A dendroclimatic investigation in the northern Canadian Rocky Mountains, British Columbia

by

Aquila Flower
B.A., Humboldt State University, 2004

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science

in the Department of Geography

Supervisory Committee

A dendroclimatic investigation in the northern Canadian Rocky Mountains, British Columbia

by

Aquila Flower
B.A., Humboldt State University, 2004

Supervisory Committee:

Dr. Dan J. Smith, (Department of Geography)
Supervisor

Dr. Ze'ev Gedalof, (Department of Geography)
Departmental Member

Dr. Barrie R. Bonsal, (Department of Geography)
Departmental Member

Supervisory Committee:

Dr. Dan J. Smith, (Department of Geography)
Supervisor

Dr. Ze'ev Gedalof, (Department of Geography)
Departmental Member

Dr. Barrie R. Bonsal, (Department of Geography)
Departmental Member

Abstract

Subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) and white spruce (*Picea glauca* [Moench] Voss) trees were sampled in an old growth forest in the northern Canadian Rocky Mountains. Dendroclimatological methods were used to analyse the relationship between annual radial-growth and climatic variability. The white spruce ring-width chronology showed stronger sensitivity to climatic variability than the subalpine fir chronology. Both chronologies were positively correlated with growing season mean and minimum temperature. Additionally, the white spruce chronology was correlated with summer maximum temperature, late spring minimum temperature, and diurnal temperature range during the growing season. The subalpine fir ring-width chronology was also correlated with maximum and minimum temperature and diurnal temperature range during the during the previous winter and with the Pacific Decadal Oscillation during each month from December to June. Analysis of the climate-growth responses of individual

trees revealed a higher level of intraspecies variability in subalpine fir than in white spruce.

The white spruce chronology was selected for use in creating a proxy climate record based on its greater length and stronger sensitivity to climatic variability. Dendroclimatological methods were used to create a regional proxy record of June-July mean temperature extending back to 1772. This reconstruction exhibits a shared pattern of low-frequency variability with other dendroclimatic reconstructions from western Canada and shows no evidence of the recent reduction in sensitivity to climatic variability that is apparent in many other northern spruce chronologies.

This study represents the first detailed dendroclimatic analysis undertaken in northern interior British Columbia. This work has elucidated the complex interactions between climate and the radial growth of alpine conifers in the northern Canadian Rocky Mountains. The climate reconstruction presented here fills in one of the remaining spatial gaps in the coverage of annually resolved climate reconstructions in western North America.

Table of Contents

List of Tables

List of Figures

Acknowledgments

Thank you first and foremost to Dan “the man” Smith for making all of this possible, and making it fun to boot. It is truly hard to believe how much I have learned and how many amazing alpine landscapes I have seen as a member of the UVTRL. Thank you to my committee members, Ze’ev Gedalof and Barrie Bonsal, and to my external examiner, Dave Spittlehouse, for their invaluable help in improving this thesis. Thank you to Leslie Abel, Bethany Coulthard, Sarah Hart, and Lynn Koehler for fighting northern mosquitoes, icy rivers, and ruthless willow thickets to help me collect my samples during the best field season ever. Special thanks to Trisha Jarrett and Lisa Wood for geeking out with me so often. I am so grateful to all the students and assistants in the UVTRL, without your help and friendship this research could never have been completed, and I feel unbelievably lucky to have been able to join such a wonderful community. Thank you to my brothers, sisters, parents, and grandparents for all their encouragement and support. And thank you of course to Branden, for giving me an infinite supply of love, support, and editing assistance; for putting up with me through this whole experience; and for always listening, or at least pretending to, even when I just had to talk about principal components at the dinner table.

Chapter 1 - Introduction

1.1 Introduction

A growing awareness of the rapid climatic changes that have occurred during the last century (Zhang *et al.* 2000; British Columbia Ministry of Environment 2007), and the even more rapid changes projected to occur over the next century (IPCC 2007), has highlighted the scarcity of, and necessity for, long-term records of climatic variability. Unfortunately, there are no instrumental climate records in Canada that pre-date 1840 (Colenutt and Luckman 1991). The lack of long instrumental climate records is especially acute in northern Canada, where few records exceed 50-60 years (Zhang *et al.* 2000). In northern interior British Columbia, the longest instrumental climate record extends back only as far as 1937 (Environment Canada 2006).

Paleoclimatic proxies offer the opportunity for reconstructing climate records that extend our knowledge of climatic variability further into the past (Fritts 1976; Markgraf *et al.* 2000; Hughes 2002; Luckman 2007). Dendroclimatic reconstructions based on variations in the width of annual tree rings offer an opportunity for developing centuries-long annually resolved proxy climate records, while simultaneously offering us insights into the impacts of climatic variability on the radial growth of trees (Fritts 1976; Hughes 2002; Luckman 2007).

1.2 Research Purpose

The purpose of the research presented in this thesis was to complete a dendroclimatic analysis in the northern Canadian Rocky Mountains of northeastern British Columbia. Specifically, the intent was: to analyse and describe the relationships between climatic variability and radial growth in white spruce (*Picea glauca* [Moench] Voss) and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) trees; and, to use these insights to reconstruct past climatic fluctuations in the northern Canadian Rocky Mountains.

1.3 Research Objectives

1) To develop ring-width chronologies using core samples collected from white spruce and subalpine fir trees in Kwadacha Wilderness Provincial Park.

2) To quantify the radial growth response of these species to an array of climate variables, including minimum, maximum, and mean temperature; precipitation; and indices of oceanic-atmospheric oscillations.

3) To assess the seasonal, interspecies, and intraspecies variability in the climate-growth responses of the two sampled species.

4) To reconstruct a proxy record of temperature fluctuations using dendroclimatological methods.

5) To compare the proxy climate record to other climate reconstructions from western Canada to explore the spatial and temporal patterns of climatic variability in this region.

1.4 Thesis Format

This manuscript-style thesis is composed of six self-contained chapters. Following this introductory chapter, Chapter Two presents a review of relevant literature on dendroclimatological principles and methods, previous dendroclimatic analyses of white spruce and subalpine fir, and the climate-radial growth responses of these species. Chapter Three provides an introduction to the study area, with an overview of its‘ physical setting, biogeography, and climate, followed by an analysis of spatial and temporal variability in instrumental climate records from northern interior British Columbia. Chapter Four focuses on a dendroclimatological analysis of the climate-radial growth responses of the white spruce and subalpine fir trees sampled for this thesis. Chapter Five presents a dendroclimatic reconstruction of June-July mean air temperature variability in the northern Canadian Rocky Mountains and a comparison of this reconstruction to other proxy climate records from western Canada. Chapter Six is composed of a summary and set of recommendations for future research.

1.5 Works Cited

British Columbia Ministry of Environment. 2007. Environmental Trends in British Columbia: 2007. Available at: http://www.env.gov.bc.ca/soe/et07/EnvironmentalTrendsBC_2007.pdf

Colenutt, M.E. and Luckman, B.H. 1991. Dendrochronological investigation of Larix lyallii at Larch Valley, Alberta. Canadian Journal of Forest Research. 21, 1222-1233.

Environment Canada, 2006. *AHCCD – Adjusted Historical Canadian Climate Data*. Available at: http://www.cccma.ec.gc.ca/hccd/index.shtml.

Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press: London.

Hughes, M.K. 2002. Dendrochronology in climatology - the state of the art. *Dendrochronologia*. 20, 95-116.

IPCC (International Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. eds. Pachauri, R.K and Reisinger, A. IPCC: Geneva.

Luckman, B.H. 2007. 'Dendroclimatology' in *Encyclopedia of Quaternary Science*. Ed. S.A. Elias. Elsevier Scientific. 465-475.

Markgraf, V.; Baumgartner, T.R., Bradbury, J.P.; Diaz, H,F.; Dunbar, R.B.; Luckman, B.H.; Seltzerg, G.O.; Swetnam, T.W. and R. Villalba. 2000. Paleoclimate reconstruction along the Pole–Equator–Pole transect of the Americas (PEP 1). Quaternary Science Reviews 19, 124-140.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*. 38, 395-429.

Chapter 2 - Research Background

2.1 Introduction

Dendroclimatology is the science of reconstructing past climatic conditions based on variations in the characteristics of tree-rings (Fritts 1976). The limited instrumental record in most of the world hampers our understanding of long-term climate variability, but dendroclimatic reconstructions can be used to extend these records by centuries or even millennia. The annual resolution of tree-ring records allows for rigorous testing against instrumental records in a way that is impossible for less precisely datable climate proxies (Hughes 2002). Significantly, dendroclimatology allows for the reconstruction of annually resolved records of climate variables and forcing mechanisms at site-specific to hemispheric scales (Hughes 2002; Luckman 2007).

2.2 Basic Concepts of Dendroclimatology

2.2.1 Tree Growth

Trees grow vertically during primary growth and radially during secondary growth, as described in detail by Kramer and Kowlowski (1960). Primary growth, in the form of elongation of both branches and stem, occurs through cell formation at the apical meristem. Secondary growth, which increases the diameter of the branches and stem, occurs at the vascular cambium. Cell division in the vascular cambium creates new phloem cells on the outside of the cambium, and new xylem cells on the inside. Phloem cells are destroyed frequently in many species, and are not considered useful for dendrochronological dating (Stokes and Smiley 1968). The xylem in gymnosperms is primarily composed of long, vertically oriented, thick-walled tracheid cells (Kramer and Kozlowski 1960). These tracheids form the woody part of trees that is used in dendroclimatological studies (Fritts 1976).

Trees growing in mid-latitude, temperate regions typically exhibit a pattern of concentric annual rings radiating outward from the pith. These annual rings are formed due to the seasonal variation of radial growth rates (Kramer and Kozlowski 1960; Fritts 1976). Tracheids produced during the beginning of the growing season are known as earlywood; these cells form the light-coloured inner portion of annual rings. Earlywood cells are relatively porous, low in density, wide and thin-walled (Kramer and Kozlowski 1960; Stokes and Smiley 1968; Fritts 1976). Tracheids produced towards the end of the growing season are called latewood and form the dark-coloured outer portion of annual rings. Latewood cells are less porous, denser, narrow, flattened and thick-walled (Kramer and Kozlowski 1960; Stokes and Smiley 1968; Fritts 1976)

Not all species produce annual rings, and even species that normally reliably produce single annual rings may, under certain circumstances, produce multiple rings in a single year or fail to produce an easily recognizable annual ring (Kramer and Kozlowski 1960; Stokes and Smiley 1968; Fritts 1976; Brubaker 1982). Missing rings or partial rings may occur during years of above average stress, when radial growth is so limited that trees are unable to produce an entire annual ring (Kramer and Kozlowski 1960; Stokes and Smiley 1968). If a period of high stress occurs within the normal growing season, an extra layer of dense, dark tracheids may form within the earlywood portion of the annual ring, thus creating a double or false ring (Stokes and Smiley 1968; Fritts 1976). Double rings may also form if favourable conditions temporarily resume toward the end of the growing season (Brubaker 1982). These anomalous patterns of ring formation can be detected and corrected for during the process of cross-dating (Stokes and Smiley 1968).

2.2.2 Limiting Factors

The principle of limiting factors states that the rate of a biological process will be limited by the environmental variable that is most scarce (Fritts 1976). This limiting factor may be a climatic condition, such as temperature or precipitation, or a non-climatic environmental factor, such as soil structure or competition with other plants (Kramer and Kozlowski 1960). The relative importance of different factors often changes within a single growing season (Kramer and Kozlowski 1960) and can vary between the parts of a single tree (Fritts 1976). If a particular climatic factor ceases to be the primary limiting factor at a site, the growth rate of the tree at that site will increase within the tree's genetic constraints, until it becomes limited by another factor (Fritts 1976). Climatic factors can influence growth during both the current and the subsequent growing season (Cook *et al.* 2004). Subsequent growing season growth rates can be influenced through climatically-induced changes in soil temperature, land surface albedo and physiological preconditioning (Cook *et al.* 2004).

The type and amount of climate-growth response exhibited by a tree varies depending on genetics and site conditions. Trees located near the margins of their ecological distribution, where conditions are less conducive to growth, are more likely to show a strong response to a single seasonal environmental variable (Fritts 1976; Hughes 2002). Tree-ring series from sites at latitudinal or upper treelines typically show a high sensitivity to temperature (Brubaker 1982; Schweingruber *et al.* 1990). Tree-ring series from lower-elevation sites, especially in arid regions, are more likely to show a high sensitivity to precipitation (Stokes and Smiley 1968; Brubaker 1982; Schweingruber *et al.* 1990).

If radial growth is limited in a consistent fashion throughout a site or region, the tree ring-series from that area will exhibit a common pattern of tree ring-width variation (Stokes and Smiley 1968; Fritts 1976). If a sample is large enough and captures sufficient covariation between the ring-width series of different individuals, the exact year in which a tree ring was formed can be determined through the procedure of cross-dating (Stokes and Smiley 1968; Fritts 1976).

2.3 Methods of Dendroclimatology

2.3.1 A model of radial tree-growth

Cook (1990) presents a linear aggregate model that treats tree-ring series as linear aggregates of five subseries. This model provides a useful summary of the primary factors influencing tree-ring growth and can help clarify which non-climatic factors need to be addressed in dendroclimatic analyses. This aggregate series is expressed as:

$$R_t = A_t + C_t + \delta D1_t + \delta D2_t + E_t$$

Where Rt is the observed ring-width series. C_t is the climatic signal; this signal needs to be isolated in dendroclimatological studies. At is the age-related growth trend in ring-width; this is removed during standardization. δ is a binary indicator of the presence or absence of $D1_t$ and $D2_t$. $D1_t$ represents the effects of localized endogenous disturbances, such as blowdowns; this type of disturbance signal is reduced through adequate replication during sampling. $D2_t$ reflects the impacts of stand-wide exogenous disturbances, such as fires; ring-width variation due to this type of disturbance is minimized through careful site and sample selection. Additional variability due to both $D1_t$ and $D2_t$ can be removed during detrending. E_t is the remaining unexplained variance; much of this variance is removed through adequate replication during sampling.

2.3.2 Sampling Techniques

Dendroclimatological studies do not usually use random sampling techniques, because the goal in sample selection is to obtain the longest possible record with as little non-climatic ring-width variation as possible (Fritts 1976). Instead, visual inspection of the trees is used to choose trees that are relatively old, undamaged by fire or wind, and in good health (Stokes and Smiley 1968; LaMarche 1982, Schweingruber *et al*. 1990).

Samples are typically taken in the form of narrow cores using an increment borer (Stokes and Smiley 1968; Fritts 1976). The cores are ideally taken at or near breast height in order to minimize the ring-width variability and ring distortion that is common near the base of trees and near branches (Stokes and Smiley 1968; Schweingruber *et al*. 1990). Sampling from the upslope and downslope sides of trees is avoided where possible, so as to minimize the amount of reaction wood in the cores (Schweingruber *et al*. 1990). Visual inspection of the cores during sampling is used to eliminate samples with visible signs of severe rot or physical damage. Typical sampling protocol calls for taking two core samples from opposite sides of each tree. This level of replication is a valuable method for removing the inconsistencies found in individual samples (Fritts 1976).

2.3.3 Sample Preparation and Measurement

Samples can be transported in paper or plastic straws to minimize breakage. In the laboratory, the cores are air-dried and are then usually glued to slotted mounting boards. The samples are then sanded with progressively finer grades of sandpaper to enhance the visibility of the tree-ring boundaries (Stokes and Smiley 1968; Fritts 1976; Pilcher 1990). Ring-widths may be measured with the aid of a microscope, or using software such as a WinDENDRO digital image measurement and analysis system (Regent Instruments Inc. 2006).

2.3.4 Cross-Dating

The first step after sample preparation in a ring-width analysis study is cross-dating, which involves measuring, counting, and comparing ring-widths among samples (Stokes and Smiley 1968; Fritts 1976). By matching characteristic patterns of width variations among samples, an annually-resolved proxy climate record can be developed (Fritts 1976; Hughes 2002).

The International Tree-Ring Data Bank software program COFECHA (Holmes 1983) can be used for quality-checking and verification of the results of visual cross-dating procedures. As described in detail by Grissino-Mayer (2001), COFECHA uses Pearson's correlation coefficients to determine the relationship between ring-width series. The standard COFECHA quality-check routine calculates correlations between 50-year segments with a 25-year lag. Statistical significance is determined at the 99% confidence level. Prior to calculating the inter-series correlations, COFECHA removes low-frequency variance by fitting the ring-width series with a smoothing spline with a standard 50% cutoff at a wavelength of 32 years. Persistence is also removed, via autoregressive modelling.

Segments that do not exhibit a high level of correlation, due to missing or false rings or measurement errors, can be corrected or removed until a relatively strong and statistically significant level of correlation is reached for the entire chronology. COFECHA also computes a variety of useful descriptive statistics, including inter-series correlation, first order autocorrelation, and mean sensitivity, which can be used to evaluate the quality of the chronology.

2.3.5 Standardization

The radial growth of trees is usually more rapid when trees are young, leading to a pattern of generally wider rings near the pith, with increasingly narrow rings towards the bark of a tree. This trait generally creates an age-dependent biological negative growth trend in a ring-width series that is removed through the process of standardization (see example in Figure 2.1). Traditional standardization removes the age-related growth trend, but commonly leaves much of the trend related to endogenous and exogenous disturbance events (Cook 1985). Because of this tendency, a double-detrending approach to standardization is often advisable, especially when analyzing ring-width series from closed canopy forests (Cook 1985).

A useful aid for standardizing ring-width series is the software program ARSTAN (Cook and Krusic 2005). ARSTAN's double detrending approach involves completing an initial standardization to remove the biological growth trend, followed by a second detrending to further reduce non-climatic variability caused by disturbance events or stand dynamics (Cook and Krusic 2005).

ARSTAN's options for initial detrending include growth curves in the form of a modified negative exponential curve (as shown in Figure 2.1), a linear regression line with a negative slope, or a horizontal line passing through the mean. These curves represent an expected ring-width value based on the age of the tree. Individual ring-width series are divided by the value of the fitted curve for a given year to calculate the index value of each ring. The resultant indices represent annual deviations from the ring-width value that would be expected if age were the only factor influencing radial growth rates. Unlike the raw ring-width series, the standardized indices are stationary processes with a defined mean and homoscedastic variance, and can therefore be averaged for each year to form a mean-value function (Cook *et al*. 1990a).

Secondary detrending is accomplished by fitting a second curve to the ring-width series. A frequently used option for the secondary detrending is a cubic smoothing spline with a 67% frequency-response cutoff. These splines preserve 50% of the variance in the ring-width series at a frequency equal to two-thirds of the length of the series. Splines with this level of stiffness are considered a good compromise between the risk of removing an excessive amount of low-frequency climatic variability and the danger of retaining too much low-frequency noise caused by disturbance events (Cook 1985).

ARSTAN can also be used to apply Auto Regressive Moving Average (ARMA) modelling techniques to ring-width series in order to remove autocorrelation. ARMA processes model the current year's ring-width as a function of radial growth during previous years and a set of serially random shocks, caused by climatic variability or disturbance events, from current and previous years (Cook *et al*. 1990b). ARMA processes express the concept of physiological preconditioning mathematically in the form of causal feedback-feed forward filters (Cook *et al*. 1990b). A pooled autoregressive model can be used to examine autocorrelation common to all the individuals in a sample. Individual ARMA models can also be created for each ring-width series. The order of the ARMA models may be defined by the user or determined using the Akaike Information Criterion (Cook and Krusic 2005).

After standardization and ARMA modelling, ARSTAN averages the individual ring-width series using either an arithmetic mean or a biweight robust mean to create a master ring-width chronology. The biweight robust mean reduces the bias and variance caused by outliers, thereby decreasing the impact of endogenous disturbance events on the final mean chronology (Cook *et al*. 1990b). The biweight robust mean is a valuable option for averaging ring-width series from closed canopy forests, which are prone to outliers due to the frequency of endogenous disturbance events (Cook *et al*. 1990b).

2.3.6 Response Function Analysis and Correlation Analysis

Response function analysis and correlation analysis are the two commonly used methods for exploring and quantifying climate-growth responses. Response functions are used to analyse the relationship between a predictor, typically a monthly climatic variable, and a predictand, typically an annual ring-width series (Guiot *et al*. 1982). In a response function analysis, principal components analysis (PCA) is used to form an ordered set of eigenvectors from a matrix of climate data (Fritts 1976). These eigenvectors are ordered according to the amount of ring-width variance that they can explain, which allows for the removal of the climate variables that explain the least variance, thereby reducing error in the model (Fritts 1976). The variables created through PCA are orthogonal, and thus acceptable for use in stepwise multiple regression, which requires independent predictor variables (Guiot *et al.* 1982). Bootstrapping may be used to test the significance of the regression coefficients obtained through stepwise multiple regression. Bootstrapped response functions use subsamples created through random extraction and replacement from within the original data set to measure error (Guiot 1991; Thompson 1994). The bootstrapped response function coefficients are averaged and their variance computed to evaluate the significance of the coefficients (Guiot 1991; Fritts 1992). These methods are the basis of the response functions calculated by the commonly used software program PRECON (Fritts 1996).

Pearson's correlation analysis is a simpler, but still very powerful, method for examining the direction and strength of the relationship between ring-width and climatic variability. The results of Pearson's correlation analysis can be checked for spurious correlations using partial correlation analysis. Partial correlation analysis is used to examine the correlation between two variables while controlling for, or holding constant, a third variable. This is potentially a very useful technique for tree-ring analysis, as the strong correlation between two or more climate variables can sometimes obscure the true relationship between ring-width and these variables.

2.3.7 Calibration and Transfer Functions

Calibration involves the development of a quantitative model that represents the relationship between climate and ring-width indices (Fritts 1976). A flexible *a priori* model is combined with a statistical *a posteriori* model to describe the climate-growth system (Fritts 1976). Transfer functions, in which a climate variable is the predictand and one or more ring-width series are the predictors, are used to reconstruct proxy records of climate variables (Lofgren and Hunt 1982; Guiot 1990). Transfer functions are usually based on linear regression models (Fritts 1976). Simple linear regression models are used to predict climate variables based on the variation in a single ring-width chronology. Multiple linear regression models are used in cases in which a climate variable is modelled based on multiple chronologies or multiple principal components extracted from chronologies or ring-width series.

2.3.8 Verification

Proxy records obtained via transfer functions are ideally verified by comparison of the predictand estimates with independent predictand observations (Gordon 1982). This can be accomplished with subsample replication techniques, in which the proxy climate record is verified using an independent subset of the climate data (Gordon 1982; Thompson 1994). One method of subsample replication is split period cross-validation, in which the transfer function is developed using only half of the available climate data, and then verified through comparison with the remaining half of the data (Fritts 1976; Blasing *et al*. 1981; Gordon 1982). An alternative method is leave-one-out verification (Blasing *et al*. 1981; Gordon 1982; Michaelsen 1987), in which a separate linear regression model is created for each of the years in the instrumental climate record. One year is left out of the calibration dataset for each model, and the model is used to predict the climate variable of interest for that year. The values predicted for each left-out year are then merged into a single climate record and compared to the instrumental climate record to verify the reconstruction. Leave-one-out verification may be more appropriate for models calibrated against relatively short instrumental climate records (Gordon

1982; Michaelsen 1987). Once the transfer function has been verified, it can be recalibrated using the entire instrumental climate record.

The ability of the models to reconstruct climatic variability accurately can be assessed using a variety of verification statistics, including Pearson's correlation coefficients, the reduction of error statistic (RE), coefficient of efficiency (CE) statistic, and the sign-product statistic. These statistics are described in detail in Fritts (1976), Fritts (1991) and Fritts *et al*. (1990). The RE statistic compares the predictive performance of the model against the predictive ability of the calibration period mean. The RE statistic is considered a very rigorous test of predictive skill because of its high level of sensitivity to even a single poor estimate. RE values can range from minus infinity to +1, with any value above 0 indicating a useful model. The CE statistic statistic is very similar to the RE statistic, the major difference being that the CE statistic compares the predictive performance of the model to the predictive capability of of the verification, as opposed to the calibration, period mean. A sign-product statistic is calculated by summing the number of cases in which the actual and estimated departures from the mean value of the calibration period are on the same side of the mean and the number of cases in which they are on opposite sides separately. If the sum of cases in which the sign of the actual and estimated departures disagree is below a threshold (determined based on the sample size), then a significant relationship can be inferred. The sign-product statistic is limited by the fact that it does not take the magnitude of disagreements into account.

2.4 Climate-Growth Responses of Select Tree Species

The two species analysed in this study, white spruce (*Picea glauca* [Moench] Voss) and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall), are well suited to dendroclimatological analysis and have been used in numerous dendroclimatological studies throughout their range in northwestern North America (Schweingruber 1993). Both species have large ecological amplitudes, but are at or near the upper limits of their elevational ranges in the northern Canadian Rocky Mountains (Schweingruber 1993). They are therefore more likely to be highly sensitive to limiting factors, especially temperature (Fritts 1976). The dendroclimatological applicability of these species and their climate-growth responses are briefly discussed below.

2.4.1 Subalpine fir

Subalpine fir trees grow at sites with cold, wet climates (Schweingruber 1993) in western North America from Alaska to New Mexico (Figure 2.2; Brayshaw 1996). Brubaker (1982) reports a maximum life span of approximately 250 years for this species. Although subalpine fir trees do not have a long life span, they have been successfully used in dendroclimatological and dendroecological studies in British Columbia (Colenutt and Luckman 1991; Splechtna *et al.* 1999; Larocque and Smith 2005) and Washington (Ettl and Peterson 1995; Peterson *et al.* 2002).

In the northern Canadian Rocky Mountains, subalpine fir is found at high elevation sites below 2700 m asl (Schweingruber 1993), where its growth is limited by a combination of temperature, precipitation and snowpack. In general, this species exhibits a positive relationship between radial growth and temperature during both the current year's growing season and the previous autumn (Splechtna *et al.* 1999; Larocque and Smith 2005). Subalpine fir responds negatively to temperature during the previous summer (Splechtna *et al.* 1999; Larocque and Smith 2005). Negative relationships have also been found between the radial growth of this species and snowpack during the previous spring (Peterson *et al.* 2002; Larocque and Smith 2005), as well as precipitation (the source of spring snowpack) during the previous fall and winter (Splechtna *et al.* 1999; Peterson *et al.* 2002).

Winter dormancy ends and photosynthesis begins as the soil temperature increases during the spring. Because snowcover retards warming of the soil, it can also delay the onset of growth. The length of the growing-season is, therefore, in part determined by snowpack depth (Peterson *et al*. 2002). Bud-burst is also triggered by warming temperatures during the spring and occurs earlier in the spring among subalpine fir trees than in other firs in British Columbia (Worrall 1983). Reproductive bud-burst occurs during the late spring and is immediately followed by vegetative bud-burst (Franklin and Ritchie 1970).

Subalpine fir trees are particularly susceptible to low-temperature photoinhibition (Germino and Smith 1999), which reduces photosynthetic capacity through the combination of low temperatures and high ultraviolet radiation levels (Man and Lieffers 1997a ; Germino and Smith 1999; Danby and Hik 2007). This phenomenon is especially common in high-elevation forests, where cold nights are frequently followed by sunny days (Man and Lieffers 1997a; Germino and Smith 1999).

Subalpine fir trees typically produce large cone crops every three years on average (Alexander *et al*. 1990; Woodward *et al*. 1994). More vegetative buds tend to be set during warm, dry summers, leading to a positive association between summer temperature and size of the cone crop in the following year (Woodward *et al*. 1994). Cone crop size is negatively correlated with radial growth because as the cones mature during the summer months, they intercept the photosynthates and other nutrients that would otherwise have been used for radial growth (Woodward *et al*. 1994).

2.4.2 White spruce

White spruce is a highly adaptable tree species that is able to tolerate a variety of climatic and soil conditions (Schweingruber 1993). It is found below 1500 m asl (Schweingruber 1993) throughout much of northern North America from the arctic treeline to as far south as the Great Lakes (Figure 2.3; Brayshaw 1996). White spruce trees have a reported maximum life-span of 350 (Brubaker 1982) to over 500 years (Szeicz and MacDonald 1994).

The wide distribution and long life of white spruce make it a useful species for dendroclimatological analyses (Schweingruber 1993). Dendroclimatological studies using white spruce have been conducted at high-latitude sites across much of northwestern North America (Jacoby *et al.* 1983; Jacoby and D'Arrigo 1989), including investigations in the Northwest Territories and the Yukon

Territory (Jacoby and Cook 1981; Szeicz and MacDonald 1994; Zalatan and Gajewski 2005; Zalatan 2006; Youngblut and Luckman 2008), and Alaska (Wiles *et al*. 1996; Lloyd and Fastie 2002; Wilmking *et al*. 2004; Wilson *et al.* 2006).

White spruce is closely related to and often hybridizes with Engelmann spruce (*Picea engelmannii* Parry ex Engelm var *engelmannii*; Mackinnon *et al*. 1999). Engelmann spruce exhibits a climate-growth response similar to that of white spruce and has been used extensively in dendroclimatic reconstructions in southern interior British Columbia (Wilson and Luckman 2002) and the southern Canadian Rocky Mountains (Wig and Smith 1994; St. George and Luckman 2001; Luckman and Wilson 2005). Due to the strong and very similar climate-growth responses of white spruce and Engelmann spruce, hybrid spruce (*Picea glauca* x *engelmannii*) can also be considered a suitable species for dendroclimatological research. Hybrid spruce and pure white spruce can be distinguished by needle characteristics and cone morphology (Mackinnon *et al*. 1999).

High elevation white spruce trees exhibit a strong sensitivity to temperature, and a weak and highly variable sensitivity to precipitation (Enright 1984; Szeicz and MacDonald 1994). White spruce generally shows a positive response to June or July temperatures during the current growing season (Jacoby and Cook 1981; Enright 1984; Szeicz and MacDonald 1994; Youngblut and Luckman 2008). A negative response to temperatures of the current spring (Jacoby and Cook 1981) and previous summer has also been identified (Szeicz and MacDonald 1994; Youngblut and Luckman 2008). Significant variability in the nature of the climate-growth relationship has been found between older trees and those younger than 100-200 years at some sites (Szeicz and MacDonald 1994).

Photosynthesis in white spruce occurs at low to non-existent rates during the winter in northern regions that are characterized by long periods of subfreezing temperatures (Man and Lieffers 1997b). Photosynthesis typically recommences in April, once soil temperatures reach 0° C or greater (Man and Lieffers 1997b). However, increasing rates of photosynthesis during the late spring are often accompanied by increasing rates of transpiration and respiration. If water uptake is limited by freezing or near-freezing soil temperatures, there is a strong risk of desiccation damage (Kramer and Kozlowski 1960; Tranquillini 1979). During warm springs, if photosynthesis is limited by factors such as moisture stress or low light levels, respiration rates may outpace photosynthesis, thereby depleting resources stored during the previous summer before they can be utilized in radial growth (Fritts 1976; Tranquillini 1979).

In central British Columbia, white spruce shoot elongation and budscale initiation are reported to begin in late April or early May (Owens *et al*. 1977). Shoot elongation is most rapid during June, and ceases entirely by August (Owens *et al*. 1977). During the growing season, low-temperature photoinhibition can lead to large decreases in the photosynthetic capacity of white spruce trees (Man and Lieffers 1997a; Germino and Smith 1999; Danby and Hik 2007). Photosynthesis in white spruce trees growing at high latitudes has been found to stop abruptly during the autumn, as soon as night-time temperatures fall below -10° C (Man and Lieffers 1997b).

2.5 Summary

A review of the basic principles and guidelines for choosing sites and samples in dendroclimatological work shows that sites with healthy, mature trees growing near the limit of their ecological range are the best candidates for sampling. Careful site selection, sample collection and preparation, and cross-dating combined with the use of appropriate standardization techniques enhance the climate signal contained in annual ring-width series. Response functions or correlation analysis can be utilized to determine the nature and strength of the climate-radial growth response, and transfer functions can be used to reconstruct annually resolved proxy records of climate variables. The two dominant tree species in the northern Canadian Rocky Mountains, white spruce and subalpine fir, have been the focus of numerous dendroclimatological studies in western North America and exhibit sensitivity to temperature variability. These species are found in the northern Canadian Rocky Mountains at the upper elevational limit of their geographical range, where they are more likely to be sensitive to temperature fluctuations. In spite of the presence of suitable tree species, very little previous dendroclimatological research has been conducted in this region. These factors suggest that the northern Canadian Rocky Mountains have excellent potential for dendroclimatological studies focusing on temperature variations.

2.6 Works cited

Alexander, RR, RC Shearer, and WD Shepperd. 1990. *Abies lasiocarpa (Hook) Nutt. In Silvics of North America: I Conifers Agriculture Handbook No. 654*. US Department of Agriculture Forest Service: Washington, DC. 60-70.

Blasing, T.J., Duvick, D.N., and West, D.C. 1981. Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree-Ring Bulletin*. 41, 37-43.

Brayshaw, T.C. 1996. *Trees and Shrubs of British Columbia*. UBC Press: Vancouver, Canada.

Brubaker, L.B. 1982. 'Western North America' in *Climate from Tree Rings*. eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 118-124.

Colenutt, M.E. and Luckman, B.H. 1991. Dendrochronological investigation of *Larix lyallii* at Larch Valley, Alberta. *Canadian Journal of Forest Research*. 21, 1222-1233.

Cook, E.R. 1990. 'A conceptual linear aggregate model for tree rings' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 98-102.

Cook, E.R. and Krusic, P.J. 2005. *Program ARSTAN manual*. Tree-Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University: Palisades, New York.

Cook, E.R., Esper, J. and D'Arrigo, R.D. 2004. Extra-tropical Northern Hemisphere land temperature variability over the past 1000 years. *Quaternary Science Reviews*. 23, 2061- 2268.

Cook, E.R, Briffa, K., Shiyatov, S., and Mazepa, V. 1990a. 'Tree-ring standardization and growth-trend estimation' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 104-122.

_______________1990b. 'Estimating the mean chronology' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 123-132.

Coupe, R., Stewart, A.C. and Wilkeem, B.M. 1991. 'Engelmann spruce - subalpine fir zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 223-236.

Danby, R.K. and Hik, D.S. 2007. Responses of white spruce (*Picea glauca*) to experimental warming at a subarctic alpine treeline. *Global Change Biology*. 13, 437–451.

Delong, C. 2004. *A field guide to site identification and interpretation for the north central portion of the Northern Interior Forest Region*. Research Branch, Ministry of Forests: Victoria, Canada.

DeLong, C., Annas, R.M. and Stewart, A.C. 1991. 'Boreal white and black spruce' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 237-250.

Edgell, M.C.R. 2001. 'Vegetation' in *British Columbia, the Pacific Province: Geographical Essays*. ed. C. J.B. Wood. Western Geographical Press: Victoria, Canada. 83-96.

Enright, N.J. 1984. Principal components analysis of tree-ring/climate relationships in white spruce (*Picea glauca*) from Schefferville, Canada. *Journal of Biogeography*. 11, 353- 361.

Ettl, G.J. and Peterson, D.L. 1995. Growth response of subalpine fir (*Abies lasiocarpa*) to climate in the Olympic Mountains, Washington, USA. *Global Change Biology*. 1, 213-230.

Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press: London.

Fritts, H.C. 1996. *Quick help for PRECON now called PRECONK version 5.11*. Laboratory of Tree-Ring Research: Tucson, Arizona.

Fritts, H.C. and Dean, J.S. 1992. Dendrochronological modeling of the effects of climatic change on tree-ring width chronologies from the Chaco Canyon area, Southwestern United States. *Tree-Ring Bulletin*. 52, 31-58.

Fritts, H.C., Guiot, J., and Gordon, G.A. 1990. 'Verification' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 178-185.

Franklin, J.F. and Ritchie G.A. 1970. Phenology of cone and shoot development of noble fir and some associated true firs. *Forest Science*. 16, 356-364.

Gadd, B. 1995. *Handbook of the Canadian Rockies*. Corax Press: Jasper, Canada.

Germino, M.J. and Smith, W.K. 1999. Sky exposure, crown architecture, and low-temperature photoinhibition in conifer seedlings at alpine treeline. *Plant, Cell & Environment*. 22, 407–415.

Gordon, G.A. 1982. 'Verification of dendroclimatic reconstructions' in *Climate from Tree Rings*. eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 58-61.

Grissino-Mayer, H.D. 2001. Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research.* 57, 205-221.

Guiot, J.. 1990. 'Methods of calibration' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 165-178.

Guiot, J. 1991. The bootstrapped response function. *Tree-Ring Bulletin*. 51, 39-41.

Guiot, J., Berger, A.L., and Munaut, A.V. 1982. 'Response functions' in *Climate from Tree Rings*. eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 38-49.

Holmes, R.L. 1983. Computer assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*. 43, 69-78.

Hughes, M.K. 2002. Dendrochronology in climatology - the state of the art. *Dendrochronologia*. 20, 95-116.

Jacoby, G.C. and Cook, E.R. 1981. Past temperature variations inferred from a 400-year tree-ring chronology from Yukon Territory, Canada. *Arctic and Alpine Research*. 13, 409-418.

Jacoby, G.C. and D'Arrigo, R. 1989. Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climatic Change*. 14, 39-59.

Jacoby, G.C., Cook, E.R., and Ulan, L.D. 1983. Reconstructed summer degree days in central Alaska and northwestern Canada since 1524. *Quaternary Research*. 23, 18-26.

Kramer, P.J. and Kozlowski, T.T. 1960. Physiology of Trees. McGraw-Hill Book Company: New York.

LaMarche, Jr., V.C., Cook, E.R., and Baillie, M.G.L. 1982. 'Sampling strategies' in *Climate from Tree Rings.* eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 2-7.

Larocque, S.J. and Smith, D.J. 2005. A dendroclimatological reconstruction of climate since AD 1700 in the Mt. Waddington area, British Columbia Coast Mountains, Canada. *Dendrochronologia.* 22, 93-106.

Little, E.L., Jr. 1971. 'Conifers and important hardwoods' in *Atlas of United States trees, volume 1*. U.S. Department of Agriculture Miscellaneous Publication 1146.

Lloyd. A.H. and Fastie, C.L. 2002. Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. *Climatic Change*. 52, 481-509.

Lofgren, G.R. and Hunt, J.H. 1982. 'Transfer functions' in *Climate from Tree Rings*, eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 50-58.

Luckman, B.H. 2007. 'Dendroclimatology' in *Encyclopedia of Quaternary Science*. ed. S.A. Elias. Elsevier Scientific: New York. 465-475.

Luckman, B.H. and Wilson, R.J.S. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics*. 24, 131-144.

MacKinnon, A., Pojar, J., and Coupe, R. 1999. *Plants of Northern British Columbia*. Lone Pine Publishing: Vancouver.

Man, R. and Lieffers, V.J. 1997a. Seasonal photosynthetic responses to light and temperature in white spruce (*Picea glauca*) seedlings planted under an aspen (*Populus tremuloides*) canopy and in the open. *Tree Physiology*. 17, 437-144.

Man, R. and Lieffers, V.J. 1997b. Seasonal variations of photosynthetic capacities of white spruce (*Picea glauca*) and jack pine (*Pinus banksiana*) saplings. *Canadian Journal of Botany*. 75, 1776-1771.

Michaelsen, J. 1987. Cross-validation in statistical forecast models. *Journal of Climate and Applied Meteorology*. 26, 1589-1600.

Nienstaedt, H. and Zasada, J.C. 1990. '*Picea glauca*' in *Silvics of North America: 1. Conifers*. *Agriculture Handbook 654*. U.S. Department of Agriculture, Forest Service: Washington, DC. 389-442.

Owens, J.N., Molder, M., and Langer, H. 1977. Bud development in Picea glauca. I. Annual growth cycle of vegetative buds and shoot elongation as they relate to date and temperature sums. *Canadian Journal of Botany*. 55, 2728-2745.

Peterson, D.W., Peterson. D.L., and Ettl, G.J. 2002. Growth responses of subalpine fir to climatic variability in the Pacific Northwest. *Canadian Journal of Forest Research*. 32, 1503-1517.

Pilcher, J.R. 1990. 'Sample preparation, cross-dating, and measurement' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 40-50.

Province of British Columbia 2001a. *Kwadacha Wilderness*. Available at: http://www.env.gov.bc.ca/bcparks/explore/parkpgs/kwadacha.html.

Province of British Columbia 2001b. *BEC Web*. Available at: http://www.for.gov.bc.ca/HRE/becweb/.

Pojar, J. and Stewart, A.C. 1991. 'Spruce - willow - birch zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 251-262.

Regent Instruments Inc. 2006. *WinDENDRO: An Image Analysis System for Tree-Rings Analysis*. Quebec.

Schweingruber, F.H. 1993. *Trees and Wood in Dendrochronology*. Springer-Verlag: Berlin.

Schweingruber, F.H., Kairiukstis, L., and Shiyatov, S. 1990. 'Sample selection' in *Methods of Dendrochronology: Applications in the Environmental Sciences.* eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 23-34.

Splechtna, B.E., Dobry, J. and Klinka, K. 1999. Tree-ring characteristics of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) in relation to elevation and climatic fluctuations. *Annals of Forest Science*. 57, 89-100.

St. George, S. and Luckman, B.H. 2001. Extracting a paleotemperature record from *Picea engelmanii* tree-line sites in the central Canadian Rockies. *Canadian Journal of Forest Research*. 31, 457-470.

Stokes, M.A. and Smiley, T.L. 1968. *Tree-Ring Dating*. The University of Chicago Press: Chicago.

Szeicz, J.M. and MacDonald, G.M. 1994. Dendroclimatic reconstructions of summer temperatures in Northwestern Canada since A.D. 1638 based on age-dependent modeling. *Quaternary Research*. 44, 257-266.

Thompson, B. 1994. The pivotal role of replication in psychological research: empirically evaluating the replicability of sample results. *Journal of Personality.* 62, 157-176.

Tranquillini, W. 1979. *Physiological Ecology of the Alpine Timberline*. Springer-Verlag: Berlin.

Wig, J.A. and Smith, D.J. 1994. Dendroclimatological investigations in the Mount Rae Area, Canadian Rocky Mountains. *Western Geography*. 4, 110-126.

Wiles, G.C., D'Arrigo, R.D., and Jacoby, G.C. 1996. Temperature changes along the Gulf of Alaska and the Pacific Northwest coast modeled from coastal tree rings. *Canadian Journal of Forest Research*. 26, 474-481.

Wilmking, M., Juday, G.P., Barber, V.A. and Zald, H.S. 2004. Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. *Global Change Biology*. 10, 1724-1736.

Wilson, R.J.S. and Luckman, B.H. 2002. Dendroclimatic reconstruction of summer temperatures from upper treeline sites in Interior British Columbia, Canada. *The Holocene*. 13, 851- 861.

Wilson, R., Wiles, G., D'Arrigo, R., and Zweck, C. 2006. Cycles and shifts: 1,300 years of multi decadal temperature variability in the Gulf of Alaska. *Climate Dynamics*. 28, 425-440.

Woodward, A., Silsbee, D.G., Schreiner, E.G., and Means, J.E. 1994. Influence of climate on radial growth and cone production in subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*). *Canadian Journal of Forest Research*. 24, 1133-1143.

Worral, J. 1983. Temperature - Bud-burst Relationships in Amabilis and Subalpine Fir Provenance Tests Replicated at Different Elevations. *Silvae Genetica*. 32, 203-209.

Youngblut, D. and Luckman, B. 2008. Maximum June–July temperatures in the southwest Yukon over the last 300 years reconstructed from tree rings. *Dendrochronologia*. 25, 153-166.

Zalatan, R. 2006. The relationship between climate and abundance cycles in barren-ground caribou herds of the Northwest Territories, Canada. Unpublished PhD dissertation. University of British Columbia: Vancouver.

Zalatan, R. and Gajewski, K. 2005. Tree-ring analysis of five *Picea glauca*-dominated sites from the interior boreal forest in the Shakwak Trench, Yukon Territory, Canada. *Polar Geography*. 29, 1-16.

2.7 Figures

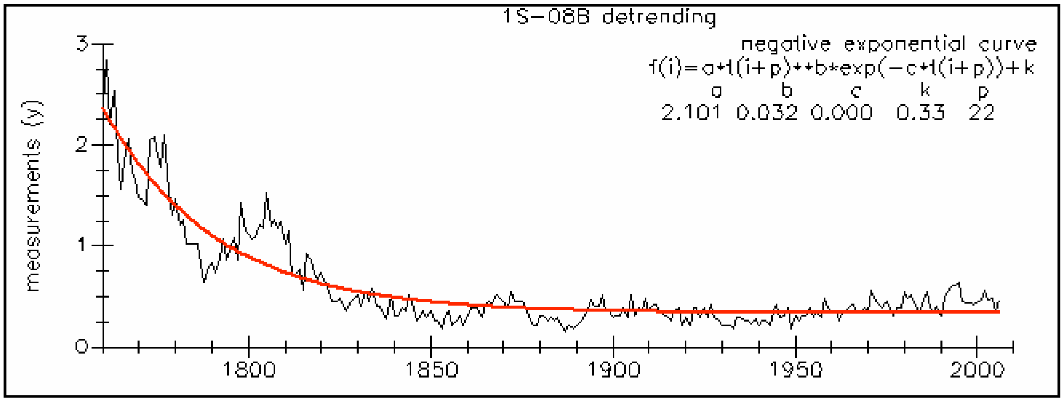


Figure 2.1: Negative exponential curve fit to a ring-width series exhibiting a biological growth-trend.

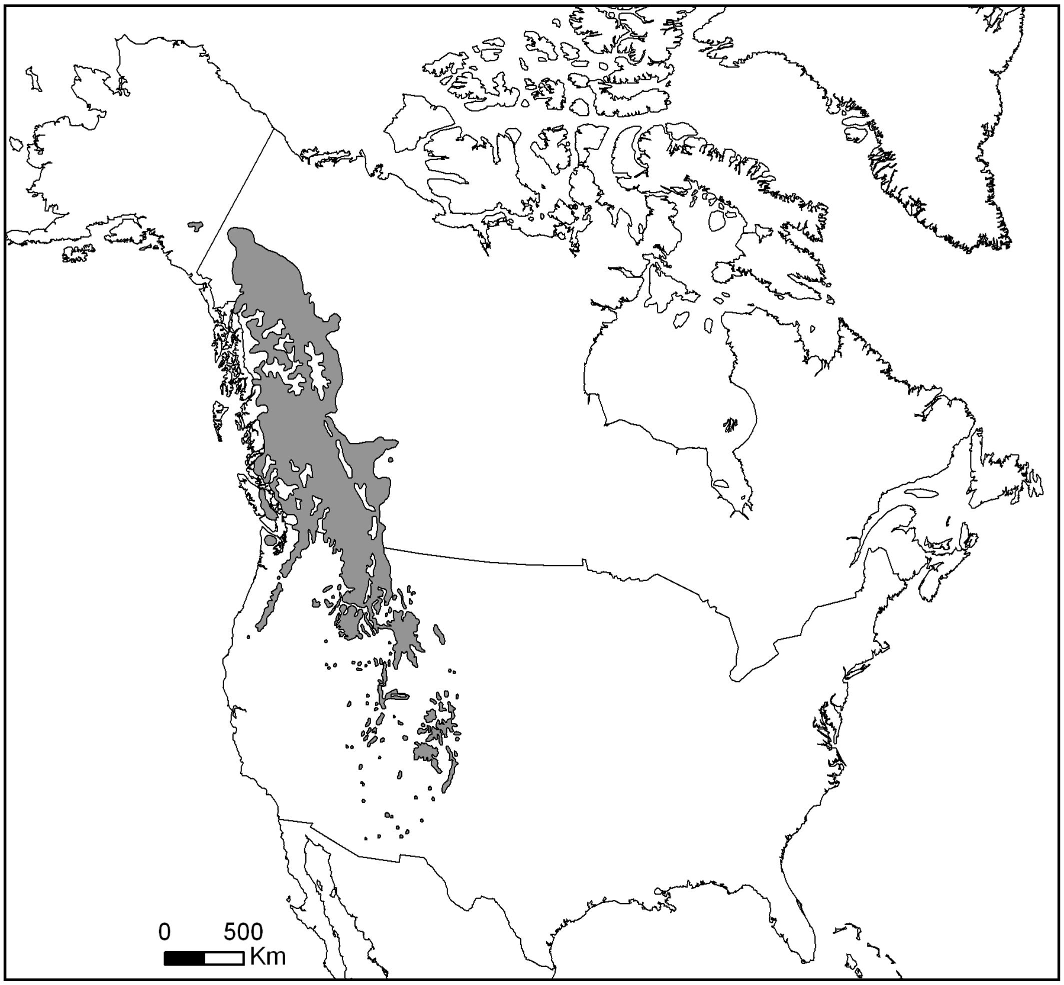


Figure 2.2: Distribution of *Abies lasiocarpa*. Distribution data from Little (1971).

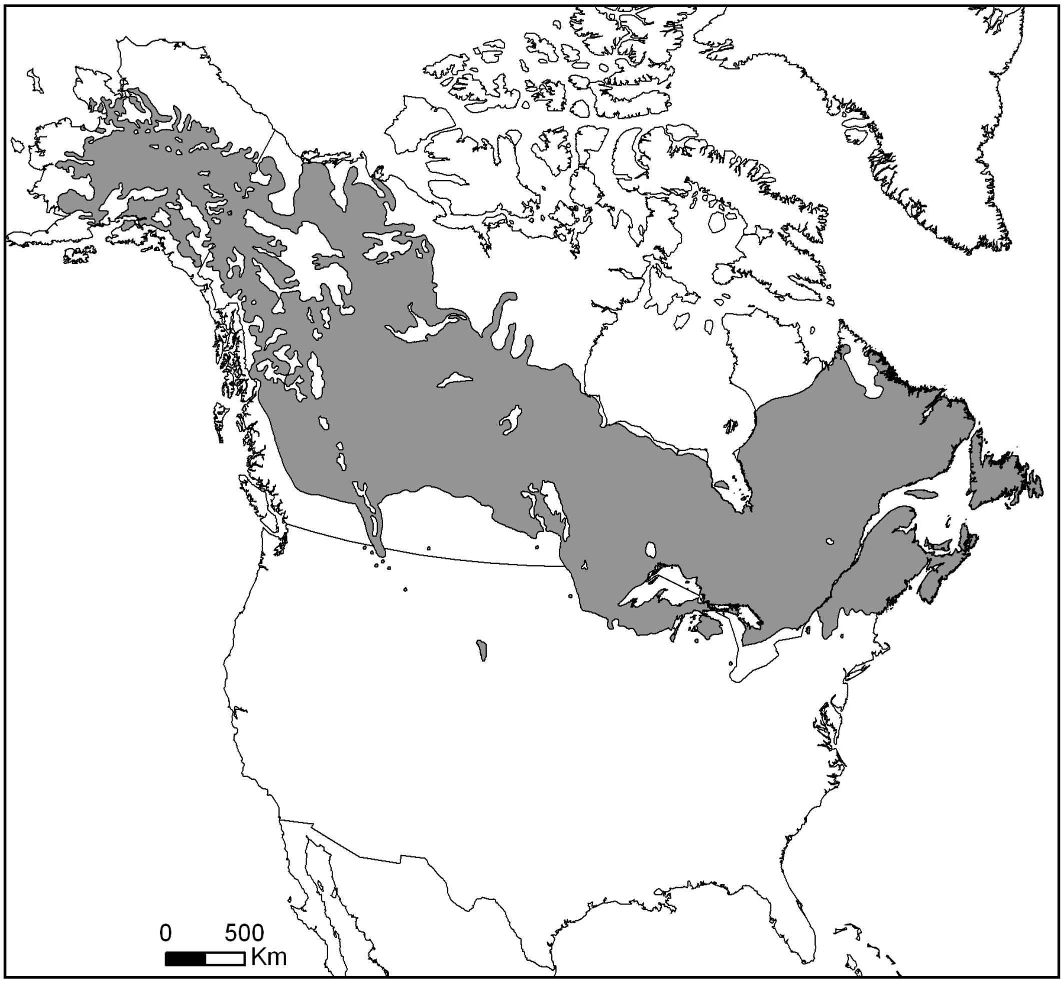


Figure 2.3: Distribution of *Picea glauca*. Distribution data from Little (1971).

Chapter 3 - Study Area

3.1 Introduction

Fieldwork for this thesis was completed in the remote Kwadacha Wilderness Provincial Park in northeastern interior British Columbia, Canada. This chapter provides an overview of the physical setting, biogeography, and climate of the study area. An analysis of spatial and temporal variability in the instrumental climate records from the region is also included.

3.2 Physical Setting

The Kwadacha Wilderness Provincial Park (Figure 3.1) straddles the crest of the Muskwa Ranges, which are part of the northern Canadian Rocky Mountains (Ommanney 2002). This 130,279 ha provincial park was established in 1974 and is now part of the 6.4 million ha Muskwa-Kechika management area (Province of British Columbia 2001a; Mitchell-Banks 2003; Shultis and Rutledge 2003). The park has no road access, and can be reached only by aircraft, horseback, or on foot via a 150 km trail (Province of British Columbia 2001a). Such isolation is a valuable feature of a potential dendroclimatological study site, as older trees are likely to be found in areas with a minimal history of human activity (Schweingruber 1993).

The park contains several peaks over 2300 m asl, as well as the Lloyd George Icefield, which is one of the few sites where glaciers can be found in the Canadian Rocky Mountains north of the Peace River (Gadd 1995; Ommanney 2002). The icefield contains the headwaters of the Muskwa and Kechika rivers, both of which eventually join the Mackenzie River. Meltwater from the Lloyd-George Icefield feeds into a number of nearby lakes, including Haworth, Quentin, Chesterfield and Fern (Figure 3.1).

The Kwadacha Wilderness Provincial Park area has a diverse and rugged topography shaped by extensive past glacial activity (Bednarski and Smith 2007). Underlying rock units in the area are primarily clastic and chemical sedimentary dominated by carbonates, with some low-grade metamorphics in the form of slate and quartzite (Pyle and Barnes 2006). Soils are primarily podzolic in forested areas (Pojar and Stewart 1991).

Sample collection and fieldwork was undertaken adjacent to Haworth Lake, near the centre of the park, at an elevation of 1100 m asl. This 7.5 km-long lake is aligned northeast to southwest. Haworth Lake is bounded on the northwest by Grey Peak (2338 m) and Lupin Ridge, on the northeast by the Lloyd-George Icefield, and on the south by Little Cloudmaker Mountain (2344 m), Cloudmaker Mountain (2506 m), and Mount Chesterfield (2376). The lake is fed by meltwater from the nearby Llanberis and Stagnant glaciers, and drains southwest into Haworth Creek via Haworth Falls.

Many of the toponyms in the Haworth Lake area were given to their respective features by P.L. Haworth and members of his party who explored the region on two separate expeditions in 1916 and 1919 (Smythe 1948; BCGNIS 2007). Additional features were named when the region was further explored and mapped by F.S. Smythe's mountaineering expedition in 1947 (Smythe 1948). Kwadacha Wilderness Provincial Park is named after *Kwadacha*, the Athabascan word for white water describing the Kwadacha River's whitish colouration caused by glacial rock flour (BCGNIS 2007).

3.3 Biogeography

The Biogeoclimatic Ecosystem Classification system identifies the Lloyd George Icefield area as primarily fitting into the Moist Cool subzone of the Spruce-Willow-Birch zone (Figure 3.2; Pojar and Stewart 1991). River valleys and other low elevations in this region are typically home to Boreal White and Black Spruce zones (DeLong *et al*. 1991). The Spruce-Willow-Birch zone gives way to the Engelmann Spruce-Subalpine Fir zone along the borders of the Kwadacha Wilderness to the south and west (Province of British Columbia 2001b). High elevation alpine zones within this region are classified as Alpine Tundra ecosystems (Province of British Columbia 2001b).

The Spruce-Willow-Birch zone is usually found in the subalpine zone of the northern Rocky Mountains at middle elevations between 1000 and 1700 m asl (Pojar and Stewart 1991). The dominant tree species in this zone are white spruce (*Picea glauca* [Moench] Voss) and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) (Pojar and Stewart 1991). White spruce is often the dominant species in valleys and on lower slopes, where it forms an intermittent to closed forest cover (Pojar and Stewart 1991). Subalpine fir is more prominent on higher slopes and may form pure stands on eastern and northern exposures (Pojar and Stewart 1991). Wildfires are relatively infrequent and localized in the zone (Pojar and Stewart 1991).

The Boreal White and Black Spruce zone fills the lower elevations below 1100 m asl of many of the large valleys west of the northern Canadian Rocky Mountains (DeLong *et al*. 1991). Near the Lloyd George Icefield, the Dry Cool subzone of the Boreal White and Black Spruce zone occupies low elevations along the Kwadacha River, the Warnerford River and Chesterfield Creek (DeLong *et al*. 1991; Province of British Columbia 2001b). These forests are dominated by lodgepole pine (*Pinus contorta* var. *latifolia*) and white spruce trees (DeLong *et al*. 1991; Edgell 2001).

The Moist Very Cold subzone of the Engelmann Spruce-Subalpine Fir zone is found between 900 and 1700 m asl (Coupe *et al*. 1991) along the southern and western borders of the Kwadacha Wilderness Provincial Park (Province of British Columbia 2001b). The dominant species in this zone are Engelmann spruce (*Picea engelmannii* Parry ex Engelm var *engelmannii*) and subalpine fir (Coupe *et al*. 1991; Edgell 2001). Forest fires are frequent throughout the Boreal White and Black Spruce zone and the Engelmann Spruce–Subalpine Fir zone, resulting in a mosaic-like pattern of disturbed forests (DeLong *et al*. 1991).

3.4 Climate of the Study Area

The landscape of northern interior British Columbia is defined by the northern Canadian Rocky Mountains. These mountains form a boundary between regions primarily influenced by continental climates to the east and those impacted more by maritime climates to the west (Raphael 2002). The climate of the northern Canadian Rocky Mountains is affected by a combination of mid-latitude and is often influenced by a number of oceanic-atmospheric oscillations. This region exhibits considerable variability in climatic conditions over relatively small spatial scales due to the high-relief local topography.

Under the Köppen climate classification system, the northern Canadian Rocky Mountains and adjacent interior areas are classified as a Dfc climate, indicating continental climatic conditions with no distinct dry season and cold summers (Peel *et al*. 2007). Annual and seasonal climate variability in this region is closely linked to the strength of the Aleutian Low and the frequency of incursions of Arctic air masses (Pojar and Stewart 1991; Tuller 2001; Stahl *et al*. 2006).

The climate of northwestern North America is influenced by oceanic-atmospheric oscillations such as the El Niño/Southern Oscillation (ENSO), the Arctic Oscillation (AO), the Pacific North American (PNA) pattern, and the Pacific Decadal Oscillation (PDO) (Wallace and Gutzler 1981; Mantua *et al.* 1997; Thompson and Wallace 1998; Bonsal *et al.* 2001; D'Arrigo *et al.* 2001; Mantua and Hare 2002; Stahl *et al*. 2006). Analysis of the impact of these oscillations on climate is complicated by the interactions between the oscillations. For instance, the impacts of ENSO have been shown to modulate or be modulated by the impacts of both the AO (Quadrelli and Wallace 2002; Bond and Harrison 2006) and the PDO (Gershunov and Barnett 1998; Bonsal *et al.* 2001; Papineau 2001).

3.5 Influence of the PDO in the northern Canadian Rocky Mountains

The most influential oceanic-atmospheric oscillation in the northern Canadian Rocky Mountains is the PDO (Bonsal *et al.* 2001). The PDO describes a coherent pattern of interdecadal climate variability in the extratropical north Pacific characterized by two modes: a warm, or positive, phase and a cool, or negative, phase. The PDO remains in a given phase for an average of 23 years (Biondi *et al.* 2001; Gedalof and Smith 2001), although it may switch between positive and negative on an interannual basis during that phase. Transitions between the two PDO phases are characterized by abrupt, step-like regime shifts (Gedalof and Smith 2001; Mantua and Hare 2002). Well-recognized PDO regime shifts occurred during the twentieth century in 1925, 1947, 1977, and possibly in 1998. During a warm phase of the PDO, sea surface temperatures (SST) are anomalously warm along the west coast of North America, and anomalously cool in the central north Pacific (Mantua and Hare 2002). These SST anomalies are accompanied by anomalously low sea level pressure (SLP) in the north Pacific, which in turn leads to enhanced cyclonic wind-flow (Mantua *et al.* 1997; Mantua and Hare 2002). Cool phases of the PDO are characterized by conditions opposite of the warm phase, with anomalously cool SST, higher SLP, and decreased counterclockwise wind-flow in the northeastern Pacific (Mantua and Hare 2002).

In northwestern North America, warm phases of the PDO generally coincide with anomalously warm surface air temperatures (hereafter referred to simply as temperature), especially during the winter (Minobe 1997; Bonsal *et al.* 2001; D'Arrigo *et al.* 2001; Mantua and Hare 2002). This pattern is due to increased advection of warmer air onto the Pacific coast of North America caused by the deepening of the Aleutian Low in the northeastern Pacific (Minobe 1997). The impact of the PDO on temperature is greatest in western North America during spring, with a strong winter component in Alaska and western Canada (Minobe 1997). Warm phases of the PDO coincide with anomalously high precipitation in the Gulf of Alaska and anomalously low precipitation in the Pacific Northwest (Mantua and Hare 2002). The northern Canadian Rocky Mountains are located between these two regions, and thus may not experience these PDO-driven precipitation patterns. Although variability in the PDO occurs primarily at low frequencies, annual variability in the PDO also influences the climate of western North America (Bonsal *et al.* 2001).

3.6 Spatial and Temporal Climate Variability

Due to the remote location of the study site, 185 km away from the nearest long-term climate station, no single climate station could be assumed to adequately represent the character of historical changes in local climatic conditions. To assess the local climatic conditions, multiple climate records from nearby stations were analysed, and a merged climate record was created. Instrumental climate records were obtained from stations located to the west, east, and north of the Canadian Rocky Mountains (Figure 3.3). One of the stations is located in the Yukon Territory, close to the provincial border shared with British Columbia. The other two stations are located in northwestern and northeastern interior British Columbia.

3.6.1 Data

Analysis was undertaken on minimum and maximum temperature, average diurnal temperature range (DTR), and average total precipitation on monthly and seasonal time-scales. Individual station data and a merged regional climate record were used in each analysis. Monthly precipitation and maximum and minimum temperature records were obtained for the Fort Nelson, Watson Lake, and Dease Lake climate stations (Table 3.1) from Environment Canada's (2006) Adjusted Historical Canadian Climate Dataset. These data have been adjusted to remove inhomogeneities that may have been caused by station alterations due to changes in factors such as site location, exposure, instrumentation, or observing program (Mekis and Hogg 1999; Vincent and Gullet 1999).

Monthly PDO indices spanning the 1900-2003 period were obtained from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington (Mantua 2006). The PDO index is defined as the leading principal component of sea surface temperature anomalies in the Pacific Ocean north of 20° (Mantua and Hare 2002).

3.6.2 Methods

Individual temperature records were combined using the procedures described in Jones and Hulme (1996) to create a regionally representative record. The monthly climate records from each station were converted to z-scores using the 1944-2003 common-period mean and standard deviation. The monthly z-scores from the three stations were then averaged to create a regional series and converted back to absolute temperature values using the average of the three stations' means and standard deviations. The individual precipitation records were not merged due to the low correlations among the three records.

Diurnal Temperature Ranges were calculated by subtracting mean monthly minimum temperatures from mean monthly maximum temperatures. Seasonal records were developed for November-January (winter), February-April (spring), May-July (summer), and August-October (autumn). These unconventional climatological seasons were chosen because they were considered more biologically meaningful than the standard astronomical seasons for alpine forests in this region, based on analysis of the relationship between radial tree growth and climatic variability (see Chapter Four). Additionally, these unconventional seasons showed a higher level of intra-season homogeneity with regards to temperature and precipitation patterns at interannual time-scales and trends over longer time-scales. Seasonal and mean monthly temperature and DTR data were calculated by simple averaging of the monthly minimum and maximum data; seasonal precipitation data were calculated by summing the monthly precipitation records.

Pearson's correlation analysis was used to analyse the interseries correlations to determine seasonal patterns of spatial homogeneity and heterogeneity in the climate records. A 95% confidence level criteria was used to determine the statistical significance of the correlations. A principal components analysis (PCA) of the three station records was also undertaken to assess spatial homogeneity in the climate data. The variance explained by the first linear component extracted in the PCA was taken as representative of the maximum amount of variance shared by the station records.

Trends in the climate data were assessed using simple linear regression models of the form:

$$\mathbf{Y_i = B_0 + B_1X_i + E_i}$$

In which $\mathbf{Y_i}$ is the predicted value of a given climate variable for a given season at Fort Nelson, Dease Lake, or Watson Lake in year **i; $\mathbf{B_0}$** and $\mathbf{B_1}$ are the parameter estimates; $\mathbf{X_i}$ is the year**;** and **E** is the error term for year **i;** with **i** being restricted to a value between 1945-2003 (the 1944 records cannot be calculated for the winter season) for temperature or 1946-2002 for precipitation. The $\mathbf{B_1}$ coefficient represents the change in $\mathbf{Y_i}$ that occurs with a one unit increase in **X** (i.e. the increase or decrease that occurs in the seasonal climate variable in one year, the magnitude of the trend, or the slope of the linear regression line) and can therefore be interpreted as the average trend per year. Although it is widely recognized that autocorrelation in climate time series can bias estimates of the statistical significance of trends (Zhang *et al*. 2000), trend analysis on the raw, not prewhitened, data was considered adequate for the general descriptive purposes of this analysis.

3.6.3 Climatic Characteristics of the Stations

3.6.3.1 Fort Nelson

Fort Nelson is characterized by continental climate conditions. As is typical for interior regions of British Columbia, this area experiences a high annual temperature range, with a 42°C difference between average summer maximum and winter minimum temperatures. Winters are very cold, with an average minimum temperature of -22 °C (Table 3.2), which has led to this region being dubbed the harshest forested climate zone in the province (Pojar and Stewart 1991; Edgell 2001). Of the three stations analysed, Fort Nelson has the warmest summers, with an average summer maximum temperature of 20°C. Precipitation at this station is relatively low, with an average annual total of only 515 mm; this low-precipitation regime is due primarily to the rainshadow created by the Canadian Rocky Mountains and to the predominance of dry Arctic air through the winter and spring (Tuller 2001). The majority of precipitation is received during the summer (Figure 3.4), mainly due to convective storms (Tuller 2001).

3.6.3.2 Dease Lake

The climate of Dease Lake, although primarily continental in character, is moderated by the proximity of the Pacific Ocean. Winters are milder than at the other two stations, with an average winter minimum temperature of -18 °C, and summers are not as hot as in eastern interior regions, with an average summer maximum temperature of 17°C (Table 3.2). The 35 °C annual range in temperature is therefore lower than that of stations located to the east of the northern Cassiar Mountains. Precipitation at Dease Lake is very low due to the rainshadow created by the Coast Mountains, with an average annual total of 492 mm. A climograph of average climatic conditions at Dease Lake shows a primary precipitation maximum in the summer-early autumn, related to convective lifting, and a smaller secondary maximum in the winter, due to cyclonic lifting (Figure 3.5; Tuller 2001).

3.6.3.3 Watson Lake

Watson Lake is located north of the Canadian Rocky Mountains, in the rainshadow of the Cassiar Mountains. Precipitation is lower than at Fort Nelson and Dease Lake, with an average annual total of 470 mm. A climograph of average climatic conditions at Watson Lake reveals a primary precipitation maximum during the summer-early autumn, with a smaller secondary maximum during the winter (Figure 3.6). Watson Lake has colder winters than the other two stations, with an average winter minimum temperature of -25°C (Table 3.2), and moderately hot summers, with an average summer maximum temperature of 18 °C, giving this station the highest annual temperature range (43 °C).

3.6.4 Spatial variability: interseries correlations and principal components analysis

The three temperature records are consistently positively correlated with one another (Tables 3.3 to 3.10). The inter-station correlations are highest during the winter and lowest during the summer. This seasonal pattern is also apparent in the PCA (Table 3.11). The PCAs of winter maximum and minimum temperature show the highest percent variance explained (94% in both cases); while the PCA of summer maximum and minimum temperature shows the lowest percentages (82% and 79%, respectively). The loadings of the first principal component on each station record are positive, indicating that the component represents a homogeneous pattern of climatic variability throughout the region.

The Dease Lake and Watson Lake temperature records exhibit the highest paired correlation for every season and variable. The Fort Nelson and Watson Lake temperature records show the lowest paired correlation for every season and variable, which is not surprising as these stations are located the furthest apart. Fort Nelson is less strongly correlated with the other two stations than they are with each other and therefore shows the lowest correlation with the regional record in every season. Although weak relative to the other stations' correlations with the regional record, the correlation between the Fort Nelson and regional records is still always above $r = 0.80$.

Compared to temperature, precipitation exhibits consistently lower levels of correlation between stations (Tables 3.12 through 3.15). The Fort Nelson and Dease Lake precipitation records are statistically significantly correlated in every season except spring, with the strongest correlation in the summer. The Dease Lake precipitation record is not statistically significantly correlated with either of the other records in any season. The maximum interseries correlation between precipitation records (Fort Nelson and Watson Lake summer records, $r = 0.516$) is lower than the lowest interseries correlation between temperature records (Fort Nelson and Dease Lake summer minimum temperature records, $r = 0.552$). PCA shows a maximum percent variance explained by the first component of 52% for the summer record. The Dease Lake record loads negatively on the first principal component, while the other records load positively, indicating primarily opposing patterns of precipitation variability between the regions west and east of the Cassiar Mountains.

3.6.5 Temporal Variability: Analysis of Trends

Winter minimum and maximum temperatures have been increasing over the instrumental period in all four records, although the increases are not statistically significant (Table 3.17). Watson Lake has the strongest warming trend compared to the other records. The climate records indicate an increase of 1.2-2.8° C over the 59-year period of analysis.

Statistically significant warming trends are apparent in all four records of spring minimum and maximum temperature. The maximum temperature records consistently show larger warming trends than minimum temperature. Of the four records, Fort Nelson's reveals the strongest warming trend. This analysis indicates that spring temperatures in this region have increased by 2.0-3.9° C during the 59-year period.

The Watson Lake, Fort Nelson and regional summer minimum and maximum temperature records show very small, statistically non-significant trends. The Dease Lake minimum temperature record exhibits a statistically significant warming trend, which indicates an increase of 0.8° C during the analysis period. The Dease Lake maximum temperature record shows a small, statistically insignificant, cooling trend.

Trends in the autumn minimum and maximum temperature records are very small and not statistically significant. The Dease Lake records reveal the strongest autumn trends. The minimum temperature records all show small increasing trends, while decreasing trends are apparent in all of the maximum temperature records except Watson Lake.

Winter DTR records from Watson Lake and Fort Nelson show almost no trend; while the regional and Dease Lake records show small decreases of up to 0.8° C over the 59-year period of analysis (Table 3.18). Only the trend in the Dease Lake winter DTR record is statistically significant. All four records of spring DTR show positive trends, although only the regional and Fort Nelson DTR records exhibit statistically significant trends. Spring DTR has increased by 0.6-1.0° C during the analysis period. The positive trend in spring DTR may be due in part to the inverse relationship between DTR and snow cover caused by the high albedo and insulating capacity of snow (Imke and Wallace 2001). The increase in spring DTR may therefore be due to earlier snow melt caused by increasing April temperature. Trends in summer DTR are close to zero and not statistically significant in all records except Dease Lake's, where summer DTR has decreased by 1.3° C during the analysis period. Trends in the autumn DTR records are not statistically significant and have slopes close to zero in all records except Dease Lake's. Autumn DTR has decreased by 1.3° C at Dease Lake.

The Watson Lake precipitation record shows a large statistically significant negative trend during the winter, indicating a decrease in average total winter precipitation of 38 mm over the analysis period. The other stations exhibit weak, not statistically significant, trends during the winter (Table 3.19). Statistically significant negative trends in the Fort Nelson and Watson Lake precipitation records are apparent during the spring, with decreases of 22-24 mm over the analysis period. The slope of the trend line calculated for the spring Dease Lake record is close to zero. Summer and autumn precipitation records show positive, not statistically significant trends in all three stations' records, except for the Dease Lake summer precipitation record, which exhibits a statistically significant positive trend indicating an increase of 46 mm over the analysis period.

3.6.6 Influence of the PDO

The winter PDO index is statistically significantly correlated with every one of the winter minimum and maximum temperature records, with correlation coefficients between 0.518 and 0.627 (Table 3.20). Similarly, the spring PDO index is statistically significantly correlated with all the spring minimum and maximum temperature records, with correlation coefficients ranging from 0.456 to 0.562. The summer PDO index is statistically significantly correlated with the Dease Lake, Watson Lake, and regional minimum temperature records, but is only weakly correlated with the Fort Nelson minimum temperature record and with all the maximum temperature records. No statistically significant correlations between the fall PDO indices and fall temperature records are apparent.

All but the weakest ($r < 0.1$) correlations between the seasonal PDO indices and their respective seasonal temperature records are positive. This indicates that, as expected, positive PDO index values are associated with warmer temperatures in this region. Correlations with the minimum temperature records are generally stronger than those with the maximum temperature records, although the spring Dease Lake and Watson Lake records are an exception to this pattern.

The strength of the correlations among monthly PDO indices and monthly temperature records is fairly consistent between the four climate records during the winter and spring. However, the summer PDO index exhibits a much stronger correlation with the summer minimum temperature record from Dease Lake than with any other record.

No statistically significant correlations were found between the seasonal PDO indices and seasonal precipitation records (Table 3.21).

3.7 Summary

The northern Canadian Rocky Mountains are characterized by diverse biogeographic and climatic conditions, with a high level of variability over small spatial scales due to the equally diverse mountainous topography of the region. Analysis of spatial variability in local instrumental climate records revealed a consistent pattern of primarily homogeneous variability in temperature records throughout this region of northern interior British Columbia, which indicates that the regional merged temperature records can be considered representative of temperature conditions throughout this region. Considerably less spatial consistency was found in the precipitation records, with low interseries correlations and opposite patterns of variability apparent in records to the west and east of the Cassiar Mountains. Analysis of temporal variability in the instrumental climate records revealed increasing temperatures throughout the region during most seasons, with the greatest increases occurring in spring maximum temperatures. Spring precipitation appears to be decreasing in the east, while winter precipitation is increasing in the west. The trend analysis results show a high level of correspondence with the results from Zhang *et al*.'s (2000) analysis of gridded climate data across Canada. The PDO has a consistent positive relationship with annual variability in winter and spring temperatures in this region, but no statistically significant relationship with precipitation.

3.8 Works Cited

BCGNIS: British Columbia Geographical Names Information System. 2007. *BC Geographical Names*. Available at: http://ilmbwww.gov.bc.ca/bcnames/.

Bednarski, J.M., and Smith, I.R. 2007. Laurentide and montane glaciation along the Rocky Mountain Foothills of northeastern British Columbia. *Canadian Journal of Earth Sciences*. 44, 445-457.

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

Bond, N.A. and Harrison, D.E. 2006. ENSO’s effect on Alaska during opposite phases of the Arctic Oscillation. *International Journal of Climatology*. 26, 1821-1841.

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

Coupe, R., Stewart, A.C. and Wilkeem, B.M. 1991. 'Engelmann Spruce - Subalpine Fir Zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 223-236.

D'Arrigo, R., Villalba, R., and Wiles, G. 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics*. 18, 219-224.

DeLong, C., Annas, R.M., and Stewart, A.C. 1991. 'Boreal white and black spruce zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 237-250.

Edgell, M.C.R. 2001. 'Vegetation' in *British Columbia, the Pacific Province: Geographical Essays*. ed. C. J.B. Wood. Western Geographical Press: Victoria, Canada. 83-96.

Environment Canada, 2006. *AHCCD – Adjusted Historical Canadian Climate Data*. Available at: http://www.cccma.ec.gc.ca/hccd/index.shtml. Accessed on:01/02/2007.

Gadd, B. 1995. *Handbook of the Canadian Rockies*. Corax Press: Jasper, Canada.

Gedalof, Z. and Smith, D.J. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. *Geophysical Research Letters*. 28, 1515-1518.

Gershunov, A. and Barnett, T.P. 1998. Interdecadal modulation of ENSO teleconnections. *Bulletin of the American Meteorological Society*. 79, 2715-2725.

Imke, D. and Wallace, J.M. 2001. Factors influencing the cold-season diurnal temperature range in the United States. *Journal of Climate*. 14, 3263-3278.

Jones, P.D. and Hulmes, M. 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology*. 16, 361-377.

Mantua, N.J. and Hare, S.R. 2002. The Pacific Decadal Oscillation. *Journal of Oceanography*.58, 35-44.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*. 78, 1069-1079.

Mekis, É. and Hogg, William D. 1999. Rehabilitation And Analysis Of Canadian Daily Precipitation Time Series. *Atmosphere-Ocean.* 37, 53-85.

Minobe, S. 1997. A 50-70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*. 24, 683-686.

Mitchell-Banks, P.J. 2003. ‘Protecting and sustaining wilderness values in the Muskwa-Kechika Management Area’ in *USDA Forest Service Proceedings* RMRS-P-27. 2003. 104-109.

Ommanney, S.L. 2002. 'Glaciers of the Canadian Rockies' in *Satellite image atlas of glaciers of the world, North America*. Eds.Williams, R.S. Jr and Ferrigno, J.G. US Geological Survey Professional Paper 1386-J-1.

Papineau, J.M. 2001. Wintertime temperature anomalies in Alaska correlated with ENSO and PDO. *International Journal of Climatology*. 21, 1577-1592.

Peel, M.C., Finlayson, B.L., and McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences Discussion*. 4, 439-473.

Pojar, J. and Stewart, A.C. 1991. 'Spruce - Willow - Birch Zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 251-262.

Province of British Columbia 2001a. *Kwadacha Wilderness*. Available at: http://www.env.gov.bc.ca/bcparks/explore/parkpgs/kwadacha.html.

________________________ 2001b. *BEC Web*. Available at: http://www.for.gov.bc.ca/HRE/becweb/.

Pyle, L.J., and Barnes, C.R.. 2006. *Taxonomy, Evolution, and Biostratigraphy of Condonants from the Kechika Formation, Skoki Formation, and Road River Group (Upper Cambrian to Lower Silurian), Northeastern British Columbia*. National Research Council of Canada: Ottawa.

Quadrelli, R. and Wallace, J.M. 2002. Dependence of the structure of the Northern Hemisphere annular mode on the polarity of ENSO. *Geophysical Research Letters*. 29, 2132, doi:10.1029/2002GL015807.

Raphael, C. 2002. The Climate of the Central and Northern Interior of BC. *Western Geography*. 12, 230-289.

Schweingruber, F.H. 1988. A new dendrochronological network for western North America. *Dendrochronologia*. 6, 171-178.

Schweingruber, F.H. 1993. *Trees and Wood in Dendrochronology*. Springer-Verlag: Berlin.

Shultis, J. and Rutledge, R. 2003. The Muskwa-Kechika Management Area. A model for the sustainable development of wilderness? *International Journal of Wilderness* 9, 12-16.

Smythe, F.S. 1948. An expedition to the Lloyd George Mountains, North-East British Columbia. *The Geographical Journal*. 111, 158-171.

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

Thompson, D.W.J. and Wallace, J.M. 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical Research Letters*. 25, 1297-1300.

Tuller, S. 2001. 'Climate' in *British Columbia, the Pacific Province: Geographical Essays*. ed. C.J.B. Wood. Western Geographical Press: Victoria, Canada. 45-64.

Vincent, L.A. and Gullet, D.W. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology*. 19, 1375-1388.

Wallace, J.M., and Gutzler, D.S. Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review*. 109, 784-812.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*. 38, 395-429.

3.9 Figures

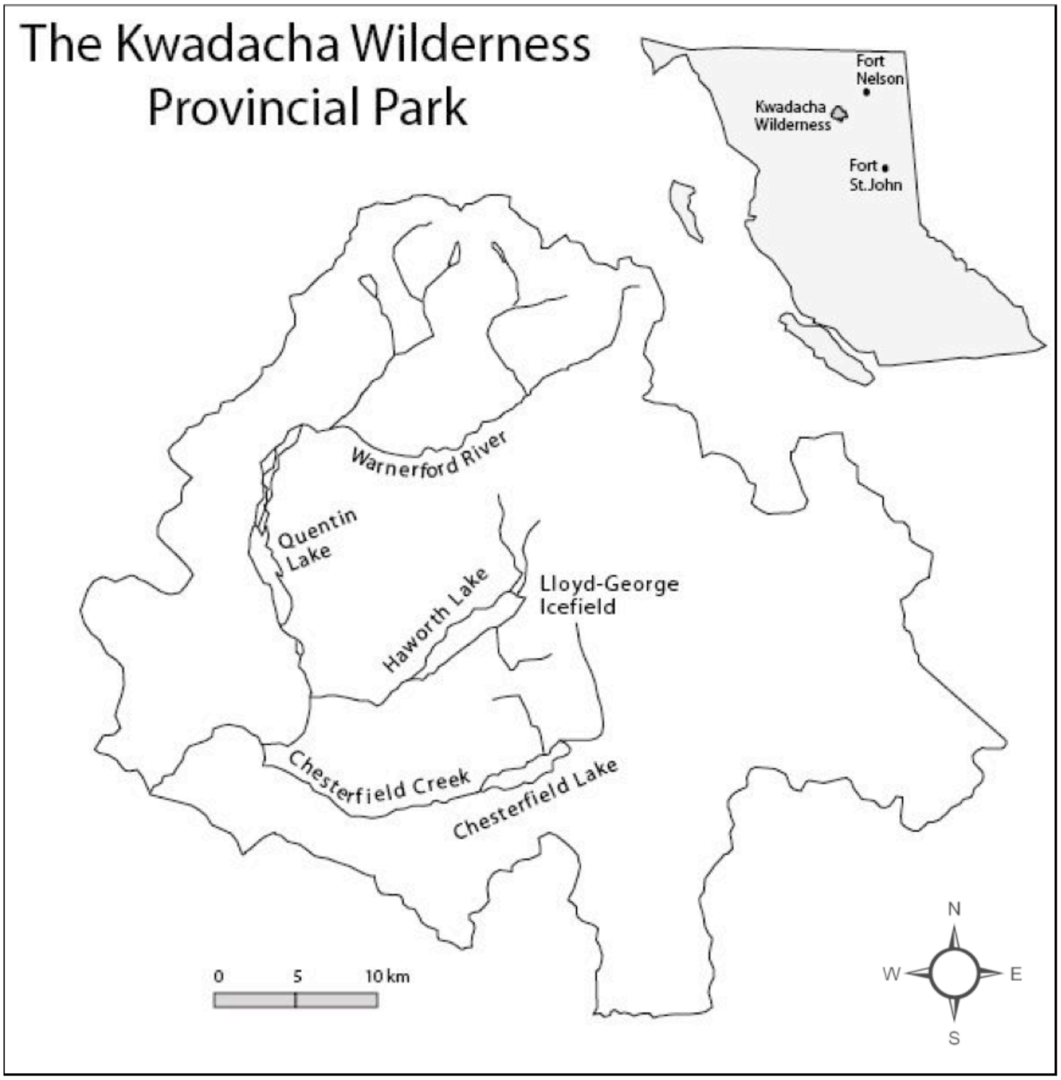


Figure 3.1: Map of the Kwadacha Wilderness Provincial Park.

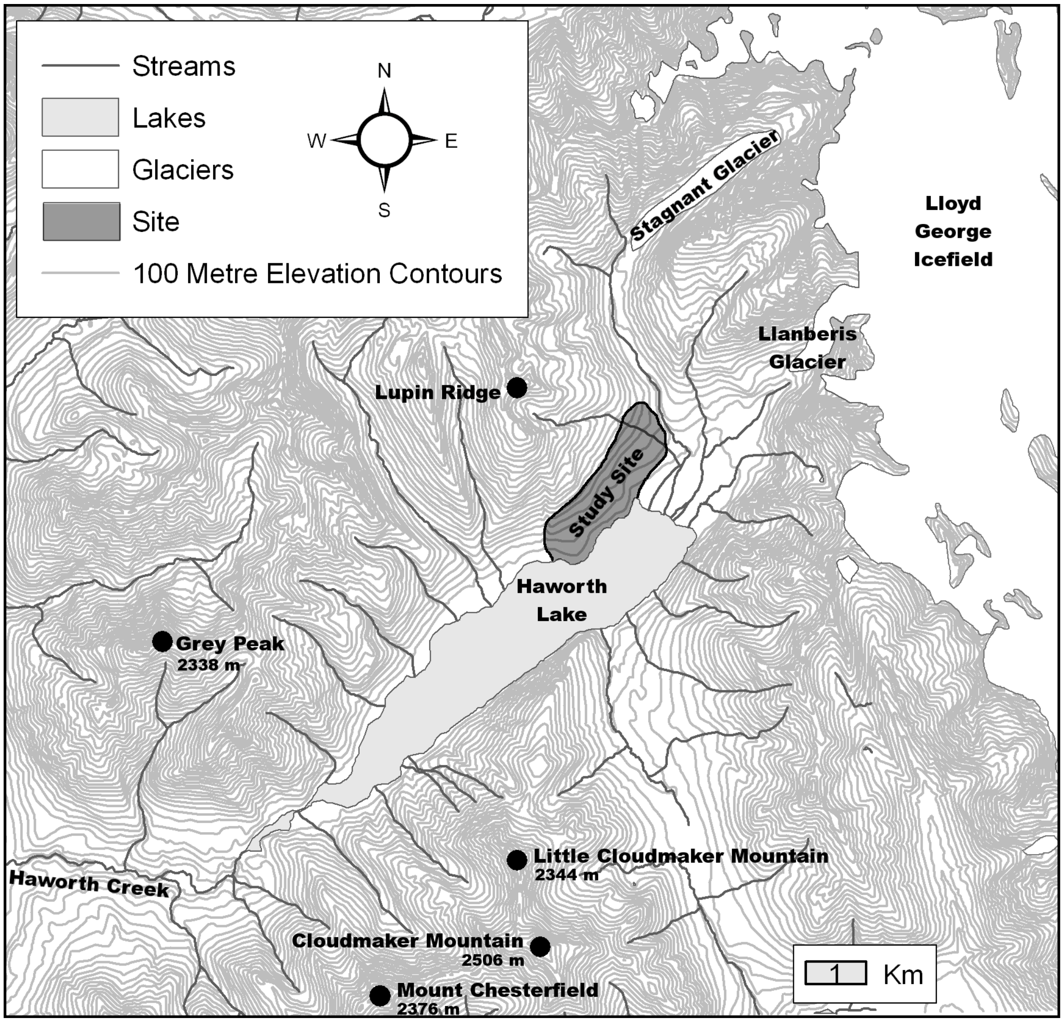


Figure 3.2: Topography and major geographic features in the Haworth Lake area of the Kwadacha Wilderness Provincial Park.

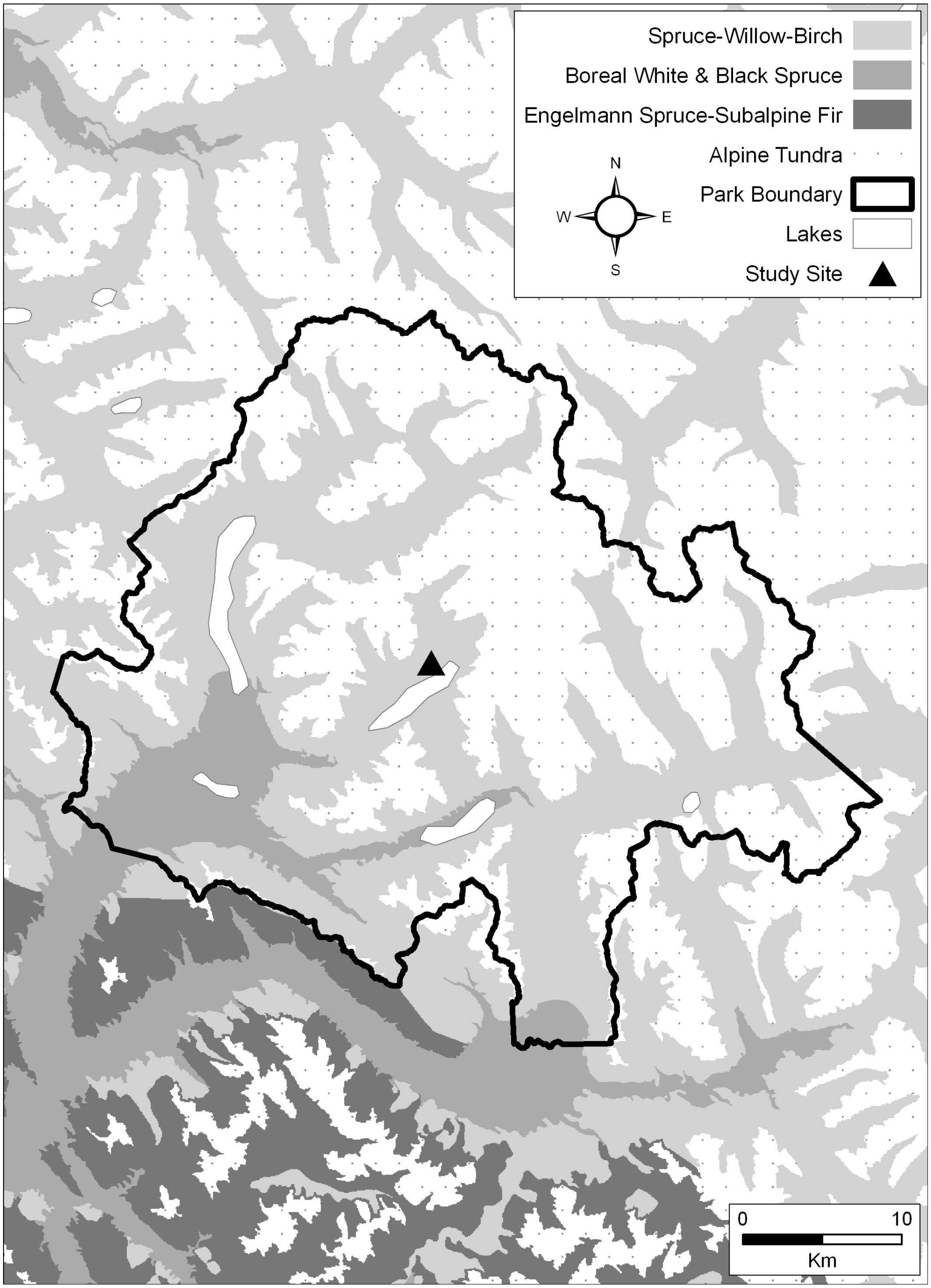


Figure 3.3: Biogeoclimatic Zones in Kwadacha Wilderness Provincial Park. Data from Province of British Columbia (2001a).

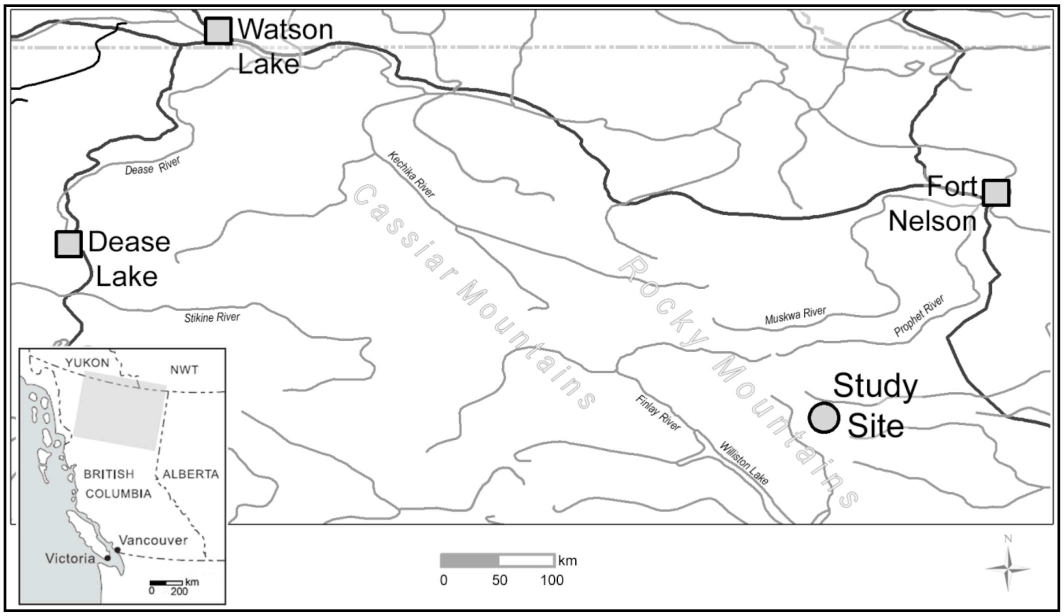


Figure 3.4: Location of climate stations.

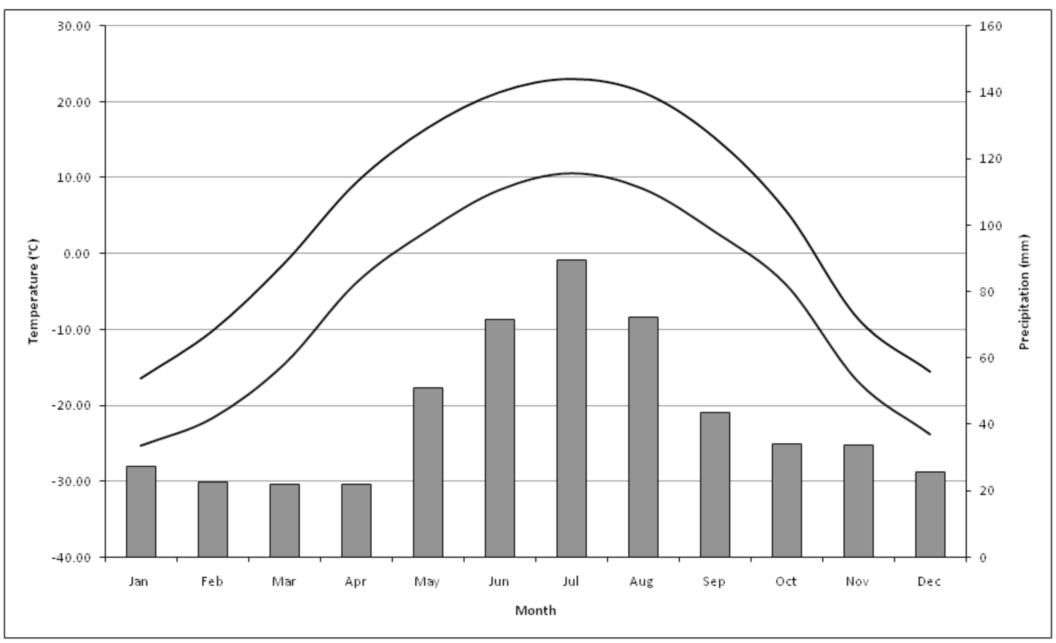


Figure 3.5: Climograph of monthly maximum and minimum temperature and total monthly precipitation at Fort Nelson.

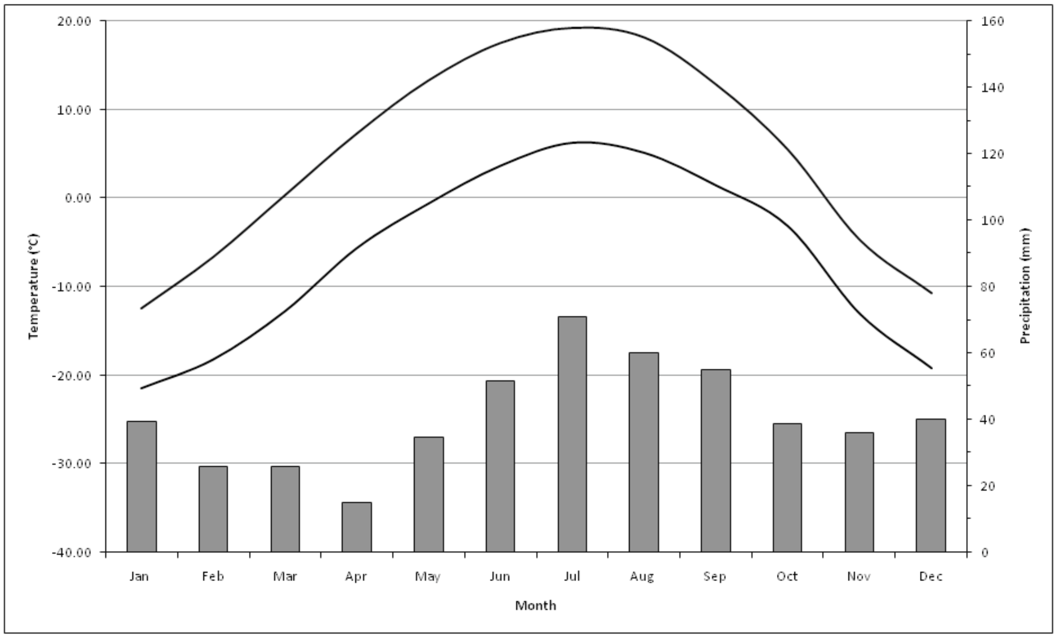


Figure 3.6: Climograph of monthly maximum and minimum temperature and total monthly precipitation at Dease Lake.

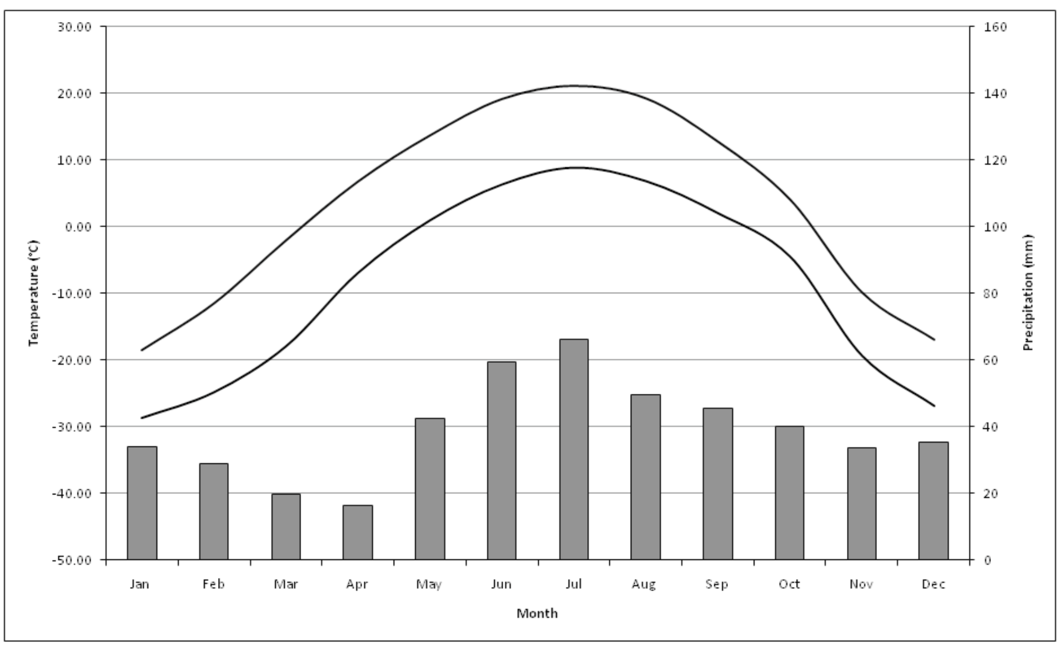


Figure 3.7: Climograph of monthly maximum and minimum temperature and total monthly precipitation at Watson Lake.

3.10 Tables

Table 3.1: Location, elevation (m asl), record length and distance (km) from the study site of the three climate stations used in this analysis.

Station	Latitude	Longitude	Elevation	Years	Distance
Fort Nelson	58° 50.4' N	122° 36.0' W	382	1937-2006	185
Dease Lake	58° 25.8' N	130° 0.6' W	807	1944-2003	296
Watson Lake	60° 7.2' N	128° 49.2' W	687	1938-2006	333

Table 3.2: Average seasonal minimum and maximum temperature (° C), DTR (° C), and total precipitation (mm) at three climate stations.

	Fort Nelson	Dease Lake	Watson Lake
Winter Minimum	-21.9	-17.9	-25.0
Winter Maximum	-13.5	-9.3	-15.2
Winter DTR	8.4	8.6	9.9
Winter Precipitation	86.4	115.3	102.7
Spring Minimum	-13.3	-12.2	-16.6
Spring Maximum	-0.7	0.4	-2.8
Spring DTR	12.6	12.6	14.3
Spring Precipitation	66.7	66.3	64.6
Summer Minimum	7.4	3.0	5.5
Summer Maximum	20.3	16.7	18.0
Summer DTR	12.9	13.7	12.6
Summer Precipitation	212.0	157.0	167.7
Autumn Minimum	2.5	1.1	1.5
Autumn Maximum	14.0	12.2	12.0
Autumn DTR	11.6	11.0	10.5
Autumn Precipitation	149.9	153.7	135.0

Table 3.3: Pearson's correlation coefficients for the four winter maximum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.875	0.903	0.959
Dease Lake	-	0.960	0.964
Watson Lake	-	-	0.967

Table 3.4: Pearson's correlation coefficients for the four winter minimum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.893	0.909	0.960
Dease Lake	-	0.944	0.975
Watson Lake	-	-	0.979

Table 3.5: Pearson's correlation coefficients for the four spring maximum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.839	0.844	0.923
Dease Lake	-	0.943	0.965
Watson Lake	-	-	0.968

Table 3.6: Pearson's correlation coefficients for the four spring minimum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.797	0.803	0.915
Dease Lake	-	0.931	0.962
Watson Lake	-	-	0.963

Table 3.7: Pearson's correlation coefficients for the four summer maximum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.564	0.721	0.844
Dease Lake	-	0.888	0.903
Watson Lake	-	-	0.962

Table 3.8: Pearson's correlation coefficients for the four summer minimum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.552	0.670	0.815
Dease Lake	-	0.838	0.908
Watson Lake	-	-	0.943

Table 3.9: Pearson's correlation coefficients for the four autumn maximum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.671	0.788	0.880
Dease Lake	-	0.889	0.926
Watson Lake	-	-	0.967

Table 3.10: Pearson's correlation coefficients for the four autumn minimum temperature records. All correlations are significant at the 0.05 level (p = .000 in all cases).

	Dease Lake	Watson Lake	Regional
Fort Nelson	0.711	0.766	0.903
Dease Lake	-	0.800	0.911
Watson Lake	-	-	0.934

Table 3.11: Percent variance explained by the first principal component extracted from a principal components analysis of the Fort Nelson, Dease Lake, and Watson Lake temperature records.

Winter Minimum	94.4
Winter Maximum	94.2
Spring Minimum	89.6
Spring Maximum	91.7
Summer Minimum	79.3
Summer Maximum	81.9
Autumn Minimum	84.0
Autumn Maximum	85.6

Table 3.12: Pearson's correlation coefficients for the three winter precipitation records. Bold correlations are significant at the 0.05 level.

	Dease Lake	Watson Lake
Fort Nelson	-0.018	**0.434**
Dease Lake	-	-0.175

Table 3.13: Pearson's correlation coefficients for the three spring precipitation records. Bold correlations are significant at the 0.05 level.

	Dease Lake	Watson Lake
Fort Nelson	-0.117	0.265
Dease Lake	-	0.105

Table 3.14: Pearson's correlation coefficients for the three summer precipitation records. Bold correlations are significant at the 0.05 level.

	Dease Lake	Watson Lake
Fort Nelson	0.037	**0.516**
Dease Lake	-	0.177

Table 3.15: Pearson's correlation coefficients for the three autumn precipitation records. Bold correlations are significant at the 0.05 level.

	Dease Lake	Watson Lake
Fort Nelson	-0.026	**0.356**
Dease Lake	-	-0.026

Table 3.16: Percent variance explained by the first principal component extracted from a principal components analysis of the Fort Nelson, Dease Lake, and Watson Lake precipitation records.

Winter	49.2
Spring	42.2
Summer	52.0
Autumn	46.0

Table 3.17: Slope of the temperature trend lines. Bold values are statistically significant at the 0.05 level. Total change over the period of analysis in °C listed in parentheses.

Variable	**Fort Nelson**	**Dease Lake**	**Watson Lake**	**Regional**
Winter Minimum	0.032 (1.9)	0.034 (2.0)	0.047 (2.8)	0.037 (2.2)
Winter Maximum	0.035 (2.1)	0.021 (1.2)	0.045 (2.7)	0.024 (1.4)
Spring Minimum	**0.051** (3.0)	**0.033** (2.0)	**0.034** (2.0)	**0.039** (2.3)
Spring Maximum	**0.066** (3.9)	**0.043** (2.5)	0.**045** (2.7)	**0.057** (3.4)
Summer Minimum	0.004 (0.2)	**0.014** (0.8)	0.003 (0.2)	0.007 (0.4)
Summer Maximum	0.005 (0.3)	-0.008 (-0.5)	0.004 (0.2)	0.001 (0.1)
Autumn Minimum	0.005 (0.3)	0.010 (0.6)	0.000 (0.0)	0.006 (0.4)
Autumn Maximum	-0.002 (-0.1)	-0.012 (-0.7)	0.002 (0.1)	-0.005 (-0.3)

Table 3.18: Slope of the DTR trend lines. Bold values are statistically significant at the 0.05 level. Total change over the period of analysis in °C listed in parentheses.

Variable	**Fort Nelson**	**Dease Lake**	**Watson Lake**	**Regional**
Winter DTR	0.003 (0.2)	**-0.012** (-0.7)	-0.002 (-0.1)	-0.013 (-0.8)
Spring DTR	**0.015** (0.9)	0.010 (0.6)	0.011 (0.7)	**0.017** (1.0)
Summer DTR	0.002 (0.1)	**-0.022** (-1.3)	0.001 (0.1)	-0.006 (-0.4)
Autumn DTR	-0.007 (-0.4)	**-0.022** (-1.3)	-0.002 (-0.1)	-0.011 (0.7)

Table 3.19: Slope of the precipitation trend lines. Bold values are statistically significant at the 0.05 level. Total change over the period of analysis in mm listed in parentheses.

Variable	**Fort Nelson**	**Dease Lake**	**Watson Lake**
Winter	-0.080 (-4.6)	0.252 (14.4)	**-0.667** (-38.0)
Spring	**-0.416** (-23.7)	-0.014 (-0.8)	**-0.386** (-22.0)
Summer	0.432 (24.6)	**0.814** (46.4)	0.598 (34.1)
Autumn	0.397 (22.6)	0.233 (13.3)	0.013 (0.7)

Table 3.20: Pearson's correlation coefficients for seasonal minimum (left column) and maximum (right column) temperature averages and seasonal PDO indices. Bold values are statistically significant at the 0.05 level.

Season	Fort Nelson		Dease Lake		Watson Lake		Regional	
Winter	**0.627**	**0.601**	**0.573**	**0.518**	**0.593**	**0.561**	**0.615**	**0.574**
Spring	**0.522**	**0.456**	**0.507**	**0.562**	**0.476**	**0.522**	**0.532**	**0.526**
Summer	0.137	-0.027	**0.500**	0.203	**0.357**	0.187	**0.387**	0.141
Fall	0.173	0.065	0.190	0.101	-0.029	0.146	0.119	0.113

Table 3.21: Pearson's correlation coefficients for average seasonal precipitation totals and seasonal PDO indices. No correlations are statistically significant at the 0.05 level.

Season	Fort Nelson	Dease Lake	Watson Lake
Winter	-0.189	-0.087	-0.242
Spring	0.135	-0.106	-0.250
Summer	-0.053	0.177	0.183
Fall	0.059	0.045	-0.102

Chapter 4 - Radial Growth Response of *Abies lasiocarpa* and *Picea glauca* to Temperature Variability in the Northern Canadian Rocky Mountains

4.1 Introduction

The climate of British Columbia has changed over the last century, with historical data showing that average annual air temperatures have increased 0.3 to 0.5ºC per decade since 1950 alone at most recording stations in the province (British Columbia Ministry of Environment 2007). Evidence of the consequences of these changing climates on forest ecosystems is already visible in British Columbia (Carroll *et al*. 2003; Gayton 2008). Further annual temperature increases of 1.8 to 4.0°C are projected by the end of the 21st century (IPCC 2007) and have the potential to cause additional widespread ecological changes (Gayton 2008).

Attempts to predict the future impact of climate changes on the forests of British Columbia often assume a uniform response for entire species, individual forest stands, or broad ecosystems (Rehfeldt *et al*. 1999). However, significant variation in responses to climatic variability can be seen both between (Fritts 1976; Schweingruber 1993) and within tree species (Callaham 1962; Ettl and Peterson 1995; Peterson *et al*. 2002; Walther *et al*. 2002; Rehfeldt 2004; O'Neill *et al*. 2008). To better understand the potential repercussions of a changing climate on the health and composition of an ecosystem, it is necessary to examine the growth responses of the individual organisms and individual species within that ecosystem.

Within British Columbia, some of the forest ecosystems most vulnerable to climate changes are those located within the Spruce-Willow-Birch biogeoclimatic zone (Hamann and Wang 2006). The dominant tree species in this zone, which occupies subalpine landscapes north of 56.5° N, are white spruce (*Picea glauca* [Moench] Voss) and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) (Pojar and Stewart 1991). Hamann and Wang (2006) predict a rapid reduction in the extent of areas with climatic conditions suitable for this ecosystem, with a 99% decrease anticipated by 2085. The total area suitable for white spruce is predicted to shrink by as much as 25% throughout North America (McKenney *et al*. 2007), and by up to 68% in British Columbia (Hamman and Wang 2006) by the end of the 21st century. A similar change in the area suitable for subalpine fir has been predicted, with a reduction of up to 28% in North America (McKenney *et al*. 2007) and 54% in British Columbia (Hamman and Wang 2006).

The vulnerability of the Spruce-Willow-Birch ecosystem to projected changes in climate highlights the importance of increasing our understanding of how tree species within this ecosystem respond to climatic variability. In this paper, we explore intraspecies and interspecies variability in the nature of radial growth responses of white spruce and subalpine fir trees to historical climate conditions. Our paper focuses on a dendroclimatological analysis of the impacts of past climatic variability on the radial growth of high-elevation white spruce and subalpine trees in the northern Canadian Rocky Mountains.

4.2 Site

Fieldwork and sample collection were undertaken in the remote Kwadacha Wilderness Provincial Park (Figure 4.1) during July 2007. Located within the Muskwa-Kechika management area of north-central British Columbia (Mitchell-Banks 2003; Shultis and Rutledge 2003), this park is situated approximately 160 kms southwest of Fort Nelson. The Lloyd-George Icefield, located near the centre of the park, is one of the few icefields remaining within the Canadian Rocky Mountains north of the Peace River (Ommanney 2002). The park's rugged mountainous topography reflects a history of extensive glacial activity (Bednarski and Smith 2007) and is located at the junction of the Fox, Finlay and Kwadacha rivers, in the Rocky Mountain Trench.

Samples were collected from trees found growing between 1150-1400 metres asl on south-east and east facing slopes near Haworth Lake (57.8° Lat N; 125.1° Long W). The forest at the sampling site was composed of co-dominant mature white spruce and subalpine fir trees, with younger cohorts dominated by subalpine fir trees. The forest floor was covered with a well-developed layer of step moss (*Hylocomium splendens*). The understory was sparsely populated with dwarf shrubs, such as *Vaccinium scoparium*, and forbs, including *Veratrum viride*. Nearby low-lying swampy areas were filled with black spruce (*Picea mariana* (Mill.) B.S.P) and dense thickets of shrubby *Salix* species.

Numerous blow-down gaps in varying stages of regeneration were found scattered throughout the forest. Pith rot was widespread, especially among the oldest trees. Although fires are frequent in this region (Pojar and Stewart 1991) and extensive fire damage was visible in adjacent areas of Kwadacha Wilderness Provincial Park, no evidence of recent fires was observed in the vicinity of our sampling sites. Ring counts from the oldest trees indicated that the last stand destroying disturbance occurred over 250 years ago.

4.3 Methods

4.3.1 Sample Collection & Preparation

Mature, dominant trees with no obvious signs of crown damage or rot were selected for sampling. Two increment cores were taken to pith near breast height with 18” borers from each tree at positions ≥ 90° apart. The cores were prepared for measurement according to standard dendrochronological methods (Stokes and Smiley 1968; Fritts 1976; Pilcher 1990). Following air drying, the cores were glued to slotted mounting boards and then polished with progressively finer grades of sandpaper to enhance the visibility of the annual tree-ring boundaries. Ring-widths were measured to the nearest 0.01 mm using a WinDENDRO 2006 digital image measurement and analysis system (Regent Instruments Inc. 2006).

Visual cross-dating of the ring-width series was verified with the International Tree-Ring Data Bank software program COFECHA (Holmes 1983). Cores with obvious signs of damage and ring-width series younger than 160 years were removed from further analysis. Additionally, series that did not show a consistently high level of correlation with the other series were also discarded.

These series exhibited low correlations with the other series primarily due to the presence of very narrow rings with faint boundaries, which made it impossible to accurately locate and measure some of the annual rings.

4.3.2 Standardization

The ring-width series were standardized using the program ARSTAN (Cook and Krusic 2005). A double-detrending approach was used to remove the biological growth trends and to reduce the effects of endogenous disturbance events (Cook 1985). The initial detrending consisted of fitting either a modified negative exponential growth curve, a linear regression line with a negative slope, or a horizontal line passing through the mean to each individual ring-width series. A secondary detrending was completed by fitting a smoothing spline with a 67% frequency-response cutoff to each ring-width series. Splines of this stiffness preserve 50% of the variance in the series at a frequency equal to two-thirds of the length of each individual series. The ring-width series were divided by the values of the fitted curves for each year to calculate an index value for each ring. Auto Regressive Moving Average (ARMA) modelling was applied to each series to remove autocorrelation (Cook 1985). Only the residual chronologies were used in further analysis.

A master chronology was created for each species by averaging the individual ring-width series using a biweight robust mean function. The biweight robust mean discounts the influence of outliers in the ring-width series, thereby decreasing the impact of endogenous disturbance events on the final mean chronology (Cook *et al*. 1990). The individual detrended series were retained for further analysis. Multiple cores from individual trees were combined by simple averaging after detrending to produce a single ring-width series for each tree.

The Expressed Population Signal (EPS) statistic was used to determine the change in chronology quality that occurs in conjunction with decreasing sample size further back in time (Wigley *et al.* 1984; Briffa and Jones 1990). EPS values were calculated for the master chronologies using 20-year moving windows, and the chronologies were truncated when the running EPS fell below the standard value of 0.85 proposed by Wigley *et al.* (1984).

4.3.3 Climate Data

The remote location of the study site, 185 km away from the nearest long-term climate station, meant that no single station's record could be assumed to be representative of the local climatic conditions. The choice of an appropriate instrumental record was further complicated by the site's position near the crest of the Canadian Rocky Mountains. This mountain range acts as a barrier between the continental climate to the east and the more maritime climate to the west (Raphael 2002), and local climatic conditions are therefore an artefact of air masses arriving from both east and west. To address the lack of representative climate data, a regional climate record was created by merging the data from the stations at Dease Lake, Watson Lake, and Fort Nelson (Figure 4.1; Table 4.1). Monthly temperature and precipitation records were obtained from the Adjusted Historical Canadian Climate Database (Vincent and Gullet 1999; Environment Canada 2006) for the 1944-2003 period common to all three stations. These records have previously been analysed and corrected for inhomogeneities caused by factors such as changes in measuring procedures or station relocation (Mekis and Hogg 1999; Vincent and Gullet 1999).

The monthly climate records from each station were standardized by subtracting their mean and dividing by their standard deviation calculated for the 1944-2003 common period following the procedures recommended by Jones and Hulme (1996). The standardized monthly records from each station were then averaged to create a standardized regional series. The regional series was converted back to absolute temperature values using the average of the three stations' means and standard deviations. Mean temperature values were calculated by simple averaging of the regional climate series for each month. Diurnal Temperature Range (DTR) data were calculated by subtracting the monthly minimum temperatures from the monthly maximum temperatures. Total seasonal precipitation was calculated by summing monthly precipitation totals

In addition to climate stations records, an index of the Pacific Decadal Oscillation (PDO) was included in the climate-growth response analysis (see below). The PDO has widespread impacts on temperature and precipitation regimes in western North America (Minobe 1997; Bonsal *et al.* 2001; D'Arrigo *et al.* 2001; Mantua and Hare 2002). A monthly PDO index spanning the years 1900-2003 was obtained from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington (Mantua 2006). This index is defined as the leading principal component of sea surface temperature anomalies in the Pacific Ocean north of 20° latitude (Mantua and Hare 2002).

4.3.4 Analysis of Climate-Growth Relationships

Pearson's correlation analysis was used to explore and quantify climate-radial growth relationships. A 95% confidence level criteria was used to determine the statistical significance of the correlations. Because strong correlations between two or more climate variables can sometimes obscure the true relationship between ring-width and these variables, partial correlation analysis was also used to detect spurious relationships by controlling for, or holding constant, one of a pair of correlated climate variables. For instance, June maximum temperature was held constant while analyzing the relationship between the ring-width series and June minimum temperature. In this example, partial correlation analysis revealed no statistically significant relationship between June minimum temperature and ring-width when June maximum temperature was held constant, and therefore the correlation between ring-width and June minimum temperature indicated by the initial Pearson's correlation analysis was deemed spurious. The ring-width chronologies were compared with a 15-month window of climate data spanning the period from May of the previous year through July of the current growing season. This 15-month window was selected based on preliminary correlation analyses which revealed no statistically significant correlations with months outside of this window. Only correlations significant at the 0.05 level were considered statistically significant.

Correlation analysis was undertaken on the master chronologies of each species to examine interspecies variability of climate-growth relationships. The same analyses were applied to the ring-width series from each individual tree to explore intraspecies variability of climate-growth relationships.

4.4 Results

In total, over 400 increment cores were collected in early July, 2007. Following an assessment of their duration and signal quality, 53 ring-width series from 29 individual white spruce trees and 32 ring-width series from 21 individual subalpine fir trees were selected for further analysis. The chronology statistics for both species demonstrate the high autocorrelation and low mean sensitivity characteristics of chronologies from closed-canopy forests (Table 4.2). The spruce and fir chronologies are only moderately correlated ($r = 0.389$, $p = 0.000$) at the annual scale, but show a common shared pattern of decadal and multi-decadal scale variability (Figure 4.2). Principal components analysis of the ring-width series from all individual trees shows that 32% of the variance in the series can be explained by the first component, which represents a homogeneous growth response from both species. The second principal component, which represents opposite growth responses from the two species, explains a further 14% of the variance in the series.

Both temperature and precipitation records were initially included in the climate-growth analysis, but no consistent pattern of correlations between ring-width and precipitation was found. The few months of statistically significant correlations with precipitation were identified as spurious by the partial correlation analysis (results not shown), in which temperature in a given month was held constant while examining the correlation between ring-width and precipitation during the same month (or set of two adjacent, highly inter-correlated months). Precipitation was therefore excluded from further analysis. The paucity of significant relationships between radial growth and precipitation could be due to an absence of moisture stress among trees in this forest. Alternatively, the lack of a significant relationship with precipitation could be more related to the high level of spatial variability in precipitation, which is especially pronounced in mountainous terrain. The climate data used in these analyses are from stations located at lower elevations and in very different topographic settings compared to the trees at Haworth Lake, and therefore experience dissimilar precipitation regimes.

The white spruce ring-width chronology was shown to be correlated with growing season (April through July) temperature (Figure 4.3). The analysis revealed that the ring-width chronology was most strongly correlated with minimum rather than maximum temperatures in April and July. Maximum monthly temperatures were strongly correlated with the ring-width series during the early- to mid growing season, in May and June. Partial correlation analysis showed that the weak correlation shown to exist between ring-width and minimum temperature in June was in fact spurious, as it disappeared when June maximum temperature was held constant. Similarly, the correlation with maximum temperature during July was deemed spurious, as it was no longer statistically significant when July minimum temperature was held constant. The white spruce chronology exhibited a positive relationship with DTR in April, May, and June.

There was no statistically significant correlation between the white spruce ring-width chronology and the monthly PDO index.

The subalpine fir ring-width chronology was correlated with temperature during the winter and late growing season (Figure 4.4). The correlation analysis results show a positive correlation with minimum temperature during July in the current growth year, and a negative correlation with minimum temperature during July of the previous year. The chronology was also positively correlated with both maximum and minimum temperature during the December and January proceeding the current growth year, and negatively correlated with DTR during those same months. The chronology exhibits a positive relationship with the PDO index for each month between December and June, as well as the annual PDO index (Figure 4.5).

Analysis of the climate-growth responses of individual trees revealed a higher level of intraspecies variability in subalpine fir than in white spruce (Table 4.3). For instance, all but two of the white spruce trees analysed show a strong, statistically significant positive response to June-July mean temperature, while no variable is statistically significantly correlated with more than two-thirds of the subalpine fir trees.

4.5 Discussion

4.5.1 White spruce

Pearson's correlation analysis shows that the white spruce ring-width series is negatively correlated with April minimum temperature. The negative relationship with April temperature indicates that warmer temperatures during mid-spring are associated with reduced radial growth. A negative response to April temperature has been noted in other dendroclimatic studies and attributed to the consequences of needle desiccation (Jacoby and Cook 1981). The potential for desiccation increases with warm late spring temperatures due to increased transpiration rates while water uptake is limited by near-freezing soil temperatures (Kramer and Kozlowski 1960). However, the correlation with minimum temperature, but not maximum temperature, makes this explanation less likely, as most transpiration occurs during the day. Warmer April temperatures also lower the frost hardiness of trees, leaving them susceptible to frost damage (Fritts 1976; Kellomaki *et al.* 1995; Danby and Hik 2007). Generally warm nights interspersed with even a few nights of freezing temperatures could therefore lead to decreased radial growth. Furthermore, warmer temperatures lead to increased respiration rates, which may use up resources stored during the previous growing season before they can be utilized in radial growth (Fritts 1976; Tranquillini 1979). This is especially likely during the spring, when respiration rates are already relatively high due to the energy demands of bud-burst and the process of repairing damage incurred during the winter (Man and Lieffers 1997) and photosynthesis is typically limited by cold air and soil temperatures (Kramer and Kozlowski 1960).

May and June maximum temperatures were both positively correlated with ring-width, although the June correlation is distinctly stronger. Higher daytime temperatures during the early growing season allow for increased photosynthesis, and thus more rapid radial growth (Kramer and Kozlowski 1960; Fritts 1976). Warmer maximum temperatures during these months also melt lingering snow and result in a lengthening of the growing season (Peterson *et al*. 2002).

The strong positive correlation with July minimum temperature initially seems somewhat harder to explain, as cessation of radial growth in late summer is more closely tied to photoperiod than temperature (Kozlowski 1979; Tranquillini 1979). However, this relationship may be explained by the danger of frost damage and low-temperature photoinhibition. Frost damage can occur at relatively warm temperatures during the growing season, before the tree has begun to harden for the winter (Kramer and Kozlowski 1960). Low-temperature photoinhibition acts as a significant limiting factor for seedling establishment and tree growth in many high-elevation and/or high-latitude forests by decreasing the potential rate of photosynthesis (Germino and Smith 1999; Johnson *et al*. 2004; Danby and Hik 2007). Low-temperature photoinhibition is a common phenomenon in high elevation forests, especially when cold nights are followed by sunny days (Germino and Smith 1999).

The white spruce ring-width chronology was positively correlated with DTR during the late spring and early summer (April-June). Increased DTR is associated with decreased cloud cover (Dai *et al.* 1999; Imke and Wallace 2001), and thus with higher levels of available light and increased potential photosynthesis rates. DTR is also inversely related to snowcover (Imke and Wallace 2001). Thus, increased DTR may represent a lengthened and more productive growing season. White spruce seedlings have been shown to reach maximum growth rates under a regime of strong diurnal temperature fluctuations (Nienstaedt and Zasada 1990), and the same may be true of mature white spruce trees.

The white spruce chronology showed no statistically significant correlation with the annual or monthly PDO index (results not shown). This outcome is probably due to the fact that the white spruce chronology responds primarily to growing season temperatures. The PDO's influence has been most pronounced on winter and spring temperatures in this region (Minobe 1997), and has thus had a minimal influence on the growing season temperatures.

4.5.2 Subalpine fir

The subalpine fir ring-width series was positively correlated with July minimum temperature during the current year and negatively correlated with July minimum temperature during the previous year. The positive response to July minimum temperature during the growing season was observed in both the white spruce and subalpine fir chronologies, and may be explained by the same mechanisms of frost damage and low-temperature photoinhibition. Subalpine fir has been shown to be especially sensitive to low-temperature photoinhibition (Germino and Smith 1999). The negative correlation with minimum temperature during the previous July is likely related to diversion of resources to cone development in the year following a warm summer. More reproductive buds are likely to be set during warm summers, leading to a commitment of carbohydrates and other nutrients to cone development, instead of radial growth, during the following year (Woodward *et al*. 1994).

The ring-width chronology was positively correlated with both minimum and maximum temperature during the months of December and January immediately preceding the growing season. Due to the extremely high level of correlation between minimum and maximum temperature ($r > 0.98$) during December and January, partial correlation analysis could not be used for these months. Warmer winter temperatures decrease the risk of both frost damage and ultraviolet radiation damage (Tranquillini 1979).

The subalpine fir ring-width chronology was negatively correlated with December and January DTR. A low DTR may be due to warmer nights, cooler days, or a combination thereof. If lower winter DTR is due to less extreme nighttime low temperatures, it will be associated with a lower risk of frost damage and low-temperature photoinhibition. If lower winter DTR is caused by lower daytime temperatures, it will correspond to a decreased risk of desiccation and reduced losses of stored carbohydrates via respiration (Tranquillini 1979). Furthermore, both minimum and maximum temperature were negatively correlated with DTR during these months, which suggests that DTR is usually high only during very cold events. Thus, the negative association with DTR may simply reflect a negative response to cold conditions in general.

The subalpine fir chronology was statistically significantly positively correlated with the monthly PDO index from the December preceding the year of ring formation through June of the current growth year (Figure 4.5). The PDO is characterized by two modes: a warm, or positive, phase and a cool, or negative, phase. In the northern Canadian Rocky Mountains, warm phases of the PDO are associated with increased temperatures due to increased onshore advection of relatively warm maritime airmasses (Minobe 1997; Bonsal *et al.* 2001; D'Arrigo *et al.* 2001; Mantua and Hare 2002). Warm phases of the PDO can be linked to reduced spring snowpack via warmer temperatures during winter and spring, which lead to less accumulation and earlier melt of snow. Heavy spring snowpacks have been noted as a significant limiting factor to the radial growth of subalpine firs in other dendroclimatic studies (Ettl and Peterson 1995; Peterson *et al*. 2002; Larocque and Smith 2005). Spring snowpack decreases annual radial growth by delaying the initiation of growth and reducing the length of the growing season (Peterson *et al*. 2002). The positive correlation between subalpine fir ring-width and the winter and spring PDO indices can therefore be attributed to warmer temperatures and decreased snowpack during warm phases of the PDO, both of which contribute to increased radial growth.

To test the stability of the relationship between ring-width and the PDO index, a second correlation analysis was undertaken in which the ring-width series was compared to the PDO index during only warm-phase (1925-1946 and 1977-1998) or cold-phase (1900-1924 and 1947-1976) years (Table 4.4). The ring-width series was strongly positively correlated with the PDO index during the cold-phases, but no statistical relationship exists during warm-phase PDO intervals. This finding suggests that the PDO may more strongly influence radial growth conditions in the northern Canadian Rocky Mountains during cold-phases than during warm-phases. This is likely due to radial growth being highly sensitive to interannual PDO variability during cold-phase years when temperatures are generally cooler and therefore more limiting to radial growth. As climatic conditions are considerably warmer during warm-phases of the PDO, even years with a low PDO index value may not take temperatures below the threshold required to induce a growth response. Thus, warm-phase years may show no significant relationship between the PDO index and radial growth because other limiting factors have a stronger influence on growth during these periods. Further research is necessary to investigate whether the strength of the influence of the PDO on tree growth at other sites and in other species also varies depending on the phase of the PDO.

4.5.3 Intraspecies variability

Intraspecies variability in climate-growth responses may be due to differences in age (Szeicz and MacDonald 1994), genetics (Callaham 1962; Rehfeldt 2004; O'Neill *et al*. 2008), or microsite conditions (Fritts 1976; Ettl and Peterson 1995). This analysis shows the climate-growth response of subalpine fir trees to be much more variable at the intraspecies level than that of white spruce. These results agree with those reported by Ettl and Peterson (1995) in which the plasticity of subalpine fir was highlighted.

There is no pattern of opposing negative and positive responders within the white spruce chronology, and only a few cases of opposite responders in the subalpine fir chronology. This indicates that while there may be varying levels of response to climate among trees of each species, there is consistency in the nature of that response.

The homogeneous and consistently strong response to temperature exhibited by individual white spruce trees indicates that white spruce forests in this region should respond in a relatively uniform manner to the warming temperatures predicted for the near future. Subalpine fir, on the other hand, shows a much higher level of individualistic response. Predictions of the impact of changing climatic conditions on subalpine fir forests must therefore be made with less certainty.

The instrumental climate record from northern interior British Columbia during the last half of the 20th century shows the strongest warming trend in the spring (Zhang *et al*. 2000). Summer and fall temperatures, however, show no statistically significant warming trend in this region (Zhang *et al*. 2000). If this seasonal pattern of warming continues into the future, the warmer spring temperatures, without a corresponding increase in summer temperatures, can be expected to lead to decreased growth in approximately a third of the white spruce trees. There is also a statistically significant warming trend in winter temperatures (Zhang *et al*. 2000), which should lead to increased radial growth in at least two-thirds of the subalpine fir trees. It should be kept in mind that other variables, such as precipitation, percent of precipitation falling as snow, and DTR may also change, and these changes could have confounding impacts on radial growth.

4.6 Conclusion

Interspecies and intraspecies variability in growth responses to climatic variability was investigated for an old growth forest in the Northern Canadian Rocky Mountains. Most dendroecological and dendroclimatological studies focus on mean temperature only. Examining both minimum and maximum temperature offers a more complete understanding of climate-growth responses and may lead to different conclusions regarding the physiological reasons for a given growth response. The biological significance of minimum and maximum temperature vary relative to each other throughout the year. Additional variables, such as indices of oceanic-atmospheric oscillations, or the daily difference between minimum and maximum temperature can also act as a good indicators of growing conditions. Therefore, it is advisable to include as many climate variables as possible in the climate-growth analysis.

A strong and consistent growth response to temperature variability was found in the white spruce master chronology and in the ring-width series from individual white spruce trees. The subalpine fir trees exhibited a weaker, and much less consistent, response to temperature variability, but did show a positive response to winter and spring PDO index values. The comparison of intraspecies growth-response variability highlighted the importance of considering the response of individuals when evaluating the impact of climate variability on a species. The growth-response of a master chronology represents an average response for a population, but can seriously underestimate or overestimate the influence of a given climate variable on individuals within that population.

Similarly, assuming a uniform growth response from a forest or ecosystem, without considering differences in species responses, may lead to spurious conclusions.

4.7 Works Cited

British Columbia Ministry of Environment. 2007. Environmental Trends in British Columbia: 2007. http://www.env.gov.bc.ca/soe/et07/EnvironmentalTrendsBC_2007.pdf

Bednarski, J.M., and Smith, I.R. 2007. Laurentide and montane glaciation along the Rocky Mountain Foothills of northeastern British Columbia. *Canadian Journal of Earth Sciences*. 44, 445-457.

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

Briffa, K. and Jones, P.D. 1990. 'Basic chronology statistics and assessment' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 137-152.

Callaham, R.Z. 1962. 'Geographic variability in growth of forest trees' in *Tree Growth*. ed. T.T. Kozlowski. The Ronald Press Company: New York. 311-326.

Carroll, A.L., Taylor, S.W., Régnière, J.; and Safrany, L. 2003. ‘Effects of climate change on range expansion by the mountain pine beetle in British Columbia’ in *Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia*. eds. T.L. Shore, J.E. Brooks, and J.E. Stone. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC. 223-232.

Cook, E.R. 1985. *A Time-Series Analysis Approach to Tree-Ring Standardization*. Ph.D. Unpublished Thesis. University of Arizona: Tucson.

Cook, E.R. and Krusic, P.J. 2005. *Program ARSTAN Manual*. Tree-Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University. Palisades, New York.

Cook, E.R, Shiyatov, S., and Mazepa, V. 1990. 'Estimating the mean chronology' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 123-132.

Dai, A., Trenberth, K.E., and Karl, T.R. 1999. Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *Journal of Climate*. 12, 2451-2473.

D'Arrigo, R., Villalba, R., and Wiles, G. 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics*. 18, 219-224.

Danby, R.K. and Hik, D.S. 2007. Responses of white spruce (*Picea glauca*) to experimental warming at a subarctic alpine treeline. *Global Change Biology*. 13, 437–451.

Ettl, G.J. and Peterson, D.L. 1995. Growth response of subalpine fir (*Abies lasiocarpa*) to climate in the Olympic Mountains, Washington, USA. *Global Change Biology*. 1, 213-230.

Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press: London.

Gadd, B. 1995. *Handbook of the Canadian Rockies*. Corax Press: Jasper, Canada.

Gayton, D.V. 2008. Impacts of climate change on British Columbia's biodiversity: a literature review. *Journal of Ecosystems and Management*. 9, 26-31.

Germino, M.J. and Smith, W.K. 1999. Sky exposure, crown architecture, and low-temperature photoinhibition in conifer seedlings at alpine treeline. *Plant, Cell & Environment*. 22, 407–415.

Hamann, A. and Wang, T. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. *Ecology*. 87, 2773-2786.

Holmes, R.L. 1983. Computer assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*. 43, 69-78.

IPCC (International Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. eds. Pachauri, R.K and Reisinger, A. IPCC: Geneva.

Imke, D. and Wallace, J.M. 2001. Factors influencing the cold-season diurnal temperature range in the United States. *Journal of Climate*. 14, 3263-3278.

Jacoby, G.C. and Cook, E.R. 1981. Past temperature variations inferred from a 400-year tree-ring chronology from Yukon Territory, Canada. *Arctic and Alpine Research*. 13, 409-418.

Johnson, D.M., Germino, M.J. and Smith, W.K. 2004. Abiotic factors limiting photosynthesis in *Abies lasiocarpa* and *Picea engelmannii* seedlings below and above the alpine timberline. *Tree Physiology*. 24, 377–386.

Jones, P.D. and Hulmes, M. 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology*. 16, 361-377.

Kellomaki, S., Hanninen, H., and Kolstrom, M. 1995. Computations on frost damage to scots pine under climatic warming in boreal conditions. *Ecological Applications*. 5, 42-52.

Kramer, P.J. and Kozlowski, T.T. 1960. *Physiology of Trees*. McGraw-Hill Book Company: New York.

Man, R. and Lieffers, V.J. 1997. Seasonal photosynthetic responses to light and temperature in white spruce (*Picea glauca*) seedlings planted under an aspen (*Populus tremuloides*) canopy and in the open. *Tree Physiology*. 17, 437-444.

Mantua, N.J. 2006. *PDO Index.* Available at: http://jisao.washington.edu/pdo/PDO.latest.

Mantua, N.J. and Hare, S.R. 2002. The Pacific Decadal Oscillation. *Journal of Oceanography*. 58, 35-44.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*. 78, 1069-1079.

McKenney, D.W., Pedlar, J.H., Lawrence, K., Campbell, K., and Hutchinson, M.F. 2007. Potential impacts of climate change on the distribution of North American trees. *Bioscience*. 57, 939-948.

Mekis, É. and Hogg, William D. 1999. Rehabilitation And Analysis Of Canadian Daily Precipitation Time Series. *Atmosphere-Ocean.* 37, 53-85.

Minobe, S. 1997. A 50-70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*. 24, 683-686.

Mitchell-Banks, P.J. 2003. ‘Protecting and sustaining wilderness values in the Muskwa-Kechika Management Area’ in *USDA Forest Service Proceedings* RMRS-P-27. 2003. 104-109.

Nienstaedt, H. and Zasada, J.C. 1990. '*Picea glauca*' in *Silvics of North America: 1. Conifers*. *Agriculture Handbook 654*. U.S. Department of Agriculture, Forest Service, Washington, DC. 389-442.

Ommanney, S.L. 2002. 'Glaciers of the Canadian Rockies' in *Satellite image atlas of glaciers of the world, North America*. Eds.Williams, R.S. Jr and Ferrigno, J.G. US Geological Survey Professional Paper 1386-J-1.

O'Neill, G.A., Hamann, A., and Wang, T. 2008. Accounting for population variation improves estimates of the impact of climate change on species' growth and distribution. *Journal of Applied Ecology*. 45, 1040-1049.

Peterson, D.W., Peterson. D.L., and Ettl, G.J. 2002. Growth responses of subalpine fir to climatic variability in the Pacific Northwest. *Canadian Journal of Forest Research*. 32, 1503- 1517.

Pilcher, J.R. 1990. 'Sample Preparation, Cross-Dating, and Measurement' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 40-50.

Pojar, J. and Stewart, A.C. 1991. 'Spruce - Willow - Birch Zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 251-262.

Raphael, C. 2002. The Climate of the Central and Northern Interior of BC. *Western Geography*. 12, 230-289.

Rehfeldt, G. E. 2004. Interspecific and intraspecific variation in *Picea engelmannii* and its congeneric cohorts: biosystematics, genecology, and climate change. U.S. Department of Agriculture, Forest Service, General Technical Report RMRS-GTR-134.

Rehfeldt, G. E., Ying C.C., Spittlehouse, D.L., and Hamilton, D.A. 1999. Genetic responses to climate in Pinus contorta : Niche breadth, climate change, and reforestation. *Ecological Monographs.* 69, 375-407.

Regent Instruments Inc. 2006. *WinDENDRO: An Image Analysis System for Tree-Rings Analysis*. Quebec.

Schweingruber, F.H. 1993. *Trees and Wood in Dendrochronology*. Springer-Verlag: Berlin.

Shultis, J. and Rutledge, R. 2003. The Muskwa-Kechika Management Area. A Model for the sustainable development of wilderness? *International Journal of Wilderness.* 9, 12-16.

Szeicz, J.M. and MacDonald, G.M. 1994. Dendroclimatic reconstructions of summer temperatures in Northwestern Canada since A.D. 1638 based on age-dependent modeling. *Quaternary Research*. 44, 257-266.

Stokes, M.A. and Smiley, T.L. 1968. *Tree-Ring Dating*. The University of Chicago Press: Chicago.

Tranquillini, W. 1979. *Physiological Ecology of the Alpine Timberline: Tree Existence at High Altitudes with Special Reference to the European Alps*. Springer-Verlag: Berlin.

Vincent, L.A. and Gullet, D.W. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology*. 19, 1375-1388.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., and Bairlein, F. 2002. Ecological responses to recent climate change. *Nature*. 416, 389-394.

Wigley, T.M.L., Briffa, K.R., and Jones, P.D. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Applied Meteorology*. 23, 201-213.

Woodward, A., Silsbee, D.G., Schreiner, E.G., and Means, J.E. 1994. Influence of climate on radial growth and cone production in subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*). *Canadian Journal of Forest Research*. 24, 1133-1143.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*. 38, 395-429.

4.8 Figures

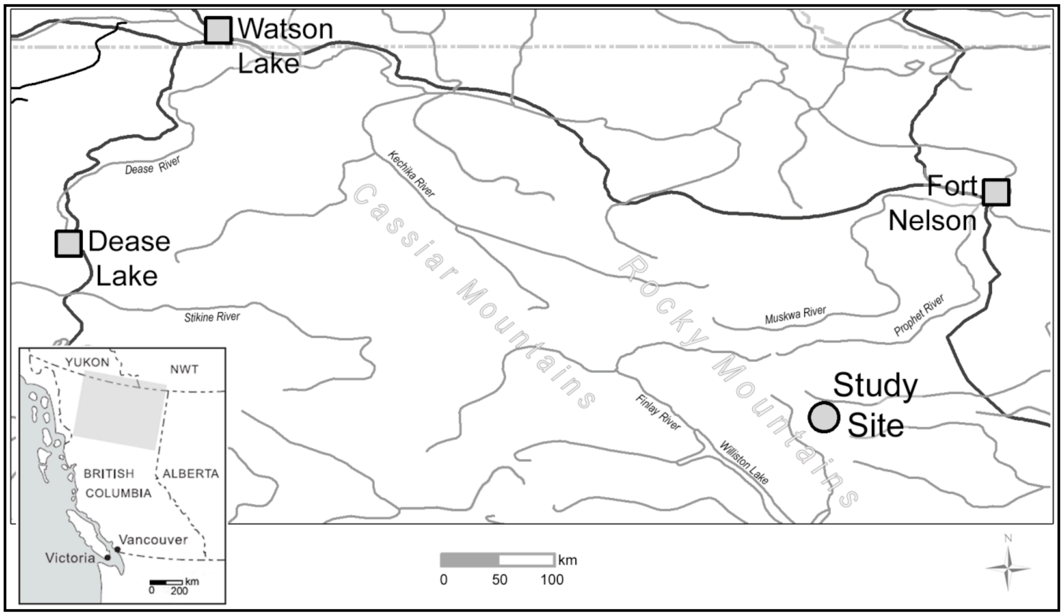


Figure 4.1: Location of study site and climate stations.

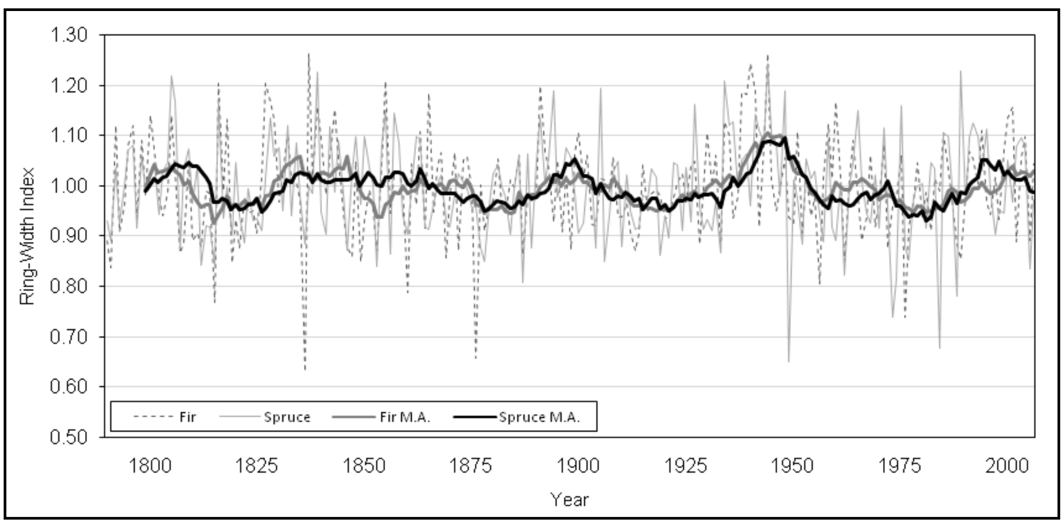


Figure 4.2: White spruce and subalpine fir master chronologies. Thick lines are ten-year moving averages.

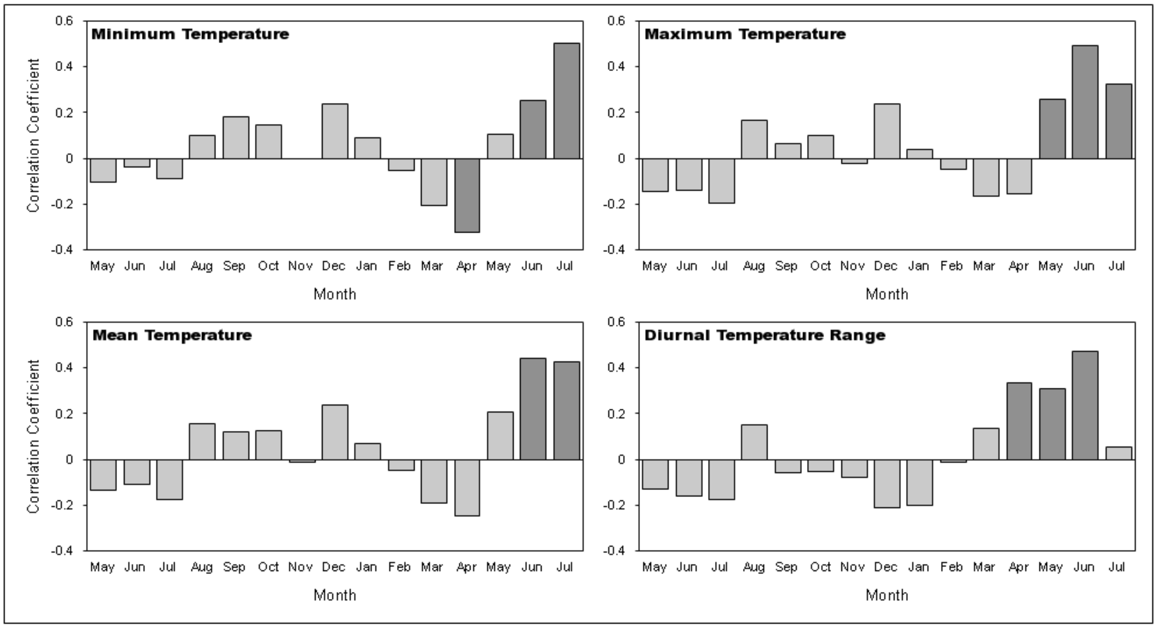


Figure 4.3: Pearson's correlation coefficients calculated for the white spruce master chronology and temperature variables. Dark gray bars represent correlations that are statistically significant at the 0.05 level.

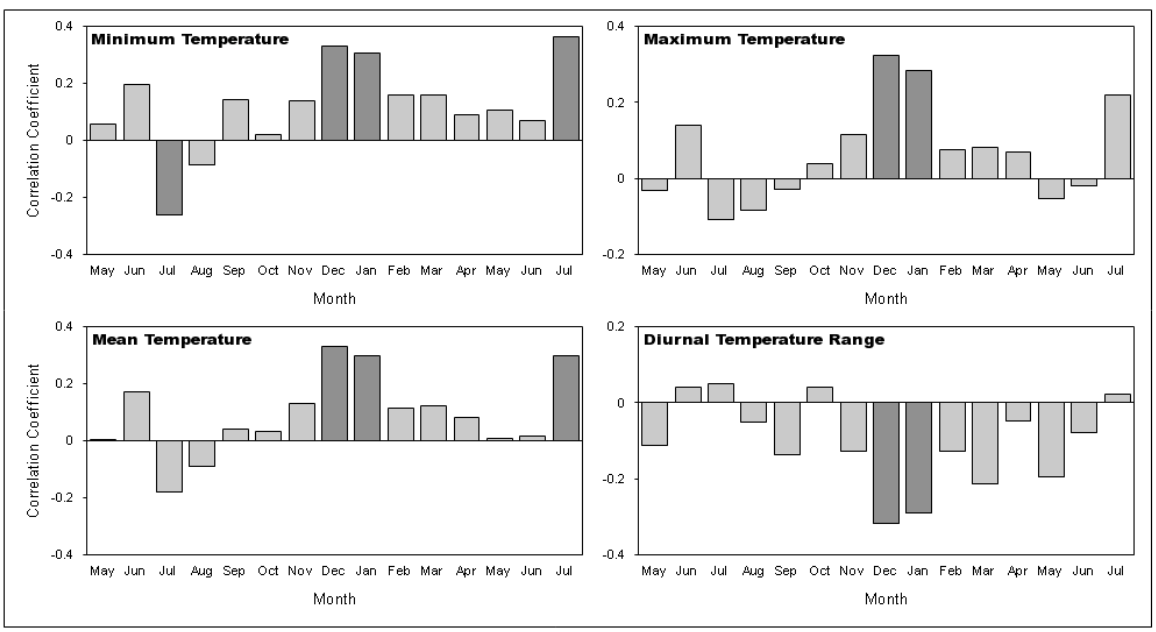


Figure 4.4: Pearson's correlation coefficients calculated for the subalpine fir master chronology and temperature variables. Dark gray bars represent correlations that are statistically significant at the 0.05 level.

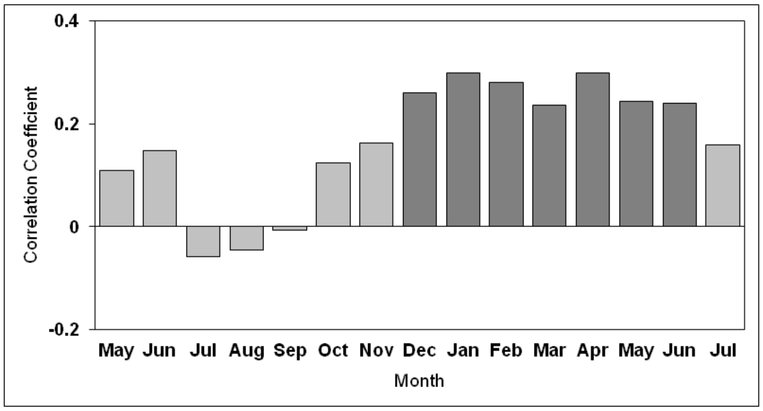


Figure 4.5: Pearson's correlation coefficients calculated for the subalpine fir master chronology and monthly Pacific Decadal Oscillation indices. Dark gray bars represent correlations that are statistically significant at the 0.05 level.

4.9 Tables

Table 4.1: Location, elevation (m asl), record length and distance (km) from the study site of the three climate stations used in this analysis.

Station	Latitude	Longitude	Elevation	Years	Distance
Fort Nelson	58° 50.4' N	122° 36.0' W	382	1937-2006	185
Dease Lake	58° 25.8' N	130° 0.6' W	807	1944-2003	296
Watson Lake	60° 7.2' N	128° 49.2' W	687	1938-2006	333

Table 4.2: Chronology characteristics, see text for further explanation.

	White Spruce	**Subalpine Fir**
Number of trees	29	21
Number of series	53	32
Start date	1723	1758
Mean series length	220	202
.85 EPS threshold	1770	1790
Interseries correlation	0.567	0.577
Mean sensitivity	0.161	0.153
Mean ring width (mm)	0.84	0.82
Standard deviation	0.439	0.290
ARMA model	3	2
Variance due to autocorrelation	33%	34%
Variance explained by 1st component	45%	46%

Table 4.3: Percentage of individual trees statistically significantly correlated (at the .05 level) with climatic variables. All listed correlations are positive, unless indicated otherwise with (-).

White Spruce	
June-July Mean Temperature	97
April-June DTR	97
July Minimum Temperature	87
June Maximum Temperature	87
April Minimum Temperature	37(-)
Subalpine Fir	
December-January Mean Temperature	64
December-June PDO	50
July Minimum Temperature	41
July Minimum Temperature, Previous Year	28 (-)

Table 4.4: Pearson's correlation coefficients for the subalpine fir chronology and the December-June PDO index. Bold Pearson's correlation coefficients are significant at the .05 level.

All phases	**0.322**
Warm-phase	0.127
Cold-phase	**0.437**

Chapter 5 - Dendroclimatic Reconstruction of June-July Mean Air Temperature in the Northern Canadian Rocky Mountains

5.1 Introduction

Dendroclimatological research methods utilize the information contained in tree-rings to produce annually resolved proxy records of climatic variability (Fritts 1976). These dendroclimatic reconstructions are used extensively as important sources of evidence in global climate research and policy papers (Hughes 2002). By extending the limited instrumental climate record, they provide long-term annually-resolved insights into natural climate variability and provide proxy historical records to which modern climate conditions can be compared.

Climate records have been reconstructed from tree-rings at numerous sites in western Canada, including the British Columbia Coast Mountains (Larocque and Smith 2005), the southern interior of British Columbia (Wilson and Luckman 2002), the southern Canadian Rocky Mountains (Wig and Smith 1994; St. George and Luckman 2001; Luckman and Wilson 2005), and the Northwest Territories and the Yukon Territory (Jacoby and Cook 1981; Szeicz and MacDonald 1995; Youngblut and Luckman 2008). Greater spatial coverage of dendroclimatic reconstructions is desirable because significant regional variations exist in the overall patterns of climate fluctuations (St. George and Luckman 2001). Within the cordillera of western Canada, one notable spatial gap in the regional coverage of dendroclimatic reconstructions exists in the mountains of northeastern British Columbia, where only limited dendroclimatological research has been completed (Schweingruber 1988; Briffa *et al.* 1994).

This paper presents the findings of a tree-ring investigation at a remote site in the northern Canadian Rocky Mountains, where dendroclimatological techniques were used to develop a proxy record of summer (June-July) mean surface air temperatures. This is the first annually-resolved temperature reconstruction completed in northern interior British Columbia.

5.2 Methods

5.2.1 Site and Sampling

A ring-width chronology was developed using increment cores extracted from white spruce (*Picea glauca* [Moench] Voss) trees growing in the remote Kwadacha Wilderness Provincial Park (Figure 5.1). The Kwadacha Wilderness Provincial Park's rugged mountainous topography is part of the Muskwa Ranges and reflects a history of extensive glacial activity (Bednarski and Smith 2007). The park is one of the few sites where glaciers can be found in the Canadian Rocky Mountains north of the Peace River (Ommanney 2002) and is the source of the meltwater draining into the headwaters of the Muskwa and Kechika rivers.

Samples were collected from trees found growing in a subalpine forest located between 1150-1400 metres asl on south-east and east-facing slopes adjacent to Haworth Lake (57.8° lat N; 125.1° long W; Figure 1). The dominant tree species at the sampling site were mature white spruce and subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) trees, with younger cohorts dominated by subalpine fir. The understory was sparsely populated with forbs and dwarf shrubs growing out of a deep layer of step moss (*Hylocomium splendens*). Nearby swampy areas were populated by black spruce (*Picea mariana* (Mill.) B.S.P) and dense thickets of *Salix* species.

Mature, dominant trees with no obvious signs of crown damage or rot were selected for sampling. Two increment cores were taken near breast height to pith with 18” borers from each tree at positions ≥ 90° apart.

5.2.2 Data Preparation

The cores were prepared for measurement following standard dendrochronological methods (Stokes and Smiley 1968; Fritts 1976; Pilcher 1990). After being air dried and glued to boards with slotted mounts, the cores were sanded with progressively finer grades of sandpaper to enhance the visibility of the annual tree-ring boundaries. Ring-widths were measured to the nearest 0.01 mm using a WinDENDRO 2006 digital image measurement and analysis system (Regent Instruments Inc. 2006).

Visual cross-dating of the ring-width series was checked using the International Tree-Ring Data Bank software program COFECHA (Holmes 1983). Cores with obvious signs of damage and series that did not show a consistently high level of correlation with the other series were removed from further analysis. Series shorter than 160 years were also discarded.

5.2.3 Standardization & Chronology Construction

The ring-width series were standardized using the program ARSTAN (Cook and Krusic 2005). A double-detrending method was used to enhance the climate signal contained in the ring-width series by reducing the noise caused by biological growth trends and endogenous disturbance events (Cook 1985). The initial detrending consisted of fitting a growth curve to each individual ring-width series. These growth curves consisted of either: a modified negative exponential curve, a linear regression line with a negative slope, or a horizontal line passing through the mean. A secondary detrending was accomplished by fitting a smoothing spline with a 67% frequency-response cutoff to each series. These splines preserve 50% of the variance in the ring-width series at a frequency equal to two-thirds of the length of each series, and therefore offer a good compromise between the risk of removing an excessive amount of low-frequency climatic variability and the danger of retaining too much low-frequency noise caused by disturbance events (Cook 1985). Individual ring-width series were divided by the values of the fitted curves for each year to calculate the index value of each ring. Auto Regressive Moving Average (ARMA) modelling was employed to remove autocorrelation in the ring-width series (Cook 1985). Individual ARMA models of the order determined using Akaike's Information Criterion were fit to each ring-width series in ARSTAN. Only the prewhitened residual ring-width series were used in further analysis.

The individual ring-width series were combined using a biweight robust mean function to create a master ring-width chronology (hereafter referred to as the RW chronology). The Expressed Population Signal (EPS) statistic was used to determine the change in chronology quality that occurs as sample size varies through time (Wigley *et al.* 1984; Briffa and Jones 1990). EPS values were calculated for the master chronology using a 20-year moving window. The RW chronology was truncated at the decade in which the running EPS fell below the standard value of 0.85 proposed by Wigley *et al.* (1984).

A second master chronology was created using an unrotated principal components analysis (PCA) of the individual trees (hereafter referred to as the PC chronology). PCA is a widely used technique in dendroclimatological studies as a data reduction tool, a solution for multicollinearity issues, and a method for assessing homogeneity within a set of time series. The principal components extracted during a PCA are orthogonal linear recombinations of the input series, with the first principal component representing the maximum amount of shared variance that can be extracted from the set of input series. In the case of ring-width series, the first principal component is therefore usually interpreted as representing the shared climate signal (Peters *et al.* 1981). PCA is commonly used in response function analysis (Fritts 1976; Fritts and Wu 1986) and as a method for extracting shared variance from multiple master chronologies in multi-site climate reconstructions (Briffa *et al.* 1988; Meko 1997). PCA has also been used as an alternative to standardization and averaging functions when creating master chronologies, by using the first principal component extracted from individual unstandardized ring-width series from a single site (Jacoby and Cook 1981; Peters *et al.* 1981; Enright, 1984). In this study a slightly different approach was taken in which the PCA was carried out on standardized residual ring-width series from individual trees instead of on raw ring-width series. The standardized ring-width series from each tree were combined by simple averaging to create a single series for each of the 29 individual trees. The first principal component was then extracted from the ring-width series of the oldest 15 trees and used as the second master chronology.

5.2.4 Climate Data

Climate data from regional stations with long-term monthly precipitation and air temperature records were obtained from the Adjusted Historical Canadian Climate Database (Mekis and Hogg 1999; Vincent and Gullet 1999; Environment Canada 2006). Due to the remote location of the study site, 185 km away from the nearest long-term climate station, no single climate station could be assumed to be representative of the local climatic conditions. The site's position near the crest of a major mountain range further complicated the choice of an appropriate instrumental climate record, as the local climatic conditions were likely influenced by air masses from both east and west of the mountain range (Raphael 2002). To address this problem, monthly mean temperature records from Dease Lake, Watson Lake, and Fort Nelson (Figure 5.1; Table 5.1) were merged to create a regionally representative record for the stations' 1944-2003 common period. The individual climate records were merged according to the procedures outlined in Jones and Hulme (1996). The monthly records from each station were first converted to z-scores using the 1944-2003 mean and standard deviation. The monthly z-scores from the three stations were averaged to create a regional series and converted back to absolute temperature values using the average of the stations' means and standard deviations. Simple averaging was used to calculate the mean temperature values from the regional climate series for each month.

5.2.5 Analysis of Climate-Growth Responses

Pearson's correlation analyses were used to explore the climate-growth relationships. A 95% confidence level criteria was used to determine the statistical significance of the correlations. Partial correlation analysis was also used to detect spurious correlations. Partial correlation analysis controls for, or holds constant, one of a pair of correlated climate variables while determining the correlation between the second climate variable and a ring-width series. The ring-width chronologies were compared with a 15-month window of climate data spanning the period from May of the previous year through July of the current growing season.

5.2.6 Reconstruction and Verification

Transfer functions were used to reconstruct records of the climate variables with the strongest relationships with each ring-width chronology. Linear regression models were utilized to predict the past values of the climate variable based on the ring-width chronologies. The transfer function models were calibrated using the full 1944-2003 instrumental climate record.

Leave-one-out verification was chosen as the most appropriate technique for evaluating the strength of the reconstruction (Blasing *et al*. 1981; Gordon

1982; Michaelsen 1987). A split period verification analysis (Fritts 1976) was deemed inappropriate due to the short length of the instrumental climate record (Gordon 1982; Michaelsen 1987). Additionally, comparing the earlier and latter halves of the instrumental climate record would have involved splitting the data in the mid 1970s, near the shift from a warm-phase to a cool-phase of the Pacific Decadal Oscillation (PDO). This could seriously bias the validation results, as the PDO has a significant impact on temperature in western Canada (Minobe 1997; Bonsal *et al.* 2001; D'Arrigo *et al.* 2001; Mantua and Hare 2002).

To complete the leave-on-out verification, a separate linear regression model was created for each of the 60 years of the instrumental climate record. One year was left out of the calibration dataset for each model, and the model was used to predict the climate variable of interest for that year. The values predicted for each left-out year were merged into a single climate record and compared to the instrumental climate record to verify the reconstruction. This procedure was repeated for each reconstruction. The ability of the models to reconstruct climatic variability accurately was assessed using correlation coefficients, the reduction of error statistic (RE) and the sign-product statistic (Fritts 1976; Fritts *et al*. 1990).

5.3 Results

5.3.1 Chronologies

Fifty-three ring-width series from 29 individual trees were included in the final analysis. The ring-width series have a mean inter-series correlation of 0.567

and a mean sensitivity of 0.161 (Table 5.2), results similar to those reported from dendroclimatic studies of Engelmann spruce (*Picea engelmannii* Parry ex Engelm var *engelmannii*) in the central Canadian Rocky Mountains (St. George and Luckman 2001). The first principal component extracted from the ring-width series belonging to the 15 oldest individual trees explained 44% of the variability within the series. Based on the EPS statistic, the RW chronology is significant back to 1770. The PC chronology is limited to the common period of all the series used in the PCA, in this case 1772-2003.

5.3.2 Climate-Growth Responses

The chronologies were compared to mean monthly precipitation and monthly records of mean, minimum, and maximum temperature. This paper is focused solely on the relationship between ring-width and temperature because the correlations between ring-width and monthly precipitation totals were relatively weak. Furthermore, partial correlation analysis revealed the few months of statistically significant correlations with precipitation to be spurious (results not shown) when temperature during the same months was held constant. The lack of a strong, consistent relationship with precipitation may be due to the absence of moisture stress in this alpine forest, or it may be due to high levels of spatial heterogeneity in local precipitation patterns caused by the diverse and mountainous terrain in this region. The only available long-term precipitation records were from climate stations located in markedly different topographic settings than the study site, and thus may reflect very different precipitation regimes.

The two chronologies show similar responses to monthly temperature variability (Figure 5.2). Both chronologies exhibit a strong positive correlation with mean monthly temperatures in the early summer. The chronologies were most strongly correlated with maximum temperatures during June and minimum temperatures in July. Previous dendroclimatic studies in British Columbia (Wilson and Luckman 2002) and the Yukon Territory (Youngblut and Luckman 2008) found stronger, more stable correlations between spruce chronologies and maximum temperature than with minimum temperature. In this case, the correlation with July minimum temperature is in fact the strongest correlation with any single monthly climate variable. Partial correlation analysis revealed that the correlation between ring-width and July maximum temperature is no longer statistically significant when July minimum temperature was held constant. The correlation with June minimum temperature was also deemed spurious based on a partial correlation analysis in which June maximum temperature was held constant. Overall, the climate variable most strongly correlated with both chronologies is the averaged June-July mean temperature ($r = 0.572$ for the RW chronology; $r = 0.597$ for the PC chronology).

The correlation analysis results indicate that warmer temperatures during the growing season lead to increased radial growth, as is typical for high-elevation and high-latitude forests (Fritts 1976; Tranquillini 1979). Warmer temperatures during May, June, and July allow for increased rates of photosynthesis, and thus more rapid radial growth (Kramer and Kozlowski 1960). Higher daytime temperatures at the beginning of the growing season also melt lingering snow, thereby increasing the length of the growing season. Warmer night-time temperatures reduce the risk of frost damage and low-temperature photoinhibition (Germino and Smith 1999; Johnson *et al*. 2004; Danby and Hik 2007).

5.3.3 Reconstruction

June-July mean temperature was selected as the optimum climate variable for reconstruction based on the results of the correlation analyses and preliminary regression analyses. Two transfer function models were developed, one based on the PC chronology and one based on the RW chronology. Both were simple linear regression models, as no lagged values of the chronologies were statistically significantly correlated with the temperature record. The RW chronology model explained 32% of the variance in the mean June-July temperature record and passed all verification tests (Table 5.2). The PC chronology model explained 35% of the variance in the mean June-July temperature record and also passed all verification tests (Table 5.2). The high RE values for both verifications are particularly encouraging, as this statistic is extremely sensitive to poor estimates and therefore represents a rigorous test of model skill (Fritts 1976; Fritts *et al*. 1990). Although the PC reconstruction explains more of the variance in the instrumental record, both reconstructions faithfully follow annual variability in the instrumental record of mean June-July temperature, aside from under-predicting some of the more extreme years (Figure 5.3).

The reconstructions show nearly identical patterns of variability ($r = 0.956$, $p = 0.000$) throughout most of the record (Figure 5.4). Slight differences are apparent in the mid 20th century, which shows greater warming in the RW reconstruction, and during a cold period in the 1870s-1890s which appears as a more anomalously cool period in the RW reconstruction. In both reconstructions, the warmest period is during the 1940s-1950s, followed by the 1990s. The coldest period in both reconstructions occurred during the late 1970s, with the second coldest period during the 1820s-1830s.

The small but consistent improvement in the reconstruction produced using the PCA-based approach compared to the reconstruction created using traditional methods suggests that PCA does in fact enhance the climate signal contained within a chronology by extracting only the variance that is common to all the individual series. The primary drawback to PCA-based chronology development is the fact that the chronology length is limited to the length of the shortest series included in the analysis. The similarity of the two chronologies indicates that the traditional averaging-based method of chronology construction performs reasonably well, and seems to be an adequate substitute for a PCA-based chronology at sites where sample-length makes a PCA infeasible.

Although the two reconstructions are very similar, the PC record is clearly a superior reconstruction based on its consistently, if only marginally, higher level of explained variance and stronger verification statistics. Therefore, only the PC reconstruction was used in further analysis (Figure 5.5).

5.3.4 Comparison with other regional chronologies

The PC reconstruction was compared with several other regional chronologies from British Columbia and the Yukon Territory. The southwestern Yukon (SWY) reconstruction is a record of June-July maximum temperature based on a composite ring-width chronology created from a network of white spruce site chronologies (Youngblut and Luckman 2008). The southern Canadian Rocky Mountains (SRM) reconstruction is a record of May-August maximum temperature created using ring-width and density chronologies primarily composed of Engelmann spruce (Luckman and Wilson 2005). The Twisted Tree-Heartrot Hill (TTHH) record is a single-site white spruce ring-width chronology from the northwestern Yukon that shows a positive correlation with June-July mean temperature (Jacoby and Cook 1981; D'Arrigo *et al*. 2004). The southern Coast Mountains (SCM) reconstruction is a record of July mean temperature based on subalpine fir ring-width chronologies from southeastern British Columbia (Larocque and Smith 2005).

Comparison with the dendroclimatic records from western Canada listed above revealed that the northern Canadian Rocky Mountains reconstruction (PC) shares similar patterns of low frequency (decadal or longer time-scales) variability (Figure 5.6), although clear regional differences are visible in the timing and magnitude of climatic events on decadal time-scales. Some of these differences may of course be attributable to the fact that these records were not developed using identical methods, nor even with the same species, making them somewhat difficult to directly compare.

There is a pattern of greater similarity between the PC reconstruction and other tree-ring records in the north than is apparent with those from further south. Many of the regional records show generally increased growth at the end of the 1700s, and dramatic decreases in growth rates in the 1820s-1830s and 1870s-1880s, with a return to normal growing conditions during the mid-1800s. Peaks in growth are apparent in most of the records near 1900 and during the mid and late 20th century. The PC reconstruction shows greater interannual temperature variability during the late 20th century than during any other period; this pattern is not apparent in any of the other tree-ring records included in this comparison.

Correlation analysis indicates a strong pattern of shared high-frequency variability with the SWY reconstruction (Table 5.3). A lower, but still statistically significant, correlation is seen with the TTHH record. The SRM and SCM reconstructions show some similarities at decadal to multi-decadal scales, but much weaker correlations at annual scales. Correlation analyses undertaken for 55-year segments revealed considerable variability in the strength of the relationships between records. The mid-1800s stand out as an anomalous period during which the usually moderate to strong positive correlation between the PC and TTHH records completely vanishes, and the otherwise relatively weak correlation between the PC and SCM reconstructions becomes much stronger. The correlation between the PC record and both the SRM and SWY records are relatively low during this period. This may represent a period of increased maritime influence on the climate of the northern Canadian Rocky Mountains.

The SWY reconstruction is the only record that is consistently statistically significantly correlated with the PC reconstruction regardless of the period of analysis. In spite of the strong correlation at the annual time-scale, comparison of the low-frequency variability in the PC reconstruction and the SWY record reveals an apparent lag in the occurrence of climatic events between these two nearby regions. Decadal-scale periods of cool or warm temperature anomalies almost always begin earlier in the PC reconstruction than in the SWY reconstruction.

5.3.5 Divergence

Although it correlates reasonably well with the PC record at annual time-scales, the TTHH record shows significant differences in low-frequency trends (Figure 5.6). The most notable difference is during the late 20th century, where the TTHH record indicates consistently and dramatically decreasing growth rates during a period in which this pattern is not apparent in the other ring-width records. The TTHH chronology is no longer statistically significantly correlated with the PC record during the late 20th century. This pattern in the TTHH chronology is an example of the so called "divergence problem" (D'Arrigo *et al*. 2004) which has been detected in many high-latitude white spruce ring-width chronologies (Barber *et al*. 2000; Lloyd and Fastie 2002; Wilmking *et al*. 2004). The divergence problem manifests as an apparent decrease in the sensitivity of ring-width series to climatic variability or as opposite trends in the ring-width and climate records (D'Arrigo *et al*. 2008).

Previous studies have detected intra-stand divergence by comparing correlations between ring-width series and climate from before a cut-off date, typically between 1950 and 1965, with correlations after that date (Lloyd and Fastie 2002; D'Arrigo *et al*. 2004; Wilmking *et al*. 2004; Wilmking *et al*. 2005). Due to the short instrumental climate record in this region, a comparable analysis could not be conducted. Comparison with longer climate records from more distant stations was deemed inappropriate due to significant differences in recent warming trends between stations in this region and those further north or south (Zhang *et al*. 2000). Century-long records of gridded and interpolated data are available for this region (New *et al*. 2000; Zhang *et al*. 2000; Wang *et al*. 2006), but these records suffer from a marked reduction in data quality before approximately 1940 due to a rapid decline in sample depth before that time.

In spite of these limitations, it was still possible to test for divergent growth patterns amongst individual trees after the mid-20th century. The ring-width series from individual trees were compared to post-1960 instrumental climate data using Pearson's correlation analysis. No pattern of mixed negative and positive growth responses to temperature variability was apparent among the individual trees. As these divergent growth patterns appear to be the reason for reduced climate-growth correlations (Wilmking *et al*. 2004; Wilmking *et al*. 2005), their absence can be viewed as evidence that no divergence-induced reduction in sensitivity has occurred in this chronology. Visual comparison of the individual series for divergent trends over their entire length also revealed no signs of divergence between series. Furthermore, there is no sign of divergence between the PC chronology and the instrumental climate record during the late 20th century (Figure 5.3).

The absence of a significant warming trend in local summer temperature records offers a probable explanation for the absence of divergence in this chronology. Divergence has been linked to moisture-stress brought on by increasing temperatures (Barber *et al*. 2000; Lloyd and Fastie 2002), differing trends in day and night-time temperatures (Wilson and Luckman 2003), and non-linear responses to increasing temperatures (D'Arrigo *et al*. 2004; Wilmking *et al*. 2004). Based on these hypotheses, divergence should only occur in areas where summer temperature is increasing over time. In the northern Canadian Rocky Mountains spring and winter temperatures show warming trends, but local summer (Figure 5.7) and fall temperature records show almost no trend (Zhang *et al.* 2000). Thus, it makes sense that no divergence is evident in this region.

5.4 Conclusion

White spruce trees were sampled for dendroclimatological analysis in the northern Canadian Rocky Mountains. The ring-width chronologies showed a strong positive relationship with mean temperature during June and July of the current growing season. A 234-year record of summer temperature variability was reconstructed using standard dendroclimatological methods. A second, 232-year reconstruction was created through the use of principal components analysis. Although the two reconstructions indicated very similar patterns of temperature variability over the last 232 years, the principal component based reconstruction was deemed superior due to its consistently greater ability to explain the variance in the instrumental temperature record and stronger performance during verification. This chronology showed no evidence of the recent reduction in sensitivity to climatic variability that is apparent in many other northern spruce chronologies. Comparison of this reconstruction with other dendroclimatological reconstructions from western Canada revealed a coherent pattern of low-frequency variability, although there was considerable spatial and temporal variability in the levels of agreement between reconstructions at annual time-scales. This reconstruction has filled in one of the remaining major gaps in the spatial coverage of dendroclimatic reconstructions in western North America.

5.5 Works Cited

Barber, V.A., Juday, G.P. and Finney, B.P. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*. 405, 668-673.

Bednarski, J.M., and Smith, I.R. 2007. Laurentide and montane glaciation along the Rocky Mountain Foothills of northeastern British Columbia. *Canadian Journal of Earth Sciences*. 44, 445-457.

Blasing, T.J., Duvick, D.N., and West, D.C. 1981. Dendroclimatic calibration and verification using regionally averaged and single station precipitation data. *Tree-Ring Bulletin*. 41, 37-43.

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

Briffa, K. and Jones, P.D. 1990. 'Basic Chronology Statistics and Assessment' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 137-152.

Briffa, K., Jones, P.D., and Schweingruber, F.H. 1994. Summer temperatures across northern North America: Regional reconstructions from 1760 using tree-ring densities. *Journal of Geophysical Research*. 99, 25835-25844.

Briffa, K., Jones, P.D., Pilcher, J.R., and Hughes, M.K. 1988. Reconstructing summer temperatures in northern Fennoscandinavia back to A.D. 1700 using tree-ring data from scots pine. *Arctic and Alpine Research*. 20, 385-394.

Cook, E.R. 1985. *A Time-Series Analysis Approach to Tree-Ring Standardization*. Ph.D. Unpublished Thesis. University of Arizona: Tucson.

Cook, E.R. and Krusic, P.J. 2005. *Program ARSTAN Manual*. Tree-Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University. Palisades, New York.

Danby, R.K. and Hik, D.S. 2007. Responses of white spruce (*Picea glauca*) to experimental warming at a subarctic alpine treeline. *Global Change Biology*. 13, 437–451.

D'Arrigo, R., Villalba, R., and Wiles, G. 2001. Tree-ring estimates of Pacific decadal climate variability. *Climate Dynamics*. 18, 219-224.

D'Arrigo, R., Kaufmann, R.K., Davi, N. and Jacoby, G.C. 2004. Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, *Canada. Global Biogeochemical Cycles*. 18, GB3021.

D'Arrigo, R., Wilson, R., Liepert, B. and Cherubini, P. 2008. On the 'divergence problem' in northern forests: a review of the tree-ring evidence and possible causes. *Global and Planetary Change*. 60, 289-305.

Enright, N.J. 1984. Principal components analysis of tree-ring/climate relationships in white spruce (Picea glauca) from Schefferville, Canada. *Journal of Biogeography*. 11, 353-361.

Environment Canada, 2006. *AHCCD – Adjusted Historical Canadian Climate Data*. Available at: http://www.cccma.ec.gc.ca/hccd/index.shtml.

Fritts, H.C. 1976. *Tree Rings and Climate*. Academic Press: London.

Fritts, H.C. and Wu, C. 1986. A comparison between response-function analysis and other regression techniques. *Tree-Ring Bulletin*. 66, 31-46.

Fritts, H.C., Guiot, J. and Gordon, G.A. 1990. 'Verification' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 178-185.

Gedalof, Z. and Smith, D.J. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. *Geophysical Research Letters*. 28, 1515-1518.

Germino, M.J. and Smith, W.K. 1999. Sky exposure, crown architecture, and low-temperature photoinhibition in conifer seedlings at alpine treeline. *Plant, Cell & Environment*. 22, 407–415.

Gordon, G.A. 1982. 'Verification of dendroclimatic reconstructions' in *Climate from TreeRings*. eds. M.K. Hughes, P.M. Kelly, J.R. Pilcher, and V.C. LaMarche Jr. Cambridge University Press: Cambridge. 58-61.

Holmes, R.L. 1983. Computer assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*. 43, 69-78.

Hughes, M.K. 2002. Dendrochronology in climatology - the state of the art. *Dendrochronologia*. 20, 95-116.

Jacoby, G.C. and Cook, E.R. 1981. Past temperature variations inferred from a 400-year tree-ring chronology from Yukon Territory, Canada. *Arctic and Alpine Research*. 13, 409-418.

Johnson, D.M., Germino, M.J. and Smith, W.K. 2004. Abiotic factors limiting photosynthesis in *Abies lasiocarpa* and *Picea engelmannii* seedlings below and above the alpine timberline. *Tree Physiology*. 24, 377–386.

Jones, P.D. and Hulmes, M. 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology*. 16, 361-377.

Kramer, P.J. and Kozlowski, T.T. 1960. *Physiology of Trees*. McGraw-Hill Book Company: New York.

Larocque, S.J. and Smith, D.J. 2005. A dendroclimatological reconstruction of climate since AD 1700 in the Mt. Waddington area, British Columbia Coast Mountains, Canada. *Dendrochronologia*. 22, 93-106.

Luckman, B.H. and Wilson, R.J.S. 2005. Summer temperatures in the Canadian Rockies during the last millennium: a revised record. *Climate Dynamics*. 24, 131-144.

Lloyd. A.H. and Fastie, C.L. 2002. Spatial and temporal variability in the growth and climate response of treeline trees in Alaska. *Climatic Change*. 52, 481-509.

Mantua, N.J. and Hare, S.R. 2002. The Pacific Decadal Oscillation. *Journal of Oceanography*. 58, 35-44.

Mekis, É. and Hogg, William D. 1999. Rehabilitation And Analysis Of Canadian Daily Precipitation Time Series. *Atmosphere-Ocean.* 37, 53-85.

Meko, D. 1997. Dendroclimatic reconstruction with time varying predictor subsets of tree indices. *Journal of Climate*. 10, 687-696.

Michaelsen, J. 1987. Cross-validation in statistical forecast models. *Journal of Climate and Applied Meteorology*. 26, 1589-1600.

Minobe, S. 1997. A 50-70 year climatic oscillation over the North Pacific and North America. *Geophysical Research Letters*. 24, 683-686.

New, M. G., Hulme, M., and Jones, P.D. 2000. Representing twentieth-century space-time climate variability. Part II: Development of 1901-1996 monthly grids of terrestrial surface climate. *Journal of Climate.* 13, 2217-2238.

Ommanney, S.L. 2002. 'Glaciers of the Canadian Rockies' in *Satellite image atlas of glaciers of the world, North America*. Eds.Williams, R.S. Jr and Ferrigno, J.G. US Geological Survey Professional Paper 1386-J-1.

Peters, K., Jacoby, G.C., and Cook, E.R. 1981. Principal components analysis of tree-ring sites. *Tree-Ring Bulletin*. 41, 1-19.

Pilcher, J.R. 1990. 'Sample preparation, cross-dating, and measurement' in *Methods of Dendrochronology: Applications in the Environmental Sciences*. eds. E.R. Cook and L.A. Kairiukstis. Kluwer Academic Publishers: Boston. 40-50.

Pojar, J. and Stewart, A.C. 1991. 'Spruce - Willow - Birch Zone' in *Ecosystems of British Columbia*. eds. D. Meidinger and J. Pojar. Research Branch, Ministry of Forests: Victoria, Canada. 251-262.

Raphael, C. 2002. The Climate of the Central and Northern Interior of BC. *Western Geography*. 12, 230-289.

Regent Instruments Inc. 2006. *WinDENDRO: An Image Analysis System for Tree-Rings Analysis*. Quebec.

Schweingruber, F.H. 1988. A new dendrochronological network for western North America. *Dendrochronologia*. 6, 171-178.

St. George, S. and Luckman, B.H. 2001. Extracting a paleotemperature record from *Picea engelmanii* tree-line sites in the central Canadian Rockies. *Canadian Journal of Forest Research*. 31, 457-470.

Stokes, M.A. and Smiley, T.L. 1968. *Tree-Ring Dating*. The University of Chicago Press: Chicago.

Szeicz, J.M. and MacDonald, G.M. 1995. Dendroclimatic reconstructions of summer temperatures in Northwestern Canada since A.D. 1638 based on age-dependent modeling. *Quaternary Research*. 44, 257-266.

Tranquillini, W. 1979. *Physiological Ecology of the Alpine Timberline: Tree Existence at High Altitudes with Special Reference to the European Alps*. Springer-Verlag: Berlin.

Vincent, L.A. and Gullet, D.W. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology*. 19, 1375-1388.

Wang, T., Hamann, A., Spittlehouse, D., and Aitken, S. N. 2006. Development of scale-free climate data for western Canada for use in resource management. *International Journal of Climatology.* 26, 383-397.

Wig, J.A. and Smith, D.J. 1994. Dendroclimatological Investigations in the Mount Rae Area, Canadian Rocky Mountains. *Western Geography*. 4, 110-126.

Wigley, T.M.L., Briffa, K.R., and Jones, P.D. 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Applied Meteorology*. 23, 201-213.

Wilmking, M., Juday, G.P., Barber, V.A. and Zald, H.S. 2004. Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. *Global Change Biology*. 10, 1724-1736.

Wilmking, M., D'Arrigo, R., Jacoby, G.C. and Juday, G.P. 2005. Increased temperature sensitivity and divergent growth trends in circumpolar boreal forests. *Geophysical Research Letters*. 32, L15715.

Wilson, R.J.S. and Luckman, B.H. 2002. Dendroclimatic reconstruction of summer temperatures from upper treeline sites in Interior British Columbia, Canada. *The Holocene*. 13, 851- 861.

Youngblut, D. and Luckman, B. 2008. Maximum June–July temperatures in the southwest Yukon over the last 300 years reconstructed from tree rings. *Dendrochronologia*. 25, 153-166.

Zhang, X., Vincent, L.A., Hogg, W.D. and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*. 38, 395-429.

5.6 Figures

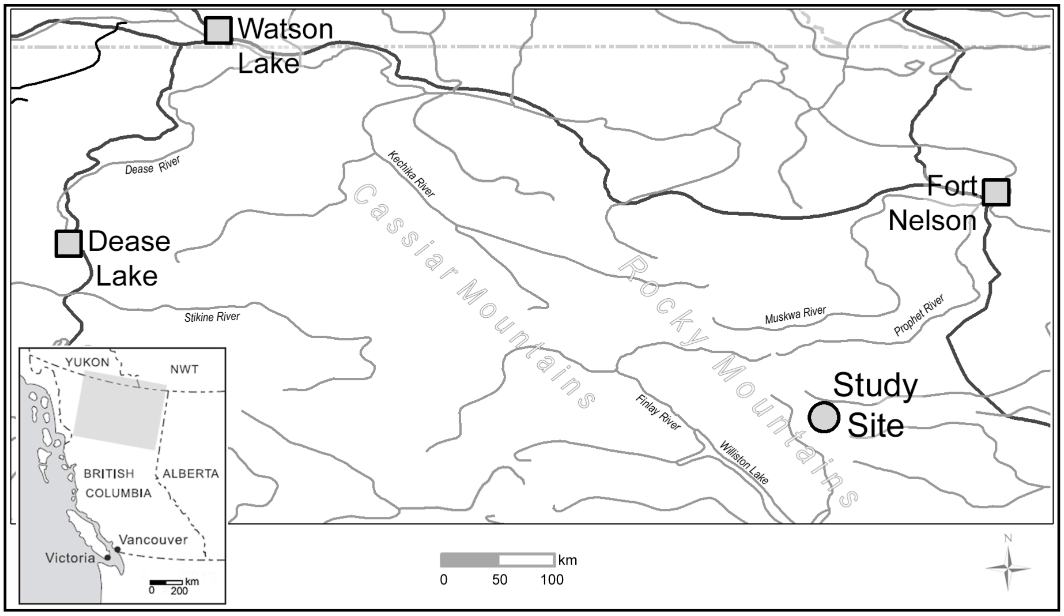
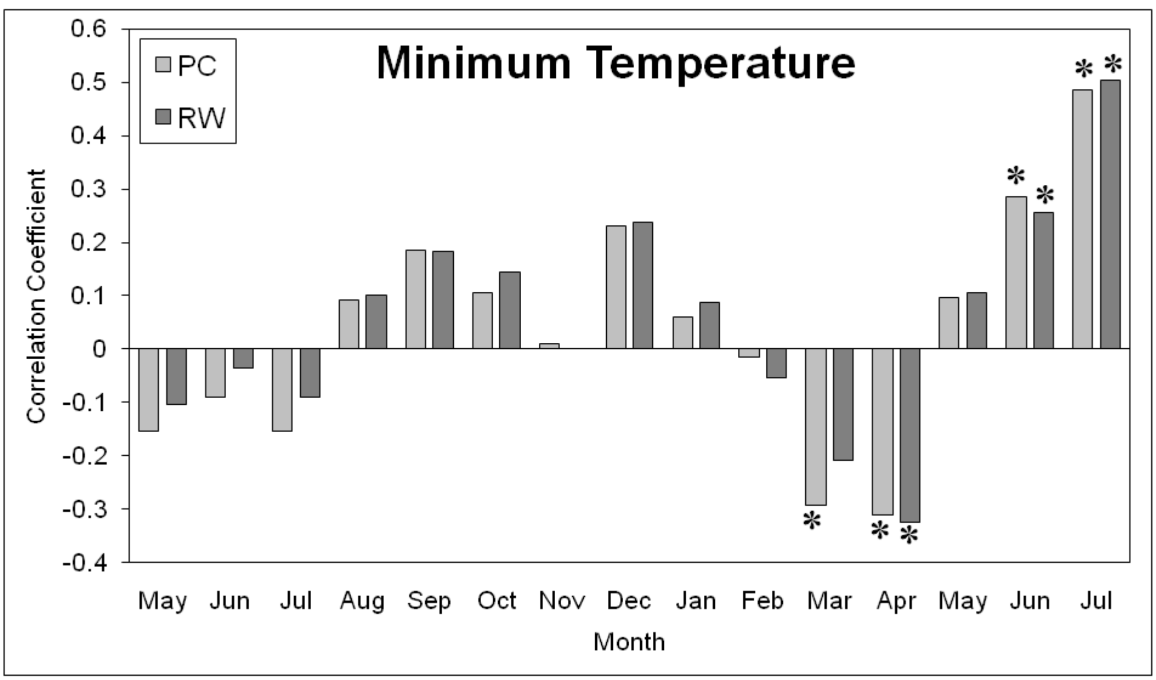
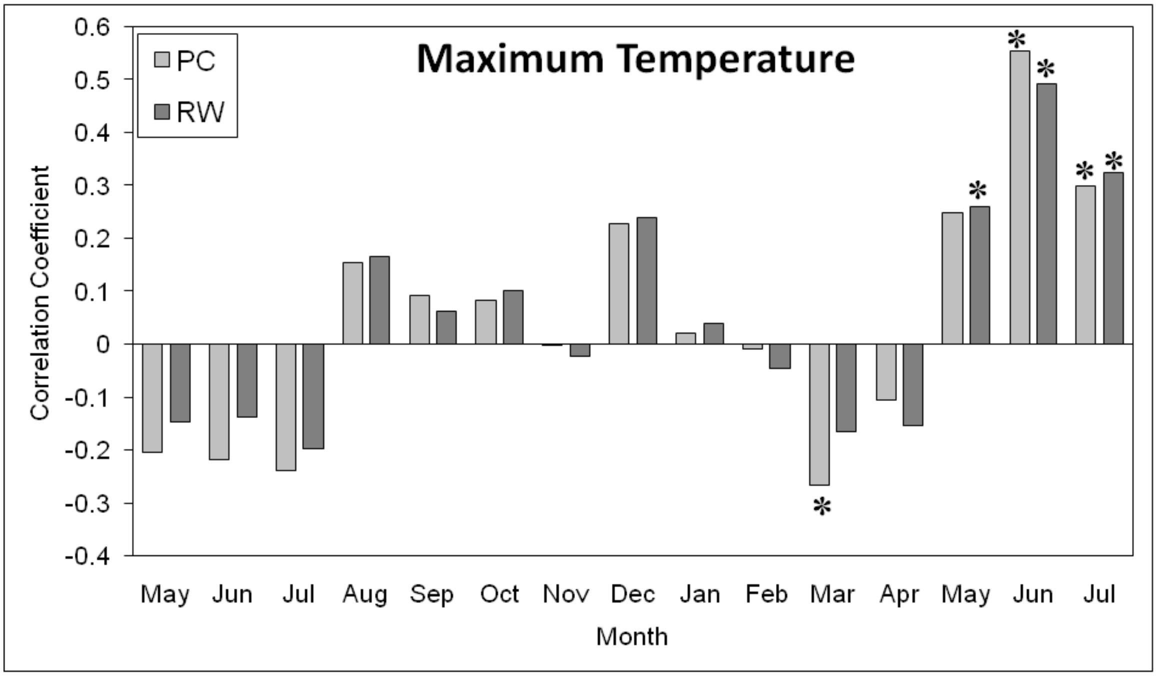


Figure 5.1: Location of study site and climate stations.





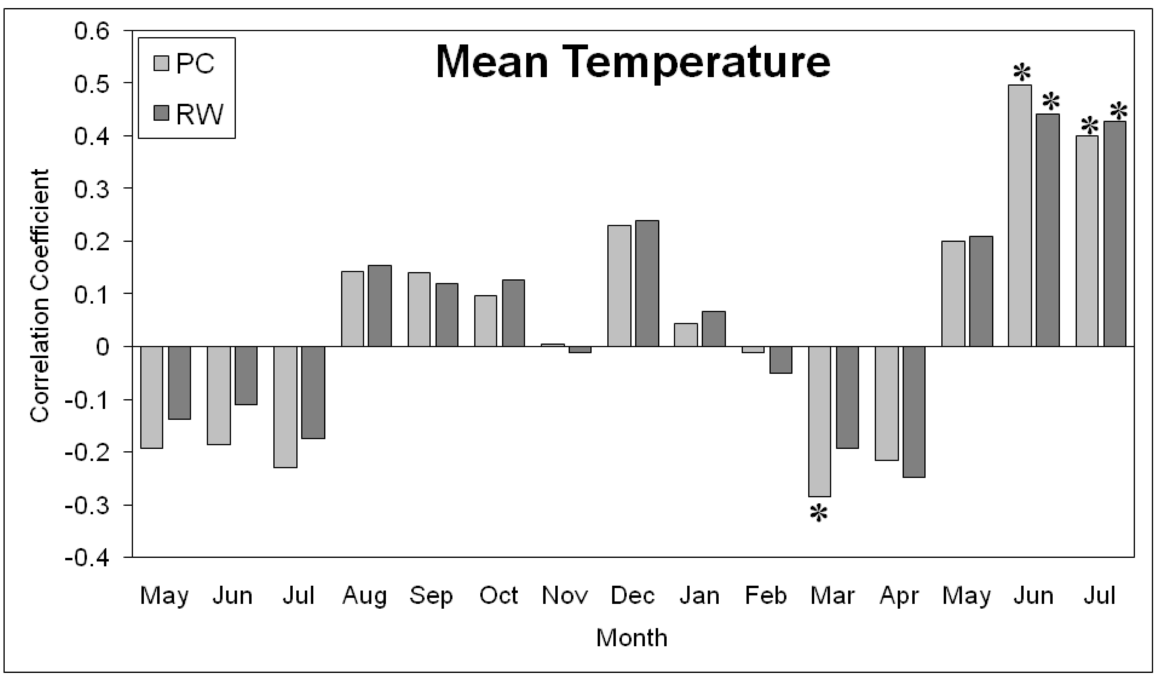


Figure 5.2: Correlation between ring-width (RW) and principal component (PC) chronologies and minimum, maximum, and mean monthly temperature. Correlations marked with * are statistically significant at the 0.05 level.

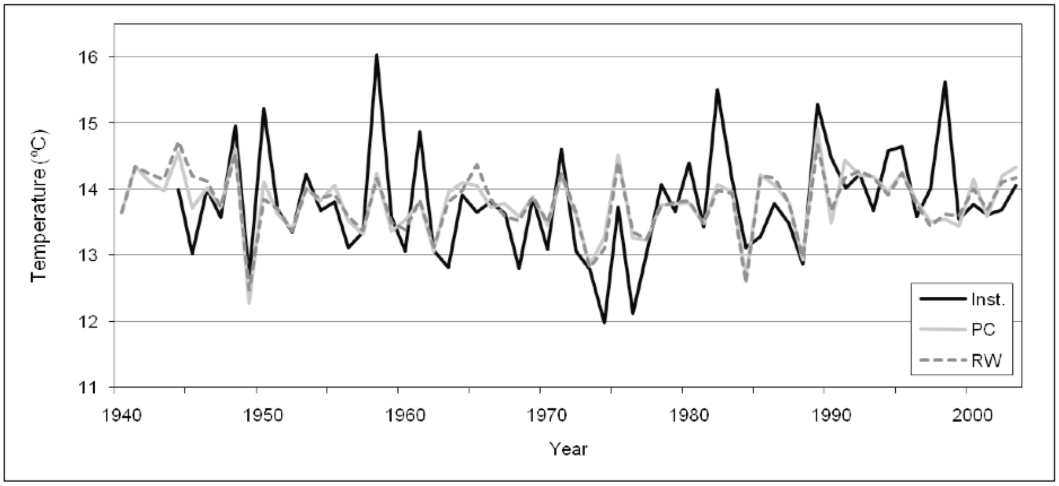


Figure 5.3: Comparison of reconstructed and instrumental records of June-July mean temperature.

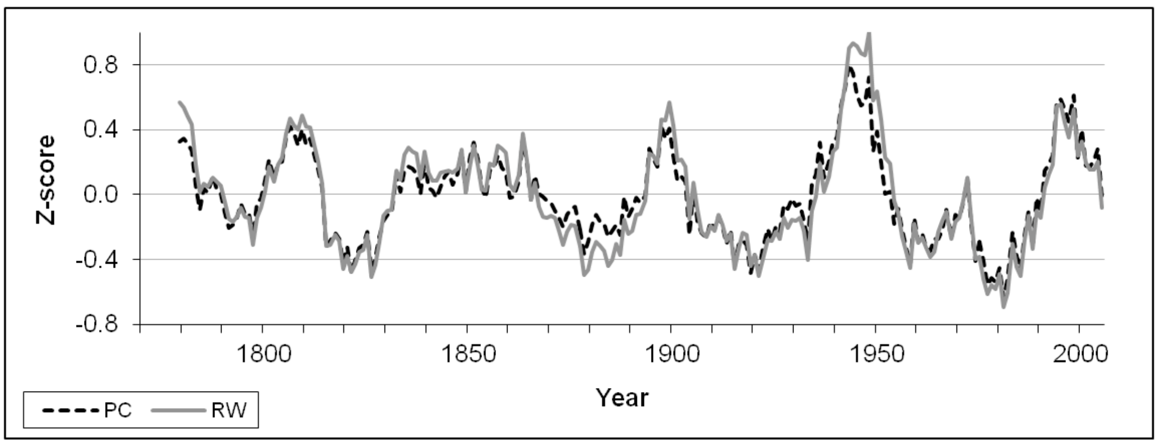


Figure 5.4: Ten-year moving averages of the PC and RW chronologies.

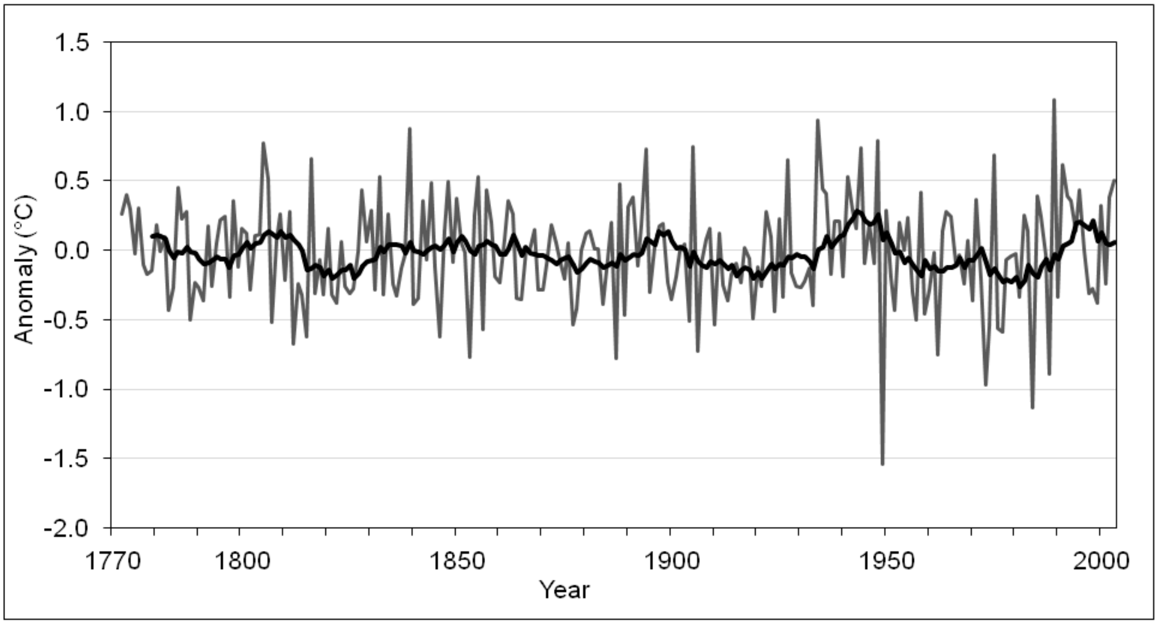


Figure 5.5: Reconstructed proxy record of June-July mean temperature. Anomalies calculated with respect to the 1971-2000 mean. Thick line is a ten-year running mean.

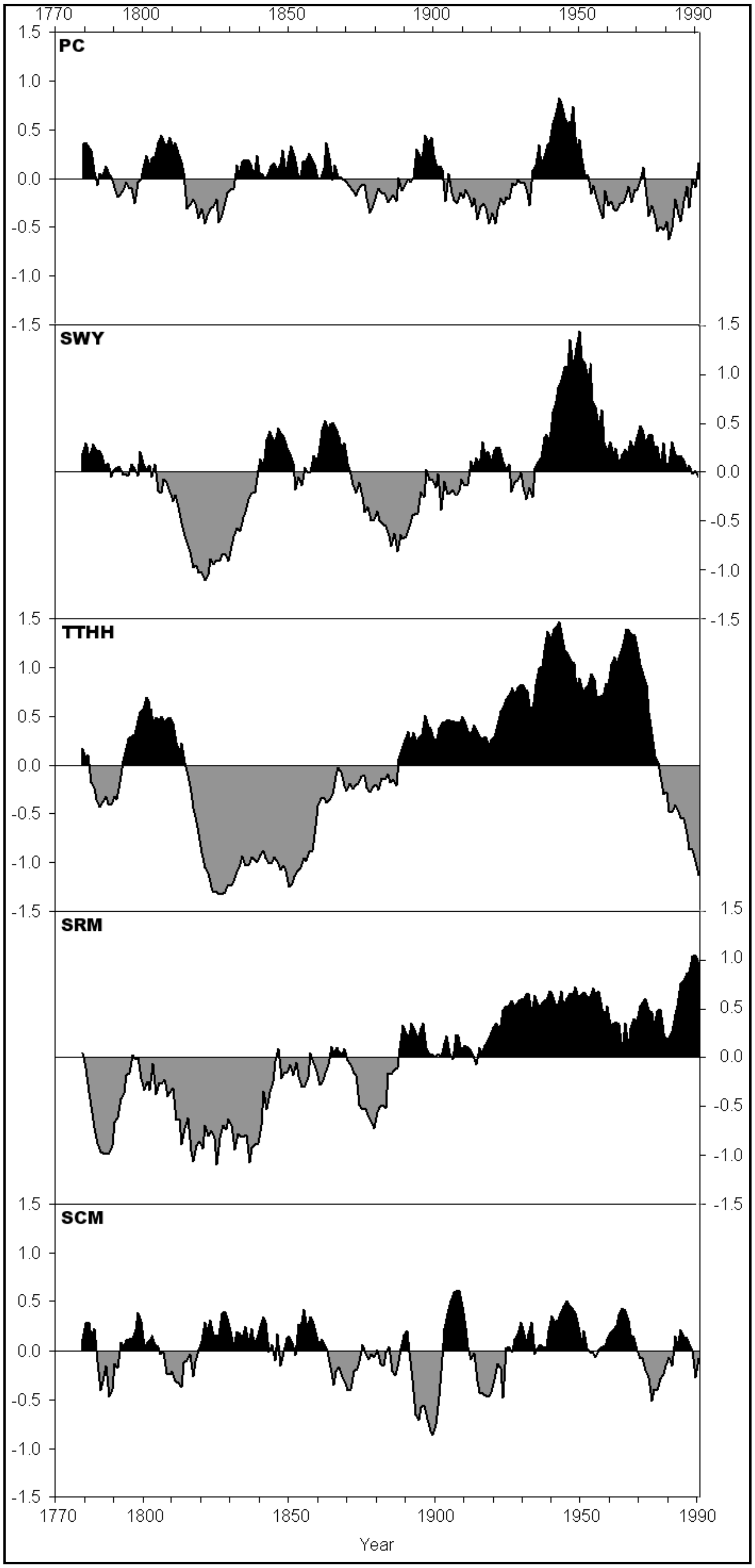

PC
SWY
TTHH
SRM
SCM
1770
1800
1850
1900
1950
1990
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Year

Figure 5.6: Standardized regional chronologies from the northern Canadian Rocky Mountains (PC), the southwestern Yukon Territory (SWY), the northwestern Yukon Territory (TTHH), the central Canadian Rocky Mountains (SRM), and the southern Coast Mountains (SCM) presented as ten-year moving averages. Vertical axes are Z-scores standardized with respect to the common period (1772-1992).

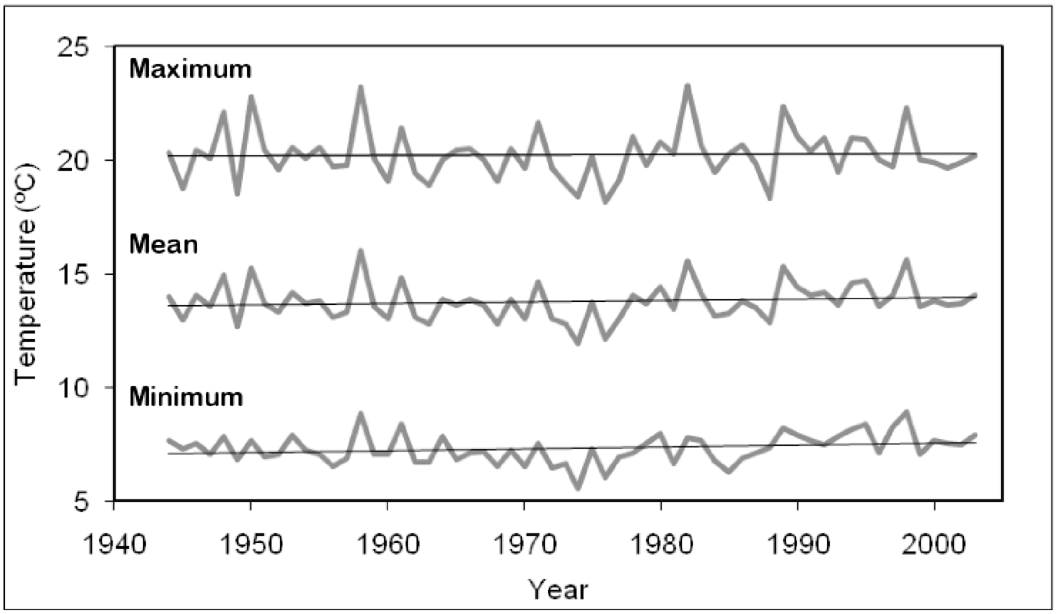


Figure 5.7: Trends in the merged instrumental climate record of June-July temperature.

5.7 Tables

Table 5.1: Location, elevation (m asl), record length and distance (km) from the study site of the three climate stations used in this analysis.

Station	Latitude	Longitude	Elevation	Years	Distance
Fort Nelson	58° 50.4' N	122° 36.0' W	382	1937-2006	185
Dease Lake	58° 25.8' N	130° 0.6' W	807	1944-2003	296
Watson Lake	60° 7.2' N	128° 49.2' W	687	1938-2006	333

Table 5.2: Chronology statistics for the residual ring-width (RW) chronology.

Number of trees	29
Number of series	53
Start date	1723
.85 EPS threshold	1770
Mean series length	220
Interseries correlation	0.567
Mean sensitivity	0.161
Mean ring width (mm)	0.84
Standard deviation	0.439
ARMA model	3
Variance due to autocorrelation	33%

Table 5.3: Verification statistics. All statistics are significant at the 0.05 level. See text for further explanation.

Chronology	r	R^2	aR^2	RE	Sign Products
RW	0.572	0.327	0.315	0.8807	8
PC	0.597	0.356	0.345	0.8848	11

Table 5.4: Correlations between the PC reconstruction presented in this paper and other regional reconstructions calculated for their full common period and for 55 year segments. Bold correlations are significant at the 0.05 level.

Time Period	SWY	SRM	SCM	TTHH
1772-1991	**0.490**	0.132	0.120	**0.206**
1772-1826	**0.481**	0.251	0.173	**0.388**
1827-1881	**0.427**	0.044	**0.314**	-0.004
1882-1936	**0.513**	0.258	0.012	**0.481**
1937-1991	**0.585**	0.140	0.019	0.213

Chapter 6 - Conclusion

6.1 Summary

Samples were collected from living subalpine fir and white spruce trees found growing in an old growth forest in the remote Kwadacha Wilderness Provincial Park. Standard dendrochronological methods were used to collect and prepare the samples, measure the annual ring-widths, cross-date the ring-width series, and create species-specific master chronologies. A double-detrending standardization technique and autoregressive modelling were used to isolate the climatic signal contained in the ring-width series. A regionally representative instrumental climate record was created by merging multiple individual station records. Correlation analysis was used to explore the radial-growth response to climatic variability, and partial correlation analysis was used to identify spurious relationships. Regression-based transfer functions were used to create two proxy records of June-July mean air temperature fluctuations in the northern Canadian Rocky Mountains.

The white spruce ring-width chronology was shown to be strongly positively correlated with minimum July temperatures and maximum May and June temperatures, and negatively correlated with minimum April temperatures. The white spruce chronology exhibited a positive relationship with diurnal temperature range in April, May, and June, but showed no statistically significant relationship with the Pacific Decadal Oscillation. The subalpine fir ring-width chronology was correlated with maximum and minimum temperature during

December and January, and with July minimum temperature during the current and previous year. This chronology was also negatively correlated with diurnal temperature range during December and January, and exhibited a positive relationship with the Pacific Decadal Oscillation during each month between December and June.

Analysis of the climate-growth responses of individual trees revealed a higher level of intraspecies variability in subalpine fir than in white spruce. The varying levels of homogeneity in the intraspecies growth-responses highlighted the importance of considering the response of individuals, as opposed to the master chronology only, when exploring the impact of climate variability on a species. Similarly, the differences in the relationships between climatic variability and the radial growth of the two species highlighted the importance of considering the response of individual species when attempting to predict the impacts of climate change on forests.

The white spruce chronology was selected for use in creating a proxy climate record based on its greater length and stronger sensitivity to climatic variability. The white spruce master ring-width chronology and the first principal component extracted from the ring-width series of the oldest 15 white spruce trees were used to create two separate regional proxy records of June-July air temperature. The latter reconstruction, which extends back to 1772, was deemed superior due to its greater ability to explain the variance in the instrumental temperature record and stronger performance during verification. This reconstruction exhibits a pattern of shared low-frequency variability with other dendroclimatic reconstructions from western Canada and shows no evidence of the recent reduction in sensitivity to climatic variability that is apparent in many other northern spruce chronologies.

6.2 Recommendations for Future Research

1) Additional chronologies should be collected at other sites in the northern Canadian Rocky Mountains to a create stronger regional climate reconstruction. This study showed that white spruce trees in this area are sensitive to temperature variability and are well suited to use in dendroclimatic reconstructions. The incorporation of chronologies from multiple sites would increase the strength of the climate signal contained in the ring-width series by removing site-specific influences and could lead to a longer reconstruction if older trees are found.

2) Additional climate variables should be included in future climate-radial growth response analyses. Precipitation and snowpack records were deemed unsuitable for this analysis due to the high level of spatial variability in precipitation and the strong orographic influences in this region. However, it is possible that more representative precipitation records could be obtained or created using techniques such as elevation corrections, downscaling of gridded climate data, or regional climate models. Inclusion of precipitation variables would give a more complete picture of how these trees respond to climatic variability.

3) Other tree-ring measurements, such as maximum density, latewood width, earlywood width, or isotopic characteristics could be used as proxies for climate variables, and might lead to different insights or stronger climate reconstructions.

Appendix A – Trends in the Instrumental Climate Records

This appendix contains graphs of the trends in seasonal temperature records from three stations in interior northern British Columbia or the southern Yukon Territory and a merged regional record produced from these station records, as well trends in seasonal precipitation records from the same three stations. Descriptions of the data source and methods can be found in Chapter 3.

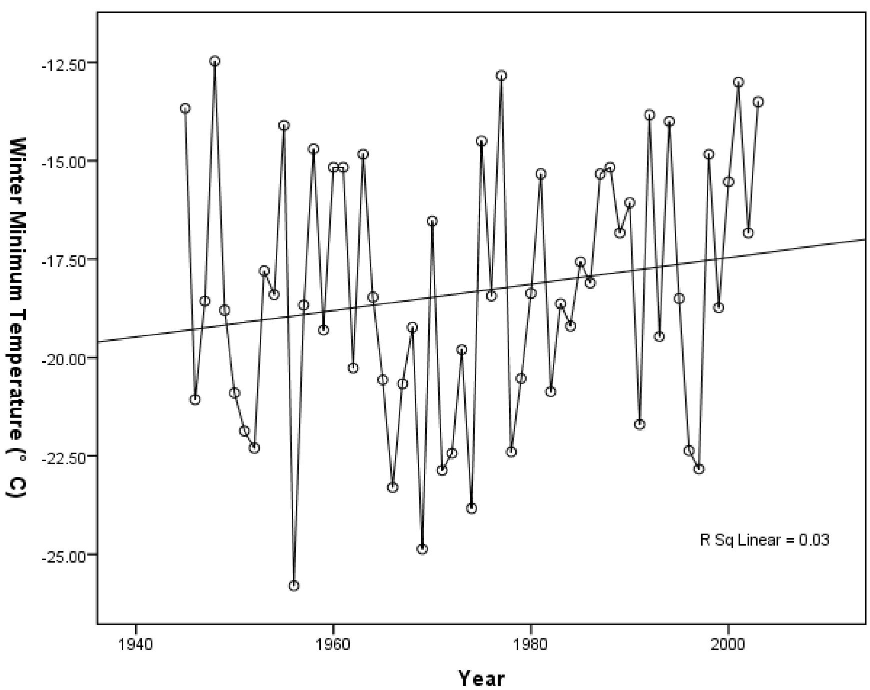


Figure A.1: Time-series of Dease Lake winter minimum temperature with trend line and coefficient of determination (R Sq Linear).

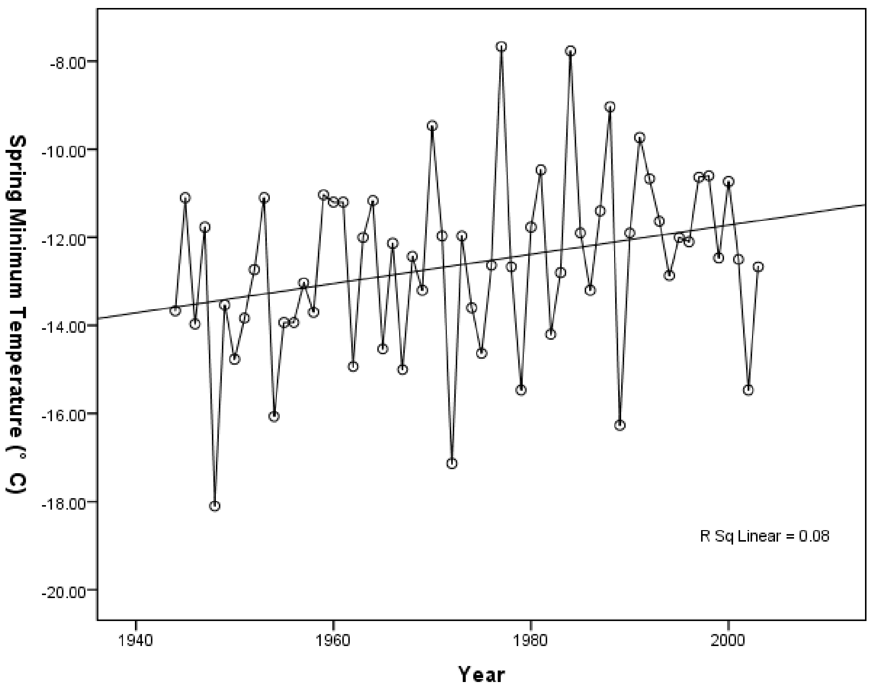


Figure A.2: Time-series of Dease Lake spring minimum temperature with trend line and coefficient of determination (R Sq Linear).

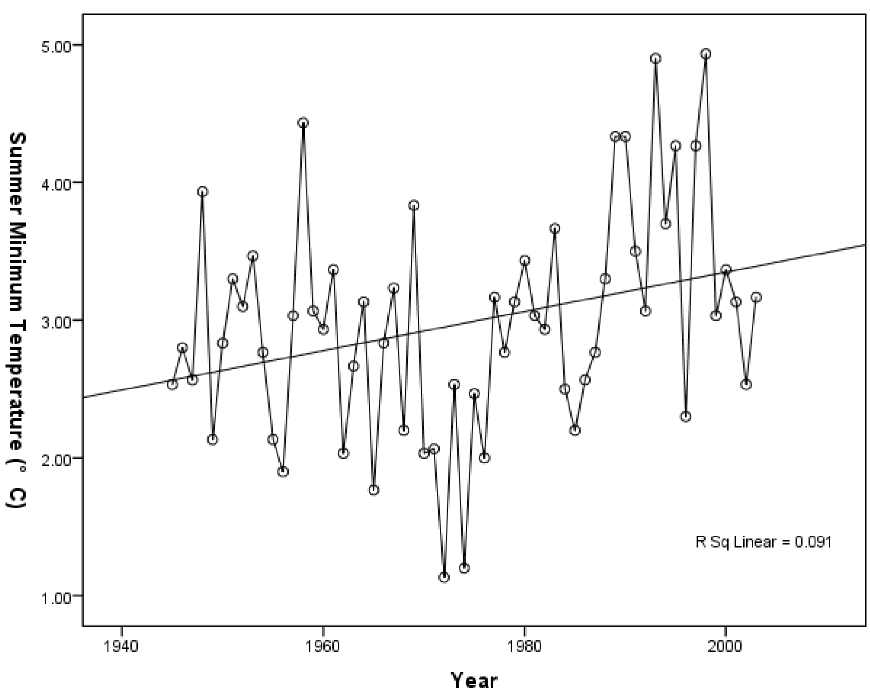


Figure A.3: Time-series of Dease Lake summer minimum temperature with trend line and coefficient of determination (R Sq Linear).

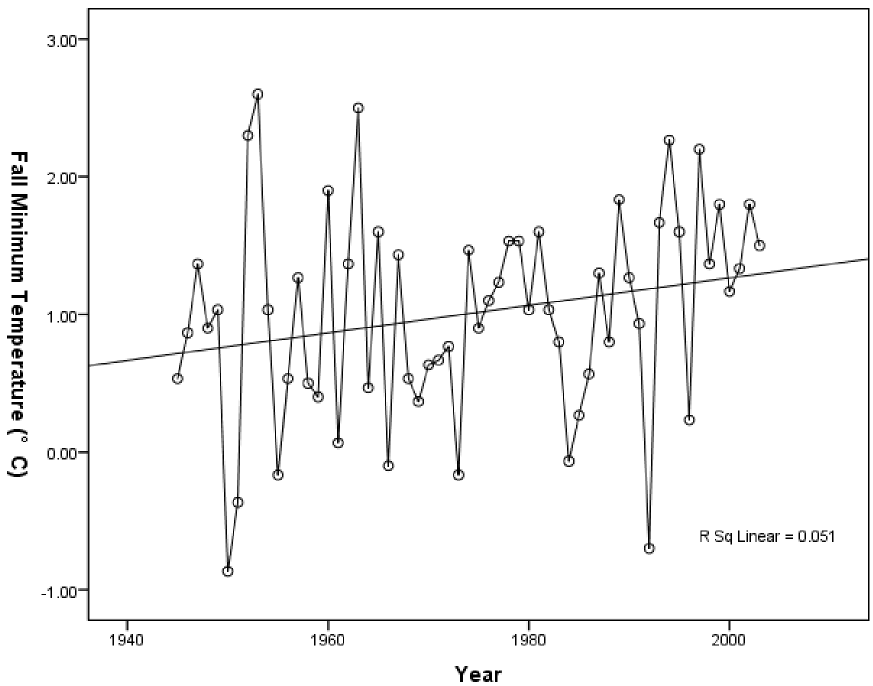


Figure A.4: Time-series of Dease Lake fall minimum temperature with trend line and coefficient of determination (R Sq Linear).

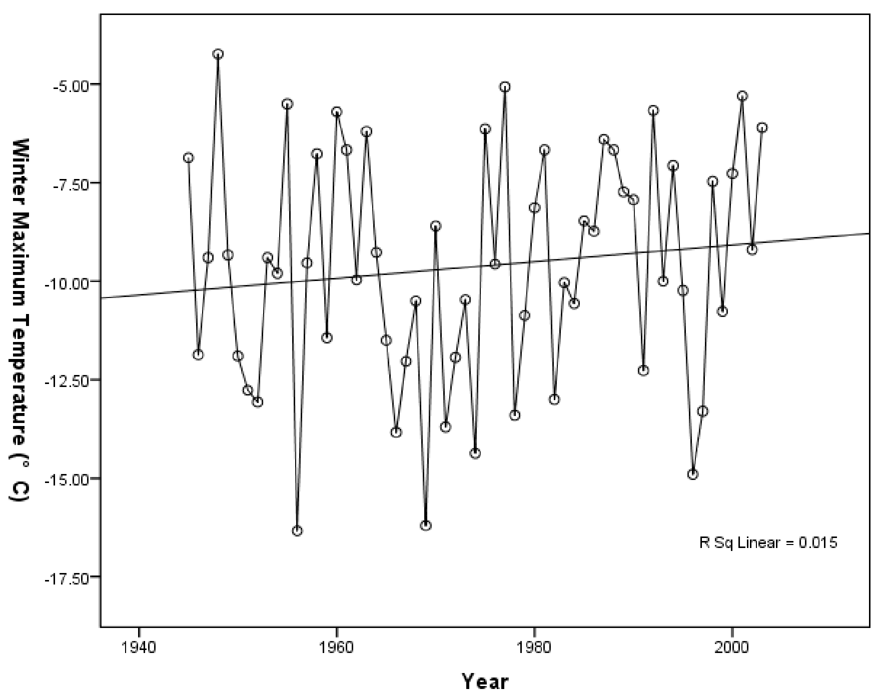


Figure A.5: Time-series of Dease Lake winter maximum temperature with trend line and coefficient of determination (R Sq Linear).

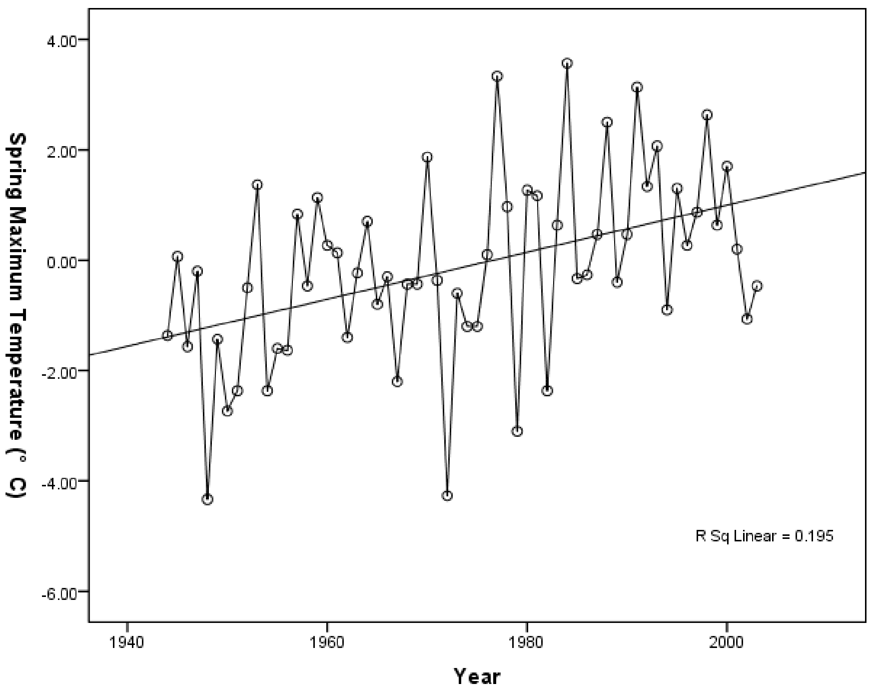


Figure A.6: Time-series of Dease Lake spring maximum temperature with trend line and coefficient of determination (R Sq Linear).

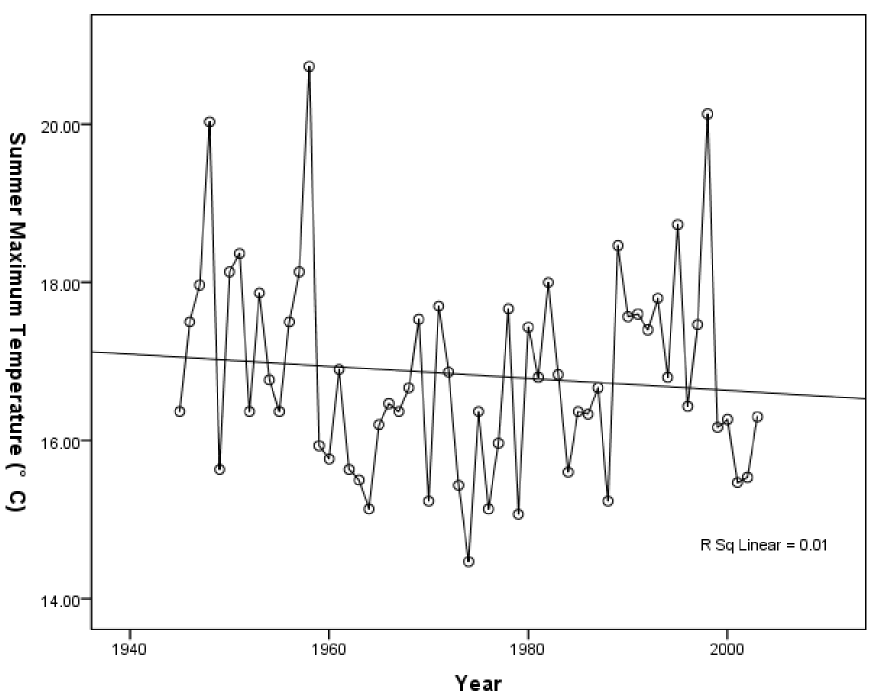


Figure A.7: Time-series of Dease Lake summer maximum temperature with trend line and coefficient of determination (R Sq Linear).

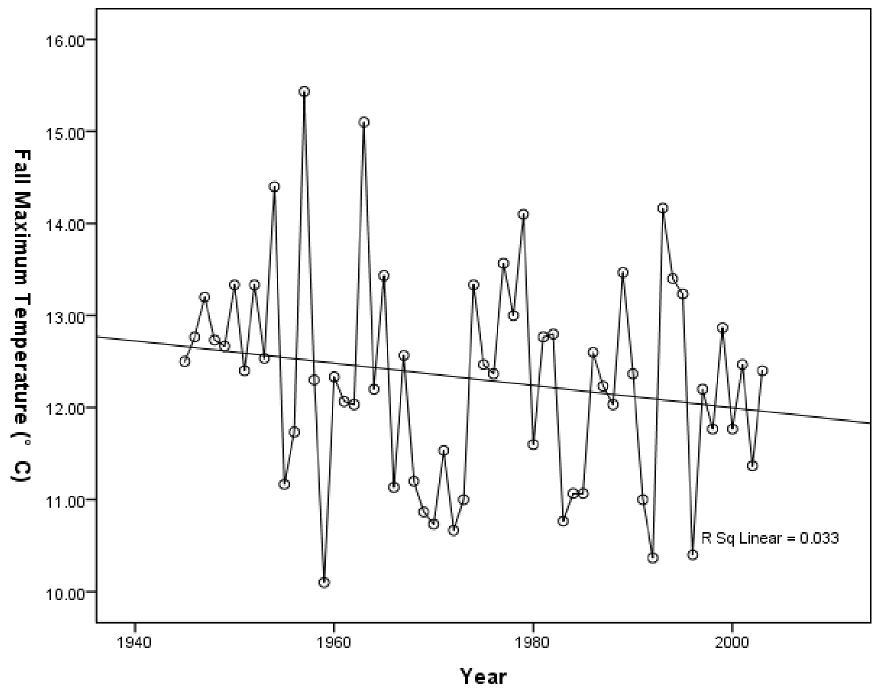


Figure A.8: Time-series of Dease Lake fall maximum temperature with trend line and coefficient of determination (R Sq Linear).

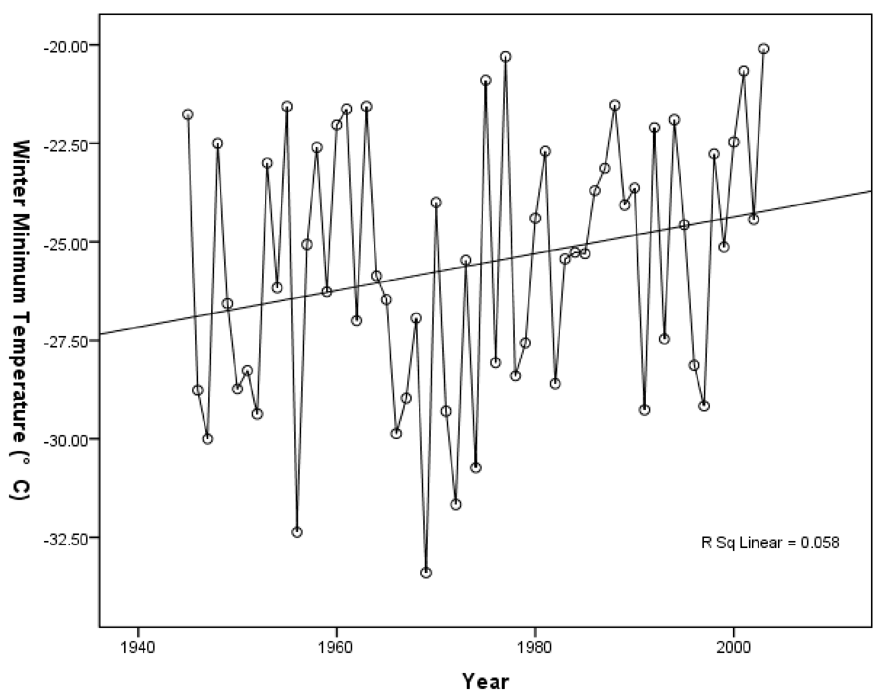


Figure A.9: Time-series of Watson Lake winter minimum temperature with trend line and coefficient of determination (R Sq Linear).

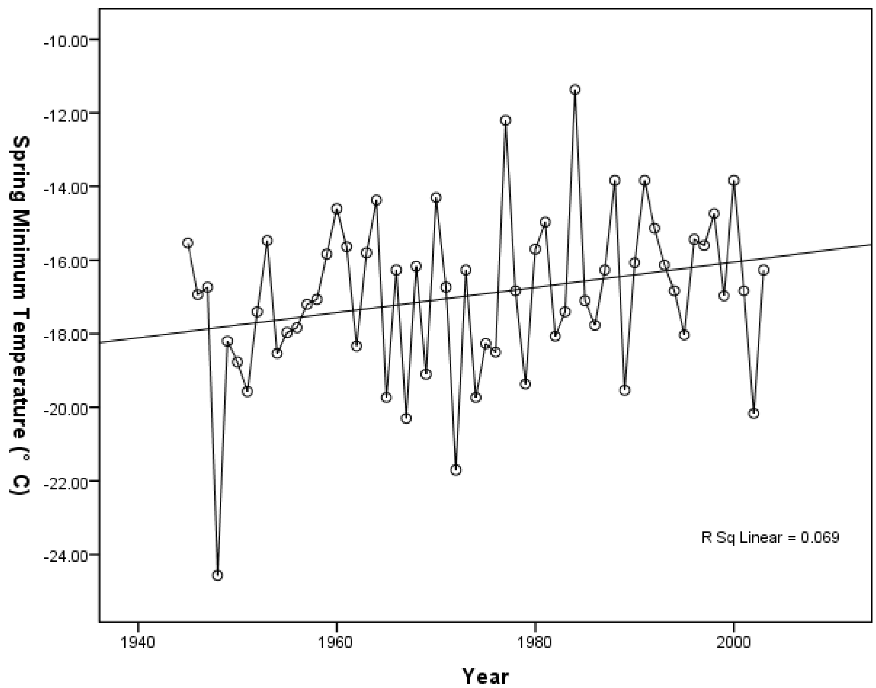


Figure A.10: Time-series of Watson Lake spring minimum temperature with trend line and coefficient of determination (R Sq Linear).

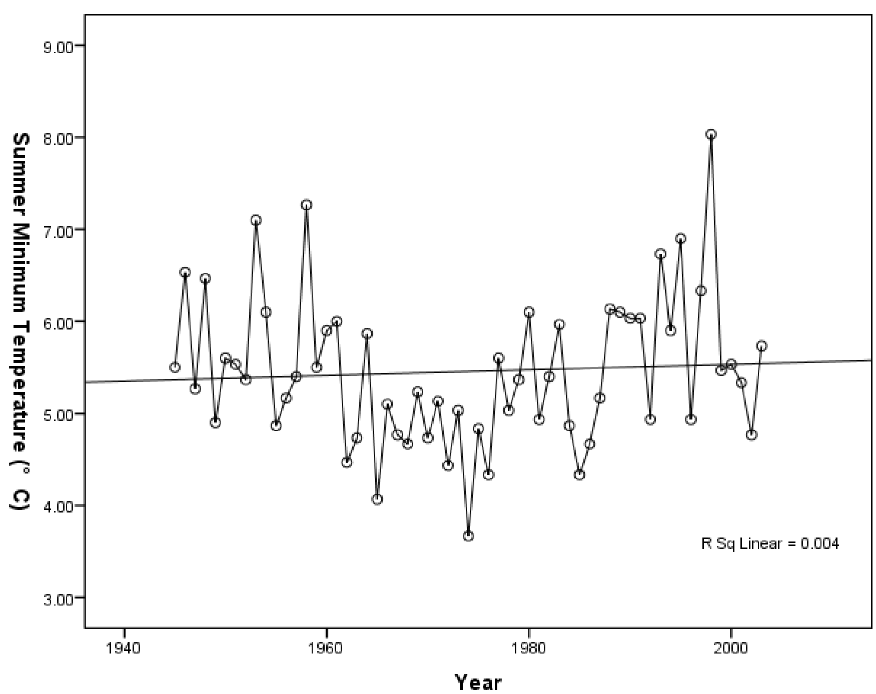


Figure A.11: Time-series of Watson Lake summer minimum temperature with trend line and coefficient of determination (R Sq Linear).

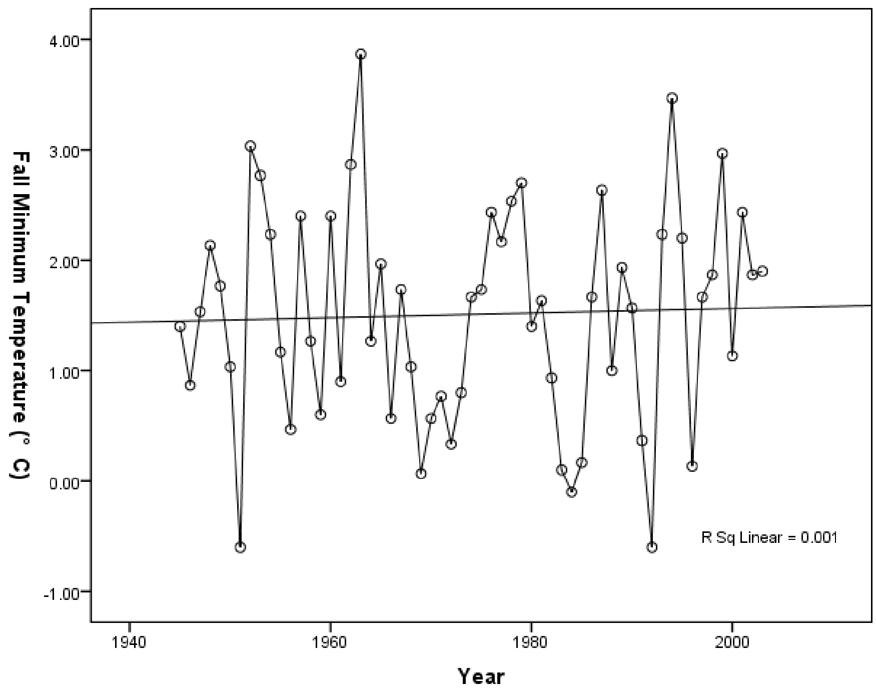


Figure A.12: Time-series of Watson Lake fall minimum temperature with trend line and coefficient of determination (R Sq Linear).

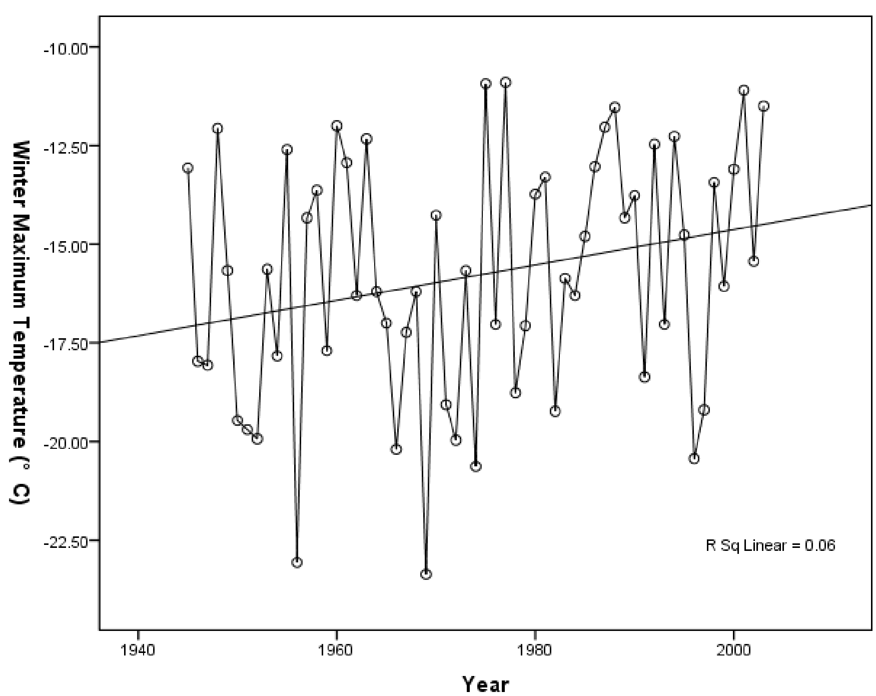


Figure A.13: Time-series of Watson Lake winter maximum temperature with trend line and coefficient of determination (R Sq Linear).

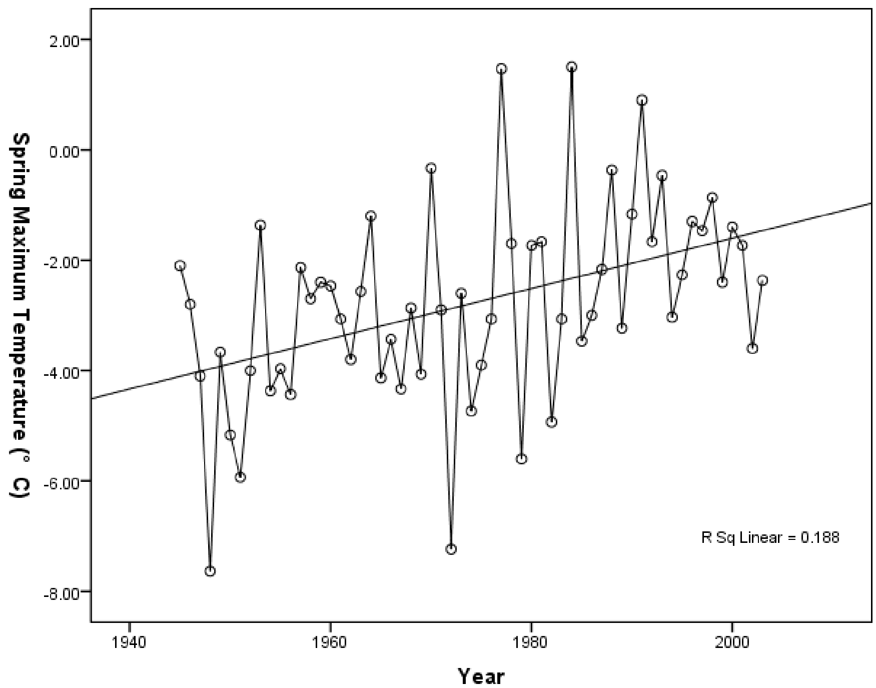


Figure A.14: Time-series of Watson Lake spring maximum temperature with trend line and coefficient of determination (R Sq Linear).

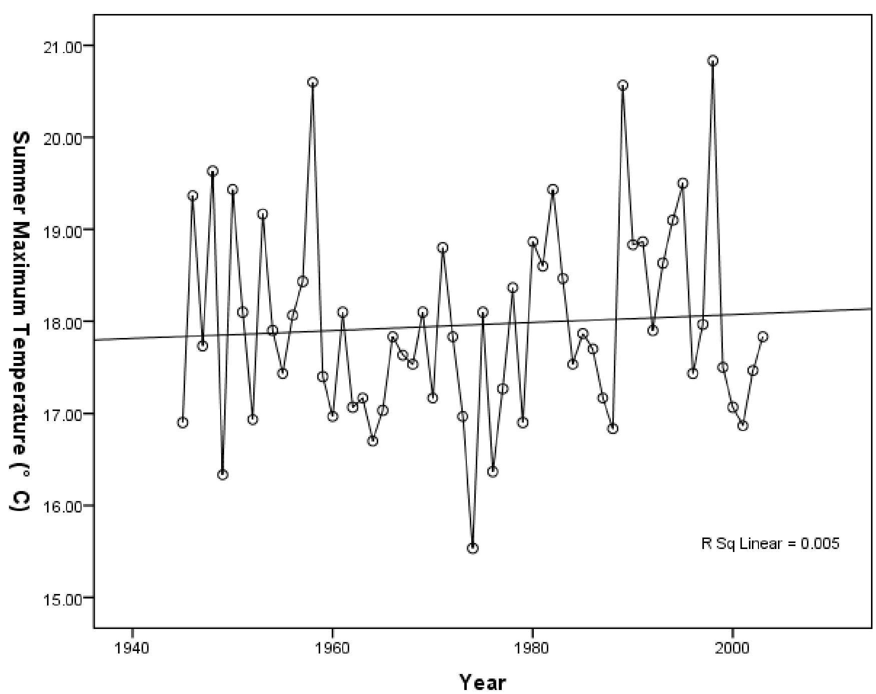


Figure A.15: Time-series of Watson Lake summer maximum temperature with trend line and coefficient of determination (R Sq Linear).

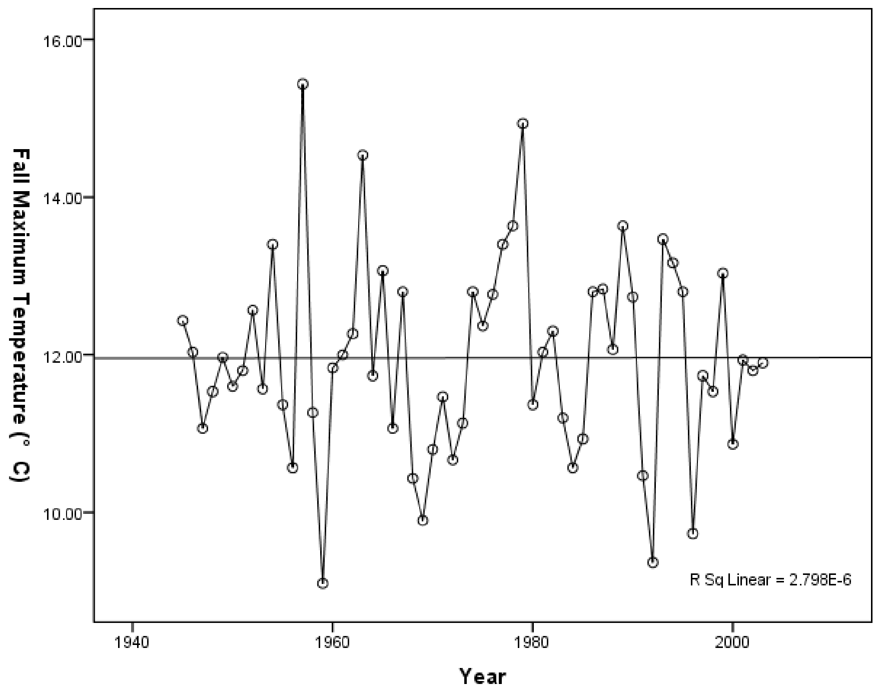


Figure A.16: Time-series of Watson Lake fall maximum temperature with trend line and coefficient of determination (R Sq Linear).

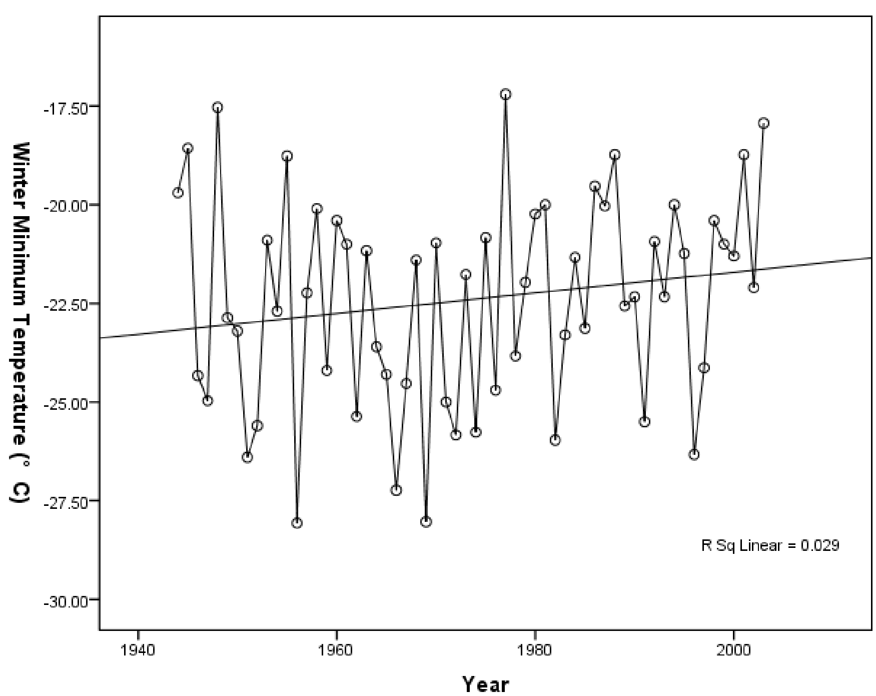


Figure A.17: Time-series of Fort Nelson winter minimum temperature with trend line and coefficient of determination (R Sq Linear).

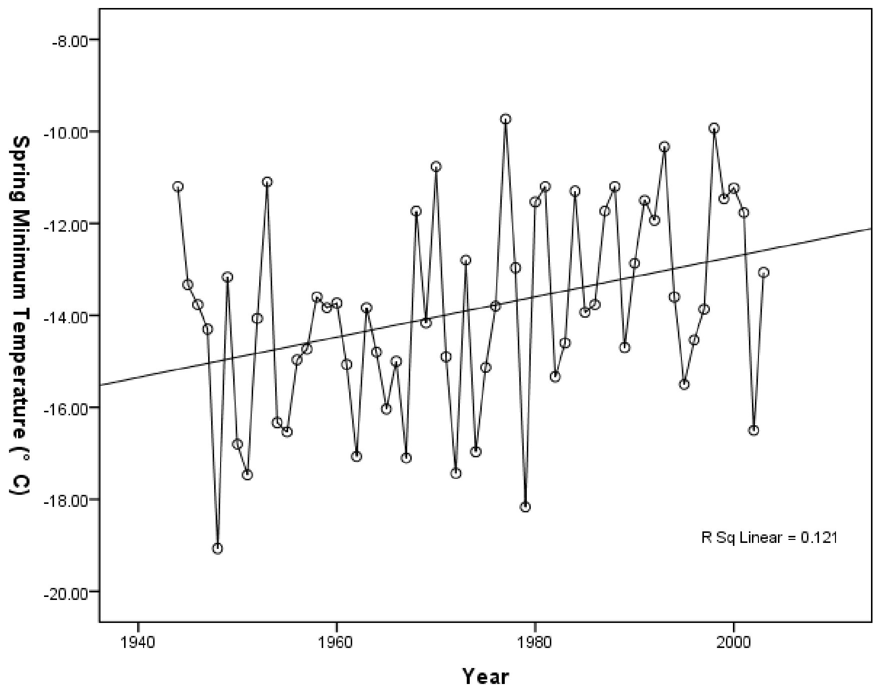


Figure A.18: Time-series of Fort Nelson spring minimum temperature with trend line and coefficient of determination (R Sq Linear).

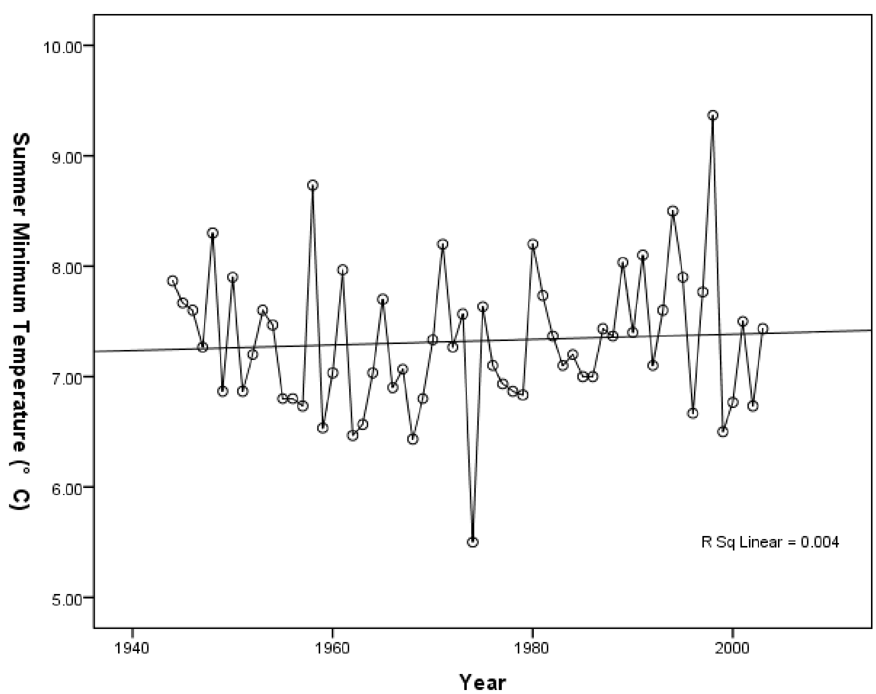


Figure A.19: Time-series of Fort Nelson summer minimum temperature with trend line and coefficient of determination (R Sq Linear).

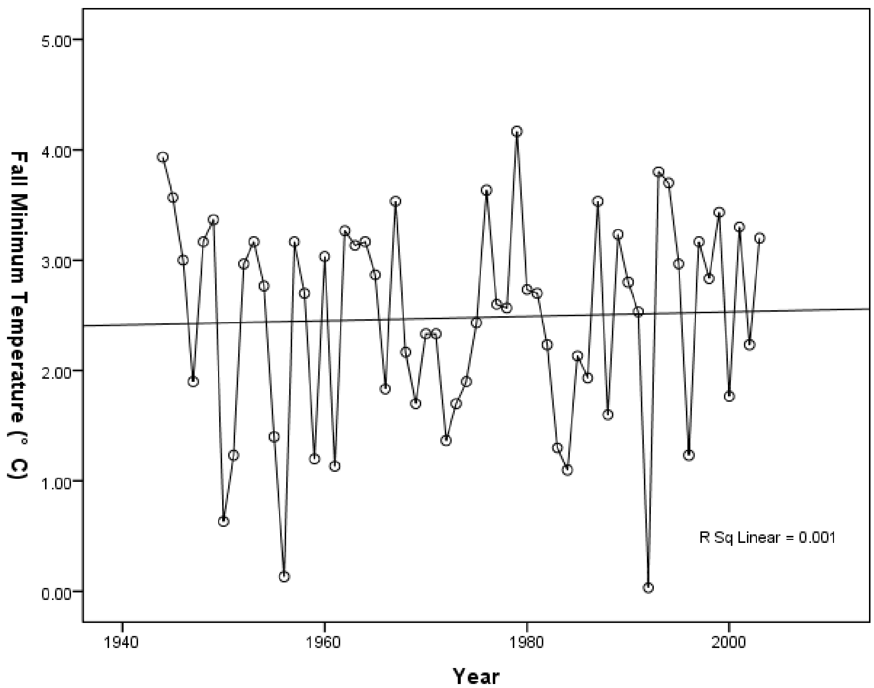


Figure A.20: Time-series of Fort Nelson fall minimum temperature with trend line and coefficient of determination (R Sq Linear).

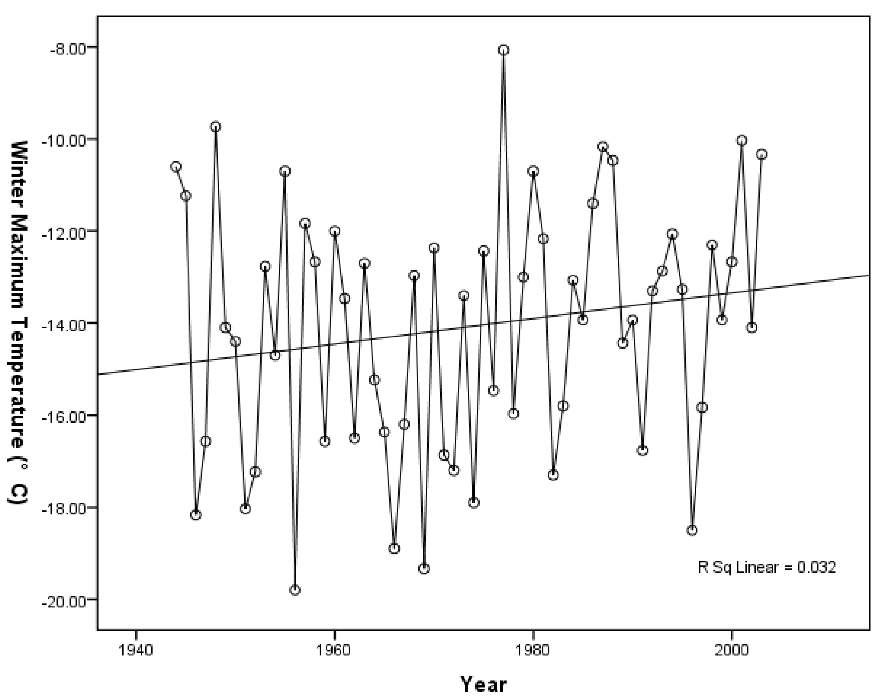


Figure A.21: Time-series of Fort Nelson winter maximum temperature with trend line and coefficient of determination (R Sq Linear).

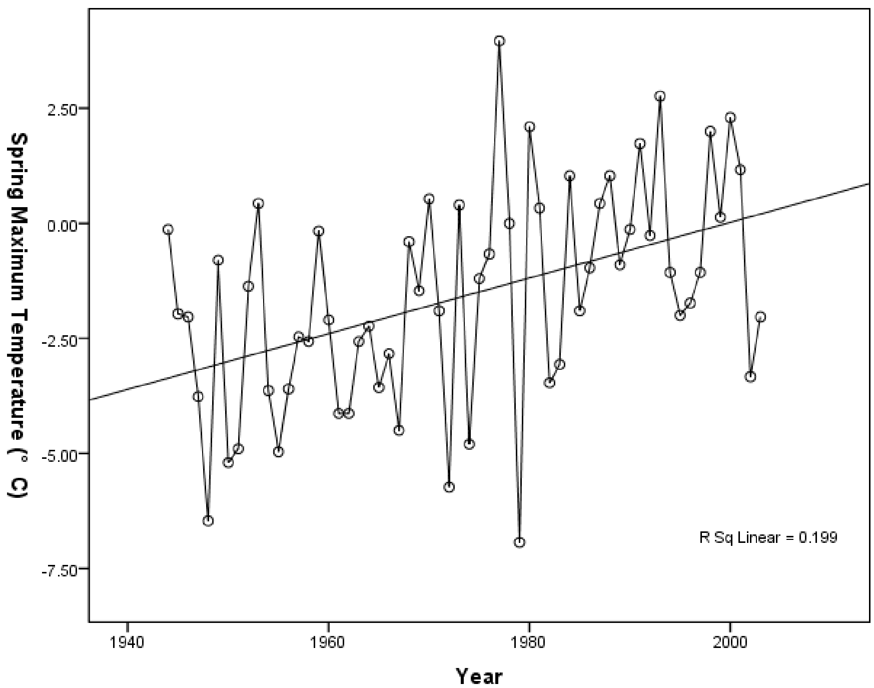


Figure A.22: Time-series of Fort Nelson spring maximum temperature with trend line and coefficient of determination (R Sq Linear).

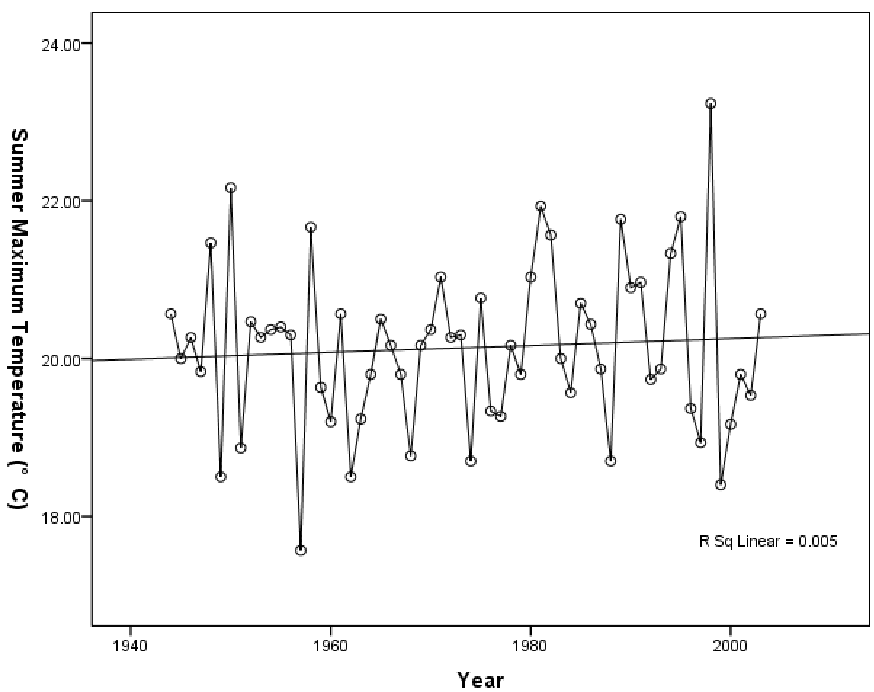


Figure A.23: Time-series of Fort Nelson summer maximum temperature with trend line and coefficient of determination (R Sq Linear).

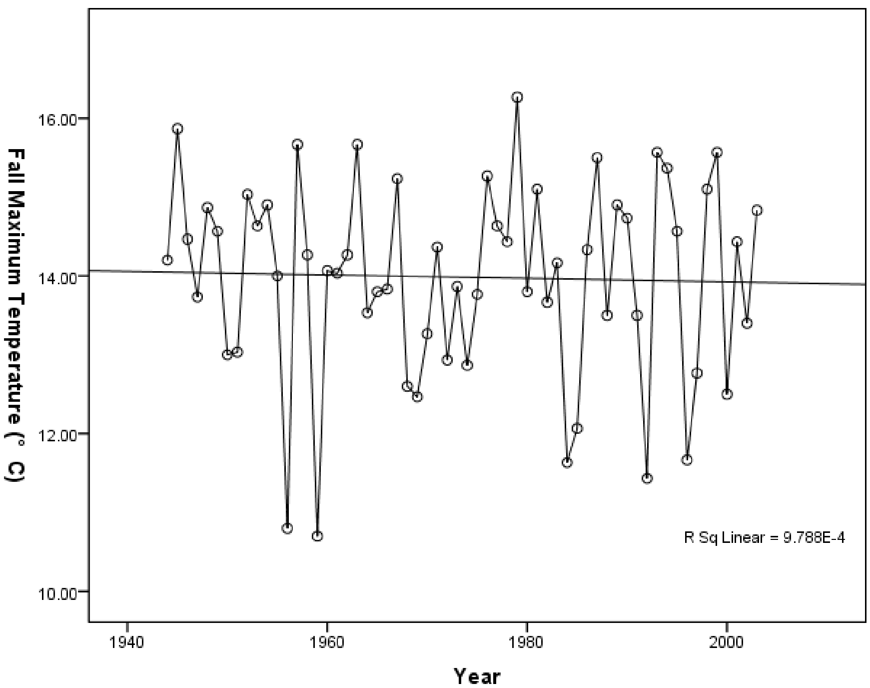


Figure A.24: Time-series of Fort Nelson fall maximum temperature with trend line and coefficient of determination (R Sq Linear).

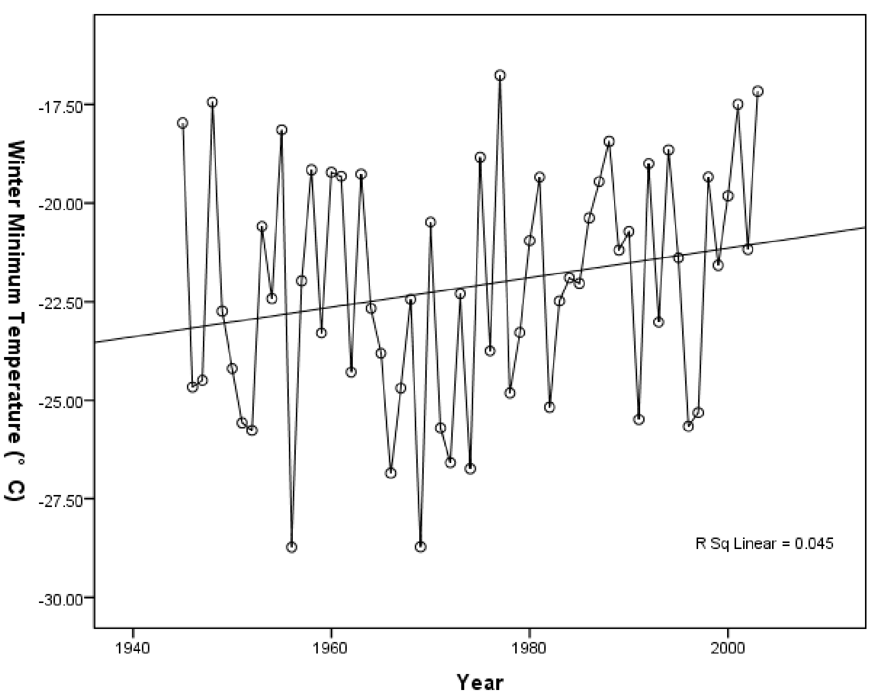


Figure A.25: Time-series of the combined regional record of winter minimum temperature with trend line and coefficient of determination (R Sq Linear).

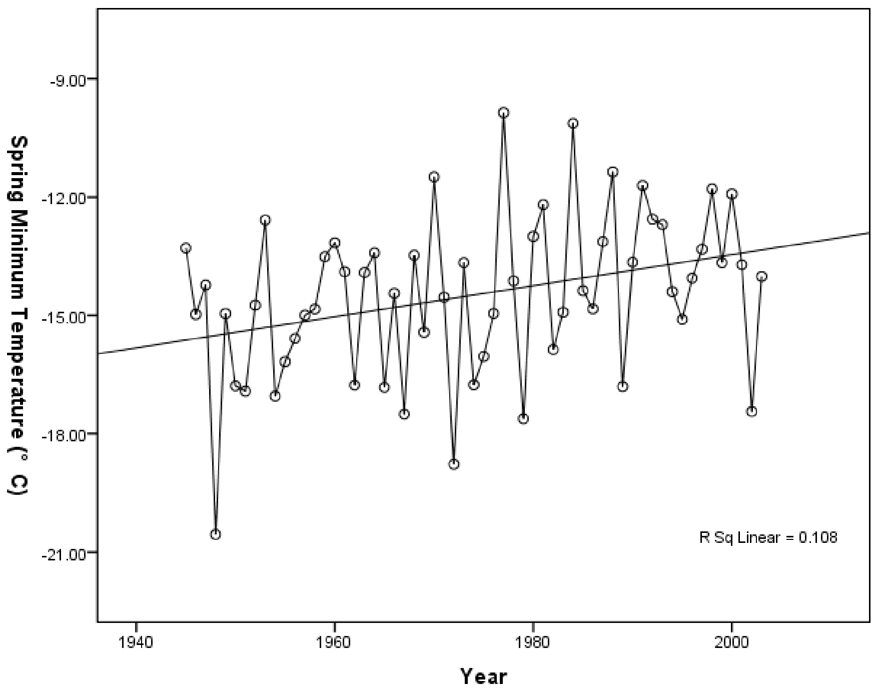


Figure A.26: Time-series of the combined regional record of spring minimum temperature with trend line and coefficient of determination (R Sq Linear).

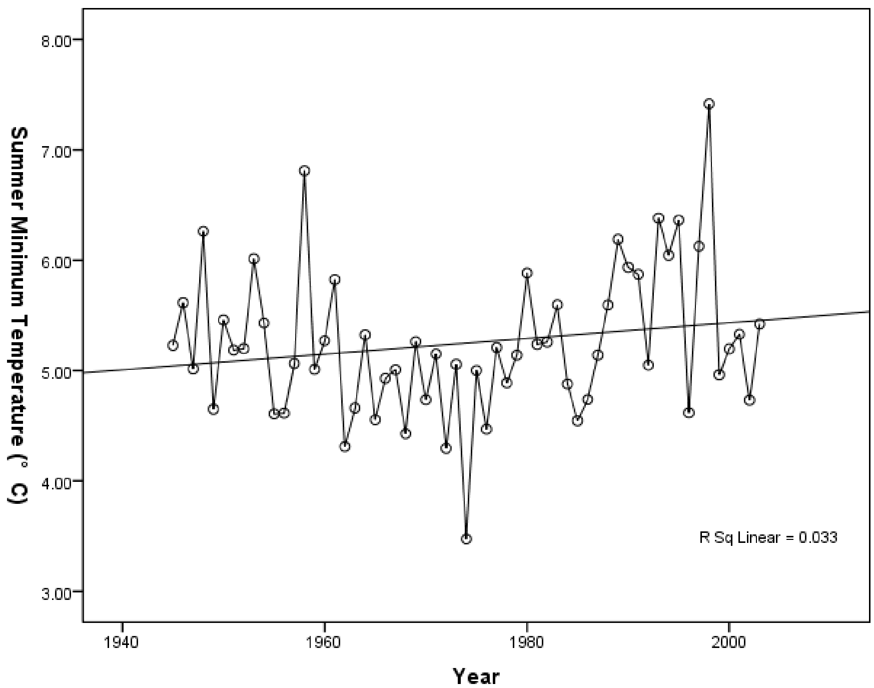


Figure A.27: Time-series of the combined regional record of summer minimum temperature with trend line and coefficient of determination (R Sq Linear).

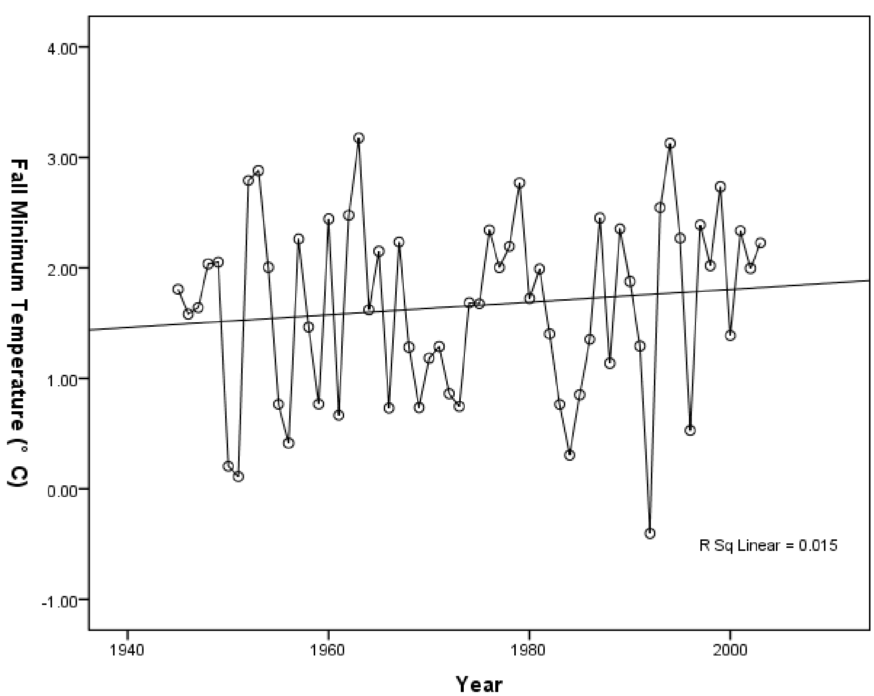


Figure A.28: Time-series of the combined regional record of fall minimum temperature with trend line and coefficient of determination (R Sq Linear).

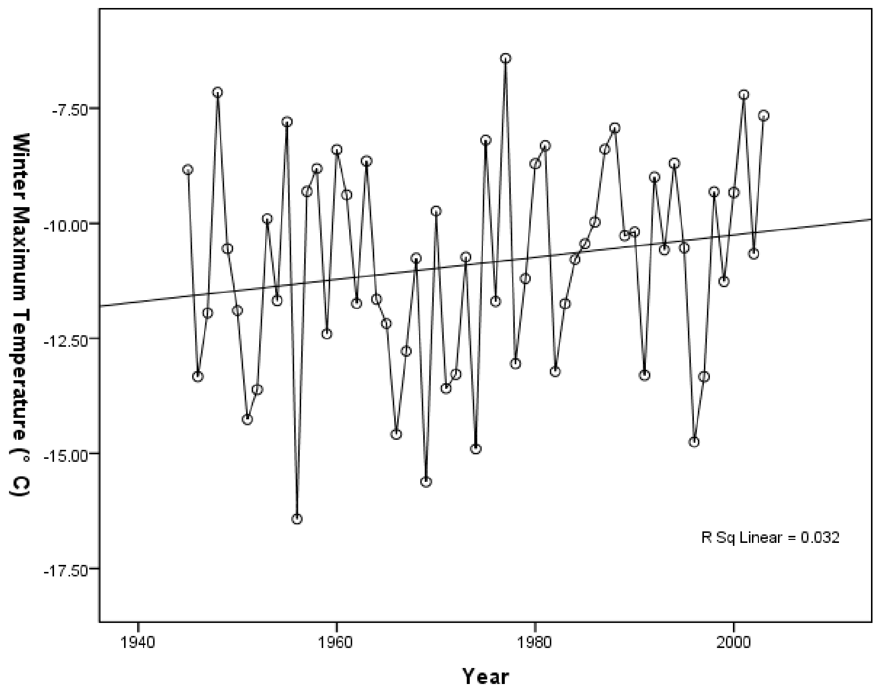


Figure A.29: Time-series of the combined regional record of winter maximum temperature with trend line and coefficient of determination (R Sq Linear).

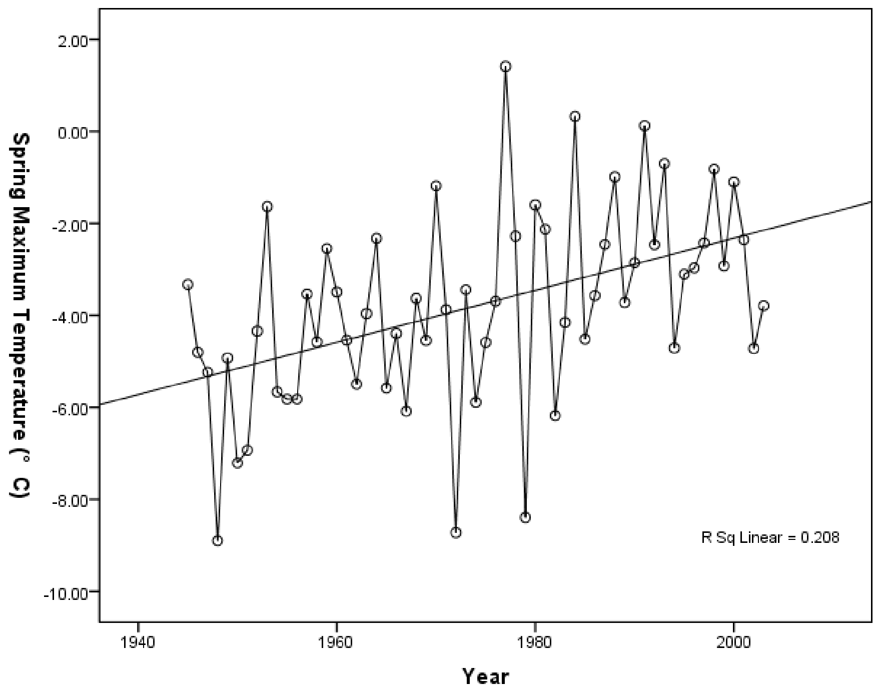


Figure A.30: Time-series of the combined regional record of spring maximum temperature with trend line and coefficient of determination (R Sq Linear).

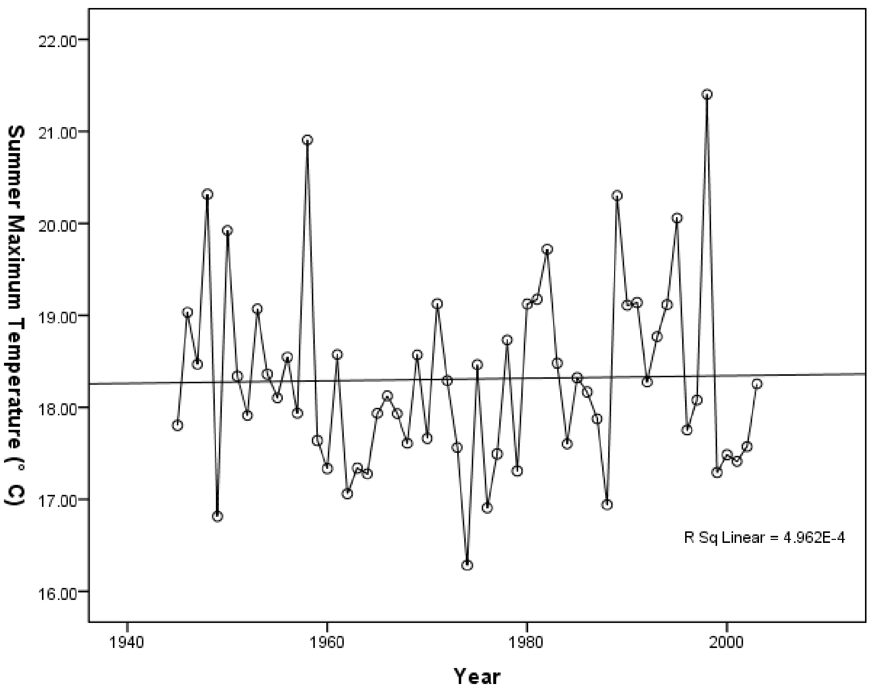


Figure A.31: Time-series of the combined regional record of summer maximum temperature with trend line and coefficient of determination (R Sq Linear).

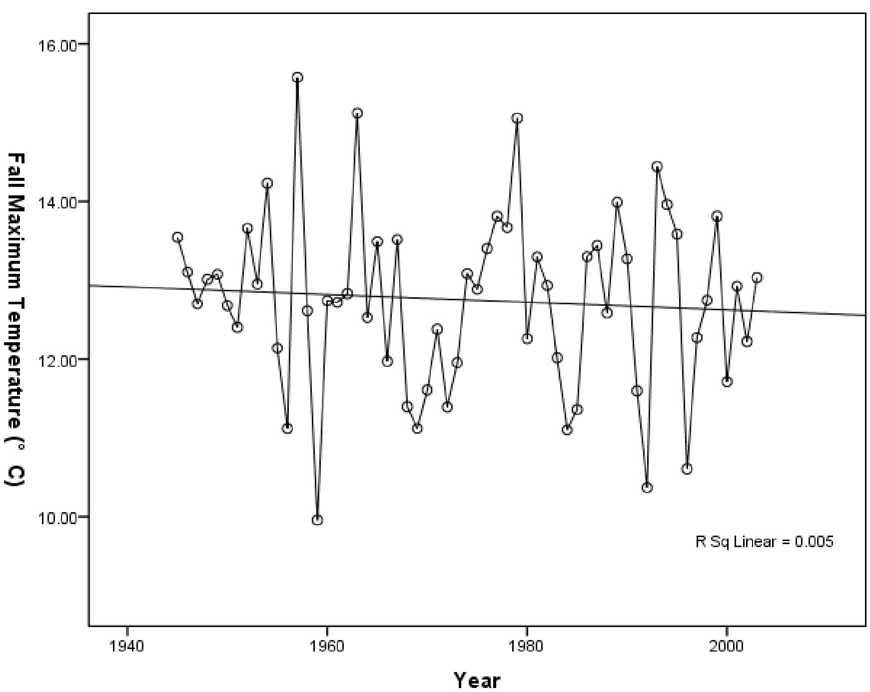


Figure A.32: Time-series of the combined regional record of fall maximum temperature with trend line and coefficient of determination (R Sq Linear).

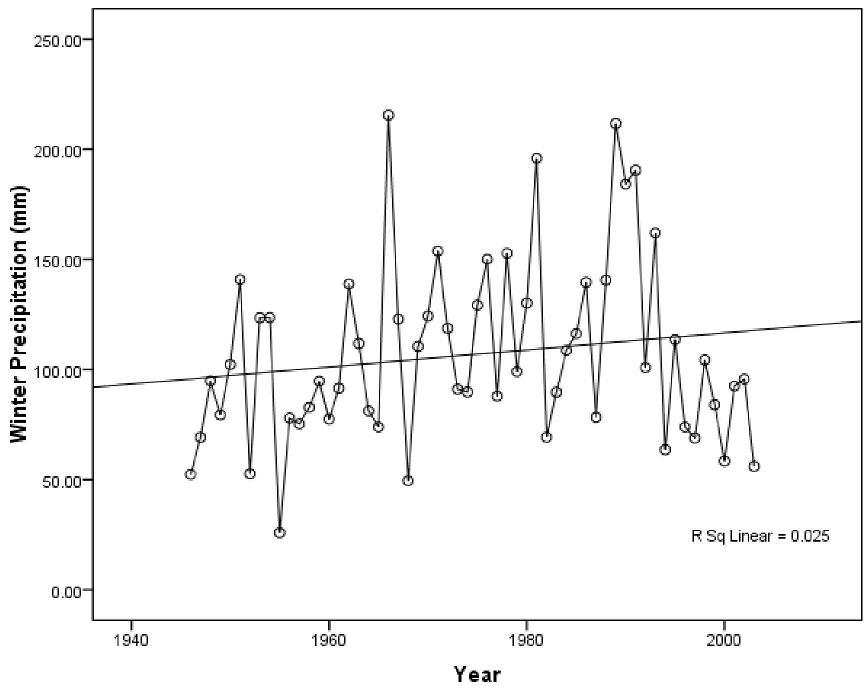


Figure A.33: Time-series of the Dease Lake record of winter precipitation with trend line and coefficient of determination (R Sq Linear).

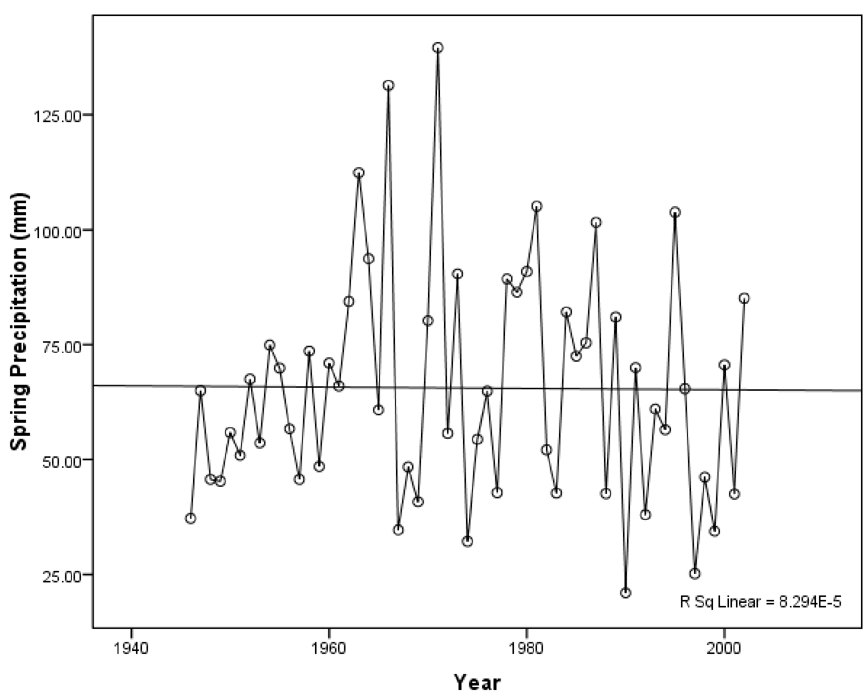


Figure A.34: Time-series of the Dease Lake record of spring precipitation with trend line and coefficient of determination (R Sq Linear).

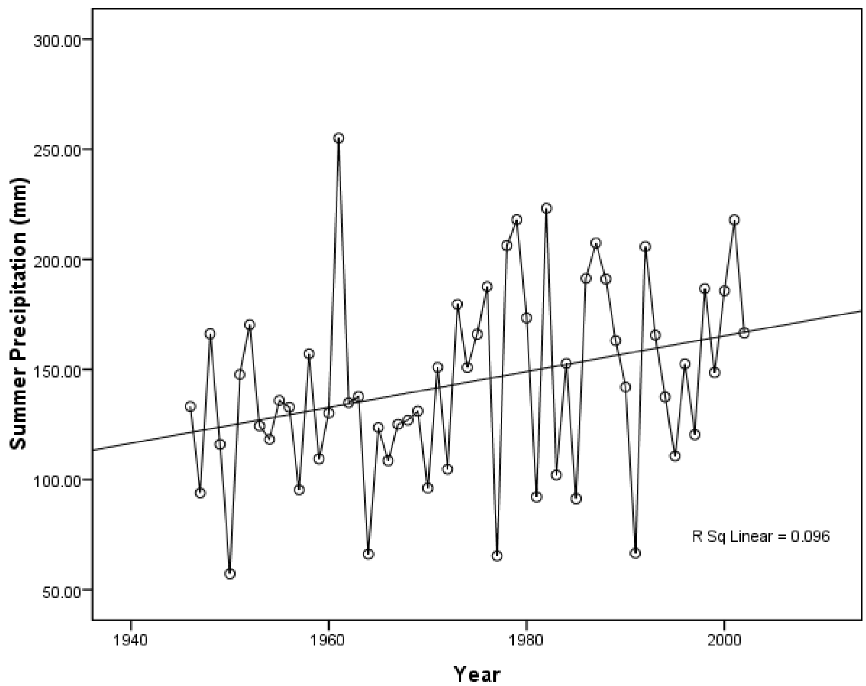


Figure A.35: Time-series of the Dease Lake record of summer precipitation with trend line and coefficient of determination (R Sq Linear).

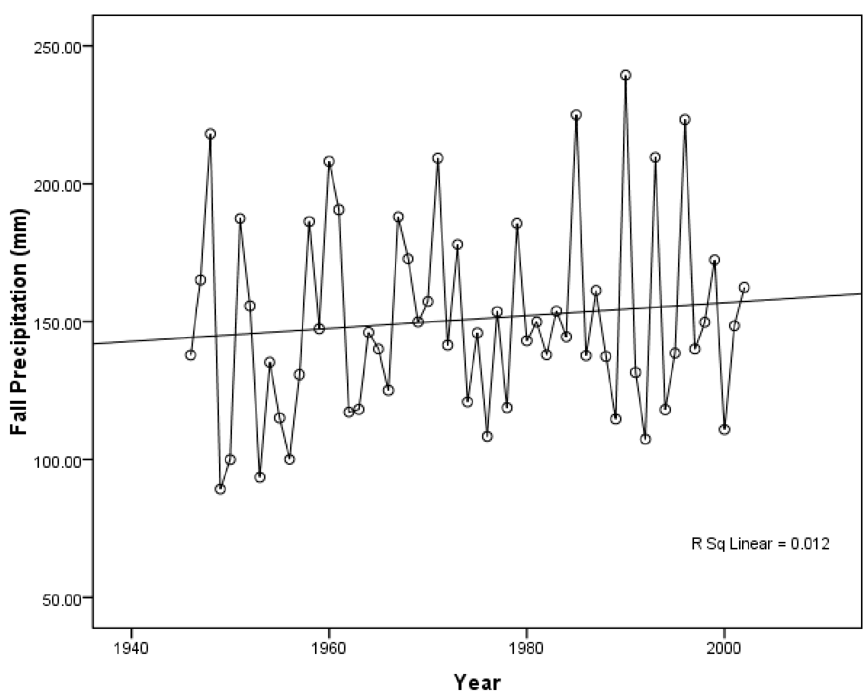


Figure A.36: Time-series of the Dease Lake record of fall precipitation with trend line and coefficient of determination (R Sq Linear).

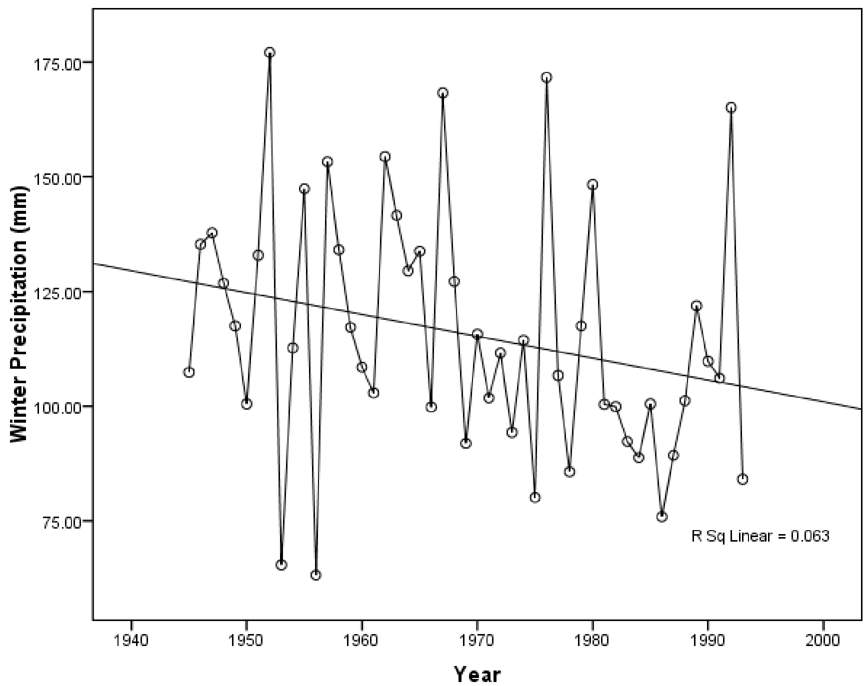


Figure A.37: Time-series of the Watson Lake record of winter precipitation with trend line and coefficient of determination (R Sq Linear).

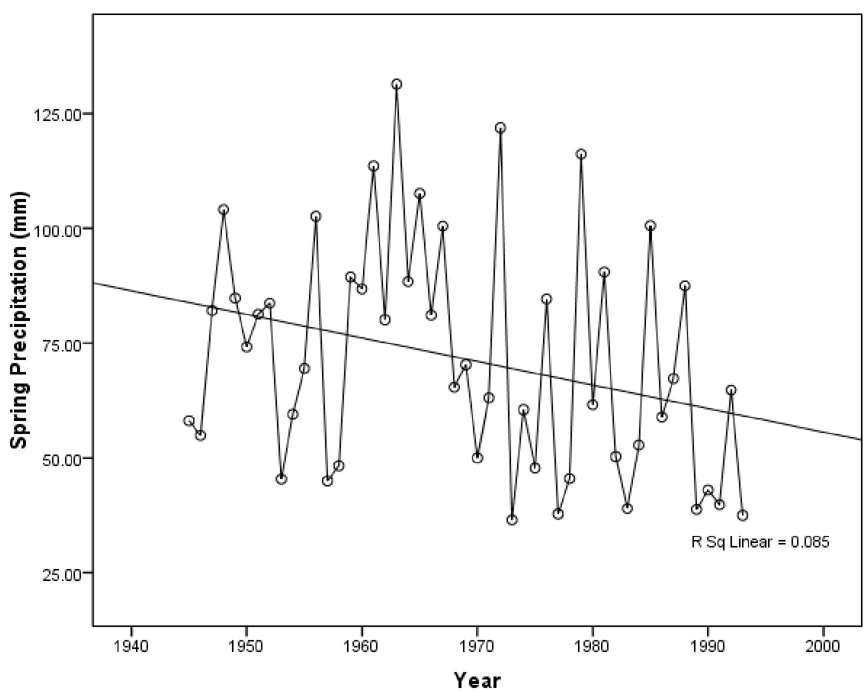


Figure A.38: Time-series of the Watson Lake record of spring precipitation with trend line and coefficient of determination (R Sq Linear).

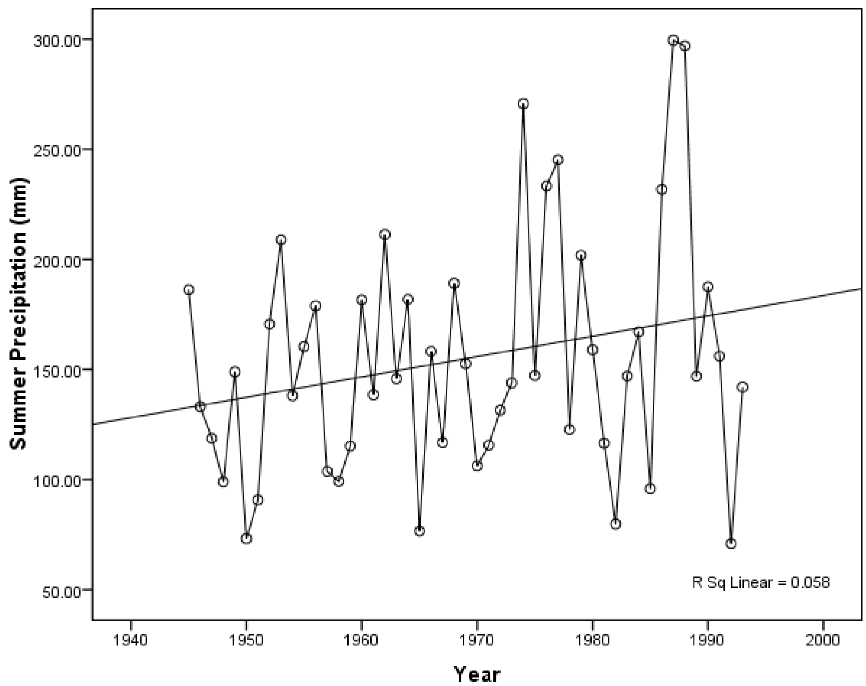


Figure A.39: Time-series of the Watson Lake record of summer precipitation with trend line and coefficient of determination (R Sq Linear).

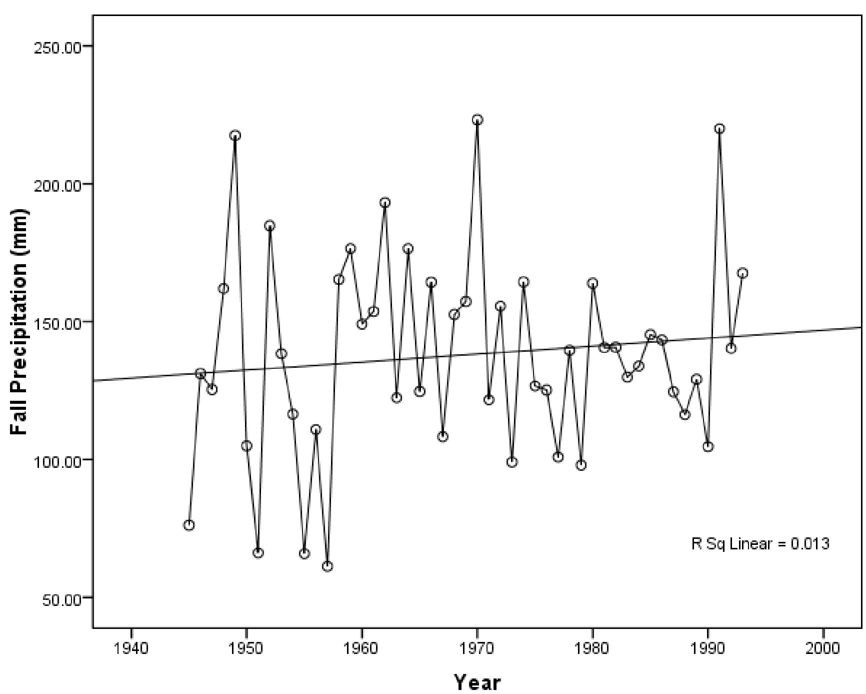


Figure A.40: Time-series of the Watson Lake record of fall precipitation with trend line and coefficient of determination (R Sq Linear).

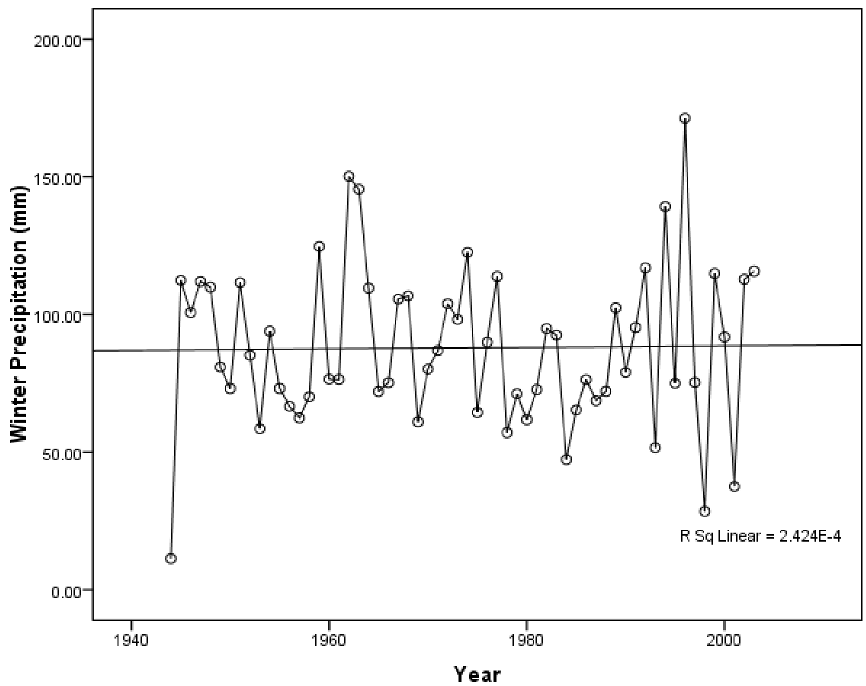


Figure A.41: Time-series of the Fort Nelson record of winter precipitation with trend line and coefficient of determination (R Sq Linear).

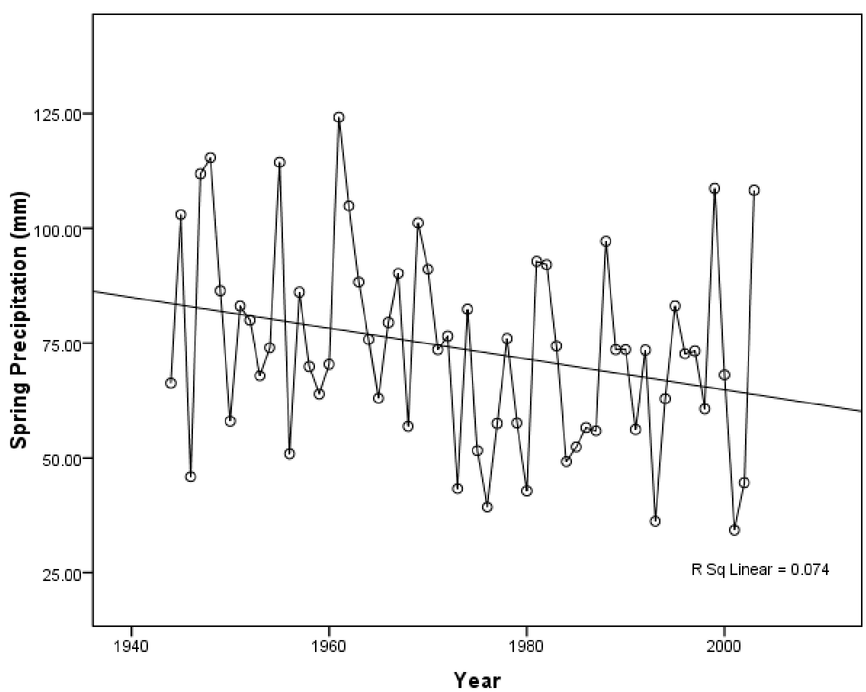


Figure A.42: Time-series of the Fort Nelson record of spring precipitation with trend line and coefficient of determination (R Sq Linear).

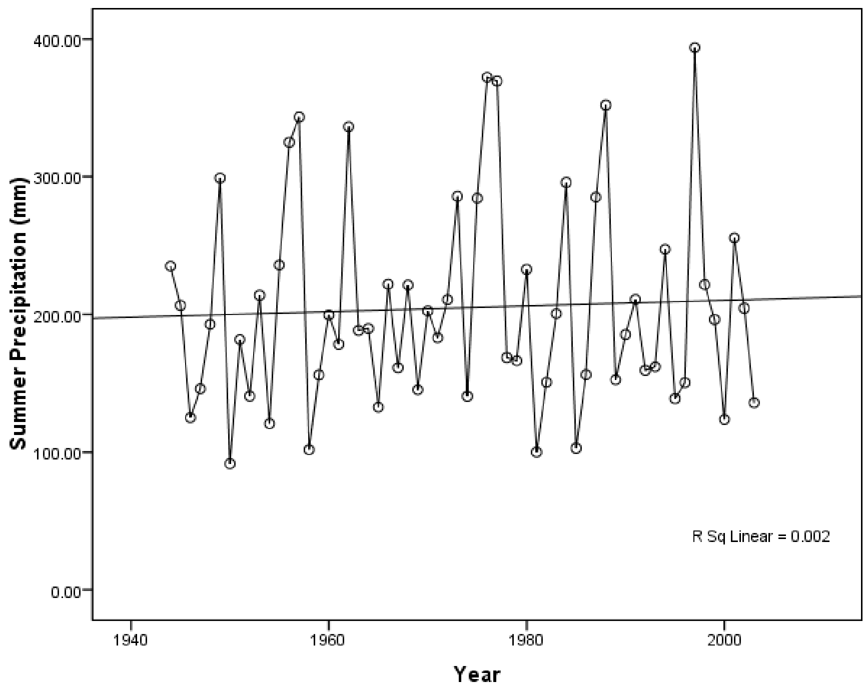


Figure A.43: Time-series of the Fort Nelson record of summer precipitation with trend line and coefficient of determination (R Sq Linear).

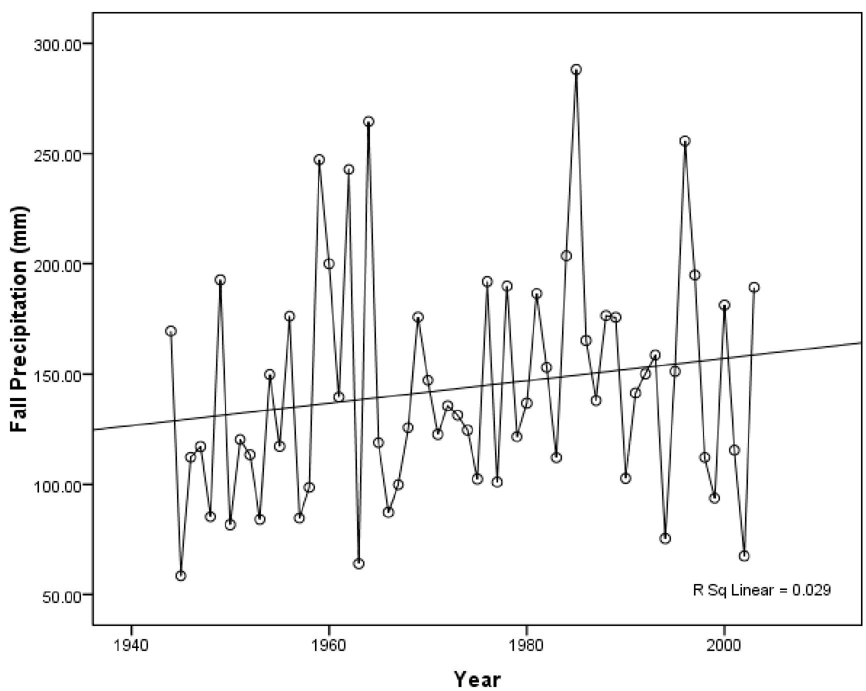


Figure A.44: Time-series of the Fort Nelson record of fall precipitation with trend line and coefficient of determination (R Sq Linear).