack declined in the Washington Cascades? Hydrology and Earth System Sciences Discussions, 4: 2073-2110.
Mote, P.W., Hamlet, A.F., Clark, M.P. and Lettenmaier, D.P., 2005b. Declining mountain snowpack in Western North America. Bulletin of the American Meteorological Society, 86: 39-49.
New, M., Hulme, M. and Jones, P., 1999. Representing twentieth-century space–time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. Journal of Climate, 12(3): 829–856.
Nijssen, B., Schnur, R. and Lettenmaier, D.P., 2001. Global retrospective estimation of soil moisture using the Variable Infiltration Capactiey land surface model, 1980-93. Journal of Climate, 14: 1790-1808.
Ohmura, A., 2001. Physical basis for temperature/melt-index method. Journal of Applied Meteorology, 40: 753-761.
Palmer, T.N., 1999. A nonlinear dynamical perspective on climate prediction. Journal of Climate, 12: 575-591.
Parson, E.A. et al., 2001a. Chapter 9 - Potential Consequences of Climate Variability and Change for the Pacific Northwest.
Parson, E.A. et al., 2001b. Chapter 9: Potential Consequences of Climate Variability and Change for the Pacific Northwest. In: National Assessment Synthesis Team (Editor), Climate Change Impacts on the United States The Potential Consequences of Climate Variability and Change. US Global Change Research Program.
Pelto, M.S., 2007. Glacier annual balance measurement, prediction, forecasting and climate correlations, North Cascades, Washington 1984-2006. The Cryosphere Discussion, 1: 17-39.
Peterson, W.T. and Schwing, F.B., 2003. A new climate regime in northeast pacific ecosystems. Geophyscial Research Letters, 30(17): 1896, doi: 10.1029/2003GL017528.
Phillips, D., 1980. The Climates of Canada, Supply and Services Canada, Ottawa.
Plummer, D.A. et al., 2006. Climate and climate change over North America as simulated by the Canadian RCM. Journal of Climate, 19: 3112 - 3132.
Post, A., Richardson, D., Tangbor, W.V. and Rosselot, F.L., 1971. Inventory of glaciers in the North Cascades, Washington. In: USGS (Editor). Prof. Paper.
Potts, D.F., 1984. Hydrologic impacts of large-scale mountain pine beetle (*Dendroctonus Ponderosae* Hopkins) epidemic. Water Resources Research, 20: 373-377.
Salathe, E.P., Mote, P.W. and Wiley, M.W., in press (2007). Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest. International Journal of Climatology.
Schiefer, E., Menounos, B. and Wheate, R., 2007. Recent volume loss of British Columbia glaciers, Canada. Geophysical Research Letters, 34(L16503): 1-6.

Shabbar, A., 1996. The impact of El Nino-Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean, 34(2): 401-416.
Shabbar, A., 2006. The impact of El Nino-Southern Oscillation on the Canadian climate. Advances in Geosciences, 6: 149-153.
Shabbar, A., Bonsal, B. and Khandekar, M., 1997. Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate, 10: 3016 - 3026.
Shea, J.M. and Marshall, S.J., 2007. Atmospheric flow indices, regional climate, and glacier mass balance in the Canadian Rocky Mountains. International Journal of Climatology, 27: 233-247.
Shea, J.M., Marshall, S.J. and Livingston, J.M., 2004. Glacier distributions and climate in the Canadian Rockies. Arctic, Antarctic, and Alpine Research, 36(2): 272-279.
Shuttleworth, W.J., 2007. Putting the "vap" into evaporation. Hydrological Earth System Sciences, 11: 210-244.
Sidjack, R.W. and Wheate, R.D., 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elvation data. International Journal of Remote Sensing, 20(2): 273-284.
Smith, T.M. and Reynolds, R.W., 2005. A global merged land and sea surface temperature reconstruction based on historical observations (1880–1997). Journal of Climate, 18: 2021–2036.
Solomon, S. et al., 2007. Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Stahl, K. and Moore, R.D., 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research, 42(W06201): 1-5.
Stahl, K., Moore, R.D., Floyer, J.A., Asplin, M.G. and McKendry, I.G., 2006a. Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. Agricultural and Forest Meteorology, 139: 224-236.
Stahl, K., Moore, R.D. and McKendry, I.G., 2006b. Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada. Climate Research, 32: 13-23.
Stahl, K., Moore, R.D. and McKendry, I.G., 2006c. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology, 26(4): 541-560.
Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., 2007 in press. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.
Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., in press. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.
Stahl, K., Moore, R.D., Shea, J.M., Hutchinson, D. and Cannon, A., submitted. Coupling modelling of glacier and streamflow response to future climate scenarios. Water Resources Research.
Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2004. Changes in snowmelt runoff timing in Western North America under a 'business as usual' climate change scenario. Climate Change, 62: 217-232.
Stewart, I.T., Cayan, D.R. and Dettinger, M.D., 2005. Changes toward Earlier Streamflow Timing across Western North America. Journal of Climate, 18: 1136-1155.
Stone, D.A., Weaver, A.J. and Zwiers, F.W., 2000. Trends in canadian precipitation intensity. Atmosphere-Ocean, 38(2): 321-347.
Storlazzi, C.D., Willis, C.M. and Griggs, G.B., 2000. Comparative impacts of the 1982-3 and 1997-8 El Niño winters on the central California coast. Journal of Coastal Research
16(1022-1036).
Sushama, L., Laprise, R., Caya, D., Frigon, A. and Slivitzky, M., 2006. Canadian RCM projected climate-change signal and its sensitivity to model errors. International Journal of Climatology, 26: 2141-2159.

Sydneysmith, R. and Walker, I.J., 2007 in press. BC Chapter. In: D. Lemmon (Editor), The Canadian National Assessment on Climate Change. Federal Government of Canada, Toronto, ON.
Toth, B., Pietroniro, A., Conly, F.M. and Kouwen, N., 2006. Modelling climate change impacts in the Peace and Athabasca catchment and delta: I - hydrological model application. Hydrological Processes, 20: 4197-4214.
Troendle, C.A. and Nankervis, J.E., 2000. Estimating additional water yield from changes in management of national forests in the North Platte Basin, Platte River Office Bureau of Reclamation, Lakewood CO.
Uunila, L., Guy, B. and Pike, R., 2006. Hydrologic effects of mountain pine beetle in the interior pine forests of British Columbia: Key questions and current knowledge. Extended Abtract. BC Journal of Ecosystems and Management, 7(2): 37-39.
Valentine, K.W.G., Sprout, P.N., Baker, T.E. and Lavkulich, L.M., 1978. The Soil Landscapes of British Columbia, BC Ministry of Environment, Resource Analysis Branch, Victoria BC.
Wade, N.L., Martin, J. and Whitfield, P.H., 2001. Hydrologic and climatic zonation of Georgia Basin, British Columbia. Canadian Water Resources Journal, 26: 43-70.
Wang, T.L., Hamann, A., Spittlehouse, D.L. and Aitken, S.N., 2006. Development of scale-free climate data for Western Canada for use in resource management. International Journal of Climatology, 26: 383-397.
Whitfield, P.H., 2001. Linked hydrologic and climate variations in British Columbia and Yukon. Environmental Monitoring and Assessment, 67: 217-238.
Whitfield, P.H., Bodtker, K. and Cannon, A.J., 2002a. Recent variations in seasonality of temperature and precipitation in Canada, 1976-1995. International Journal of Climatology 22: 1617-1644.
Whitfield, P.H. and Cannon, A.J., 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25: 19-65.
Whitfield, P.H., Reynolds, C.J. and Cannon, A.J., 2002b. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal 27(4): 427-456.
Whitfield, P.H. and Taylor, E., 1998. Apparent Recent Changes in Hydrology and Climate of Coastal British Columbia. In: Y. Alila (Editor), Mountains to Sea: Human Interaction with the Hydrologic Cycle. Proceedings of 51st Annual Canadian Water Resources Conference, pp. 22-29.
Whyte, J., 2006. Extreme weather impacts on PEP and Public Safety. CWRA Conference Proceedings, CWRA Conference, Victoria, BC.
Zhang, X., Harvey, D.K., Hogg, W.D. and Yuzyk, T.D., 2001a. Trends in Canadian streamflow. Water Resources Research, 37(4): 987–998.
Zhang, X., Hogg, W.D. and Mekis, É., 2001b. Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate, 2001(14): 1923-1936.
Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th Century. Atmosphere-Ocean 38(3): 395–429.
Zhang, Y., Wallace, J.M. and Battisti, D.S., 1997. ENSO-like interdecadal variability:1900–93. Journal of Climate, 10: 1004–1020.