Climate Change, Impacts, and Adaptation Scenarios: Climate Change and Forest and Range Management in British Columbia

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Ministry of Forests and Range
Forest Science Program

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PREFACE

This Technical Report is one of two foundation papers for the B.C. Ministry of Forest and Range (MOFR) Future Forest Ecosystems Initiative (FFEI). These papers will increase the awareness of the potential impact of climate change on forest and range resources in British Columbia. They will also provide information to aid in assessing the vulnerability of British Columbia's forest and range resources and their management, leading to the development of adaptation strategies for a changing climate. The FFEI was initiated by the Chief Forester with a symposium and workshop in December 2005. At the same time the MOFR Climate Change Task Team was preparing a report on how the MOFR should strategically position itself with respect to the potential impacts of climate change on the province's forest and range resources. The present report draws on the Task Team report, recommendations from the FFEI workshop, and numerous other documents including the most recent reports from the Intergovernmental Panel on Climate Change. It provides a summary of future possible climates for British Columbia, a brief review of possible impacts on forest and range resources, and options for and challenges to adapting to climate change. Finally, there are recommendations on how the MOFR might respond to climate change. The report contains four appendices that expand on material presented in the body of the report, including information on the past as well as on future climates of British Columbia.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change states that warming of the climate system is unequivocal. It notes with a very high level of confidence that much of this warming is due to human activities through the release of greenhouse gases. The continued increase in greenhouse gas concentration over the next century could result in an increase in global mean annual temperatures by up to 4°C and changes in precipitation regimes. The rate of warming will be faster than has occurred in the past and there will be an increase in the frequency and intensity of extreme temperature and precipitation events.

British Columbia will have greater warming and changes in the precipitation regime than the global average. All models and emissions scenarios predict an increase in winter and summer temperature. Warming would be greater in northern British Columbia than in southern British Columbia and larger in the winter than in the summer, particularly in the winter minimum temperature. Warming is least in coastal areas where it is moderated by the oceans.

If there is limited success internationally to control future emissions (e.g., the A2 emissions scenario), British Columbia could see a warming of 3–5°C by the 2080s. With significant reduction in emissions (e.g., the B1 emission scenarios), the warming is 2–3°C by the 2080s. These two scenarios have the winter minimums in northern British Columbia increasing by 4–9°C by the 2080s and summer maximums increasing by 3–4°C. The frost-free period, growing-degree days, and frequency of extremely warm days will also increase.

Changes in precipitation will accompany changes in temperature. Southern and central British Columbia are expected to see the summer precipitation decreasing by 10–40% by 2080s under all emission scenarios. Summers in northern British Columbia range from a small decrease to a 25% increase. Winters will be wetter across British Columbia, with increases ranging from 5 to 40%, depending on the emissions scenario and global climate model. We can expect an increase in precipitation intensity and reduction in the return period of extreme events. In most cases, the changes in mean precipitation are smaller than the inter-annual variability in precipitation resulting from inter-annual and inter-decadal variation in ocean conditions. Warming will result in less precipitation falling as snow, reduced snowpack depth, and earlier spring snowmelt, with the snow disappearing up to a month earlier under the highest warming scenarios. There will be an increase in evaporative demand of the atmosphere.

Ecosystems and species have responded to past changes in climate; however, future responses may not be compatible with our patterns of use or desires. Consequently, there could be significant biological, economic, and social impacts with major implications for resource management. Species will be able to survive and grow in their current location under a changing climate. However, growth rates will be affected and there will be increased competition from other species or genotypes more suited to the climate. Warming and drying will increase forest fire frequency and severity. Disturbance due to insects and disease is expected to increase and this will likely have significant negative impacts on the forest and range carbon balance. The potential ranges of species will move northward and upward in elevation, and new assemblages of species will occur in space and time. Species may be unable to move into areas of suitable climate due to barriers to movement, slow migration rates, unsuitable growing substrate, or lack of habitat.

Although many of the impacts of climate change are decades away, resource managers need to start evaluating the vulnerability of forest and range resources to climate change. This will facilitate development of adaptation strategies to maintain the resilience of ecological systems and our uses of them. A guide to such activities and some challenges to implementing adaptation strategies are identified. A major challenge is the uncertainty in the magnitude and timing of future climate change. Another significant challenge is the size of the forest and range land base in British Columbia. It is likely that much of the vegetation will have to adjust without human intervention, and society will have to adapt to this. In some areas, adaptation to reduce the vulnerability of resources such as water quality and quantity, and biological conservation, may become the highest priorities.

The various emissions scenarios have similar warming trends over the next 20 years. During this period the global response to the risks of climate change should become evident, the resolution and capabilities of global climate models will improve, and we should have a clearer idea of the climate change to expect. This period should also see significant improvements in our understanding of the vulnerability of forest and range resources to climate change. In the meantime, it is recommended that:

- Vulnerability analyses use climate simulations for the B1 and A2 scenarios, and simulations from at least two global climate models with different climatologies (e.g., the Canadian and Hadley Centre models).
- Analyses should use annual, as well as mean, data to evaluate the effects of changes in the inter-annual variability, and the frequency and intensity of extremes.

It is recommended that the B.C. Ministry of Forests and Range respond to the potential impacts of climate change on forest and range management by co-operating with other agencies and groups in taking the lead to:

- Develop databases and methods for assessing vulnerabilities to climate change and promote adaptation in forest and range management.
- Create a set of climate-change scenarios for British Columbia at a high spatial resolution so that all users can work from a common database.
- Provide a "one stop" facility that is a source of climate-change scenarios and other climate data for vulnerability analyses, and would facilitate access to the latest information.
- Determine user needs with respect to climate variables, time periods, and tools for climate-change vulnerability analyses.
- Develop adaptive capacity within the forest and range management community.
- Develop a set of key indicators of climate change that can help in monitoring the response of forest and range resources to climate change.
- Investigate management responses that can be applied in the short term that might alleviate some of the vulnerability without compromising the long term.

Current actions by the Ministry of Forest and Range and the British Columbia provincial government are addressing many of these recommendations.

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Comments by reviewers on earlier drafts are gratefully acknowledged. Discussions with Trevor Murdock, Pacific Climate Impacts Consortium (PCIC), and the provision of climate change scenarios by PCIC, were particularly helpful. Interpolation and interpretation of climate change data for British Columbia would not have been possible without the ClimateBC software developed by Andreas Hamann (University of Alberta) and Tong-Li Wang (University of British Columbia). ClimateBC was made possible by funding from the Forest Investment Account–Forest Science Program and the Ministry of Forests and Range. Adrian Walton (MOFR) provided the high spatial resolution maps of current and future British Columbia climates. Responsibility for the interpretation of data and any errors are solely the responsibility of the author.

> *"There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something more bizarre and inexplicable. There is another theory that states this has already happened."*
>
> — Douglas Adams, *The Hitch Hiker's Guide to the Galaxy*, 1979, Pan Books, London.

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The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPPC WG I 2007) reports that over the last 100 years there has been a 0.7°C warming of the global climate. The report states with a very high level of confidence that much of this warming is a result of human activities through the release of greenhouse gases to the atmosphere from the burning of fossil fuels, deforestation, and agricultural activities. IPCC WG I (2007) presents a range of future greenhouse gas emission scenarios based on estimates of economic growth, technological development, and international co-operation. Even the most optimistic scenarios require a few decades before emissions start to decline. According to the climate models, a global warming of 1–4°C is possible by the end of the century along with an increase in the frequency and intensity of extreme temperature and precipitation events. Canadell et al. (2007) report that current emissions are now higher than those used in the IPCC WG I (2007) analyses.

Changes in British Columbia's climate over the last 100 years are consistent with global trends (B.C. Ministry of Water, Land and Air Protection 2002; Vincent and Mekis 2006; Rodenhuis et al. 2007; Pike et al. 2008a,b). Although ecosystems and species have responded to past changes in climate, future responses may not be compatible with our patterns of use or desires. Consequently, there will be significant economic and social as well as biological impacts (McCarthy et al. 2001; Spittlehouse and Stewart 2003; IPCC WG II 2007). Although large changes in climatic conditions may not occur for decades, resource managers must start developing responses now to adapt to the future climate and ecological conditions.

Before we can implement adaptive actions we need predictions of possible future climates and we need to assess vulnerabilities. In doing this it is important to recognize the scale of the issue and to manage expectations of our ability to respond. For example, the size of the forested land base in British Columbia means that much of the forest will have to adjust without human intervention. Adaptation will likely focus on the major commercial tree species and perhaps a few animal species, while most of forest plants and animals will have to adapt as best they can.

This paper describes some possible future climates for British Columbia and briefly reviews possible impacts. This is followed by a framework to help resource managers evaluate vulnerabilities to climate change and to determine adaptive actions (Spittlehouse and Stewart 2003; Ohlson et al. 2005; Spittlehouse 2005; Johnson and Williamson 2007). Challenges to adapting to climate change are also reviewed. Additional reference material can be found in the Appendices. A companion paper (Campbell et al. 2008) is addressing how we might manage forest ecosystems in an era of rapid environmental change.

Future global temperature and precipitation regimes

Forecasts of future climates are available from numerous global climate models (GCMs). These models simulate oceanic and atmospheric processes and their interaction with the land surface for a range of future greenhouse gas emission scenarios. These scenarios depend on future developments in technology, economic growth, and international co-operation (IPCC WG I 2007). The GCMs are also a source of variability in the future climate simulations because of differences in how certain processes are modelled. A wide range of climate variables are available from the models. However, it is useful to focus on the average values of temperature and precipitation variables for certain periods. The models simulate well the rise in temperature over the last century, showing the influence of past increases in greenhouse gas concentrations (Hengeveld et al. 2005). At present, no one simulated future climate should be considered more likely than another.

Predictions of the change in mean annual temperature for the suite of global climate models and scenarios used in the Fourth Assessment (IPCC WG I 2007) are shown in Figure 1. Changes in the global mean temperature

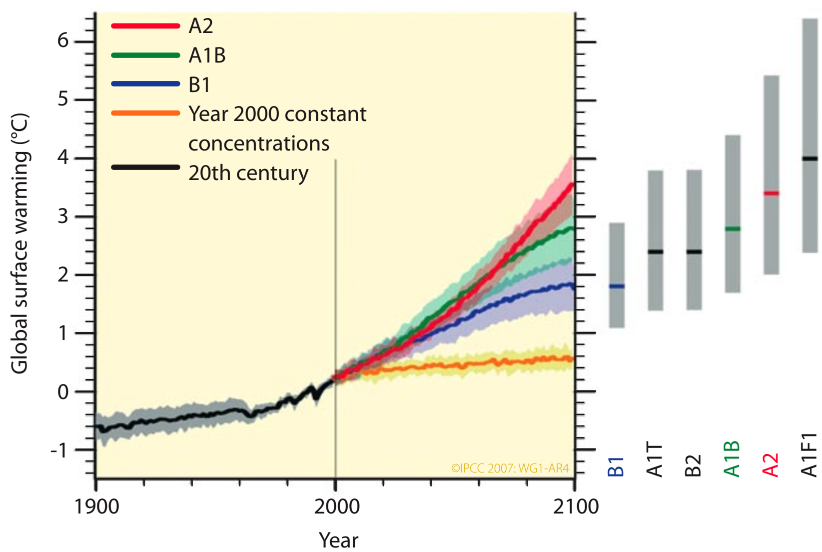

FIGURE 1 *Simulated change in global mean temperature from 1900 to 2100 referenced to the 1980–1999 mean value. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B, and B1, shown as continuations of the 20th-century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the Atmosphere-Ocean Global Climate Models in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. (Figure SPM.5 in IPCC WG I 2007.) The B1 and A2 carbon dioxide emission scenarios are shown in Figure A4, Appendix 2.*

of 1–6°C by 2100 are indicated. The A2 scenario assumes that emissions will continue to increase without significant efforts globally to reduce them (Figure A4, Appendix 2). The B1 scenario assumes that the rate of emissions will slow down and begin to decrease by the middle of the century. The orange line shows that even with an immediate cessation of all emissions we are committed to a further 0.5°C warming above current conditions. Changes in temperature will be accompanied by changes in precipitation. Summer precipitation is predicted to decrease in equatorial and temperate latitudes but to increase in northern latitudes (Figure A6, Appendix 2). In the winter, the precipitation increase is greater than in summer and the increase tends to extend into the temperature latitudes.

All of the scenarios predict similar warming trends over the next 20 years. During this period, the response of the global community to calls for reducing emissions should become evident. Also, the GCMs will have improved such that we should have a much better idea of the climate change to expect for 2050 and beyond. It is accepted that emissions of greenhouse gases cannot cease immediately. Consequently, emission reduction targets have been proposed to limit warming to certain levels or to avoid certain climate impacts (Rive et al. 2007). Weaver et al. (2007) note that a reduction in emissions is not sufficient to avoid certain negative impacts and that we will require direct capture of carbon dioxide from the atmosphere.

British Columbia's future temperature and precipitation regimes

The data presented in this section are based on the Intergovernmental Panel on Climate Change's Third Assessment Report (Houghton et al. 2001) as well as the recent Fourth Assessment Report (IPCC WG I 2007). The Fourth Assessment uses a reference period of 1980–1999, which is about 0.5°C warmer for British Columbia than the 1961–1990 period used in the Third Assessment (Rodenhuis et al. 2007). However, allowing for the different reference period, the predicted climate changes for the various emission scenarios in the Third Assessment are similar to those in the Fourth Assessment (Rodenhuis et al. 2007).

TABLE 1 *Changes in temperature and precipitation predicted for British Columbia for 2020s, 2050s, and 2080s from seven global climate models and for eight emission scenarios. Data are changes from 1961–1990 climate expressed as a change in mean temperature or as a percentage change in total precipitation (PPT %). The range of the data represents the differences in the emission scenarios and in the climate models. Values are based on data at www.ccsn.ca and www.pacificclimate.org/scenarios/.*

	2020		**2050**		**2080**	
	Temp. °C	**PPT %**	**Temp. °C**	**PPT %**	**Temp. °C**	**PPT %**
Southern British Columbia						
Winter	0 to 2	-5 to +15	1.5 to 3.5	0 to +20	2 to 7	0 to 25
Summer	0.5 to 2	-30 to +5	1.5 to 4	-35 to 0	2.5 to 7.5	-50 to 0
Central British Columbia						
Winter	0 to 2	-5 to +15	1.5 to 4	0 to +30	2.5 to 6	+5 to +40
Summer	0.5 to 1.5	-10 to +5	1.8 to 3.5	-20 to 0	2.5 to 6.5	-20 to +5
Northern British Columbia						
Winter	0 to 2.5	0 to 20	1.5 to 5.5	0 to +25	2.5 to 9	0 to +45
Summer	0.5 to 1.5	-10 to +10	1.5 to 3.5	-10 to +15	2 to 6	-15 to +25

British Columbia will have greater warming and changes in precipitation than the global average (Table 1, Appendix 2). All models and emissions scenarios predict a continued increase in temperature. There is a tendency for the warming to be greatest in northern British Columbia and greater in the winter than in the summer. This warming is largest in the winter minimum temperature. Changes in precipitation vary in space as well as time. Southern and central British Columbia are expected to get drier in the summer, while northern British Columbia is more likely to be wetter. Winters will likely be wetter across all of British Columbia.

The global climate models provide climate-change data at a coarse scale. These data were downscaled with the ClimateBC software that uses the delta method to produce values for individual locations and as high spatial resolution gridded data (Spittlehouse 2006; Wang et al. 2006a). The high resolution of the figures does not imply a high accuracy. Climates for the B1 and A2 emissions scenarios (Figure A4, Appendix 2) are from the Canadian Global Climate Model version 2 (CGCM2) (Flato et al. 2000). The simulated climates are in the middle of the range of projections of the various GCMs and span the range of the most likely future climates for British Columbia. Mean annual changes in temperature and precipitation for the A2 scenario are presented in Figures 2 and 3. Seasonally based climate maps and data for selected locations in British Columbia for the B1 and A2 scenarios are presented in Appendix 2.

The A2 scenario predicts a warming of 3–5°C across British Columbia over the next century (Figure 2). The lower emissions for the B1 scenario result in a warming of 2–3°C by 2080, similar to that for the A2 in 2050 (Tables A2 and A3, Appendix 2). Annually, most of British Columbia is predicted to have an increase in precipitation that continues to increase over time. Seasonal data presented in Appendix 2 show that the southern half of the province could be drier in the summer. The increase in winter precipitation is large enough to result in an increase on an annual basis. Changes in mean precipitation are smaller than the inter-annual variability that results from inter-annual and inter-decadal changes in ocean conditions. As with temperature, the B1 precipitation climate of 2080 is similar to that of the A2 in 2050. In contrast to CGCM2 simulations, the Hadley Centre HadCM3 model tends to produce a warmer and drier summer for the A2 scenario.

Changes in temperature and precipitation influence other climate variables of interest in resource management. Under the B1 and A2 scenarios frost-free periods and growing-degree days will increase (Tables A2 and A3, Appendix 2). The depth of the snowpack and length of the snow season will decrease by up to a month while the atmospheric evaporative demand and climatic moisture deficits will likely increase (Appendix 2; Huntington 2008; Pike et al. 2008b).

The data presented above are average conditions for specific time periods. Inter-annual variability in weather conditions and frequency and magnitude of extreme conditions also has a significant effect on the production and use for forest and range resources. Analyses on a global basis from the Fourth Assessment (Tebaldi et al. 2006; Kharin et al. 2007) are applicable to British Columbia.

Changes in warm extremes follow changes in the mean summertime temperature. Extreme maximum temperatures would be higher than at present and cold extremes will warm faster, particularly in areas that see a retreat of snow with warming. There will also be an increase in intensity and maximum amount of precipitation. For both temperature and precipitation there will be a reduction in return periods of current extreme events (Tebaldi et al. 2006; Kharin et al. 2007), and it is very likely we will see an increase in the number of heat waves and heavy precipitation events (IPCC WG II 2007).

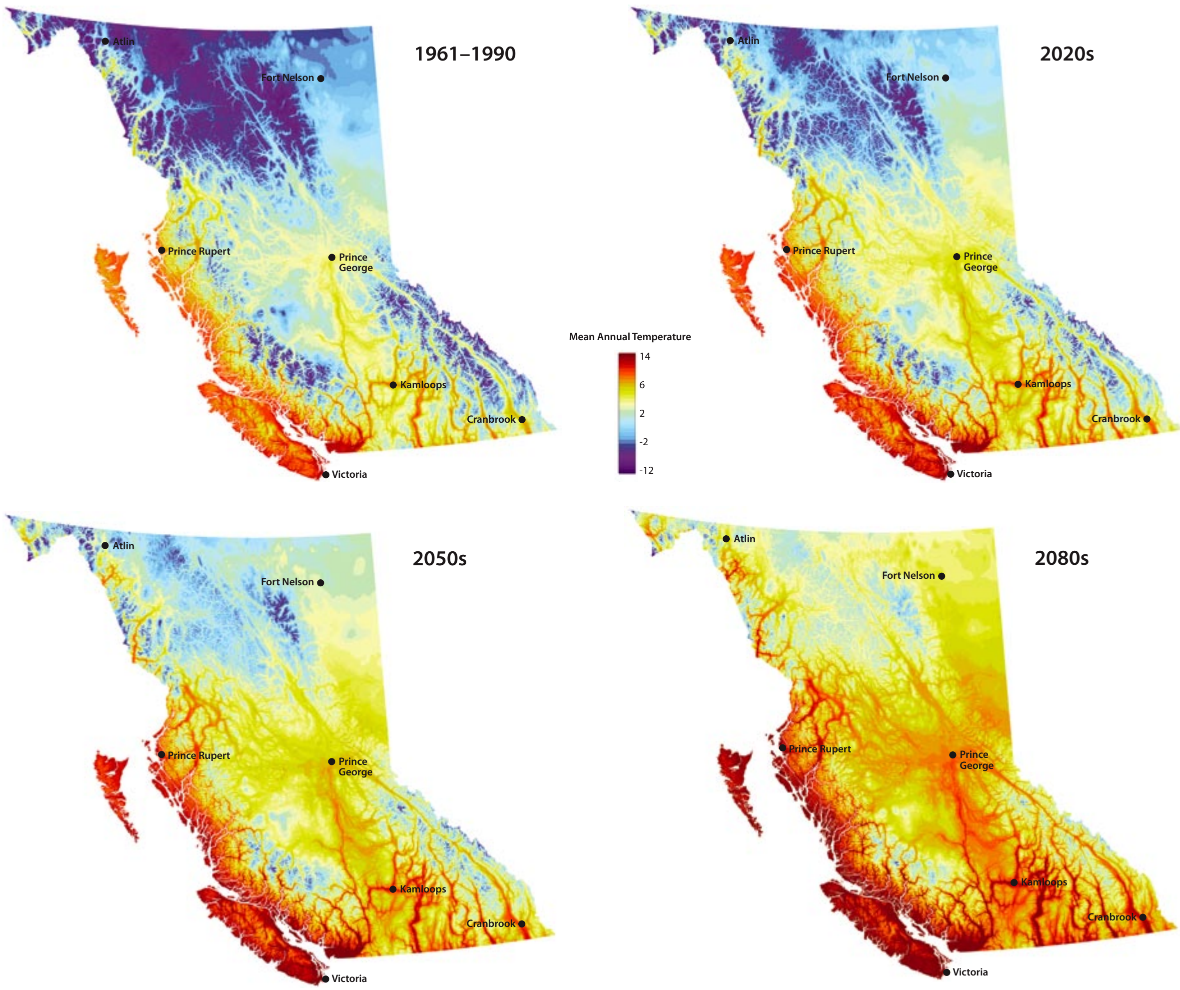

FIGURE 2 *Mean annual temperature for British Columbia for 1961–1990 and that predicted for British Columbia in 2020s, 2050s, and 2080s for the A2 scenario from CGCM2. Downscaling was done with the ClimateBC software. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

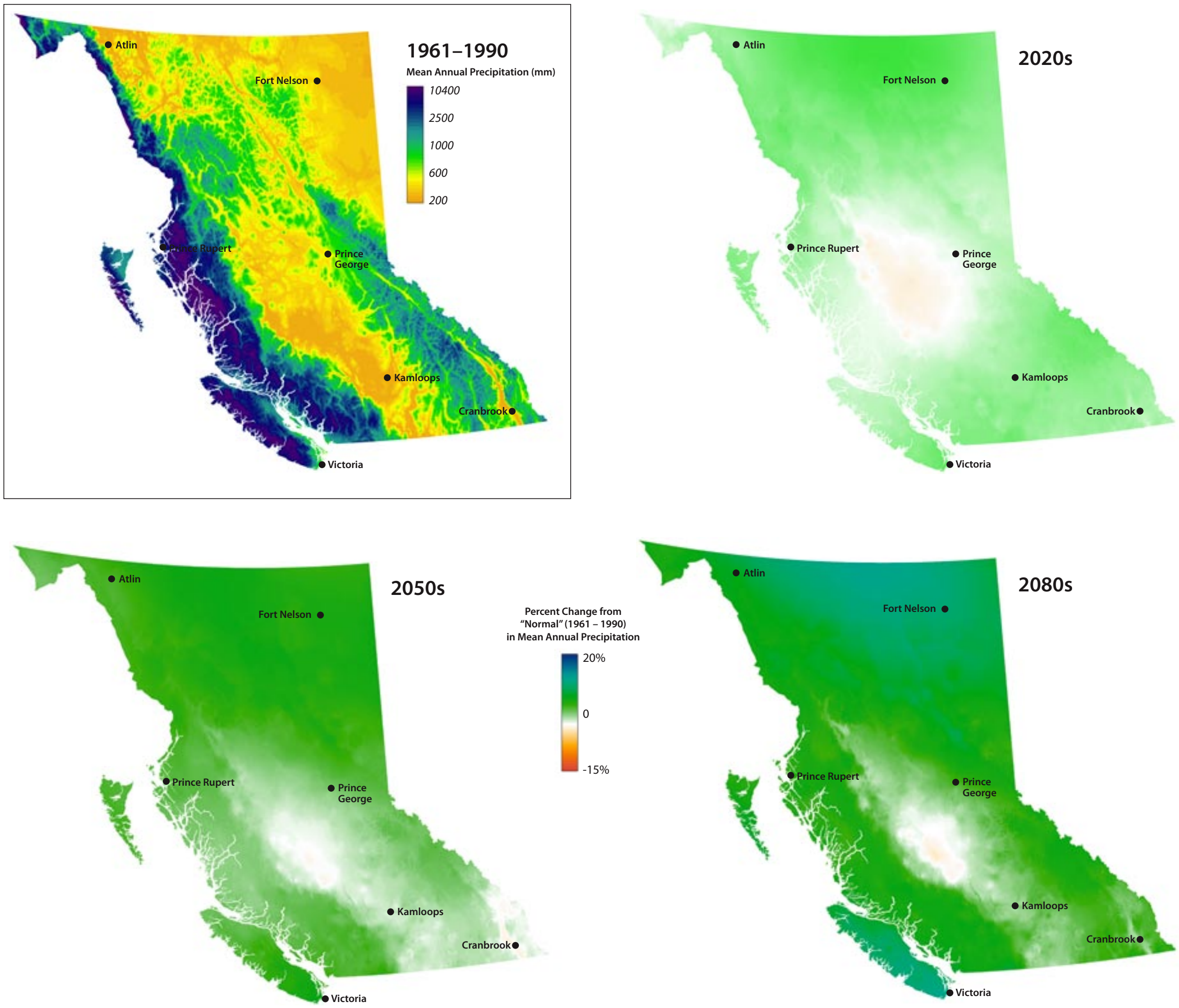

FIGURE 3 *Mean annual precipitation for British Columbia for 1961–90 and the percentage change predicted for British Columbia in 2020s, 2050s, and 2080s for the A2 scenario from CGCM2. Downscaling was done with the ClimateBC software. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

IMPACTS OF CLIMATE CHANGE ON BRITISH COLUMBIA'S FOREST AND RANGE RESOURCES

There are numerous reports worldwide of the response of plants and animals to the increase in temperature in over the last century (Walther et al. 2002; Breshears et al. 2005, Gulledge 2006; Parmesan 2006; IPCC WG II 2007). British Columbia is already experiencing biological and physical responses that at least may partially be a response to current climate changes (Leith and Whitfield 1998; BCMWLAP 2002; Carroll et al. 2004; Gillet et al. 2004; Woods et al. 2005; Geertsema et al. 2006; Pike et al. 2008a). These responses will be exacerbated under the climate changes described in the previous section.

IPCC WG II (2007) states that climate impacts will be mostly negative and will fall hardest on those least able to adapt to changes, such as the poor, developing countries, and certain ecosystems. Extreme heat events could become more frequent and deadly for people, crops, and animals. Warming will result in an increase in forest disturbance by drought, fire, insects, and disease. Sea-level rise will be a threat to coastal communities and result in a loss of estuarine ecosystems. Although some high-latitude areas may see improvements in the growth of crops, global mean losses for a 4°C warming could be 1–5% of gross domestic product. Not every one will bear the costs equally.

British Columbia's 60 million hectares of forest and range provide a wide range of resources for human use. Wood-based products, such as lumber, oriented strand board, and paper, and other forest products, such as mushrooms, berries, and botanicals, are important for the provincial economy. Forests are the source of many streams that are the water supply for human consumption. Forest and range provide habitat for fish and other wildlife, are important reserves for endangered species, provide areas for recreation in all seasons, and are culturally and spiritually significant. Although British Columbia may be less vulnerable economically, socially, and climatically than some other countries, impacts will be significant and require responses.

Some generalizations can be made on species responses to climate change. The potential ranges of species will move northward and upward in elevation, and new assemblages of species will occur in space and time (Cummings and Burton 1996; Hebda 1997, 1998, 2007; Hansen et al. 2001; Hamann and Wang 2006; Wang et al. 2006b). Using ecosystem-based climate envelop modelling, Hamann and Wang (2006) found that tree species with their northern range limit in British Columbia could gain climatically suitable habitat at about 100 km per decade. Common hardwoods appeared to be less sensitive to climate change while some of the most important conifer species in British Columbia lost a large portion of their climatically suitable habitat. However, species may be unable to move into areas where the climate is suitable because of barriers to movement, slow migration rates, unsuitable growing substrate, or lack of habitat (Stewart et al. 1998; Gray 2005).

Optimum growing conditions for local populations (genotypes) of trees can be relatively narrow (Rehfeldt et al. 1999, 2001; Parker et al. 2000; Wang et al. 2006b). Consequently, although species will be able to survive and grow in their current location under a changed climate, growth rates will be affected and there will be increased competition from other species or genotypes more suited to the climate. Concurrent with a changing climate are changes in the frequency and intensity of disturbance by fire, insects, and disease (Sieben et al. 1997; Dale et al. 2001; Flannigan et al. 2005; Volney and Hirsh 2005). Insects and diseases may adapt to new environmental conditions more quickly than their long-lived hosts (Cammell and Knight 1992; Volney and Hirsh 2005).

Forest management, as well as species occurrence and growth, will be affected by climate change. For example, access to sites for harvesting, fire protection activity, and road design and maintenance are all weather-dependent activities (Spittlehouse and Stewart 2003). The role of forests and forest management in the global carbon balance will be affected by climate change through changes in forest growth and disturbance. Future disturbances by fire, insects, and disease will likely have a much greater influence on the carbon balance than changes in tree species occurrence and growth rates (Kurz et al. 2007, 2008a, b). Further discussions on the implications of climate change for British Columbia's ecosystems can be found in Appendix 3.

Adapting to climate change reduces vulnerability. This reduces risks and capitalizes on benefits by maintaining social and ecological resilience (Nelson et al. 2007). Vulnerability is the degree to which an entity (e.g., organism, ecosystem, company, community, or province) is susceptible to or unable to cope with climate change (Smit and Pilifosova 2002). Different entities are vulnerable to different aspects of change, and what may be detrimental to one entity could be beneficial to another.

Determining adaptive actions requires a framework for analysis (Spittlehouse and Stewart 2003; Kellomäki and Leinonen 2005; Metzger and Schroter 2006; Johnson and Williamson 2007). The first step of the procedure involves defining the issue; second is evaluating vulnerability to the changing climate; third is determining how to reduce vulnerability (i.e., adaptation); and fourth is implementing an adaptation strategy. For example:

- **Issue:** Define the subject, scale, and time (i.e., the resource issue of concern, the location, and the future time horizon).
- **Vulnerability assessment:** Select a range of climate-change scenarios for the chosen time horizon. Determine the climatic, economic, social, and other factors that influence the vulnerability of the resource. A lack of information on the climate sensitivity of the resources in question should not stall the process of making a first-cut vulnerability assessment. Educated guesses may be required at the beginning, but the analysis is an iterative process, with continual updating of the vulnerability assessment as more information becomes available. Different issues, people, companies, and organizations will have different timeframes to consider and different vulnerabilities.
- **Adaptation strategy:** Determine what needs to be done to reduce vulnerability. Options can be developed and their cost-effectiveness evaluated. Extension activities will be a critical component for the strategy. Immediate activities include those that facilitate future responses to reduce vulnerability. Adaptation strategies must include the ability to incorporate new knowledge about the future climate and forest vulnerabilities as they are developed. They should also recognize the impediments to implementation, such as funding, policy, resistance to change, and risk aversion. It is unlikely that any single issue or value can be considered in isolation. Thus, an important component of adaptation is balancing different timeframes, needs, and values. An adaptation strategy should include a monitoring program to determine the state of the forest and to evaluate the success of the adaptation strategy.
- **Implementing the adaptation strategy:** This step should be self-evident. As noted above, this is an iterative process and the vulnerability assessments and adaptation strategies will be revisited as more information such as improved simulations of future climate becomes available.

There are many smaller steps within the over-arching four steps outlined above. Details on processes for doing this work can be found in Ebi et al. (2004), Ohlson et al. (2005), and Evans et al. (2006). Doing vulnerability assessments and developing adaptation strategies is an iterative process, with assessments and strategies being revisited as more knowledge becomes available. It is likely that a first run through the framework on an issue would be done to identify information needs and refine the issue. The vulnerability and adaptation steps would be cycled through a number of times before implementation of an adaptation strategy.

Numerous adaptive actions proposed for forest and range management are summarized by Spittlehouse and Stewart (2003). They can be grouped into two categories: adaptation of forests and range to a changing climate, and societal adaptation to the response of forests and range to the changing climate. Adapting the forest includes species selection, tree breeding, stand management, and creating fire-smart landscapes. Societal adaptation includes revising conservation objectives, changing expectations, developing policies to encourage adaptation, adapting forest management techniques, changing rotation age, using more salvage wood, and modifying wood processing technology.

CHALLENGES TO ADAPTING TO CLIMATE CHANGE

Consideration of weather and climate conditions is part of forest and range management. For example, fire protection activities include calculating drought codes and developing fire-smart communities. Climate is implicitly included in growth and yield modelling and ecosystem mapping. The challenge is to develop explicit descriptors of species and ecosystem responses to climate that can be used in vulnerability assessments and in developing adaptation strategies (e.g., Wang et al. 2006b).

A major challenge in taking adaptive actions in the short term is the uncertainty in the magnitude and timing of future climate change. This uncertainty is compounded by the uncertainty in the future markets for our forest and range resources and the concern that climate change may lead to relative increases in the timber and forest products supply from other nations (Sohngen and Sedjo 2005). The development of adaptation measures for some time in the future, under an uncertain climate, in an unknown socio-economic context is bound to be highly speculative (Burton et al. 2002). Some groups may believe that responding is a greater risk than doing nothing, or that impacts can be dealt with only when they happen. Furthermore, there is a lack of awareness in the forestry community of the risks of climate change (Williamson et al. 2005), although this is changing.

The size of the forested land base in British Columbia means that much of the forest will have to adjust without human intervention. Of the approximately 60 Mha of forest in British Columbia there are about 35 Mha in the non-timber harvest land base (including parks, wilderness areas, and areas with operational constraints) where forest management consists mainly of fire protection and conservation. The remaining 25 Mha, the timber harvest land base, is harvested at about 0.2 Mha per year. Adaptation will likely focus on the major commercial tree species and perhaps a few animal species, while most forest and range plants and animals will have to adapt as best they can. Any large-scale disturbances caused by climate change would be particularly difficult to address. In some areas, adaptation to reduce the vulnerability of resources such as water quality and quantity and biological conservation will become the highest priority.

There are institutional and policy barriers to responding to climate change. For example, seed planning zones, reforestation standards, and hydrologic and wildlife management guidelines are designed for the current climate regime. There are no requirements for adaptation strategies in forest management plans, nor are there guidelines and sufficient experienced personnel to aid such activities. Also, it is often difficult to get the long-term funding required to address such a wide-ranging issue as climate change.

Assessing vulnerabilities and developing adaptation strategies requires information about possible future climates. At present, all of the future climate scenarios should be considered to have equal likelihood of occurrence. The next 20 years will see improvements in our knowledge of the future climate, along with improved understanding of the vulnerability of forest and range resources to climate change. We may need to apply interim responses, but these actions must not have negative consequences if the future does not unfold as assumed. Short-term actions include: forest policies to facilitate adaptation, training to develop adaptive capacity in forest managers, and doing vulnerability assessments.

CONCLUSIONS AND RECOMMENDATIONS

The next 20 years will clarify the global response to the risks of climate change. Global climate models will have improved, and we should have a clearer idea of the climate change to expect. This period should also see significant improvements in our understanding of the vulnerability of forest and range resources to climate change. In the meantime, it is recommended that:

- Vulnerability analyses use climate simulations for the B1 and A2 scenarios, and simulations from at least two global climate models with different climatologies (e.g., the Canadian and Hadley Centre models).
- Analyses should use annual, as well as mean, data to evaluate the effects of changes in the inter-annual variability, and the frequency and intensity of extremes.

Although many of the impacts of climate change may be decades away, assessing forest vulnerability to climate change, developing adaptation strategies, and strengthening monitoring programs should start now. Most of British Columbia's forests and range are on Crown land. The provincial government is responsible for: developing management objectives; setting standards for species selection, seed transfer, stocking, and biodiversity; allocating land to parks and wilderness areas; and maintaining health and growth monitoring plots.

It is recommended that the B.C. Ministry of Forests and Range respond to the potential impacts of climate change on forest and range management by co-operating with other agencies and groups in taking the lead to:

- Develop databases and methods for assessing vulnerabilities to climate change and promote adaptation in forest and range management.
- Create a set of climate-change scenarios for British Columbia at a high spatial resolution so that all users can work from a common database.

- Provide a "one stop" facility that is a source of climate-change scenarios and other climate data for vulnerability analyses, and facilitate access to the latest information.
- Determine user needs with respect to climate variables, time periods, and tools for climate-change vulnerability analyses.
- Develop adaptive capacity within the forest and range management community.
- Develop a set of key indicators of climate change for monitoring the response of forest and range resources to climate change.
- Investigate management responses that can be applied in the short term to alleviate some of the vulnerability without compromising the long term.

It is encouraging to note that current actions by the Ministry of Forest and Range and the British Columbia provincial government are addressing many of these recommendations. Recent announcements from the British Columbia provincial government setting emission reduction targets for British Columbia are also welcomed.

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British Columbia's climate has changed dramatically since the glaciers receded about 12 000 years ago. A dry, cold late-glacial climate was followed by a period of rapid warming, a warm and dry interval, and then a warm and relatively moist interval. Today's relatively cool climate in British Columbia began about 4500 years ago (Rosenberg et al. 2004). Most of the vegetation regimes we are familiar with were established 4000–6000 years ago, although there have been adjustments in ranges and species composition due to fluctuations in climate and human activity during this period.

The last 1000 years in the Northern Hemisphere was a period of slow cooling of about 0.7°C, followed by a warming that started about 200 years ago (Figure A1). The rate of warming over the last 100 years has been faster than any time in the past 2000 years. Temperatures are now as warm, if not warmer, than any time in the past 2000 years and are about 1°C warmer than the early 1800s. The concentration of carbon dioxide has risen from 280 ppm before the start of the Industrial Revolution to about 381 ppm and is currently increasing at about 1.9 ppm per year (Canadell et al. 2007). Other greenhouse gases such as methane have shown similar rates of increase. Concentrations are greater than any seen in the last 650 000 years (Houghton et al. 2001; Hengeveld 2006; IPCC WG I 2007).

The temperature variation in British Columbia in the last 2000 years has, in general, been similar to that of the Northern Hemisphere (Rosenberg et al. 2004; Hebda 2007). In the last 100 years there has been a tendency for a greater warming in the winter than in the summer air temperature. The warming has been greater in northern British Columbia than in southern

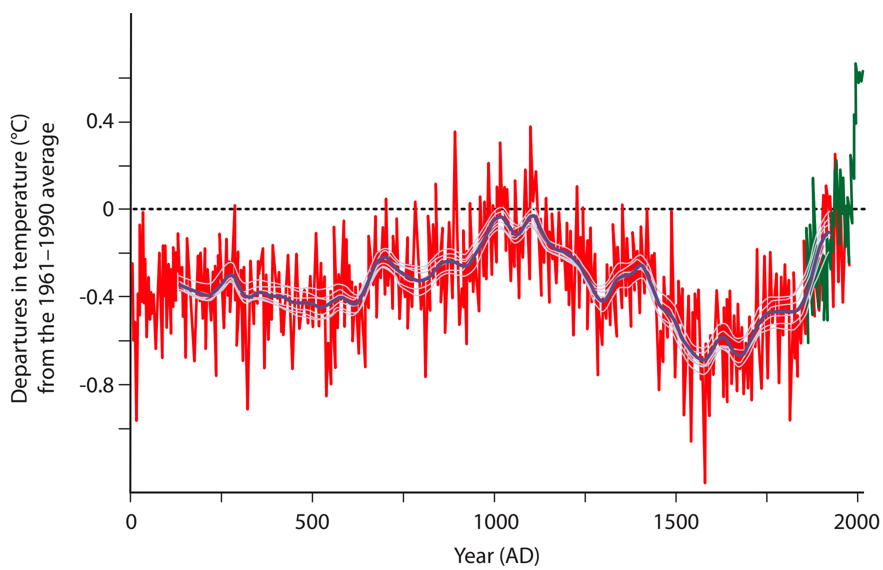

FIGURE A1 *Variation in the annual Northern Hemisphere temperature over the last 2000 years expressed as the difference between the annual values and the 1961–1990 average. The green line shows data from the instrumental record and the red line is a multiproxy reconstruction from tree rings, ice cores, and corals. The blue line is the low-frequency component with uncertainty. (Adapted from Moberg et al. 2005.)*

and coastal British Columbia (Figure A2) (Zhang et al. 2000; B.C. Ministry of Water, Land and Air Protection 2002; Vincent and Mekis 2006; Rodenhuis et al. 2007; Pike et al. 2008a). There have been fewer cold nights, cold days, and frost days and more warm nights and warm days. Similar conditions have been found for most of southern Canada (Vincent and Mekis 2006). There is insufficient coverage in the first half of the 1900s to quantify changes in northern Canada.

Trends in annual precipitation over the 20th century were positive but spatially variable. Increases have occurred in winter and summer but have been larger in the winter than in the summer in northern British Columbia and larger in the summer in southern British Columbia (Figure A3). Over the last 50 years there has been a reduction in winter precipitation and an

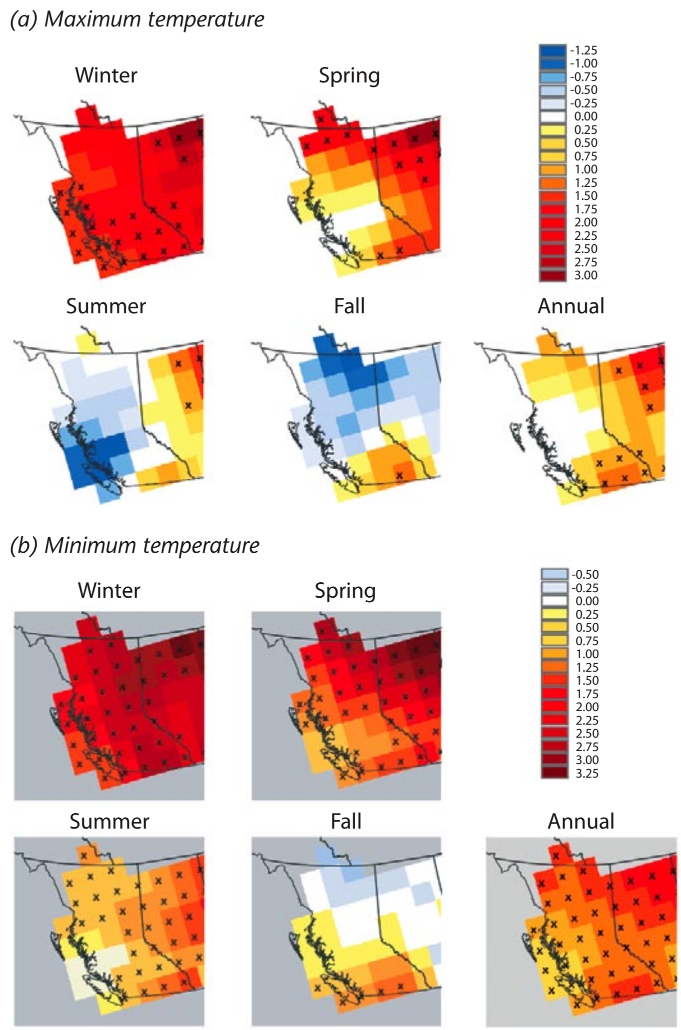

FIGURE A2 *Seasonal trends in (a) maximum and (b) minimum temperatures for western Canada for 1900–2003 (Moore et al. 2008). Units are °C over 104 years. Grid cells with crosses indicate trends that are significant at a 5% significance level. Grey cells indicate areas with insufficient data to estimate gridded temperatures. Winter is December, January, and February; spring is March, April, and May; summer is June, July, and August; and fall is September, October, and November.*

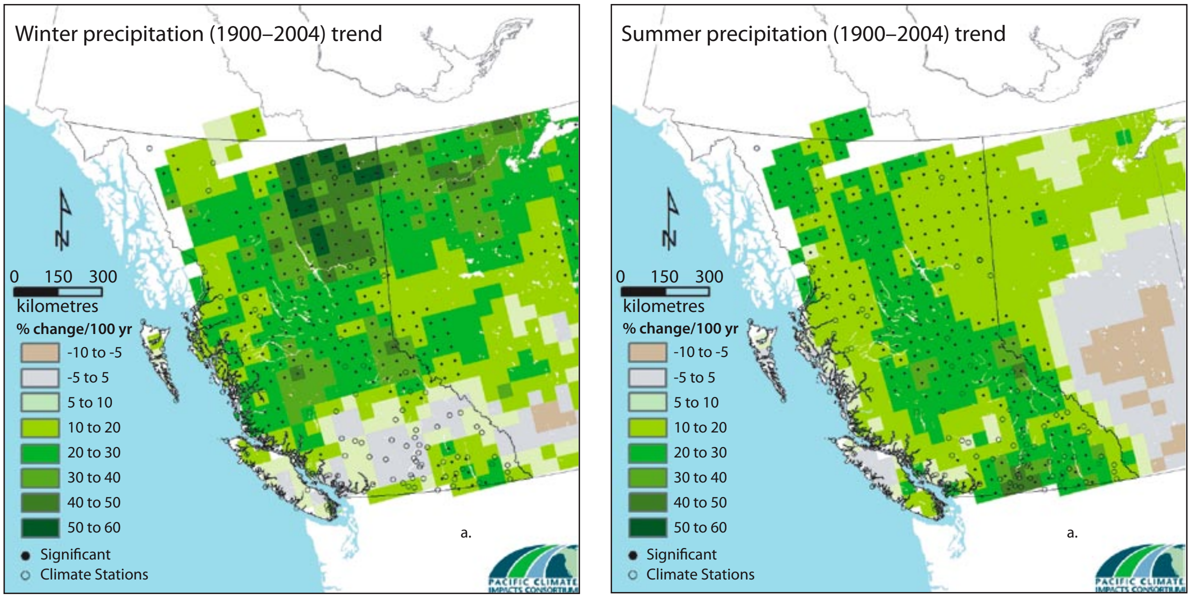

FIGURE A3 *Trends in winter and summer precipitation (percent change/100 years) in British Columbia from 1900 to 2004 (Rodenhuis et al. 2007). Black solid circles indicate statistical significance at 95% confidence level. Summer is June, July, and August and winter is December, January, and February.*

increase in summer precipitation over most of British Columbia (Zhang et al. 2000; Vincent and Mekis 2006). There has been an increase in the number of days with precipitation and a decrease in the number of consecutive dry days since early in the 1900s. Woods et al. (2005) suggested that the recent increase in wet and warm days has resulted in an increase in the occurrence of a needle disease that kills lodgepole pine trees. Annual snowfall and snowpack depth have declined substantially in the last 50 years (Mote et al. 2005; Vincent and Mekis 2006). Similar conditions have been found for most of southern Canada (Vincent and Mekis 2006). Trends in precipitation are superimposed on large inter-annual and inter-decadal variations in precipitation that are affected by ocean conditions such as El Nino/La Nina events and the Pacific Decadal Oscillation (Rodenhuis et al. 2007; Moore et al 2008).

Climate model simulations use a range of emissions scenarios that are based on possible future technological and economic developments and international co-operation (IPCC WG I 2007). An example for carbon dioxide is shown in Figure A4, and similar patterns occur for other greenhouse gases such as methane, nitrous oxide, and dust particles. Canadell et al. (2007) report that current rates of emissions are now higher than those used in the IPCC WG I (2007) analyses.

Future global temperature and precipitation regimes

The corresponding simulated global air temperatures for the two emission scenarios in Figure A4 are shown in Figure 1 of the main body of this report. All scenarios have a temperature increase with time, and the size of the change increases towards the poles (Figure A5).

Changes in precipitation have a more variable pattern and there is a greater range of variation between models and scenarios than there is with temperature. Summer precipitation is predicted to decease in equatorial and temperate latitudes but to increase in northern latitudes (Figure A6). In the winter, the precipitation increase is greater than in summer and the increase tends to extend into the northern temperate latitudes.

British Columbia's future temperature and precipitation regimes

The examples for British Columbia are based on Canadian global climate model version 2 (CGCM2) for the A2 and B1 emission scenarios (Figure A4). Data were downscaled using the ClimateBC software (Spittlehouse 2006; Wang et al. 2006a). This method assumes that the relative geographical distribution of temperature and precipitation will remain the same under

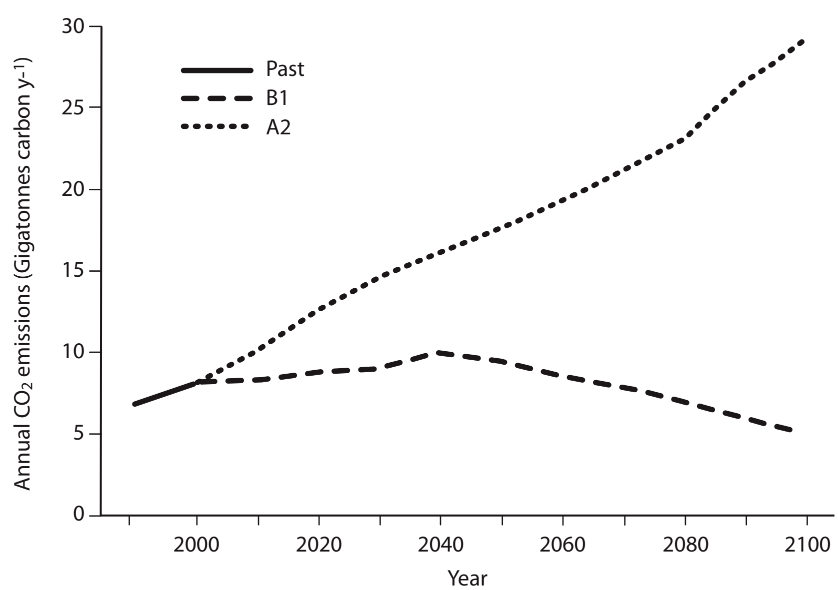

FIGURE A4 *The B1 and A2 emissions scenarios for carbon dioxide used in global climate modelling. Other greenhouse gases such as methane and nitrous oxide, and particulates such as sulphur, follow a similar trend. The simulated global mean air temperature for each scenario is shown in Figure 1. (Adapted from information at http://www.ipcc.ch.)*

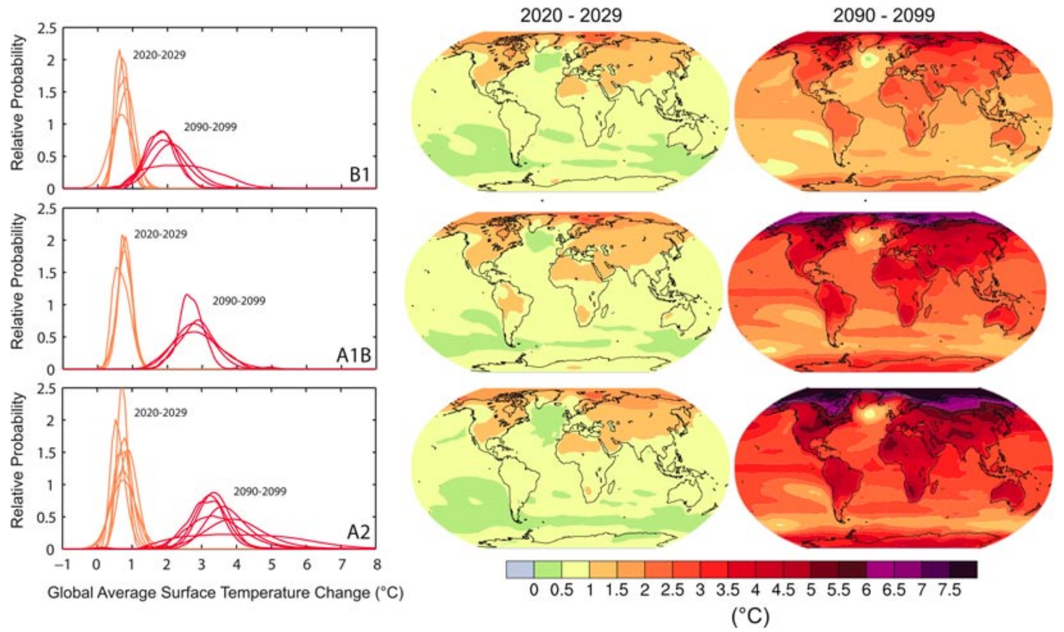

FIGURE A5 *Projected global surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle), and A2 (bottom) SRES scenarios averaged over the decades 2020–2029 (centre) and 2090–2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different Atmosphere-Ocean Global Climate Models and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results. (Figure SPM.6 in IPCC WG I 2007.)*

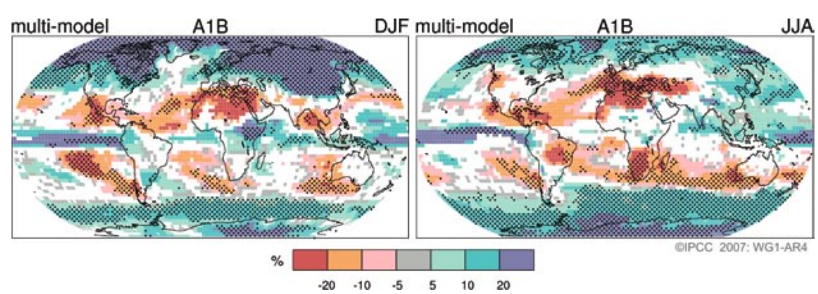

FIGURE A6 *Relative changes in global precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left), and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. (Figure SPM.7 in IPCC WG I 2007.)*

climate change as at present. The high resolution of the figures does not imply a high accuracy, that being limited by the GCM data and the interpolation methodology. Wang et al. (2006a) reported an accuracy of ±1°C for temperature and ±15 mm for precipitation in a test against the 1961–1990 normals. The grid-based data for monthly temperature and precipitation at 400 m spacing for current climate and the A2 scenario are available at: ftp://ftp.for.gov.bc.ca/HRE/external/!publish/Climate/. ClimateBC software and a web-based version are available at http://genetics.forestry.ubc.ca/cfgc/climate-models.html .

Mean annual temperature and precipitation data for 1961–1990 and for 2020s, 2050s, and 2080s for the A2 scenario were presented in the main part of the report (Figures 2 and 3). This Appendix focuses on seasonal changes in temperature and precipitation for the A2 emissions scenario (Figures A7 and A8) and presents data for specific locations in British Columbia (Tables A2 and A3) for the A2 and B1 emissions scenarios.

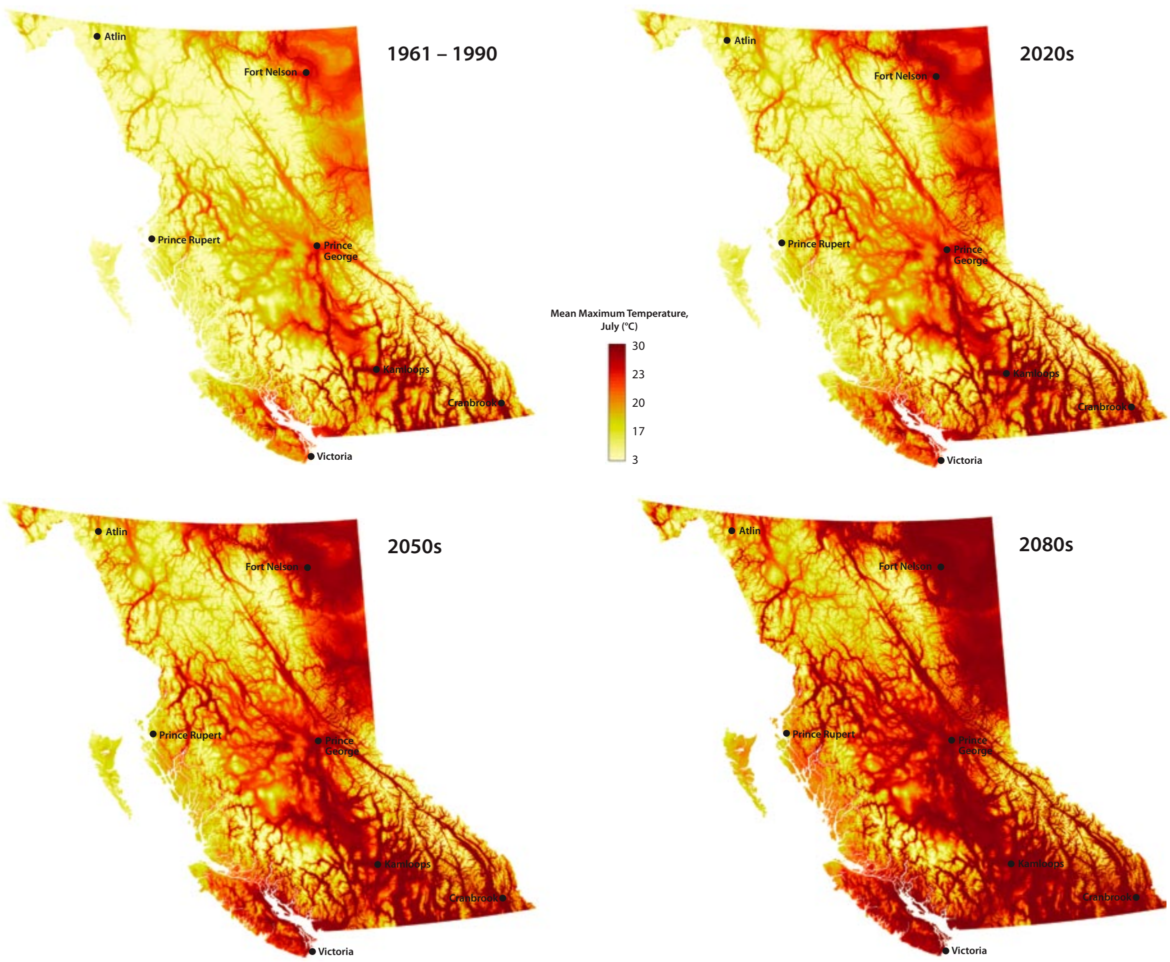

FIGURE A7 *(a) Mean maximum July temperature for British Columbia for 1961–1990 and that predicted for British Columbia in 2020s, 2050s, and 2080s. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

The reduced emissions under the B1 scenario result in less warming than under the A2 scenario. Climate in 2080s for B1 is similar to that for A2 in 2050s (Tables A2 and A3). In both scenarios, the temperature increases with time. There is a tendency for the warming to be greatest in northern British Columbia and larger in the winter than in the summer. The warming is greater in the winter minimum temperature than in the winter maximum temperature, with warming in winter greater than summer. For example, for Cranbook by 2080 under the A2 scenario winter minimum rises by 7°C, winter maximum by 3°C, summer minimum by 4°C, and summer maximum by 3.5°C. The respective values for Fort Nelson of 9, 6, 4.5, and 3.5°C, show the greater warming in northern British Columbia. Warming is least in coastal areas where it is moderated by the ocean. Increasing temperature is accompanied by an increase in the frost-free period and growing degree-days.

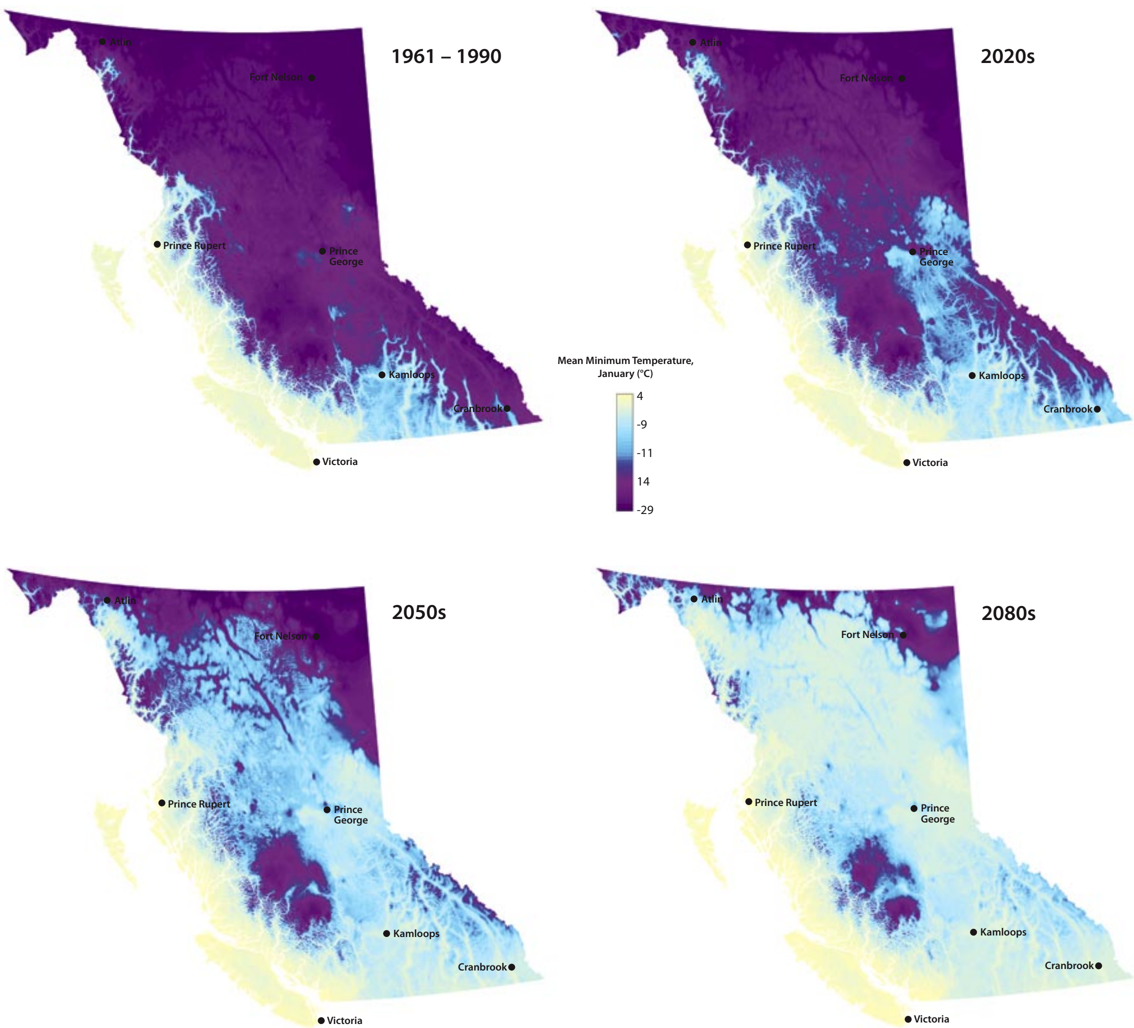

FIGURE A7 *(b) Mean minimum January temperature for British Columbia for 1961–1990 and that predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software that downscaled change data for the A2 scenario from CGCM2. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

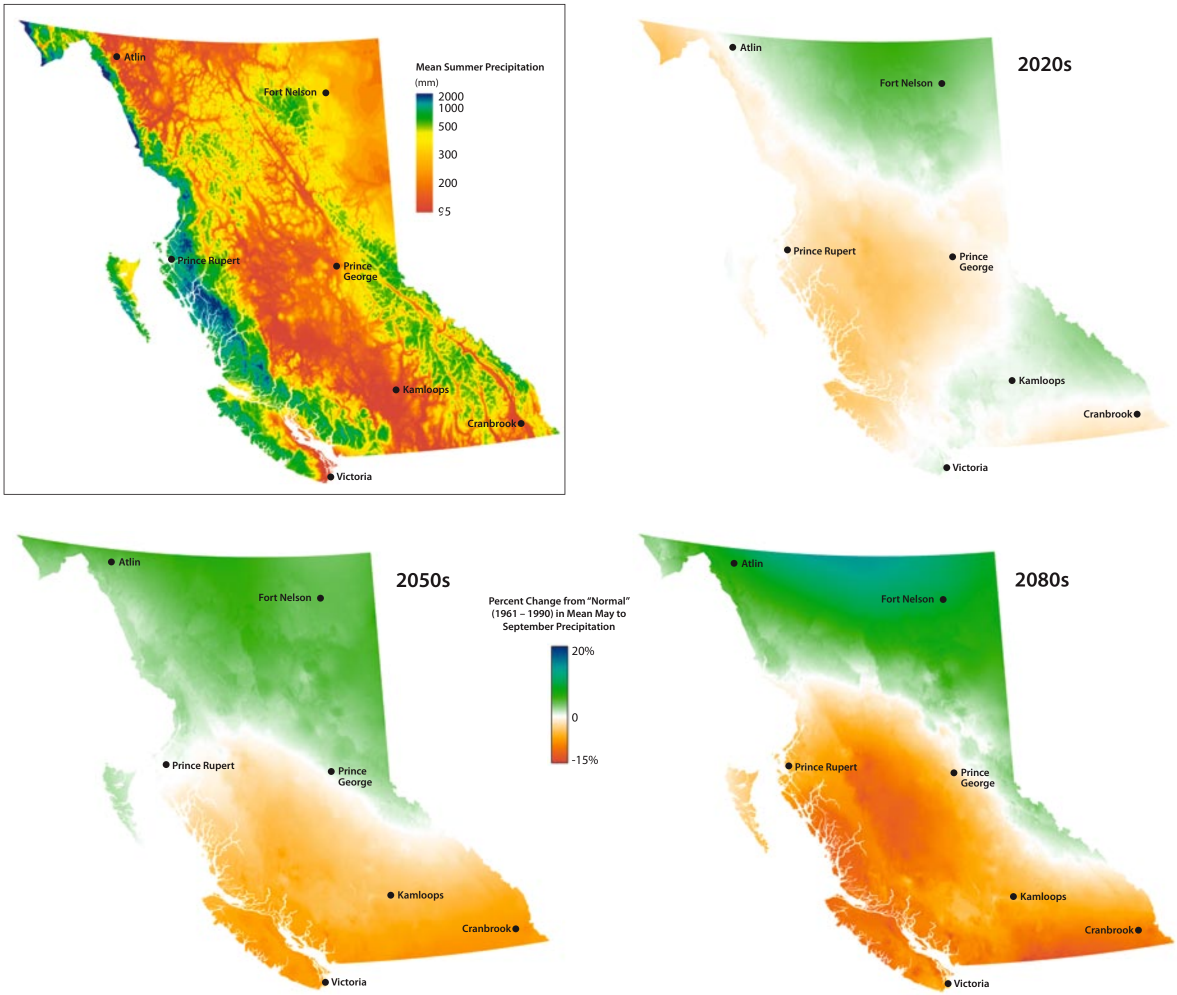

FIGURE A8 *(a) Mean May to September precipitation for British Columbia for 1961–1990 and the percentage change predicted for British Columbia in 2020s, 2050s, and 2080s. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

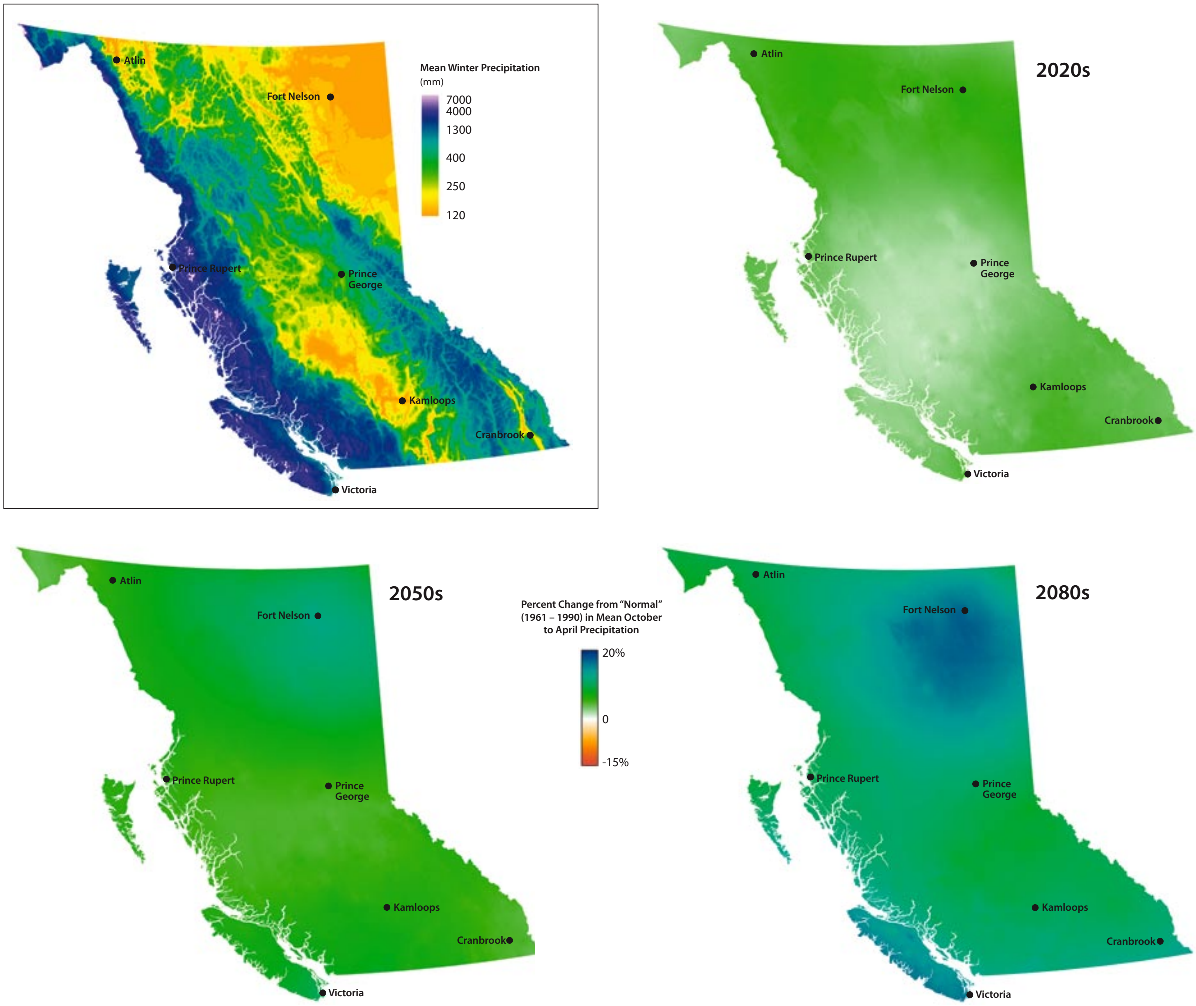

FIGURE A8 *(b) Mean October to April precipitation for British Columbia for 1961–1990 and the percentage change predicted for British Columbia in 2020s, 2050s, and 2080s. Data were produced by the ClimateBC software that downscaled change data for the A2 scenario from CGCM2. (Source: ClimateBC v.2.2 [Wang et al. 2006]. Cartography by Ministry of Forests and Range, Research Branch.)*

TABLE A1 *(a) 1961–1990 climate normals for biogeoclimatic zones, and (b) one standard deviation on these values (next page). Data were obtained by overlaying biogeoclimatic ecosystem variants (Meidinger and Pojar 1991) on a high spatial resolution (400 m grid) climate database created with ClimateBC (Spittlehouse 2006; Wang et al. 2006a). Climate variable and zone abbreviations are explained below the table. Data use to create this table are available at: ftp://ftp.for.gov.bc.ca/HRE/external/!publish/Climate/ .*

(a)1961–1990 climate normals

Zone	MAP mm	MSP mm	PAS mm	MAT °C	MTCM °C	MTWM °C	xTmin °C	FFP days	DD<0	DD>5	SHM
BAFA	1090	447	598	-2.6	-13.4	9.1	-44.6	15	2071	340	22
BG	342	161	100	6.1	-6.3	17.5	-35.8	118	575	1717	115
BWBS	514	308	178	-0.3	-16.0	14.3	-46.5	77	2090	1023	48
CDF	1091	201	61	9.6	3.0	16.9	-15.4	204	31	1965	88
CMA	3198	816	1795	-0.3	-9.7	9.6	-40.0	43	1364	440	15
CWH	2893	651	427	6.7	-0.4	14.5	-22.1	151	191	1339	28
ESSF	1096	404	566	0.3	-10.6	11.5	-41.8	51	1413	650	31
ICH	920	342	379	3.3	-8.4	14.7	-38.9	88	922	1152	46
IDF	493	210	178	4.0	-7.7	15.1	-38.6	84	813	1238	74
IMA	1539	473	959	-2.0	-11.3	8.4	-43.1	20	1791	301	20
MH	3119	730	1198	2.8	-5.7	12.0	-33.2	76	690	781	20
MS	648	261	292	1.9	-9.3	12.8	-40.8	62	1101	848	511
PP	382	165	112	6.3	-5.9	17.9	-35.2	120	517	1762	113
SBPS	473	228	191	1.7	-10.3	12.6	-43.2	35	1176	843	58
SBS	657	280	274	2.2	-10.3	13.6	-41.9	75	1169	988	20
SWB	691	352	322	-1.8	-13.9	10.9	-44.6	37	2038	525	13

MAP = Mean annual precipitation
MSP = Mean summer precipitation (May to September)
PAS = Precipitation as snow (water equivalent)
MAT = Mean annual temperature
MTCM = Mean temperature of coldest month
MTWM = Mean temperature of warmest month
xTmin = Extreme minimum temperature
FFP = Frost-free period
DD<0 = Degree-days less than 0°C
DD>5 = Degree-days greater than 5°C
SHM = Summer heat/moisture index
BAFA = Boreal Altai Fescue Alpine
BG = Bunch Grass
BWBS = Boreal Black and White Spruce
CDF = Coastal Douglas-fir
CMA = Coastal Mountain-heather Alpine
CWH = Coastal Western Hemlock
ESSF = Engelmann Spruce-Subalpine Fir
ICH = Interior Cedar-Hemlock
IDF = Interior Douglas-fir
IMA = Interior Mountain-heather Alpine
MH = Mountain Hemlock
MS = Montane Spruce
PP = Ponderosa Pine
SBPS = Sub-boreal Pine-Spruce
SBS = Sub-boreal Spruce
SWB = Spruce-Willow-Birch

TABLE A1 (*b) One standard deviation on mean values of 1961–1990 climate normals*

Zone	MAP mm	MSP mm	PAS mm	MAT °C	MTCM °C	MTWM °C	xTmin °C	FFP days	DD<0	DD>5	SHM
BAFA	524	150	345	1.2	1.6	1.2	1.5	19	330	114	7
BG	30	19	12	0.5	0.5	0.6	1.1	9	66	134	16
BWBS	61	37	24	0.7	2.1	0.7	1.4	8	259	107	7
CDF	166	47	13	0.3	0.5	0.4	1.3	19	14	87	18
CMA	1252	397	737	2.2	3.5	1.9	5.0	32	554	218	7
CWH	785	186	205	0.9	1.4	0.9	3.2	23	88	181	8
ESSF	251	76	156	0.8	0.9	0.8	1.2	15	176	116	6
ICH	197	59	111	1.0	1.0	1.0	1.7	14	162	175	9
IDF	82	27	39	0.7	0.7	0.9	1.3	13	101	160	11
IMA	351	113	251	1.2	1.2	1.4	1.6	20	278	133	6
MH	888	234	446	1.3	2.0	1.3	3.8	28	254	192	7
MS	128	46	74	0.6	0.7	0.7	1.0	11	103	110	10
PP	43	17	19	0.7	0.6	0.8	1.3	10	78	161	15
SBPS	55	32	31	0.6	0.7	0.7	1.0	18	90	104	11
SBS	107	38	58	0.6	0.8	0.6	1.0	11	108	104	3
SWB	134	77	89	0.7	1.5	0.8	1.2	18	191	97	3

TABLE A2 *Climate in 2020s, 2050s, and 2080s for five locations in British Columbia for the A2 emission scenario. The data are based on ClimateBC interpolation of the CGCM2 simulation. Data adjusted to 1961–1990 normals reported in AES (1993) for the airport weather stations. Scenario temperature data rounded to 0.5°C and precipitation to 5 mm.*

	MAT	MWMT	MCMT	MAP	MSP	FFP	DD>5	SHM
Cranbrook								
1961–90	5.6	18.2	-8.3	384	185	109	1671	98
2020s	7.0	19.5	-6.5	390	185	125	1960	105
2050s	8.0	20.5	-4.5	380	175	140	2220	117
2080s	10.0	22.0	-3.5	395	175	170	2680	126
Fort Nelson								
1961–90	-1.1	16.7	-22.0	449	303	106	1289	55
2020s	0	18.0	-20.5	465	310	115	1480	58
2050s	1.5	19.5	-18.0	475	315	130	1670	62
2080s	3.5	21.0	-14.5	500	330	145	1950	64
Kelowna								
1961–90	7.4	18.8	-4.5	366	171	125	1864	110
2020s	8.5	20.0	-3.5	375	170	140	2100	118
2050s	9.5	21.0	-2.0	370	160	150	2390	131
2080s	11.0	22.5	-1.0	375	160	175	2820	141
Prince George								
1961–90	3.7	15.3	-9.9	615	287	93	1238	53
2020s	5.0	16.5	-8.0	615	280	110	1450	59
2050s	6.0	17.5	-6.5	630	285	125	1700	61
2080s	7.5	19.0	-5.0	635	275	150	2070	69
Port Hardy								
1961–90	8.1	13.9	3	1871	410	183	1379	33
2020s	9.0	15.0	4.0	1885	395	205	1770	38
2050s	10.0	16.0	5.0	1935	385	260	2020	42
2080s	11.5	17.0	6.0	2035	375	325	2510	45

MAT = mean annual temperature (°C)
MWMT = mean warmest month temperate (July, °C)
MCMT = mean coldest month temperature (January, °C)
MAP = mean annual precipitation (mm)
MSP = mean May to September precipitation (mm)
FFP = frost-free period (days)
DD>5 = degree-days above 5°C
SHM = Summer heat/moisture index

TABLE A3 *Climate in 2080s for five locations in British Columbia for the B1 emission scenario. Data based on ClimateBC interpolation of the CGCM2 simulation. For an explanation of symbols and 1961–1990 normals see Table A2.*

	MAT	MWMT	MCMT	MAP	MSP	FFP	DD>5	SHM
Cranbrook	8.0	20.6	-6.1	395	185	140	2060	111
Fort Nelson	1.5	19.0	-18.5	460	305	115	1690	62
Kelowna	9.5	21.0	-3.5	390	170	160	2400	124
Prince George	6.0	18.0	-6.5	600	275	130	1700	65
Port Hardy	10.0	16.5	4.5	1975	390	255	1940	42

Changes in precipitation are quite variable in time and space. Southern and central British Columbia are predicted to get drier in the summer, while northern British Columbia is more likely to be wetter (Figure A8), although the change in volume is not large. Winters will be wetter across British Columbia, with a greater percentage increase in the north, though coastal British Columbia sees the greatest volume increase in winter precipitation (Tables A2 and A3). Warming means that less of the precipitation will fall as snow. For example, at Cranbrook there is a reduction from 120 mm to 70 mm (water equivalent) of the winter precipitation as snow by 2080s under the A2 scenario. At Fort Nelson the change is from 130 mm to 115 mm.

Influence of climate change on snow accumulation and melt

Mote et al. (2005) and Rodenhuis et al. (2007) report a general decline in snowpacks over much of western North America in the last 50 years. Increasing winter temperatures under climate change are expected to continue this trend. This is illustrated (Figure A9) with data for the Upper Penticton Creek Experimental Watershed on the Okanagan Plateau (Winkler et al. 2004) for climate conditions equivalent to the CGCM2 A2 scenario in 2050s and 2080s. A snow accumulation and melt model was used to determine the daily snow depth under a forest canopy for winter 2001/02. The effect of a changing climate was evaluated by modelling the response to 2 and 4°C increases in the 2001/02 daily temperatures. A third simulation involved a 4°C increase in temperature plus a 10% increase in winter precipitation. Winter precipitation in 2001/02 and snow on the ground at the end of March and April were slightly below the 15-year average for Upper Penticton Creek.

A 2°C warming early in winter did not affect the snow accumulation (Figure A9) because conditions still remained cold enough for precipitation to fall mainly as snow. There was also minimal snowmelt. By mid to late

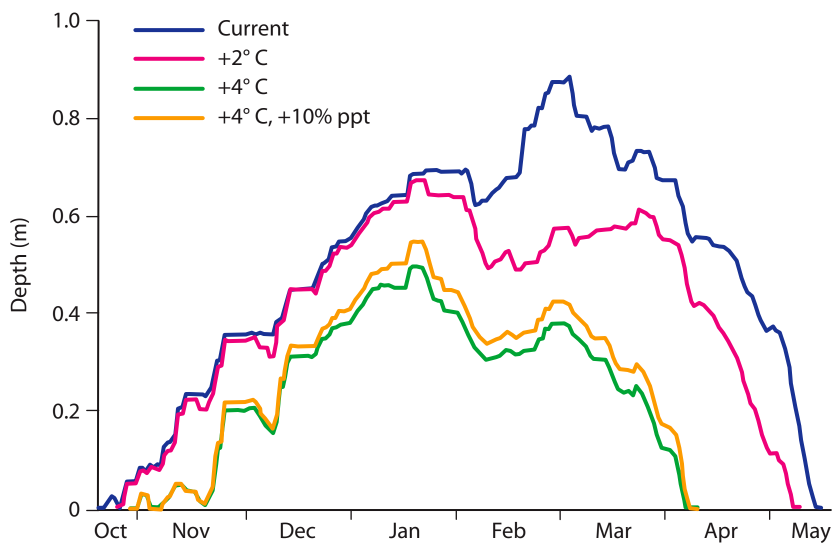

FIGURE A9 *Simulated winter snow depth at the Upper Penticton Creek Experimental Watershed under winter 2001/02 temperature and precipitation conditions (blue line) and three climate-change scenarios. The scenarios are: 2°C warming (increase to daily temperature record for winter 2001/02) with no precipitation change (purple line), 4°C warming with no change in precipitation (green line), and 4°C warming with a 10% increase in precipitation (orange line).*

winter, conditions had warmed sufficiently that snowmelt could start earlier than under the current climates, the maximum snowpack depth was reduced by about 30% and it disappeared about 2 weeks earlier than under current conditions. A 4°C warming was large enough that early snow accumulation was reduced resulting in a reduction in peak snow depth by 50% (Figure A9). The warming also resulted in snowmelt occurring earlier in the year and the snowpack disappearing about a month earlier than under current conditions. Increasing precipitation only slightly offset the effect of a 4°C temperature increase.

Influence of climate change on evaporative demand and climatic moisture deficit

Estimates of the evaporative demand for water and measurements of precipitation can be combined to give indicators of plant water stress and to predict water demand for agricultural irrigation and domestic use. A climatic moisture deficit occurs if the monthly precipitation is less than the monthly evaporative demand. If precipitation is greater than the evaporative demand there is a moisture surplus. Monthly evaporative demand was calculated following Allen et al. (1998) for months when the air temperature was above 0°C. The analysis was done with the 1961–1990 normals and 2080s' CGCM2 B1 and A2 climate scenarios for the Campbell River, Cranbrook, and Fort St. John areas. Temperature and precipitation data at 2080 were obtained from ClimateBC (Spittlehouse 2006; Wang et al. 2006a). The average monthly sunshine or solar radiation data and a mean wind speed for the 1961–1990 period (AES 1993) were used for the 2080s calculations.

Evaporative demand increased at all locations due to an increase in the length of time the air temperature was above zero and to an increase in the vapour pressure deficit. This result is consistent with the assessment of Huntington (2008). Under the B1 scenario, by 2080s the demand increased by about 8% while under the A2 scenario, with greater warming, it increased by 15–20%. There was a greater difference between locations in the climatic moisture deficit, reflecting the balance between changes in temperature and changes in precipitation (Figures A7 and A8). By 2080s under the B1 scenario, the deficit at Campbell River increased by 20%, at Fort St. John by 25%, and at Cranbrook by 30%. For the A2 scenario, Campbell River and Fort St. John increased by 30%, while Cranbrook increased by 60%. The larger increase at Cranbook reflects the decrease in summer rainfall and an initially relatively low average deficit for 1961–1990. A moisture surplus did not occur during the summer at any of the locations. A comprehensive analysis should assess the inter-annual variability in evaporative demand and climatic moisture deficit under a changing climate.

The response of forest and range species to climate change and the changing operating environment will challenge our ability to use forest and range resources. The wood supply for the next 50–100 years in most of British Columbia is already "in the ground" or will be planted in the next few years with minimal consideration about climate change. Losses in productivity of natural and planted stands are expected to occur in the drier and warmer regions of British Columbia, while modest increases are anticipated in the short to mid term in the north (Rehfeldt et al. 1999, 2001; Spittlehouse 2003; Johnson and Williamson 2005). These changes will affect rotation age, wood quality, wood volume, and size of logs. An increase in disturbance by fire, insects, and disease could lead to a greater amount of the harvest consisting of salvaged wood (Spittlehouse and Stewart 2003; Volney and Hirsch 2005). Technological change, trade disputes, changes in exchange and interest rates and changes in consumer tastes and preferences will take place along with climate change. Countries that are expected to be significant beneficiaries of climate change from a production standpoint (e.g., in South America and Oceania) are already replacing Canadian products in the global market (Sohngen and Sedjo 2005).

Access to timber and harvest scheduling will change because warmer and/or wetter winters will limit site access for winter logging, and warmer and drier summers will reduce access due to increased fire risk. Expected higher rainfall intensities and a reduction in the return period of high-intensity rains will affect road design and maintenance (Spittlehouse and Stewart 2003). More severe winter storm events in coastal British Columbia are likely to increase the probability of landslides, including debris flows (Wieczorek and Glade 2005; Pike et al. 2008b). This has implications for forest development planning and operations. Increase in warming in the north and an accompanying increase in permafrost melt will increase the risk of landslides (Geerstma et al. 2006).

Reforestation is based on the selection of species and genotypes that are genetically adapted to the site (climate and soil). A changing climate means that the appropriate plants for a site would change (Rehfeldt et al. 1999, 2001; Parker et al. 2000; Spittlehouse 1996; Spittlehouse and Stewart 2003; Wang et al. 2006b). Hamann and Wang (2006) indicate that tree species with their northern range limit in British Columbia could gain climatically suitable habitat at a pace of about 100 km per decade. Common hardwoods appear to be less sensitive to climate change, while some of the most important conifer species in British Columbia could lose a large portion of their climatically suitable habitat. Similar results were obtained for the western United States by Rehfeldt et al. (2006). The climate will continue to change over the life of the stand and we must decide which climate regime the planting stock should be selected to meet. Increased competition from species more suited to this climate means that there may be a need to increase stand management activities in established stands (Parker et al. 2000; Spittlehouse and Stewart 2003).

Future disturbances by fire, insects and disease will have a large influence on the future forest carbon balance. The effect will be greater than the effects of changes in tree species occurrence and growth rates (Kurz et al. 2007, 2008a, b). Recent forest fires and insect attacks have resulted in a negative carbon balance for Canada's managed-forest, and a much reduced positive balance for British Columbia's forests (Kurz et al. 2008a, b). In some areas of British Columbia, the distribution of ages of the trees is biased towards old trees. The resultant build-up of fuels for fire and an increase in the susceptibility of trees to diseases and pests increases the risk of disturbance. Increase in disturbance will lead to an increase in the area of younger forests, which along with changes in forest growth and species composition will affect habitat quality and availability for wildlife (Harding and McCullum 1997; Stenseth et al. 2002). Changes in fire regime will also have a direct impact on the safety of people and property (Volney and Hirsch 2005), as illustrated by the fires near Kelowna and Barriere in 2003. Smoke from forest fires can have health impacts many kilometres from the fire.

Increased occurrence of wildfires would increase the likelihood of post-wildfire flood and landslide risks to human life, property, and infrastructure. Forest harvesting and road building may have to increase efforts to mitigate the impacts of changes in the timing of peak flow and volume in streams on infrastructure, fish habitat, and potable water supplies (Mote et al. 2003; Pike et al. 2008b). Warmer and drier summer conditions will increase the pressure to maintain cool stream temperatures by maintaining riparian cover in harvested areas (Moore et al. 2005). A priority may be placed on preserving habitat for conservation. However, the values and attributes that parks and wilderness areas were designed to protect may no longer exist within the protected areas under a changed climate (Scott and Lemieux 2005). Warmer winters will shorten the winter recreational season while the summer recreational season will increase, although increased fire risk may limit this increase. Increases in disturbance by fire may favour certain mushrooms and berry-producing shrubs (Spittlehouse 2005).

Some specific implications of climate change for British Columbia's ecosystems are:

- Coastal forests: In the southern part of the area, warmer and drier late spring and summers could increase fire risk and decrease water availability. Increased water stress will affect species such as western redcedar on marginal sites on the east side of Vancouver Island. The wet, cool mid and north coasts will likely see an improvement in growing conditions. Increase in storm number and intensity will likely increase windthrow and breakage of trees. An increase in the severity of storms could increase the probability of landslides and debris flows.
- Lower elevations in southern interior: Drier sites may experience regeneration problems due to an increase in summer droughts. Grasslands are expected to expand and the current encroachment of forests on grasslands may be reversed by climate change. The range of invasive species may also expand.
- Higher elevations in southern interior: A shorter snow season and increased length of growing season may initially be beneficial to regeneration and growth. In drier areas, reduction in summer precipitation and increase in temperature will increase the risk of fires and drought stress.
- Northern interior: Warming and only small changes in summer precipitation have the potential to result in increased tree growth in the short to mid term. A shorter winter season will reduce access to sensitive terrain.

- Alpine: The length of the snowpack season, soil conditions, and slow regeneration rates will limit the rate of forest encroachment. Artificial warming studies in tundra ecosystems have shown changes in the occurrence of existing species.

Assessment of the implications of a changing climate change on ecosystems

The high spatial resolution climate data (e.g., Figures 2 and 3 and Appendix 2) can be used in detailed assessments of climate-change impacts on forest and range resources. The climate data were combined with a spatial distribution of British Columbia's ecosystem units to determine the realized climate space (characteristic values) of these units (Hamann and Wang 2006). Under the A2 scenario, substantial shifts in climate zones could occur by the 2080s. The drier and warmer climate produced by the Hadley model produced a further northward movement of zone climates. The B1 emissions scenario would produce a zone climate map for 2080s similar to that of the A2 in 2050s. This work is a preliminary assessment and the analysis needs to incorporate climate data from Alberta and the northwestern United States to determine if analogues of climates of these areas may develop.

Another approach to assessing vulnerability of ecosystems is to evaluate possible impacts of a changing climate at a location. In this approach, ecosystem maps are overlain on grid-based climate data from ClimateBC to obtain descriptions of the climate of these units for current conditions (Table A1) and under various climate scenarios. The example presented here (Table A4) is based on the A2 scenario in 2050 (Spittlehouse 2006). The very dry maritime Coastal Western Hemlock (CWHxm2) is on the eastern slope of the Vancouver Island Mountains. The wet cool Sub-Boreal Spruce (SBSwk1) is in the central interior of British Columbia on the west side of the Quesnel Highlands and on the MacGregor Plateau. Climate varies within a unit but the climate-change scenario shifts all values of a variable by about the same amount, so the standard deviation on the means stays the same. Both units are warmer by about 2°C and wetter in the winter. The CWHmx2 has less rain in the summer, while there is a slight increase in summer rainfall for the SBSwk1. The CWHxm2 climate changes towards that of the coastal plain on the east coast of the island. The implications for tree growth are that Douglas-fir should continue to grow well but western redcedar could disappear from currently marginal sites. The SBSwk1 climate is moving towards that of some units of the Interior Cedar-Hemlock zone. Warming of this unit may favour the growth of interior Douglas-fir and lodgepole pine over spruce.

TABLE A4 *The 1961–1990 normals and possible future climate (CGCM2-A2x scenario) of two biogeoclimatic ecosystem units for 2050s. Means and one standard deviation (± SD) of each variable are presented (from Spittlehouse 2006).*

	Very Dry Maritime Coastal Western Hemlock (CWHxm2)			Wet Cool Sub-Boreal Spruce (SBSwk1)		
Area (ha)	**580250**			**785950**		
	1961–90	**2050s**	**± SD**	**1961–90**	**2050s**	**± SD**
Mean annual temperature (°C)	8.3	10.3	0.7	2.5	4.9	0.5
Mean July monthly maximum temperature (°C)	21.3	23.4	1	20.7	23.0	1
Mean January monthly minimum temperature (°C)	−1.0	0.8	1	−14.8	−10.0	1
Frost-free period (days)	173	223	22	78	116	10
May to September precipitation (mm)	370	350	120	350	380	40
October to April precipitation (mm)	1870	2020	590	488	510	90
Water equivalent of the annual snowfall (mm)	190	100	90	340	280	70
Summer heat/moisture index	48	58	15	41	47	5

The use of the framework is illustrated with two forestry-related issues that have already undergone a partial assessment of vulnerabilities and have started to develop adaptation strategies.

The Ministry of Forests and Range (MOFR) is developing an adaptation strategy in response to the threat of climate change for British Columbia's forest and range resources. The first iteration of the Ministry's response can be placed in the framework as follows:

- **Issue:** Climate change will play a major role in shaping the future composition and use of forest and range resources in British Columbia.
- **Vulnerability assessment:** Climate-change impacts are poorly known. There is a lack of awareness of the issue within the forest and range community. Some of the vulnerability may not be related to climate change. Changing social and economic conditions are influencing forest and range resource utilization. There is a lack of research knowledge and policies to enable adequate response to these vulnerabilities.
- **Adaptation strategy:** The MOFR established a Climate Change Task Team to review potential impacts of climate change on provincial forest and range resources, identify knowledge gaps, and develop recommendations on how the MOFR should proceed. The Future Forest Ecosystems Initiative (FFEI) was launched to consult with a wide cross-section of society in British Columbia on the future threats to the province's forest and range resources and possible responses. Although it will be some years before operational adaptation actions are implemented, consultation, capacity building, and vulnerability assessments are viewed as important first steps in the adaptation process.
- **Implementing the adaptation strategy:** Recommendations from the Task Team were released in a report (B.C. Ministry of Forests and Range 2006). The MOFR consulted widely on the reports of the Task Team and the FFEI. The recommendations from these reports and the consultations were amalgamated under the goal of adapting British Columbia's forest and range management framework to changing climatic conditions. The FFEI is ongoing and has become part of the MOFR business plan.

The forest genetics research community is a leader in forestry in assessing vulnerability and developing adaptation strategies to respond to climate change. Examples can be found in Rehfeldt et al. (1999, 2001, 2006), Hamann and Wang (2006), and Wang et al. (2006b), and are used here to illustrate application of the framework at a provincial scale.

- **Issue:** Forest policies on the use of seed for reforestation are designed to minimize the risk of maladaptation. Thus there is a requirement to use "local" seed under the assumption that local seed is best adapted to the local climate. Under climate change, this assumption may be invalid within the next 50 years. This is a province-wide issue for all commercial species of trees.
- **Vulnerability assessment:** The risk is that by 2080 the climate will have changed such that trees growing from the "local" seed may be in condi-

tions well outside their envelopes for optimum survival and growth. Seed planning units are geographically based and only implicitly account for climatic conditions. Consequently, under a changing climate these management units may not be appropriate for managing seed selection (Wang et al. 2006b).

- **Adaptation strategy:** Determine the climates of the sources of seed used for reforestation. Develop response functions of various seed sources to a wide range of climatic conditions using provenance trials. Determine the patterns in growth response to climate among populations. Predict impacts of climate changes on productivity with different seed deployment strategies. Develop climate-based seed planning units.
- **Implementating the adaptation strategy:** Development of a high spatial resolution climate database is facilitating determining the climate of seed sources and the trial sites (e.g., Hamann and Wang 2006; Wang et al. 2006a,b). Plans are in place to increase the number of provenance trials for commercial tree species and to establish them over a wide climatic range.