PACIFIC CLIMATE IMPACTS CONSORTIUM

Preliminary Analysis of Climate Variability and Change in the Canadian Columbia River Basin: Focus on Water Resources

COLUMBIA BASIN TRUST

October 2006

This report focuses on the geographic area that is designated in the shaded area above and is consistent with the Columbia Basin Trust Act. Except where noted, most analysis and discussion excludes the Okanagan and the U.S. portions of the Columbia Basin.

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[1] Through participants in the draft BC Chapter National Assessment of Climate Change
[2] The aim of the Western Canadian Cryospheric Network (WC^{2}N) is to understand the behaviour of the climate system and its effects on glacier mass balance in the mountain ranges of British Columbia and western Alberta.

ABBREVIATIONS AND ACRONYMS

AHCCD	Adjusted Historical Canadian Climate Data
Basin	Canadian Portion of the Columbia River Basin, excluding the Okanagan sub-basin.
BC	British Columbia
CBT	Columbia Basin Trust
CO_2	Carbon Dioxide
CRB	Columbia River Basin *including both Canadian and American portions.*
ENSO	El Nino/Southern Oscillation
GCMs	Global Climate Models
GDD	Growing Degree Days
IPCC	United Nations Intergovernmental Panel on Climate Change
PDO	Pacific Decadal Oscillation
PCIC	Pacific Climate Impacts Consortium
PNW	Pacific Northwest
SWE	Snow-water equivalent (depth of water from a column of melted snow)
WLAP	BC Ministry of Water, Land and Air Protection (now Ministry of Environment)

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EXECUTIVE SUMMARY

Earth's climate is maintained through radiation balance of solar heating and infrared cooling, moderated through the effects of clouds and trace gases, and the present temperatures at the surface of the Earth where we live are sustained through the action of a greenhouse effect. There is a scientific consensus that increases of trace gases including carbon dioxide have already increased the mean temperature of the Earth system of land, oceans, and ice. Moreover, this warming process is expected to accelerate, not only because of the continued accumulation of carbon dioxide, but also because of positive feedbacks from changes that have already occurred. Subsequently, the social, economic, and biological responses to these changes will be large and will include unexpected consequences.

Although the Columbia River Basin (CRB) is only a small fraction of the globe, this basin is extraordinarily important as a fresh water resource for agriculture, fisheries, power-generation, First Nations, and urban users in the Pacific Northwest. The mountain snowpack and glaciers of the CRB are critical, since 30% of the annual flow is derived from these natural storage resources. Moreover, this resource is shared between Canada and the United States.

The critical issues of water resources management in the Pacific Northwest have been identified in several studies over the past 10 years. Climate impacts on the CRB may be inferred, and some differentiation between the northern and southern portions of the basin can be estimated.

- A small increase in the average temperature may cause profound changes in runoff by increasing the frequency of melt events (even) without addition increases in precipitation.
- The sensitivity of snowpack and glacier water storage to increased temperatures is greater where winter temperature is near freezing (to the south and at lower elevations).
- The effect of warmer temperatures is to shift the timing of the runoff freshet to earlier in the spring, thus depleting the storage that would have been available for the later summer season. This pattern is independent of any seasonal precipitation changes.
- The changes in the water storage capacity of the CRB and timing of the runoff have serious consequences for the competing interests of water resources. These changes are expected to become greater in the coming decades, posing a serious challenge to water managers and users.

The historical observations of temperature and precipitation at five stations within the Canadian watershed of the CRB were evaluated for this report. The results are, over a 90-year historical record:

- Annual temperature trend increased by 1.4°C, somewhat greater than the trend for Pacific Northwest.
- Annual precipitation increased by +26% (+32% rainfall; -6% snowfall).

Furthermore, climate projections from an ensemble of Global Climate Models were evaluated for the Canadian portion of the CRB. The results are:

- increased annual temperature for the 2020s, 2050s, and 2080s of 1.3°C, 2.6°C, and 4.3°C, respectively.
- increased annual precipitation for the 2020s, 2050s, and 2080s of 2%, 3%, and 7%, respectively but drier summers.

The impacts of these observed changes and projections on water resources of the CRB are a matter of considerable concern:

Glaciers and Snowpack

- *All* glaciers within the CRB have experienced a net loss in area during the past 15 years (ending in 2000). The average loss was -16%, and some small glaciers have retreated up to -60%. This is consistent with the reduction of glaciers worldwide.
- A reduction in snowpack in the Canadian portion of the CRB of -4% and -12% for the 2020s and 2040s, respectively. Recent projections of snowpack inferred from hydrological modeling for the US sector of the CRB indicate extraordinary losses of snowpack of -21% and -35% for the 2020s and 2040s, respectively. This projection also implies continued erosion of glacier mass and area.

Streamflow and Soil moisture

- Hydrological models of streamflow at selected sites (Waneta and Mica) indicate a shift to early runoff and late summer reductions in streamflow.
- For the entire CRB, reductions in peak streamflow of 20% have been projected. These declines could result in severe reductions in power generation and power deficits throughout the summer season.
- Increased summer temperatures, low summer precipitation, and low runoff in the CRB would increase drought potential.

In addition to global climate change and warmer average temperatures, the CRB and the Pacific Northwest are also exposed to the variability of the Pacific Decadal Oscillation and the Pacific North American oscillation that carries El Niño and La Niña influences from the tropics. These sources of climate variability may reinforce the impacts of climate change, or may introduce additional impacts that have not yet been described.

Therefore, the uncertainty of the future climate must be balanced with the available evidence that has been assembled. Several next steps are recommended for monitoring and documenting the inevitable changes that will occur in the CRB, including:

- Monitoring of the water resources of the CRB.
- Repeated applications of Global Climate Models and hydrological models to refine current understanding and revise the projections.
- Study the storage capacity of the CRB watersheds
- Document past changes in human water use/consumption and develop potential scenarios of future use
- Quantify risks of spring flooding, hydropower deficits in the summer, and threat of low water for salmon in the fall
- A collective effort to prepare communities and industry for change
- Begin a dialogue to understand the risks and adaptive capacity to hydrologic changes
- Develop flexibility; prepare for surprises
- Consult seasonal climate predictions for yearly planning, and climate change projections for long-range planning

PREFACE

It is a pleasure to introduce the first regional assessment report of the Pacific Climate Impacts Consortium. In so doing, I must immediately acknowledge the assistance of a team of editors, contributors, and reviewers, as well as the support of the Columbia Basin Trust. The report draws heavily upon the work of others, in particular the University of Washington's Climate Impacts Group in Seattle. All contributors are identified in the *Acknowledgements* of this report.

In response to a need for more information on the physical impacts of climate change, the Columbia Basin Trust (CBT) Water Initiatives Program commissioned this report last year. Subsequently, an informational brochure, *Climate Change in the Canadian Columbia Basin: Starting the Dialogue* was developed. The audience for this report is managers, planners, and citizens of the Basin.

The importance of the Columbia Basin in Pacific North America cannot be overstated, especially for the people who live in the Basin and in the Province of British Columbia. The context for the management of water resources is the international treaty that will soon be renegotiated by British Columbia, Canada and the United States.

Although this report has become publicly available today, the formal date of publication recognizes the foundation work that was concluded in October 2006. About that time there was a new national and international recognition of the importance of global warming. Subsequently, the IPCC Fourth Assessment Report published in the spring of this year (2007) reinforced the analysis of this report. Although there has been rigorous editing, the essential message has not changed and the regional impacts that are described are more relevant that ever.

This report is published, but not finished. The cascade of new information on global climate change demands that regional impacts be monitored and reassessed frequently. PCIC brings a multi-disciplinary consortium to focus on water resources and our awareness of regional climate impacts. Further, I hope this report will be a useful foundation for subsequent regional assessments in Pacific North America with updated information and with the addition of socio-economic and ecosystem impacts.

Dave Rodenhuis, Acting Director
Pacific Climate Impacts Consortium
27 July 2007

1 INTRODUCTION

1.1 Purpose

This report was commissioned by The Water Initiatives Program of the Columbia Basin Trust (CBT) in order to provide preliminary technical background information on climate change in the Canadian portion of the Columbia River Basin as defined by the Columbia Basin Trust Act (see map on inside front cover). This area, bounded by the Monashee Mountains to the west and the Rocky Mountains to the east, is referred to in this report as “the Basin”.

The report provides a preliminary technical analysis of historical climate trends and variability in the Canadian portion of the Columbia River Basin and an overview of projected future climate change. It also provides information about the past and potential future impacts of climate change on water resources in the region. Its purpose is to inform the development of educational brochures and materials to inform stakeholders in the CBT region about the potential impacts of climate change. It is principally a synthesis and overview of existing technical knowledge, with some additional contributions on historical trends and future projections. It is not intended to be a full and final assessment of climate change implications for the Basin. Significant gaps in knowledge remain, and more research and monitoring are required to more fully understand this complex and important issue. This information may inform the development and implementation of adaptation strategies to prevent damage, reduce costs, and protect members of the community, as well as realize any potential benefits of these changes.

1.2 Geography and Hydrology of the Columbia River Basin

Most of the Columbia River Basin (CRB) in Canada and the United States lies in the Intermountain Region delineated by the Rocky Mountains to the east and north, and the Cascade Mountains to the west[3]. CRB topography is characterized by a series of mountain ranges that climb to significant elevations.

The natural hydrology of the CRB is strongly dominated by winter snow accumulation and melt, as most of the precipitation in the area falls between October and March. Natural runoff shows a characteristic low flow period in the fall and winter months, and a large spring peak flow or freshet from snow melt. However, the annual hydrograph of the Columbia River over the last 40 years is not characteristic of natural processes because the flow of the river is heavily regulated through many dams. Greater than natural flows occur in winter due to releases of reservoir storage for cold season energy production, followed by less than natural flows in the spring, reducing the peak flow for flood control. Flood control is achieved by evacuating reservoirs in mid-winter and then refilling them in the early summer with the freshet waters that might otherwise create flood conditions.

Approximately 25-50 percent (depending on the season) of the total runoff for the Columbia River system originates in the Canadian portion of the system, although it is only 15 percent of the total CRB area (Hamlet, 2003; Muckleston, 2003; BPA, 2001). The contribution from Canada is most significant in late summer – for example in late summer roughly 50% of the flow in the Columbia River at The Dalles, Oregon originates in Canada.

1.3 Global Context of Climate Change

Significant variations and changes in climate occurred around the globe in the 20th century. For example, the average global temperature increased by approximately 0.6°C over the 20th century and will continue to increase during the 21st century by 1.9 to 4.0°C (IPCC, 2001). In southern Canada, annual mean temperature has increased an average of 0.9°C over the past century (Zhang *et al.* 2000).

[3] A small portion of the total CRB lies west of the Cascade Mountains; the climate, hydrology, and water management issues are fundamentally different for this area than for the rest of the CRB.

Although these changes seem small compared to normal seasonal and even the daily temperature ranges usually experienced by citizens of the Basin, a change of apparently small magnitude can have large impacts. For example, an average global temperature increase of 4ºC between approximately 18,000 to 10,000 years ago was sufficient to melt the vast ice sheets that once covered much of North America (Walker and Pellatt, 2003). Further comparisons of historical climate trends and future climate projections at the regional and global scale to the Basin are made in section 3.10.

A number of uncertainties about the rate and timing of climate change remain. In addition to uncertainties in modeling the climate system, the rate of climate change over the next century depends on the amount of greenhouse gas emissions produced globally. However, the scientific consensus is that Earth's climate in the twenty-first century will be different than the climate of recent history (IPCC, 2001).

1.4 Overview of the Report

- Section 2 of this report describes concepts such as weather, climate variability, and climate change and provides a foundation for the chapters that follow
- Section 3 describes historical climate trends and future climate projections for the Basin.
- Section 4 describes the impacts of past and potential future climate change on water resources in the Basin.
- There are two appendices. Appendix A describes data sources and procedures for analysis. Appendix B describes the procedure for determining historical climate trends.

2 CLIMATE CONCEPTS, TERMS AND MEASUREMENT

The science of climate variability and change incorporates specialized concepts, technical terminology and measurement practices. In this section concepts and terms are listed and discussed, with some additional attention to those that are often misunderstood.

2.1 Climate Time Scales, Concepts and Terms

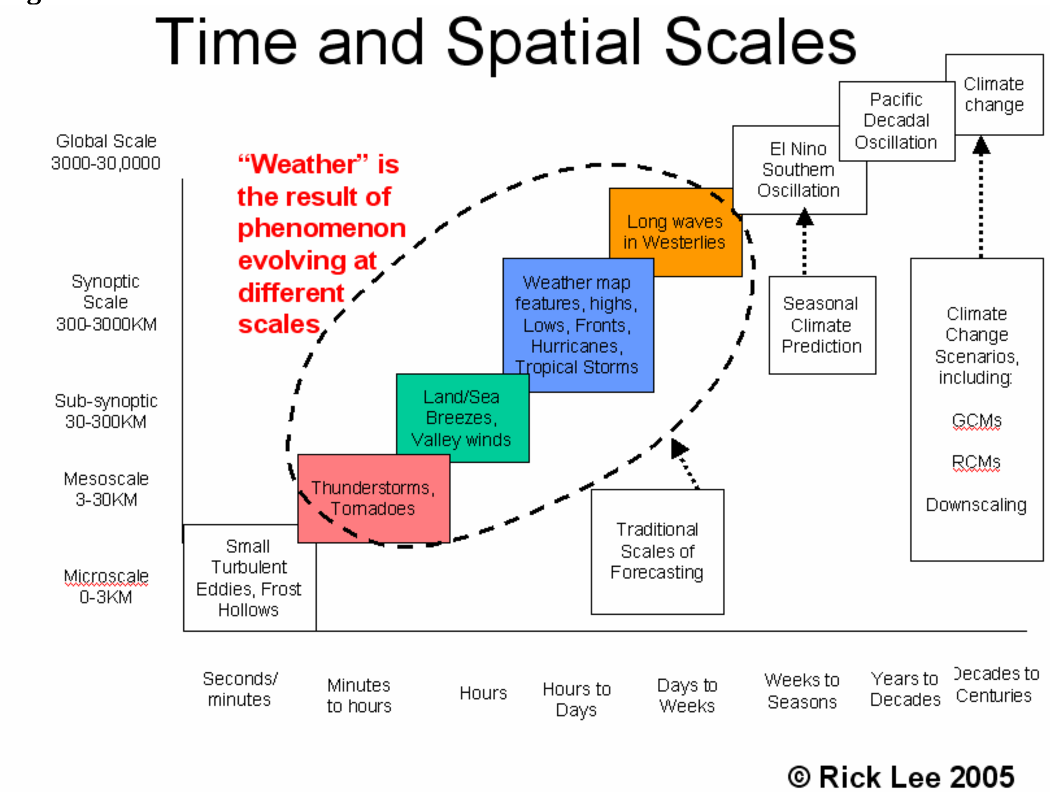
2.1.1 Climate and Weather

Climate[4]	*Climate in a narrow sense is usually defined as the "average weather" or more rigorously as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The traditional period is 30 years, as defined by the World Meteorological Organization (WMO). The climate of an observational site is often described by average value of relevant observations, such as temperature, precipitation, or wind. Climate in a wider sense is the state of the global climate system, including a statistical description of all relevant variables.*
Weather	*The term 'weather' describes the day-to-day and hour-by-hour changes in atmospheric conditions at a given location.*

Although the terms "climate" and "weather" are often used interchangeably, there is an important distinction. Weather describes the atmospheric conditions at a given time and location. Climate is the synthesis of day-to-day variations into a set of average conditions, often based on a statistical summary such as average 30-year record of weather observations. Figure 2.1 shows the relationship between weather and climate.

[4] Definitions are based on the Intergovernmental Panel on Climate Change (IPCC 2001 Annex B) and supplementary information provided by PCIC and other contributors. Environment Canada's website http://www.ec.gc.ca/climate/ provides detailed information on other climate concepts.

Figure 2.1: Time scales of weather and climate



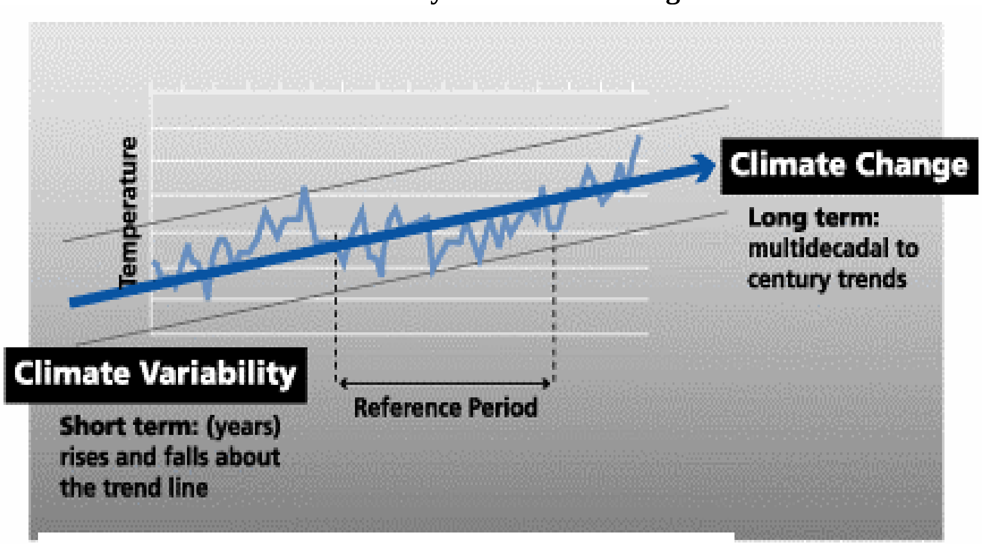
2.1.2 Climate Change and Climate Variability

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Climate change: Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, over an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcing such as persistent anthropogenic changes in the composition of the atmosphere or in land use.

The terms "climate variability" and "climate change" are sometimes used interchangeably just as weather and climate are, though they too denote different phenomena. The convention adopted in this document is to distinguish between the two based on time scale only. Recall from 2.1.1 that climate can be defined on various time scales. Consider for this report a standard period of a few decades. Climate variability then refers to oscillations and variations experienced on shorter time scales such as years or decades, and climate change refers to changes on longer time scales such as half a century or more. Figure 2.2 shows the time scales of climate variability and change as they are used in this document.

Figure 2.2: Time scales of climate variability and climate change



WLAP 2002

2.1.3 Important aspects of climate variability and climate change

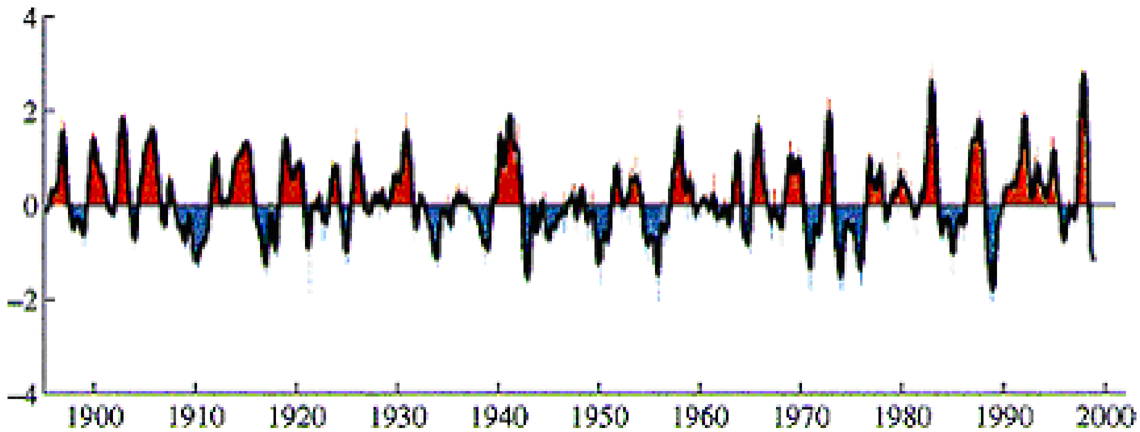
Climate variability is natural and is caused by several different mechanisms that redistribute the heat and motion of the atmospheric-ocean-and hydrological system of the Earth. In particular, the Basin and the Pacific Northwest as a whole are strongly influenced by changes to the sea surface temperature of the Pacific Ocean and the hemispheric atmospheric flow patterns that develop as a consequence. In particular the El Nino/Southern Oscillation (ENSO) influences climate variability on the scale of seasons to years, while the Pacific Decadal Oscillation (PDO) occurs over 20-30 years. These two phenomena, as well as other global factors affecting climate variability are described below.

- **El Nino/Southern Oscillation (ENSO)**

ENSO is an irregular tropical Pacific ocean-atmosphere phenomenon that influences climate around the world. Its effects are different from one episode to the next, depending on the strength and structure of ENSO. The influence on B.C.'s climate is strongest in spring and winter, and ENSO can enhance or reduce the normal seasonal variations in climate. During the "warm phase" (El Niño) of ENSO, when sea temperature is relatively high off the western coast of South America, generally warmer than normal winter and spring temperatures occur in western Canada, accompanied by reduced precipitation. During the "cool phase" (La Niña), western Canada normally experiences cooler and wetter winters. During the years of neutral conditions when ENSO conditions in the tropical Pacific are not well developed, the climate of the Pacific Northwest follows the normal seasonal variations.

ENSO tends to shift between the two extremes and the neutral state irregularly within a two to seven year period (Figure 2.3). Usually it does not remain in either the warm or cold phase for any longer than a year or two although longer instances have occurred.

Figure 2.3: Monthly Average Values for the Niño 3.4 ENSO Index. Positive (red) index values indicate an El Niño event. Negative (blue) values indicate a La Niña event.[5]



- **Pacific Decadal Oscillation (PDO)**

The PDO is a large-scale climate oscillation characterized by spatial variations in the sea surface temperature and atmospheric pressure anomalies in the northern Pacific Ocean (Zhang *et al.* 1997; Mantua *et al.* 1997). It has a warm and a cool phase; during the 20th century it remained in each phase for 20 to 30 years. In B.C., average air temperatures and precipitation have fluctuated with this cycle. The PDO amplifies or dampens the effects of ENSO (Mantua *et al.* 1997, Newman *et al.* 2003). For example, during the warm phase of the PDO, El Niño years tend to be warmer than they are during the cool PDO phase. La Niña years are coolest during the PDO cool phase.

Sea surface temperature records indicate that the PDO was in a cool phase from about 1890 to 1924 and from 1947 to 1976 and was in a warm phase from 1925 to 1946 and from 1977 until at least the mid-1990s (Hare and Mantua, 2006). A change from warm to cool may have occurred since the mid- to late-1990s, but it is difficult to positively identify the change between phases until sufficient records have been accumulated, many years after the shift occurs.

- **Natural and human climate change**

Climate change typically occurs over longer time scales. Natural factors, including variations in solar output, the orientation of the earth's axis, and the shape of the earth's orbit vary over hundreds to hundreds of thousands of years and are associated with longer-term global climate change. The term "climate change", however, is sometimes used to refer exclusively to the effect on climate of increased greenhouse gas emissions from the burning of fossil fuels and changes in land use. Today, both natural and human-induced influences are at work simultaneously. The empirical view used in this analysis makes no distinction made between natural and human-caused climate change. The future climate projections included in this report are based on results from climate models that are driven by scenarios of future greenhouse gas emissions.

[5] Index is based on Sea Surface Temperatures in the tropics and provides an indication of the strength of an ENSO event (and thus effects on the Basin).

2.1.4 Extreme weather events and climate change

Extreme weather event: *An extreme weather event is an event that is rare within its statistical reference weather distribution at a particular place. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition the characteristics of what is called extreme weather may vary from place to place.*

Natural climate variability normally includes temperature, precipitation and wind events at the outer margins of that observed on a regular basis. Events are characterized by their 'return periods' as 100-year or 50-year events, for example, and a particularly severe event would have a longer return period. Individual extreme weather events cannot be tied directly to climate change. However, climate change may change the frequency (the return period) or the magnitude of such events compared to what would be expected from return periods based on historical observations.

2.2 Measuring and Analyzing Historical Climate

2.2.1 Paleoclimate

The paleoclimate record is based on terrestrial and marine records such as fossils, tree rings, pollen, sand dunes, and other information preserved in sediments and glacial ice. Such records are affected by climate and can be used to provide evidence about the climate that existed prior to the recording of instrumental observations.

In addition to providing information about climatic conditions over long periods of time, paleoclimatic analysis can provide useful information about ecosystem responses to climate variability and change that have occurred in the past, which can be considered when projecting realistic responses to future climate change.

2.2.2 Historical Weather Measurements and Climate

The Meteorological Service of Canada (Environment Canada) has maintained weather stations at locations throughout the country for over a century. At these stations, instruments record temperature, precipitation, wind speed and other weather conditions. Information from these stations is the foundation for the weather reports and forecasts that citizens are familiar with.

The historical climate dataset used for this report is Environment Canada's *Adjusted Historical Canadian Climate Data* (AHCCD) (Environment Canada, 2005). The records from these stations have been refined specifically for climate research in order to account, where possible, for station moves, changes in instruments or exposure and changes in observing practices during the period of record.

Air temperature is a weather variable that is also used to describe climate. It is easily measured, directly observable, and geographically consistent. Thus it can be used to construct the statistical properties of climate and infer climatic conditions by computing average conditions, variance, and trends. Table 2.1 describes common observations and calculations used to measure temperature.

Table 2.1: Temperature measures

Measure	Observation/calculation
Daily minimum	Usually observed (i.e. measured) near dawn
Daily maximum	Usually observed during the afternoon
Daily average or mean	The average of measured minimum and maximum temperature. Also, less commonly, hourly temperatures are used to compute a daily average, or mean.
Daily diurnal temperature range	The difference between daily maximum and minimum temperatures.
Extreme minimum or maximum	Respectively the lowest and highest recorded values. Must be accompanied by time period to which it refers – daily, monthly annually or period of record. (Not reported in this analysis).

Precipitation is also an important property of weather and climate. It is highly variable spatially because of the influence of local features such as topography, elevation, aspect and exposure. Not only is total (accumulated) precipitation over a time important, but also the rate at which it falls, the form (rain or snow) and its spatial distribution.

Table 2.2: Precipitation measures

Measure	Observation/calculation
Rainfall	Amount of precipitation falling as rain (mm)
Snowfall	Amount of precipitation falling as snow (cm)
Precipitation	Total precipitation: rainfall plus snowfall converted to equivalent amount of rain (mm)
Snowpack / snow depth	Depth of snow on ground (cm)
Snow water content / snow water equivalent	Amount of water in snowpack (kg/m^2, mm)
Snowcover	Area covered by snow (km^2)

2.2.3 Analysing Historical Climate Trends

Climate trends provide a picture of how much change has occurred in the past, for example over a period of 50-100 years. Climate trends are derived from statistical analysis of historical climate data or from analysis of paleoclimate records (before direct measurements).

A historical climate trend based on past weather observations describes the climate that occurred over a certain period. To determine whether climate trends reflect climate variability or climate change, the statistical significance of trends over time periods of several decades must be considered, and comparisons of trends between stations and between adjacent regions need to be made (section 3.10). A linear trend cannot be extrapolated into the future because the climate system is non-linear**.**

2.3 Projections of Future Climate

Chapter 3 of this report describes future climate projections for southern B.C. and the Basin. A collection, or ensemble, of climate projections (also known as scenarios - described more fully below) describe a range of plausible climates at some future time (usually the 2020s, 2050s, and/or 2080s) for a geographical region. They are based on numerical models of the climate system and assumptions about future greenhouse gas emissions.

2.3.1 Long-term Climate Projections and Scenarios

This report uses the following terms:

Climate model	A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. At present, coupled atmosphere/ocean/sea ice global climate models (GCMs) provide the most comprehensive representation of the climate system. There several GCMs, each run by a different research group, and most future climate change projections are based on the use of more than one GCM.
Climate projection	A projection of the response of the climate system to greenhouse gas emissions or concentrations, often based on simulations by climate models. The use of the word 'projection' rather than 'prediction' reflects the uncertainty in these forecasts.
Emissions scenario	Plausible future greenhouse gas emissions, based on assumptions about future socio-economic and technological developments. There are a number of emissions scenarios, based on different sets of assumptions.
Ensemble of projections	A collection of projections can provide a range of plausible future outcomes from different models run with different emissions scenarios. Climate models are imperfect, and there is considerable uncertainty regarding the release (amount and timing) of future greenhouse gases worldwide over the next century. The uncertainty is reflected by the use of a range of plausible climate projections, rather than a single projection.
Climate scenario	A climate scenario (or climate change scenario) is information about future climate that is used for decision-making. Although there are many kinds of climate scenarios, the most commonly used scenarios are *ensembles of GCM projections* – and the two terms are often used interchangeably.
Climate baseline	Average climate during a historical reference period, usually a 30-year period.

Future climate conditions will result from a dynamic combination of overlapping climate variability on different time scales (such as ENSO and PDO) that react non-linearly with the mean state and with each other. Superimposed on this is long-term climate change caused by non-linear forcing acting over long periods and distances. Because historical climate trends cannot be extrapolated, dynamic climate models based on physical principles are used. Climate projections from global climate models (GCMs) are not empirically based but rather simulations based on first principles such as the dynamics of the climate system (see climate model definition above). A climate projection refers to an individual set of results for temperature, precipitation and other parameters from a given climate model run under a specified set of assumptions about global climate systems and the amount of greenhouse gases released into the atmosphere. Projections are generally run over the 21st century and results are analyzed on 30-year average periods: for the 2020s (average of 2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099).

The word scenario is used in many contexts in different fields. Indeed, although emissions scenarios are plausible future greenhouse gas emissions, the term climate scenario is often used to describe a range of climate projections from different climate models (such as those shown in section 3) run with different emissions scenarios. The important concept is that climate models are imperfect and there is considerable uncertainty governing the release (amount and timing) of greenhouse gases worldwide over the next century. It is best to consider a number of climate projections from different models based on different assumptions about future emissions, together as a collection.

2.3.2 High Resolution Projections

High-resolution climate change projections may be constructed from GCM results to drive higher resolution regional climate models (RCMs) or by using empirical techniques to downscale results to a higher resolution for localized areas with finer topography (section 3.1.5). However, it is important to note that the information contained in the projections comes from different spatial scales even though it is depicted at the finest scale.

2.4 Continuing Emergence of Climate Information

Investigations into climate variability and change are continuing to generate new information and insights. For example, the National Climate Change Assessment is currently being conducted by Natural Resources Canada. Some information relevant to the Basin from a draft (Walker and Sydneysmith *et al.*, 2006) has been included in this report. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) is also scheduled for release in 2007 and will present an international peer-reviewed consensus of thousands of climate researchers. IPCC has published several reports on: the physical basis of climate change; impacts, adaptation, and vulnerability and mitigation of climate change. IPCC summary documents for policy makers as well as technical documents are publicly available at http://www.ipcc.ch/. The Pacific Climate Impacts Consortium is also compiling a draft assessment report on climate change impacts and water resources in BC, for release in 2007.

2.5 Sources of information

2.5.1 Paleoclimate

Paleoclimate studies exist for the Columbia River system specifically (e.g., Gedalof, *et al.*, 2004), as well as across BC (Gedalof *et al.* 2006). Such studies provided background information for the BC Chapter of the National Climate Change Assessment (Walker and Sydneysmith *et al.*, 2006) which was also used as a source of paleoclimate information for this report.

2.5.2 Historical observations

Analysis of historical temperature and precipitation data was performed by PCIC for five stations within the Basin, located at Cranbrook, Golden, Castlegar, Kaslo and Revelstoke (Appendix B). Data were available for a 90-year period from 1913 to 2002. Results of the analysis are presented with additional details in the appendices. Historical trends will also be published in the National Climate Change Assessment (ibid.). Trend analyses from the B.C. Ministry of Environment[6], Environment Canada[7], and the University of Washington Climate Impacts Group[8] are also presented for comparison.

2.5.3 Future climate projections

The climate projections in this report were prepared specifically for the Basin by PCIC. Projections are based on results from several Global Climate Models (GCMs) run with a range of plausible global

[6] http://www.env.gov.bc.ca/air/climate/indicat/abouttrends.html
[7] http://www.ecoinfo.ec.gc.ca/env_ind/region/climate/climate_e.cfm
[8] http://www.cses.washington.edu/

greenhouse gas emissions (and concentrations) over the next century (Table 2.3). The analysis for the Basin was conducted for a regional average of several grid boxes centered on the Basin, as shown in Figure 2.4 for the Canadian Global Climate Model. Other climate models have different resolution and thus slightly different number of grid boxes may be used.

Figure 2.4: Grid boxes for regional Basin projections (e.g., Canadian Global Climate Model)

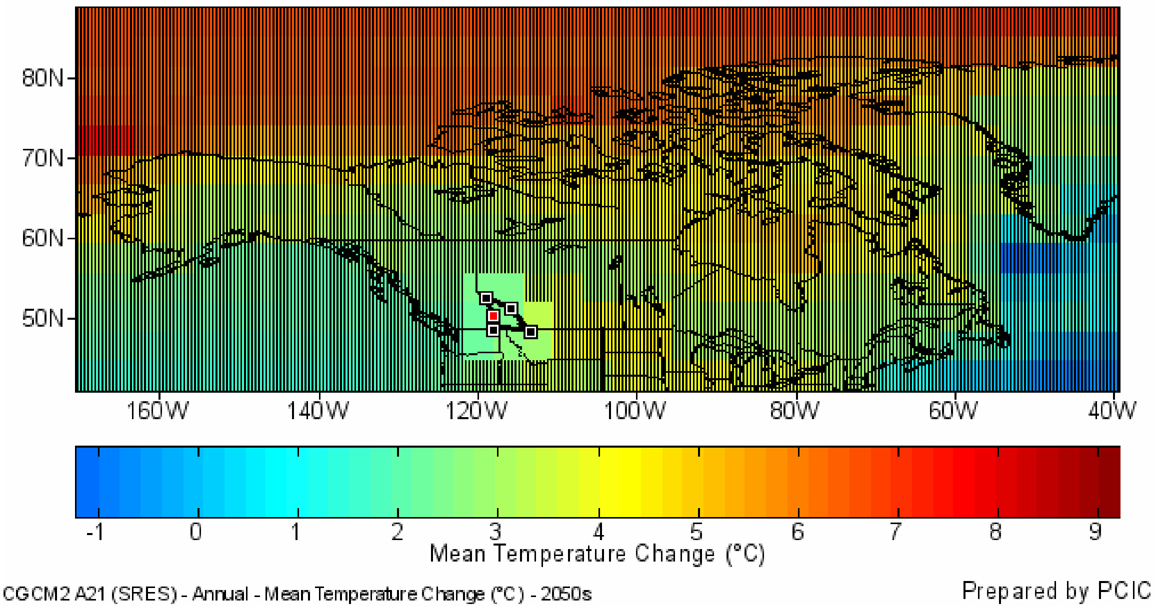


Table 2.3:Climate model and emissions scenarios used for boxplots

Model	Abbreviation	Emissions scenarios (number of experiments)
Canadian Global Climate Model version 2	cgcm2	A2 (3), B2 (3)
Geophysical Fluid Dynamics Laboratory R30	gfdlr30	A2 (1), B2 (1)
European Centre/Hamburg Model 4	echam4	A2 (1), B2 (1)
Commonwealth Scientific Industrial Research Organization Mk2b	csiromk2b	A1 (1), A2 (1), B1 (1), B2 (1)
Center for Climate Research - National Institute for Environmental Studies (Japan)	ccsrnies	A1FI (1), A1T (1), A1 (1), B1 (1), A2 (1), B2 (1)
Hadley Centre Coupled Model version 3	hadcm3	A2 (3), B2 (2), B1 (1), A1FI (1)
National Center for Atmospheric Research Parallel Climate Model	ncarpcm	A2 (1), B2 (1)

See IPCC, 2001 for more information on emissions scenarios.

The ensemble of projections is presented as "box and whisker plots" (e.g., Figure 3.2) that show the median value within the box, the upper 75th and lower 25th percentile of the projections as the upper and lower boundaries of the box, and the full range of the projections, or 1.5 standard deviations, whichever is less, as the upper and lower 'whisker' marks at the end of the lines above and below the box. The boxes thus represent the middle 50% of the range of projections and the whiskers represent the wider range of projections. Each plot shows the projected difference over the 21st century from the historical baseline. Note that the plotted boxes represent averages for each of the entire 30-year periods (2020s, 2050s, and 2080s). Individual model results, regional statistics, plots and seasonal results are also available online[9]. In addition, the geographical region under consideration may be modified.

2.5.4 High resolution future climate projections

For this report, projections were mainly based on coarse resolution Global Climate Models (GCMs). The effects of local topography can be addressed by empirical downscaling from GCMs or by using Regional Climate Model projections such as those prepared by the Ouranos Consortium[10] which are currently available online at the Canadian Centre for Climate Modelling and Analysis[11] for most of North America.

In addition to some results from the VIC model, high-resolution future climate projections that were prepared for display at the Royal British Columbia Museum are included in section 3.4. For these maps, GCM results (at a scale of several hundred kilometers) were applied to higher resolution observations (roughly 4 km x 4 km), which incorporate the effects of elevation, aspect, and exposure on interpolated climate station data (PRISM climatology; Daly *et al.* 1994). Maps are also available online for winter and summer temperatures, precipitation, cost of cooling, cost of heating, harvest crops, climatic suitability of cedar, and other parameters for BC and surrounding areas[12].

2.5.5 Hydrological trends and projections

Historical trends and future projections for selected hydrological parameters were obtained from the University of Washington's Climate Impacts Group[13] Variable Infiltration Capacity (VIC) hydrological and energy balance model. Detailed information can be found in the work of Hamlet and Lettenmaier 2005; Mote *et al.* 2005; Hamlet *et al.* 2005; Hamlet *et al.* 2006; Hamlet and Lettenmaier 2006).

2.6 Analyzing Trends and Identifying Climate Change

Assuming that the data exist, it is relatively easy to identify historic tends, but more difficult to assign causes. One of the challenges in identifying whether trends reflect climate variability or change for the Basin is to determine the influence of the PDO and ENSO (section 2). The effect of the start date on historical temperature trends is shown in Figure 2.5 for mean temperature. The figure demonstrates that the trend must be interpreted in the context of the time period from which it was derived. For example, of the mean temperature trends that go to the end of the century, the largest change occurred between 1971-2000, followed by 1951-2000, and then 1913-2002 with equivalent rates of increase per century of 4.2°C, 2.4°C, and 1.4°C respectively. In this case the shorter trend reflects the combined influences of more warming towards the end of the century as well as the larger influence of variability, particularly PDO. Note that the larger influence of climate variability in the shorter time periods implies neither that the trends are not robust nor that they are inconsistent with the long-term trend. Trends in longer records must also be interpreted with care. Precipitation in the early part of the 20th century, for example, was very low in comparison to later decades due to large-scale drought in North America during the dust bowl years (Hamlet *et al.* 2005).

The methodology for computing the trends, and in particular the limitations of computing a regional average trend from only four to five stations in the Basin is discussed in Appendix B. Further analysis with additional stations would improve results, especially for precipitation.

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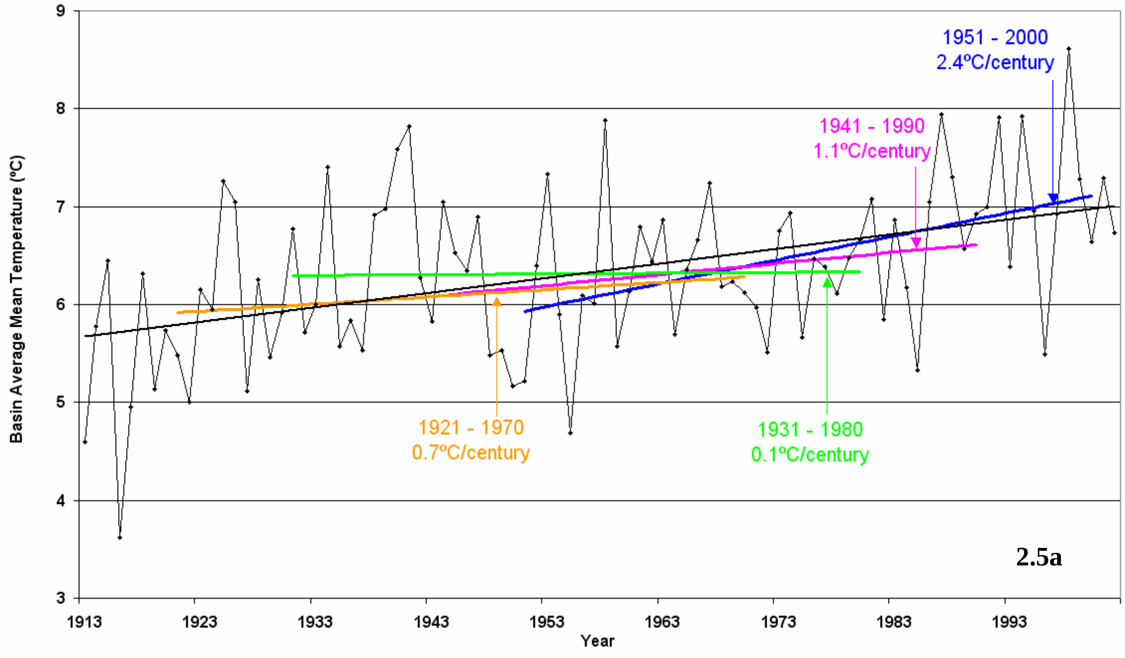
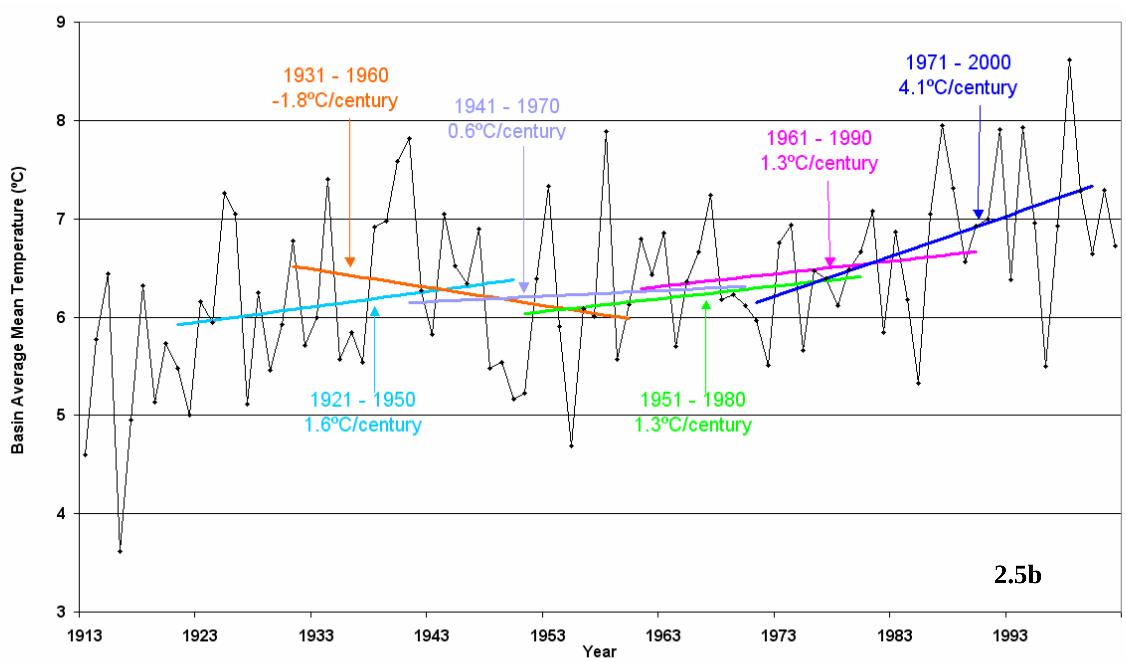
[9] http://www.PacificClimate.org/tools/select/
[10] http://www.ouranos.ca
[11] http://www.cccma.ec.gc.ca/data/data.shtml
[12] http://www.PacificClimate.org/impacts/rbcmuseum/
[13] http://www.cses.washington.edu/

Figure 2.5: (a) Basin average annual mean temperature record and 50-year trends (b) Basin average annual mean temperature record and 30-year trends.





3 CLIMATE CHANGE IN THE BASIN: PAST TRENDS AND FUTURE PROJECTIONS

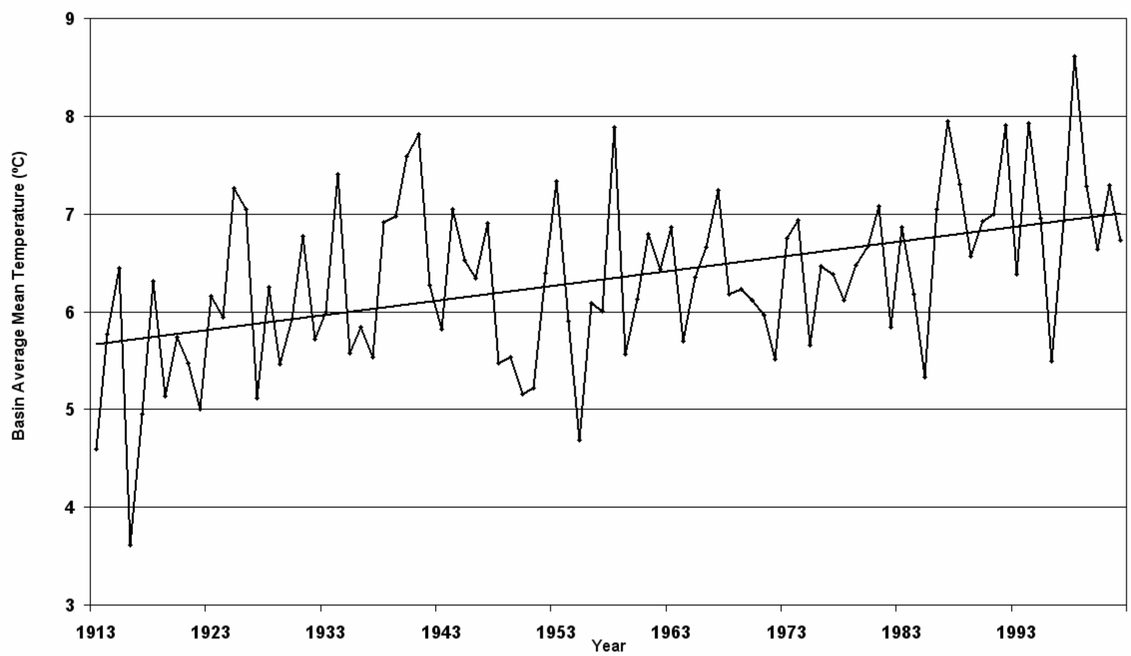
This section provides an overview of climate variability and climate change that are important in the Basin. Essential information is presented on paleoclimate (before the historical record), observed climate trends based on long term historical records from five monitoring stations within the Basin, and future projections from global climate models (GCMs).

3.1 Annual mean temperature

3.1.1 Historical Annual mean temperature Trends

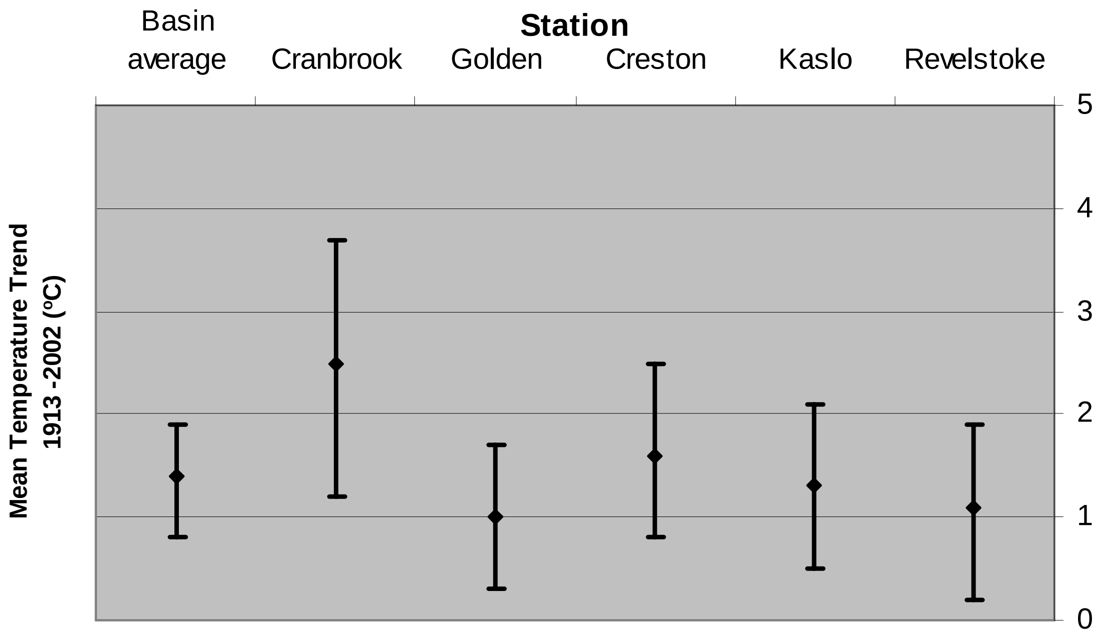
The annual mean temperature is an average of daily mean air temperatures over a calendar year. Based on data from the five designated stations, the annual mean temperature in the Basin increased by 1.4°C over the 90-year period from 1913 to 2002 (Figure 3.1a-b). This is equivalent to a rate of change of 1.5°C per century. All of the trends are statistically significant at the 95% confidence interval (see Appendix for statistical definitions).

Figure 3.1: (a) Annual mean temperature record and trend for the Basin 1913-2002



3.1a

Figure 3.1: (b) Annual mean temperature trends and confidence intervals for each station and Basin average 1913-2002.



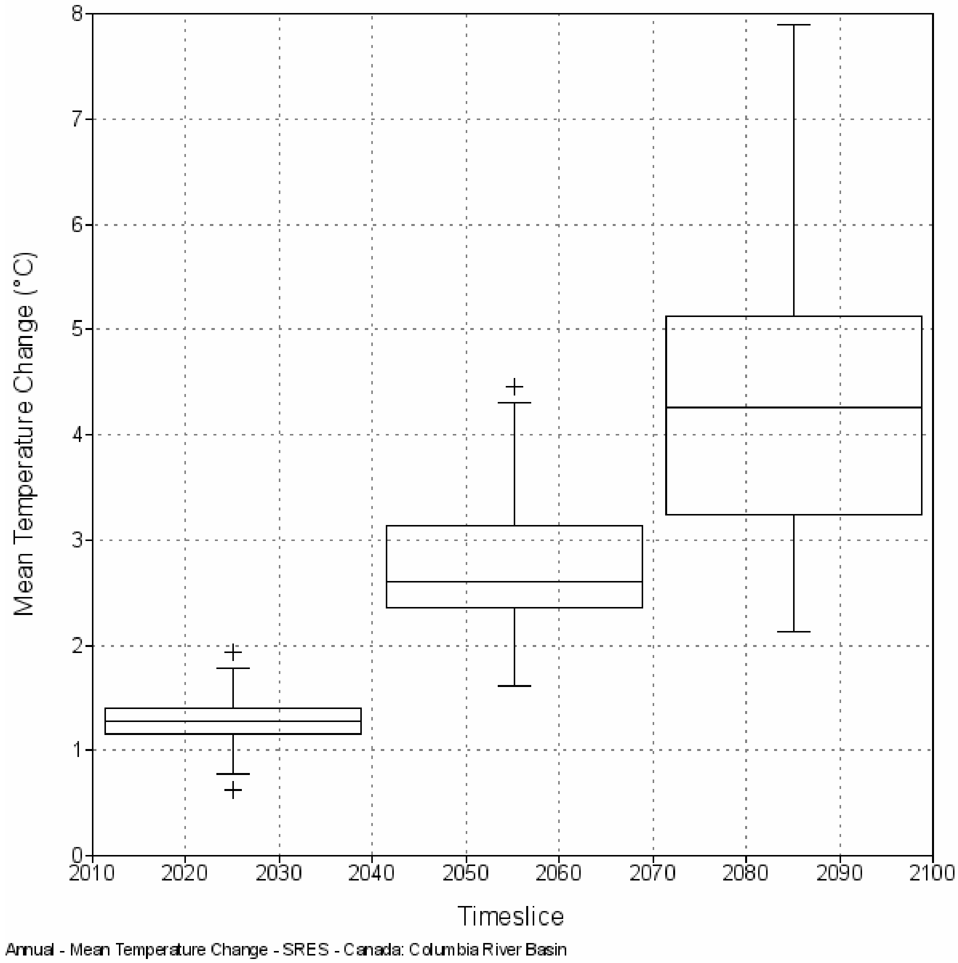
3.1b

3.1.2 Future Mean Annual Air Temperature Projections

Annual mean temperature across the Basin will continue to vary from year to year in response to natural climate variability. Figure 3.2 below shows that mean temperature is expected to rise within the Basin by approximately 1.1 to 1.3°C by the 2020s, 2.4 to 3.0°C by the 2050s and 3.3 to 5.0ºC by the 2080s using the 25^{th} and 75^{th} percentiles. It is important to note the consistent projections for warming among the various models and emissions scenarios used.

While these may seem like relatively small changes in temperature, comparing the annual mean temperatures for the 1961-1990 baseline period for each of the five stations in the Basin illustrates the implications of these small changes. During the baseline period, there was roughly a 1ºC difference between Golden (with annual mean temperature of 4.7 ºC) and Cranbrook (5.6 ºC) in the Rocky Mountain Trench. There was a 3ºC to 4ºC difference between these stations and the West Kootenay stations of Revelstoke (7.0ºC), Kaslo (7.3ºC), and Creston (7.7ºC). The 3ºC increase projected by 2050s for the West Kootenay communities would create mean average temperatures similar to Osoyoos, where the mean annual baseline temperature was 10.1ºC. Small changes in temperature are also associated with important physical and biological changes (sections 4 and 5). Finally, it is possible for small changes in annual mean temperature to result in large increases to frequency of occurrence of extreme events (IPCC, 2001; pp. 80-81).

Figure 3.2: Annual mean temperature projections for the Basin 2020s, 2050s, and 2080s



3.2 Annual Maximum and Minimum Temperature

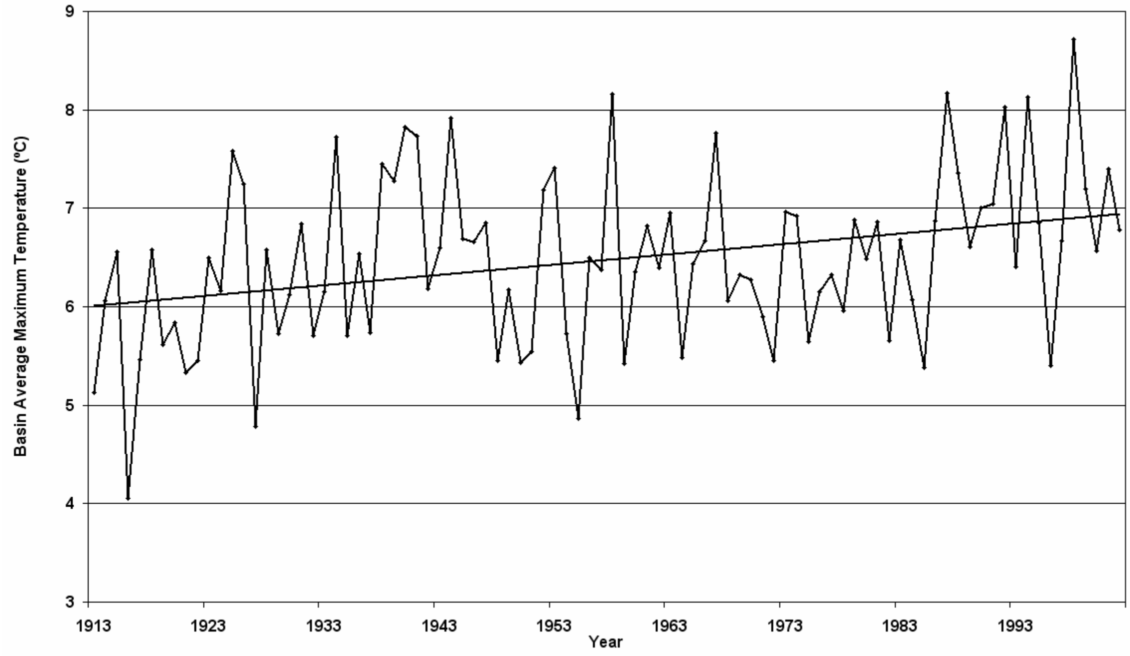
3.2.1 Historical Maximum and Minimum Temperature Trends

The annual maximum temperature is an average of daily afternoon maximum air temperatures over a calendar year. Based on data from the five designated stations, the annual maximum temperature in the Basin rose 0.9°C between 1913 and 2002 (90 years) (Figure 3.3a). This is equivalent to a rate of 1.0°C per century.

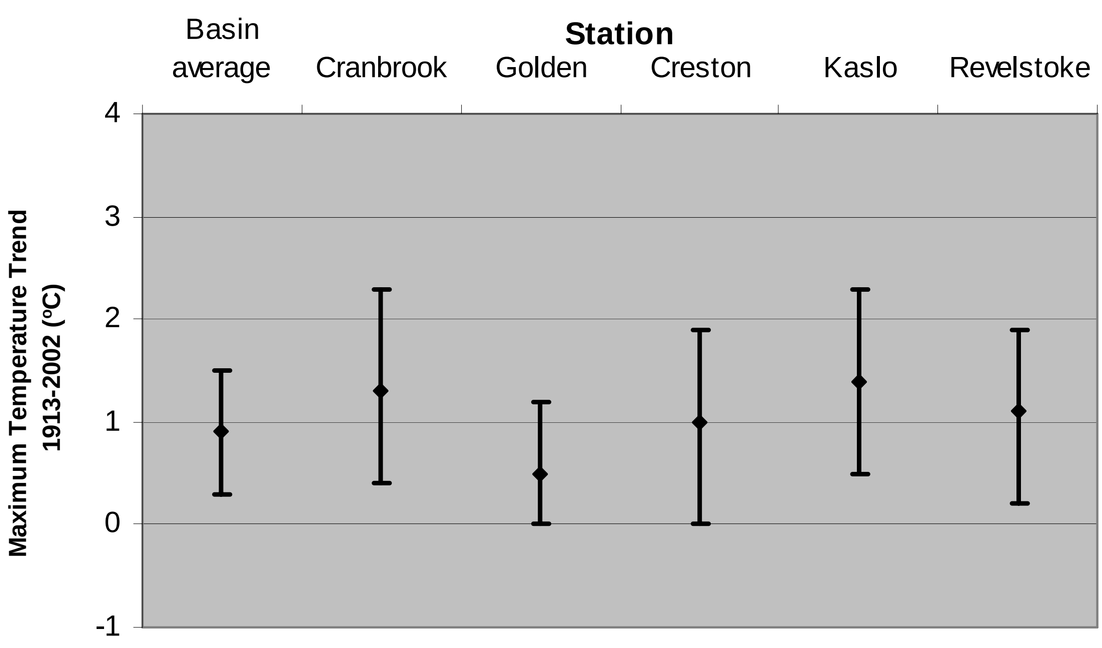
The annual minimum temperature is an average of daily nighttime low temperatures over a calendar year. Based on data from the five designated stations, the annual minimum temperature in the Basin rose 1.6°C between 1913 and 2002 (90 years) (Figure 3.3b). This is equivalent to a rate of 1.8°C per century. Because nighttime temperature warmed more than afternoon temperature during this period, the diurnal (daily) temperature range became slightly narrower.

All of the minimum temperature trends and most of the maximum temperature trends are statistically significant at the 95% confidence interval (see Appendix for statistical definitions).

Figure 3.3: (a) Annual maximum temperature record and trend for the Basin 1913-2002 (b) Annual maximum temperature trends and confidence intervals for each station and Basin average 1913 – 2002.

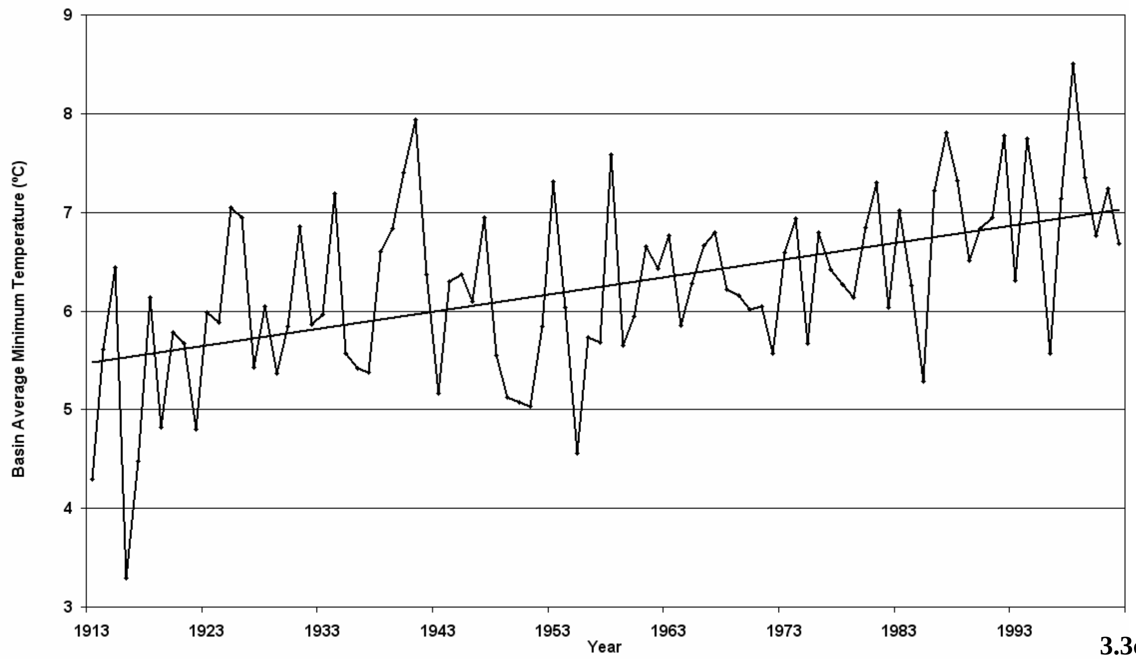


3.3a

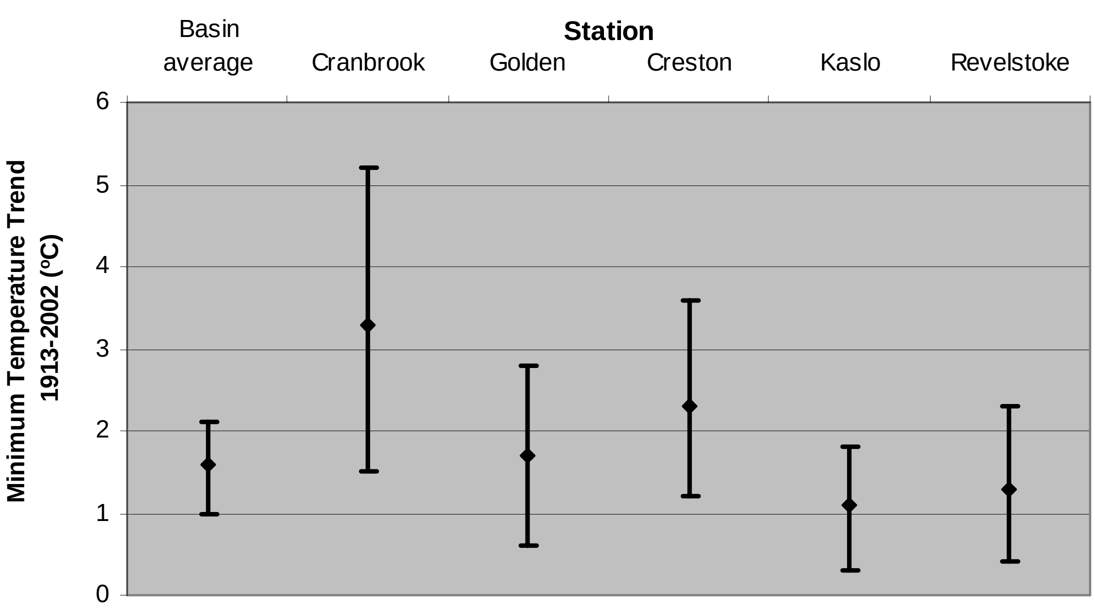


3.3b

Figure 3.3: (c) Annual minimum temperature record and trend for the Basin 1913-2002 (d) Annual minimum temperature trends and confidence intervals for each station and Basin average 1913 – 2002.



3.3c



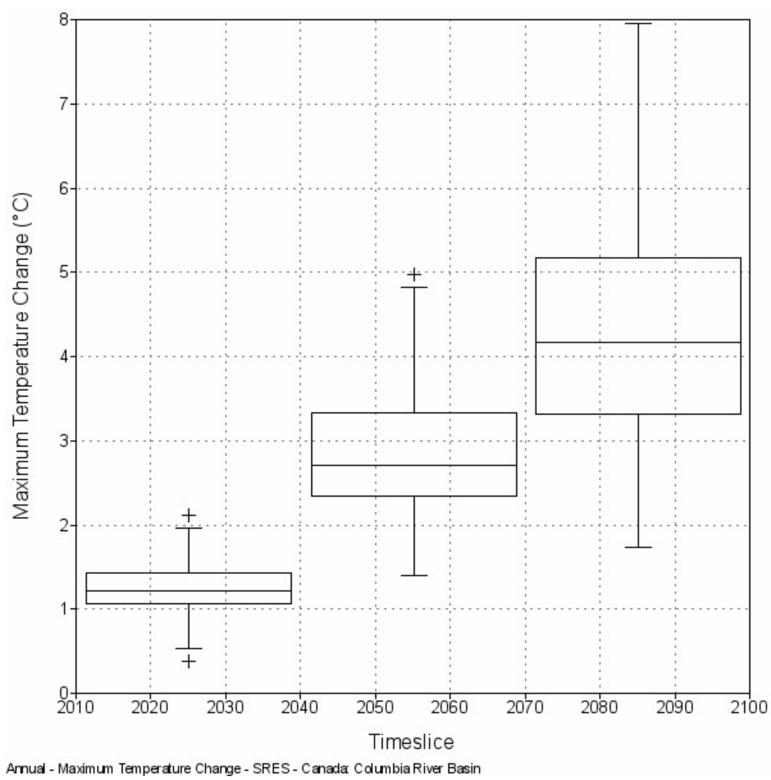
3.3d

3.2.2 Future Maximum and Minimum Temperature Projections

A number of Global Climate Models suggest that in the Northern Hemisphere, the gap between the daily maximum and minimum temperatures will decrease in winter and increase in summer (IPCC, 2001). The projections for the Basin also indicate that the mean annual nighttime minimum temperatures increase slightly more that the day-time maximum temperatures, but that the difference will be smaller than demonstrated in the historical trends (Figure 3.4a).

Figures 3.4c-f show temperatures in British Columbia for the baseline period (1961-1990) and for the 2050s. Figures 3.4c-d show average July daytime maximum temperatures. Figures 3.4e-f show average January nighttime minimum temperatures. The figures for 2050s are based on a median scenario for emissions and for global climate change. These maps are high resolution climate projections originally developed for display at the Royal British Columbia Museum[14].

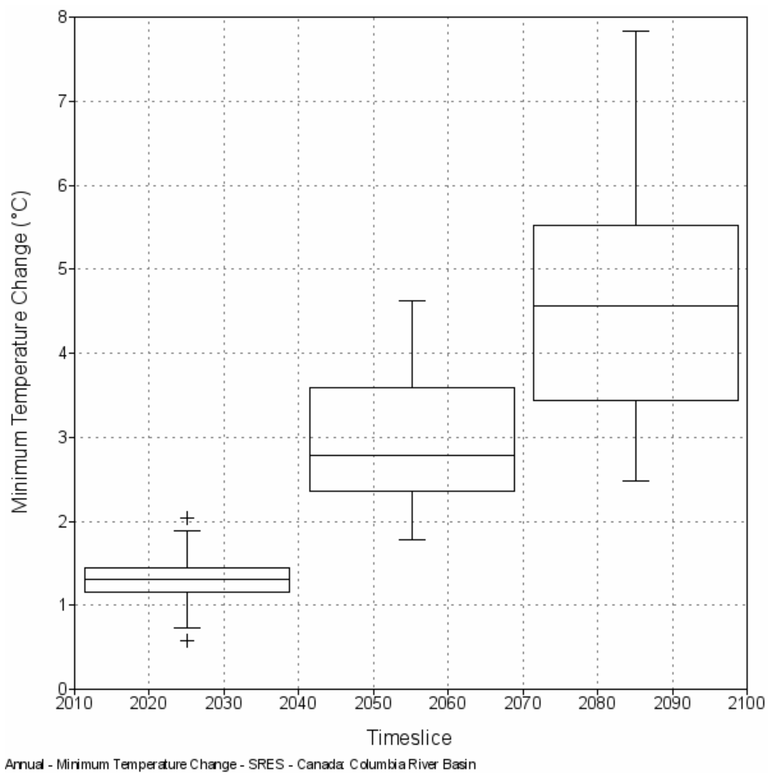
Figure 3.4: (a) Annual maximum temperature projections for the Basin 2020s, 2050s, and 2080s



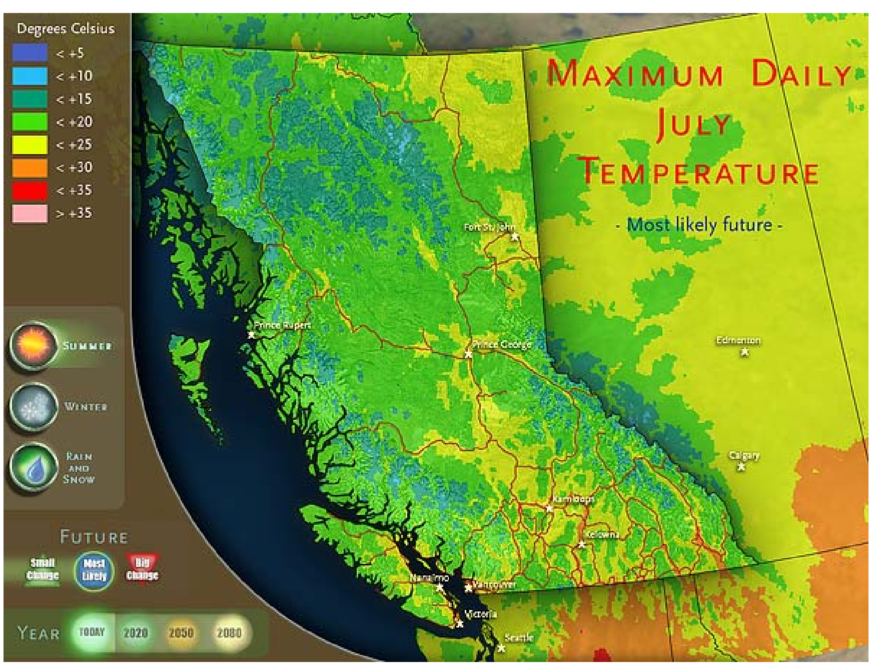
3.4a

[14] http://www.PacificClimate.org/impacts/rbcmuseum/

Figure 3.4: (b) Annual minimum temperature projections for the Basin 2020s, 2050s, and 2080s (c) High Resolution Temperature Baseline: July Mean Monthly Daytime High

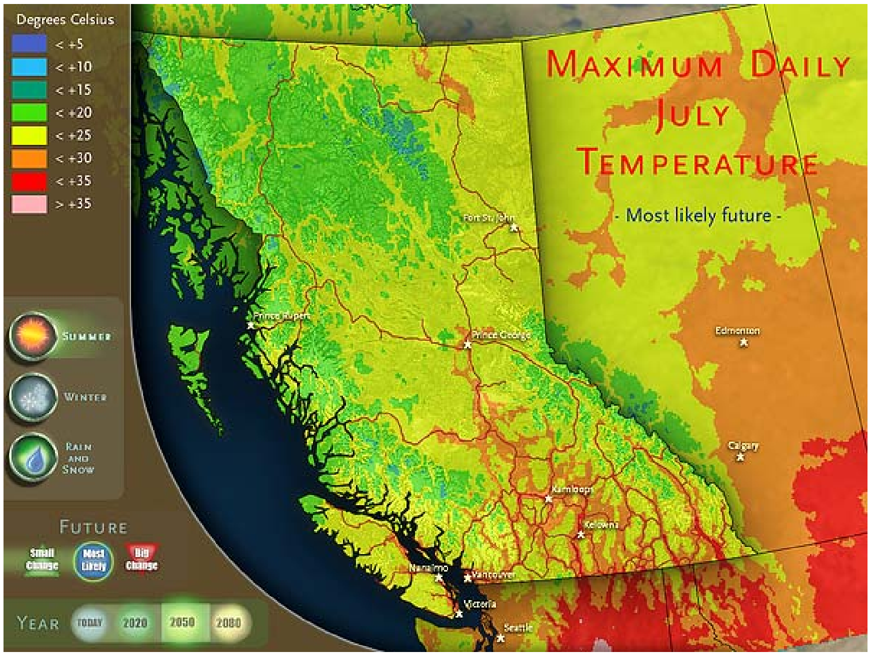


3.4b



3.4c

Figure 3.4: (d) High Resolution Temperature 2050s median Projection: July Mean Monthly Daytime High (e) High Resolution Temperature Baseline: January Mean Monthly Nighttime Low



3.4d

3.4e

Figure 3.4: (f) High Resolution Temperature 2050s median Projection: January Mean Monthly Nighttime Low

3.4f

3.3 Annual Precipitation

As discussed in Section 2.2, precipitation varies more than temperature from one location to another. With observations from only five stations, and with large differences in precipitation between these stations, it is difficult to identify meaningful historical changes in precipitation for the Basin. To fully understand precipitation trends, additional analysis with more stations is needed and detailed investigation into the differences between stations and into how well the stations represent the region would be worthwhile. Finally, any study of precipitation should be linked to related estimates of streamflow and snowpack, and changes in glacier mass.

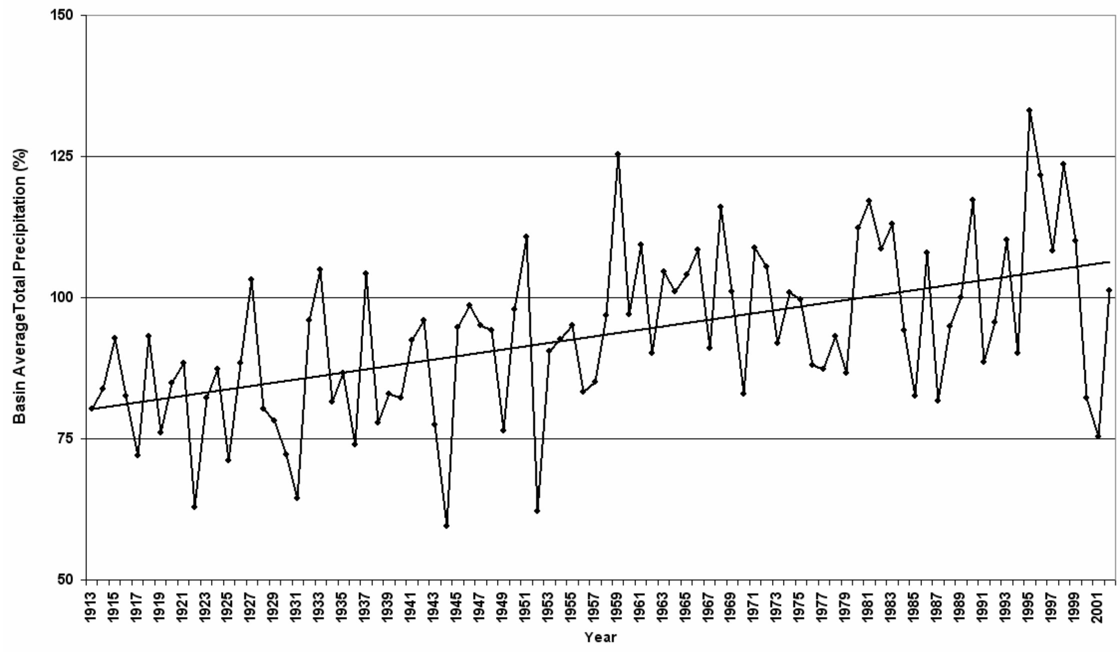
3.3.1 Historical Trends in Annual Precipitation

Annual precipitation includes both rain and snow, which will be discussed in the sections to follow. As shown in Figure 3.5, annual precipitation increased 26% (or 151 mm averaged over the Basin) over the 90-year period from 1913 to 2002, equivalent to a rate of change of 3% per decade. The differences between the stations are more substantial than for temperature, with trends ranging from a 10% increase in Golden to a 44% increase in Kaslo. Three of the five stations the trends are not significant at the 95% confidence interval (see Appendix for statistical definitions). Trends lacking statistical significance may be interpreted as trends smaller than the range of historical climate variability over the period of the trend.

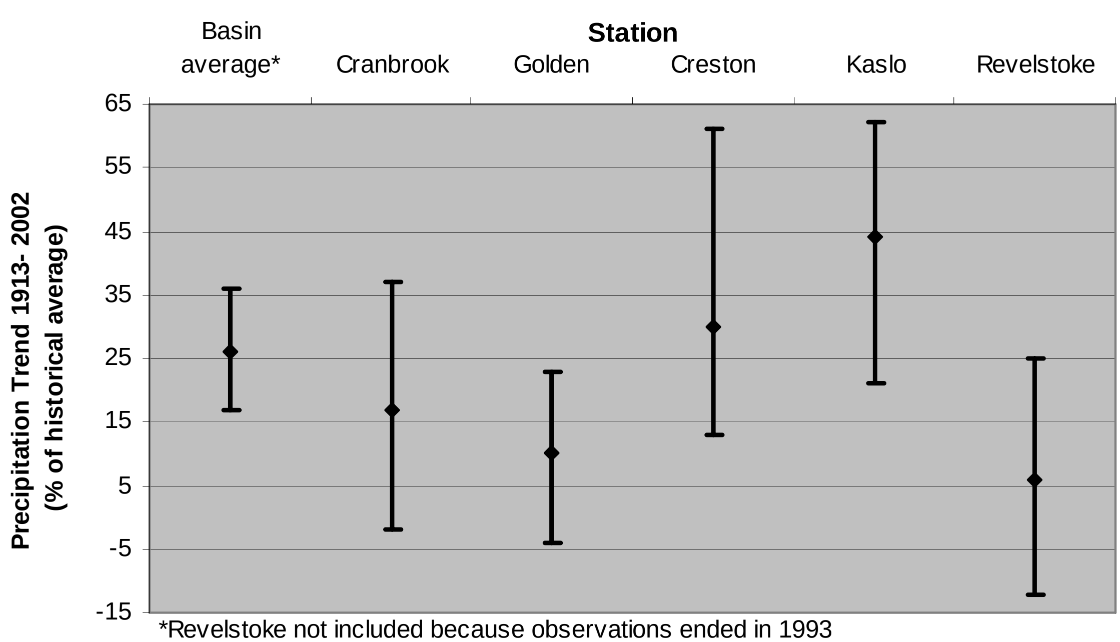
3.3.2 Future Projections of Annual Precipitation

Average annual precipitation in the Basin will continue to vary from year to year in response to natural atmospheric and oceanic cycles. Climate models generally project annual precipitation increases in the mid-latitudes of the Northern Hemisphere (IPCC, 2001). The uncertainty in annual precipitation projections is larger than in temperature projections as indicated by the relatively large range (section 3.4 and 3.5) and the small magnitude of projected changes in precipitation in comparison with natural variations (Figure 3.7). Note that an increase in annual precipitation is not inconsistent with increased occurrence of drought, as the latter depends on the timing and distribution of precipitation events.

Figure 3.5: (a) Annual precipitation record and trend for the Basin 1913-2002 (b) Annual precipitation trends and confidence intervals for each station and the Basin average 1913-2002.



3.5a



3.5b

Figure 3.6: Annual precipitation projections for the Basin 2020s, 2050s, and 2080s

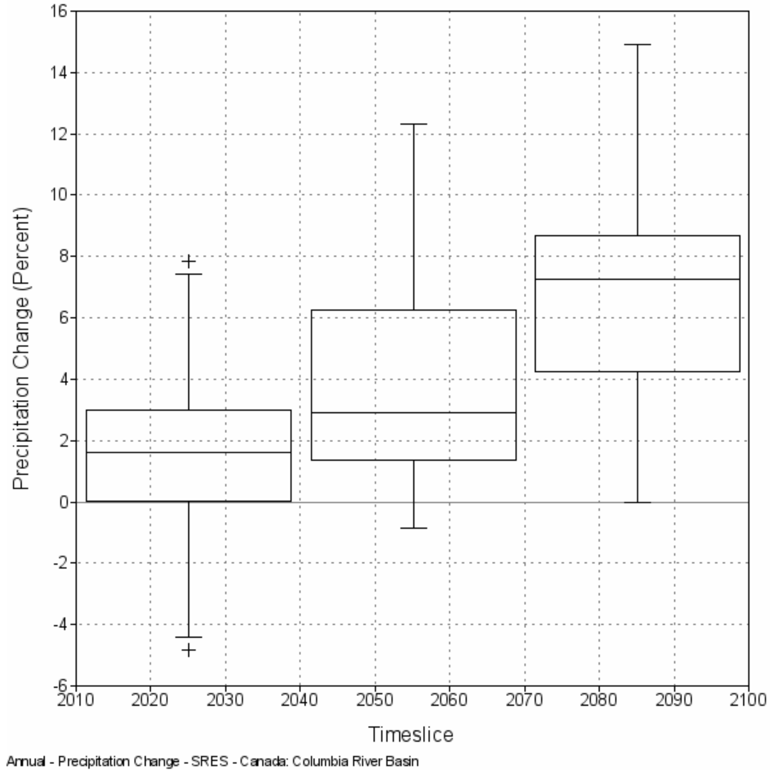
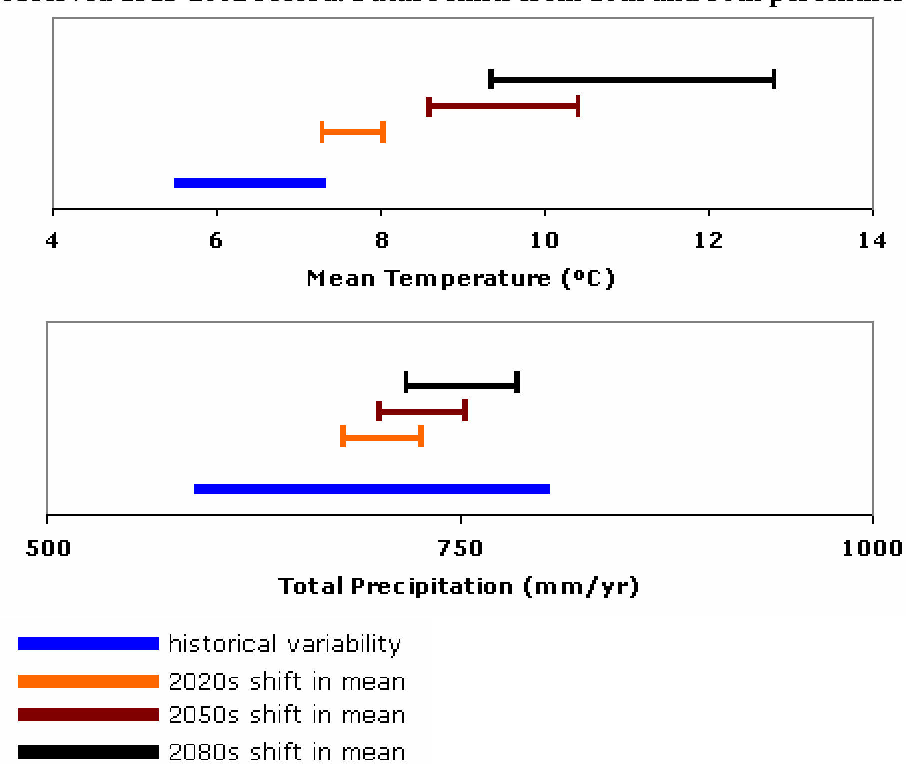


Figure 3.7: Comparison of 20th century observed variability to 21st century range of shift in mean for the Basin. Adapted from similar figure by the University of Washington, Climate Impacts Group. Blue bars for historical variability based on ±1 standard deviation from observed 1913-2002 record. Future shifts from 10th and 90th percentiles.



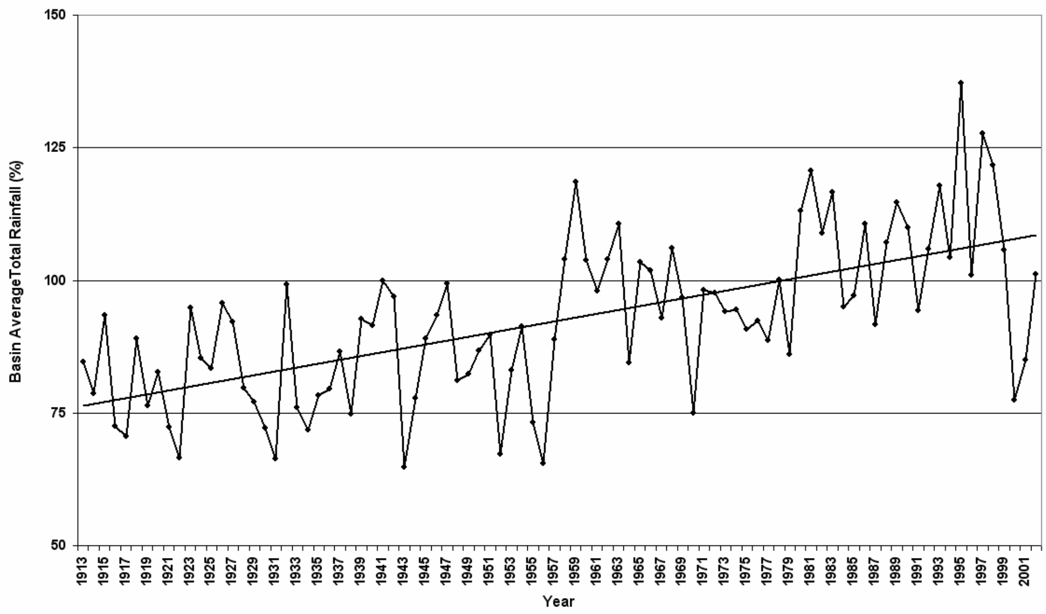
3.4 Rain and Snow

In addition to annual precipitation, the distribution of precipitation between rain and snow is important for streamflow and ecological systems. Snow in particular is a distinguishing feature of the Basin's climate and a critical component of Basin hydrology. It acts as a temporary storage system for winter precipitation and contributes to the longer-term storage of water in mountain glaciers (section 4.1). This section discusses historical and future changes in rainfall, snowfall, and snowpack, which represents accumulated snow.

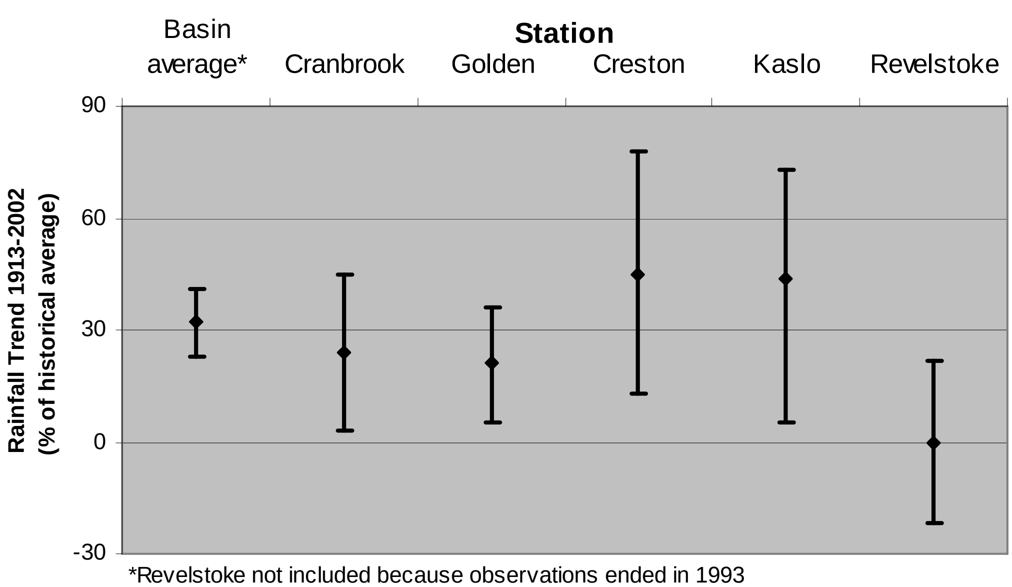
3.4.1 Historical Rainfall Trends

As shown in Figure 3.8, annual rainfall increased by 32% (or 142 mm averaged over the Basin) over the 90 year period from 1913 to 2002, or at a rate equivalent to 3% per decade.

Figure 3.8: (a) Annual rainfall record and trend for the Basin 1913-2002 (b) Annual rainfall trends and confidence intervals for each station and Basin average 1913-2002



3.8a



3.4.2

3.8b

*Revelstoke not included because observations ended in 1993

3.4.3 Future Rainfall Projections

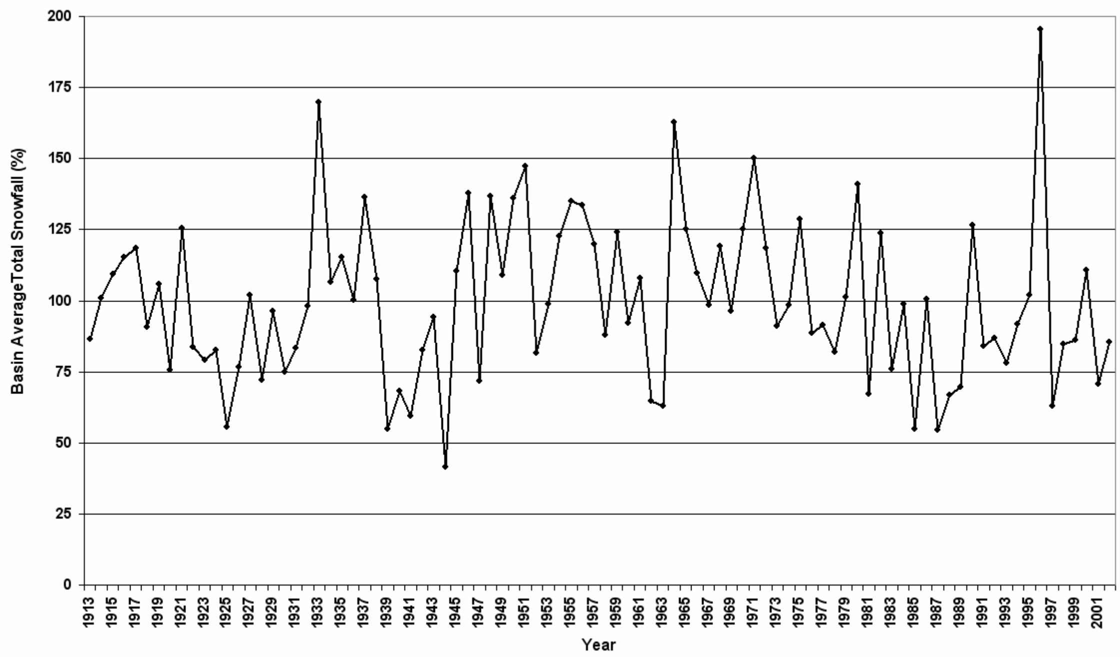
Precipitation projections in section 3.6.2 above combine rainfall and snowfall (as equivalent amount of rainfall). Future rainfall projections were only available to PCIC from a small number of climate models during preparation of this report. This limitation prevented computation of snowfall projections for the Basin.

3.4.4 Historical Snowfall Trends

Although average annual snowfall trends can be computed for the five designated stations in the Basin, the differences between the individual stations are large, and the resulting trends have wide confidence intervals and are without statistical significance. Moreover, the differences between stations are larger than the regional average. Evaluation of historical snowfall trends is a key area where additional stations are needed for a more complete analysis.

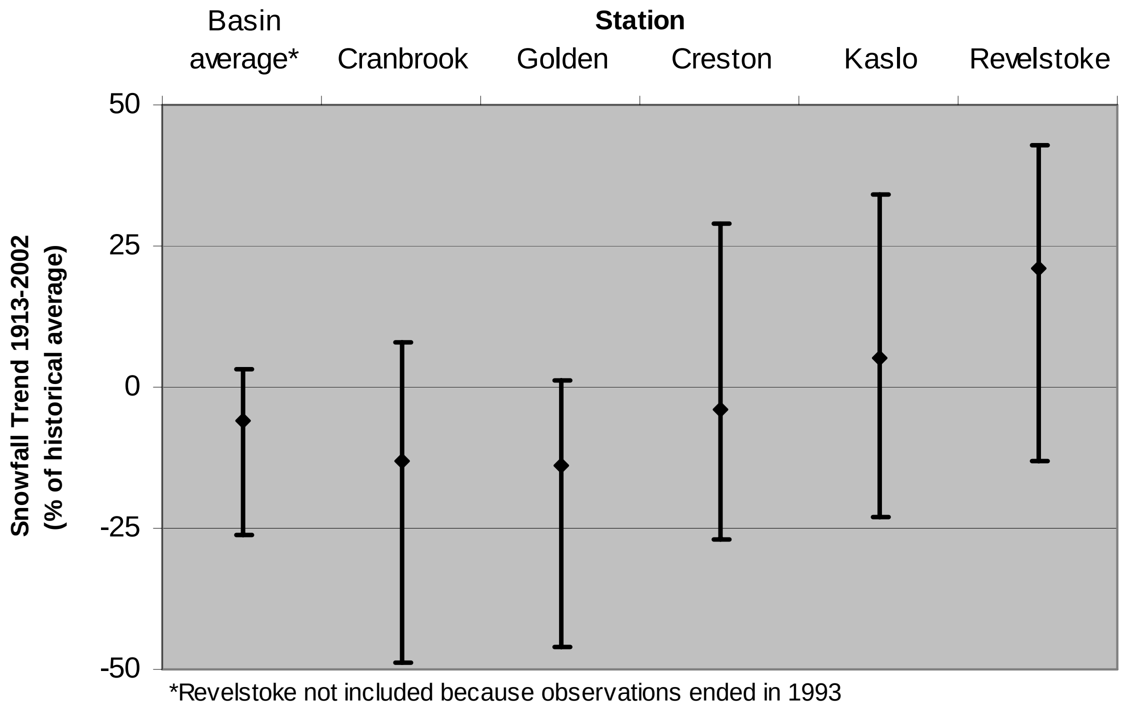
As shown in Figure 3.9, annual snowfall decreased by 6 percent (10 mm on average over the Basin excluding Revelstoke) between 1913 and 2002, or a decline of about 1 percent per decade over the 20th century.

Figure 3.9: (a) Annual snowfall record and trend for the Basin 1913-2002



3.9a

Figure 3.9: (b) Annual snowfall trends and confidence intervals for each station and Basin average 1913-2002



3.9b

The fraction of precipitation that falls as snow depends on a complex relationship between precipitation physics and air temperature, influenced by local terrain. If the surface air temperature is well below freezing, precipitation is likely to fall as snow. If the surface temperature is near freezing, even slight warming can change snowfall to rain. Downward trends in spring snowpack are thus strongest where mid-winter temperatures are close to the freezing point (for example, on the Pacific Northwest and B.C. coasts), and are largely due to changes in temperature. This is not the case in the Basin, where winters are colder and year-to-year variations in snowpack are largely related to variability in precipitation.

The interaction between large-scale climate change and local land use may also have an important influence on snowfall and snowcover. For example, the Golden snowfall record shows an abrupt decrease in snowfall totals in the early 1970s. The decline coincides with completion of the Mica Dam in 1973, as well as with a warming ENSO event in 1973, followed by the well-documented PDO climatic regime shift in 1976-77 (Hare and Mantua, 2006) which affected cool season precipitation across the PNW (Mantua and Hare 2002). Precipitation data for Kaslo, Cranbrook, and Creston also exhibit abrupt functional changes in the late 1950s, with similarly unclear causes. Further investigation into the impacts of reservoir creation and PDO and ENSO (as in Moore and McKendry, 1996) on abrupt functional changes in precipitation could improve the understanding of local climate variability in the Basin. Cool season precipitation variability changed markedly in western North America after about 1973, coincident with (although not necessarily related to) the period of rapid warming at the end of the 20th century (Hamlet and Lettenmaier, 2006).

3.4.4 Future Snowfall Projections

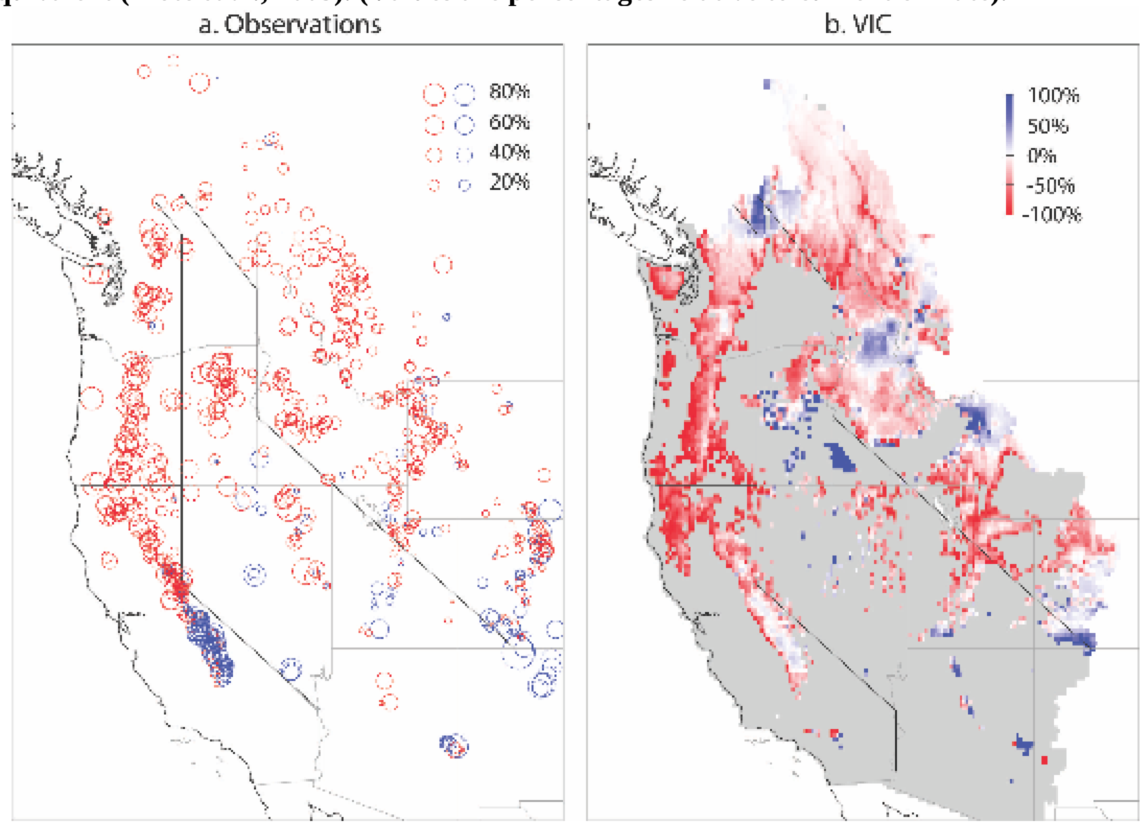
Future snowfall projections were only available to PCIC from a small number of climate models during preparation of this report. This limitation prevented computation of snowfall projections for the Basin.

3.4.5 Historical Snowpack Trends

"Snowfall" represents the amount of precipitation falling as snow, "snowpack" the amount of snow that accumulates on the ground, and snow water equivalent (SWE) the weight of water in a column of snow. Snowpack measurements averaged over snow courses are typically taken at several times throughout the year[15], with April 1st being the date on which snowpack is traditionally considered to be maximum in the Basin. Spring snowpack is an integrated, approximate measure of frozen precipitation over the preceding season, minus losses – which are typically small at mid and high elevations.

Several recent studies combining observations and modeling studies using the Variable Infiltration Capacity (VIC) hydrologic model and statistical approaches have demonstrated that observed snowpack is declining with increasing temperatures in the Pacific Northwest. The results in Figure 3.10 show that from 1950 to 1997 the April 1 snowpack in the Basin decreased, particularly at lower elevations, with up to 50% reductions in the U.S. portion of the Pacific Northwest (Mote *et al.*, 2005). Hamlet *et al.* (2005) and Mote (2006) also show that over much of the region the changes are predominantly due to warming rather than to changes in precipitation.

Figure 3.10: Observed snowfall trends and VIC model trends for April 1 Snow Water Equivalent (Mote *et al.*, 2005). (Values are percentages relative to current climate).



Snowfall measures the amount of precipitation falling as snow whereas snowpack measures snow accumulation on the ground. The snowfall trends in Figure 3.10a are based on direct station observations. The snowpack trends in Figure 3.10b are outputs from the VIC model which provides a

[15] Current snowpack and related water supply outlook for British Columbia are available from the BC Ministry of Environment River Forecast Centre http://www.env.gov.bc.ca/rfc/river_forecast/bulletin.htm

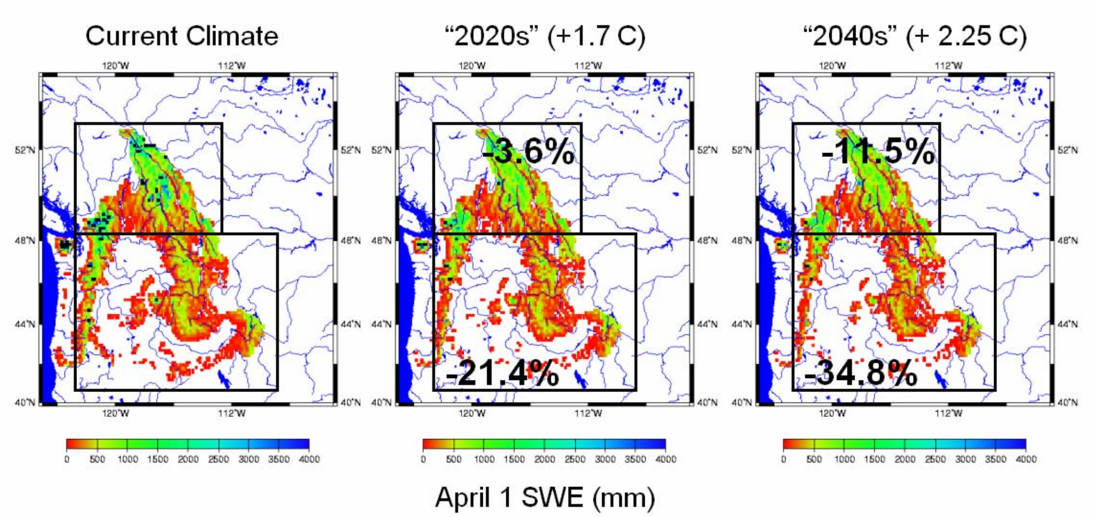
fine scale, physically-based reanalysis of observation data. The trends for snowfall and snowpack are computed for different time periods (section 3.2). Despite the differences between the two trends, both relate to snow. Viewed together, they suggest that snow disappeared in the Pacific Northwest at a faster rate during the later half of the 20th century than during the century as a whole. This result is consistent with the findings that temperature increases occurred mostly in the later half of the century (section 2.6), and that precipitation is the dominant determinant of snowfall in many Basin locations (section 3.4).

3.4.6 Snow Projections for the Future

In a scenario of increasing temperature, snowfall should contribute relatively less to precipitation at most locations, regardless of changes in overall amount of precipitation itself. However, at some locations (with cold enough winter temperatures), warming may have little effect and at these locations changes in snow will depend on overall changes to precipitation (possible slight increases, as shown above).

Snowfall, the extent of snowcover and the development of snowpack are highly dependent on topography and localized conditions. Figure 3.11 shows the results of high resolution VIC model projections of snowpack on April 1st in the Columbia River system (Mote *et al.*, 2003; Snover *et al.* 2003). According to the VIC model, snowpack will decrease by 3.6% by the 2020s and 11.5% by the 2040s in the entire Basin. These results show much larger *percentage* decreases in lower elevation areas (warmer current temperature), where a relatively small temperature change can drive a major change in snow conditions.

Figure 3.11: Changes in projected April 1 snowpack from VIC model. (Values are in inches except the middle figure which is percentage change relative to historical average snowpack).



This projected reduction in snow cover for much of the Basin can amplify local temperature changes, since exposed ground absorbs and retains more heat than snow covered ground does. This mechanism (called the positive albedo feedback) hastens further snow cover loss. The geographical extent and duration of snow cover is controlled by precipitation during winter and by the sequence of weather systems during spring and summer. An increase in average spring temperature, for example will melt snow earlier and reduce the spatial extent of snow cover (Mote 2003; Mote *et al.*, 2005).

The projected snow changes due to modest increases in temperature in the U.S. portion of the Columbia River Basin are relatively larger than the Canadian portion, since snow covered areas in the U.S. are generally closer to the freezing level.

3.5 Extreme Weather Events

Neither detailed historical data nor future projections are available for changes in extreme weather events for the Basin. Although there is short term evidence that the frequency and severity of drought and heavy rainfall events may be increasing (Whyte, 2006), individual extreme weather events cannot be ascribed to climate change without thorough analysis of how frequently these events are occurring now in comparison to the past.

The IPCC (2001) reports that 'it is likely that for many mid- and high latitude areas, primarily in the Northern Hemisphere, statistically significant increases have occurred in the proportion of annual precipitation derived from heavy and extreme precipitation events; it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events over the later half of the 20th century.'

Paleoclimate evidence suggests that recent climate in the Basin is relatively benign with respect to drought, and that in the distant past the likelihood of severe sustained droughts was higher than in the recent past (Gedalof *et al.* 2004). In southern BC, severe sustained droughts occurred more frequently during previous centuries than over the past few decades (Walker and Sydneysmith, *et al.*, 2006.; Fye *et al.*, 2003; Gedalof *et al.*, 2004; Watson and Luckman, 2005).
The following extreme weather events are listed by the IPCC (2001) as likely or very likely for continental land areas during the 21st century:

- higher maximum temperatures with more hot days and heat waves with increased heat index (which combines temperature and humidity);
- increased risk of summer drought; and
- more intense precipitation events.

Increased frequency of extreme precipitation events has also been projected for North America as a whole by Kharin *et al.* (2005) using the Canadian GCM. Paleoclimate evidence (Dallimore *et al.*, 2005) suggests the possibility that a period of increased storm events and precipitation may occur over the coming decades, possibly associated with a change in polarity of the PDO. The last time this occurred in 1976, profound changes in weather and ecosystems were noted around the PNW region (Chavez *et al.*, 2003).

The potential for an increase in the occurrence of extreme weather events in the Pacific Northwest has prompted the Climate Impacts Group at the University of Washington to implement an experimental short lead-time (7-14 day) extreme weather risk assessment forecast for the US and Canada[16] In these forecasts an event is characterized as "extreme" if it exceeds ± 1.5 standard deviations from the long-term mean for a particular climate variable (e.g. snowfall, rainfall, temperature) on a particular day.

3.6 Historical Trends and Future Projections by Season

3.6.1 Historical Trends by Season

Seasonal trends for mean, minimum and maximum temperature and precipitation for the Southern Interior Mountains eco-province, which includes the majority of the Basin are shown in Table 3.1 below based on information from WLAP (2002). Note that the annual trends do not correspond precisely to the trends computed by PCIC for the five stations in the Basin in this analysis, as different stations were used. The consistency between the annual results from each analysis is reassuring, and suggests that WLAP (2002) provides a reasonable estimate of seasonal distribution of temperature and precipitation.

[16] http://www.cses.washington.edu/cig/fpt/extreme.shtml

Table 3.1:Climate trends – annual and by season - from WLAP (2002) for the Southern Interior Mountains Eco-province.

Climate parameter	Annual trend	Seasonal trends			
		Spring (March-May)	Summer (June-Aug.)	Fall (Sept. – Nov.)	Winter (Dec. –Feb.)
Mean air temperature (1895-1995)	+1.1°C per century *	+1.4°C per century *	+1.2°C per century *	+0.7°C per century	+1.2°C per century
Minimum air temperature (1895-1995)	+1.3°C per century *	+1.4°C per century *	+1.6°C per century *	+0.8°C per century *	+1.6°C per century *
Maximum air temperature (1895-1995)	+0.9°C per century *	+1.4°C per century *	+0.8°C per century	+0.6°C per century	+0.9°C per century
Precipitation (1929-1998)	+4% per decade *	+6% per decade *	+6% per decade *	+4% per decade *	+2% per decade *

* Statistically significant trend at the 95% level –(data from technical report to WLAP, 2002)

3.6.2 Future Climate Projections by Season

Results of analyses by PCIC for projections of future climate within the Basin by seasons for the 2050s are shown below in Table 3.2. Individual box plots are available online[17]. See also the high resolution representations of winter minimum and summer maximum temperatures in section 3.5.

Table 3.2: Climate projections: increase from 1961-1990 average by the 2050s (25th – 75th percentile range) – annual and by season

Climate parameter	Annual projections	Seasonal projections			
		Spring (March-May)	Summer (June-Aug.)	Fall (Sept. – Nov.)	Winter (Dec. –Feb.)
Mean air temperature	2.4 to 3.1°C	1.7 to 2.8°C	2.4 to 4.0°C	1.9 to 3.3°C	2.3 to 3.6°C
Minimum air temperature	2.4 to 3.6°C	1.8 to 3.6°C	2.3 to 3.6°C	1.8 to 3.3°C	2.8 to 4.2°C
Maximum air temperature	2.3 to 3.3°C	1.7 to 3.0°C	2.4 to 4.4°C	2.4 to 3.7°C	1.6 to 3.6°C
Precipitation (% of baseline)	+1 to +6%	+5 to +12%	-16 to –5%	-1 to +4%	+7 to +17%

[17] http://www.PacificClimate.org/scenarios/select/

3.7 Regional and Global Context

3.7.1 Regional and Global Historical Trends

Anthropogenic climate change is linked with historic temperature trends for the entire globe (IPCC, 2001) and for the Pacific Northwest (Stott, 2003). PNW temperature trends are broadly consistent with the global time series (Hamlet and Lettenmaier 2006). The historical rates of change and future climate projections for the Basin were compared and contrasted with the findings of studies of climate trends and projections for BC, the Pacific Northwest and the globe (Table 3.3). Most of the warming in the Basin since 1950 has occurred in the last thirty years (section 3.4 and 3.5). Globally, the 1990s were the warmest decade in the last 1,000 years (IPCC 2001:45).

Although the snowfall trends for the Basin are not statistically significant, a general reduction in the proportion of precipitation falling as snow on an annual basis and in the spring particularly is evident in observations for western Canada over the last 50 years (Zhang, Vincent, Hogg and Niitsoo, 2000).

Table 3.3: Climate trends for the Basin, BC Southern Interior Mountains, PNW, and globe.

Climate parameter	**Rate of past change**			
	Basin[1]	**BC Southern Interior Mountains[2]**	**PNW[3]**	**Global[4]**
Annual mean temperature (°C per century)	+1.5	+1.1	+0.8	+0.6
Annual precipitation (% per decade)	+3%	+4%	1-4%	0.5-1%

Sources: [1]Observations from 1913-2002 (see Appendix A and B); [2]WLAP, 2002; [3]Mote, 2003; [4]IPCC, 2001.

3.7.2 Regional and Global Future Projections

Projections for the Basin were compared with those for larger regions by PCIC (data, maps, and plots available online) and with global projections for the 2050s. The 25th – 75th percentile ranges were used for the Basin, BC, and PNW projections. The results for the Basin, the Columbia River Basin, and B.C. are not directly comparable to the global range, which utilizes a different range of models and emissions scenarios.

Table 3.4: Future climate projections for the Basin, BC, the PNW and the globe.

Climate parameter	**Projected change by 2050s**			
	Basin[1]	**CRB[1]**	**BC[1]**	**Globe[2]**
Annual mean temperature	2.4 to 3.1°C	2.4 to 3.2°C	2.2 to 3.1°C	0.5 to 1.7°C
Annual precipitation (% of baseline)	+1 to +6 %	-1% to +4%	+5 to +10%	+1% to +2%

Sources: [1]PCIC www.PacificClimate.org/tools/select 25th and 75th percentile range; [2]IPCC, 2001 (SRES A2 and B2).

3.8 Summary of Historic Climate Trends and Future Climate Projections for the Basin

The climate of the Basin is influenced by the complex interactions between two global cyclical climate patterns functioning at different time scales (ENSO over several years; PDO over several decades) and natural and anthropogenic climate change.

Historical trends identified in this report were computed through analysis of historical temperature and precipitation observations from 1913 to 2002 for five weather stations within the Basin. Future climate projections were determined for the Basin by using area-averages from several Global Climate Models. These results were supplemented with trends and projections for the region identified in the literature and by experts participating in this assessment. The results provide an indication of past climate trends and future climate projections in the CRB. The analysis in this document illustrates that the climate of the Basin has changed in some important aspects outside of the range of past variability over the last century, and that these changes are projected to continue.

The available paleoclimate evidence shows the climate of the Basin has changed significantly in the past, often within less than a decade. In particular, it appears that the normal precipitation pattern for the Basin could be one with much more frequent and persistent drought than has occurred during the last half-century.

Key findings from this assessment are as follows:

Temperature

- Past increases in average annual temperature (+1.5°C per century) were higher in the Basin than in the Pacific Northwest or the globe as a whole.
- Most of the warming in the Basin occurred in the last thirty years, which is consistent with global trends.
- Minimum temperatures increased almost twice as much as maximum temperatures in the Basin (1.8°C versus 1.0°C over the past century), creating a narrower range in daily temperatures.
- Temperature increased more in winter than in other seasons, with minimum winter temperatures in the Basin an average of 3°C per century warmer.
- Annual mean temperatures are likely to continue to increase by 2.4 to 3.1°C by the middle of this century. Increases are expected to be larger in winter minimum and summer maximum temperatures than other seasons**.** This is consistent with global and Pacific Northwest projections,
- Seemingly small differences in average annual temperature matter - a global 4ºC rise in average temperature about 18,000 to 10,000 years ago was enough to melt the vast ice sheets that once covered much of North America (Walker and Pellatt, 2003).

Precipitation

- Precipitation is naturally more variable than temperature, and is influenced by local factors such as topography, elevation, aspect and exposure. The variable geography of the Basin means that precipitation, and especially snowfall varies significantly from one location to another.
- Annual precipitation in the Basin increased by 3% per decade over the last century. A further increase of +1 to 6% by the middle of this century is projected from Global Climate Models.

- Snowpack on April 1 has decreased by 20-40% since 1950 in some locations in the Basin, particularly at lower elevations, with up to 50% reductions in the U.S. portion of the PNW.
- Snowfall is expected to continue to decrease, especially at low elevations and in the late fall and early spring when warming will shift temperatures above freezing more frequently.
- Snowpack is expected to continue to decline, primarily due to warming, and snowmelt will continue to occur earlier.

Seasonal climate

- Summers are projected to warm by more than the average annual warming, with higher maximum temperatures in particular, and 5 to 16% less rain is projected.
- Winters are projected to warm, with more precipitation and an increase in the portion of precipitation in the form of rainfall rather than snowfall, particularly at lower elevations.

Extreme weather events

- Neither historical trends nor future projections are available for extreme weather events in the Basin.
- Global models project decreases in summer precipitation in the Basin (which could increase summer drought)
- Global model project increases in intense precipitation events for North America as a whole

4 CLIMATE IMPACTS ON BASIN WATER RESOURCES

Climate change directly and indirectly controls hydrological processes that in turn affect ecosystems and the social and economic well-being of the people in the Basin. This section considers potential climate change impacts on glaciers, streamflow, evapotranspiration and soil moisture content in the Basin. It is based on a review of current literature and linked to the temperature and precipitation trends and projections discussed in Section 3.

4.1 Glaciers[18]

Glaciers occupy the upper reaches of many of the major watersheds in the Basin (see map on inside front cover). They serve as frozen freshwater reservoirs that supplement snowmelt runoff during late spring and summer in the Basin. This runoff is important in the Basin where 10-20% of annual flows and up to 50% of summer flows in some years can originate from glaciers (Brugman *et al.*, 1996). As described in section 3.1.1, glaciers are sensitive indicators of climate change because they hold many years of information about past climate.

4.1.1 Impacts of Climate Change on Glaciers

Glaciers in western Canada are sustained by winter snowfall and depleted by melting in summer. Glaciers accumulate mass at higher elevation and lose (or ablate) it at lower elevation, a consequence of the higher air temperatures at lower elevations. When climate is stable, the boundary between the zones of net accumulation and net ablation (the equilibrium line altitude or ELA) is in balance. When climate warms, the ELA rises, reducing the catchment area of the accumulation zone and also shrinking the ablation zone through retreat of the terminus of the glacier.

Annual or longer term changes in glacier mass balance manifest as changes in glacier width, length, and thickness. Since most valley glaciers are constrained along their sides and ice deforms under its own weight, changes in length are the most common response to climate variability, with consequent movement of the glacier terminus. Typical alpine glaciers in western North America have response times on the order of 20-50 years to changes in the long-term average climate.

Climate variability during the warm season can also cause glacial retreat, with the glacier terminus responding more quickly than the entire glacier. For example, at Place Glacier in the southern Coast Mountains of B.C. the rate of frontal retreat slowed following a single year of high snowfall (Moore and Demuth, 2001). Late-lying snow in the ablation zone increased albedo, resulting in greater sun reflection, lower surface temperatures, and hence lowered summer melting.

Throughout the Canadian Cordillera and Pacific Northwest rapid changes in glacier termini have been observed (Burbank, 1982; Osborn and Luckman, 1988; Menounos *et al.*, 2005). Variations in glacier termini also depend on glacier dynamics and topographic setting (Bahr *et al.*, 1998; Klok and Oerlemans, 2003; Oerlemans, 2005). Steep gradients increase the climate sensitivity of glaciers; frontal response times as short as four years have been observed for steep glaciers in the Pacific Northwest (Pelto and Hedlund, 2001).

Detailed mass balance studies in the Canadian Cordillera began in 1965 in conjunction with the International Hydrologic Decade. A west-to-east transect of glaciers through the southern Canadian Cordillera was chosen to show how the link between climate and glacier mass balance changes from maritime (Sentinel and Helm glaciers) to continental (Peyto and Ram River glaciers) environments.

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[18] This section is based on information provided by Brian Menounos on behalf of the Western Canadian Cryospheric Network.

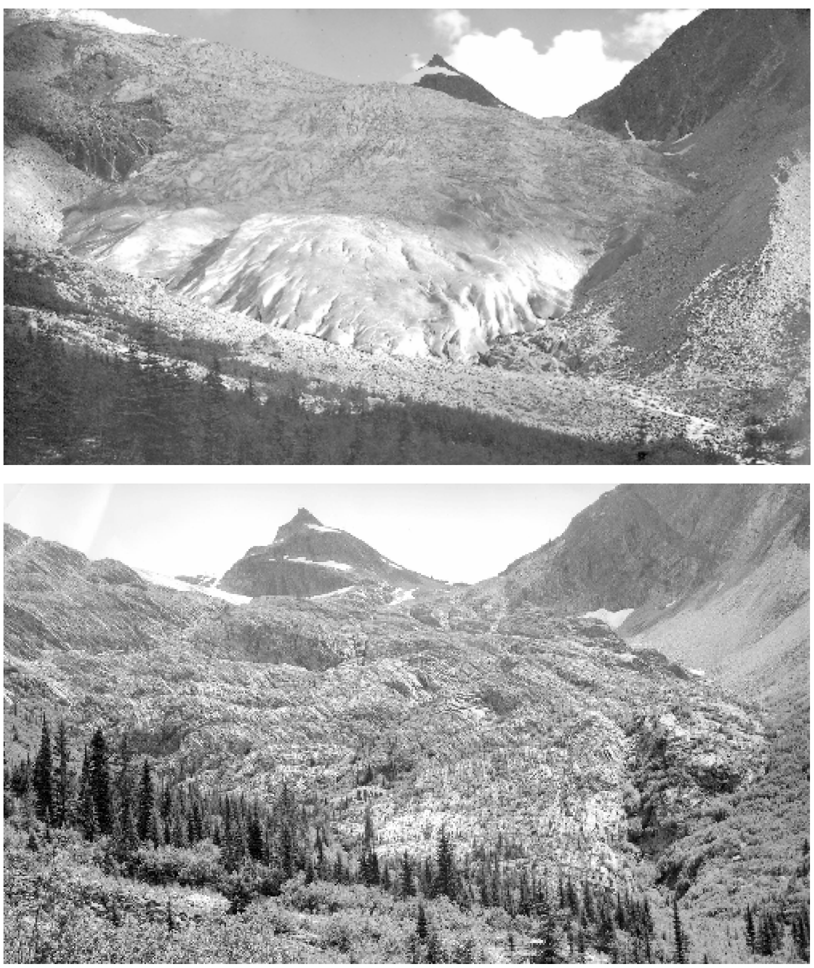
These studies found that continental glaciers were responding to decadal scale climate patterns in both ENSO and PDO, through their influence on summer temperatures and in particular, on winter precipitation (Yarnal, 1984; Walters and Meier, 1989; Letréguilly, 1988; Bitz and Battisti, 1999). The minor advances of glaciers in the Canadian Cordillera in the late 1960s and early 1970s (Osborn and Luckman, 1988) coincided with the negative phase of the PDO when temperatures and precipitation in the Canadian Cordillera were, respectively, cooler and wetter (Mantua *et al.*, 1997; Menounos, 2002). Most of the other glaciers and icefields that have been studied in Alberta and B.C. have lost significant ice volume in the 20th century (WLAP, 2002).

The IPCC (2001) recognizes that globally there is ample evidence to link the observed major retreat of alpine and continental glaciers with 20th century warming. Satellite data show that there have been decreases of about 10% in the extent of snow cover globally since the late 1960s. In particular, a statistically significant correlation exists between decreases in snow cover and increases in Northern Hemisphere land temperatures.

4.1.2 Historical Glacier Recession in the Basin

Glacier retreat can be observed throughout the Basin. The Illecillewaet Glacier in Rogers Pass retreated 1020 metres between 1887, when measurements were initiated, and 1995. Figure 4.1 below illustrates the retreat of the Illecillewaet Glacier over the last century.

Figure 4.1 Retreat of the Illecillewaet Glacier between 1902 – 2002. Source: Dr. Henry Vaux.



A recent glacier inventory of the Basin (Menounos *et al.*, unpublished report to the CBT) indicates that glacier cover decreased 16% from 2,097 km^2 to 1,753 km^2 over the period 1986-2000. This change represents a loss of 344 km^2 of glacier cover or approximately 1% yr^{-1} for the Basin. Sub-basins with the smallest percent glacier cover, such as the Bull and Slocan river basins lost close to half of their ice cover in the period 1986-2000 (Table 4.1).

Table 4.1 Loss of glacier cover by watershed (1986-2000)

Basin	Basin Area (km2)	1986 Ice (km^2)	2000 Ice (km^2)	% Loss
Bull River	3,829	1.13	0.45	60.2
Canoe River	3,166	160	120	25.0
Columbia River Headwaters	7,867	852	748	12.2
Columbia River	4,455	103	83	19.4
Duncan River	4,758	206	168	18.5
Elk River	5,885	13	11.9	8.62
Kicking Horse River	5,654	201	168	16.4
Kootenay Lake	9,378	12	7.50	37.5
Kootenay River	5,372	22	15	31.8
Lardeau River	6,607	NA	NA	NA
Lake Revelstoke	5,633	316	258	18.4
Slocan River	3,419	2.21	1.18	46.6
St. Mary's River	6,598	6.00	4.30	28.3
Upper Arrow Lakes	6,483	203	167	17.7
Total area/percentage	79,105	2,097	1,753	16

Based on well-known scaling relations between the area and volume of glaciers (Bahr *et al.*, 1997), this retreat in glacier cover in the Basin approximates 67 km^3 of permanent ice loss. Annual and April-September temperatures (Willmott and Matsuura, 2001) during the period 1986-2000 were approximately 0.6-1.2 ºC above the 1950-1996 average for the Basin, and this period includes some of the warmest years on record. During this period, winter season (October-March) precipitation was about average, suggesting the loss in glacier mass is largely due to temperature increases.

Converting the loss of ice into runoff and distributing these flows to the months when glacier runoff occurs would indicate glacier retreat increased the streamflow of rivers in the Basin by 700-800 cubic metres/second (using an ice-runoff coefficient of 0.8-0.9) during 1986-2000. Over longer time scales, however, the net effect of glacier contraction following melt is to reduce late summer flows. For example in the eastern slopes of the Rocky Mountains glacier recession over the last 50 years has led to significantly lower summer discharges despite modest increases in annual precipitation over the same period (Demuth and Pietroniro, 2002).

4.1.3 Future Glacier Conditions

Additional research is needed to better understand the impact of projected future climate changes to glacier response in the Basin through careful coordination of glaciological, hydrological, and atmospheric research. As discussed above (section 4.1.1), however, glacier mass balance is expected to depend in particular on factors such as albedo (Takenchi, 2002), temperature, precipitation, wind, and humidity.

The impact on glaciers of projected future temperature increases in particular (section 3) would be continued retreat throughout the Basin. Rivers and streams that are now fed by the runoff from glaciers could be significantly impacted, initially by the increased summer runoff while glacier retreat accelerates. An increased likelihood of late summer and fall floods during high melt periods is possible. Afterwards, once much of the glaciers have melted, a significant reduction in late summer and fall flow would be expected. There is already evidence that this has occurred in several basins in B.C. (Stahl, K. and Moore, R.D. 2006). The transition from high to minimal flow can occur within only a few years near the end of the glacier's life (Brugman *et al*., 1997).

As has been emphasized by others (e.g., Dyurgerov and Meier, 2000), the present trend of mountain glacier recession began in the 19th century, but it is not simply an adjustment to the end of the Little Ice Age. When climate change occurs rapidly, glacier adjustment will lag climate and glaciers can become far out-of-balance with present climate conditions. Although glacier accumulation and ablation (section 4.1.1) responds to year-to-year and decadal variability, glacier mass balance responds to decadal and longer climate trends (figure 2.1). As an example, a recent modelling study has shown that the Vatnajökull ice cap in Iceland is far out-of-step with its present climate and that, even if the present warming trend ended and the current climate was maintained, the ice cap would shrink to a small fraction of its present size (Marshall *et al.*, 2005a). Thus, some of the larger glaciers in the Basin are probably responding to increased air temperatures that occurred decades ago. Analysis is underway using air photos and historical maps to develop a comprehensive inventory of glacier extent for the twentieth century. These data will be used in conjunction with climate models to better understand the links between climate variability and glacier nourishment. Improved understanding of these links will allow the development of predictive models to assess changes in glacier extent over the next 50 to 150 years.

4.2 Streamflow

Approximately 25-50 percent of the total runoff (depending on the season) for the Columbia River system originates in the Canadian portion of the system, although the Canadian portion represents only 15 percent of the total CRB area (Hamlet, 2003; Muckleston, 2003; BPA, 2001). The Canadian contribution is most significant in late summer – for example roughly 50% of the flow in the Columbia River at The Dalles, OR originates in Canada in late summer. The highest streamflow volumes in the Columbia River historically occurred between April and September, with the lowest volumes from December to February. The vast majority of water resources in western North America, including those in the Basin depend on snow that accumulates in the winter and early spring, and melts as runoff in spring and summer.

4.2.1 Impacts on Streamflow

Streamflows within the Basin are influenced by a number of factors, with complex interactions. Many of these factors will be impacted by climate change:

- **Snow and glacier melt**: Snow-water retention and release dominate the hydrology of the Columbia River system with melting snow and glaciers providing crucial spring and summer streamflow. Snowpack volume and density and glacier properties are highly susceptible to changes in temperature and precipitation as described above (sections 3.1-3.4). Increasing temperatures prompt earlier melting and increased rain-to-snow ratios. Rain-on-snow events melt larger volumes of snow than melting driven by warm air temperatures alone. The time period between the end of snow melt and the start of fall rains is also increasing, creating a longer period of low flows. The timing of snow melt has moved earlier in the year because spring temperatures have been steadily rising in many areas (Mote *et al.* 2005; Hamlet *et al.* 2005). This is true even in very cold areas but in such areas timing has not shifted by as much (ibid). Across western North America, analysis of changes in the timing of peak spring runoff in 279 snowmelt dominated streams found that peak spring runoff had advanced 10-30 days by 2000 compared to 1948, with the greatest change occurring in the PNW (Stewart, I.T. et. al, 2004).

- **Soil conditions and evapotranspiration:** Soil conditions are dependent in any year on conditions from the preceding seasons, winter snowpack and the rate of melting, and rates of summer evapotranspiration. In years following a dry fall, the dry soil absorbs more of the spring snow melt than it does following a normal or wetter year. This in turn reduces, summer streamflow. Increases in summer evapotranspiration will also reduce summer streamflow as more water evaporates before it reaches a streambed. These factors can change summer streamflow up to 20% (Hamlet and Lettenmaier, 1999) as discussed in more detail below.

- **Precipitation**: More precipitation in spring (section 3.3), which is already a season of high streamflow in the Basin, may create faster, fuller rivers. In some areas, soils may become saturated with water, increasing the likelihood of landslides and debris torrents. Summer precipitation does not have much effect on summer streamflows; however, it may have an impact on late summer and fall soil moisture levels (Hamlet and Lettenmaier, 1999). More precipitation in fall, typically a season of lower streamflow in the Basin, may mean higher water levels.

Evidence of changes in historical streamflow linked to the climate changes described in Section 3, is available in studies conducted across North America. See Karl and Riebsame 1989; Huntington 2003; and Dudley and Hodgkins 2002 for examples. In 2001, Zhang *et al.* released trends in Canadian streamflow for 30 to 50 years showing annual mean streamflows had decreased, especially in the southern part of the country, with March and April being the only months with increased streamflow. Leith and Whitfield (1998) investigated the effects of climate change on streamflow in south central BC from 1970 to 1995, with the following results:

- the spring runoff (freshet) occurred 20 days earlier in the period from 1984 to 1995 than during the period form 1970 to 1983;
- warmer temperatures and lower summer precipitation caused a longer low-flow period and lower flows at the end of the summer; and
- during late fall and early winter, warmer air temperatures resulted in more precipitation falling as rain than as snow, yielding increased streamflow in winter.

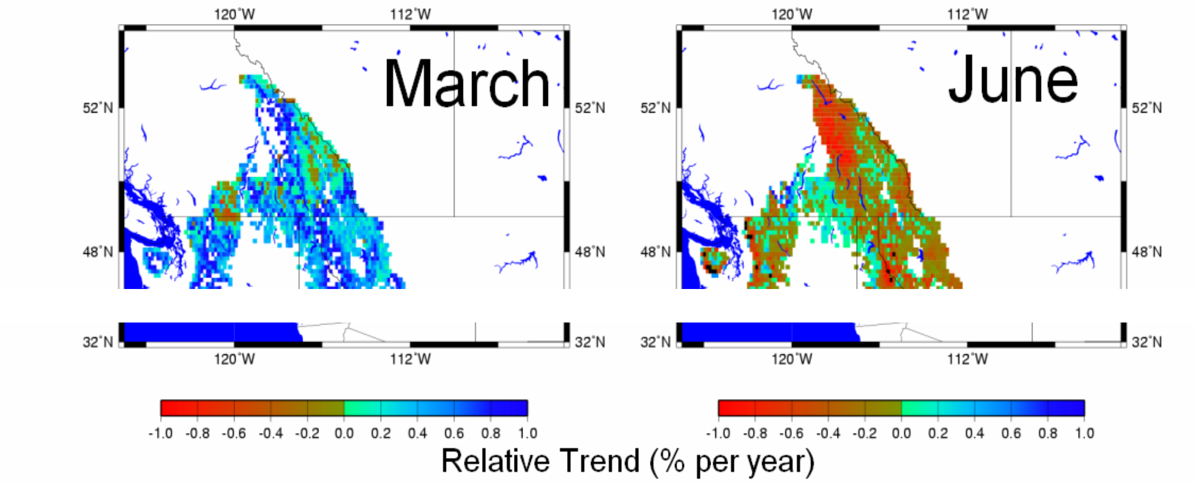
A study of streamflow during the hot, dry summer of 2003 in the Kootenay portion of the Basin (Land and Water BC, 2003) found the following:

- the Moyie River was near record historical (30-year) lows
- the Slocan River experienced the lowest flow levels since 1968; and
- the Kootenay River discharge in July 2003 was the lowest ever recorded.

These conditions were attributed to low snow packs from the previous winter, hot and extremely dry conditions in summer, and a delay in the onset of fall precipitation.

Seasonal trends in streamflow for the Columbia River system from the VIC model (section 3.1.3) are shown in Figure 4.2 for 1974 to 2003. Results are consistent with the earlier spring freshet and lower summer flows described above. The total amount of snow in the Columbia River Basin is mainly influenced by warming which shifts precipitation from snow to rain as discussed in section 3 above, thus changes in streamflow timing have been largely due to temperature trends during the observed record (Hamlet *et al.*, 2006; Stewart *et al.*, 2005). It is worth noting however, that much of the Canadian portion of the system has high elevation snowfields that are more sensitive to precipitation trends.

Figure 4.2: Trends in simulated proportion of annual streamflow in each month from 1974-2003 (cells > 50 mm of SWE on April 1) from VIC model. Source: Climate Impacts Group, University of Washington.



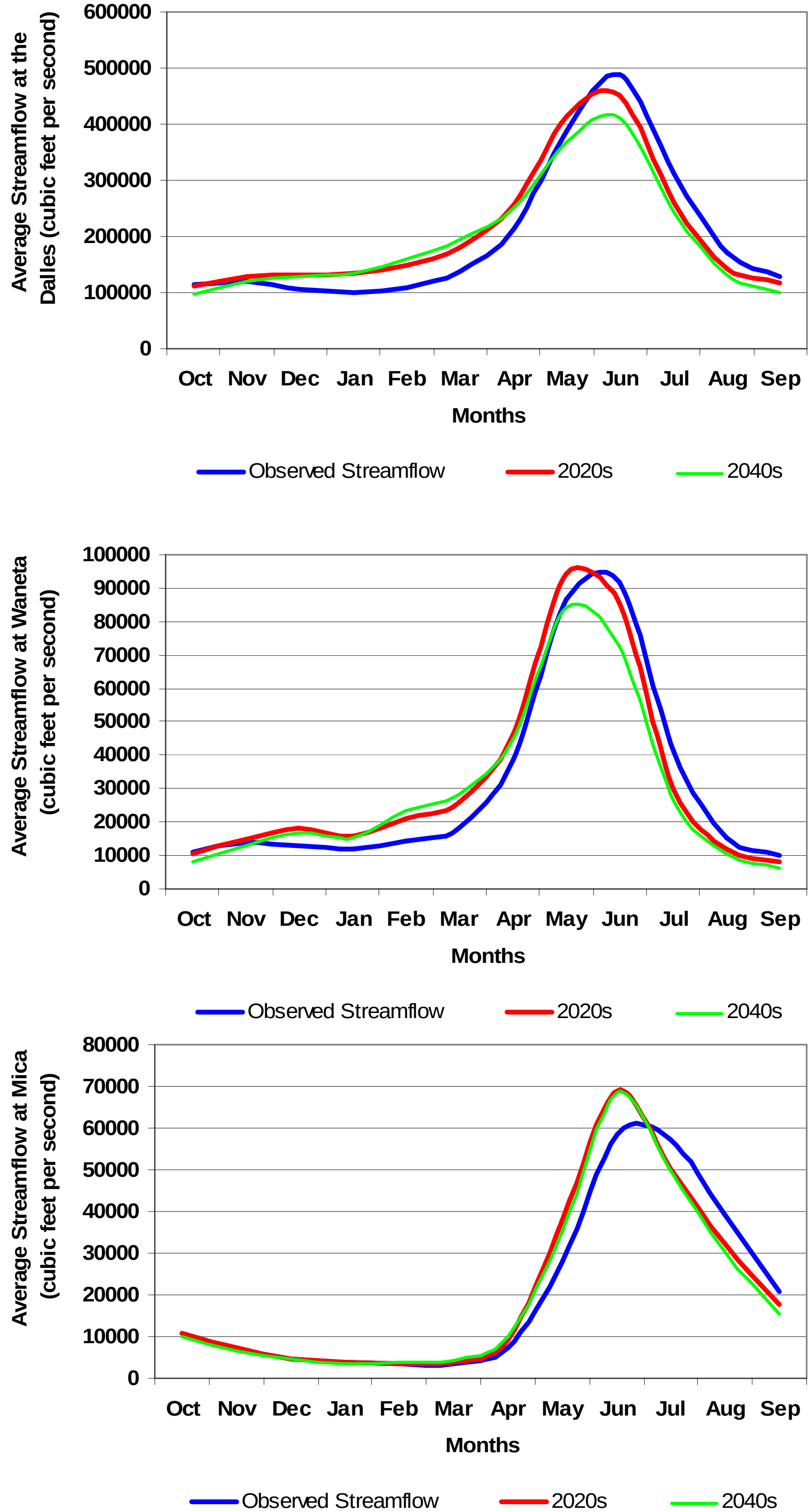
4.2.2 Future Streamflow Conditions

A sensitivity analysis derived from GCM results was used to evaluate possible future climate change, the surface water response of the Columbia River Basin, and the ability of the Columbia River reservoir system to meet regional water resources objectives (Payne *et al*. 2004; Hamlet and Lettenmaier 1999). Results showed significant increases in winter runoff volumes (along with reductions in snow pack) due to increased winter precipitation and warmer winter temperatures. Average March 1st snow water equivalents are projected to be 15-25% below present day by 2025, and 35-45 % below present day by 2045 (Hamlet and Lettenmaier 1999). The study concluded that by 2045, reduced snowpack and earlier snowmelt, coupled with higher evapotranspiration in early summer, lead to earlier spring peak flows and reduced runoff volumes from April to September (ibid) in the Columbia River Basin.

Results from the VIC model (section 3.1.3) show net impacts over time of climate change on streamflow at three locations along the Columbia River: the Mica dam at the northern end of the system, the Waneta dam just before the River goes into the US and the Dalles near the bottom of the system (Figure 4.3). Note the earlier timing of the peak flow at Mica and Waneta, and the projected lower flows at Waneta and the Dalles. More information on the streamflow projections is available online.[19]

[19] http://cses.washington.edu/cig/fpt/ccstreamflowtool/sftscenarios.shtml

Figure 4.3: Observed and projected future streamflow for selected sites on the Columbia River. Source: Climate Impacts Group, University of Washington.



4.3 Evapotranspiration and Soil Moisture Content

Rainfall and snowmelt dominated watersheds in Columbia Basin will respond differently to climate change. In rainfall dominated watersheds, soil moisture is at its lowest in October and is replenished by fall rains. Warmer temperatures will result in drier soil at the end of the summer, which will absorb a greater portion of fall rain. However, in snowmelt dominated watersheds, soil moisture is replenished by spring snowmelt (and is therefore likely at its lowest just before this). Warmer temperatures mean earlier spring melt and soil recharge. Climate change thus increases the length of time between spring recharge and fall rains, and thus enhances the potential for soil moisture loss during the summer and early fall.

4.3.1 Historical Impacts of Climate Change on Evapotranspiration and Soil Moisture Content

Soil moisture is usually lowest in the Basin at the beginning of October. At this time, low temperatures limit evapotranspiration and heavy fall and winter precipitation allows the soil to accumulate water throughout the winter in areas where temperatures are above freezing.

Soils in snow-dominant watersheds tend to accumulate moisture in spring, with the onset of snowmelt. In such watersheds, soil moisture peaks in spring or early summer. In summer, longer days, decreased cloud cover, lower precipitation, increased plant growth, and higher temperatures contribute to depletion of soil moisture over much of the PNW. The return of fall rains and cooler temperatures allow the soils to recharge, continuing the cycle (Casola *et al.* 2005).

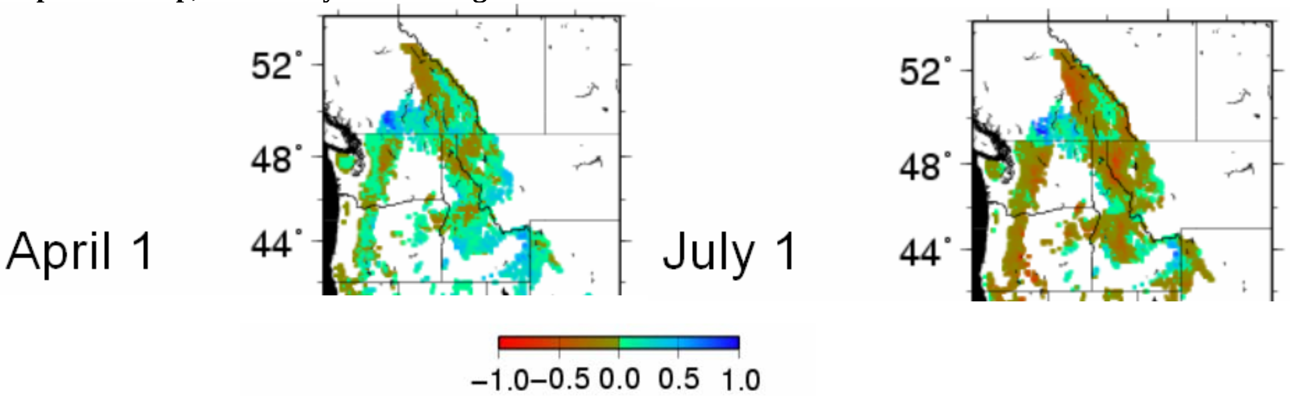
Future warming may lead to changes in evapotranspiration rates, but the literature on this is contradictory. Some studies suggest an increase in evaporation with increasing temperature and moisture, while others suggest decreasing evaporation under these conditions (Brusaert and Parlange, 1998; Golubev *et al*., 2001; Labat *et al.*, 2002; Milly *et al*., 2001; Ohmura and Wild, 1995; Peterson *et al*., 1995; Roderick and Farquhar, 2002).

The potential impacts of climate change on evapotranspiration are complex:

- Longer dry periods resulting from longer summer seasons may lead to decreased soil moisture and reduced evapotranspiration capabilities, but these impacts may be mitigated by observed increases in warm season precipitation (Hamlet *et al.* 2006);
- In low lying areas, where slopes are shallow, intense precipitation events are more likely to saturate the soil surface layer and runoff. This will reduce the infiltration into the deeper soil layers, resulting in less soil water to support evapotranspiration;
- Projected precipitation decreases in summer, may exacerbate the potential loss of soil water and streamflow due to higher temperatures and higher rates of evaporation and plant transpiration.

Hydrological simulations using the VIC model for 1947-2003 show that areas with substantial snow accumulation in winter experienced increased evaporation in spring (denoted by April 1 in Figure 4.4) due to earlier snowmelt and soil recharge (Hamlet *et al.* 2006). These effects were largely due to temperature-related timing shifts in water availability. In mid-summer (denoted by July 1) soil moisture in most of these areas decreased in response to changes in temperature and precipitation.

Figure 4.4: Soil Moisture Content trends from VIC 1947-2003 (% per year). Source: Climate Impacts Group, University of Washington.



4.3.2 Future Evapotranspiration and Soil Moisture Content Projections

Climate change projections for the Basin (section 3) include increasing temperatures, reduced snow pack, and an earlier onset of snowmelt. Under these conditions, soil moisture recharge can be expected to occur earlier in the year in watersheds that are largely snowmelt dominated. Changes in soil moisture in the summer and fall are more difficult to predict, since they are sensitive to changes in many factors including solar radiation (cloudiness), wind speed, precipitation, humidity, and temperature (Casola *et al.* 2005). East of the Cascades, where warm season evaporation in natural settings is almost entirely determined by water availability, summer soil moistures will likely be most sensitive to precipitation changes. Trends in late summer soil moisture may be most sensitive to changing precipitation regimes (Hamlet *et al.* 2006).

Evapotranspiration also depends on vegetation cover. This is of particular importance where major land use changes alter soil water and streamflow processes; the impact of large land-use changes on hydrology is similar to and in some cases greater than the impact of climate change (Matheussen *et al.* 2000). Given the current outbreak of mountain pine beetle that is in part related to climate change (Hélie *et al.*, 2005), and the accelerated logging of infested trees in pine-dominated forests, it is anticipated that major changes to the landscape will occur. Evapotranspiration rates will be affected as well as the soil moisture regime and the processes in the hydrological cycle that are responsible for generating runoff. Changing forest cover could result in higher soil surface temperatures, less snow accumulation, faster snow melting, and large changes in evapotranspiration. These changes have important implications for streamflow and water temperatures (Carignan and Steedman, 2000).

4.4 Summary of Impacts on Hydrology in the Basin

Streamflow and soil moisture within the Columbia River system are dominated by snow and glacier melt and depend largely on the timing and amount of meltwater. Currently, in some years 10-20% of annual flows and 50% of summer flows originate from glaciers. Water temperatures are also regulated by the influx of cold snowmelt, and especially glacial meltwater, in the summer.

Approximately 40 percent of the total runoff for the Columbia River Basin (CRB) system originates in the Canadian portion of the system, although the Canadian portion represents only 15 percent of the total CRB area. The Canadian contribution is most significant in late summer – for example roughly 50% of the flow in the Columbia River at The Dalles, Oregon originates in Canada in late summer.

A review of current literature shows that climate change affects the water resources of the Basin. Warming has had the greatest impacts at most locations. The impacts of past and ongoing climate change and future projections are synthesized below for glaciers, streamflow, and evapotranspiration and soil moisture:

Glaciers

- Glacier retreat has occurred throughout the Basin. An average of 16% of ice cover (area) was lost in the Basin between 1986 and 2000, with the Slocan and the Bull watersheds losing 47% and 60% of their total ice area.
- Continued warming will cause glaciers in the Basin to continue to retreat, with potentially significant impacts on hydrology. In the initial stages of glacial retreat, rapid melting of glaciers increases summer streamflow. Once glacial retreat stabilizes or glaciers are gone, flows will dramatically decrease.
- Though glaciers are sensitive indicators of climate change, glacier melt can lag behind temperature increases by years to decades. Studies suggest some of the large glaciers in the Basin are probably responding to temperature increases from decades ago.

Streamflow

- Several studies provide evidence of links between climate change, and historical changes in streamflow across North America.
- Observed changes in Basin streamflow during the past century include:
  - increased streamflow in winter due to more precipitation falling as rain
  - spring freshets occurring 20 days earlier in 1984-1995 than in 1970-1983
  - longer periods of low flow
  - lower flows at the end of summer;
- Projected changes in temperature and precipitation within the Basin will likely continue to drive streamflow changes including increased winter flows, early freshets and lower summer flows that extend over longer periods.

Evapotranspiration and soil moisture

- Simulations using the VIC model for 1947 to 2003 suggest that in areas with substantial winter snow accumulation, warmer spring temperatures and earlier snowmelt contributed to increased evaporation in spring.
- Increased summer temperature, evaporation, and transpiration would reduce soil moisture, reduce summer base streamflow, and increase drought potential.

5 NEXT STEPS – MONITORING AND RESEARCH OPPORTUNITIES

This report is a compilation of analysis and information about the past and future climate conditions in the Basin. Section 3.8 provides a summary of historic climate trends and future climate projections while section 4.4 provides a summary of impacts on hydrology.

Further monitoring and research is needed to enrich the understanding of Basin climate and impacts, and to support adaptation decisions. The following list compiles the suggestions that were made throughout the report. Asterisks (*) identify the opportunities that the authors of this report believe to have the greatest potential to realize the most scientific gains.

a) Basin climate variability

- Analyze historic records to illuminate ENSO and PDO impacts on Basin climate, particularly on extremes*
- Analyze historic records using water years instead of calendar years
- Examine the paleoclimate record to provide insights into past climate variability*
- Examine spatial variations in the historic temperature and precipitation records to understand impacts of elevation, geographic location and terrain*
- Develop Basin-specific “seasonal climate predictions” (year-to-year variability)
- Establish adequate hydrometric monitoring* including:
    - temperature
    - precipitation (rainfall, snowfall), snowpack, and snowline elevation
    - freezing and thawing (first date of permanent ice, date of complete freezing, date of first melt, ice free date)
    - glaciers (ice extent, volume and flow, glacier runoff, terminus position, high elevation radiation, energy balance)
- Monitor ecosystem responses (e.g. indicator tree species range)*

b) Temperature and precipitation

- Further historic trend analysis of the precipitation record with more stations
- Analyze extreme weather events to identify trends
- Analyze the timing, frequency, and intensity of past summer rainfall events to explore the relationship with increases in wildfire, drought, and precipitation in the Basin*

c) Streams, rivers and lakes

- Analyze historic streamflow trends*
- Sustain and expand the hydrologic monitoring network, including stream temperature monitoring to assess suitability for preferred fisheries species and aquatic system impact
- Expand the forecasts of future streamflow conditions under different climate, glacier melt and snowpack regimes**

d) Snow and rain

- Analyze historic snowline elevation trends to better understand possible implications for winter recreation activities*
- Examine the impacts of land use (i.e. reservoir creation) on local historic precipitation trends*
- Undertake a high resolution study of past and future regional rainfall, snowfall and snowpack based on improved understanding of regional influences on seasonal precipitation, and global warming responses*

e) Glaciers

- Examine the impact of glacier retreat on air temperature
- Explore links between future climate variability and change and glacier response

f) Evapotranspiration and soil moisture

- Extend the literature search

g) Water Use

- Document past changes in human water use/consumption *
- Develop potential scenarios of future human water use*

h) Risks

- Quantify risks to humans and large scale ecosystems associated with hydrologic changes associated with warming*
- Understand the risks and adaptive capacity of human systems to hydrologic changes*

In addition to hydrological topics, further assessment of the biophysical impacts of climate change in the Basin should be completed, including possible relationships between historical pest outbreaks and wildfire trends and climate conditions, and impacts of climate variability and change on growing degree days. Furthermore, this analysis, and any future monitoring and research results should be broadly distributed in formats that are readily useable by Basin organizations and citizens. This can best be accomplished through ongoing dialogue. Two-way communications are needed so decision makers and citizens can better understand climate science and the types of information that are available, and climate scientists can understand more about how people use climate information to make decisions. This report is intended to be one step in creating this dialogue.

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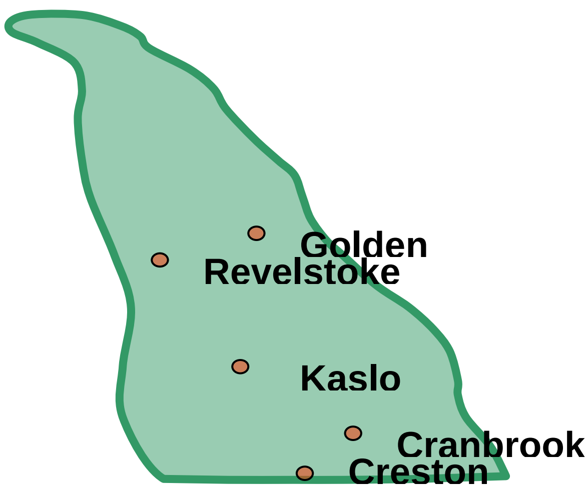
APPENDIX A – HISTORICAL RECORDS AND ANALYSIS METHODS

Data Sources for Historical Trends

The data used in this analysis were obtained from Environment Canada's Adjusted Historical Canadian Climate Data (AHCCD) website (Environment Canada, 2005). This site provides rehabilitated precipitation and homogenized temperature data sets specifically for climate change research. These data are not the same as the official Meteorological Service of Canada *in situ* station records as they incorporate a number of statistical adjustments to the original station data to account for station moves, changes in instruments or exposure, and changes to observing practices. In some cases, stations with short records are joined to create a long-term time series. These data are intended for research purposes only.



Data Station Information

Golden, Kaslo, Cranbrook, Creston, and Revelstoke were the locations selected by Casselman (2005) for analysis in a previous report on climate change that was prepared for the CBT Water Initiatives. In the Basin there are 21 long-range precipitation and six long-range temperature AHCCD stations. Values are available at monthly or annual time scales. The above five were selected from these because they have both temperature and precipitation data dating back at least 90 years. They are also somewhat distributed throughout the Basin. Of these five stations Golden and Revelstoke are located the farthest north in the Basin, Cranbrook and Creston are located in the most southern extent of the Basin, and Kaslo is between the other four. At each point the precipitation and temperature sites are identical or closely located (Table A.1).

The selected stations are generally representative of the more densely populated areas in the Basin; they are not necessarily representative of the Basin as a whole. Steep elevation gains add complexity to the climatology of the Basin. The chosen stations represent the response of temperature and precipitation to climate change at a range of elevations, but are not representative of higher elevations in the Basin. Unfortunately, the availability of higher elevation data is often limited in general because of challenges in accessing and maintaining these remote sites. Table A.1 below lists the latitude, longitude and elevation of the stations.

Table A.1 Station locations

Temperature Data Source Locations

	Lat	Long	Elevation (m)
Cranbrook A	49.53	115.77	918
Creston	49.10	116.52	597
Golden	51.30	116.98	785
Kaslo	49.92	116.92	591
Revelstoke	50.97	118.18	443

Precipitation Data Source Locations

	Lat	Long	Elevation (m)
Cranbrook	49.60	115.78	939
Creston	49.10	116.52	597
Golden	51.30	116.97	787
Kaslo	49.92	116.92	591

When comparing climate trends from multiple stations, it is desirable to select stations with records from the same time period. The AHCCD database for most stations is complete to the end of the 2002. Although most of the records started before 1913, precipitation data for the Kaslo location did not start until 1913. To ensure trends were comparable the analysis for all stations was limited to 1913 – 2002, exactly 90 years. The precipitation record for Revelstoke dates back to 1903 but ends in 1994 thus no precipitation trend was calculated for Revelstoke. The precipitation analysis could benefit from employing a greater number of stations than temperature; however, it was outside the scope of this report to analysis additional stations. This is an area of future work that would provide considerable additional value in understanding the spatial variability of trends in precipitation across the Basin. Future analyses could also include gridded temperature and precipitation data sets or adjustments to account for topographic variations in precipitation (e.g. Hamlet and Lettenmaier 1999).

Data Analysis Methodology

Analyses of trends were performed for individual stations as well as for the regional average. For temperature and precipitation trends, the average annual climatology at each station was computed over the 1961-1990 period to provide a baseline. For the temperature stations, the temperature for each year was subtracted from the 30-year average climatology for that station for each year to give the anomaly. For the precipitation stations, the precipitation for each year was first subtracted from and then divided by the 30-year average for that station for each year to give the percent anomaly. Dividing by the 30-year average for the station facilitates comparison between stations that could have large differences in precipitation amounts. Due to geographical characteristics of the Basin, the difference between precipitation totals at different stations can be quite large. A regional average annual anomaly for the Basin was computed by averaging the annual anomalies for the stations. This methodology is similar to that used for the Environment Canada State of the Environment Report 92-2 (SOE 1992), the Canada Country Study on Climate Impacts and Adaptation for British Columbia and the Yukon, and the BC Indicators Report (WLAP 2002). It should be noted that these methods do not rigorously weight the precipitation data to adjust for differences between stations that result as a function of topographic variations. In the mountainous terrain like that of the Basin this influence could be significant. Although more sophisticated techniques are available (e.g. Zhang *et al.* 2000; Mote *et al.* 1999) it was beyond the scope of the project to apply them here.

The 90-year series of yearly average anomalies of minimum, maximum, and mean temperature, snow, rain, and precipitation trends in the time series were analyzed with the MAKESENS program. This program applied the non-parametric Mann-Kendall test to test for the statistical significance of the trend and the non-parametric Sen's method to estimate the magnitude of the trend (Salmi *et al.*, 2002; Mann 1945; Kendall 1955). Pre-whitening was used to reduce auto-correlation, only for those stations with a significant coefficient (Pearson's R) of correlation between the time series and lag^{-1} of the time series. This process was recommended by Wang and Swail (2001), who demonstrated that the Mann-Kendall test is sensitive to autocorrelation. If autocorrelation was found to be significant it was removed, to "pre-whiten" the data by subtracting the partial correlations of the times series. This process was applied to the individual stations but not to the regional average. This is because averaging the records from the individual stations reduced autocorrelation in the record by equally weighting the values from multiple stations, diminishing the influence of local affects.

As a check a Mann-Kendall covariance analysis was applied to test for the similarity between trends for the individual stations. The average of the cross-correlations for all stations was considered to be a measure of the coherence between the stations. For the Basin stations, the average for annual mean temperature is 0.86, for annual precipitation 0.46, annual rain 0.40, and snow 0.55. Therefore the use of a regional average to represent the change in the Basin is stronger for temperature than it is for precipitation parameters. This is what would be expected as precipitation is known to be more spatially variable than air temperature.

APPENDIX B – HISTORICAL CLIMATE TRENDS ANALYSIS

The table below summarizes the results of the trends analysis described in Appendix A. The following brief descriptions of the rows are provided as a guide to interpretation:

Elevation: station elevation in metres above sea level; (note: regional average elevation is the average of the stations used, not representative of the average elevation of the Basin).

Trend: the trend over the full time period; denoted with an * if ***statistically significant*** at the 95% level (there is a 5% chance that the trend is actually zero or of opposite sign based on random chance); the trend is evaluated over the 1912-2001 period for individual stations and over the 1913-2002 period for the regional average.

Confidence Interval: this may be thought of as the upper and lower bounds of possible values for the trend; at the 95% confidence level there is a 5% chance that the trend would fall above or below this range; this provides a measure of the uncertainty in the statistical estimate.

Standard Deviation: a measure of the variability over the period; higher standard deviation values mean that there is more variability in the record and less confidence in a trend. This is useful for comparison to the trend to judge the relative size of an absolute trend

1961-1990 Baseline Climatology: the condition over the period from 1961-1990; may be considered as a "recent historical average climate"; this is an absolute value, not a change over time.

Notes:
* Statistically significant at the 95% confidence level
** Regional trends, confidence intervals, and standard deviations for precipitation, rain, and snowfall exclude Revelstoke.

Table B.1 Summary of historical trends for each station and Basin average

	"Regional Average" (1913-2002)	**Cranbrook** (1912-2001)	**Golden** (1912-2001)	**Creston** (1912-2001)	**Kaslo** (1912-2001)	**Revelstoke** (T 1912-2001)
Elevation (m)	n/a	918	785	597	591	443
Annual Mean Air Temperature Trends						
Trend (°C)	+1.4*	+2.5*	+1.0*	+1.6*	+1.3*	+1.1*
Confidence Interval (°C)	0.8 to 1.9	1.2 to 3.7	0.3 to 1.7	0.8 to 2.5	0.5 to 2.1	0.2 to 1.9
Standard Deviation (°C)	0.9	0.8	0.9	1.3	1.1	1.2
1961-1990 Baseline Climatology (°C)	6.4	5.6	4.7	7.7	7.3	7.0
Maximum Air temperature Trends						
Trend (°C)	+0.9*	+1.3*	+0.5	+1.0	+1.4*	+0.7
Confidence Interval (°C)	0.3 to 1.5	0.4 to 2.3	0.0 to 1.2	0.0 to 1.9	0.5 to 2.3	-0.3 to 1.7
Standard Deviation (°C)	0.9	1.2	0.9	1.3	1.2	1.3
1961-1990 Baseline Climatology (°C)	11.7	11.4	10.4	12.9	12.3	11.8
Minimum Air Temperature Trends						
Trend (°C)	+1.6*	+3.3*	+1.7*	+2.3*	+1.1*	+1.3*
Confidence Interval (°C)	1.0 to 2.1	1.5 to 5.2	0.6 to 2.8	1.2 to 3.6	0.3 to 1.8	0.4 to 2.3
Standard Deviation (°C)	0.9	2.4	1.5	1.7	1.1	1.4
1961-1990 Baseline Climatology (°C)	1.1	-0.3	-0.9	2.4	2.2	2.1

	"Regional Average" (1913-2002)	**Cranbrook** (1912-2001)	**Golden** (1912-2001)	**Creston** (1912-2001)	**Kaslo** (1912-2001)	**Revelstoke** (P 1912-1993)
Annual Precipitation Trends						
Trend (%) (average**)	+26*	+17	+10	+38*	+44*	+6
Confidence Interval (%) (average**)	17 to 36	-2 to 37	-4 to 23	13 to 61	21 to 62	-12 to 25
Standard Deviation (%) (average**)	15	22	16	36	28	19
1961-1990 Baseline Climatology (mm) (average**)	601	444	490	612	861	1079
Annual Rainfall Trends						
Trend (%) (average**)	+32*	+24*	+21*	+45*	+44*	0
Confidence Interval (%) (average**)	23 to 41	3 to 45	5 to 36	13 to 78	15 to 73	-22 to 22
Standard Deviation (%) (average**)	15	25	19	45	35	25
1961-1990 Baseline Climatology (mm) (average**)	445	296	326	489	668	696
Annual Snowfall Trends						
Trend (%) (average**)	-6	-13	-14	-4	+5	+21
Confidence Interval (%) (average**)	-26 to 15	-49 to 20	-46 to 25	-27 to 22	-23 to 31	-13 to 50
Standard Deviation (%) (average**)	28	38	44	35	34	37
1961-1990 Baseline Climatology (cm) (average**)	157	148	164	123	192	383