**University of Alberta**

# Developing Adaptation Strategies for Forest Management under Uncertain Future Climate

by

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## Abstract

Bioclimate envelope models are widely used to project potential species habitat under changing climate. Conceptually, these models are also well suited to match natural resource management practices to new climatic realities, for example by guiding species choice in reforestation programs. Nevertheless, uncertainty due to a variety of causes has so far limited the practical application of bioclimate envelope models. The goal of this thesis is to examine sources of uncertainty, to reduce uncertainty if possible, and to develop methodology to systematically deal with the remaining variability in model projections. Secondly, this thesis develops practical climate change adaptation strategies for the forestry sector in western Canada. This requires answering what species should be used for reforestation for a particular site, and subsequently selecting planting stock of the species that is best adapted to current and anticipated environments.

Using a novel approach to partition variance in results from multiple model runs, climate data were identified as arguably the most important source of uncertainty. Variation was primarily caused by different general circulation models, followed by different emission scenarios. Also, the method used to interpolate current weather station data was an important contributor to uncertainty at specific locations. Other sources of uncertainty were the choice of predictor variables and different bioclimate envelope modeling methods, which primarily contributed to uncertainty through interaction effects. For example, different modeling methods provided similar habitat projections for western

Canada on average, but under certain climate change scenarios their results differed markedly.

Given the large uncertainties in model projections, it is important to remember that ultimately, climate change adaptation has to be guided by climate trends that actually materialize. A considerable portion of this thesis therefore analyzes climate trends in western Canada over the past century. In a case study for aspen, it is shown that the combined information from multiple bioclimate envelope model runs, climate trends that have already materialized, and observed climate change impacts can make a strong case for implementing adaptation strategies in central Alberta. Amendments to aspen reforestation practices are proposed, avoiding the use of the species in areas where it is likely to lose habitat in the future, and recommending movement of planting stock so that it is reasonably well adapted under a range of future climate scenarios.

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## Chapter 1. Introduction and literature review

### 1.1. Past climate trends and observed biological impact

According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007b), global surface temperatures have increased by approximately 0.7°C over the last 100 years. The rate of northern hemisphere change in temperature has almost been twice the global average with warming greater in winter (1.5°C) than the summer (1.2°C) (Brohan et al. 2006; Hansen et al. 2001; Smith and Reynolds 2005). In contrast, temperature increase during the 20$^{th}$ century was about 0.4°C in the tropics and 0.6°C at middle latitudes (Hansen et al. 2001). The warming trend is a recent phenomenon that has been accelerating to 0.3°C per decade since the mid 1980s (Brohan et al. 2006; Hansen et al. 2001; Smith and Reynolds 2005). Temperature changes have been larger for minimum than maximum land-surface air temperature (Vose et al. 2005). On the other hand, precipitation changes over the 20$^{th}$ century have not been globally directional but variable in both space and time. In North America, mean annual precipitation has generally increased in mid to high latitudes while largest decreases were observed in Mexico during the 21$^{st}$ century (Dai et al. 1997; Shein et al. 2006). In addition, precipitation changes have been variable over time. Globally, significant increase in precipitation was observed in the first half of the 20$^{th}$ century, followed by a reduction until the 1990s, and a global increase in precipitation thereafter (Trenberth et al. 2007), mirroring the temperature trend.

In Canada, Zhang et al (2000) studied temperature trends during the 1901 to 1998 period for areas lying between latitudes 49°N and 60°N and found that mean annual temperature increased by 0.9°C on average. Warming was most pronounced in the Prairies (+1.5°C), whereas cooling of the same magnitude was observed in the northeast. Similar to global trends, they described an increase in temperatures up to the 1940s, a decrease thereafter up to the 1970s, followed by an accelerated increase from the 1990s onwards. The Meteorological Service of Canada (MSC 2007) reports that five of the ten warmest years since records began in Canada occurred in the last decade (1996-2007). Specifically, the warming trend has been driven by increased frequency of warm days in winter as well as warmer spring and fall temperatures, leading to a longer growing season (Bonsal et al. 2001). Though by a smaller magnitude, summer warming in western Canada has also accelerated from about 0.15°C per decade between 1961 and 1990 to about 0.3°C per decade between 1990 and 2005 (Chapin et al. 2005). Precipitation has increased by about 12% across Canada between 49 and of 60°N with the greatest precipitation increase in the east (Zhang et al. 2000).

In the long term, and from global to regional scales, climate is perhaps the most significant factor that governs the distribution of species, ecosystems and biomes (Adams 2007; Davis and Shaw 2001). There are numerous examples of recent climate change related impacts on species and ecosystems. These include changes in the occurrence, intensity and frequency of disturbances (Dale et al. 2000; Dale et al. 2001) and increased incidence and frequency of fire (Girardin 2007; Girardin et al. 2008; Westerling et al. 2006). Recent changes in climate have also been associated with a shift towards earlier bud break in spring of approximately 1-3 days/decade (Menzel et al. 2006; Walther et al. 2002; Wolfe et al. 2005), expansion of the treeline to northern latitudes and higher altitudes (Gamache and Payette 2005; Parolo and Rossi 2008; Piotti et al. 2009; Sturm et al. 2001; Tape et al. 2006), and range expansion of forest pests and diseases such as the mountain pine beetle and *Dothistroma* needle blight in western Canada (Berg et al. 2006; Carroll et al. 2006; Stahl et al. 2006; Volney and Fleming 2000; Woods et al. 2005). Other observed impacts of climate change include drought related tree mortality (Hogg et al. 2008; van Mantgem and Stephenson 2007; van Mantgem et al. 2009). In some locations, change in climate has resulted in faster growth rates (Baker and Moseley 2007; Walther et al. 2005; Weber et al. 2007) and increased productivity (Asshoff et al. 2006; Martinez-Vilalta et al. 2008; Norby et al. 2002; Zhang et al. 2008; Zhou et al. 2003).

Given the recent changes in climate and associated biological impacts, climate change during the 21$^{st}$ century will continue to pose significant challenges to natural resource management. To ensure continued productivity of forests and protection of ecosystems, resource managers will have to change forest management practices and policies to adapt to uncertain future climates. Adaptation strategies should ensure reduced vulnerability of species to climate change while at the same time taking advantage of the potential benefits of longer growing seasons and higher precipitation to increase forest productivity (Lawler 2009; Spittlehouse 2005).

### 1.2. Modeling species response to climate change as the basis for adaptation strategies

Predicting species response to climate change is increasingly becoming an important part of natural resources management (Brooker 2006). Data on species response to climate variability and climate change has been generated through various approaches including climate controlled experiments (Andalo et al. 2005; Bouriaud and Popa 2009; Thomson and Parker 2008; Vitas 2004; Vitas and Erlickyte 2007), long term monitoring (Beier et al. 2008; Martinez-Vilalta et al. 2008; Rehfeldt et al. 1999; van Mantgem et al. 2009) or dendrochronological studies (Chen et al 2010). Such data have also been used to parameterize process-based models to make predictions of species response to projected climate change (Landsberg and Waring 1997). The disadvantage of process-based models however is that they require large amounts of empirical data which are not always available and results from these models cannot easily be extrapolated beyond where empirical data were collected (Hickler et al. 2008).

Alternatively, bioclimate envelope models have been used – not to directly predict species response to climate change, but to characterize and project changes to suitable habitat of species (Araujo and Guisan 2006). Bioclimate envelope models build statistical relationships between species inventory data and the environmental conditions in which they occur, developing a species-climate space or "envelope" which is then mapped under projected climate to show the species potential habitats in the future (Pearson and Dawson 2003). Because at a minimum they require only climate data and species presence/absence records, BEMs are technically not difficult to implement. Bioclimate envelope modeling has roots in ecological niche modeling as described by Hutchinson (1957), who defined a species fundamental niche as a multidimensional space where a species can survive. Due to constraints such as competition, pests and diseases, a species only occupies part of the fundamental niche, which is referred to as the realized niche (Jackson and Overpeck 2000). Bioclimate envelope models are developed on the basis of observed species distribution, thus they model a species' realized niche (Jeschke and Strayer 2008).

Several techniques are now available for modeling changes to species niches in response to changes in climate. These include statistical models such as logistic regression (Hosmer and Lemeshow 2000), generalized linear models (GLM), generalized additive models (GAM) (Hastie and Tibshirani 1990), artificial neural networks (ANN), Classification and regression trees (CART) and genetic algorithm (GARP) (Stockwell and Peterson 2002). Other techniques do not directly rely on statistical relationships between species census data and climate variables. Instead they make predictions based on similarity or climatic distance of climate envelopes that are defined for species or ecosystems using current climate conditions. Examples are box-type climate envelope techniques implemented in various software packages: ANUCLIM, BIOCLIM, DOMAIN, FEM, HABITAT (Beaumont et al. 2005), and Mahalanobis distance based bioclimate envelope modeling techniques (Farber and Kadmon 2003; Hamann and Wang 2006; Rotenberry et al. 2006).

The use of different bioclimate envelope modeling methods reveals a surprising amount of variability in model predictions (Araujo and New 2007; Kadmon et al. 2003; Pearson et al. 2006; Segurado and Araujo 2004; Thuiller 2004). Other important factors that contribute to uncertainty are future climate projections (Beaumont et al. 2008; Houlder et al. 2001), the quantity of biological census data (Kadmon et al. 2003), environmental data (Beaumont et al. 2005; Guisan and Thuiller 2007; Heikkinen et al. 2006b; Luoto and Heikkinen 2008; Luoto et al. 2007), and the quality of baseline climate data used in model calibration (Heikkinen et al. 2006a). The general conclusion from such sensitivity analyses is that quantifying uncertainty and filtering out biologically or statistically unreasonable results is an essential task before bioclimate envelope model results can be used for developing strategies for natural resources management under changing climate.

### 1.3. Adaptation strategies to climate change in forest management

Projected species habitat shifts from bioclimate envelope models are usually alarming, and certainly exceed the natural migration capacity of most tree species (Malcolm et al. 2002). Thus as climate changes during the 21st century, tree species will be growing in suboptimal climate conditions (O'Neill et al. 2008). It has therefore been recommended that adaptation to changing climate could be achieved through human interventions such as assisted migration involving transfer of planting material to new locations to ensure survival of species under changing future climate (McLachlan et al. 2007; Millar et al. 2007). The term assisted migration usually refers to moving species to new locations outside their current range limits (Aitken et al. 2008). However, equally important may be the movement of locally adapted populations within the current range of species to reduce the vulnerability of forests to changes in climate, as well as take advantage of potential benefits associated with an extended growing season (Spittlehouse 2005). Movement of planting stock of a species within its current range is already a standard forest management practice to optimize forest productivity and forest health (Morgenstern 1996; O'Neill et al. 2008).

Whereas several forms of assisted migration or movement of planting stock have been carried out by foresters in one form or the other for various reasons in the past (McLachlan et al. 2007), there is lack of information about where or how far planting stock can be moved without risking mal-adaptation. The situation is complicated by the high variation in projected future climate as well as uncertainty in predicted potential future climate impact of species suitable habitats. One of the important questions in seed transfer is to determine the best climatic or geographic transfer distances. The distance must further account for current climate conditions to ensure seedling survival, as well as anticipated climates to ensure long-term forest health and productivity (McKenney et al. 2009). Attempts to implement seed transfer based on the best information available are already underway in British Columbia (Marris 2009; O'Neill et al. 2008), emphasizing the need for good predictive models to support such decisions.

Developing such models requires assembling information from various sources. Obviously, we need information about how climate is expected to change in the future. However, future climate projections at local scales also depend on a good representation of current (baseline) climate on which climate change projections from general circulation models can be based. Secondly, we need information about locally observed climate trends to which forest management practices will ultimately have to adapt. Both sources of climate data can be used as input by bioclimate envelope models to project species habitat and determine the best planting stock for reforestation. If long-term climate trends do materialize as predicted (or otherwise), climate change adaptation strategies should also be guided by observed biological problems. Not all climate change impacts will be negative and will require human intervention. Long-term monitoring studies and transplant experiments to areas that currently have warmer climate may provide further empirical data on how species and populations within species may respond to climate change.

In summary, bioclimate envelope models should only be one source of information to develop climate informed adaptation strategies for the forestry sector. They will yield useful results for medium to long term planning, but implementation of climate change adaptation strategies should also rely on information that reflects local realities of observed climate change and actual climate change impacts that pose threats to forest health and productivity.

## 1.4. Research objectives and thesis structure

The overall goal of this thesis is to develop methodology that can be used to guide the choice of species for reforestation and locally adapted planting stock that will grow well under a variety of anticipated future climates. This thesis addresses six specific research questions in the following order:

1) What are the most appropriate methods to interpolate weather station data to generate climate surfaces that accurately represent current climate conditions?
2) How do climate change projections for western Canada differ, and which/how many individual or ensemble projections should be used for bioclimate envelope modeling?
3) How do future climate projections compare to observed climate trends and associated biological response, and what role should observed trends play in developing climate change adaptation strategies?
4) What are the relative contributions of baseline climate data, selection of predictor variables, modeling method, general circulation models and emission scenarios to variability in predictions of bioclimate envelope modeling?
5) Can uncertainty be reduced by filtering out biologically or statistically unreasonable modeling results, and provide practitioners with an improved range of predictions for climate informed natural resource management?

6) How can predictions from multiple runs of bioclimate envelope models be used to guide the choice of species for reforestation and guide recommendations for planting stock that is adapted to anticipated future environments?

Because of the importance of the quality of climate data to bioclimate envelope modeling, the first two research chapters (thesis chapters 2 and 3) are devoted to critical examination of climate databases. Chapter 2 covers climate normal data as well as future climate scenarios, and chapter 3 evaluates historical climate data for the last century. I assemble and evaluate the quality of a comprehensive database of 15,000 high resolution climate surfaces for western Canada, including a standard set of precipitation and temperature variables as well as biologically relevant climate variables, such as growing and chilling degree days, temperature extremes, and dryness indices. In the third research chapter (thesis chapter 4), I present a novel approach to partition variance in results from bioclimate envelope models with analysis of variance. Five factors, namely baseline climate data, selection of predictor variables, choice of modeling technique, general circulation model, and emission scenarios were examined with respect to their relative contributions of uncertainty to model results. The last research chapter (thesis chapter 5) is a case study with trembling aspen, where I demonstrate how bioclimate envelope models can guide the choice of species and planting stock for use in reforestation under uncertain future climates. What follows is a more detailed outline of the individual thesis chapters:

In **Chapter 2**, I evaluate climate datasets (both baseline and projected) that comprise an important component in modeling potential future climate impact on species suitable habitat. Baseline climate data are important because they are used to establish a reference point for assessing changes in climate, are combined with projected anomalies to create future climate scenarios, and are used to calibrate models for assessing climate change impact on species. Three baseline (1961-1990) climate grids, one from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), and two developed using thin-plate spline interpolation, a high resolution dataset that I refer to as ANUSPLIN and low resolution CRU-TS-2.1 (New et al. 1999) were evaluated with a selected number of weather stations on the basis of five climate variables (mean annual temperature, mean July temperature, mean January temperature, mean annual precipitation and mean summer precipitation). For future projections, I evaluate whether choosing worst, best or median scenarios on the basis of one or two climate variables e.g. temperature or precipitation adequately represents the range of future climate projections. Another question addressed in this chapter is whether differences among interpolated baseline climate grids matter when compared to the magnitude of changes projected by general circulation models.

Ultimately we will not need to adapt to a multitude of possible future scenarios, but to locally observed climate trends. In **Chapter 3**, I develop high resolution interpolated surfaces of historical climate data for Western Canada from 1901 to 2006 to investigate the importance of changes in climate change that have already materialized. Recent climate trends over the last 25 years are represented as the difference between the 1961-1990 climate normal period and the most recent decade (1997-2006) for which data was available. I discuss whether observed climate trends over the last 25 years conform with future projections, and I make the case for the use of observed climate trends and observed biological response to these changes in order to decide on the implementation of changes to natural resource management and policies.

**Chapter 4** is the center-piece of this thesis, in which I carry out a systematic evaluation of uncertainty in bioclimate envelope modeling predictions. I use 144 model runs of BEM projections for western Canada biome and species suitable habitat for the 2041-2070 normal period hereafter referred to as the 2050s to evaluate how bioclimate envelope model predictions are influenced by modeling method, baseline climate data, selection of predictor variables, general circulation models and emission scenarios. Modeled changes to ecosystem and species suitable habitat were evaluated as dependent variables in a complete factorial design where the sources of uncertainty were represented as treatments. The relative contribution of each of factor to total uncertainty was evaluated in four case-study type queries that investigate the elevation shift of subalpine forest habitat in British Columbia, latitudinal shifts of grassland – boreal forest transitional habitat in Saskatchewan, and boreal forest habitat loss in northern Alberta. The last case study of this chapter partitions variation in predictions trembling aspen habitat for an Alberta forest management area.

Assisted migration has been promoted as one of the options of ensuring that planted forests are adapted to future climate (O'Neill et al. 2008), and results of bioclimate envelope modeling be used for this purpose. However once the models show that projected climate in an area is suitable for a given species, an important question remains, which genotypes of that species should be used in reforestation. In **Chapter 5**, I address the question of choosing locally adapted planting stock once the species choice has been made. Genotypes of trembling aspen (*Populus tremuloides*) in western Canada are represented by seedzones, and I model habitat shifts corresponding to these seedzones under projected climate. Recommendations of aspen seed deployment are then made on the basis of a majority vote of the most appropriate seedzone under a variety of climate change scenarios.

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# Chapter 2. Selecting baseline and projected climate data for bioclimate envelope modeling


## Summary

Bioclimate envelope models rely on species census data together with current and projected climate data to make spatial predictions of species habitat. In this chapter, I test the suitability of various baseline and projected climate databases for bioclimate envelope modeling. I compare three available baseline climate datasets for the 1961-1990 normal period and evaluate the effect of grid resolution and interpolation methods on statistical accuracy and data quality in areas where weather station coverage is sparse. I found that statistical accuracy in areas with good weather station coverage was mainly a function of grid resolution. In contrast, interpolation methods noticeably differed by up to 4°C in mean annual temperature, and up to 10°C in monthly temperature estimates where weather station coverage was lacking. For future projections, I investigate 22 scenarios from general circulation models to determine if “worst case”, “best case” and “median” scenarios can be selected for western Canada with respect to multiple biologically relevant variables. This proved to be difficult because of spatial variability (a “worst case” scenario for one region may be a “median scenario” in another area), and because multiple variables need to be considered (a scenario may be a “worst case” with respect to temperature, but “median” for precipitation). I conclude that a full range of climate change scenarios needs to be considered. Secondly, it was notable that local differences in baseline climate data exceeded all climate change projections for the 2050s and most climate change projections for the 2080s. These differences in baseline climate could be a major potential source of uncertainty in bioclimate envelope model projections that has rarely been investigated.

## 2.1. Introduction

Bioclimate envelope models rely on species census data as well as current and projected climate data to make spatial predictions of species habitat (Botkin et al. 2007; Hijmans and Graham 2006; Pearson and Dawson 2003). Climate data (both current data and projections for the future) comprise an important part in modeling potential climate change impact on species. Baseline climate data serve as the reference point for describing climate change. The commonly used reference point is the 1961-1990 period, also referred to as a 30-year climate normal. Data from this period can be combined with climate change projections to create climate projections for future 30-year normal periods. The 1961-1990 normal is the preferred reference period for changes over the course of the 21$^{st}$ century for a number of reasons. First, the 1961 to 1990 period has the very good global weather station coverage, there was a steady increase in the number of weather stations up to the 1990s and a reduction thereafter. Secondly, it is the period recommended by the IPCC for use in creating future climate scenarios. In addition, the 1961-1990 represents a period of relatively stable climate with a major warming trend starting in the early 1990s.

Climate surfaces of 30-year normals are usually created from weather station data using a variety of interpolation techniques, including nearest neighbor and inverse distance weighting for simple datasets (Jones et al. 1986; Milewska et al. 2005); kriging (Cressie 1993), neural networks (Attorre et al. 2007), thin plate splines (Hutchinson 1995; Hutchinson and Gessler 1994); or parameter-elevation regressions on independent slopes model – PRISM (Daly et al. 1994; Daly et al. 2002). With several interpolation techniques available, the best method is often based on how well interpolation methods perform in terms of explaining variation in observed weather station data (Hofstra et al. 2008). Generally, no interpolation method is optimal for all situations (Attorre et al. 2007), although the parameter-elevation regressions on independent slopes model appears to perform well under a large variety of landscapes and for both temperature and precipitation variables (Daly 2006). Daly (2006), however, also cautions that all interpolation methods are essentially restricted to modeling macroclimatic patterns, such as temperature gradients along mountain slopes, or orographic rainfall patterns along mountain ranges. Interpolation techniques have yet to incorporate small scale climatic phenomena that become relevant at fine resolution (≤1km).

Future climate projections are typically generated by general circulation models (GCMs) at very coarse resolution, usually at grid cells of several hundred kilometers, requiring downscaling before they can be used regionally or locally. GCMs simulate the global climate by calculating hour-by-hour three dimensional evolution of the atmosphere based on the physical laws for atmospheric mass, momentum, total energy, and the effects of various atmospheric components such as water vapor (Randall et al. 2007). GCMs are realized on the basis of greenhouse gas emission scenarios. Emission scenarios are alternative representations of the future, also referred to as “story lines” of potential population growth and economic development and corresponding levels of greenhouse gases in the atmosphere (Nakicenovic et al. 2000).

Future climate projections by different modeling groups are highly variable (Stainforth et al. 2005). Variation in projections arises from unknowns in the climate system and difficulty in accurately representing highly unpredictable variables such as precipitation (Bonsal et al. 2003; CCSP 2008; Willett et al. 2007). How future climate projections are represented locally and regionally is of importance in modeling potential changes to species and ecosystem habitats under future climate. Given the large number of available climate change projections generated by different GCMs under various emission scenarios, it is common for biological researchers or resource managers to select one or a few projections of future climate to use as the basis for predictive modeling.

In this study I compare three interpolated baseline climate datasets; one by the parameter-elevation regressions on independent slopes model (PRISM) and two developed using thin-plate spline interpolation one based on latitude longitude and elevation (ANUSPLIN), and the other, the CRU 2.1 developed at 0.5 degree grids covering the globe for only latitude and longitude (Mitchell and Jones 2005). The climate grids are evaluated against weather station dataset that meet the quality standards of the World Meteorological Organization (WMO). Regarding baseline climate data the study attempts to answer two questions: which interpolation method is most appropriate to generate baseline climate data for western Canada, and what is the appropriate resolution? Secondly, the study evaluates 22 climate change projections from 8 general circulation models and 4 emission scenarios for western Canada. I calculate projections for biologically relevant climate variables for each scenario that may be used to select “optimistic”, “pessimistic” or “median” projections for a particular purpose and location. To simplify subsequent bioclimate envelope modeling tasks, I also investigate if climate change scenarios can be identified that can generally be described as “optimistic”, “pessimistic” or “median” for the western Canada study area, where a “pessimistic” scenario would have comparatively high temperature and low precipitation projections throughout the year and over the entire study area.

## 2.2. Methods

### *2.2.1. Baseline climate grids*

Three 1961 - 1990 baseline climate datasets that are publicly available for western Canada were compared. The first dataset evaluated was developed by the parameter - elevation regressions on independent slopes model (PRISM), which is a knowledge-based climate mapping system that uses point data and a digital elevation model (DEM) to generate gridded estimates of climate parameters (Daly et al. 1994; Daly et al. 2002). The model involves dividing areas into “facets” defined by topographic barriers that influence climate based on the assumption that topography is the most important factor determining the distribution of temperature and precipitation (Daly et al. 2000). Within each facet, the model computes a linear climate-elevation relationship using simple regression, assigning higher weight to stations within the same topographic “facet”. The method is best suited for generating climate data in regions with significant terrain features and coastal influence, temperature inversions, rain shadows or cold air drainage, which are otherwise difficult to map accurately (Daly 2006b; Hijmans et al. 2005). PRISM is also called an expert system because it relies on knowledge of local climate phenomena in defining "facets". This method has been used to generate temperature, precipitation and other climate variables for Unites States, Canada and several other countries (Daly et al. 2000).

The second and third datasets were developed using thin-plate spline interpolation. Thin plate smoothing splines is a generalization of standard multivariate linear regression replacing the parametric models with a suitably smoothing function (Hutchinson 2004). The interpolation works by fitting a statistically smoothed surface to weather station data as a function of one or more independent variables i.e. latitude, longitude and elevation (Hutchinson 1995; McKenney et al. 2006). One of these datasets (hereafter referred to as ANUSPLIN) was developed using latitude, longitude and as well as elevation at a 30 arcsecond resolution (Rehfeldt 2006). The last dataset was part of a global dataset-CRU TS 2.1 developed by thin spline interpolation based on only latitude and longitude (Mitchell and Jones 2005). The data contains monthly minimum and maximum temperature and precipitation available at 0.5° resolution. Development of the CRU data involved using an automated method to fill missing station data by correlating neighboring stations, enabling the generation of data from a relatively higher number of weather stations (New et al. 1999).

### *2.2.2. Calculating biologically relevant climate variables*

Climate data was available as monthly maximum and minimum temperature and monthly precipitation. From these, biologically relevant climate variables were calculated. Annual variables include: mean annual temperature (MAT), mean warmest month temperatures (MWMT), mean coldest month temperatures (MCMT), temperature difference between MWMT and MCMT (TD – a measure of continentality), mean annual precipitation (MAP), mean summer precipitation (MSP – the sum of monthly precipitation from May through September), an annual heat moisture index (AHM – calculated as a temperature precipitation ratio (MAT + 10)/(MAP × 1000)) and a summer heat moisture index (SHM – calculated as MWMT/(MSP × 1000)). Other variables included the extreme minimum temperature recorded at a weather station over a 30 year period, number of frost free days and several growing and chilling degree days, as described by Wang et al (2006). Degree days represent an accumulated temperature sum of a mean daily temperature value above or below a predefined threshold temperature. Examples are chilling degree days (below 0°C) and growing degree days (above 5°C).

### *2.2.3. Future climate projections*

Surfaces of future climate were based on data generated by various climate modeling groups implementing the SRES and the newer AR4 emission and population growth scenarios (A1FI, A2, B1, B2), recommended by the Intergovernmental Panel for Climate Change (Nakicenovic et al. 2000): A1 represents a trend of globalization, resource-intensive economic growth, and rapid population increase, A2 assumes slower population growth and regionally fragmented economic growth, B1 assumes the same global population growth as A1, but a shift towards a service and information economy, and B2 represents the lowest population increases and local, environmentally sustainable economies.

I used implementation of these scenarios by 5 general circulation models for the 2011-2040, 2041-2070, and the 2071-2100 normal periods. Hereafter, I refer to these periods as 2020s, 2050s and 2080s. The 5 GCMs are the second generation Canadian model-CGCM2 (Flato et al. 2000), the Australian model-CSIRO2 (Watterson et al. 1995), ECHAM4 from Europe (Roeckner 1996), the third generation model HADCM3 of the Hadley Climate Center, United Kingdom (Johns et al. 2003), and the Parallel Climate Model, PCM from the US (Washington et al. 2000). In addition to runs for the four scenario families A1FI, A2, B1 and B2 the evaluation, more recent individual model runs based on IPCC's fourth assessment report -AR4 that is BCM2-A2, CGCM3-A2, MIROC-HIRES-B1, and MIROC-MEDRES-A2) were included.

### *2.2.4. Evaluating the quality of interpolated climate data*

A relative evaluation of the three normal climate grids was performed using weather station data from weather stations in western Canada. Weather stations used in the evaluation of interpolated data were also used in the development of all interpolated grids. Therefore, the evaluation is not an independent validation of the interpolated climate datasets and is strictly interpreted in terms of a relative comparison of statistical accuracy.

Weather station data for the 1961-1990 normal period were acquired from the Adjusted Historical Canadian Climate Database-AHCCD (Mekis and Hogg 1999; Vincent and Gullett 1999; Vincent and Mekis 2006) as mean monthly minimum, maximum and mean temperature and monthly precipitation for individual years. I used a total of 218 weather stations for precipitation and 84 for temperature that had virtually complete data for the 1961-1990 period and meet the quality standards of the World Meteorological Organization for calculating climate normals (the location of these stations is shown in Figure 2-1). Gridded climate datasets were evaluated using five representative climate variables namely, mean annual temperature, mean warmest month temperature, mean coldest month temperature, mean annual precipitation and mean summer precipitation for the 1961-1990 period.

First, I evaluated how well interpolated normal surfaces account for variance explained ($R^2$) in original weather station data. $R^2$ is a useful measure for this comparison because it quantifies the statistical precision of the estimate. Additionally, I also calculated the mean average error (using absolute values instead of sums of squares) to obtain an estimate of typical deviations in units of degree Celsius and millimeters precipitation. $R^2$ and mean average error (MAE) were computed between observed weather station locations and the CRU, ANUSPLIN and PRISM climate grids. Climate surfaces were also mapped for a visual comparison of the behavior of interpolation methods outside weather station coverage.

### *2.2.5. Visualizing regional and spatial variability in future climate projections*

To evaluate spatial variability in future climate projections for western Canada, scatter plots were generated to summarize projected change (expressed as anomalies from 1961-1990 normals) for a representative set of biologically relevant climate variables. These included mean annual temperature and mean annual precipitation, degree days above 5°C and mean summer (May-September) precipitation, projected precipitation as snow and degree days below 0°C and continentality or difference between warmest and coldest month temperature (temperature difference) and annual heat moisture index. Scatter plots were generated for two major western Canadian biomes: the boreal forest and the prairies. For a more detailed regional comparison, anomalies were mapped for western Canada using a representative selection of annual and seasonal climate variables. These included, mean annual temperature and precipitation, as well as mean winter (December, January and February), spring (March, April and May), summer (June, July and August) and fall (September, October and November) temperature and precipitation.

## 2.3. Results

### *2.3.1. Comparison of interpolated climate surfaces*

Climate grids from PRISM and ANUSPLIN appear to be of similar quality, providing near identical $R^2$ values between observed and interpolated climate data (Table 2-1). Similarly, mean absolute errors are in the same range (Table 2-1). In contrast, the low resolution CRU dataset exhibits lower $R^2$ values and higher mean average errors.

In addition to evaluating statistical accuracy, I compare the mapped climate grids (Figure 2-2 and 2-3). Since the CRU dataset uses the same interpolation technique as ANUSPLIN behaving similarly in areas outside of weather station coverage (data not shown) maps of CRU data are not presented here. Notably, I find distinct differences among PRISM and ANUSPLIN surfaces for the climate variable mean coldest month temperature in the northeast of the study area (Figure 2-2) and precipitation at high elevation in the Rocky Mountains and the coast mountain ranges of British Columbia. For a better comparison, differences between the ANUSPLIN surfaces and PRISM surfaces are mapped in Figures 2-4 and 2-5. The most pronounced regional differences up to 4° C in mean annual temperature are found in the boreal highlands and subarctic regions of northern Alberta and Saskatchewan (Figure 2-4). These differences are driven by winter temperature values that are up to 10°C warmer in the ANUSPLIN dataset than in the PRISM dataset (Figure 2-5). Precipitation differences are most pronounced at high elevation, with the PRISM dataset mean annual precipitation estimates regularly exceeding the ANUSPLIN estimates by 1000mm or more on the coast, and 400mm or more in the Rocky Mountains.

### *2.3.2. Future climate projections for western Canada*

Projected climate change for western Canada shows interesting patterns across western Canada (Figures 2-6 to 2-10). Projections for changes in mean annual temperature by the 2050s are relatively uniform, generally showing more warming for the interior than the coast, and some models showing a weak trend towards more warming in the north (Figure 2-6). The degree of warming is also clearly a function of the emission scenarios with the more pessimistic storylines (A1F1 and A2) leading to higher warming projections that the optimistic resource use and population growth story lines (B1 and B2). In contrast, projected changes in mean annual precipitation are idiosyncratic for each model and show high spatial variability (Figure 2-6,). Variability is more pronounced in the different seasons with the summer drier for most scenarios (Figure 2-9 and 2-10). There is a general trend towards more precipitation on the west coast and the north east most of if occurring during winter and fall.

Next, I am looking at a larger range of variables in the form of regional summaries for the prairie and boreal forest regions of western Canada (Figure 2-11 to 2-14). A consistent and expected trend that can be observed across all variables is that uncertainty increases the further into the future predictions are made. As pointed out in the previous section, climate scenarios that project the largest changes in temperature or precipitation in one region do not necessarily do the same in other regions. For instance, the PCM-A1FI scenario which predicts the largest changes in precipitation for the prairies has moderate precipitation changes for the boreal (Figure 2-11). Projections also vary with respect to biological variables of interest: assuming that higher summer precipitation combined with more growing degree days could be viewed as an “optimistic” scenario, there is clearly no easy answer which of the scenarios would be an appropriate representation (Figure 2-12). Another dimension to the variability in projected changes in climate are rank changes in future projections. For example, the MEDRES-A2 scenario predicts the largest changes in annual heat moisture index for the 2020s, but has approximately median projections for the 2080s (Figure 2-14).

## 2.4. Discussion

### *2.4.1. Choice of baseline climate*

Interestingly, a statistical evaluation of different interpolation methods could not reveal major difference between the two high resolution ANUSPLIN and PRISM baseline datasets (although a data quality reduction due to the low resolution used by the CRU dataset was apparent). The differences among the PRISM and ANUSPLIN climate surfaces are restricted to areas of sparse or no weather station coverage (compare Figures 2-1 and 2-4), with surfaces behaving differently primarily in high elevation and remote northern areas. With no data available for validation, an educated guess has to be made about which model behavior outside weather station coverage appears more reasonable. PRISM surfaces indicate winter temperature inversions with warmer temperatures on the high plateaus of northern Alberta than the surrounding lowlands. However, ecosystem classifications and predictive ecosystem models (Schneider et al 2009) indicate harsher winter environments on these high plateaus, so I think that the ANUSPLIN may behave more realistically in this case.

It is not easy to tell which model behaves more realistically at high elevation in the Rocky Mountains with respect to precipitation estimates. It appears logical that ANUSPLIN fails to model precipitation in the southern Coast Mountains correctly because it interpolates weather station data between the dry Coast Mountains and the relatively dry Georgia Depression that is in the rain shadow of Vancouver Island. In contrast, PRISM should correctly account for orographic precipitation and rain shadows in this area, which are incorporated in the model (Daly 2006).

These results provide a sense how the quality of climate variable estimates for regions with poor weather station coverage deteriorate, indicated by how different interpolation techniques behave in these areas. I would also like to emphasize that besides statistical accuracy, model behavior outside weather station coverage is an important factor that should be considered when evaluating interpolation methods. Do errors in baseline climate grids matter for bioclimate envelope modeling? Baseline climate is used to calibrate predictive models and regional deviations that exceed all climate change projections for the 2050s and most climate change projections for the 2080s could be a major source of errors. While the effect of different climate change projections is routinely evaluated in bioclimate envelope projections, I think that the quality of climate baseline data could be an important factor influencing the projections of bioclimate envelope models.

### *2.4.2. Choice of future climate projections*

For practical reasons, it is common to select “worst case”, “best case”, and “median” to predict potential impacts of climate change. Scatter plots of projections from general circulation models for multiple variables show that it is probably impossible to determine “worst case” or “best case” scenarios, except for local studies with a clearly defined objective. For example, if loss of snow-cover in winter is a major concern for a wildlife management application, “worst case” and “best case” scenarios may be quite easily be determined. However, for bioclimate envelope modeling studies that almost always involve large geographic regions, I think that a full suite of climate change scenarios needs to be implemented to arrive at a corresponding range of biological predictions that represent “worst case” and “best case” outcomes. While most climate projections conform for the 2020s, evaluating a comprehensive suite of climate change scenarios becomes more important the further into the future predictions are made.

Table 2-1. $R^2$ and average deviation (in parentheses) between observed station data with CRU, ANUSPLIN and PRISM interpolated climate data for western Canada for the 1961-1990 period.

| Climate Variable | $R^2$ (mean absolute error) | | |
|---|---|---|---|
| | CRU | ANUSPLIN | PRISM |
| Mean annual temperature | 0.70 *(0.7°C)* | 0.97 *(0.3°C)* | 0.95 *(0.3°C)* |
| Mean Jul temperature | 0.74 *(1.1°C)* | 0.94 *(0.3°C)* | 0.93 *(0.3°C)* |
| Mean Jan temperature | 0.94 *(0.9°C)* | 0.98 *(0.5°C)* | 0.97 *(0.6°C)* |
| Mean annual precipitation | 0.78 *(41mm)* | 0.90 *(37mm)* | 0.93 *(35mm)* |
| Mean May-Sep precipitation | 0.67 *(23mm)* | 0.95 *(19mm)* | 0.97 *(19mm)* |

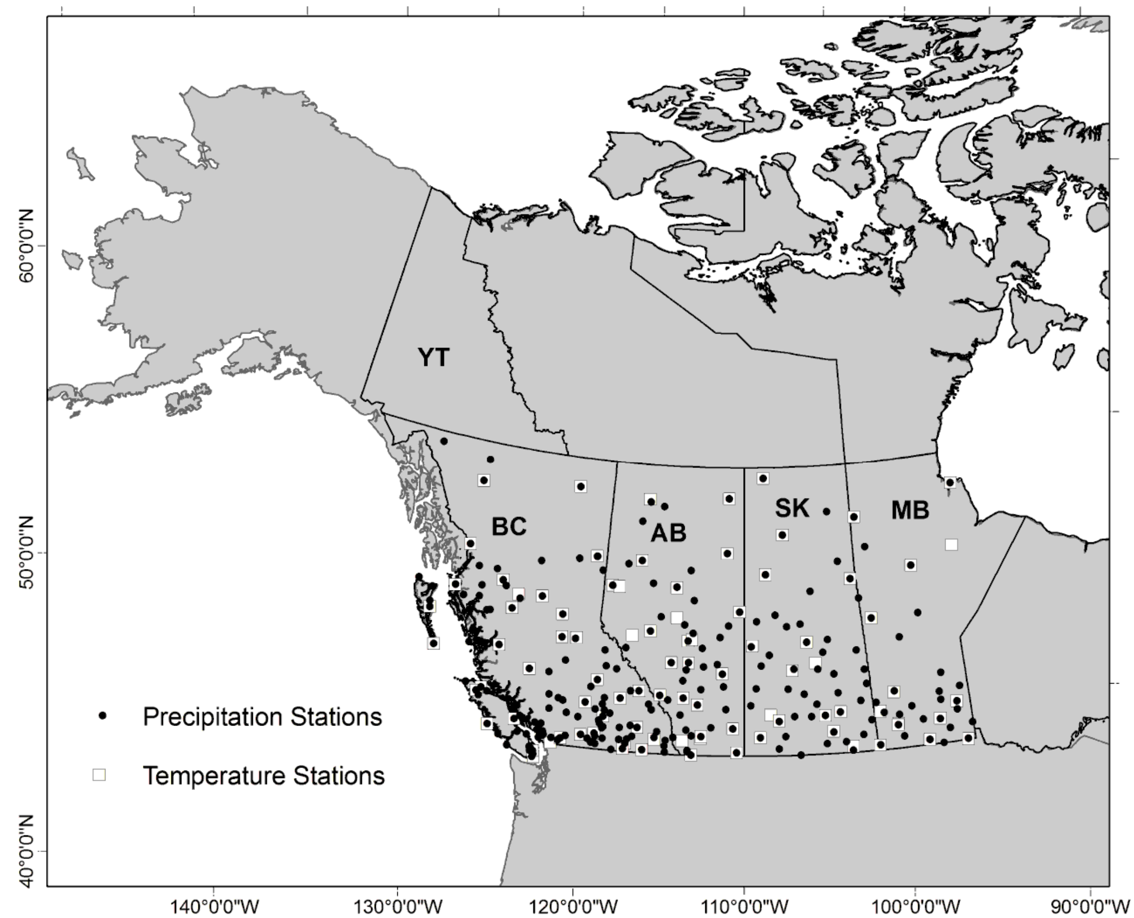


Figure 2-1. Location of weather stations used in the evaluation of western Canada (British Columbia-BC, Alberta-AB, Saskatchewan -SK and Manitoba-MN) 1961-1990 climate normals generated by CRU, ANUSPLIN and PRISM interpolation techniques.

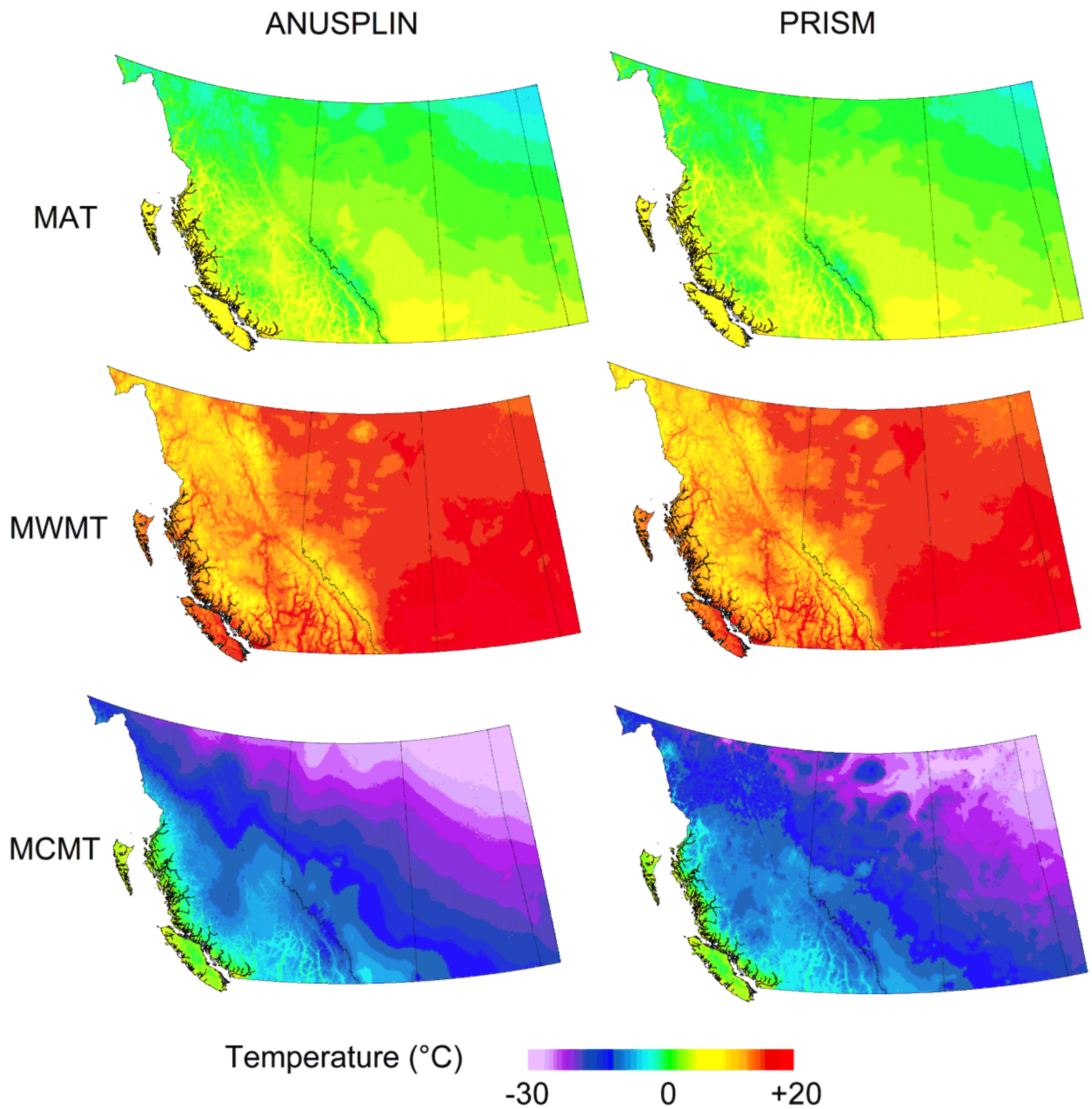


Figure 2-2. Western Canada 1961-1990 normal mean annual temperature-MAT, mean July temperature-MWMT and mean January temperature-MCMT grids based on ANUSPLIN and PRISM interpolation techniques.

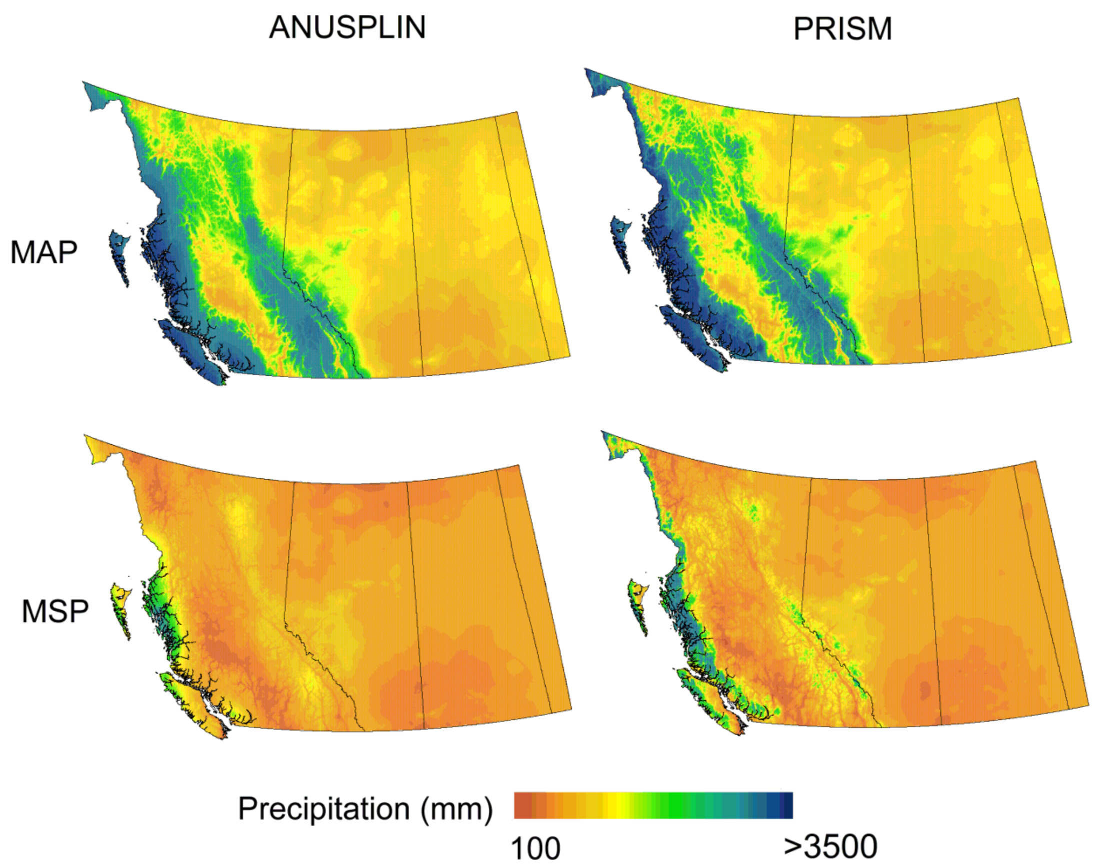


Figure 2-3. Western Canada 1961-1990 normal mean annual precipitation-MAP and mean summer (May to September) precipitation-MSP grids based on ANUSPLIN and PRISM interpolation techniques.

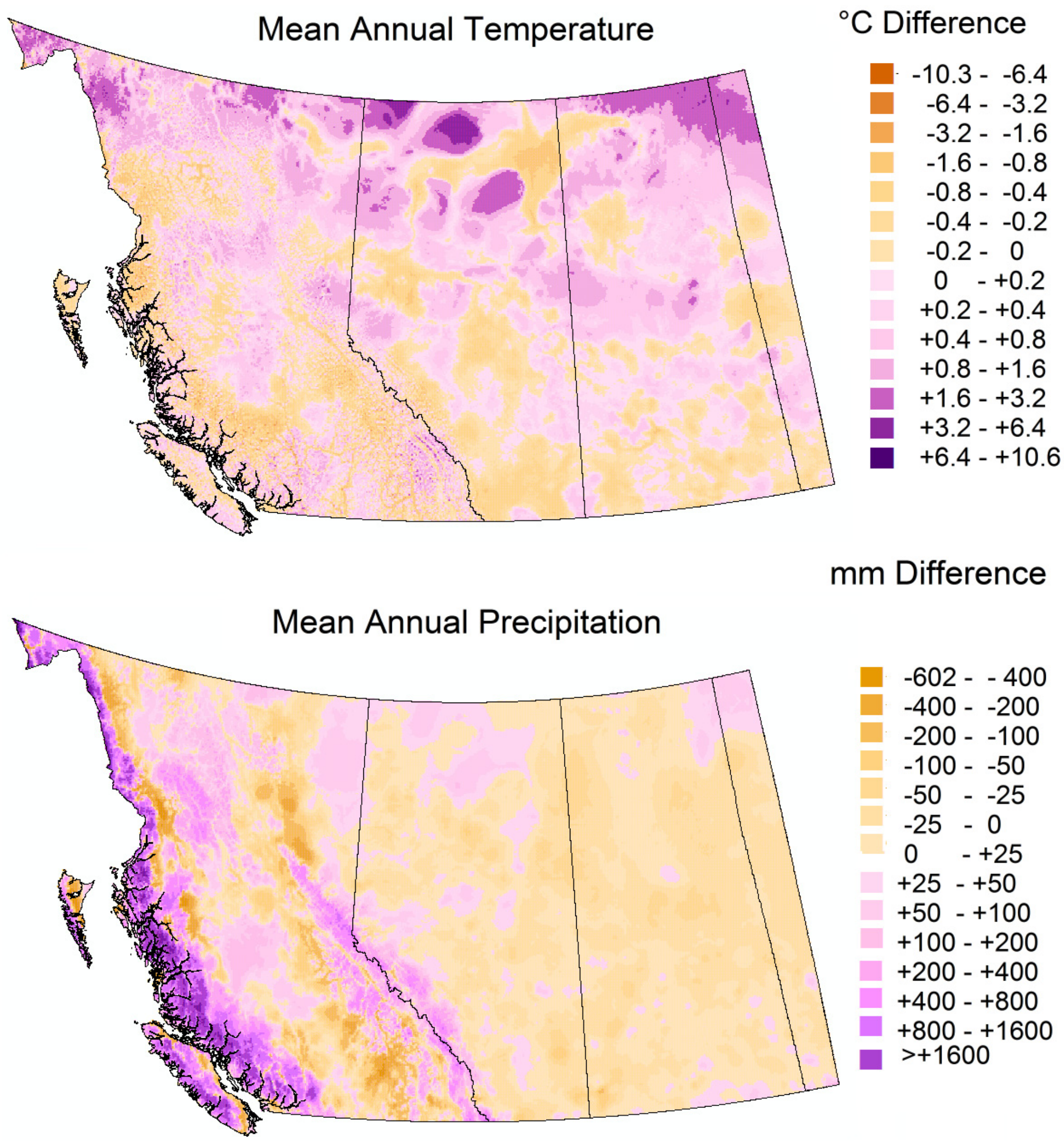


Figure 2-4. Difference between ANUSPLIN and PRISM 1961-1990 normals for western Canada for mean annual temperature and mean annual precipitation.

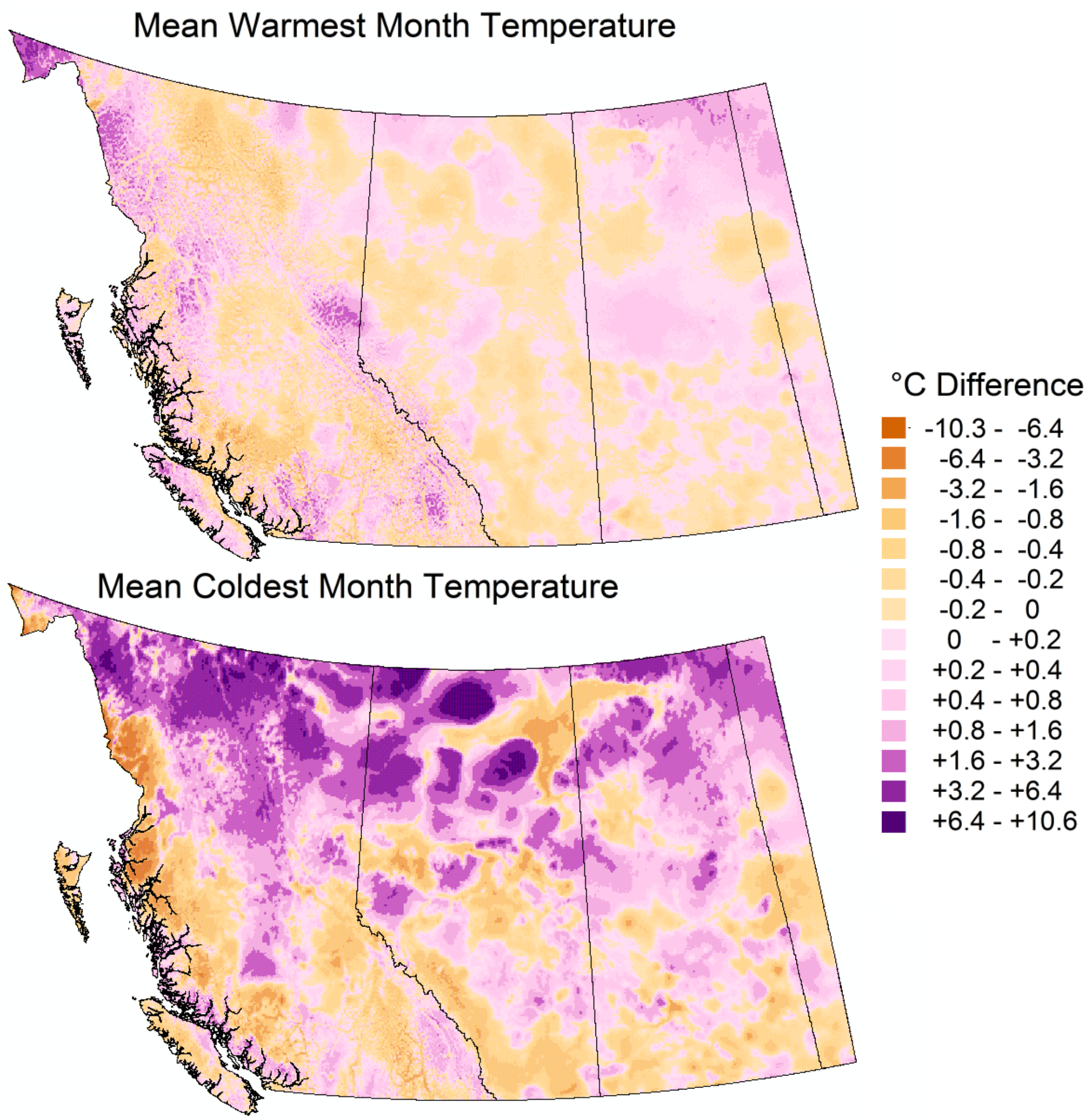


Figure 2-5. Difference between ANUSPLIN and PRISM 1961-1990 normals for western Canada for mean July and mean January temperature.

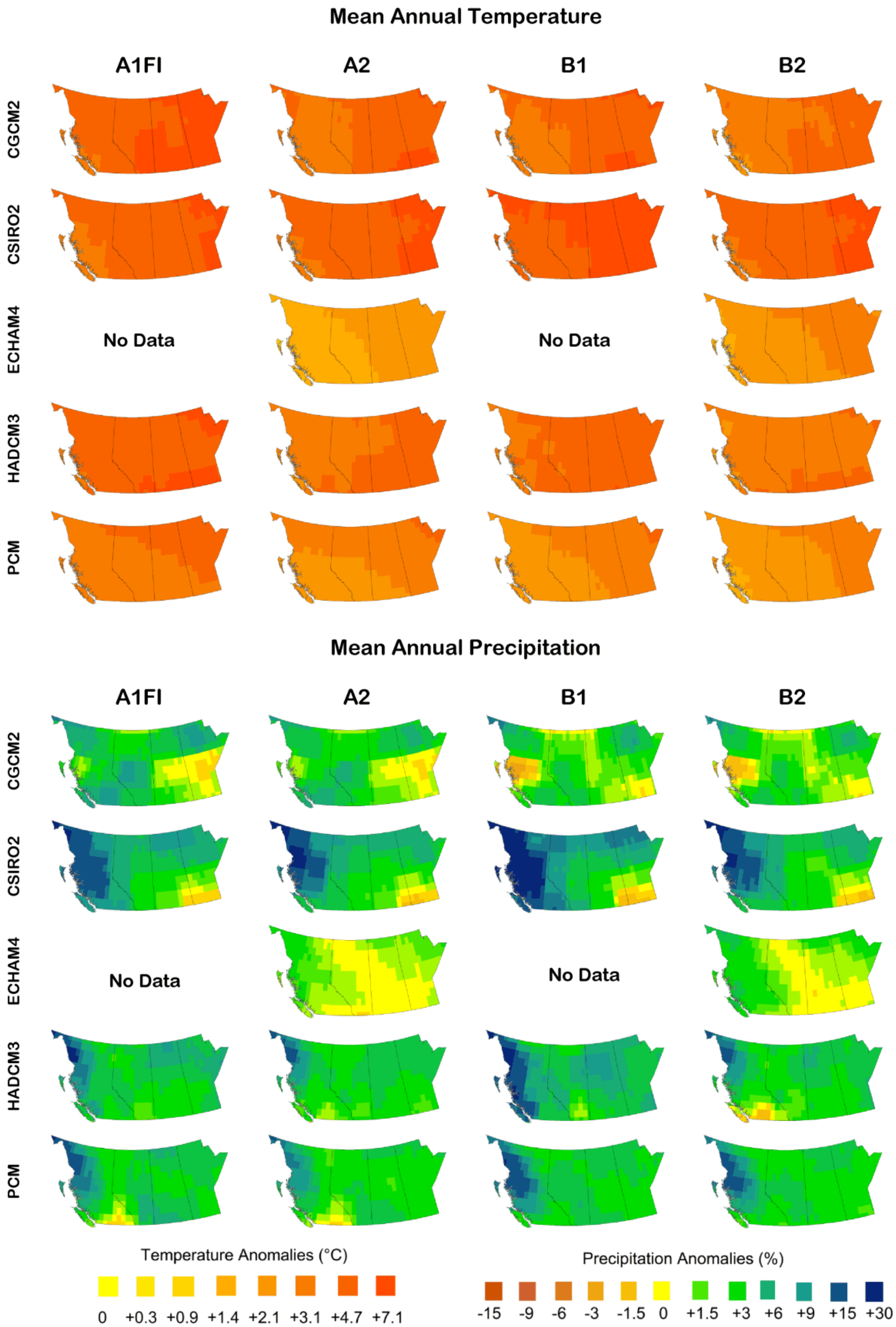


Figure 2-6. Projected 2050s mean annual temperature and mean annual precipitation anomalies for western Canada from five GCMs (CGCM2, CSIRO2, ECHAM4, HADCM3 and PCM) for four emission scenarios (A1FI, A2, B1 and B2).

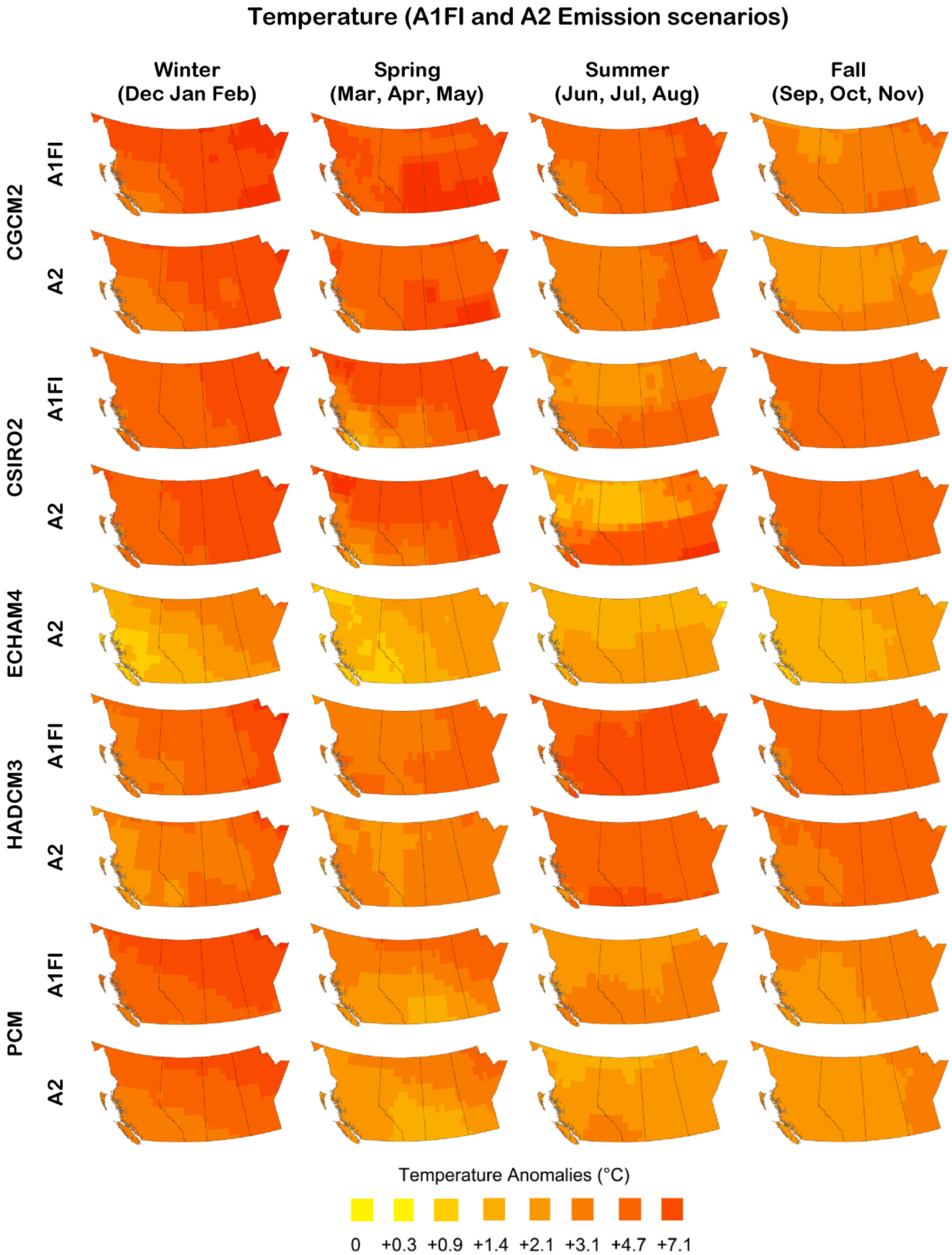


Figure 2-7. Projected mean seasonal 2050s temperature anomalies expressed in degree Celsius for western Canada for two emission scenarios (A1FI and A2) realized by five general circulation models -GCMs (CGCM2, CSIRO2, ECHAM4, HADCM3 and PCM).

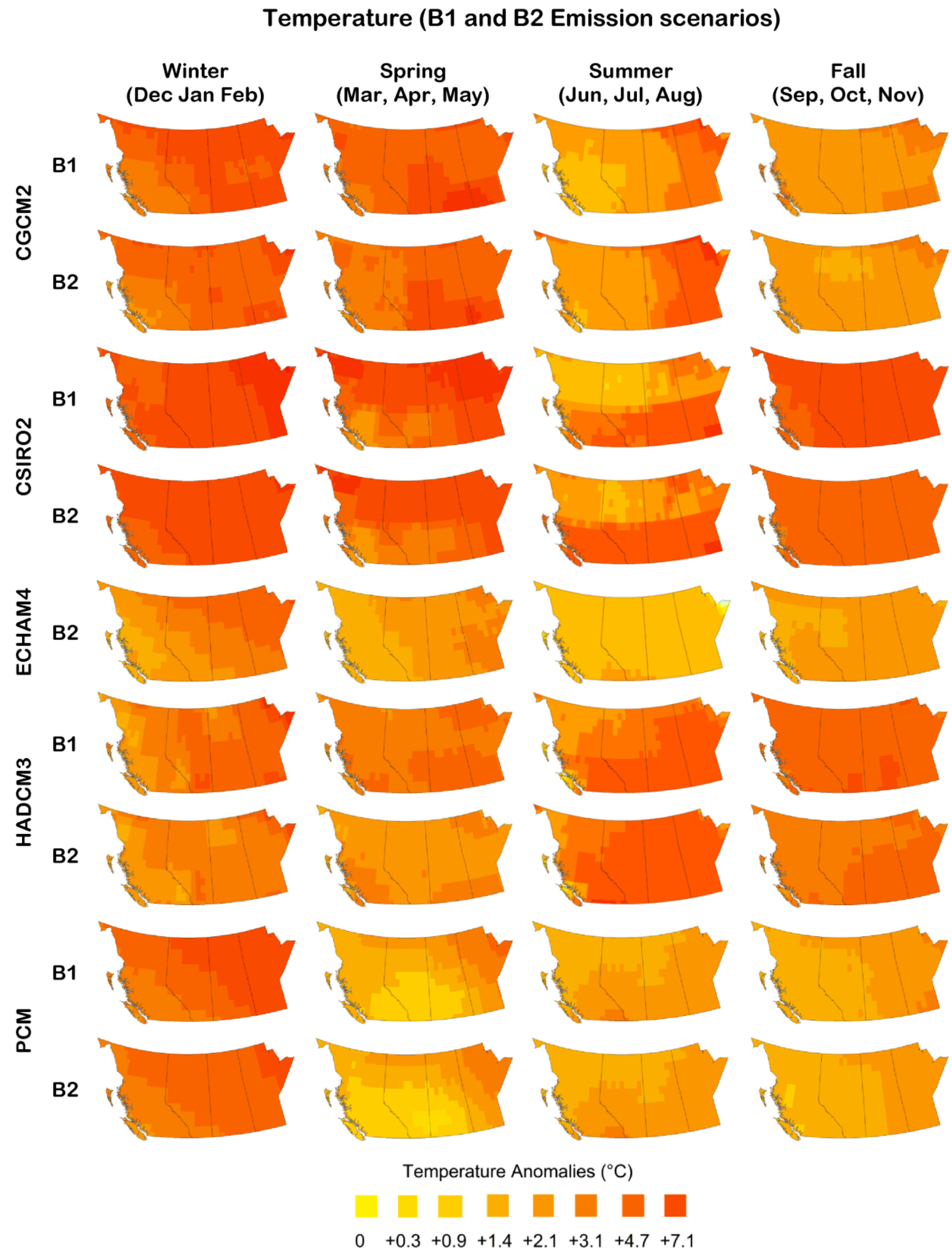


Figure 2-8. Projected mean seasonal 2050s temperature anomalies expressed in degrees Celsius for western Canada for two emission scenarios (B1 and B2) realized by five general circulation models-GCMs (CGCM2, CSIRO2, ECHAM4, HADCM3 and PCM).

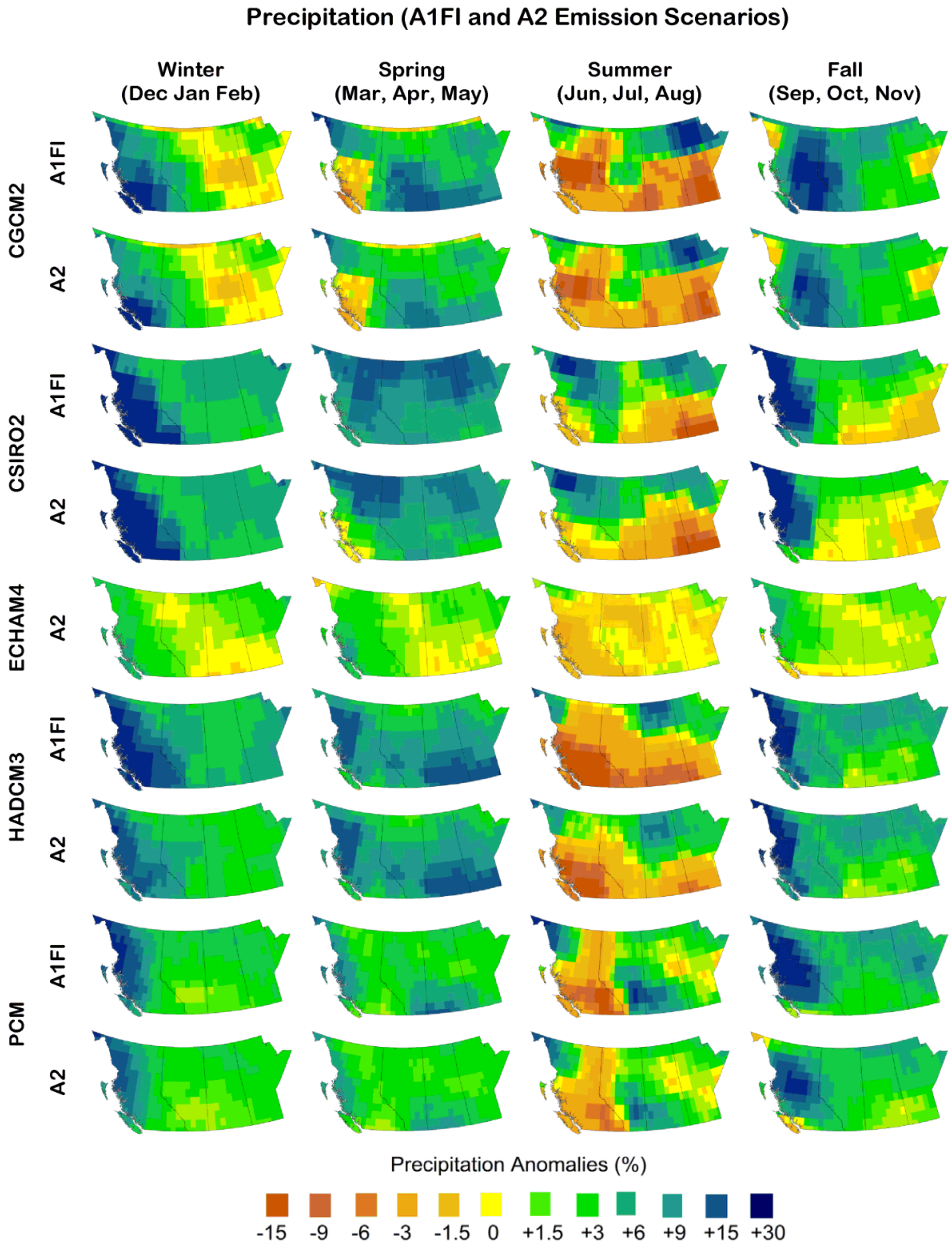


Figure 2-9. Projected mean seasonal precipitation 2050s anomalies expressed as percent change for western Canada for two emission scenarios (A1FI and A2) realized by five general circulation models-GCMs (CGCM2, CSIRO2, ECHAM, HADCM3 and PCM).

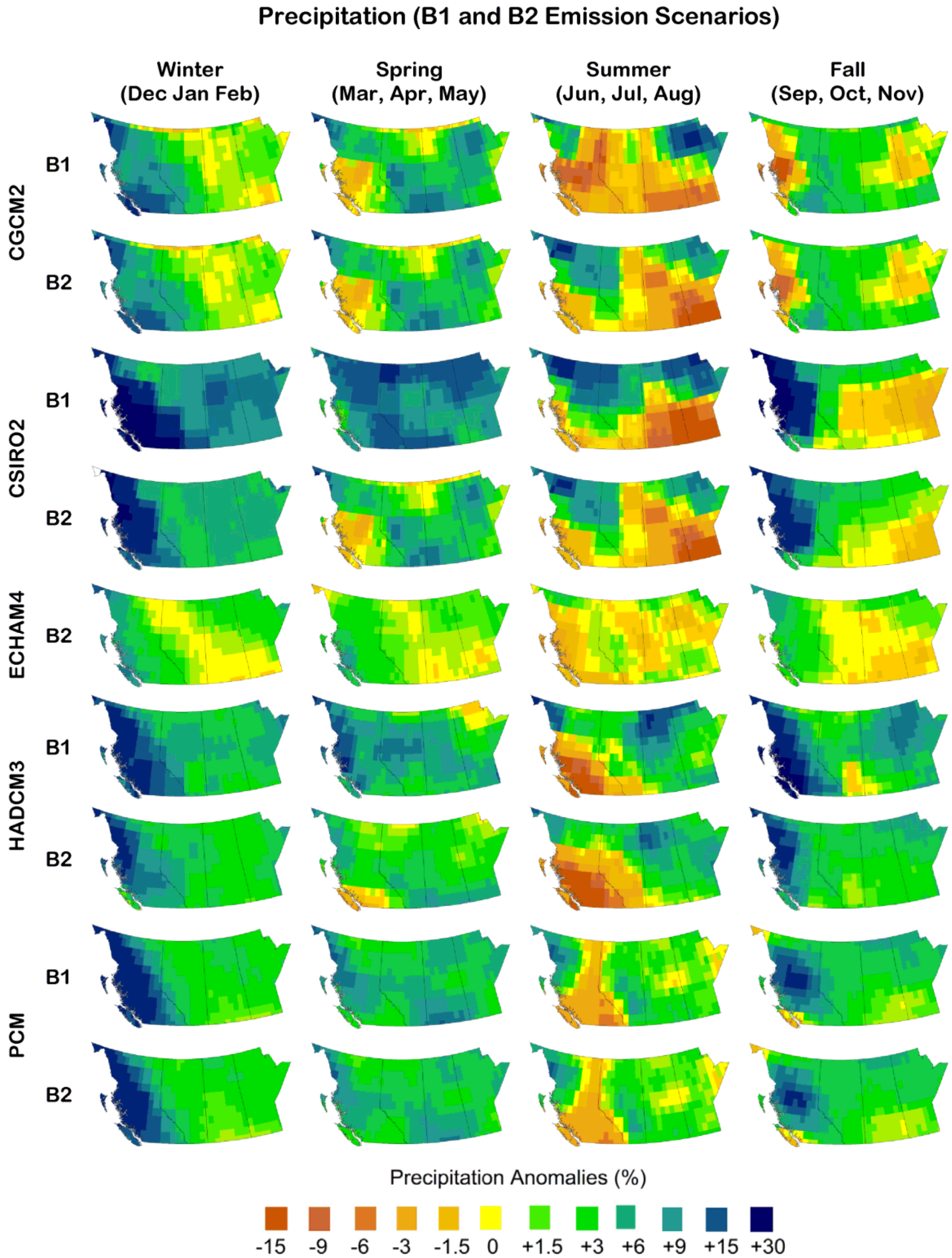


Figure 2-10. Projected mean seasonal precipitation 2050s anomalies expressed as percent change for western Canada for two emission scenarios (B1 and B2) realized by five general circulation models-GCMs (CGCM2, CSIRO2, ECHAM, HADCM3 and PCM).

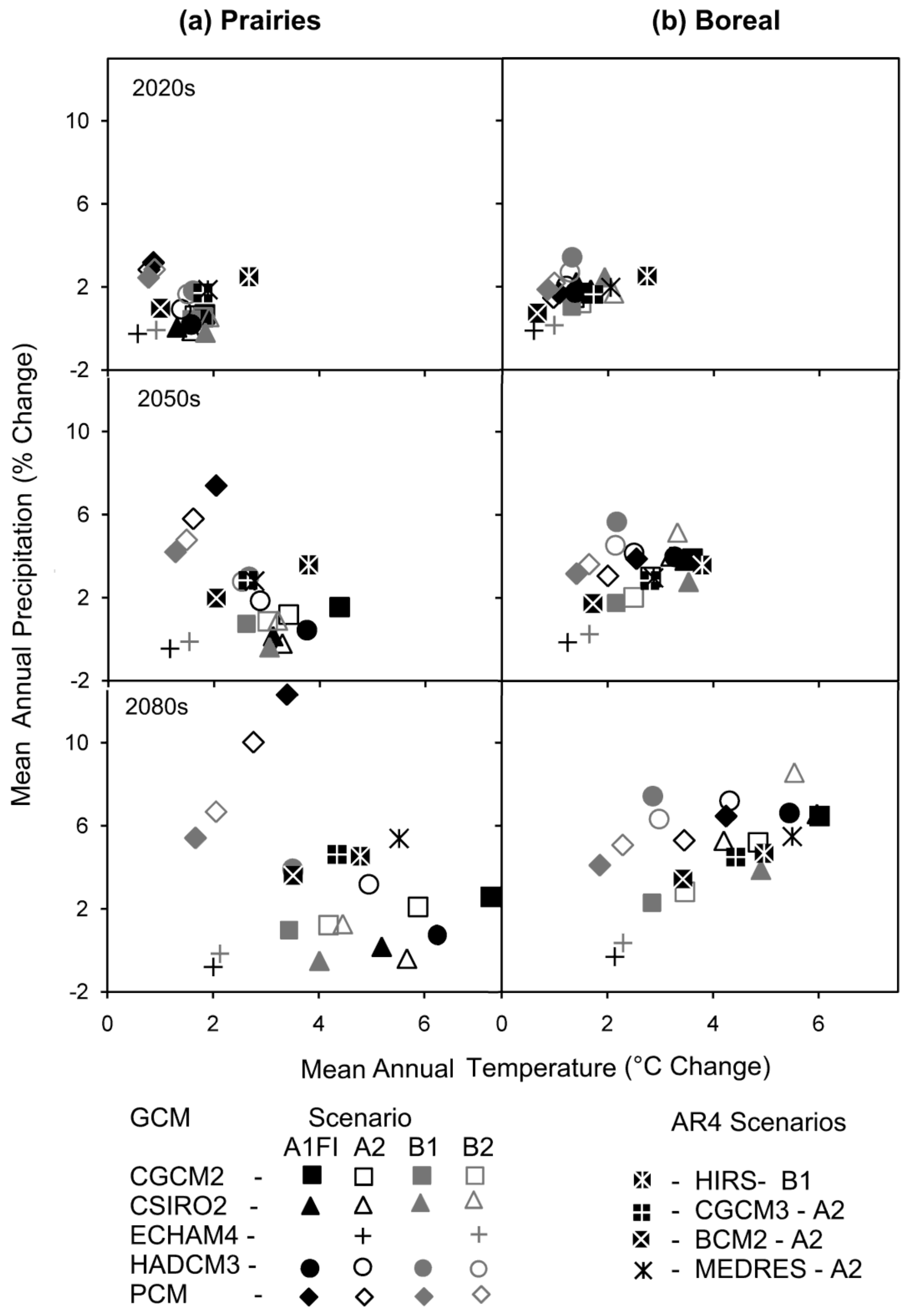


Figure 2-11. Relative change in projected mean annual temperature and mean annual precipitation for Prairies (A) and the southern Boreal (B) western Canada biomes based on ensemble runs of 4 SRES scenario families and 5 general circulation models, as well as 4 individual model runs selected from the IPCC's Fourth Assessment Report (AR4) for the 2020s, 2050s and the 2080s.

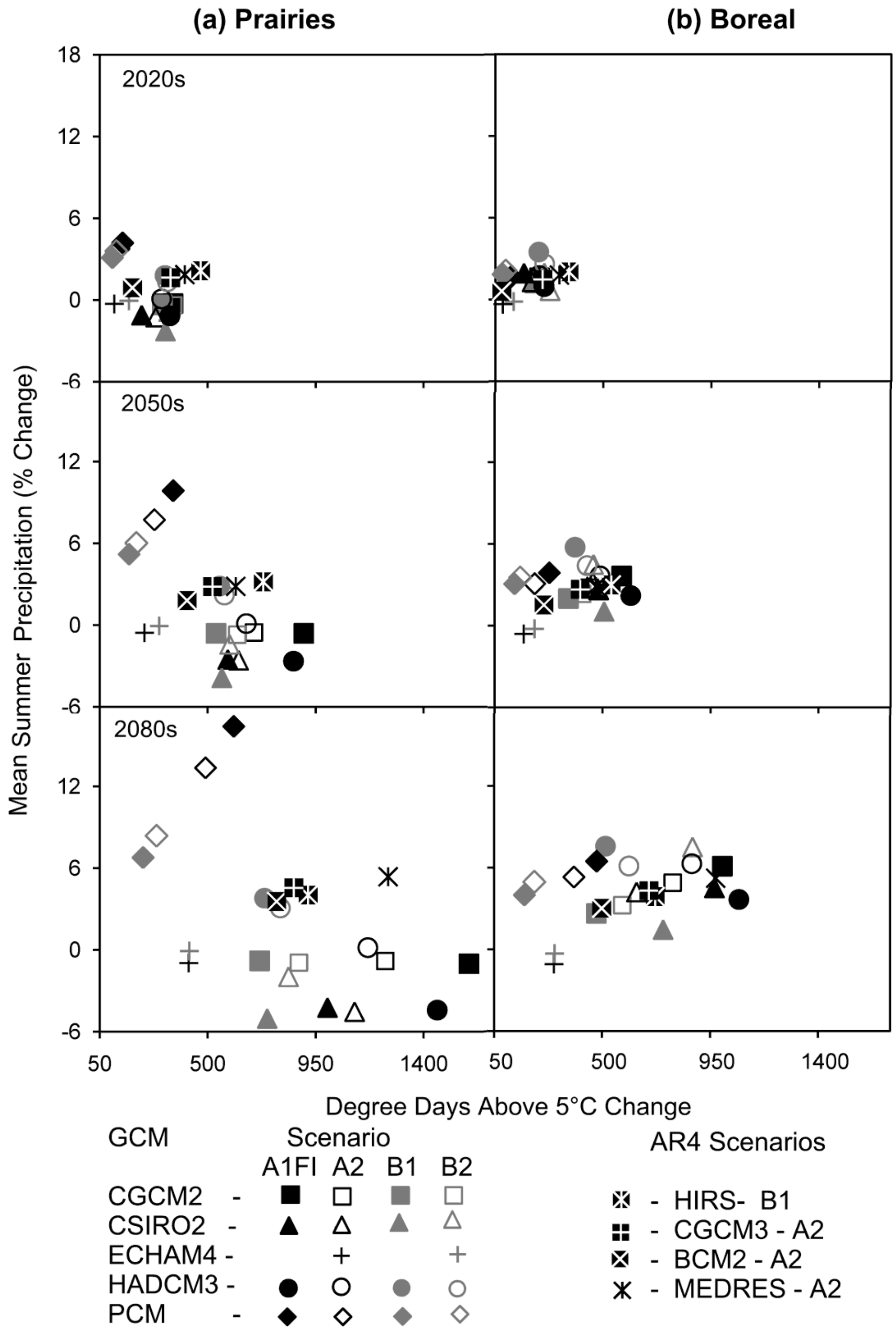


Figure 2-12. Relative change in projected degree days above 5°C and mean summer (May-September) precipitation for Prairies (A) and the southern Boreal (B) western Canada biomes based on ensemble runs of 4 SRES scenario families and 5 general circulation models, as well as 4 individual model runs selected from the IPCC's Fourth Assessment Report (AR4) for the 2020s, 2050s and the 2080s.

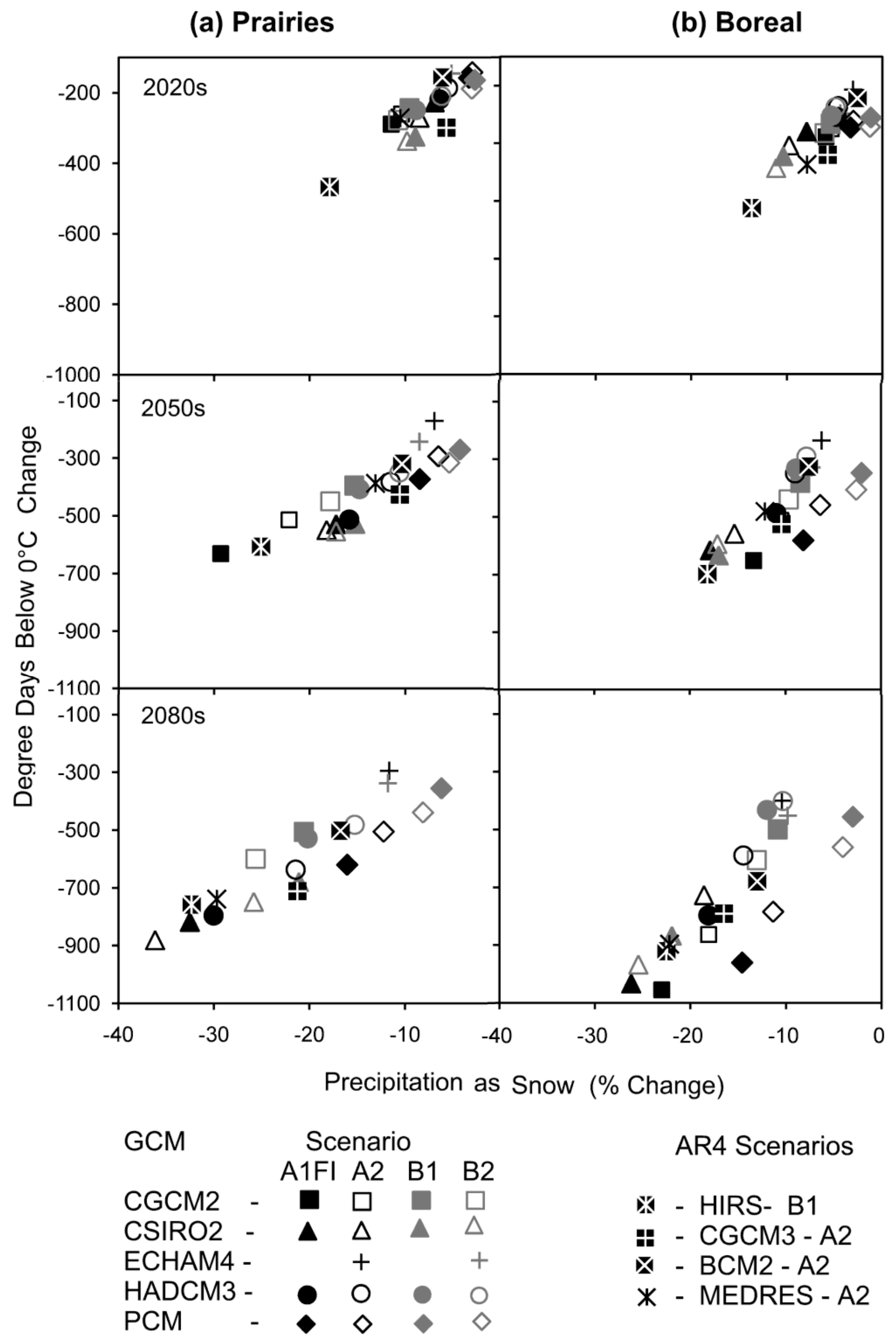


Figure 2-13. Relative change in projected precipitation as snow and degree days below 0°C for Prairies (A) and the southern Boreal (B) western Canada biomes based on ensemble runs of 4 SRES scenario families and 5 general circulation models, as well as 4 individual model runs selected from the IPCC's Fourth assessment Report (AR4) for the 2020s, 2050s and the 2080s.

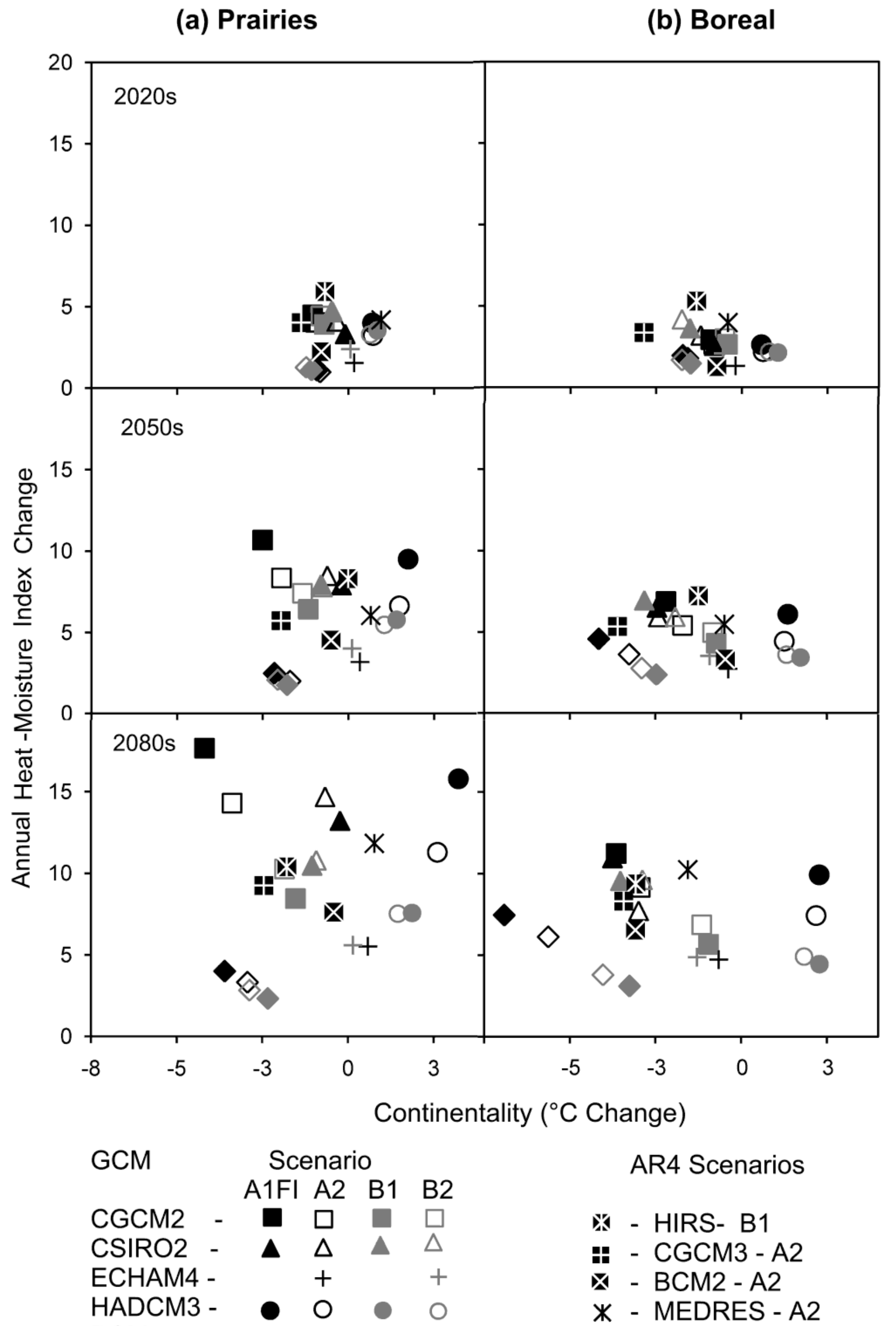


Figure 2-14. Relative change in projected difference between warmest and coldest month temperature (temperature difference) and annual heal moisture index for Prairies (A) and the southern Boreal (B) western Canada biomes based on ensemble runs of 4 SRES scenario families and 5 general circulation models, as well as 4 individual model runs selected from the IPCC's Fourth assessment Report (AR4) for the 2020s, 2050s and the 2080s.

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## Chapter 3. Historical climate data for natural resources management in western Canada[1]

### Summary

The chapter presents a comprehensive set of historical interpolated climate data for western Canada, including monthly data for the last century (1901–2006) as well as decadal averages and multiple climate normals. For each of these time periods, a large set of basic and derived biologically relevant climate variables, such as growing and chilling degree days, growing season length descriptors, frost free days, extreme minimum temperatures is provided. To balance file size versus accuracy for these approximately 15,000 climate surfaces, a stand-alone software solution that adds or subtracts historical data as medium resolution anomalies (deviations) from the high resolution 1961–1990 baseline normal dataset is also provided. For a relative quality comparison between the original normal data generated with the Parameter-elevation Regressions on Independent Slopes Model (PRISM) and derived historical data, the amount of variance explained ($R^2$) in original weather station data for each year and month from 1901 to 2006 were calculated. $R^2$ values remained very high for most of the time period covered for most variables. Reduction in data quality was found for individual months (as opposed to annual, decadal or 30-year climate averages) and for the early decades of the last century. Limitations of the database are discussed and an overview of recent climate trends for western Canada provided.

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## 3.1. Introduction

Projections of future climate change are highly variable due to a number of reasons such as, differences in modeling techniques, assumptions or emission scenarios chosen (CCSP 2008). Thus from a resource management perspective, future climate projections may be irrelevant for climate change adaptation efforts if they do not materialize locally as projected. Recent changes in climate on the other hand are what resource managers can already adapt to, more so if observed climate trends sharply contrast projections from models. Moreover, regardless of future efforts to reduce the concentration of greenhouse gases in the atmosphere, global temperatures have been projected to continue rising during the 21 century even if GHG concentration in the atmosphere is bought down to 2000 levels. Whereas global temperature change during the 1990–2005 period of about 0.2°C, was correctly projected to lie between 0.15°C and 0.3°C, local and regional changes have been larger in many locations and harder to predict. Given this local variability, recent climate trends provide perhaps the most appropriate guidance in the development of adaptation strategies to climate change and should certainty not be ignored.

Climate grids for Canada are available from various regional, continental and global-scale climate interpolation efforts. A global scale dataset for the 1950-2000 period "WorldClim" has been developed by Hijmans et al (2005) using the smoothing spline software ANUSPLIN (Hutchinson 1995; Hutchinson and Gessler 1994; Mitchell and Jones 2005). Mitchell and Jones (2005) developed coarse resolution global monthly historical data covering the 1901 to 2002 period for 5 degrees. The ANUSPLIN software package has also been used to develop monthly historical data at approximately 10km resolution for minimum and maximum temperature and monthly precipitation for Canada and the United States for the 1901–2000 period (McKenney et al. 2006) Another modeling group at Oregon State University uses the Parameter-elevation Regressions on Independent Slopes Model (PRISM) to develop monthly climate grids for North America at resolutions ranging from 30 arcsecond (~800 m) to 2.5 arc minutes (~ 4 km) (Daly 2006a; Daly et al. 2002; Daly et al. 2000). More regionally, daily temperature and precipitation grids have been developed for Alberta for the 1961–1997 period (Shen et al. 2001) as well as 30 year normals for the 1961-1990 period (Alberta Environment 2005). Comparisons of interpolated data have found ANUSPLIN and PRISM data to produce comparable results and to be superior to several other modeling methods  (Daly 2006a; Milewska et al. 2005; Price et al. 2000; Simpson et al. 2005).

All the above cited climate databases have their strengths and limitations that have been addressed using various trade-offs in different ways. First, resolution of spatial coverages have to be balanced against the size of the climate database. A useful resolution for climate normal data that seems to emerge as a standard is 30 arc seconds (approximately 800m), corresponding to widely used digital elevation models (USGS 1996).  At this resolution, climate gradients due to topography are usually quite well represented and the resulting coverages for a single climate variable are still reasonably small even at continental scales (Hijmans et al. 2005). However, monthly historical data for multiple variables quickly amounts to thousands of spatial coverages and in order to limit the total size of the database, a resolution of 10km or more is usually chosen (McKenney et al. 2006; Mitchell and Jones 2005).

Second, an important decision for producing gridded climate data is the method of interpolation. Many papers have discussed the merits and limitations of various interpolation techniques e.g. (Attorre et al. 2007; Daly 2006a; Hamann and Wang 2005; Price et al. 2000; Simpson et al. 2005). This study emphasizes the importance of another technical aspect with regard to climate data interpolation that is, interpolating anomalies which is particularly relevant for generating multiple comparable surfaces over time. Usually, interpolations are based on absolute climate values observed at weather stations. However, for series of interpolated historical data this method is vulnerable to missing values in weather station coverage (Mitchell and Jones, 2005). Missing values for station data in certain years may lead to temporary changes in interpolated surfaces that are highly undesirable when analyzing biological response to historical climate data. An alternative approach I employ here and used by Mitchell and Jones (2005) is to interpolate anomalies from climate normals.

The major objective of this chapter therefore is to generate a database of recent climate trends in Western Canada to support implementation of changes to forest management practices and policy. Specifically, I am generating a recent climate average 1997-2006 that is used like a general circulation model projection in bioclimate envelope modeling. The database is also valuable for applications beyond this thesis. Work for this study involved compiling spatial climate data for western Canada from various sources. The resulting dataset is made available for use by biologists and natural resources managers through a software package that I co-developed with Andreas Hamann and Tongli Wang. The approach of using medium resolution anomalies instead of high resolution surfaces against original weather station data is thoroughly tested and limitations of the database (particularly the loss of spatial heterogeneity in anomaly data due to the preferred interpolation approach) discussed. In order to demonstrate the value of recent climate in adapting to future climate, changes to ecosystem climate envelope under recent climate are compared to predicted changes to ecosystem climate envelope under climate projected for the 2020s.

## 3.2. Methods

### *3.2.1. Climate datasets*

Compiling spatial climate data for the 1901–2006 was based on several existing spatial climate datasets. One of the spatial datasets is a 2.5 arcminute (approximately 4km) resolution interpolated climate data of average monthly minimum temperature, maximum temperature, and precipitation for the 1961-1990 normal period. These climate grids have been developed by Daly et al. (2002) using the Parameter-elevation Regressions on Independent Slopes Model (PRISM). This method was previously shown to particularly be well suited for modeling precipitation in mountainous regions of British Columbia and the Yukon Territories (Hamann and Wang 2005), and that a combination of bi-linear interpolation and elevation adjustment can be used for “intelligent” downscaling of temperature data to higher resolution in mountainous regions, thereby improving the statistical precision and accuracy of temperature estimates and derived climate variables (Hamann and Wang 2005; Wang et al. 2006). This study applies the same methodology to an extended study area, now covering the Yukon Territory, British Columbia, Alberta, Saskatchewan, Manitoba and parts of the United States (Figure 3-1).

The other spatial climate dataset was developed by Mitchell and Jones (2005) for the 1901-2002 period at 30 arcminute resolution with worldwide coverage (CRU TS 2.1). Original anomaly surfaces (deviations from the 1961-1990 normals) were obtained by subtracting the 1961-1990 average from their gridded surfaces of individual years and months. These anomalies were also downscaled with bi-linear interpolation and overlaid on the high resolution PRISM generated climate normal data, described above, which provides much better estimates of absolute climate values than Mitchell and Jones’ (2005) low resolution climate normals.

Evaluation of historical climate grids was carried out with observed climate data at weather station locations in the region. Station data was acquired from the Adjusted Historical Canadian Climate Database available as monthly minimum and maximum temperature and total precipitation (Mekis and Hogg

1999; Vincent 1998; Vincent and Gullett 1999; Vincent et al. 2002). The data covers the 1901-2006 period and was used to generate western Canada climate grids for the 2000-2006 period as well as evaluate the quality of the 1901–2006 interpolated climate surfaces.

### *3.2.2. Interpolation of 2000-2006 climate data*

A major contribution of this study was to update the available spatial western Canada climate data from the original 2002 to cover up to 2006. Climate grids for the 2000-2006 period were generated using interpolation of anomalies to update the historical anomalies by Mitchell and Jones (2005) with more recent climate grids. Observed anomalies were computed using weather station data from the Adjusted Historical Canadian Climate Database (Mekis and Hogg 1999; Vincent 1998; Vincent and Gullett 1999; Vincent et al. 2002). The number of stations with complete monthly data ranged from 90 to 120 for temperature and 120 to 210 for precipitation with the best coverage in the 1980s and 1990s. Monthly anomalies for the 2000–2006 weather station data were calculated as the difference of the observed temperature data from 1961-1990 normals for each station. Precipitation anomalies were expressed as percentage of the 1961-1990 normals.

Interpolation of anomalies calculated for weather stations was then carried out using thin plate spline method implemented by PROC G3GRID (SAS Institute Inc. 2005). For consistency with Mitchell and Jones (2005) grids visual comparisons of climate surfaces for three overlapping years (2000 through 2002) were conducted. A spline smoothing factor of 0.01 (PROC G3GRID, option SMOOTH), was chosen which resulted in visually similar results to Mitchell and Jones' (2005) surfaces, which are based on different interpolation methods.

### *3.2.3. Relative quality comparison of historical data*

The next step after compiling a 1901 – 2006 climate grid for western Canada based on interpolation of anomalies from 1961 – 1990 normals involved evaluation of the quality of the data. This was done by generating interpolated climate data for weather station locations and comparing it with recorded climate data at those locations. Interpolated climate surfaces for the 2000 – 2006 period were compared to earlier interpolated climate data from Mitchell and Jones (2005) covering the 1901 – 2002 period using three overlapping years 2000, 2001 and 2002 for these datasets.

Because PRISM climate normals as well as anomalies for the 1901 – 2002 period were calculated from all available station locations in the study area, I could only carry out relative quality comparisons of interpolated data as there is no independent test dataset available. This is however not a problem for this study because the objective was not to evaluate the interpolation techniques themselves, but to verify that the quality of historical climate data is not degraded by the procedure of overlaying medium resolution anomaly surfaces on high resolution baseline data. For this comparison, I evaluated how well historical gridded data, overlaid on the high resolution normal, accounts for variance explained ($R^2$) in original weather station data. $R^2$ is a useful measure for this comparison because it quantifies the statistical precision of the estimate. This evaluation is less concerned with statistical accuracy for this test, because historical anomalies are evaluated from the climate normal model, which have previously been shown to have reasonably good statistical accuracy (Hamann and Wang, 2005). To provide a sense of the magnitude of errors in units of degree Celsius and millimeters precipitation, the average deviation (absolute values) of interpolation estimates from observed station data were also calculated.

To keep the quality check for historical data for the 106 years manageable, only five climate variables were evaluated, representing two annual climate summaries: mean annual temperature (MAT) and mean annual precipitation (MAP); two monthly variables: mean warmest month temperature (MWMT) – July, mean coldest month temperature (MCMT) – January; and one seasonal variable: mean summer precipitation (MSP) – May to September. Estimates for each year and each variable were extracted from interpolated grids for all station locations to calculate $R^2$ values between estimated and observed data for each year. This evaluation was also carried out separately for the western Cordillera mountain ranges and the Canadian Prairies to detect potential data issues in regions with mountainous topography.

### *3.2.4. Evaluating anomalies-based interpolation*

To evaluate historical normals, quality of 1931 – 1960 anomaly derived normals was compared to that of directly interpolated 1961 – 1990 normals. Historical data was generated by overlaying a low resolution (30 arcminutes) 1931 – 1960 anomaly surface onto the 1961 – 1990 baseline data to obtain a different climate normal period. This comparison was carried out separately for the Mountain Cordilleras and the Canadian plains.

To have a direct comparison of original and derived 30-year normal periods, I also evaluated the precision of the five variables for the anomaly-derived 1931 – 1960 climate normal versus the original 1961 – 1990 normal data. Data was averaged for mountains and plains regions of the study to separate the likely influence of elevation resulting climate surfaces. Thus observed climate data at weather stations in the mountains (Northern and Montane Cordillera) was compared with interpolated climate data at these station locations. A similar comparison was separately performed for weather station locations in the plains (Prairies, Boreal Plains and Boreal forest).

### *3.2.5. Applications of recent climate data*

A comparative evaluation of past decade (1997 – 2006) changes in climate with projections for the 2010 – 2040 or the 2020s period was performed to demonstrate how near future projections compare with trends currently underway. Observed and projected climate anomalies from 1961-1990 normals were evaluated for 5 climate variables (MAT, MAP, MWMT, MCMT and MSP). Changes were expressed as anomalies in degree Celsius for temperature and percentage change for precipitation. Observed changes or anomalies of the 1971-2006 10 year climate from the 1961– 1990 normals were mapped and compared to anomalies from projected climate from a selected future scenario (CGCM2-B2) describing a future with very moderate change to temperature and precipitation.

As an illustration of how recent climate trends could be used, I model western Canada ecosystems under last decade climate (1997 – 2006) and compared this to mapped ecosystems, ecosystem climate niche under baseline (1961 – 1990) and projected climate for the 2020s. Modeling was based on discriminant analysis and the three periods are chosen as an indication of recent climate change trends as a good indicator of what is likely to happen or changes that are already underway as these provide sound ground for the development of adaptation strategies to climate change.

## 3.3. Results

### *3.3.1. Quality of historical climate normals*

The first comparison evaluated 1931 – 1960 anomaly surfaces that were created by overlaying low resolution anomalies for this period over high resolution 1961 – 1990 normals. The $R^2$ values as well as the average error of climate estimates indicate that the derived 1931 – 1960 normal period maintains good statistical precision. $R^2$ and MAE for the 1931 – 1960 are comparable to those for the 1961 – 1990 normals. Further, there appears to be no major quality differences between the mountainous areas and the plains (Table 3-1).

### *3.3.2. Quality of monthly, seasonal, annual historical data*

Testing of the anomaly derived climate surfaces of annual variables for individual years shows that statistical precision remains very high, except for the first third of the century (Figure 3-2, MAT and MAP). Also, my own interpolations that update Mitchell and Jones (2005) dataset for the most recent years are of similar quality and the surfaces for the overlapping years 2000, 2001, and 2002 visually conform when displayed as maps (data not shown). The seasonal variable MSP shows considerably more variation in statistical precision among individual years. Monthly temperature variables have quite high $R^2$ values compared to their corresponding 30-year normal (Figure 3-2, MWMT, MCMT). However, they show sharp declines in precision for approximately one out of 10 years.

### *3.3.3. Recent climate trends for western Canada*

To visualize these recent changes starting in the 1980s, I display anomalies of the latest decade for which I had data (1997 – 2006) as a difference from the 1961–1990 reference period (Figure 3-3 and 3-4). Obviously, the shorter the time period for which an anomaly is calculated (a decade in this case), the less indicative the result is of a trend because of cyclical or stochastic climate variability, especially for precipitation. However the 10 year changes in climate show the direction of changes in climate that are underway (Table 3-2).

Recent temperature trends in western Canada roughly follow the direction and magnitude of the CGCM2-B2 projections (Figure 3-3). While most GCMs predicted more warming in winter temperatures than in summer temperatures, the differences appear to be more pronounced in the observed trends. Average winter temperature changes over the last quarter century already exceed projections for the 2020s for most regions in western Canada. Observed trends in precipitation (Figure 3-4) are different from CGCM2-B2 projections and, in fact, projections from any GCM. This is not surprising as the confidence in GCM projections of precipitation changes are generally low (IPCC 2007a) Chapter 8). Observed data shows up to 20% less annual precipitation for Alberta and up to 10% less precipitation for British Columbia with the exception of the Rocky Mountains along the southern BC/AB border and a section of coastal British Columbia around 558 latitude, where we observe a strong increase in summer precipitation by approximately 20%. Similar patterns of change have also been found in long-term statistical trend analysis for the study area (Rodenhuis et al. 2007).

An explanation for these changes may lie in historical trends in the northern jet stream. In a recent paper, Archer and Caldera (2008) show that since 1979 the northern jet stream has significantly moved northward (approximately half a degree latitude over the last 25 years), risen in altitude, and weakened in strength. Jet streams are meandering, high altitude, westerly air streams that are responsible for the formation and evolution of storm tracks. When they move away from a region, high pressure and clear skies tend to predominate. Over the Pacific and the Pacific Northwest, Archer and Caldera (2008) find a significant north-shift of the jet stream and more complex seasonal and spatial patterns of change over continental North America. Such shifts could potentially account for regional precipitation changes that are observed in our study area, e.g. drier southern climate conditions displacing the main storm tracks over central Alberta at around 56° latitude.

## 3.4. Discussion

### *3.4.1. Quality of climate surfaces*

The absence of differences between quality of climate surfaces in mountains and plains is due to a previously described lapse-rate based elevation adjustments for mountainous areas (Hamann and Wang 2005; Wang et al. 2006). In principle the elevation-adjustment step works as follows: when the PRISM climate normal surface is queried through the ClimateBC/PP software packages, the program first finds the four 2.5 arcminute resolution cells that surround the location of interest (e.g. a sample point) and reads the original PRISM based climate estimates and the elevation values on which the climate estimates are based. The program then generates a first estimate of climate values and elevation for the location of interest through simple bi-linear interpolation. If this elevation estimate is different than the location of interest, say, the interpolated elevation value is 650 m, but the location of interest is located in a valley and actually has an elevation of only 500 m, temperature values will be adjusted upwards using a set of formulas for individual climate variables that vary with geographic location (Wang et al. 2006). This step is carried out by the ClimateBC/PP software whenever an elevation value for the location of interest is provided.

The second comparison focuses on historical climate estimates for shorter periods than 30-year normals, i.e. individual years, seasons, and months of the last century. Naturally, the quality of these estimates would be expected to degrade. However quality remained high particularly for annual climate variables (MAT and MAP). Because of stochasticity in weather patterns, it will always be more difficult to estimate a climatic variable for shorter periods such as individual years, seasons, months, or days (Shen et al. 2001).

The results show clearly that particular weather patterns that are unique to an individual month or season cannot always be accounted for by the climate grids that were evaluated. Any local stochastic variation in weather patterns that does not conform to rules that can be incorporated into interpolation models could cause the observed loss of precision. To give an example, the ‘‘rule’’ incorporated in virtually all interpolation models that temperature decreases as elevation increases does not apply under inversion weather patterns in winter, a regular occurrence in mountain valleys. The PRISM 30-year climate normal model, in fact, models these temperature inversions. But these inversions do not occur everywhere in every winter with the same frequency, so modeling temperature for an individual winter month is much more difficult than for a 30-year climate average. High $R^2$ values for the mean coldest month temperature (Figure 3-2, MCMT) indicate that a particular winter does not have pronounced local stochasticity, and the coarse resolution anomaly surfaces almost perfectly capture the deviation of an individual month from long-term climate normals. The spikes of low $R^2$ values point toward winter months with unique weather patterns that could not completely accounted for. Since precipitation variables show stochastic behavior to a much higher degree than temperature (Bonsal et al. 2003), it is not surprising that the precision of historical precipitation estimates for individual months are more variable and generally lower than for temperature.

### *3.4.2. Advantages and disadvantages of the anomaly approach*

From an end-user perspective, the question arises whether these climate surfaces are suitable (or at least the best available) to analyze biological response to past climate variation. Unlike many others, Mitchell and Jones (2005) interpolate anomalies (deviations from the 1961 – 1990 normal) and not the absolute station values. Thus, they sacrifice data from new or temporary weather stations that have no or poor coverage for the required 1961 – 1990 reference period. This substantially reduces the potential to account for local stochastic weather patterns that are prevalent over shorter time intervals. Visual inspection of anomaly surfaces provides a good sense for the lack of fine-scale spatial variation in interpolated anomalies, both due to the low resolution and the choice of smoothing parameters (e.g. Figure 3-3). Therefore, users of this database should be aware that historical time series obtained for nearby sample points are very similar, although I will argue later that this does not matter for most practical applications.

An alternative to the ‘‘anomaly approach’’ is to interpolate all available station data for the historical time interval of interest. While there are less than 200 stations for western Canada that meet the standards of completeness by the World Meteorological Organization for the 1961 – 1990 normal period, there are approximately 3000 stations with useful data for short time periods. These additional stations can be used to generate interpolated coverages for shorter historical time intervals that better capture climate patterns that are unique for a particular time interval (McKenney et al. 2006). Also, sophisticated methods exist that utilize the space–time covariability observed during short intervals with dense station networks to even better account for spatial variability due to particular weather patterns, e.g. empirical orthogonal function decomposition (Richman 1986). However, the ‘‘direct interpolation approach’’ leads to variations among grids for different time intervals that are driven by the temporal presence of short-term weather stations (or missing values in long-term stations). Secondly, the approach becomes inferior to the anomaly method when station coverage is very sparse (e.g. for the early century or for northern latitudes), because the interpolation model has to be built exclusively from stations available for the period of interest. This again leads to variation among grids for different time intervals that are not driven by differences in climate but by the quality of the interpolation models for different time periods.

In contrast, under the ‘‘anomaly approach’’ surfaces can be forced towards zero if there is little or no station data, i.e. the climate estimates approach the 1961 – 1990 normal period. This is very graceful behavior for the study of biological response to historical climate: envision a regression of a biological response variable over an independent climate variable. Erroneous values due to lack of data in the independent variable approach the center of the distribution (zero anomaly) and minimally influence the relationship. Although the database provided never leads to anomaly surfaces to completely default to zero, anomalies show less amplitude in some northern regions for the early century, i.e. starting to approach zero. I consider this behavior a convincing argument for using the ‘‘anomaly method’’ for our study area, whereas ‘‘direct interpolation approach’’ may be applied with more confidence in Europe or the United States, where the historical network of weather stations is much better.

### *3.4.2. Applications of the climate data*

Environment Canada provides graphs of climate trends, expressed as a regression of climate over time, for various geographic regions of Canada (MSC 2006). Here I make use of our gridded historical database to show recent climate trends in a different and spatially more explicit way. It is widely acknowledged that global temperatures have started to increase more rapidly due to the effect of greenhouse gases since the 1980s, preceded by a cooling trend for several decades (IPCC 2007a), Chapter 3).

Area of increased summer precipitation in Coastal British Columbia was identified and this was recognized as a cause for an unprecedented Dothistroma needle blight epidemic of lodgepole pine in western BC (Woods et al. 2005). Interestingly, virtually all GCMs predict drier climate for this area, which would imply that a shift in forestry practices towards increased use of lodgepole pine would be a sensible adaptation strategy. This serves as a good illustration that adaptation strategies for local, on-the ground management should not solely be based on GCM projections, which are meant to indicate the future directions of climate change at large, continental scales. While observed trends may or may not continue into the future at the same rate, I believe that they are the most realistic basis for developing adaptation strategies, and should be used in combination with GCM projection. Managers should prepare for making changes to management based on models, but only implement those adaptation strategies when observed trends on the ground confirm the predictions. This database, which will be regularly updated, can be used for decision support.

Secondly, I suggest that the spatial coverages of observed anomalies presented in this chapter may be used for modeling applications in a similar way as GCM projections. For illustration, I use a simple ecosystem climate envelope model, equivalent to Hamann and Wang (2006) to model Canadian ecozones for the 1997 – 2006 average and compare them with results from a selected future climate projection,  CGCM2-B2 (Figure 3-5). Both predict similar expansion of the Prairie grassland ecosystems into current boreal forest ecosystems. The area of predicted transitions has, in fact, seen large dieback and productivity loss of aspen and spruce (Hogg et al. 2008). The combined information from GCM projections, climate trends that have already materialized, and observed biological response make a strong case for implementing adaptation strategies in this area, e.g. reforestation programs should rely on more drought tolerant species or genotypes in the future.

### *3.4.3. Limitations of the historical climate data*

The ClimateBC and ClimatePP software packages provide easy access to historical and future climate data at any resolution. It should be kept in mind, however, that there are important limitations that need to be pointed out. As previously discussed, the shorter the historical time interval of interest, the less reliable the climate surfaces are due to the inability to represent unique local weather patterns over short time intervals. The databases are best suited to analyze biological response to inter-annual variability where the climate variables of interest cover several months (e.g. growing season length, mean annual precipitation, spring temperature). Regarding spatial accuracy, climatic features such as rain shadows, temperature inversions, slope and aspect effects are modeled at a scale of several kilometers, suitable to represent mountain ranges. Lapse-rate driven temperature differences as a function of elevation are accurately represented at a much finer scale, informative at a resolution of hundreds of meters. Small-scale climate features such as frost pockets or local slope and aspect effects are not represented.

Table 3-1. $R^2$ values and the average deviation in absolute values (in parentheses) to compare the quality of original interpolated climate data (1961–1990) and a derived surface (1931–1960). The dataset was subdivided into a primarily mountainous area(British Columbia and Yukon Territory), and an area consisting primarily of plains (Alberta, Saskatchewan, Manitoba).

| Variable | Mountains | | Plains | |
|---|---|---|---|---|
| | 1961–1990 | 1931–1960 | 1961–1990 | 1931–1960 |
| Mean annual temperature - MAT | 0.98 (0.6 $^o$C) | 0.97 (0.8 $^o$C) | 0.98 (0.3 $^o$C) | 0.97 (0.4 $^o$C) |
| Mean warmest month temperature - MWMT | 0.94 (0.7 $^o$C) | 0.93 (0.9 $^o$C) | 0.95 (0.3 $^o$C) | 0.93 (0.5 $^o$C) |
| Mean coldest month temperature- MCMT | 0.97 (1.3 $^o$C) | 0.97 (1.5 $^o$C) | 0.96 (0.9 $^o$C) | 0.94 (1.3 $^o$C) |
| Mean annual precipitation - MAP | 0.97 (93 mm) | 0.96 (99 mm) | 0.98 (45mm) | 0.80 (55 mm) |
| Mean summer precipitation- MSP | 0.94 (27 mm) | 0.92 (28 mm) | 0.90 (18mm) | 0.70 (24 mm) |

Table 3-2. Climate normals for the 1961 – 1990 period (in absolute values) and observed anomalies for the 1997-2006 10 year period and projections for the 2011–2040 (2020s) period based on pessimistic (CGCM2-A1), moderate (CGCM2-A2) and optimistic (PCM-B2) scenarios A2 for the Foothills ecoregions of Alberta. Differences in climate variables are shown as an increase (+) or decrease (-) and are given as percentages for mean annual precipitation, mean summer precipitation and precipitation as snow.

| **Climate variable** | **Baseline (1961–1990)** | Observed Change (1997–2006) | Projected Change (2020s) | | |
|---|---|---|---|---|---|
| | | | PCM (B2) | CGCM2 (A2) | CGCM2 (A1FI) |
| MAT (°C) | **1.6** | +1.1 | +0.8 | +1.1 | +1.3 |
| MWMT (°C) | **13.2** | +0.4 | +0.9 | +1.0 | +1.1 |
| MCMT (°C) | **-12.5** | +2.2 | +2.0 | +1.7 | +1.9 |
| TD (°C) | **26.7** | -1.8 | -1.1 | -0.7 | -0.8 |
| MAP ( %) | **603** | -7.2 | +2.5 | +2.3 | +2.7 |
| MSP (mm, %) | **407** | -6.2 | +2.5 | +1.8 | +2.1 |
| PAS (mm, %) | **159** | -15 | -1.6 | -3.6 | -5.1 |
| AHM | **19.4** | +3.6 | +0.9 | +1.4 | +1.6 |
| DD< 0°C | **1422** | -359 | -184 | -187 | -209 |
| DDD>5°C | **1081** | +30 | +91 | +190 | +211 |
| NFFD | **149** | +1 | +8 | +14 | +15 |
| FFP | **86** | +3 | +11 | +17 | +18 |
| DD5_100 | **139** | +1.4 | -0.5 | -8 | -9 |
| EMT (°C) | **-45.4** | +2.5 | 2.0 | 2.2 | 2.4 |

MAT- mean annual temperature, MWMT -mean July temperature, MCMT – mean January temperature, TD - temperature difference, MAP - mean annual precipitation, MSP - mean summer precipitation, PAS - precipitation as snow, AHM - annual heat moisture index, DD>0 - degree days below 0°C, DD>5 - degree above 5°C, NFFD - number of frost free days, FFP - frost free period, DD5_100 - growing degree days, EMT - Extreme minimum temperature.

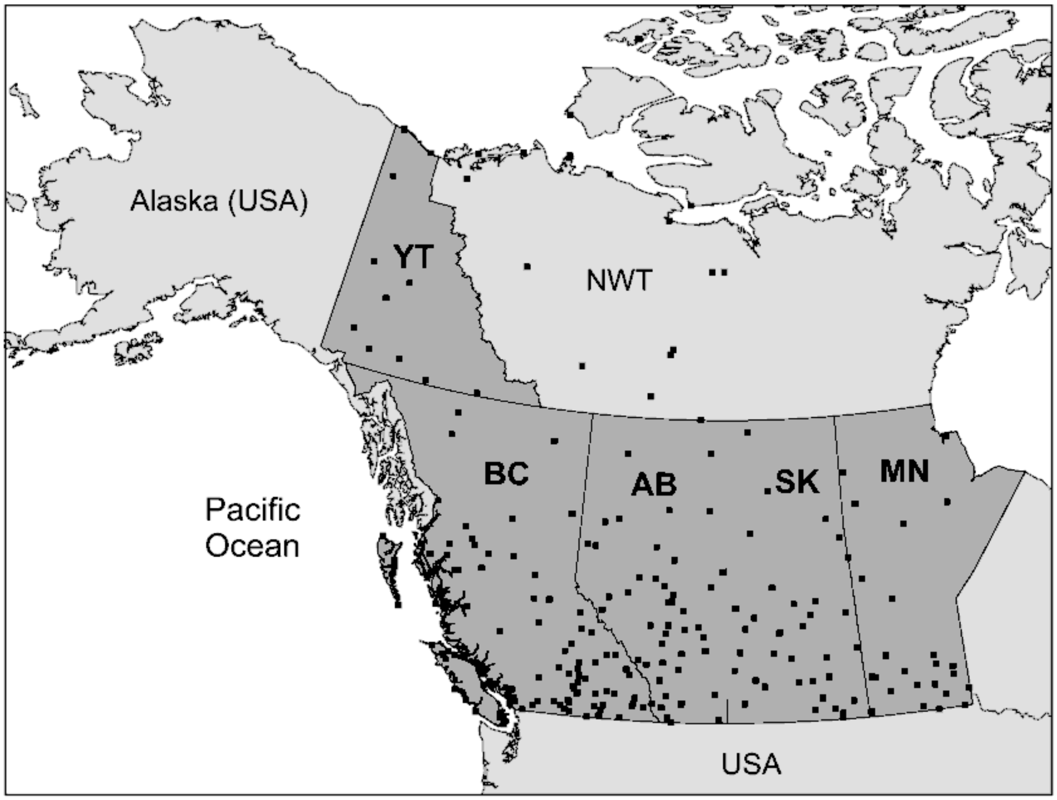


Figure 3-1. Map of the study area in western Canada (dark grey), showing locations of weather stations with data for the 1901 – 2006 period. Yukon Territory (YT), British Columbia (BC), Alberta (AB), Saskatchewan (SK) and Manitoba (MN).

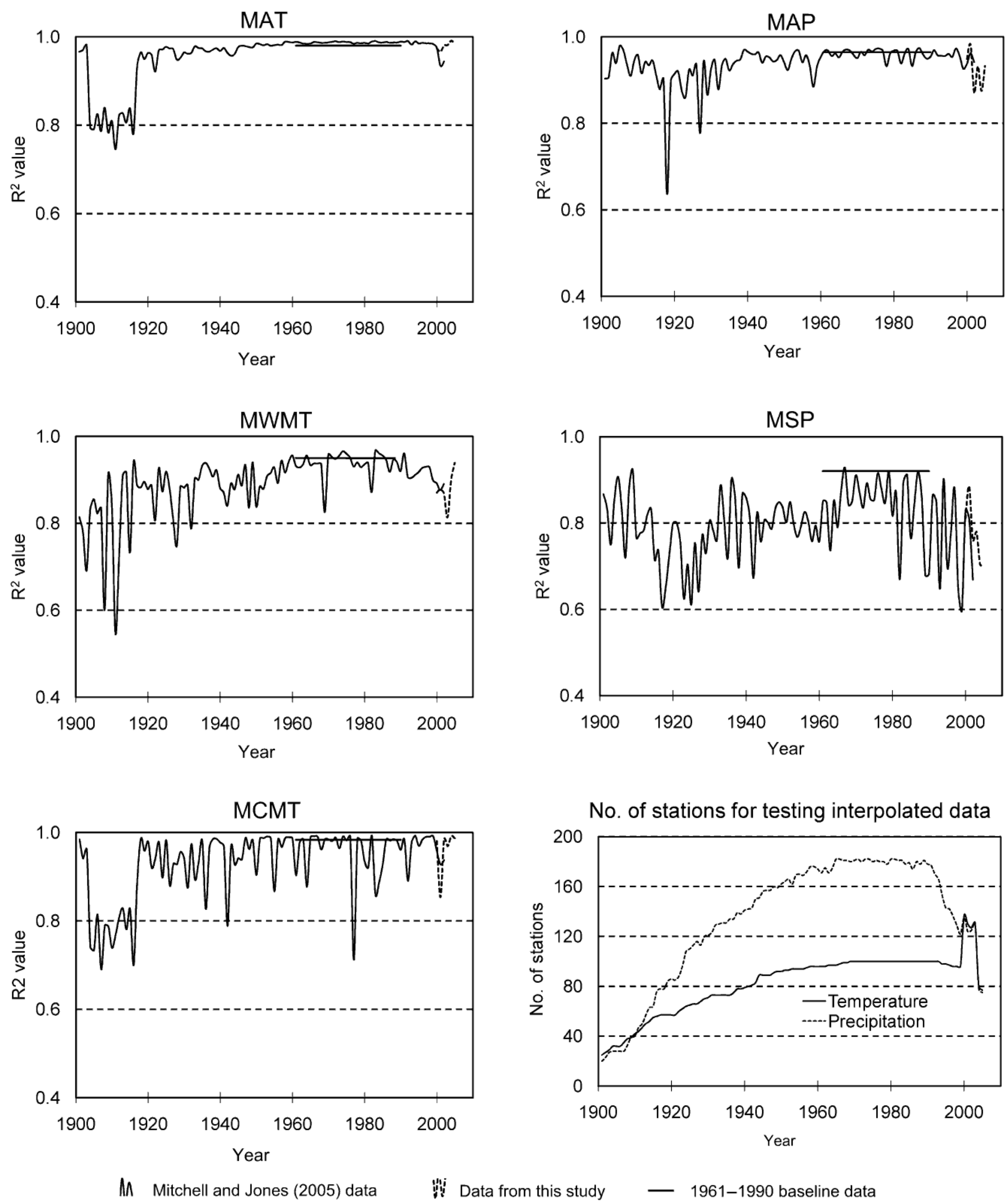


Figure 3-2. $R^2$ between observed and interpolated mean annual temperature (MAT), mean warmest month temperature (MWMT), mean coldest month temperature (MCMT) data, mean annual precipitation (MAP) and mean summer precipitation (MSP) for the 1901–2002 period and corresponding values for the 1961–1990 normals comparison with observed data. Number of stations for data comparison for each year is also shown.

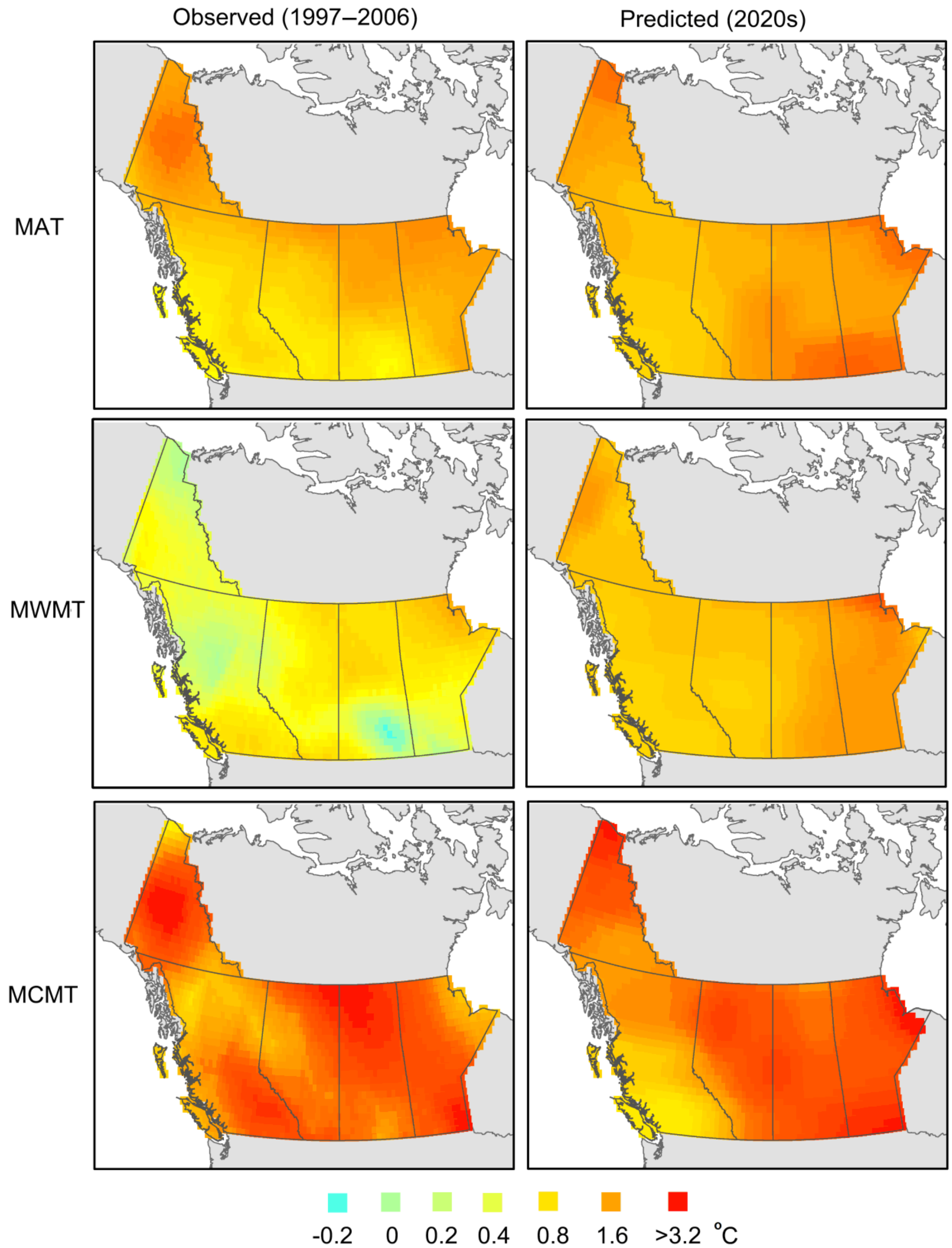


Figure 3-3. Maps of anomalies (deviations from 1961 - 1990 normals) of a recent 10-year average (1997 - 2006) and predicted by CGCM2-B2 for the 2020s for mean annual temperature (MAT), mean warmest month temperature (MWMT) and mean coldest month temperature (MCMT).

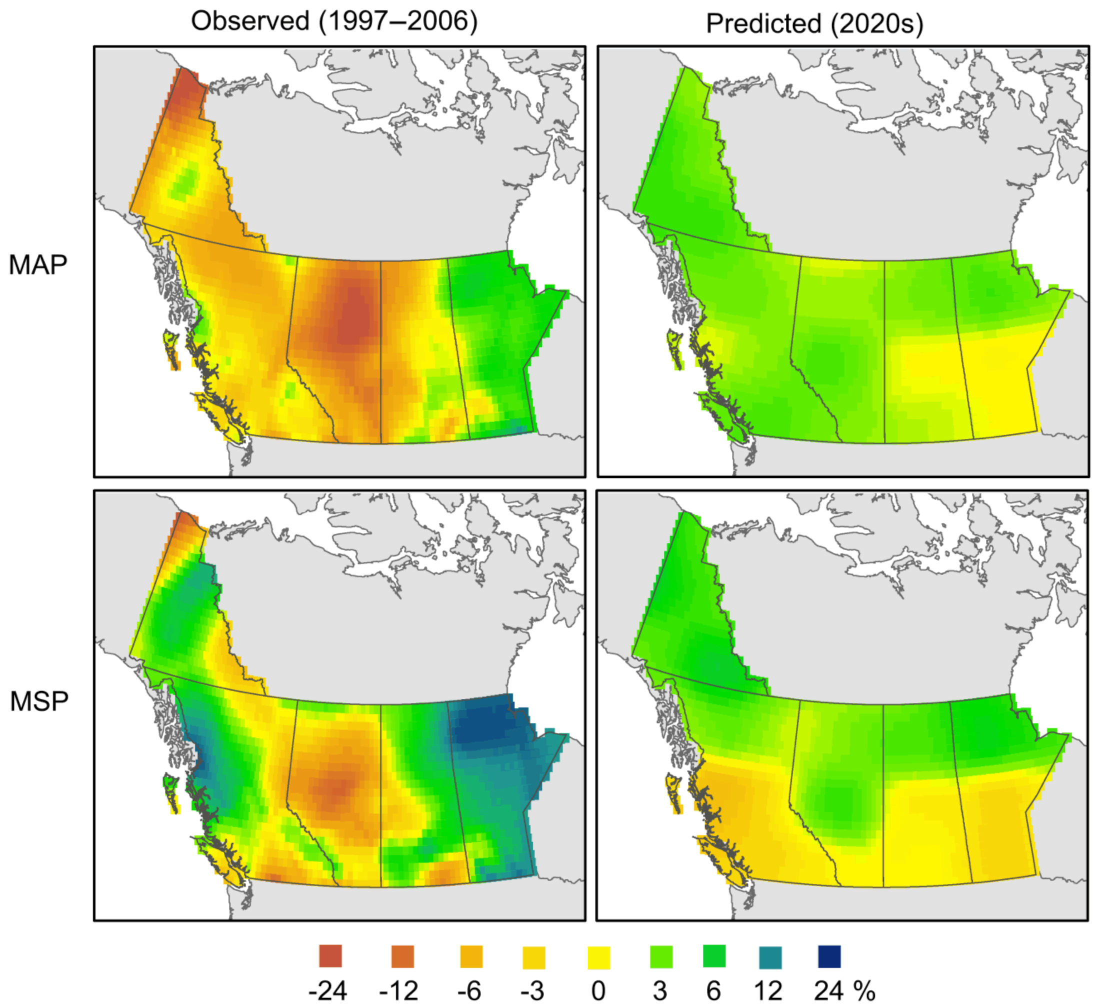


Figure 3-4. Maps of anomalies (deviations from 1961 - 1990 normals expressed as percentage) of a recent 10-year average (1997 - 2006) and predicted by CGCM2-B2 for the 2020s for mean annual precipitation (MAP) and mean summer precipitation (MSP).

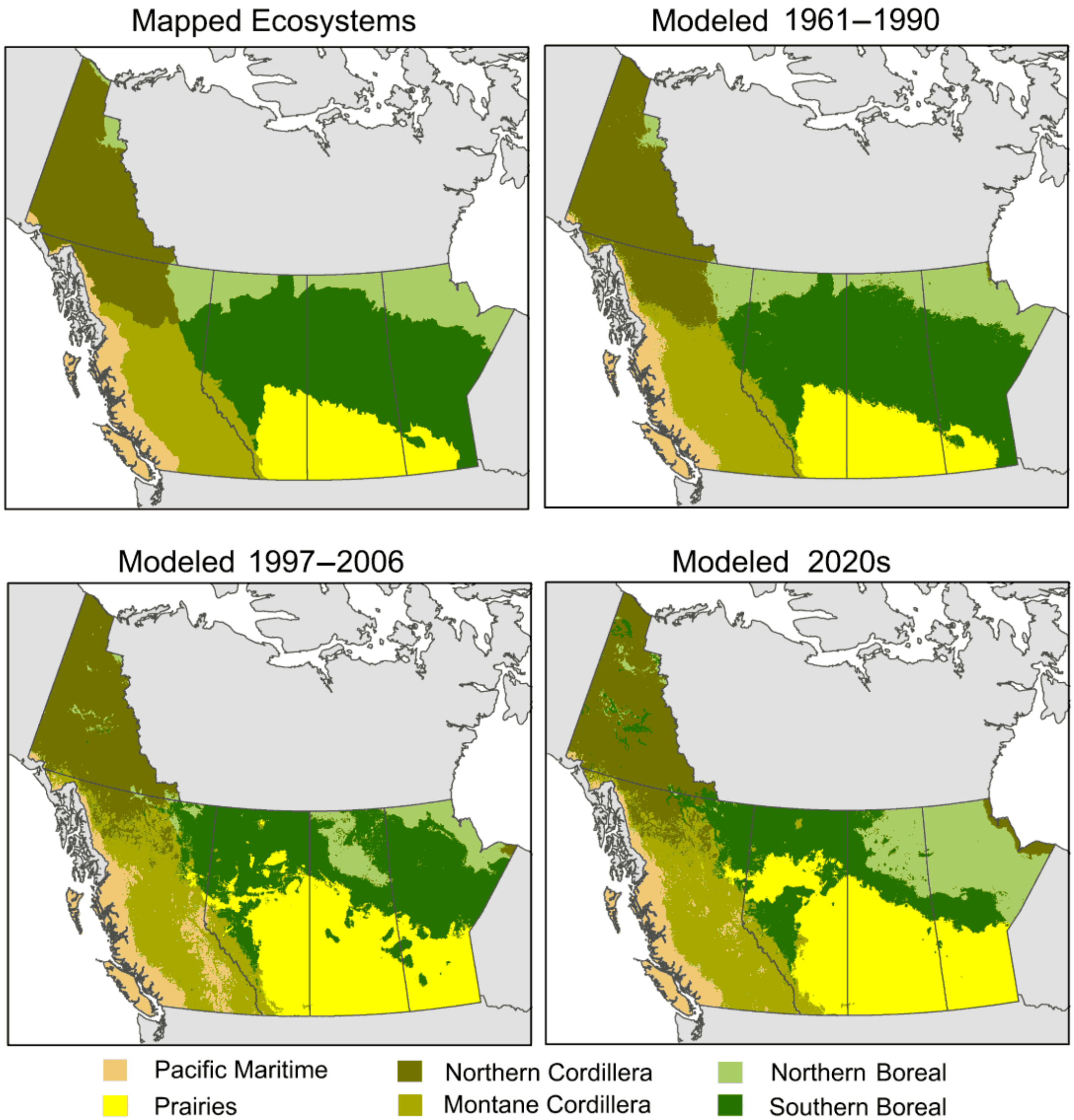


Figure 3-5. Mapped ecosystems and modeled ecosystem climate envelope based on baseline climate normals (1961 - 1990), a recent 10-year average (1997 - 2006) and projected climate for the 2020s based on the Canadian Global Circulation Model (CGCM2-B2).

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## Chapter 4. Bioclimate envelope model predictions for natural resource management under climate change: dealing with uncertainty[2]

### Summary

In this chapter I present a novel approach to evaluate uncertainty in model-based recommendations for natural resource management. Rather than evaluating variability in modeling results as a whole, I extract a particular statistic of interest from multiple model runs, e.g. species suitability for a particular reforestation site. Then, this statistic is subjected to analysis of variance, aiming to narrow the range of projections that practitioners need to consider. In four case studies for western Canada I evaluate five sources of uncertainty with two to five treatment levels, including modeling methods, interpolation type for climate data, inclusion of topo-edaphic variables, choice of general circulation models, and choice of emission scenarios. As dependent variables I evaluate changes to tree species habitat and ecosystem distributions under 144 treatment combinations. For these case studies, I find that the inclusion of topo-edaphic variables as predictors reduces projected habitat shifts by a quarter, and general circulation models had major main effects. The contrasting modeling approaches primarily contributed to uncertainty through interaction terms with climate change predictions, i.e. the methods behaved differently for particular climate change scenarios (e.g. warm & moist scenarios) but similar for others. Partitioning of variance components helps with interpretation of modeling results and reveals how models can most efficiently be improved. Quantifying variance components for main effects and interactions among sources of uncertainty also offers researchers the opportunity to filter out biologically and statistically unreasonable modeling results, providing practitioners with an improved range of predictions for climate-informed natural resource management.

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### 4.1. Introduction

Over the last decade, the reality of global climate change has gained wide acceptance among policy makers and natural resource managers, and the demand for modeling and forecasting climate change impacts on the biosphere is growing. Public sector planners would like accurate forecasts of potential land-use changes, threats to biodiversity, or forest health. In the private sector, decision makers need to know if their natural resource management strategies and long-term business plans are viable in the face of changing environments. One of the most widely discussed issues involves the choice of species and genotypes in reforestation programs (e.g. Marris, 2009, McKenney et al., 2009). Changing practices and policies for large-scale commercial reforestation programs is a powerful tool to adapt to anticipated climate change, involving little extra cost in addition to current operations.

A useful class of models to guide species choice under observed and anticipated climate change is bioclimate envelope models, also referred to as niche models or species distribution models. Bioclimate envelope models are simplistic in that they do not model demographic or any other ecological processes. Instead, they correlate species census data with environmental predictor variables using a wide range of statistical and machine-learning methods, e.g. reviewed by Guisan and Zimmermann (2000). Limitations and weaknesses of the bioclimate envelope model approach have been thoroughly discussed (Austin 2007; Botkin et al. 2007; Guisan et al. 2006; Hampe 2004; Pearson and Dawson 2003; Rushton et al. 2004; Thuiller et al. 2008). However, some of the most important limitations of bioclimate envelope models do not apply when they are used to match management practices with anticipated climate conditions. Unlike natural species populations, management practices can "migrate" as rapidly bioclimate envelope model results suggest. In plantation forestry, seeds are already being moved considerable distances from source to planting locations under normal management, and competition and species interactions can be controlled through spacing of plantations and choice of planting stock.

To guide species choice in reforestation, simple models based on the realized niche space may be preferable to difficult-to-obtain empirical data on species tolerance to climate change. For example, results of a reciprocal transplant experiment to determine growth across the fundamental niche of lodge pole pine showed that the species may grow well under projected climate warming in many areas as long as there are no moisture limitations (Wang et al., 2006, O'Neill et al., 2008). However, warm and moist growing season conditions also lead to Dothistroma needle cast outbreaks (Woods et al., 2005), which reduces the fundamental niche space due to a biotic interaction. A judicious recommendation for reforestation under climate change should therefore exclude warm and wet climate conditions, i.e. a conservative approach to species choice for reforestation should be guided by projections of the realized niche, not the fundamental niche. While this approach may possibly forgo some potential gains in tree growth due to climate change, it is less risky and corresponds to the widely adopted reforestation policy of not planting species outside their observed range. The same principle applies to other applications, such as ecosystem restoration, selection of protected areas, or assisted migration.

Before bioclimate envelope models can be used in practical applications, they need to be validated. Two aspects, model accuracy and robustness to small changes in model parameters are helpful to evaluate the reliability of predictions (Botkin et al., 2007). A previous study by Hamann and Wang (2006) evaluated model accuracy using an independent validation approach by projecting habitat to new geographic regions according to Araujo et al. (2005). Here, I focus on the second aspect, uncertainty in model projections due to data quality, modeling approach, and model parameters. A thoroughly investigated source of uncertainty is the choice of modeling method with conclusions ranging from a fair degree of model consensus to very pessimistic assessments (e.g. Pearson et al., 2006, Araujo and New, 2007, Thuiller et al., 2004, Lawler et al., 2006, Hijmans and Graham, 2006). A second important aspect is the choice of climate change scenarios (Bakkenes et al., 2006, Beaumont et al., 2007, Iverson et al., 2008, Beaumont et al., 2008). Further, the type and quality of predictor variables as well as biological census data has shown considerable effects on modeling results (Beaumont et al., 2005, Coudun et al. 2006, Guisan et al., 2007, Luoto et al., 2007, Luoto and Heikkinen, 2008, Taverna et al. 2005). To avoid the danger that minor sources of uncertainty are reported and major sources of uncertainty are ignored, as many factors as possible should be considered in sensitivity analysis (Botkin et al., 2007). Examples of such efforts include Kadmon et al. (2003), Guisan et al. (2007) and Diniz-Filho et al. (2009).

In this chapter I present an approach to evaluate uncertainty in bioclimate envelope model predictions that yields valuable results for practitioners. Rather than evaluating variability in modeling results as a whole, I extract a particular statistic of interest from multiple model runs, e.g. species suitability for a particular reforestation site. Then, this statistic is subjected to analysis of variance, where sources of uncertainty are represented as treatments in a complete factorial design. I evaluate five sources of uncertainty with two to five treatment levels, including modeling methods, interpolation type for climate data, inclusion of topo-edaphic variables, choice of general circulation models, and choice of emission scenarios. As dependent variables I use an ecosystem class variable for a more general evaluation of results from sensitivity analysis. To illustrate a practical application of the modeling results, I also predict suitable habitat of aspen (*Populus tremuloides* Michaux.), an important forestry species in western Canada.

## 4.2. Methods

### *4.2.1. Bioclimate envelope modeling*

To assess the effect of modeling method on climate envelope predictions, I included two contrasting modeling techniques, discriminant analysis implemented by PROC DISCRIM of the SAS statistical package (SAS Institute 2008) and classification tree analysis implemented by the RandomForest software package (Breiman 2001) for the R programming environment (R Development Core Team 2008). The methods were chosen because they can use class variables as predictor variables. The RandomForest procedure grows multiple classification trees from bootstrap samples of the training data and determines the predicted class by majority vote over all classification trees. Predictions of a class variable with discriminant analysis are based on a reduced set of independent canonical discriminant functions of the original variables to remove multi-collinearity (Hamann and Wang 2006). The approach is similar to using Mahalanobis distances, which uses principal component analysis to remove collinearity (e.g. Farber and Kadmon 2003). Mahalanobis distances to the mean vector of a class are equivalent to Fisher's discriminant functions (Kshirsagar and Arseven 1975)

The key difference between the two methods I used is that the scaling of the predictor variables matters in discriminant analysis where the classification is ultimately based on a Euclidean distance. In contrast, the scaling of the predictor variables is irrelevant for classification trees. Log-transformation of a predictor variable, for example, simply results in different threshold values at tree nodes, but the binary decision trees and the predictions remain the same. While these two methods represent contrasting modeling approaches, I not could evaluate a full range of predictive models in this study because many widely used methods require "probability of presence" as a dependent variable and cannot predict an ecosystem class variable.

As dependent class variable I used mapped ecosystems for western Canada and the United States, rasterized at 1km resolution. From each of approximately 400 mapped ecosystems, 100 grid cells were randomly sampled to be used as training data for classification tree and discriminant analysis. For British Columbia I used the "Variant" level of the Biogeoclimatic Ecological Classification system version 4 (Meidinger and Pojar 1991). In Alberta, I used the "Seedzone" level of Natural Regions and Subregions System, 2005 release (NRC 2006). "Ecodistricts" of the National Ecological Framework for Canada were used for Saskatchewan and Manitoba (Selby and Santry 1996), and "Level 4" delineation of the United States Ecoregion System were used for the area west of 100° longitude and north of 42° latitude (EPA 2007).

I aggregated predictions of the ecosystem modeling units at a higher hierarchical level of "Ecoregions" for reporting, and inferred species distribution maps from known species frequencies for ecosystems as described in Hamann and Wang (2006). This approach has some disadvantages (e.g. spatial autocorrelations in the ecosystem response variables requires a different approach to model validation), but the method has been shown to reliably predict species range limits and outlying populations far beyond data coverage (Hamann and Wang 2006). On the other hand, the approach has the practical advantage that the underlying modeling units are used as a framework for natural resource management. Predicted ecosystem or seedzone units directly suggest a set of management practices for anticipated future climates.

### *4.2.2. Predictor variables*

Two baseline climate datasets based on thin-spline interpolation (Rehfeldt et al. 2006), and generated with the Parameter-elevation Regressions of Independent Slopes Model (PRISM) (Daly et al. 2008) were compared. Both datasets are based on climate normal data observed at weather stations for the period 1961–1990 for the United States and Canada. These interpolated climate surfaces are near identical in areas with good weather station coverage, but diverge significantly in their estimates of climate values for mountainous areas and northern latitudes. The most prominent differences are estimates of seasonal temperatures north of 55° latitude with differences of up to 6°C, and precipitation estimates in high elevation mountainous regions that can exceed a 50% difference in seasonal precipitation values. From both datasets I calculated biologically relevant climate variables for modeling according to Wang et al. (2006). Variables include mean annual temperature, mean warmest month temperature (July), mean coldest month temperature (January), continentality (difference between mean January and mean July temperature), mean annual precipitation, mean summer precipitation (May to September), annual heat moisture index, summer heat moisture index, number of forest free days, chilling degree days below 0°C, growing degree days above 5°C, and extreme minimum temperature.

The IPCC (2007) recommends that climate change projections for different emission scenarios and from different general circulation models should be treated with equal probability, and ideally a full range of climate projections should be used in predictive biological models to reflect uncertainty in projections. I therefore used the four major SRES emission and population growth scenario families (A1FI, A2, B1, B2) and implementations of these scenarios by five modeling groups (CGCM2, Canada; HADCM3, UK; ECHAM4, Europe; CSIRO2, Australia; and PCM, United States). Future climate projections were limited to one future time slice, the 2041–2070 normal period, hereafter referred to as the 2050s. Interpolated anomalies of climate change projections from various general circulation models were added as deviations from the 1961–1990 normal period to the 1km resolution baseline climate datasets according to Mbogga et al. (2009), using a software package that is freely available[3].

Since a number of ecosystem classes in the study area are primarily defined by bedrock and soil factors, I replicated all model runs including a set of static, topo-edaphic predictor variables in addition to climate variables. As topo-

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[3] Available for download at http://www.ualberta.ca/~ahamann/climate.html

edaphic predictor variables, I used a relative radiation index as a proxy for exposure due to slope and aspect, and a topographic convergence index as a proxy of water availability. The relative radiation index was generated for a custom digital elevation model according to Pierce *et al.* (2005). This index is an estimate of the amount of solar radiation received as a function of sun angle, slope, aspect and shadowing by adjacent topography. A compound topographic index to describe the effect of soil water accumulation resulting from topography was calculated according to Gessler *et al*. (1995). This index accounts for slope and the upstream contributing area per unit width of the perpendicularly oriented down-slope water flow. In addition to these topographic indices, I used soil descriptors that are available from the International Geosphere-Biosphere Programme at relatively low resolution of 5 arcminutes or approx. 10km (GSDT, 2000). This data was joined to the 1km master dataset without manipulations except for re-projection and gap-filling. The variables include soil-carbon density (kg/m$^2$), total nitrogen density (g/m$^2$), field capacity (mm), wilting point (mm), profile available water capacity (mm), and bulk density (g/cm$^3$).

#### *4.2.3. Sensitivity analysis*

The modeling effort was organized in a factorial experimental design with multiple treatment levels (Table 4-1) and resulted in 144 projections of approximately 400 ecosystem climate niches for the 2050s (2 baseline climate datasets × 2 modeling methods × 2 sets of predictor variables × 5 GCMs and × 4 emission scenarios, minus two GCM-emission scenario combinations that were not available: ECHAM4-A1FI and ECHAM4-B1). As the next step, projections of the 400 fine scale ecosystems were converted into 12 major macroclimatic ecosystem classes (Figure 4-1 legend) for display as maps and for analysis. Alternatively, the ecosystem projections were converted to maps of potential species habitat of aspen (*Populus tremuloides* Michx.) by replacing the ecosystem classes with their corresponding species frequencies. Species frequencies for mapped ecosystems were calculated based on forest inventory plot data for Canada according to Hamann et al. (2005) and the data coverage was extended to the United States with the Forest Inventory and Analysis database (Bechtold and Patterson 2005). For this case study suitable aspen habitat was defined as all forested ecosystems where the average areal crown coverage of aspen projected to the ground exceeds 5%, i.e. aspen would be a major component on the landscape.

These projected biome and aspen habitat maps were the basis for queries that were performed on data tables with PROC UNIVARIATE in SAS (SAS Institute 2008). Data tables were arranged so that rows represent the 1km grid cells of predicted maps, and 144 columns represent the projections based on various combinations of factors that contribute to uncertainty. Additional columns contained geographic information required for queries such as latitude, longitude, elevation, province, state, protected area information, mapped ecosystem, or forest management units. A typical query consisted of a series of conditional statements that narrowed the total study area to an ecosystem, species, jurisdiction, or management unit of interest (or a combination of these). For the remaining data rows, I calculated statistics for each column of projections. Statistics included the 90$^{th}$ percentile of the latitude of a species or ecosystem to measure latitudinal shifts of climate envelopes. Similarly, shifts along elevation gradients were measured by the 10th, 50th, or 90th percentile of the elevation variable depending on the typical position of an ecosystem on a mountain range. Counts of raster cells where an ecosystem or species was present were used as measures of the amount of potential habitat for an area of interest. Changes in the amount, elevation, or latitude of potential habitat were calculated as the difference from projections for the 1961–1990 reference climate. These queries were performed on biome summaries of ecosystem predictions as well as projections of changes to aspen suitable habitat (Figure 4-1, a).

Tables of summary statistics were then merged and transposed to obtain a new data table where treatments (or sources of uncertainty) were represented by five class variables and summary statistics of changes in projected habitat as dependent variables in columns (one for each query). The data were then subjected to an analysis of variance and estimation of variance components with the restricted maximum likelihood method implemented with PROC VARCOMP/REML of the SAS statistical software package (SAS Institute 2008). Additionally, I used box plots for visual representation of variation due to different sources of uncertainty.

**4.3. Results and Discussion**

First, I discuss three case studies that I found educational from a scientific perspective, with data queries carried out at the ecosystem level (Figure 4-1).

Secondly, I discuss how multiple projections may be used to guide species choice for reforestation using projections of suitable habitat for trembling aspen. I do not display or evaluate the United States section of the study area. These ecosystems were included in the training data to cover climate niche space equivalent to what is expected under climate change projections in Canada.

### *4.3.1. Grassland–forest transition in Saskatchewan*

This first query evaluates the northward shift of the grassland climate envelope between 105 and 107° longitude. The shift under climate change scenarios for the 2050s is expressed in kilometers relative to the 1961-1990 reference projection, and is measured as the location of the 90$^{th}$ percentile of grid cells. By using the location of a percentile rather than the most northern grid cell of the grassland climate envelope, a more robust estimate for the location of its northern boundary is obtained. The northward expansion of the grassland climate envelope in Saskatchewan depends largely on whether or not topo-edaphic variables are included as predictor variables and climate change projections indicated by the interquartile range are a large contributor to uncertainty (Figure 4-2). A formal analysis of variance reveals another dimension to the modeling results. It has already been recognized that topo-edaphic are an important factor, accounting for approximately 15% of the variance (Table 4-2) but surprisingly there are no main effects of GCM and SRES emission scenarios. Climate projections only appear in interaction terms, mainly with modeling methods. Under RandomForest, the results for warm and wet scenarios are comparable to a dry scenario, while under discriminant analysis, dry and wet scenarios have very different outcomes (e.g. compare Figure 4-1b and 1c).

In this case, I think that the discriminant analysis based approach provides a biologically more plausible result (increased precipitation compensates for increased temperature). RandomForest either used a fairly high precipitation value for the relevant node in the decision tree or did not use precipitation variables to determine the grassland transition zone at all. This is quite plausible because the latitudinal temperature gradient matches the grassland transition zone very closely. One could therefore dismiss RandomForest-based model runs for this particular query. In this way we can narrow plausible results from 144 projections to a smaller number by examining which factors contribute most to the uncertainty in modeling results, and then excluding biologically improbable or statistically questionable results. A smaller number of plausible model projections will usually also result in a narrower range of projections that practitioners need to consider in developing climate change adaptation strategies.

### *4.3.2. Coastal subalpine forests of southern British Columbia*

This second query evaluates the $50^{th}$ percentile of elevation for the subalpine forest climate envelope for the Coast Mountains of southern British Columbia (Figure 4-3), representing elevational shifts of the climate envelope for this ecosystem. Contrary to the first example, there is no effect due to including topo-edaphic variables. The soils database I used is too low in resolution to provide meaningful information in mountainous areas. However, the high resolution topographic predictor variables CTI and PRR representing exposure and soil moisture due to slope position and aspect did not contribute to variance in modeling results, indicating that they are not essential to characterize the subalpine ecosystem class at this relatively high-level ecosystem summary.

I primarily chose this query because in this area PRISM and ANUSPLIN baseline climate data are quite different, with the PRISM methodology accounting for orographic lift, rain shadows, and slope aspect when estimating climate variables. What I perceive as a much better baseline climate model for this area (PRISM) results in smaller climate envelope shift and slightly less variable results. However, it is apparent that the quality of baseline climate models for this region is not critical, accounting only for 11% of the total variation, and further improvement of climate data for this region may not be a worthwhile effort.

Another notable observation in this example comes from a comparison with a previous study, which reported an envelope shift of the Mountain Hemlock Zone of +418m in elevation (Table 3, Hamann and Wang 2006). This is a sufficiently similar query based on a median scenario for British Columbia, but yielding a relatively high value compared to this study. This discrepancy is explained by the fact that a median scenario for British Columbia was not a median scenario for the south coast. Secondly, the previous study selected a median scenario with respect to mean annual temperature and mean annual precipitation, but these may not be the variables that determine the niche space of interest. Third, a median climate change scenario may not always lead to a median modeling result due to the stochastic nature of most predictive models. Therefore, I want to stress that practitioners would be ill-advised with recommendations that are based on a single or a small number of model runs, i.e. the widely used set of a "median", a "pessimistic", and an "optimistic" scenario.

#### *4.3.3. Northern Boreal forests of Alberta*

The third example evaluates the count of boreal forest raster cells that are predicted to be within a different biome climate envelope by the 2050s (almost always dry forest or grassland). The changes are expressed as percent loss of boreal forest climate envelope relative to the projection based on 1961-1990 reference climate (Figure 4-4, Table 4-2). We see a repeat of patterns that I have discussed before. Topo-edaphic variables as predictors have an influence, warm and wet scenarios cause an interaction effect in the GCM-method term that is somewhat less pronounced than in the first example, and we see a relatively small baseline climate influence. As in the previous example, the climate baseline datasets differ substantially for this region. The ANUSPLIN estimates for the northern boreal highlands exceed PRISM estimates by 3°C in mean annual temperature and up to 6°C in winter temperature, a difference that is larger than projected climate change. Nevertheless, these discrepancies in baseline climate data account for only a minor portion of the total variance in results (Table 4-2). Again, it appears that bioclimate envelope modeling techniques are surprisingly robust to how ecosystems or species' ranges are climatically characterized with baseline climate.

This query is an example for very high uncertainty in modeling results for the study area. For both subsets, "climate only" and "climate and topo-edaphic" as predictor variables, we see a very large range of possible outcomes (about 10% – 70% of boreal climate envelope replacement). If the results of the RandomForest model runs for the wet scenarios as previously discussed are dismissed, the overwhelming source of uncertainty are different climate projections. The variable results may to some degree reflect the biological systems that were subject to this query. Northern boreal ecosystems receive low precipitation (around 300-450mm mean annual precipitation) and generally have thin, nutrient-poor and acidic soils. Many areas are water-logged coniferous forests or wetlands, such as sphagnum bogs. There are no obvious biological outcomes if these possibly highly buffered, water-saturated ecosystems are subjected to grassland or dry forest type climates in the future.

#### *4.3.4. Aspen habitat in the Ainsworth FMA*

In many cases, model projections are less variable and easier to interpret than in the previous case study. In the following example I evaluate projections of aspen habitat in the forest management area G16 in Alberta. The area is managed for hardwood supply of a nearby oriented strand board plant, which processes approximately 1 million cubic meter of hardwood timber annually. Here I ask if this forest management unit will continue to provide suitable habitat for aspen in the future, and evaluate changes in the count of raster cells with suitable aspen habitat projected for the 2050s (Figure 4-5, Table 4-2). Projections range from 0-20% loss of habitat and most variation in projections is explained by different climate change scenarios and higher order interactions that are due to erratic behavior in some model projections for this region (outliers in Figure 4-5). There is no need for filtering these reasonably consistent model results, and thus only minor changes to hardwood supply from this forest management area would be expect by the 2050s, assuming that there are no negative impacts due to maladaptation of local aspen genotypes.

Another way to visualize uncertainty in model projections for aspen habitat over larger geographic areas are composite maps of all model runs (Figure 4-6). Maps of average species frequency indicate where aspen is expected to be a major forest component in the future (Figure 4-6C), and counts of presence or absence from all model projections indicate the risk of habitat loss (Figure 4-6D). These two measures can guide climate-informed forest management. For example, aspen is currently most frequent in the dry Mixedwood ecosystem north and northeast of the G16 forest management area of Alberta (Figure 4-6A). A majority of model runs, however, project a complete loss of habitat for aspen over much of this area (Figure 4-6D). In contrast, moderately high aspen frequencies and low probability of habitat loss are expected along a jet stream driven storm track that originates in the Rocky Mountains and crosses Alberta in northeast direction. Reforestation or management practices encouraging aspen regeneration should therefore shift to the central Mixedwood ecosystems that receive more rainfall.

To further help with confident decisions, I think it is useful to provide model runs based on observed climate trends (Figure 4-6B). The 1997-2006 average climate represents an approximately 25-year climate trend relative to the 1961-1990 normal period. Already, a northward shift of high frequency aspen habitat and habitat loss along the southern edge of the species distribution in Alberta are observed. This corresponds to drought-related dieback and loss of productivity observed in the parkland ecosystems (Hogg et al., 2008, Hogg and Bernier, 2005). Thus, the combined information from GCM projections, climate trends that have already materialized, and observed biological response make a strong case for implementing adaptation strategies in the dry Mixedwood and aspen parklands: e.g. reforestation programs should rely on more drought tolerant species or genotypes in the future, and aspen forestry should concentrate on the moister central Mixedwood ecosystems in Alberta.

### 4.5. Conclusions

In this chapter, I make the case for using bioclimate envelope modeling to match natural resource management practices to anticipated future climates. Because of considerable uncertainty in bioclimate envelope projections, such recommendations should be based on the widest feasible selection of modeling methods, climate change projections, and data sources. If these factors of uncertainty are systematically investigated in a factorial design, large main effects and interaction terms can effectively point to shortcomings in methodology or data quality. This offers an opportunity for the researcher to exclude model runs with biologically or statistically implausible results, and to provide a narrower range of projections that practitioners need to consider in developing climate change adaptation strategies. The task of interpreting a large number of queries is not onerous for the researcher. Even for the varied landscape in this study a relatively small number of qualitatively different results for variance partitioning was observed. Therefore the following general conclusions about how potential sources of uncertainty contribute to variance in modeling results can be drawn:

1) Different interpolation techniques for baseline climate did not contribute more than 10% to the uncertainty in modeling results, even though local differences due to interpolation techniques sometimes significantly exceeded climate change projections. It appears that modeling results are

surprisingly robust to how ecosystems or species' ranges are climatically characterized with baseline climate.

2) In several queries, topo-edaphic factors were relevant predictor variables, which had a constraining effect on climate change projections as observed in other studies (e.g. Coudun et al. 2006; Luoto and Heikkinen 2008; Taverna et al. 2005). However, multi-collinearity among static factors and climate variables can lead to under-estimation of climate change impacts (e.g. Araujo and Guisan 2006). Further, the use of indirect proxies for plant resources (here, CTI and PRR) are not suitable for modeling techniques that rely on a constant statistical relationships over large study areas (Guisan and Zimmerman 2000). The two modeling techniques used in this study are fairly robust to multi-collinearity and account for local interactions of predictor variables. For some queries, it may therefore be worthwhile to think about whether soil or climate variable are causally related to ecosystem type or species habitat. Again, the objective would be to dismiss a subset of the model projections and narrow the range of projections that practitioners need to consider.

3) Contrary to other studies (e.g. Pearson et al 2006, Hijmans and Graham 2006), modeling methods were not the largest contributors to uncertainty. However, since I only employ two modeling approaches, one needs to be careful in drawing general conclusions. In a recent paper that compares a larger range of methods using a similar variance partitioning approach, Diniz-Filho et al (2009) found that modeling methods account for most of

the variance while interactions account for approximately 15% in overall species turnover.

4) In this study, general circulation models and their interactions with emission scenarios and modeling methods were the largest contributors to uncertainty. In this situation, a valuable check before implementing adaptation strategies is to analyze locally observed climate trends. I showed that model projections, observed climate trends, and observed biological impacts can make a strong case for changing current management practices. Otherwise, I propose that bioclimate envelope model projections should be used to guide management changes on a moderate scale, e.g. using different species or genotypes for reforestation on 5% of the harvested land base. Over the next decades the success or failure of these changes will provide invaluable empirical data to complement guidance from imperfect models.

Table 4-1. Factorial experimental design to determine which factors and interactions contribute most to the uncertainty in bioclimate envelope model projections.

| Treatments and treatment levels |
|---|
| 1) Predictor Variables (2 levels) |
| 1a) 12 Climate variables |
| 1b) 12 Climate variables and 8 topo-edaphic variables |
| 2) Modeling Method (2 levels) |
| 2a) RandomForest classification tree analysis |
| 2b) Mahalanobis distance based discriminant analysis |
| 3) Climate Baseline Data (2 levels) |
| 3a) Thin plate smoothing spline interpolation (ANUSPLIN) |
| 3b) Interpolation with the Parameter-elevation Regression of Independent Slopes Model (PRISM) |
| 4) General Circulation Model (5 levels) |
| 4a-4e) CGCM2, CSIRO2, ECHAM4, HADCM3, PCM |
| 5) SRES Emission Scenario (4 levels) |
| 5a-5d) A1FI, A2, B1, B2 |

Table 4-2. Variance components corresponding to sources of uncertainty and their interactions. The location of queries are shown in Figure 4-1.

| Treatments | Query 1 (SK Grasslands) | Query 2 (BC Mountains) | Query 3 (AB Boreal) | Query 4 (AB FMA) |
|---|---|---|---|---|
| **Main effects** | | | | |
| Predictor Variables | 15% | 0% | 20% | 1% |
| Modeling Method (MM) | 0% | 3% | 2% | 0% |
| Climate Baseline data | 1% | 11% | 7% | 0% |
| General Circulation Model (GCM) | 0% | 43% | 0% | 24% |
| Emission Scenarios (SRES) | 2% | 7% | 21% | 11% |
| **Interactions** | 42% | 11% | 31% | 15% |
| GCM x MM | 25% | 12% | 12% | 11% |
| GCM x SRES | 15% | 13% | 7% | 38% |
| Other | | | | |

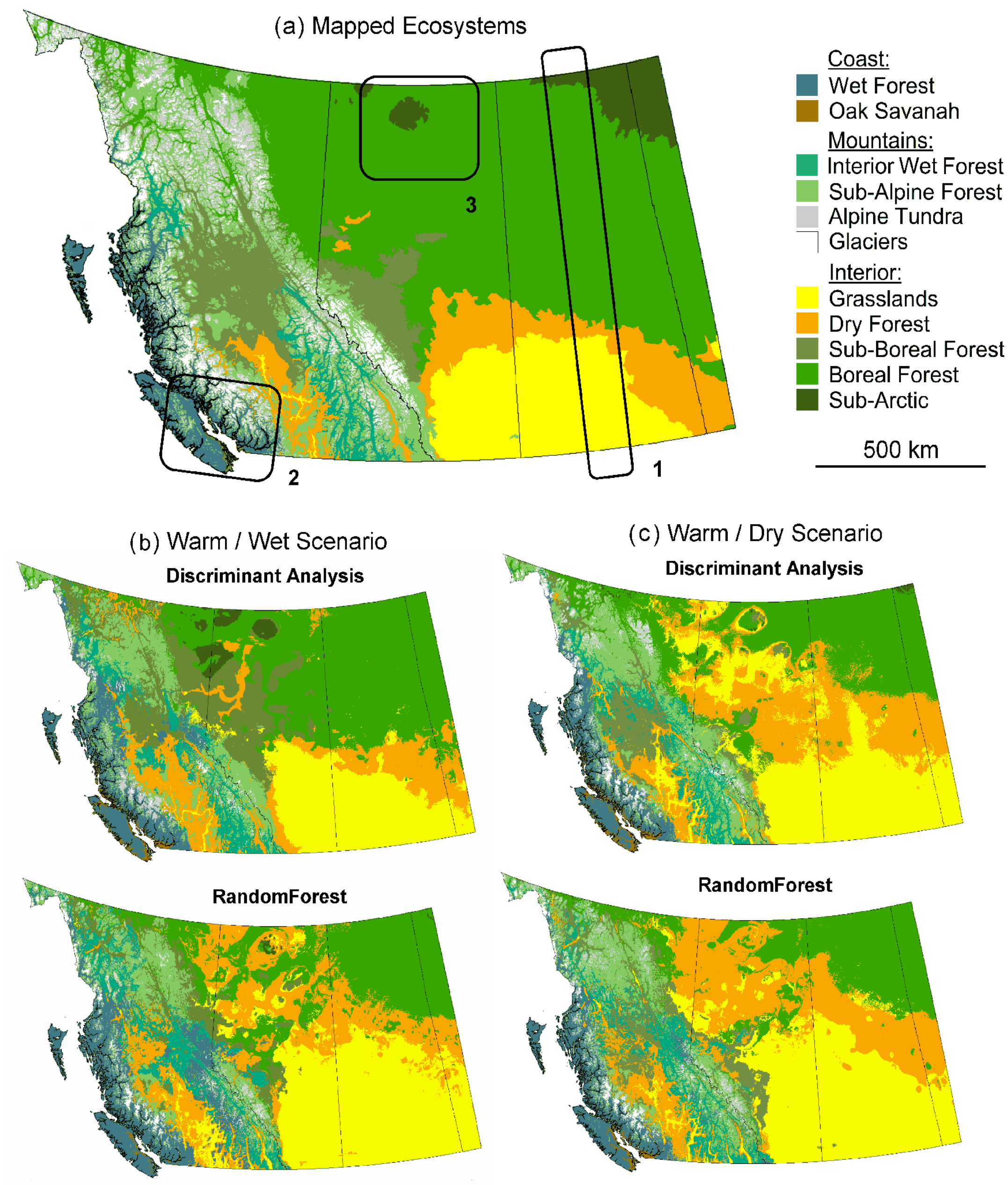


Figure 4-1. Current and projected ecosystem climate envelopes for the 2050s. (a) shows the location of queries numbered in the order of discussion in the text, (c) shows different behavior of modeling methods for a warm and wet scenario (CSIRO-A1) and (c) shows similar model behavior for a warm and dry scenario (CGCM2-B2).

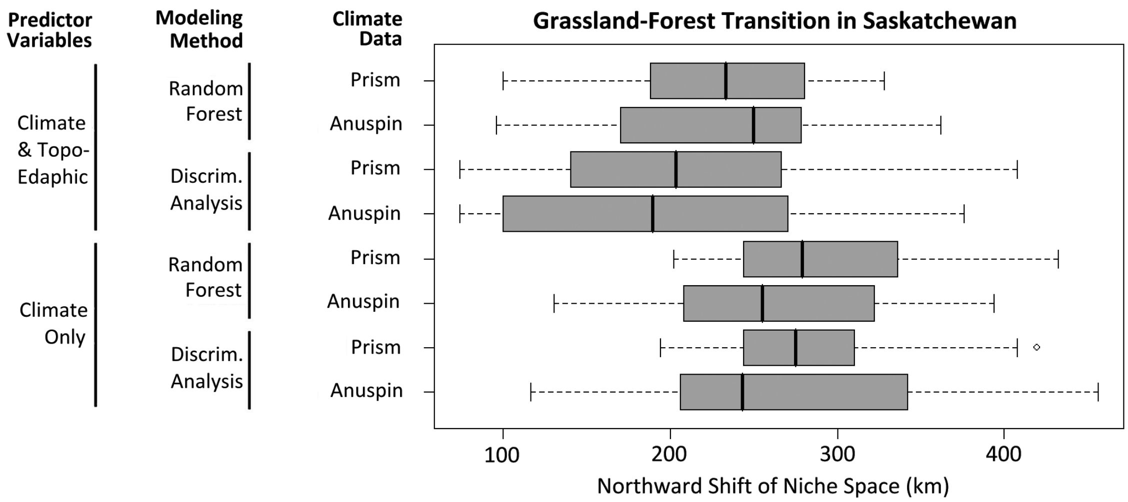


Figure 4-2. Variation in bioclimate envelope modeling results for different datasets and methods (left) and different climate change projections (boxplots). The measured variable is the 90$^{th}$ percentile of latitude of projected grassland ecosystems, reported as northward shift in kilometer relative to the 1960-1990 reference climate projection.

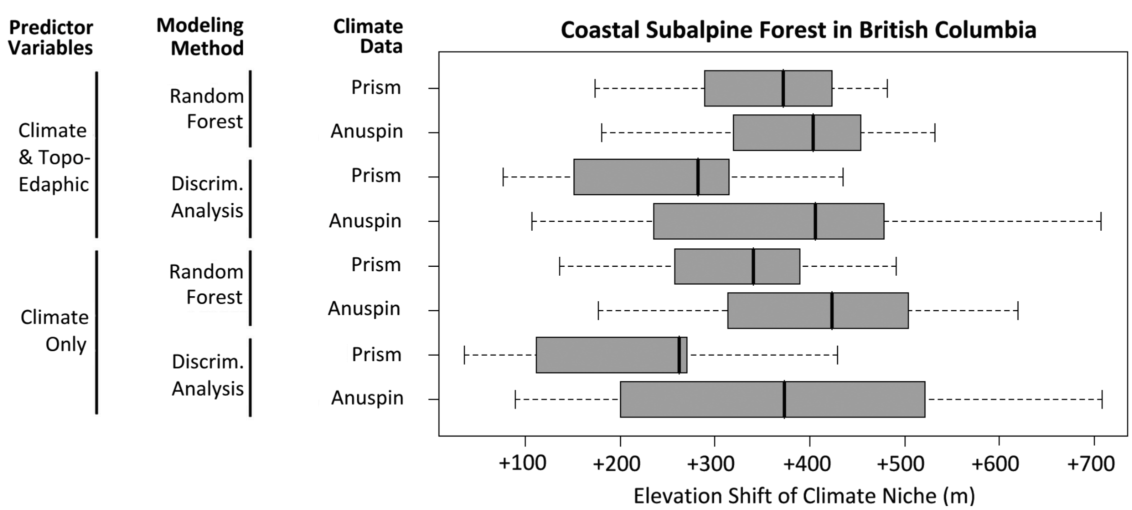


Figure 4-3.Variation in bioclimate envelope modeling results for different datasets and methods (left) and different climate change projections (boxplots). The measured variable is the 50$^{th}$ percentile of elevation of the subalpine forest biome, reported as elevation shift in meters relative to the 1960-1990 reference climate projection.

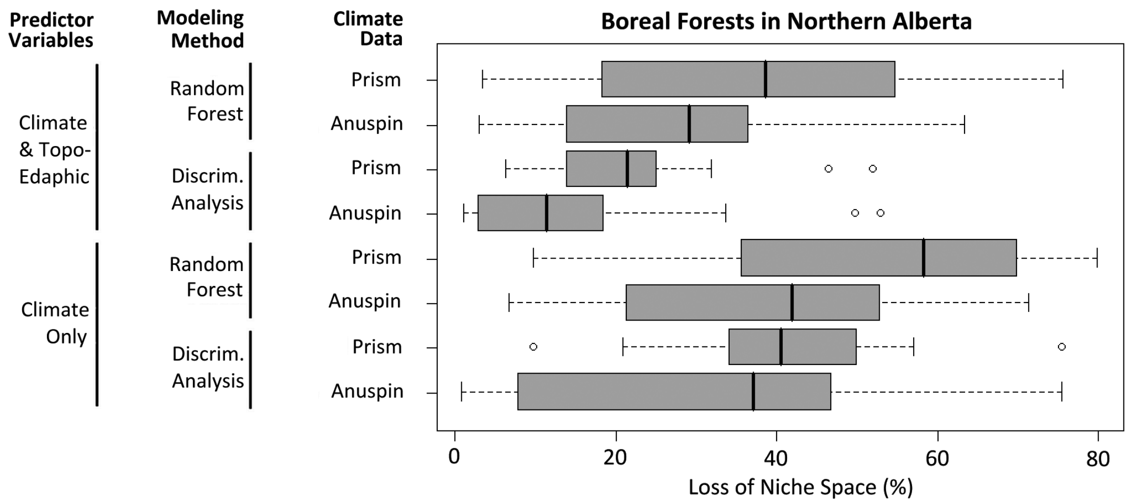


Figure 4-4. Variation in bioclimate envelope modeling results for different datasets and methods (left) and different climate change projections (boxplots). The measured variable is the area of projected boreal forest ecosystems, reported as percent loss relative to the 1960-1990 reference climate projection.

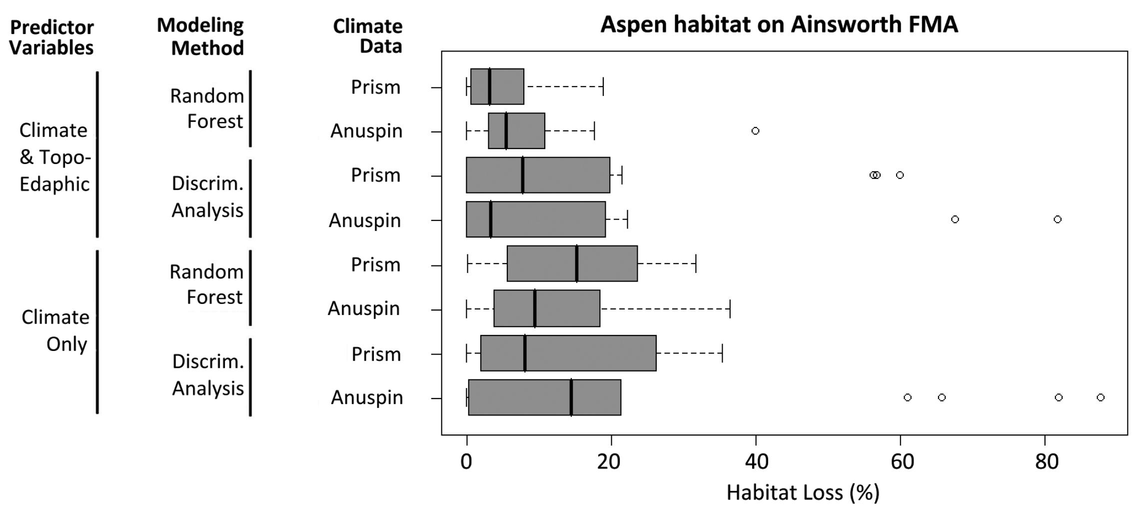


Figure 4-5. Variation in bioclimate envelope modeling results for different datasets and methods (left) and different climate change projections (boxplots). The measured variable is the area of projected aspen habitat, reported as percent loss relative to the 1960-1990 reference climate projection

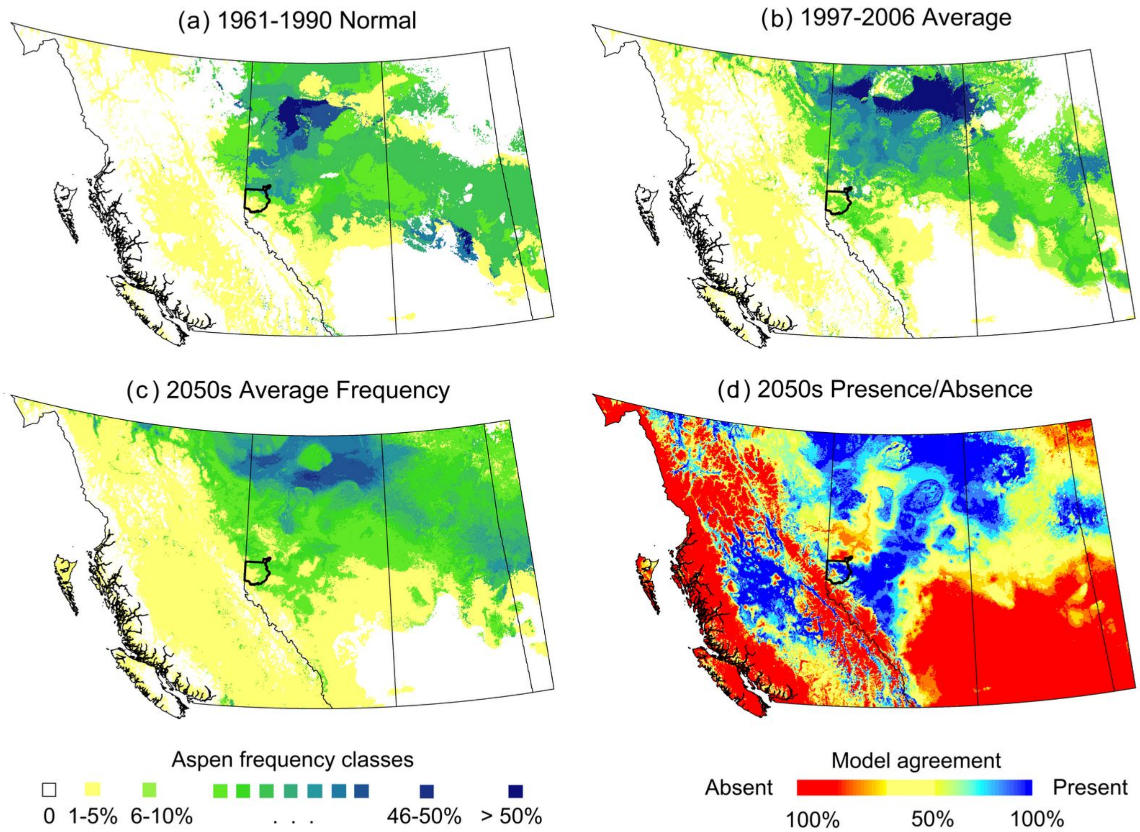


Figure 4-6. Predicted aspen frequencies for under for (a) the 1961-1990 climate normal period, representing the model training data, (b) a recent 10-year average, representing observed climate trends over the last 25 years relative to the climate normal, (c) average aspen frequency projections for the 2050s and (d) model agreement with respect to suitable aspen habitat predicted for the 2050s. The G16 management area for Query 4 is shown as a black outline.

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## Chapter 5. Assisted migration to address climate change: recommendations for aspen in western Canada[4]

### Summary

Bioclimate envelope models are widely used to predict species habitat under projected future climates. Such information is useful to guide species choice for uncertain future climates in reforestation programs. It is also acknowledged, however, that most wide ranging tree species should probably not be modeled as a homogenous unit because they consist of different populations that are adapted to the local environments in which they occur. This genetic structure is reflected in forest management through seed transfer guidelines or seedzones, which restrict movement of seed sources to avoid maladaptation. A reforestation strategy for uncertain future climates must therefore go beyond species recommendations and determine which locally adapted genotypes should be used at particular planting sites. I present a modeling approach to address this issue. In a case study for aspen, I subdivide the species range into zones that represent similarly adapted genotypes, and then use regression tree analysis to predict the distribution of habitat for these genotypes under multiple climate change scenarios.

Subsequently, I use a consensus approach to determine the genotype that emerges as best adapted under the majority of climate change scenarios. I also report the degree of uncertainty in making a recommendation for locally adapted planting stock. In the case of aspen, recommendations of moving planting stock 1° to 2° latitude north can be made with high confidence over a 10-20 year planning horizon. However, confidence in planting stock recommendations decreases

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dramatically for the 2050s and 2080s, even for areas where species habitat is projected to be maintained with high certainty. Nevertheless, it appears unlikely that by the 2050s and 2080s aspen planting stock that is adapted to moist environments of the Rocky Mountain Foothill ecosystems and the adjacent Boreal Plains zone of western Canada could still be deployed in the study area.

## 5.1. Introduction

The transfer of locally adapted planting stock in reforestation programs to areas whose climate is predicted to be suitable in the future has been suggested as a viable adaptation strategy to climate change for reforestation and has often been described as assisted migration (Marris 2009; Millar et al. 2007; Ying and Yanchuk 2006). Thus, identifying suitable species for reforestation under changing climate is important but only a first step in the process. This has to be accompanied by identifying locally adapted genotypes to be matched with planting sites to ensure adaptation to future climate. This study explores the question of selecting genotypes for reforestation under uncertain future climate following a decision about species choice, for which I provided a methodological approach in a previous paper (Mbogga et al 2010).

Tree populations normally exhibit adaptation to local environmental conditions (Langlet 1963). Local populations usually have higher relative fitness than genotypes transferred to a planting site from other locations (Kawecki and Ebert 2004; Savolainen et al. 2007). Local adaptation of tree populations occurs with respect to a number of selective forces such as climate conditions, pathogens, or edaphic factors (e.g. Morgenstern 1996). In practical forest management, sub-structure of a species into locally adapted populations is reflected by a seedzone system to guide reforestation (e.g. Ying and Yanchuk 2006). Usually, the assumption of optimal local adaptation of tree populations is made in order to develop tree breeding areas or seedzones. Tree seedzones have been delineated as areas within which individuals of a population are similarly adapted and can therefore be moved freely to new planting sites. Since it is difficult to investigate geographic patterns of genetic variation in tree populations, this information is not available for all species. In such cases, environmental surrogates are often used for the delineation of seedzones (Parker 2000; Post et al. 2003; Ying and Yanchuk 2006). As genetic information becomes available, seedzone delineation has usually been refined (O'Neill and Aitken 2004; Xie 2008). Sometimes, genetic information proves the assumption of local optimality wrong, which is then reflected in asymmetric seed transfer guidelines that encourage practitioners to move seed sources to new locations (Ying and Yanchuk 2006). Similar asymmetric transfer guidelines to move planting stock within (or beyond) the current species range would be an obvious adaptation strategy to changing climate (Spittlehouse 2005; St Clair and Howe 2007).

To predict species habitat for locally adapted genotypes, bioclimate envelope models could be developed for similarly adapted genotypes, rather than the species as whole. While this approach has been previously proposed (e.g. Botkin et al. 2007), I am not aware of any implementations of this idea. One difficulty is the appropriate delineation of similarly adapted genotypes. Another problem could be insufficient census data to build bioclimate envelope models at the genotype rather than the species level. Here, I am using an ecosystem-based modeling approach to stratify a species into similarly adapted genotypes. In a case study for trembling aspen (*Populus tremuloides* Michx.), I first determine which areas will maintain suitable for aspen under multiple climate change scenarios at the species level, and subsequently I determine the best adapted aspen genotypes through a majority voting approach. Given the large uncertainty in future climate projections, I further quantify the degree of confidence in making recommendations for changes to the current seed zone system.

## 5.2. Methods

### *5.2.1. Climate datasets*

Baseline climate data for the 1960 - 1990 normal period and projected climate changes were generated for a 1x1km western Canada grid. Climate datasets were generated using the climateBC/PP software applications that generate scale-free baseline climate data for the mountains and plains regions of western Canada (Mbogga et al. 2009; Wang et al. 2006). The software applies bi-linear interpolation and elevation adjustment to 1961-1990 climate grids developed by the parameter - elevation regressions on independent slopes model-PRISM. The software also downscales medium resolution projected anomaly surfaces, and then overlays these deviations onto a high resolution 1961–1990 baseline normal dataset to generate future climate grids as described by Wang et al (2006).

Future climate data was generated for 18 future climate projections based on five general circulation models (A1FI, A2, B1, B2) and implementation of these scenarios by five modeling groups (CGCM2, Canada; HADCM3, UK; ECHAM4, Europe; CSIRO2, Australia; and PCM, United States). ECHAM climate projections were only available for only 2 out of the 4 SRES scenarios. Projected climate was generated for three future time slices that is the 2011-2040, 2041–2070 and the 2071-100 normal periods, hereafter referred to as the 2020s, 2050s and 2080s respectively. The scenario family A1 represents a trend of globalization, resource-intensive economic growth and rapid population increase, A2 assumes slower population growth and regionally fragmented economic growth. B1 assumes the same global population growth as A1, but a shift towards a service and information economy, B2 represents the lowest population increases and local, environmentally sustainable economies (Nakicenovic et al. 2000).

### *5.2.2. Aspen distribution data*

The first step in getting aspen distribution data for western Canada involved assembling ecological information from different jurisdictions which was combined and harmonized. For British Columbia I used the "Variant" level of the Biogeoclimatic Ecological Classification system version 4 (Meidinger and Pojar 1991). In Alberta, I used the "Seedzone" level of Natural Regions and Subregions System, 2005 release (NRC 2006). "Ecodistricts" of the National Ecological Framework for Canada were used for Saskatchewan and Manitoba (Selby and Santry 1996), and "Level 4" delineation of the United States Ecoregion System were used for the area west of 100° longitude and north of 42° latitude (EPA

2007). Aspen frequencies for mapped ecosystems were then calculated based on forest inventory plot data for Canada according to Hamann et al. (2005). Aspen frequency data from inventories were then overlaid over maps of ecological units to generate an overall mean aspen frequency in each ecological unit. Observed aspen frequency for each ecological unit was calculated as the mean of aspen frequency for all raster grids falling within the ecological unit. Suitable aspen habitat was defined as all forested ecosystems where the average crown coverage of aspen projected to the ground was more than 5%.

Additional information used comprised delineation of the major trembling aspen seedzones in western Canada. Four major aspen seedzones have been delineated in western Canada based on performance of genotypes in reciprocal transplant experiments (Gylander et al, unpublished manuscript). These seedzones are named after the major ecological regions, with which they approximately coincide; Taiga, the Northern Boreal, the Boreal Plains and the Rocky Mountain Foothills (Figure 5-1).

### *5.2.3. Bioclimate envelope modeling*

Bioclimate envelope modeling was carried out using RandomForest (Breiman 2001; Cutler et al. 2007) implemented by R software (R Development Core Team 2008) using 10 climate variables determined after careful elimination of highly correlated variables. RandomForest grows multiple classification trees from bootstrap samples of the training data and determines the predicted class by majority vote over all classification trees (Cutler et al. 2007). Climate variables used for modeling include, mean annual temperature, mean warmest month (July) temperature, mean coldest month (January) temperature, continentality or the difference between warmest and coldest month temperature, mean annual precipitation, mean summer precipitation, growing degree days or degree days above 5°C, frost free period, annual climate moisture index and climate moisture index for the summer months (June, July and August). Bioclimate envelope modeling of changes to aspen suitable habitat was done at the smallest ecological subdivisions and predictions subsequently summarized in terms of corresponding aspen frequency for each ecological unit.

Predictions of change to the four aspen seedzone suitable habitats based on 18 future climate projections were summarized using a voting system whereby projected change for each 1x1km grid was computed as a majority vote from the 18 individual predictions. The result then was a proportion of current seedzones that will remain suitable for aspen and that expected to change into another seedzone or to lie outside the range of the four seedzones as well as where suitable habitat equivalent to any of the seedzone is likely to be in the future depending on a majority of the projections. For each grid, the level of agreement of the 18 predictions based on several general circulation models and emission scenarios were computed, to provide for the level of consensus for the predicted change in aspen seedzone climate niche.

## 5.3. Results

### *5.3.1. Climate change and climatology of the study area*

Over the last 25 years, there has been a temperature increase across the study area that was more pronounced in the north (+1.4°C) than the south (+0.8°C) with more warming in winter than in summer temperatures (Table 5-1). This matches global patterns described in the IPCC fourth assessment report (IPCC 2007) and essentially matches climate projections that were made by general circulation models for the 2020s (Table 5-2). Further, there was a trend towards drier climate conditions throughout the ecosystems listed in Table 5-1. Reduction in precipitation was more pronounced in winter, and together with warmer winter temperature have resulted in major reductions in precipitation as snow (Table 5-1). Observed trends in mean annual precipitation are opposite in direction to projections by most general circulation models (Table 5-2).

Before spatial modeling of climate envelope shifts, it is instructive to examine the climatology of the study area. The Foothill ecosystem stands out with higher precipitation and a more maritime climate (cooler summers and warmer winters) than all other zones. Excluding the foothills, there is a clear north-south gradient in temperature, as well as a hump-shaped latitudinal precipitation gradient that has a maximum at 55-56°N corresponding to the jet-stream storm track over the Boreal Plains region. From there, precipitation declines toward the Northern Boreal ecosystems and the aspen parklands in the south. Taking climate trends observed over the last 25 years into account, the Boreal Plains for the

1997-2006 period (MAT=1.6, MAP=444) starts to resemble the Aspen Parkland. The northern Boreal zone under the 1997-2006 period is very dry, but does not reach the 1961-1990 temperature values of the aspen parkland. The most northern Taiga Plains under the 1997-2006, does not quite reach the temperature values of the current Northern Boreal zone, but exceeds it in dryness. This implies a general north shift of climate envelopes for a recent 10-year period, excluding the foothill forest ecosystem.

### *5.3.2. Suitable aspen habitat under future climate*

Bioclimate envelope model projections for the 2020s, 2050s, and 2080s generally show a northward shift of suitable aspen habitat (Figure 5-2). Aspen frequency inferred from model predictions indicate that northern Alberta remains highly suitable for the species under projected climate. As expected from the climatology data, there is a remarkable similarity between aspen frequency based on a recent decadal average (1997-2006) and projected 2020s climate. Both indicate loss of suitable habitat in the south as well as increased expected aspen frequency in the north.

Uncertainty in model projections is quantified by calculating the proportion of models that predict either absence or presence of suitable habitat (Figure 5-2). Model agreement is high for predictions for the 2020s, but quite drastically decreases towards the 2050s and 2080s, reflecting increasing uncertainty in future climate predictions. Model consensus is more than 15 out of the total 18 for the projected shifts during the 2020s (Figure 5-2). Thus, predictions for the 2020s can be used with high confidence in determining species choice for reforestation. Areas with low levels of agreement are restricted to the prairie-forest transitions, which are biologically sensitive changes in climate (Camill et al. 2003; Williams et al. 2009).

### *5.3.3. Projected climate envelopes of aspen seedzones*

Projections of the climate envelope of aspen seedzones within the species distribution based on the 1961-1990 reference climate closely matches mapped seedzones, with misclassification error rates between 2% and 13% for individual seedzones. Projections of the seedzone climate envelopes based on the climate average of the last decade (1997-2006) already indicate that aspen populations are likely not optimally adapted as the climate envelope for these populations has shifted generally northward (Figure 5-3).

For the 2050s and 2080s, there is a further northward displacement and reductions in size of suitable deployment areas for planting stock from current seedzones. The Boreal Plains seedzone and the Foothills seedzone climate envelopes, which are both characterized by relatively high precipitation, are particularly affected (Figure 5-3, blue and light green). Nevertheless, the models indicate that aspen is likely to maintain habitat in these areas, but genotypes that are adapted to drier and warmer climate conditions from the current aspen parkland (orange) are predicted to be better suited for reforestation in the Boreal Plains. Other genotypes that were not specifically delineated from British Columbia and/or the United States are predicted to be best adapted for the Rocky

Mountain Foothills area (Figure 5-3, grey). Model predictions further indicate that planting material suitable for the Northern Boreal aspen seedzone maintains potential deployment area that gradually shifts further north (Figure 5-3, dark green).

## 5.4. Discussion

Analysis of recent climate trends indicates substantial changes in temperature and precipitation for aspen seedzones in western Canada. A higher heat-moisture index signifies reduction in the amount of moisture available for plant growth. These changes in climate will likely affect growth and productivity of tree species in western Canada (Hogg et al. 2008). As climate continues to change, information about potential changes to species suitable habitat is therefore required to develop adaptation strategies to future climate.

Numerous and sometimes contradicting projections of future climate change make it difficult for scientists or natural resource managers to choose a representative future climate scenario or corresponding biological model result as the basis for adaptation strategies. In this study I used a representative selection of available general circulation models to arrive at detailed seed transfer guidelines for aspen. In addition to making recommendations for assisted migration of planting material in reforestation programs, I also report the degree of confidence in these recommendations. Model consensus is generally high for the 2020s, but shows dramatic reductions towards the 2050s and 2080s. Does this suggest that we should develop relatively short-sighted adaptation strategies, i.e. focus on the

2020s projection and dismiss longer-term projections as too uncertain for practical resource management?

The answer to this question is “yes”. Despite consideration of their long lifetime, it is important to realize that the most vulnerable phase of trees remains their seedling and sapling stage. In a changing environment, we cannot focus on optimizing planting stock for maximum growth during mid-rotation, when this means that seedlings planted today will die due to mal-adaptation because climate conditions of predicted for the 2050s have yet to materialize. The high degree of uncertainty in longer-term climate projections is an additional argument to develop adaptation strategies for the immediate future with a 10- to 20-year planning horizon.

In broad terms, our recommendations for a 10- to 20-year planning horizon is to implement asymmetric seed transfer guidelines, allowing northward transfer of aspen planting stock by an additional 1° to 2° latitude, while reducing allowable southward transfer of aspen genotypes by the same amount. This recommendation is further supported by the projected shift of seedzone envelopes that were made on the basis of observed climate change over the last 25 years (Figure 5-3) as well as observed climate change impacts in the form of reduced productivity and dieback of aspen forests in the central parkland regions of Alberta and Saskatchewan (Hogg and Bernier 2005; Hogg et al. 2002) and other areas (Rehfeldt et al. 2009; Worrall et al. 2008). In other words, our results suggest that there is a risk of deploying maladapted planting stock if current transfer guidelines are not adjusted to new climatic realities. While such adjustments have already been implemented for British Columbia (O'Neill et al. 2008), similar legislation has yet to be implemented in Alberta or Saskatchewan.

While there is a high degree of uncertainty in determining optimal seed sources for deployment by the 2050s and 2080s, I recognize that applied tree improvement programs regularly have planning horizons of several decades or even a century. What can be recommended with respect to developing long-term breeding programs and establishment of seed- and cutting orchards for improved aspen planting stock? It certainly appears that there will be limited future demand for aspen planting stock that is adapted to moist environments of the Rocky Mountain Foothill ecosystems and the adjacent Boreal Plains zone (Figure 5-3, blue and light green). These areas, which currently receive relatively high summer precipitation along the jet stream storm track, are predicted to be more suitable for genotypes adapted to drier growing conditions by the 2050s and 2080s (Figure 5-3, orange). At the same time the climate envelope of the current Foothill and Boreal Plains climate envelopes are predicted to disappear from the study area.

A breeding program or seedzone corresponding to the parkland ecoregion (Figure 5-3, orange) currently does not exist and I think the establishment of tree improvement programs with genotypes from this region would be a worthwhile consideration. Interestingly, seed sources from the very southern edge of the Foothill and Boreal Plains region, bordering the parkland ecosystem already outperform local seed sources in genetic test plantations within the Foothill and Boreal Plains zone (Gylander et al, unpublished manuscript), underscoring the potential value of this genetic resource. This study also provides an explanation why these southern sources perform better than local planting material in Gylander's et al. genetic trial series that have been established and evaluated over the last 10 years. Climate trends that have already materialized render local sources maladapted, while providing optimal growing conditions for sources transferred to new planting locations further north.

An important resource management question is the potential shift of a species suitable habitat to higher elevations as climate changes. For instance aspen has recently been shown to regenerate on mineral soil at higher elevations of the Rocky Mountains Foothills (Landhausser et al. 2010). Genetic data to delineate aspen seedzones used in this study did not cover higher elevations and therefore precise predictions about recommended elevation shifts of aspen seedzone could not be made. Nevertheless, this remains an important consideration that could be explored further with more refined data.

Table 5-1. The difference between the 1961-1990 reference period and a recent decadal average from 1997-2006. This represents a 25-year observed climate trend (~1975 to ~2000), which is given in parentheses for aspen seedzones in western Canada.

| Climate Variable* | Aspen Parkland | | Foothills | | Boreal Plains | | Northern Boreal | | Taiga | |
|---|---|---|---|---|---|---|---|---|---|---|
| MAT (°C) | 1.9 | (+0.8) | 1.9 | (+0.8) | 0.5 | (+1.1) | -0.6 | (+1.1) | -2.5 | (+1.4) |
| MWMT (°C) | 17.5 | (+0.3) | 13.9 | (+0.4) | 16.5 | (+0.6) | 15.4 | (+0.6) | 15.6 | (+0.8) |
| MCMT (°C) | -16.7 | (+1.9) | -11.5 | (+1.8) | -18.7 | (+2.0) | -20.2 | (+1.9) | -23.9 | (+2.4) |
| TD (°C) | 34.2 | (-1.6) | 25.4 | (-1.4) | 35.2 | (-1.4) | 35.6 | (-1.3) | 39.5 | (-1.6) |
| MAP (mm) | 437 | (-3%) | 620 | (-5%) | 472 | (-6%) | 454 | (-9%) | 392 | (-7%) |
| MSP (mm) | 294 | (-1.6%) | 395 | (-4%) | 316 | (-4%) | 284 | (-5%) | 238 | (+0.2%) |
| PAS (mm) | 106 | (-12%) | 183 | (-13%) | 127 | (-13%) | 145 | (-17%) | 144 | (-16%) |
| AHM | 27.4 | (+2.9) | 19.5 | (+2.5) | 22.3 | (+3.9) | 20.8 | (+4.9) | 19.3 | (+5.5) |
| SHM | 60.1 | (+1.9) | 35.7 | (+2.6) | 52.8 | (+3.8) | 55.9 | (+4.9) | 67.8 | (+3.0) |
| DD0 (dd) | 1776 | (-290) | 1289 | (-252) | 2049 | (-346) | 2233 | (-375) | 2778 | (-466) |
| DD 5 (dd) | 1519 | (+12) | 1028 | (+26) | 1333 | (+479) | 1177 | (+30) | 1129 | (+41) |
| NFFD (days) | 164 | (-1.0) | 144 | (+0.4) | 156 | (+0.1) | 148 | (+0.1) | 142 | (+1.5) |
| bFFP | 142 | (+3.2) | 159 | (-0.1) | 147 | (+1.3) | 152 | (+0.7) | 155 | (+0.5) |
| eFFP | 248 | (+2.8) | 236 | (+1.4) | 244 | (+4.1) | 239 | (+3.3) | 238 | (+4.7) |
| FFP (date) | 107 | (-0.4) | 79 | (+1.5) | 97 | (+2.8) | 87 | (+2.6) | 83 | (+4.3) |
| EMT (°C) | -47.4 | (+1.2) | -44.2 | (+1.9) | -48.4 | (+1.0) | -48.6 | (+0.8) | -49.6 | (+0.6) |

* MAT- mean annual temperature, MWMT -mean July temperature, MCMT – mean January temperature, TD - temperature difference, MAP - mean annual precipitation, MSP - mean summer precipitation, PAS - precipitation as snow, AHM - annual heat-moisture index, SHM - summer heat-moisture index, DD0 - degree days below 0°C, DD5°C - degree above 5°C, NFFD - number of frost free days, FFP - frost free period, DD5_100 - growing degree days, EMT - Extreme minimum temperature.

Table 5-2. Projected changes in mean annual temperature, mean annual precipitation and summer heat-moisture index over 1961-1990 normals for aspen seedzones in western Canada.

| Climate Variable* | Unit | Foothills | Boreal Plains | Northern Boreal | Taiga |
|---|---|---|---|---|---|
| 2020s | | | | | |
| MAT | °C | +0.5 to +1.9 | +0.6 to +2.0 | +0.5 to +2.1 | +0.6 to +2.1 |
| MAP | % | +0.3 to +3.2 | -0.2 to +3.1 | -0.4 to +3.9 | -0.1 to +4.2 |
| SHM | N/A | +1.6 to +5.6 | +1.0 to +6.0 | -0.9 to +5.5 | -2.2 to +5.8 |
| 2050s | | | | | |
| MAT | °C | +1.0 to +3.1 | +1.2 to +3.8 | +1.1 to +3.4 | +1.3 to +3.6 |
| MAP | % | +0.5 to +5.8 | -0.4 to +5.1 | -0.7 to +6.4 | -0.3 to +6.9 |
| SHM | N/A | +2.7 to +13.7 | +1.9 to +14.5 | -0.6 to +13.2 | -3.2 to +13.7 |
| 2080s | | | | | |
| MAT | °C | +1.5 to +5.3 | +1.8 to +6.4 | +1.9 to +5.6 | +1.4 to +5.9 |
| MAP | % | +0.8 to +9.6 | -0.8 to +7.5 | -1.4 to +11 | -13 to +11.6 |
| SHM | N/A | +3.5 to +24 | +2.0 to +25 | +0.7 to +22 | -2.6 to +22.4 |

*MAT- mean annual temperature, MAP - mean annual precipitation, and SHM – Summer heat-moisture index.

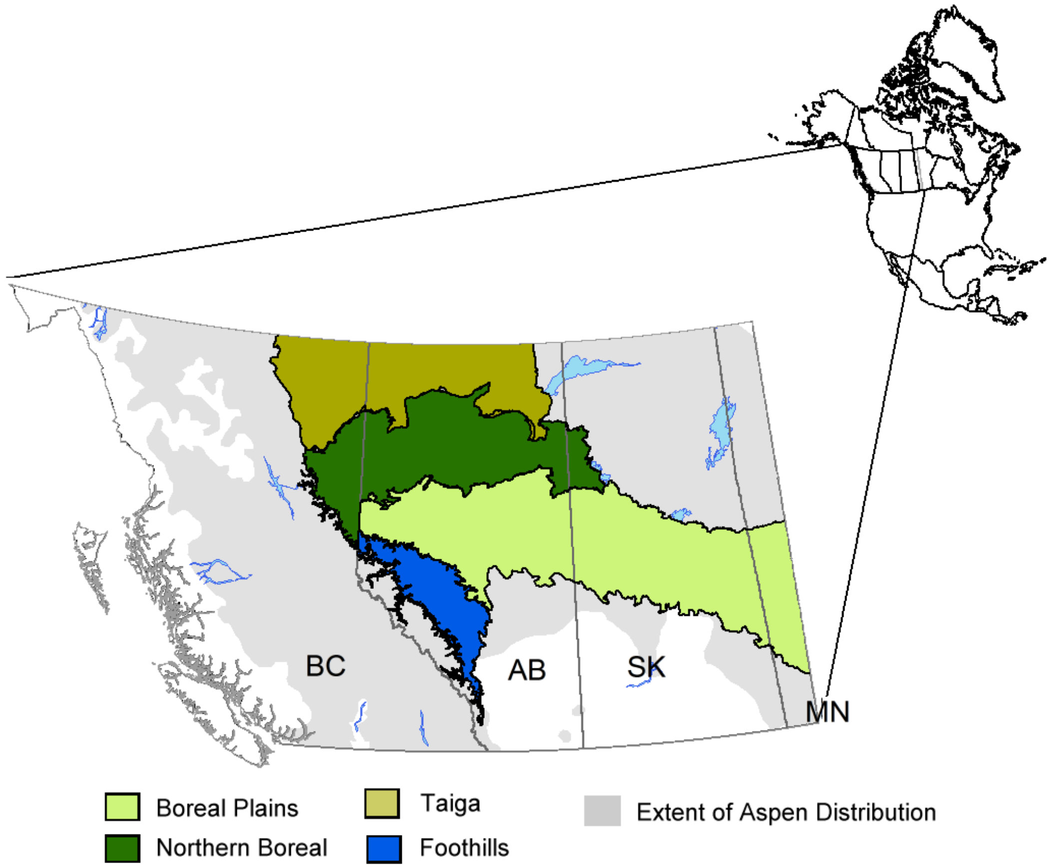


Figure 5-1. Trembling aspen (*Populus tremuloides*) distribution range and major aspen seedzones in Western Canada (British Columbia-BC, Alberta-AB, Saskatchewan-SK and parts of Manitoba-MN.

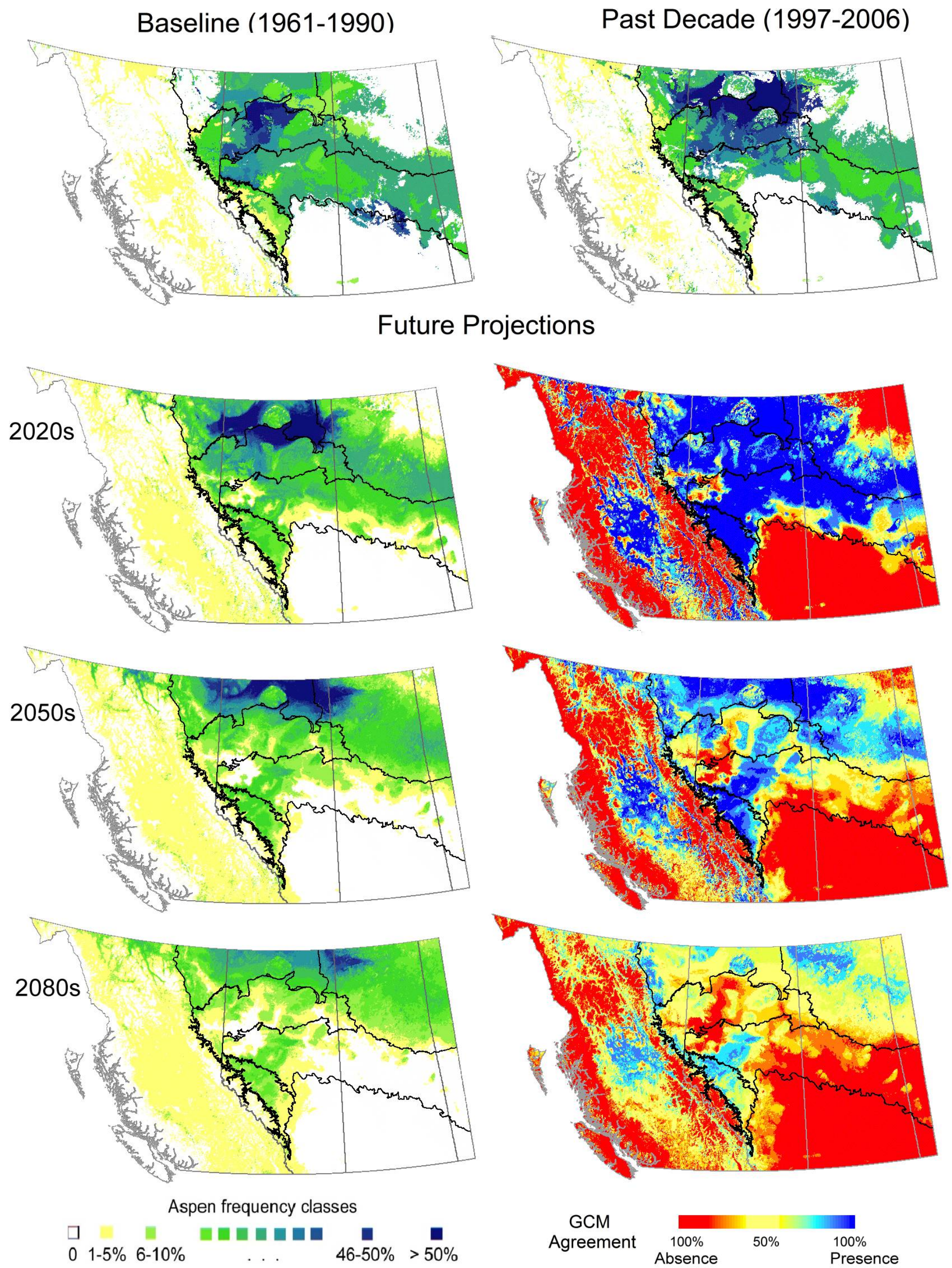


Figure 5-2. Aspen frequency under baseline (1961-1990), recent decade (1997-2006) and projected future climate scenarios for the 2020s, 2050s and 2080s time slices. General circulation model (GCM) agreement for modeled aspen frequency under future climate is also provided. Outlines of current aspen seedzones are added for orientation.

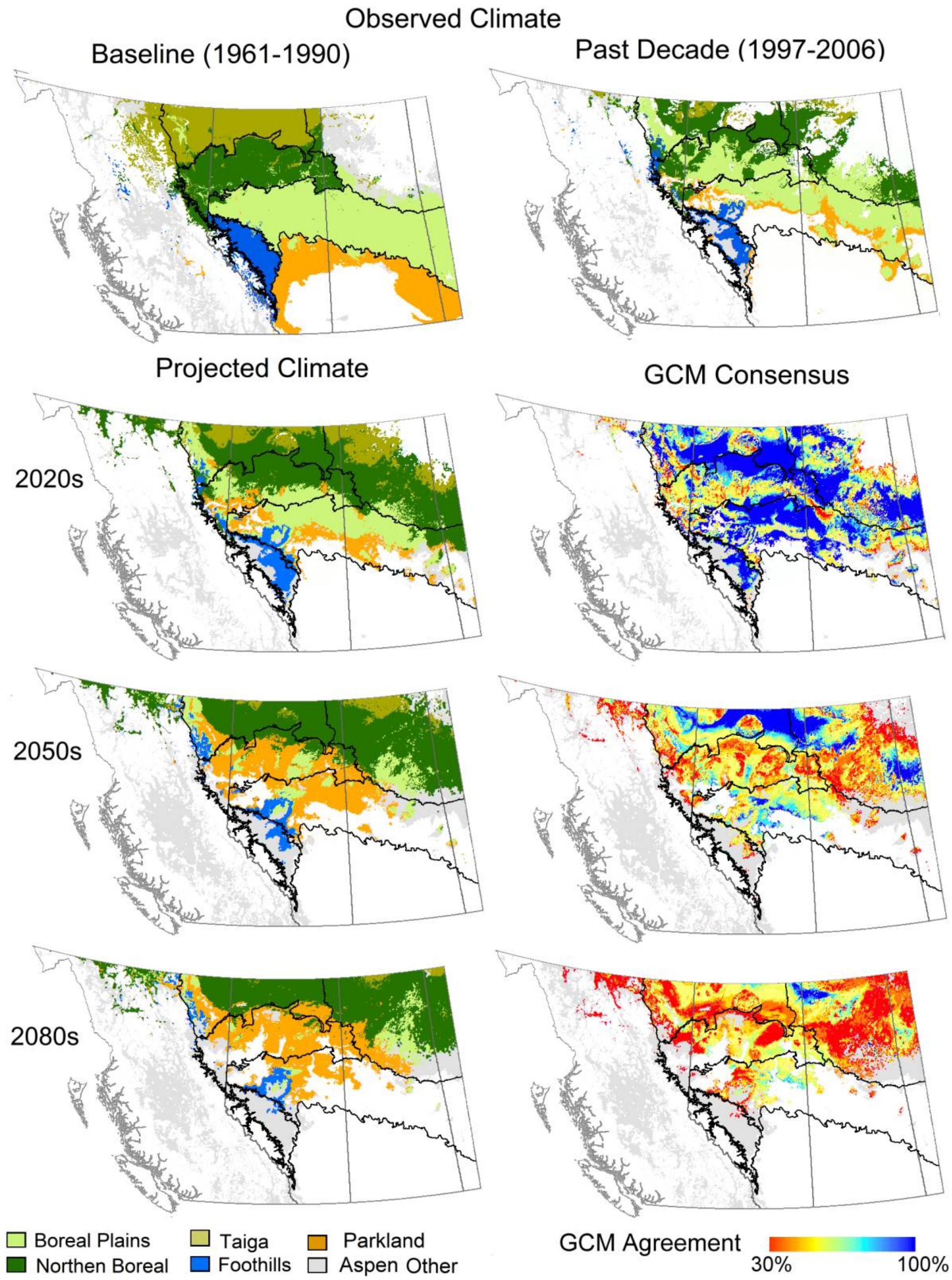


Figure 5-3. Aspen seedzone climate envelope under baseline (1961-1990), recent decade (1997-2006) and future climate scenarios for the 2020s, 2050s and 2080s, and general circulation model (GCM) consensus for predicted shifts under future climate. Outlines of current aspen seedzones are added for orientation.

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## Chapter 6. Synthesis and Conclusions

The overall goal of this thesis was to develop methodology that can be used to guide the choice of species for reforestation and to select locally adapted planting stock that will grow well under a variety of anticipated future climates. In the introductory section, I posed six major questions that guided this research project, which I will answer as comprehensively as possible in this section:

1) What are the most appropriate methods to interpolate weather station data to generate climate surfaces that accurately represent current climate conditions?

I compared three baseline climate datasets for the 1961-1990 normal period that were available for western Canada, and evaluated the effect of grid resolution and interpolation methods on statistical measures of accuracy and data quality in areas where weather station coverage is sparse. I found that statistical accuracy in areas with good weather station coverage was mainly a function of grid resolution. In contrast, interpolation methods noticeably differed by up to 4°C in mean annual temperature, and up to 10°C in monthly temperature estimates where weather station coverage was lacking. A notable result is that besides statistical accuracy, model behavior outside weather station coverage is an important factor that should be considered when evaluating interpolation methods. The thin-plate spline interpolation method emerged as the most suitable choice when validated against weather station data for a 1961-1990 normal period, and evaluated for model behavior over the arctic highlands of Alberta that lack station coverage.

2) How do climate change projections for western Canada differ, and which/how many individual or ensemble projections should be used for bioclimate envelope modeling?

For future projections, I investigate 22 scenarios from general circulation models to determine if “worst case”, “best case” and “median” scenarios can be selected for western Canada with respect to multiple biologically relevant variables. This proved to be difficult because of spatial variability (a “worst case” scenario for one region may be a “median scenario” in another area), and because multiple variables need to be considered (a scenario may be a “worst case” with respect to temperature, but “median” for precipitation). I conclude that a full range of climate change scenarios needs to be considered. Secondly, it was notable that local differences in baseline climate data exceeded all climate change projections for the 2050s and most climate change projections for the 2080s. These differences in baseline climate could be a major potential source of uncertainty in bioclimate envelope model projections that has rarely been investigated.

3) How do future climate projections compare to observed climate trends and associated biological response, and what role should observed trends play in developing climate change adaptation strategies?

Ultimately we will not need to adapt to a multitude of possible future scenarios, but to local climate trends that actually materialize. Climate trends over the last 25 in western Canada roughly follow the direction and magnitude of GCM projections for the 2020s. While most GCMs predicted more warming in winter temperatures than in summer temperatures, the differences are more pronounced in the observed trends. Average winter temperature changes over the last quarter century already exceed projections for the 2020s in western Canada. Observed trends in precipitation exceed projections from any GCM with up to 20% less annual precipitation for central Alberta and up to 10% less precipitation for British Columbia. Based on these pronounced observed changes, I make the case that observed climate change is equally if not more important than highly variable climate change projections as input data for bioclimate envelope modeling.

4) What are the relative contributions of baseline climate data, selection of predictor variables, modeling method, general circulation models and emission scenarios to variability in predictions of bioclimate envelope modeling?

In four case studies that evaluate modeling results in representative set of ecosystem in western Canada (costal subalpine forest in BC, sub-boreal mixedwood forests in AB, northern boreal forest in AB, and boreal-parkland transitional forest in SK), we find that uncertainty in climate change projections contributed most to the variance in modeling results. The inclusion of topo-edaphic variables as predictors reduces projected habitat shifts by a quarter, and differences in climate baseline data had a surprisingly small impact on modeling results, suggesting that the choice of baseline interpolation method is not as important as initially thought. Bioclimate envelope modeling methods primarily contributed to uncertainty through interaction terms with climate change predictions, i.e. the methods behaved differently for particular climate change scenarios (e.g. warm & moist scenarios) but similar for others.

5) Can uncertainty be reduced by filtering out biologically or statistically unreasonable modeling results, and provide practitioners with an improved range of predictions for climate informed natural resource management?

Quantifying variance components for main effects and interactions among sources of uncertainty offers researchers the opportunity to filter out biologically and statistically unreasonable modeling results, and to provide the practitioners with an improved range of predictions for climate-informed natural resource management. First, variance partitioning helps to focus on the aspects that need to be interpreted. For example, if different climate baseline datasets do not contribute to variance in the results, we do not have to think about which interpolation method is conceptually or statistically more appropriate. Secondly I found examples where one modeling method provides a biologically more plausible result than another (e.g. increased precipitation compensated for increased temperature in one instance but not another). The general insight is that we can narrow plausible results from a large suite of projections. This may sometimes also favor non-conforming, but statistically and biologically more plausible results that would have been eliminated by a simple consensus approach.

6) How can predictions from multiple runs of bioclimate envelope models be used to guide the choice of species for reforestation and guide recommendations for planting stock that is adapted to anticipated future environments?

In a case study for aspen, I subdivided the species range into zones that represent similarly adapted genotypes, and then use regression tree analysis to predict the distribution of habitat for these genotypes under multiple climate change scenarios. I found that a recommendation of moving planting stock 1° to 2° latitude north can be made with high confidence over a 10-20 year planning horizon. However, confidence in planting stock recommendations decreases dramatically for the 2050s and 2080s, even for areas where species habitat is projected to be maintained with high certainty. Nevertheless, some long-term trends appear to be plausible: by the 2050s and 2080s aspen planting stock that is adapted to moist environments of the Rocky Mountain Foothill ecosystems and the adjacent Boreal Plains zone of western Canada is generally predicted to be mal-adapted throughout the study area, which should be a consideration in planning long-term tree improvement programs for these populations. Instead, breeding programs should focus on populations that are adapted to drier and warmer climates.

Transfer of planting material within a species range is a form of assisted migration that can be used to ensure that planted trees are adapted to future climates. This research has shown that using genetic information on local adaptation of different populations of a species, bioclimate envelope modeling can be used to identity locally adapted planting material. In this way modeling does not treat a species as a homogenous unit but emphasizes the diversity between different populations. Assisted migration should only be implemented in a situation where the benefits of its implementation outweigh the negative impacts of climate change. For instance like in the case of trembling aspen for western Canada, information about adaptation lag from provenance trials and observed aspen dieback due to drought can be combined with modeled changes to the species suitable habitats to identify areas where the species will thrive under future climate conditions.