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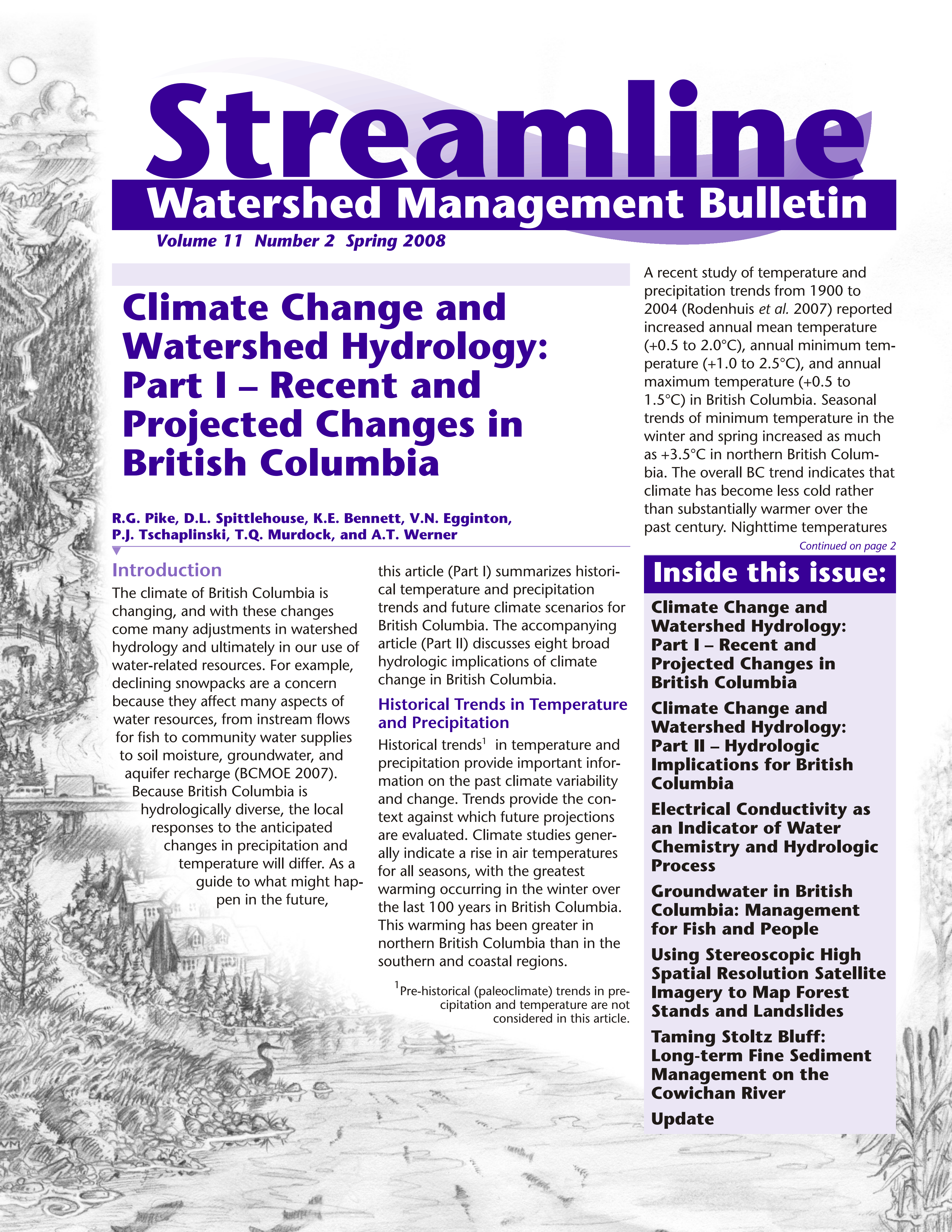

Climate Change and Watershed Hydrology: Part I – Recent and Projected Changes in British Columbia

R.G. Pike, D.L. Spittlehouse, K.E. Bennett, V.N. Egginton, P.J. Tschaplinski, T.Q. Murdock, and A.T. Werner

Introduction

The climate of British Columbia is changing, and with these changes come many adjustments in watershed hydrology and ultimately in our use of water-related resources. For example, declining snowpacks are a concern because they affect many aspects of water resources, from instream flows for fish to community water supplies to soil moisture, groundwater, and aquifer recharge (BCMOE 2007). Because British Columbia is hydrologically diverse, the local responses to the anticipated changes in precipitation and temperature will differ. As a guide to what might happen in the future, this article (Part I) summarizes historical temperature and precipitation trends and future climate scenarios for British Columbia. The accompanying article (Part II) discusses eight broad hydrologic implications of climate change in British Columbia.

Historical Trends in Temperature and Precipitation

Historical trends[1] in temperature and precipitation provide important information on the past climate variability and change. Trends provide the context against which future projections are evaluated. Climate studies generally indicate a rise in air temperatures for all seasons, with the greatest warming occurring in the winter over the last 100 years in British Columbia. This warming has been greater in northern British Columbia than in the southern and coastal regions.

A recent study of temperature and precipitation trends from 1900 to 2004 (Rodenhuis *et al.* 2007) reported increased annual mean temperature (+0.5 to 2.0°C), annual minimum temperature (+1.0 to 2.5°C), and annual maximum temperature (+0.5 to 1.5°C) in British Columbia. Seasonal trends of minimum temperature in the winter and spring increased as much as +3.5°C in northern British Columbia. The overall BC trend indicates that climate has become less cold rather than substantially warmer over the past century. Nighttime temperatures

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[1] Pre-historical (paleoclimate) trends in precipitation and temperature are not considered in this article.

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Suite 702, 235 1st Avenue
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Project Manager:
Todd Redding
Tel: (250) 713-1184

Distribution/Mailing List:
Gord Austin
Tel: (250) 371-3923

Technical review committee:
T. Redding, R.D. Moore, R. Pike

Technical reviewers this issue:
K. Bennett, V. Carmichael, D. Campbell, N. Coops, R. Guthrie, M. Hayashi, D. Hutchinson, R.D. Moore, M. Nelitz, O. Niemann, R. Pike, T. Redding, M. Schnorbus, M. Shrimpton

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Graphic Layout: **SigZag Design**

Editing: **Ros Penty**

Cover Illustration: **William McAusland**
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appear to have increased more than daytime temperatures (Vincent and Mekis 2006). This can be seen in a statistically significant but small decrease in the diurnal temperature range (–0.5 to 1.5°C) at some stations in southern British Columbia.

Trends in annual precipitation across British Columbia for the last century are more varied than for temperature. Average annual precipitation trends have increased (+22%) but were spatially variable, with the larger increases occurring in regions with comparatively low annual precipitation (Rodenhuis *et al.* 2007). Vincent and Mekis (2006) found an increase in the number of days with precipitation and a decrease in the number of consecutive dry days. Seasonally, precipitation has increased over the past century across most of British Columbia in the winter and spring by up to 50%, especially in the northern Interior (Rodenhuis *et al.* 2007). However, analyses of the last half-century generally show declining trends of precipitation at some locations, especially in the winter. For example, from 1950 to 2002 there was an overall reduction in winter precipitation and an increase in summer precipitation (Zhang *et al.* 2000). Precipitation indices for Canada over the 20th century have shown an increase in annual snowfall from 1900 to the 1970s followed by a considerable decrease until 1980 (Vincent and Mekis 2006).

The interactions between increased temperature and changes to precipitation in British Columbia are complex and not fully understood. Research in the western United States suggests that the snow-to-rain ratio is changing and less snow is falling during winter at lower elevation sites on the U.S. west coast owing to the increase in temperatures (Knowles *et al.* 2006). Mote *et al.* (2005) report a general decline in snowpacks over much of western North America from 1950 to 1997, despite increases in precipitation. The change in temperatures over the past 50 years has also been linked to increased atmospheric water vapour and associated dewpoint and specific humidity trends during the winter and spring (Vincent *et al.* 2007). In British Columbia, the Ministry of Environment reported overall decreasing trends in snow water equivalent (SWE) from 1956 to 2005 based on data from 73 long-term snow courses analyzed (63 decreased, 10 increased) (BCMOE 2007). The largest decreases occurred in the mid-Fraser basin while the Peace, Skeena, and Nechako basins had no notable change over the 50-year study period; the provincial average SWE decreased 18% (BCMOE 2007).

Trends in extreme events for the past 50 years indicate that precipitation characteristics in western Canada may be shifting, especially when the seasonal patterns are examined. Stone *et al.* (2000) found a significant increase in heavy rainfall events during spring (May, June, July, 1950–1995). Zhang *et al.* (2000) examined the differences between the first and the second half of the century and found an increase in both extreme wet and extreme dry conditions that occurred in summer (1950–1998). However, while only the number of days with heavy precipitation increased significantly over the past 50 years (based on the national trend), some stations in southern British Columbia show significant increases in two extreme indices: the highest 5-day precipitation and very wet days (the number of days with precipitation $\geq$ 95th percentile) (Vincent and Mekis 2006; Figure 5).

Climate variability from atmosphere-ocean oscillations can confound historical trends. British Columbia's relevant modes of climate variability include the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Pacific North American pattern (PNA), and Arctic Oscillation (AO) (Moore *et al.* 2008). Climate variability on the scale of years and decades may cause changes in temperature and precipitation of the same magnitude or greater than changes in historical, long-term trends (Rodenhuis *et al.* 2007). For example, El Niño winter mean temperatures are generally +3.9°C warmer than average years, compared with the historical, long-term winter mean temperature trend (+2.1°C per century) (Rodenhuis *et al.* 2007). The two most commonly considered modes of variability are ENSO and PDO; the positive phase of ENSO (El Niño) can cause BC winters to be warmer and drier than average, whereas the negative phase (La Niña) can bring colder and wetter winters (Shabbar and Khandekar 1996; Shabbar *et al.* 1997). In the past century, there also have been two PDO cycles. Cool phases occurring from 1890 to 1924 and from 1947 to 1976, and warm phases 1925 to 1946 and 1977 to 1998 and possibly to the present, which have affected BC winter temperatures and precipitation (Mantua and Hare 2002).

During El Niño winters, British Columbia is generally drier, except for northern Vancouver Island, Haida Gwaii, and parts of the South Coast, which display an opposite (wet) signal, while most of the province is wetter during La Niña winters, with the exception of Haida Gwaii (Rodenhuis *et al.* 2007). During spring, the El Niño (La Niña) response is weaker than in the winter at most locations, with wetter (drier) conditions occurring throughout most of British Columbia. Warm (cool) PDO conditions during winter generally exhibit the same pattern as El Niño (La Niña) winter but signals are weaker (Rodenhuis *et al.* 2007). During spring, the PDO warm (cool) precipitation response is strong and widespread (Rodenhuis *et al.* 2007).

The interaction of PDO and ENSO can amplify responses in a particular region (Gershunov and Barnett 1998; Storlazzi *et al.* 2000). For example, results from southwestern British Columbia illustrate that in-phase La Niña/cool PDO precipitation is +19% to +25% higher than during non-ENSO and out-of-phase (PDO) years, and +39% greater than during in-phase El Niño/warm PDO years (Kiffney *et al.* 2002). During these in-phase periods, ENSO and PDO reinforce each other and hence there may also be increased likelihood of extreme weather events. The PNA pattern's positive phase also brings warmer winters to British Columbia with a reduced snowpack (Moore and McKendry 1996). The AO affects the extent of cold Arctic air into British Columbia with the negative (positive) phase bringing an increase (decrease) in the number of cold days (Higgins *et al.* 2002). These atmosphere-ocean patterns are further complicated by interactions with each other (Bond and Harrison 2006; Moore *et al.* 2008). Importantly, the influence of climate variability and resulting effects on streamflow must be taken into account when assessing climate change impacts (Fleming *et al.* 2007).

Historical Trends in Glaciers, Ice Cover, and Streamflow

The overriding trend is that most BC glaciers are out of equilibrium with the current climate. They are slowly adjusting to changes in seasonal precipitation and elevated temperatures with widespread glacial volume loss and retreat in most areas. For example, the Illecillawaet Glacier in Glacier National Park has receded over 1 km since measurements began in the 1880s (Parks Canada 2005). Glacial volumes have increased in some areas of British Columbia (e.g., northwest) at high elevations, where precipitation has increased and temperatures have remained cold enough (Rodenhuis *et al.* 2007). Schiefer *et al.* (2007) reported that the recent rate of glacier loss in the Coast Mountains is approximately double that observed for the previous two decades.

> *The recent rate of glacier loss in the Coast Mountains is approximately double that observed for the previous two decades.*

Increasing temperatures have also affected the length and date of seasonal lake ice cover. A Canada-wide

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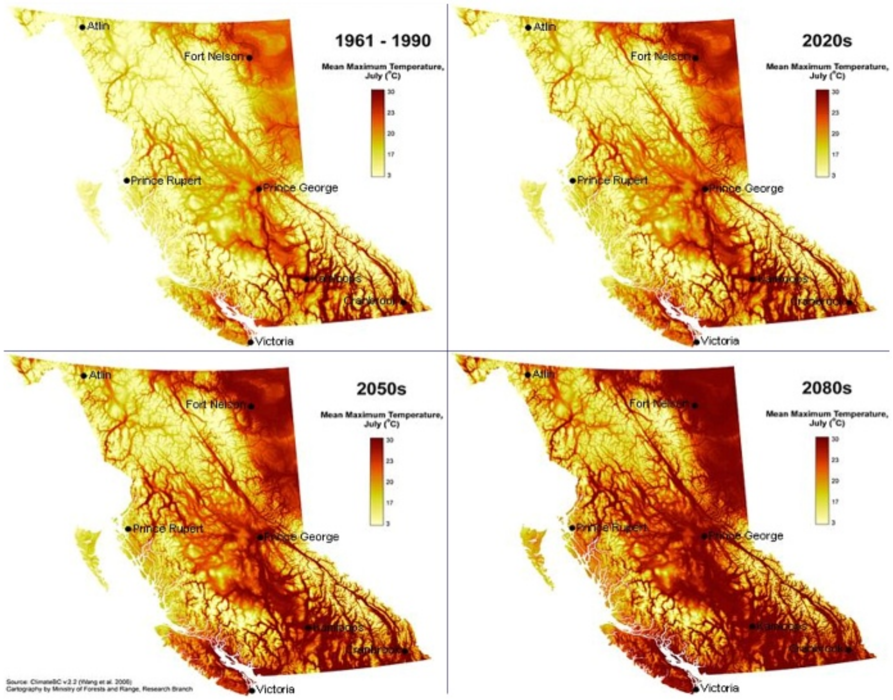
Table 1. Changes in seasonal air temperature and precipitation by 2050 for regions in British Columbia for the A2 scenario from the Canadian GCM3. Updated from Rodenhuis *et al.* 2007.

Region	Temperature				
	Winter	Spring	Summer	Fall	Annual
Columbia Basin	1.8	1.5	2.4	1.8	1.9
Fraser Plateau	1.9	1.6	2.0	1.8	1.8
North Coast	1.5	1.3	1.4	1.5	1.4
Peace Basin	2.4	1.7	1.8	1.8	1.9
Northwest	2.0	1.6	1.8	1.7	1.8
Okanagan	2.0	1.8	2.6	2.0	2.0
Southern Coast	1.5	1.3	1.7	1.6	1.5
BC	**1.9**	**1.6**	**1.8**	**1.7**	**1.7**

Region	Precipitation				
	Winter	Spring	Summer	Fall	Annual
Columbia Basin	7%	8%	-8%	8%	4%
Fraser Plateau	8%	10%	-4%	11%	7%
North Coast	6%	7%	-8%	9%	6%
Peace Basin	9%	9%	3%	10%	7%
Northwest	10%	9%	4%	8%	8%
Okanagan	5%	12%	-8%	8%	5%
Southern Coast	6%	7%	-13%	9%	6%
BC	**7%**	**8%**	**-3%**	**9%**	**6%**

Winter = Dec-Jan-Feb / Spring = Mar-Apr-May / Summer = Jun-Jul-Aug / Fall = Sept-Oct-Nov



Source: ClimateBC v2.2 (Wang et al. 2006)
Cartography by Ministry of Forests and Range, Research Branch

Figure 1a. Mean maximum July temperature for British Columbia for current climate (1961–1990 average) and that predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software, which downscaled change data for the A2 scenario from the Canadian global climate model version 2 (Wang et al. *2006). Source: Spittlehouse (2007).*

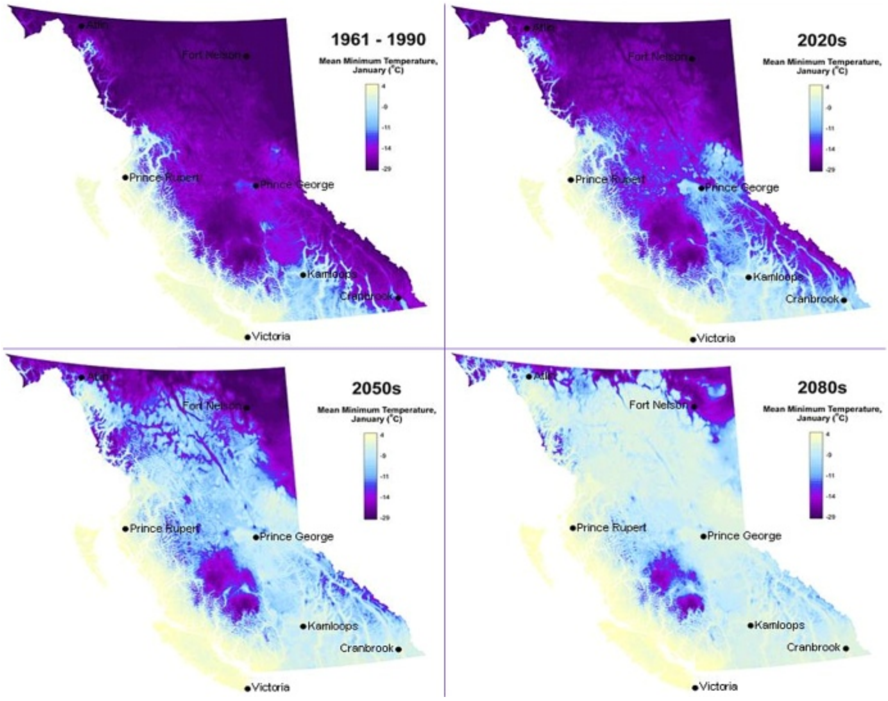


Figure 1b. Mean minimum January temperature for British Columbia for current climate (1961–1990 average) and that predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software, which downscaled change data for the A2 scenario from the Canadian global climate model version 2 (Wang et al. *2006). Source: Spittlehouse (2007).*

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study showed significantly earlier lake "ice-free" dates for the 1951 to 2000 period (Duguay *et al.* 2006). In several BC lakes, the first melt date and ice-free date decreased 2–8 days per decade from 1945 to 1993, while the duration of ice cover decreased by up to 48 days over the 1976 to 2005 period (BCMOE 2002; Rodenhuis *et al.* 2007).

Few studies are available that have documented the influence of past climate change on streamflow in British Columbia. This may be due to the limited amount of available long-term hydro-climatic data, and the confounding influences of varying levels of land use (i.e., forest harvesting) and natural disturbance on watershed processes and function. A few studies, however, do provide some insight. Leith and Whitfield (1998) examined long-term streamflow records for six watersheds in south-central British Columbia, the results of which demonstrated an "earlier onset of snowmelt runoff followed by an increasingly long and dry summer, with the possibility of water shortages in late summer" (Leith and Whitfield 1998, p. 230). In their study, land use was not a factor as the main study site was inside a park. Observed increases in winter streamflows were attributed to a greater percentage of rain falling versus snow accumulation during this season. Similar results were found in a more recent study of streamflow trends across Canada (Whitfield and Cannon 2000). In both studies, the hypothesized effect (increases in winter streamflow via a greater percentage of rain falling vs. snow accumulation during this season) was not statistically significant. However, recent analysis has now determined that the effect is significant (i.e., increased flows in early winter due to precipitation as rain rather than snow in November/December) (P. Whitfield, pers. comm., 2007).

In another study, Zhang *et al.* (2001) reported that annual mean streamflow has decreased based on trend analysis for the past 30–50 years (three time periods: 1967–1996, 1957–1996, 1947–1996) across Canada. Their results also included:

- an increase in mean monthly streamflow across Canada in March and April, with decreases in summer and fall;
- a decrease in annual minimum daily mean streamflow in southern Canada, with increases in northern British Columbia and Yukon Territory;
- a decrease in annual maximum daily mean streamflow;
- an earlier starting date of spring high-flow season;
- an earlier date of annual maximum daily mean streamflow;
- an earlier centroid (date) of annual streamflow; and
- an earlier date of spring ice break-up.

For many of these variables, Zhang *et al.* (2001) identified southern British Columbia as a significantly impacted region. Advances of 10–30 days in the centre of mass of annual streamflow (date by which half of the annual total runoff has occurred) were measured in streams in Pacific North America (Stewart *et al.* 2005).

These trends indicate that shifts are occurring in hydrologic regimes. The magnitude and direction of these shifts vary across British Columbia and among studies. For example, mean annual streamflow has been reported to be decreasing in southern British Columbia, increasing in the central Interior and northeastern British Columbia, and decreasing in the northwest (Rodenhuis *et al.* 2007). This is not surprising given the relative importance of the different hydrologic processes on the Coast versus Interior and differing drivers of streamflows (e.g., winter rain storms vs. spring snowmelt). Differences between studies also occur due to the use of different time periods in trend analyses (i.e., newer studies are based on more and [or] longer time series of data).

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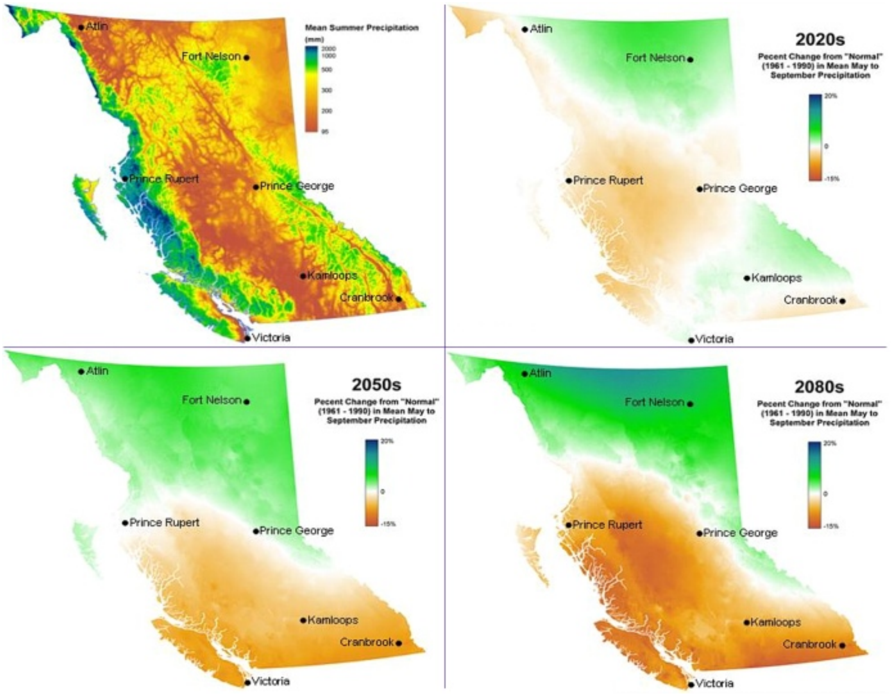

Figure 2a. Mean May to September precipitation for British Columbia for current climate (1961–1990 average) and the percentage change predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software, which downscaled change data for the A2 scenario from the Canadian global climate model version 2 (Wang **et al.** *2006). Source: Spittlehouse (2007).*

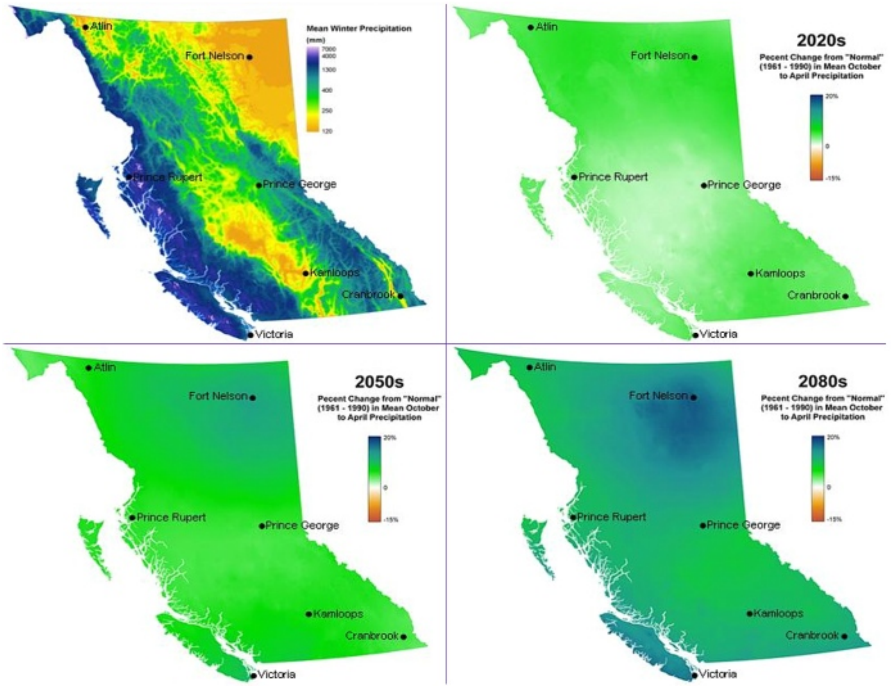

Figure 2b. Mean October to April precipitation for British Columbia for current climate (1961–1990 average) and the percentage change predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software, which downscaled change data for the A2 scenario from the Canadian global climate model version 2 (Wang **et al.** *2006). Source: Spittlehouse (2007).*

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For example, Rodenhuis *et al.* (2007) reported differing trends in mean annual streamflow for British Columbia than those reported by Zhang *et al.* (2001). Rodenhuis *et al.* (2007) attributed these differences to the different PDO phases that occurred during their analysis period (1976–2005) compared with Zhang *et al.*'s (1967–1996). The detailed trends presented in Rodenhuis *et al.* (2007) are beyond the scope of this section, and the reader is referred to this report for more detailed descriptions of regional streamflow trends in British Columbia.

The influence of modes of climate variability on streamflow, such as ENSO and PDO, are evident and can confound identification of historical trends. On the South Coast, some streams that are normally rainfall-dominated have snowmelt runoff in the spring during cool La Niña years (Fleming *et al.* 2007). This results in years with two run-off peaks in a watershed where there normally may be only one. During El Niño years, substantially less streamflow may occur from May to August in snowmelt-dominated basins, especially those in the Okanagan Basin (Rodenhuis *et al.* 2007). Warm-PDO phases, like the one that occurred from 1977 to 1998, advance the spring or summer freshet, lower peak flows, and cause drier summer periods for many streams in British Columbia. Some exceptions occur in northern British Columbia where the opposite response, such as increased peak flows, takes place during warm-PDO phases (Rodenhuis *et al.* 2007).

Future Temperature and Precipitation Regimes

Projections of future climates are available from numerous global climate models (GCMs) and for a range of emission scenarios. These scenarios depend on future developments in technology, economic growth, and international co-operation (IPCC 2007). Differences in how certain processes are modelled mean that the GCMs can produce different future climates for the same emissions scenarios. Projections by the GCMs of the direction and magnitude for temperature changes are generally closer in agreement than projections of precipitation changes (Barnett *et al.* 2005; Rodenhuis *et al.* 2007). Figures 1 and 2 illustrate the magnitude of climate change for British Columbia, based on simulations from the Canadian CGM for the A2 scenario. The A2 scenario has emissions continuing to increase over the 21st century without significant global efforts to reduce them. In contrast, the B1 emissions scenario is based on the assumption that the global community will be somewhat successful in reducing emissions. For Figures 1 and 2, the projected changes in temperature and precipitation for the B1 scenario in 2080s are similar to those presented for the A2 in the 2050s. The Canadian model tends to project warmer and wetter summers compared with the UK Hadley Centre model (Spittlehouse 2007).

> *The depth of the snowpack and length of the snow season will decrease while the atmospheric evaporative demand and climatic moisture deficits will increase.*

All models and emissions scenarios predict an increase in winter and summer temperatures with the greatest increase for the higher emissions scenarios. An ensemble of projections from 15 GCMs (including both the Canadian and UK Hadley models), with one projection from each of the A2 and B1 emissions scenarios, was used to compute a range of projections for the 2050s climate of British Columbia (Rodenhuis *et al.* 2007). Based on these results, the BC annual average temperature is projected to warm by 1.7°C compared with the recent 1961–1990 period. Uncertainty is represented by the range +1.2 to 2.5°C (from the 10th to 90th percentile of projections). The 2050s BC annual precipitation is projected to increase by 6%, with a range of 3 to 11%. The seasonal temperature projections were relatively uniform but seasonal precipitation projections varied: 2% drier to 15% wetter for winter and 9% drier to 2% wetter for summer. Rodenhuis *et al.* (2007) discuss uncertainty in depth, compare the magnitude of projected changes to historical variability, and compare GCM results to a higher resolution regional climate model projection.

Detailed results from the Canadian model show that projected warming is greater in northern than southern British Columbia and larger in the winter than in the summer, particularly in the winter minimum temperature (Table 1; Figures 1a and 1b). Changes in precipitation vary in space as well as in time. Southern and central British Columbia are expected to get drier in the summer while northern British Columbia is more likely to be wetter (Table 1; Figures 2a and 2b). Winters will be wetter across British Columbia (Rodenhuis *et al.* 2007).

Although this paper primarily presents mean changes in climate, future changes in the variability or the extremes of temperature and precipitation are anticipated to have significant effects on hydrologic resources. Indices of extreme events may include changes in the frequency of occurrence or changes in the magnitude of events, examples of which are discussed below. Global climate model ensembles show that changes in warm temperature extremes follow changes in the mean summertime temperature (Kharin *et al.* 2007). Extreme maximum temperatures would be higher than at present and cold extremes would warm at a faster rate, particularly in areas that see a retreat of snow with warming (Kharin *et al.* 2007). There will also be an increase in intensity and maximum amount of precipitation (Kharin *et al.* 2007). Changes in extreme events may not be proportional to mean changes, and the changes may not be equal in either direction (Tebaldi *et al.* 2006). For example, increases in the frequency of extreme maximum temperatures are anticipated; however, the frequency of extreme cold temperatures are anticipated to decline in the future (Tebaldi *et al.* 2006; Kharin *et al.* 2007).

Changes in temperature and precipitation extremes can be examined by considering indices of this change that interest resource managers. For example, under the temperature and precipitation scenarios described above, the frost-free period and number of growing degree days will increase. The depth of the snowpack and length of the snow season will decrease while the atmospheric evaporative demand and climatic moisture deficits will increase. GCMs are becoming increasingly sophisticated in their inclusion of land-surface schemes from which some of these changes may be diagnosed directly and quantitatively.

Conclusion

British Columbia's climate has changed over the last 100 years. This article (Part I) summarized historical temperature and precipitation trends and future climate scenarios for British Columbia. The changes resulting from global warming will result in adjustments in watershed hydrology and ultimately in our use of water-related resources. A detailed knowledge of trends and projections is therefore important to develop local mitigation and adaptation strategies. The changes we have seen over the last 100 years should help to inform the development of these actions.

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For further information, contact:

BC Ministry of Forests and Range
Dave.Spittlehouse@gov.bc.ca (contact)
Robin.G.Pike@gov.bc.ca
Peter.Tschaplinski@gov.bc.ca
Vanessa.Egginton@gov.bc.ca

Pacific Climate Impacts Consortium
Katrina Bennett: *kbennett@uvic.ca*
Trevor Murdock: *tmurdock@uvic.ca*
Arelia Werner: *wernera@uvic.ca*

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