HISTORICAL CLIMATE VARIABILITY FROM THE INSTRUMENTAL RECORD IN NORTHERN BRITISH COLUMBIA AND ITS INFLUENCE ON SLOPE STABILITY

by

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ABSTRACT

This thesis examines historical climate variability and its effects on slope stability in northern British Columbia. It comprises three parts: (1) an analysis of climate trends and variability from the instrumental climate record; (2) an examination of climate controls on historic, large landslides; and (3) a demonstration of the utility of weather satellite imagery in determining landslide triggers. The climate of northern British Columbia has become wetter and warmer since the beginning of instrumental observations. Documented trends are complex due to ocean-atmosphere oscillations such as the Pacific Decadal Oscillation and the El Niño Southern Oscillation. Long periods of increasing precipitation and temperature are associated with most dated, large landslides in the study area. Convective storms, large cyclonic storms, and other weather events commonly trigger slope failure. Weather satellite images facilitated the analysis of climate triggers of landslides in remote areas and at high elevations.

Keywords: climate variability, slope stability, landslides, northern British Columbia, natural hazards, weather.

DEDICATION

To my family, who have missed me for years,

so that I could pursue my academic career.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

1.1 Overview

This thesis documents historical climate variability in northern British Columbia and its influence on slope stability. It also examines possible causes of an apparent increase in the frequency of large landslides in the region. A major objective of the research was to better understand the causes and triggers of historic slope failures.

The thesis comprises, in addition to the introduction and a short concluding section, three chapters. Chapter 2 examines climate variability inferred from the instrumental record in northern British Columbia. All available meteorological data for climate stations in northern British Columbia were obtained from Environment Canada, and trends in total precipitation and mean, maximum, and minimum temperatures were determined from the data. Chapter 3 analyzes climate trends associated with historic large landslides in northern British Columbia. Analyzed landslides are from Geertsema et al. (2006*a*), and associated long- and short-term climate conditions are from Chapter 2. Chapter 4 investigates the utility of weather satellite imagery for investigating landslide triggers. This study was conducted after it was found that weather recorded at climate stations that are nearest landslides can be very different from that at the failure sites. Many landslides in northern British Columbia occur in remote areas distant from climate stations or at high elevations where there are no stations.

This study differs from previous similar studies in its focus solely on northern British Columbia and in its more thorough analysis of climate data from a larger number of meteorological stations. Climate differs considerably in northern British Columbia due to the large size and complex physiography of the region, as well as the spatially variable influence of the Pacific Ocean. A thorough analysis of all available meteorological data thus was required to quantify changes in climate through the period of record, to infer current and future trends, and to understand the causes of the trends. This research has broader significance to other areas of landslide-prone terrain where meteorological conditions influence slope stability. Further, an understanding of the possible impacts of future climate change on slope stability is important for reducing losses due to landslides and for remediation and adaptation.

1.2 Study area

The study area is delimited by available Meteorological Services of Canada (Environment Canada) meteorological stations in British Columbia approximately north of 53°N latitude. The area encompasses the Northern Interior Forest Region as defined by the British Columbia Ministry of Forests; however, the climate analysis was extended to include the Queen Charlotte Islands, Robson Valley, and southern Yukon (Figure 1.1). Northern British Columbia has an extent of about 600 000 km^2, includes diverse physiography, and spans a wide range of climate and vegetation zones (Meidinger and Pojar 1991). Elevations range from sea level to over 4000 m, and the region includes many mountain ranges, large plateaus, river valleys, and lowlands (Holland 1976). Climate is controlled by two main factors: the Pacific Ocean, which is a reservoir of heat and moisture; and mountain ranges, which largely determine the distribution of precipitation and the balance between maritime and continental air masses (Meidinger and Pojar 1991).

Steep mountain slopes and valley walls are the main sites of landslides in northern British Columbia, but more gentle slopes underlain by glacial sediments, including till, glaciolacustrine, and glaciomarine deposits are also failure-prone.

1.3 Objectives and methods

This research addressed the following questions: (1) Are there historic trends in the climate of northern British Columbia that can be extracted from meteorological data? (2) What is the relation between climate variability in the area, the El Niño Southern Oscillation (ENSO), and Pacific Decadal Oscillation (PDO)? (3) What meteorological conditions trigger landslides? (4) Are changes in climate responsible for an apparent increase in the frequency of landslides in northern British Columbia in the twentieth century? These questions were answered by: (1) statistically analyzing data from all available Environment Canada climate stations in northern British Columbia; (2) relating climate variability documented from the data to the timing of ENSO and PDO; (3) investigating the relation between meteorological conditions and known landslide events; and (4) discussing how current and anticipated climate in northern British Columbia may affect slope stability.

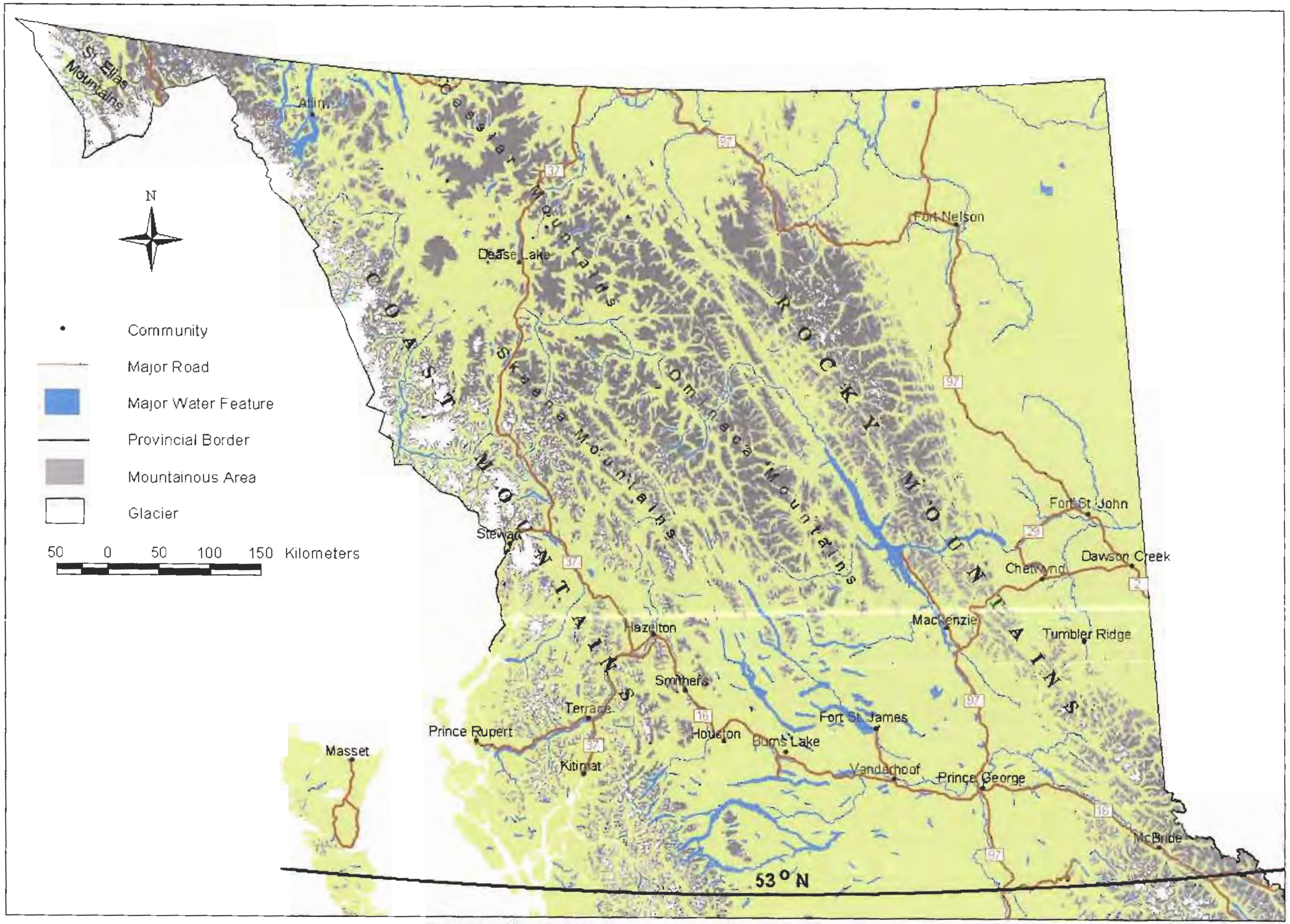

Figure 1.1. Study area. (Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/).

CHAPTER 2 CLIMATE VARIABILITY IN NORTHERN BRITISH COLUMBIA INFERRED FROM THE INSTRUMENTAL RECORD

2.1 Abstract

Records for 210 meteorological stations in northern British Columbia, spanning the period 1886-2003, were obtained from the Meteorological Service of Canada and analyzed for climate variability and trends. At each station, daily climate data were used to calculate monthly and yearly trends in total precipitation and mean, maximum, and minimum temperatures. Results show that northern British Columbia has become wetter and warmer since the beginning of the instrumental record, with the exception of the area east of the Rocky Mountains where there is drying or no significant trend. The annual and seasonal analyses show that minimum temperatures changed most and maximum temperatures least. Seasonally, the greatest warming trend is in winter and the least is in spring. The only cooling trend is in spring maximum temperatures. The largest increase in precipitation is in the summer; in contrast, winter overall is drier. The largest overall increase in temperature is in the Fraser Basin.

2.2 Introduction

A variety of data sources and methods have been used in studies of historic climate change in Canada (Powell 1965; Gullet and Skinner 1992; Gullet et al. 1992; Environment Canada 1995; Chiotti 1998; Zhang et al. 2000; BC Ministry of Water, Land, and Air Protection 2002*a*, *b*). Most studies have documented changes of mean climatic conditions, which suggest that weather patterns are changing throughout the country, particularly in the north (>55°N) (Zhang et al. 2000). Extreme weather events may also be increasing (Chiotti 1998). Heat waves and convective storms appear to be increasing in frequency and intensity in summer; and cold spells may be decreasing, and intense snowstorms becoming more frequent in winter (Chiotti 1998).

In 1992, an historical Canadian climate database was created for climate change analysis using Meteorological Service of Canada reference weather stations (Gullet et al. 1992). Eleven climate stations in northern British Columbia were included in the database. Data from these stations were the basis for the early and mid-1990s State of the Environment reports issued by Environment Canada (Gullet and Skinner 1992; Environment Canada 1995). The studies used departures from the mean of 1951-1980 climate normals to examine temperature and precipitation changes. Three distinct periods were inferred from the national temperature record: warming from the 1890s to the 1940s, cooling from the 1940s to the 1970s, and renewed warming from the 1970s onward (Gullet and Skinner 1992). Annual average temperature in the last century has increased 0.8-1.3°C in northwestern Canada, accompanied by a small increase in annual precipitation (Gullet and Skinner 1992; Environment Canada 1995).

Powell (1965) calculated annual and seasonal temperature and precipitation trends in British Columbia from 1890 until the early 1960s to investigate the link between climate and mountain pine beetle populations. He determined trends in average temperature and total precipitation using five-year running means and 30-year averages. The analysis included 21 climate stations in northern British Columbia. Temperatures in northern British Columbia increased until the 1940s, after which they levelled off or decreased. The greatest temperature increase was in winter and the least in spring. The greatest increase in precipitation was in winter.

A recent study by the British Columbia Ministry of Water, Land, and Air Protection (BC Ministry of Water, Land, and Air Protection 2002*a*) confirmed Powell's (1965) findings. It reported five climate parameters over the period 1895-1995: average temperature, maximum temperature, minimum temperature, precipitation, and snow. It defined groups of meteorological stations on the basis of the ecoprovinces of Demarchi (1996). In some cases, an entire ecoprovince was represented by only one meteorological station, and northern British Columbia was represented by 16 climate stations. Climate parameters were plotted as time series with best-fit trend lines and calculated variance. Anomalies, defined as the difference between the mean value of the parameter and its historical average (1961-1990 climate normals) were also reported (BC Ministry of Water, Land, and Air Protection 2002*b*). The key conclusions of the study, with regard to northern British Columbia, are: (1) an increase of 0.6-1.7°C in average annual temperature; (2) no change in maximum temperature; (3) an increase of 0.9-2.1°C in minimum temperature; (4) an increase in precipitation of up to 4% per decade; and (5) an increase in snow of up to 6% per decade (BC Ministry of Water, Land, and Air Protection 2002*a*).

The term 'climate change' is commonly used to describe trends in climate operating on a timescale of many decades or hundreds of years, whereas 'climate variability' is used to describe trends on shorter timescales (BC Ministry of Water, Land, and Air Protection 2002*a*). Climate variability in British Columbia is thought to be driven by cyclical changes in ocean surface temperatures, specifically those related to the El

Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (BC Ministry of Water, Land, and Air Protection 2002*a*). During the negative phase of the Southern Oscillation Index (El Niño), western Canada experiences warmer air, especially in the winter, and greater rainfall due to moist tropical air over the western United States (Bigg 2003). The positive phase (La Niña) brings cooler air and more outbreaks of severe cold (Bigg 2003). The PDO affects Pacific Northwest climate on a longer time scale than ENSO. It has produced cool phases from 1890 to 1924 and 1947 to 1976, and warm phases from 1925 to 1946 and 1977 to at least the mid-1990s (Mantua and Hare 2002). In the Pacific Northwest, the cool phases are thought to be associated with anomalously wet periods and the warm phases with dry periods; however, the PDO mechanisms are not fully understood (Mantua and Hare 2002).

This study analyzes the climate of northern British Columbia from 1886 to 2003, based on historical instrumental meteorological records from 210 Meteorological Service of Canada climate stations (Figure 2.1). Past climate studies have typically been national in scope and were done on such a large scale that only a few select weather stations in northern British Columbia were used. Studies of British Columbia climate trends, for example, have used data from only 10% of the climate stations in the northern part of the province. The objectives of this study are to quantify historical climate trends and variability in northern British Columbia using all available, reliable climate data. As in previous studies, trends in annual and seasonal total precipitation and mean temperatures were calculated. In contrast to previous studies, however, extreme maximum and minimum temperatures were also analyzed. Trends were compared to overall climate station means, rather than the 30-year climate normals used in earlier studies, thus eliminating the bias imposed by the shorter period.

2.3 Methods

2.3.1 Data collection

Available daily climate data for 210 stations in northern British Columbia were obtained from the Meteorological Service of Canada (© Environment Canada, 2005, by permission). Station information, including identification number, location, elevation, period of record, and missing data (if any), is provided in Appendix A (CD-Rom-1). Fifty of the 210 stations have less than 10 years of consecutive data and were not analyzed. Climate parameters recorded at each station differ, but mean, maximum, and minimum temperatures, total rain, total snow water equivalent, and total precipitation are available for most stations. Nineteen stations record only precipitation, and two record only temperature. Snow data were not analyzed due to time constraints and unreliable and unavailable data.

Daily data were used to calculate monthly mean, maximum, and minimum temperatures, and monthly total precipitation. Monthly calculations were not made if more than 10 days of data in a given month were missing. Monthly mean temperatures were calculated as the average of the daily mean temperatures. In contrast, other researchers have calculated mean monthly temperature as the average of monthly maximum and minimum temperatures (Gullet and Skinner 1992; Zhang et al 2000; BC Ministry of Water, Land, and Air Protection 2002*b*). Extreme maximum and minimum temperatures were extracted from the daily data, rather than by calculating a monthly mean maximum and mean minimum temperature from the average of the daily maximum and minimum temperatures (e.g. Zhang et al. 2000; BC Ministry of Water, Land, and Air Protection 2002*b*). Total monthly precipitation was calculated from the daily total precipitation data.

Seasonal and annual values of mean, maximum, and minimum temperature and total precipitation were calculated from monthly values using the method described above. Standard climatological seasons were used: winter - December of previous year, January, and February; spring - March, April, and May; summer - June, July, and August; and fall - September, October, and November (Powell 1965; Environment Canada 1995; Mekis and Hogg 1999; Zhang et al. 2000; BC Ministry of Water, Land, and Air Protection 2002*b*). Seasonal calculations were not made if one or more months of data were missing. Annual calculations were not made if two or more months of data were missing, or if a single missing month would have substantially affected the annual value.

Homogenization techniques are commonly used to eliminate discrepancies in climate data resulting from station relocation, changes in data collection equipment, changes in observation procedures, and missing data. Environment Canada has applied homogenization techniques to many of its climate stations to increase the quality of the data (Mekis and Hogg 1999; Vincent et al. 2002). Data adjustments have been made for 17 stations for temperature and 33 stations for precipitation in northern British Columbia (Mekis and Hogg 1999; Vincent et al. 2002). A bias would result if two different datasets were used in this study - one based on those stations with adjusted data, and the other based on stations with unadjusted data. Further, homogenization techniques have not yet been perfected and still contain errors (Ducré-Robitaille et al. 2003). Therefore, no attempt was made to adjust the daily climate data or to use adjusted data in this study. Most data used in this study, however, have been quality checked by Environment Canada and, to some degree, by the author.

2.3.2 Calculation of cumulative departures from the mean

Cumulative departures from the overall station mean were calculated from annual and mean temperature and total precipitation values and then graphed. Graphs were used to identify steps in the data indicative of changes in data collection or observation procedures; none was found. Yearly percent departure from the mean was calculated according to the formula (Karanka 1986):

$$y_i = 100 * \sum((x_i / \bar{x}) - 1) \qquad (1)$$

where y_i is the cumulative percent departure from the mean to year i of the record, x_i is the total precipitation (or average temperature) for year i, and $\bar{x}$ is the mean precipitation (or mean temperature) for the period of record. This method provides a graphical representation of trends in the data series. A section in the data series with a zero slope represents a period of normal climate conditions; a section with a positive slope represents a period of above-normal climate conditions; and a section with a negative slope represents a period of below-normal climate conditions (Karanka 1986).

This method can also be used to calculate monthly percent departure from the mean (Hogan and Schwab 1991). Mean temperature for the first month of the first year of record, for example, is compared to the station record of that month. The process is repeated for subsequent months of the first year, and then continued with the next year of the record. Monthly departures from the mean are then summed chronologically from one month to the next. Examples of graphs showing annual and monthly cumulative departures from the mean are give in Figures 2.2-2.5.

This method is not appropriate for calculating percent departures from the mean for average monthly temperatures in cooler climates, because of the presence of negative temperatures. Another, more appropriate method is that of Moore and McCabe (1999):

$$z = \frac{x -- u}{\sigma} \tag{2}$$

where z is the deviation from the mean, x is the average temperature for a given month of a given year of the station record, u is the mean temperature for the given month of the record, and σ is the standard deviation of all mean temperatures of the given month.

2.3.3 Baseline climate trends

Graphs of annual and seasonal mean temperatures, maximum and minimum temperatures and total precipitation were made to quantify trends in the cumulative departure from the mean curves. Trend lines were determined by regression, and the slope of the trend line was used to quantify the overall trend in the data. The equation for the slope of the least squares regression line (b_1) is (Moore and McCabe 1999):

$$b_1 = r\frac{s_y}{s_x} \tag{3}$$

where s_y is the standard deviation in the climate parameter, s_x is the standard deviation in the time, and r is the correlation.

The slope of the trend line was multiplied by the number of years of station record to calculate the overall trend of the climate parameter. Examples of baseline climate trend graphs are given in Figures 2.6-2.9. A *t*-test of slope was made for a number of stations to determine if the trends are significantly different from zero (Appendix 1).

2.3.4 Regional groupings

Meteorological data were grouped into regions and changes were determined for each region. Regional groupings were done on the basis of ecoregions, which are areas of similar physiography, climate, and vegetation (Demarchi 1996). There are 15 ecoregions in the study area; some were combined to increase the number of climate stations for analysis, and others were omitted due to a lack of climate stations (Figure 2.10, Appendix 2). Biogeoclimatic zones (Meidinger and Pojar 1991) were considered for regional grouping, but most climate stations are in only three zones, and some zones have few or no stations. Lengths of station records differ among the regions, thus weighted averages were used to calculate annual and seasonal mean, maximum, and minimum temperatures and total precipitation, as well as changes in climate parameters in each region. The following formula was used to calculate weighted averages (Bland and Kerry 1998):

$$\bar{x}_w = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{4}$$

where $\bar{x}_w$ is the weighted average, w_i is the weight (number of years of station record), x_i is the station total precipitation or mean, maximum, or minimum temperature over the entire record, i is a given station, and n is the number of stations within the region.

Weighted standard deviation and standard errors were calculated to test the statistical significance of the weighting procedure (Appendix 3). If the weighted average change is larger than two times the standard error, there is a 95% likelihood that the value is statistically different from zero (Moore and McCabe 1999).

This method was used for the entire period of record of each region, thus giving a total change. Since the length of record is different for each region, a rate of change per decade was calculated for comparison. This was done by dividing the total change by the number of years of record and multiplying this value by ten.

2.4 Results

Graphs of baseline trends of annual and seasonal total precipitation and mean, maximum, and minimum temperature were constructed for each of the 160 stations. Annual and monthly cumulative departures from the mean for total precipitation and mean temperature were also graphed. In total, 24 climate trend graphs were made for each station. Representative graphs are presented in Figures 2.2-2.9. All of the graphs are included in Appendix B (CD-Rom-1).

2.4.1 Cumulative departures from the mean

Graphs of monthly and annual cumulative departure from the mean have similar overall trends; however, the former have more variability than the latter (Figures 2.2-2.5). In view of the similarity of the two datasets, the monthly results will not be considered further. Stations with 50 years or more of temperature and precipitation data are examined here because they provide the most information on trends (Appendix 4). The climate trends of the shorter and longer recording stations, however, are similar, especially for temperature. Precipitation is more variable in space and time than temperature, which is not surprising given the geographic diversity of northern British Columbia.

2.4.1.1 Annual mean temperature

Bella Coola, Fort St. James, and Barkerville are the longest-running meteorological stations in the study area, with data extending back into the late nineteenth century. The Bella Coola record shows a cooling trend from the early 1900s until the 1920s, followed successively by a warming trend until the 1940s, a sharp cooling trend until the late 1950s, and an increase in temperature until the present. The Fort St. James record shows cooling until the 1920s, followed by gradual warming until the 1940s, then a decade of cooling, and finally warming since the late 1950s. At Barkerville, temperatures increased from the start of the record until approximately 1907, after which there was a long period of decreasing temperatures until the 1970s, followed by warming until the present.

Climate stations with shorter records show similar trends to Bella Coola, Fort St. James, and Barkerville. A shift from a cooling trend to a warming trend in the 1920s can be seen in data from Masset, Bella Coola, and Stewart (Appendix 4). Climate cooled again in the 1940s (Stewart, Wistaria, and Baldonnel), followed by a warming trend in the 1970s that continued to the present (Langara, Sandspit, Cape St. James, Kemano, Terrace, Smithers, Germansen Landing, Wistaria, Prince George, Baldonnel, Fort St. John, Dease Lake, Fort Nelson, Watson Lake, Teslin, and Whitehorse).

Two years of abnormal temperature are apparent in the data: 1981 was a particularly warm year and 1996 an especially cold one. At the time the State of the Environment Report was released, 1981 was Canada's warmest year (Gullet and Skinner

1992). 1996 appears in most of the graphs as an anomalous dip in the warming trend of the last few decades.

2.4.1.2 Annual total precipitation

Bella Coola, Fort St. James, and Barkerville have more than 100 years of precipitation data. A period of lower-than-average precipitation at Bella Coola ended in the 1920s, with an overall increase in precipitation until the present. At Fort St. James, precipitation was lower than average from the beginning of the record until the 1940s, at which time it increased to the present. An early dry phase at Barkerville ended about 1910, followed by average precipitation conditions until the 1930s. A subsequent wet phase persisted into the 1970s, when precipitation returned to normal, decreasing slightly to the present. Precipitation increased in the 1940s at Fort St. James, McBride, and Baldonnel, and a similar shift occurred in the 1970s at Langara, Germansen Landing, and Dease Lake. In contrast, at Prince George and Fort St. John, precipitation decreased in the 1970s.

2.4.2 Annual baseline climate trends and regional change

Annual average total precipitation and mean, maximum, and minimum temperature were used to calculate averages for each station, weighted averages for each region (Table 2.1), and weighted average changes for each region (Table 2.2). Standard errors of the annual change are presented in Appendix 5. Figures 2.11-2.14 summarize the results graphically. Note the period of each region differs: Gwaii Haanas, 1897-2002; Boundary Ranges/Yukon Stikine Highland, 1910-2003; Coastal Gap, 1888-2003; Nass Ranges, 1912-2003; Skeena/Omineca Mountains, 1951-2003; Fraser Plateau, 1922-2003;

Fraser Basin, 1895-2003; Columbia Highlands/Northern Columbia Mountains/Western Continental, 1888-2003; Southern Rocky Mountain Trench, 1914-2003; Central Canadian Rocky Mountains, 1963-2003; Peace River Basin, 1916-2003; Central Alberta Uplands, 1944-2003; Northern Rockies/Hay River Lowlands, 1937-2003; Yukon Southern Lakes/Liard Basin, 1938-2003; and Boreal Mountains and Plateaus, 1905-2003.

2.4.2.1 Total precipitation

Changes in total precipitation range from -5.0% to 18.6% (-38.0 to 195.7 mm). Twelve of the 15 regions show increases in precipitation over the period of record, but only four are statistically significant at the 95% level: Gwaii Haanas (12.4%), Skeena/Omineca Mountains (10.2%), Fraser Basin (13.0%), and Columbia Highlands/Northern Columbia Mountains/Western Continental (18.6%). The Columbia Highlands/Northern Columbia Mountains/Western Continental region experienced the greatest percent change in precipitation and increases occurred at all the climate stations (Figure 2.11). Most climate stations in the Fraser Basin region and in regions east of the Rockies show either no trend or drying over the period of record (Figure 2.11).

2.4.2.2 Mean temperature

Fourteen of the regions show increasing temperature trends. Values range from no change to 1.3°C, with the largest increase in the Skeena/Omineca Mountains region, Fraser Basin, and Northern Canadian Rocky Mountain/Hay River Lowlands. These three regions and seven others have statistically significant values: Gwaii Haannas (0.7°C), Boundary Ranges/Yukon Stikine Highland (0.6°C), Coastal Gap (0.7°C), Nass Ranges (0.8°C), Southern Rocky Mountain Trench (0.8°C), Yukon Southern Lakes/Liard Basin

(0.7°C), and Boreal Mountains and Plateaus (1.2°C). All climate stations in Gwaii Haanas, Nass Ranges, and Northern Rockies/Hay River Lowlands show positive mean temperature trends (Figure 2.12).

2.4.2.3 Maximum temperature

Nine of the regions record increases in maximum temperature. Weighted average values range from -0.9 to 1.1°C. The largest increase is in the Boreal Mountains and Plateaus region, and the largest decrease is in the Peace River Basin. Trends in both of these regions are statistically significant, as is that in the Columbia Highlands/Northern Columbia Mountains/Western Continental region (0.9°C). All stations in the Peace River Basin show a decrease in maximum temperature (Figure 2.13).

2.4.2.4 Minimum temperature

Fourteen regions show an increase in minimum temperature. Values range from -0.8 to 4.4°C, with the greatest increase in the Fraser Basin. Trends in ten of the regions are statistically significant: Coastal Gap (2.2°C), Skeena/Omineca Mountains (2.7°C), Fraser Plateau (2.3°C), Fraser Basin (4.4°C), Southern Rocky Mountain Trench (3.8°C), Peace River Basin (3.0°C), Central Alberta Uplands (3.2°C), Northern Rockies/Hay River Lowlands (3.3°C), Yukon Southern Lakes/Liard Basin (2.6°C), and Boreal Mountains and Plateaus (2.1°C). Most climate stations in these regions show increases in minimum temperature, and all stations in Yukon Southern Lakes/Liard Basin, Northern Rockies/Hay River Lowlands, Central Alberta Uplands, and the Skeena/Omineca Mountains record increases (Figure 2.14). Conversely, all stations in the Columbia Highlands/Northern Columbia Mountains/Western Continental region show decreasing minimum temperature, although the weighted average of the trends is not statistically significant (Figure 2.14).

2.4.3 Seasonal baseline climate trends and regional change

Seasonal average total precipitation and mean, maximum, and minimum temperatures were used to calculate averages for each station, weighted averages for each region, and weighted average change for each region (Tables 2.3-2.6). Standard errors of the annual change are presented in Appendix 5. Figures 2.15-2.18 summarize the results graphically.

2.4.3.1 Winter

Winter weighted average changes in total precipitation and mean, maximum, and minimum temperatures are presented in Table 2.3; standard errors are given in Appendix 5. Values range from -41.6 to 18.6%. Nine of the regions show a decrease in winter precipitation, but only two of them (Northern Rockies/Hay River Lowlands, -41.6%; and the Yukon Southern Lakes/Liard Basin, -24.5%) have trends that are statistically different from zero.

Changes in winter mean temperature range from 0.2 to 2.8°C, with the Fraser Basin, Northern Rockies/Hay River Lowlands, and Boreal Mountains and Plateaus having the greatest increase. All regions have increasing mean temperature trends and 12 of them are statistically significant: Gwaii Haanas (1.0°C), Boundary Ranges/Yukon Stikine Highlands (1.5°C), Coastal Gap (1.6°C), Nass Ranges (1.3°C), Skeena/Omineca Mountains (2.5°C), Fraser Plateau (1.4°C), Fraser Basin (2.8°C), Peace River Basin (2.3°C), Central Alberta Uplands (2.3°C), Northern Rockies/Hay River Lowlands (2.8°C), Yukon Southern Lakes/Liard Basin (1.6°C), and the Boreal Mountains and Plateaus (2.8°C).

Twelve regions show an increase in maximum temperature in winter, with the greatest increase occurring in the Boreal Mountains and Plateaus (1.4°C). This region and the Coastal Gap (0.7°C) and Fraser Basin (0.9°C) have statistically significant trends. Regional values range from -0.8 to 1.4°C.

Minimum winter temperature changes range from -0.2 to 4.3°C. Thirteen regions have positive trends, with the greatest increase in the Fraser Basin. Trends in 11 of the 13 regions are statistically significant: Gwaii Haanas (1.2°C), Coastal Gap (2.6°C), Nass Ranges (2.2°C), Skeena/Omineca Mountains (2.5°C), Fraser Plateau (2.3°C), Fraser Basin (4.3°C), Peace River Basin (2.7°C), Central Alberta Uplands (3.0°C), Northern Rockies/Hay River Lowlands (2.8°C), Yukon Southern Lakes/Liard Basin (1.7°C), and Boreal Mountains and Plateaus (2.7°C).

2.4.3.2 Spring

Weighted average changes in total precipitation and mean, maximum, and minimum temperatures in spring are given in Table 2.4; standard errors are presented in Appendix 5. Precipitation change ranges from -15.2 to 27.0%, with the largest increase in the Nass Ranges region. Twelve regions have positive trends and five of these are statistically significant: Nass Ranges (27.0%), Fraser Plateau (18.6%), Fraser Basin (23.0%), Columbia Highlands/Northern Columbia Mountains/Western Continental (20.3%), and Southern Rocky Mountain Trench (15.8%).

Spring mean temperature change ranges from -0.7 to 1.2°C. Eleven regions have positive trends, with the highest increases in the Fraser Basin and Boreal Mountains and Plateaus regions. The trends in seven regions are statistically significant: Gwaii Haanas (0.8°C), Coastal Gap (0.8°C), Nass Ranges (0.8°C), Fraser Basin (1.2°C), Northern Rockies/Hay River Lowlands (1.1°C), Yukon Southern Lakes/Liard Basin (0.7°C), and Boreal Mountains and Plateaus (1.2°C).

Spring maximum temperature change ranges from -2.2 to 1.8°C, with negative trends in ten of the regions. The Central Canadian Rocky Mountains have the largest decrease, but the change is not significant. Trends for only four regions are significant: Coastal Gap (1.8°C), Nass Ranges (-0.9°C), Fraser Plateau (-1.7°C), and Yukon Southern Lakes/Liard Basin (-1.4°C).

Spring minimum temperature change ranges from -4.0 to 4.3°C. Twelve regions have positive trends, with the greatest change in the Fraser Basin. Only four regions, however, have significant trends: Coastal Gap (1.3°C), Nass Ranges (2.6°C), Fraser Basin (4.3°C), and Boreal Mountains and Plateaus (1.7°C).

2.4.3.3 Summer

Summer weighted average changes in total precipitation and mean, maximum, and minimum temperatures are presented in Table 2.5; standard errors are given in Appendix 5. Precipitation changes range from -18.4 to 23.4%, with increasing trends in 14 regions. The largest increase is in the Fraser Basin. Nine regions have statistically significant trends: Gwaii Haanas (14.4%), Nass Ranges (13.1%), Fraser Plateau (11.9%), Fraser Basin (23.4%), Columbia Highlands/Northern Columbia Mountains/Western Continental (19.3%), Southern Rocky Mountain Trench (18.4%), Central Canadian

Rocky Mountains (-18.4%), Northern Rockies/Hay River Lowlands (18.7%), and Boreal Mountains and Plateaus (16.6%).

Mean summer temperatures increased, with 13 regions recording positive trends. Values range from -0.1 to 1.0°C, with the largest increase in the Fraser Basin. Seven regional trends are significant: Coastal Gap (0.5°C), Nass Ranges (0.6°C), Skeena/Omineca Mountains (0.7°C), Fraser Basin (1.0°C), Southern Rocky Mountain Trench (0.7°C), Northern Rockies/Hay River Lowlands (0.8°C), and Boreal Mountains and Plateaus (0.8°C).

Maximum summer temperature change ranges from -0.8 to 0.9°C, with positive trends in 13 regions. The greatest increase occurred in the Boreal Mountains and Plateaus. This region and the Columbia Highlands/Northern Columbia Mountains/Western Continental region (0.6°C) have the only significant trends.

Summer minimum temperature change ranges from -1.4 to 1.8°C, with 13 regions having positive trends. The greatest increase is in the Fraser Basin. Trends in ten regions are significant: Gwaii Haanas (0.5°C), Boundary Ranges/Yukon Stikine Highlands (0.9°C), Coastal Gap (0.7°C), Nass Ranges (1.1°C), Fraser Plateau (0.8°C), Fraser Basin (1.8°C), Southern Rocky Mountain Trench (1.3°C), Central Canadian Rocky Mountains (-1.4°C), Peace River Basin (0.7°C), and Boreal Mountains and Plateaus (0.8°C).

2.4.3.4 Fall

Weighted average changes in total precipitation and mean, maximum, and minimum temperature are given in Table 2.6; standard errors are given in Appendix 5. Changes in precipitation range from -8.9 to 19.3%, with positive trends in 13 regions and the greatest increase in Fraser Basin. Trends in four regions are significant: Gwaii Haanas (12.5%), Fraser Plateau (13.1%), Fraser Basin (19.3%), and Boreal Mountains and Plateaus (15.5%).

Mean fall temperature trends are positive in 11 regions. Values range from -0.7 to 1.0°C. The Central Canadian Rocky Mountains experienced the largest increase in fall temperature, but the increase is not significant. Six regions have significant trends: Gwaii Haanas (0.7°C), Coastal Gap (0.3°C), Nass Ranges (0.3°C), Skeena/Omineca Mountains (0.8°C), Fraser Basin (0.9°C), and Yukon Southern Lakes/Liard Basin (-0.7°C).

No dominant trend is evident in fall maximum temperatures. Eight regions show negative trends and seven regions positive ones. The values range from -2.5 to 2.1°C, with the largest decrease in Yukon Southern Lakes/Liard Basin and the largest increase in Columbia Highlands/Northern Columbia Mountains/Western Continental. Trends in these two regions and two others are significant: Coastal Gap (-0.8°C) and Boreal Mountains and Plateaus (-1.0°C).

Fall minimum temperatures have increased in 12 regions, with values ranging from -2.0 to 7.4°C. The largest increase is in the Central Canadian Rocky Mountains. Trends in this region and three others are statistically significant: Skeena/Omineca Mountains (3.3°C), Fraser Basin (2.9°C), and Northern Rockies/Hay River Lowlands (3.5°C).

2.4.4 Rate of change of climate trends

Average annual and seasonal rates of change per decade were calculated from the total change for each region in order to more easily compare regions with different length of records. Only the changes per decade in regions with significant total changes are mentioned in this section; all of the changes, however, are presented in Tables 2.7-2.11.

2.4.4.1 Total precipitation

The Gwaii Haanas, Skeena/Omineca Mountains, Fraser Basin, and Columbia Highlands/Northern Columbia Mountains/Western Continental regions have significant positive trends in annual total precipitation, with changes of 1.2%, 1.9%, 1.2%, and 1.6% per decade, respectively. Winter precipitation in the Northern Rockies/Hay River Lowlands and Yukon Southern Lakes/Liard Basin decreased by 6.2% and 3.7% per decade, respectively. Changes in spring precipitation per decade for regions with significant trends are: 2.9%, Nass Ranges; 2.3%, Fraser Plateau; 2.1%, Fraser Basin, 1.7%, Columbia Highlands/Northern Columbia Mountains/Western Continental; and 1.8%, Southern Rocky Mountain Trench. Significant summer changes per decade are: 1.4%, Gwaii Haanas, Nass Ranges, and Fraser Plateau; 2.1%, Fraser Basin; 1.7%, Columbia Highlands/Northern Columbia Mountains/Western Continental; 2.0%, Southern Rocky Mountain Trench; -4.5%, Central Canadian Rocky Mountains; 2.8%, Northern Rockies/Hay River Lowlands; and 1.7%, Boreal Mountains and Plateaus. Gwaii Haanas, Fraser Plateau, Fraser Basin, and Boreal Mountains and Plateaus have significant increasing precipitation trends in fall of 1.2%, 1.6%, 1.8%, and 1.6% per decade, respectively.

2.4.4.2 Mean temperature

Annual mean temperature increased 0.1°C per decade in Gwaii Haanas, Boundary Ranges/Yukon Stikine Highland, Coastal Gap, Nass Ranges, Fraser Basin, Southern

Rocky Mountain Trench, Yukon Southern Lakes/Liard Basin, and Boreal Mountains and Plateaus. The corresponding increase in Skeena/Omineca Mountains and Northern Rockies/Hay River Lowlands is 0.2°C per decade. Winter increases per decade in regions with significant mean temperature trends are: 0.1°C in Gwaii Haanas, Coastal Gap, and Nass Ranges; 0.2°C in Boundary Ranges/Yukon Stikine Highland, Fraser Plateau, and Yukon Southern Lakes/Liard Basin; 0.3°C in Fraser Basin, Peace River Basin, and Boreal Mountains and Plateaus; 0.4°C in Central Alberta Uplands and Northern Rockies/Hay River Lowlands; and 0.5°C in Skeena/Omineca Mountains. Spring mean temperature increased 0.1°C per decade in Gwaii Haanas, Coastal Gap, Nass Ranges, Fraser Basin, Yukon Southern Lakes/Liard Basin, and Boreal Mountains and Plateaus, and 0.2°C per decade in Northern Rockies/Hay River Lowlands. Summer mean temperature increased 0.1°C per decade in Nass Ranges, Skeena/Omineca Mountains, Fraser Basin, Southern Rocky Mountain Trench, Northern Rockies/Hay River Lowlands, and Boreal Mountains and Plateaus. Fall mean temperature increased 0.1°C per decade in Gwaii Haanas, Skeena/Omineca Mountains, and the Fraser Basin, and decreased 0.1°C per decade in Yukon Southern Lakes/Liard Basin.

2.4.4.3 Maximum temperature

Maximum temperature increased 0.1°C per decade in the Columbia Highlands/Northern Columbia Mountains/Western Continental and Boreal Mountains and Plateaus regions and decreased 0.1°C per decade in Peace River Basin. Winter maximum temperature increased 0.1°C per decade in Coastal Gap, Fraser Basin, and Boreal Mountains and Plateaus. Spring maximum temperature decreased 0.2°C per decade in Fraser Plateau and Yukon Southern Lakes/Liard Basin and 0.1°C per decade in

Coastal Gap. It increased 0.2°C in per decade Boundary Ranges/Yukon Stikine Highland. Summer maximum temperature increased 0.1°C per decade in Columbia Highlands/Northern Columbia Mountains/Western Continental and Boreal Mountains and Plateaus. Fall maximum temperature decreased 0.1°C per decade in Coastal Gap and Boreal Mountains and Plateaus, and 0.4°C per decade in Yukon Southern Lakes/Liard Basin. It increased 0.2°C per decade in Columbia Highlands/Northern Columbia Mountains/Western Continental.

2.4.4.4 Minimum temperature

Annual minimum temperatures trends are significant in several regions, with changes of 0.2°C per decade in Coastal Gap and Boreal Mountains and Plateaus; 0.3°C per decade in Fraser Plateau and Peace River Basin; 0.4°C per decade in Fraser Basin, Southern Rocky Mountain Trench, and Yukon Southern Lakes/Liard Basin; and 0.5°C per decade in Skeena/Omineca Mountains, Central Alberta Uplands, and Northern Rockies/Hay River Lowlands. Seasonal minimum temperature changes per decade for regions with significant total trends are as follows: Gwaii Haanas, 0.1°C winter; Boundary Ranges/Yukon Stikine Highland, 0.1°C summer; Coastal Gap, 0.2°C winter, 0.1°C spring and summer; Nass Ranges, 0.2°C winter, 0.3°C spring, and 0.1°C summer; Skeena/Omineca Mountains, 0.5°C winter and 0.6°C fall; Fraser Plateau, 0.3°C winter and 0.1°C summer; Fraser Basin, 0.4°C winter and spring, 0.2°C summer, and 0.3°C fall; Southern Rocky Mountain Trench, 0.1°C summer; Central Canadian Rocky Mountains, -0.3°C summer and 1.8°C fall; Peace River Basin, 0.3°C winter and 0.1°C summer; Central Alberta Uplands, 0.5°C winter; Northern Rockies/Hay River Lowlands, 0.4°C winter and 0.5°C fall; Yukon Southern Lakes/Liard Basin, 0.3°C winter; and Boreal Mountains and Plateaus, 0.3°C winter, 0.2°C spring, and 0.1°C summer.

2.5 Discussion

2.5.1 Comparison with other studies

The trends identified in this study are similar to those reported by MWLAP (BC Ministry of Water, Land, and Air Protection 2002*a*, 2002*b*), but the larger database and additional methods used in this study allow for a more detailed regional analysis. MWLAP found that annual precipitation in northern British Columbia increased 2 to 4% per decade between 1929 and 1998, whereas this study has shown that the increase is 1 to 2% per decade between 1886 and 2003. Annual mean temperature change from 1895 to 1995, according to MWLAP, ranges from 0.6 to 1.7°C; the range according to this study is 0.2 to 1.3°C for the period 1886-2003. The previous study showed no trend in annual maximum temperatures in northern British Columbia, whereas this study documented significant trends of -0.9 to 1.1°C in three regions over the period 1886-2003. Differences are also apparent in changes in annual minimum temperatures: 0.9 to 2.1°C for the period 1895-1995 (MWLAP) and 2.1 to 4.4°C for the period 1886-2003 (this study). Overall, changes in annual precipitation and mean temperature in the two studies are similar, whereas changes in annual maximum and minimum temperatures are very different. The temperature differences are explained by the fact that MWLAP used mean maximum and mean minimum temperatures, whereas this study used extreme maximum and extreme minimum temperatures.

MWLAP concluded that winter precipitation increased 2% per decade in the southwestern part of northern British Columbia. No corresponding significant trend was found in this study. Decreases in winter precipitation of 4 to 6% per decade, however, are evident in the far northeast and north-central parts of the study area. The two studies document positive spring precipitation trends of 2 to 3% per decade; however, MWLAP reported an increase of 6% per decade in the southeastern part of the study area. MWLAP did not report significant trends in summer precipitation, whereas this study found increases of 1 to 3% per decade in most regions, but a decrease of 5% per decade in the central Canadian Rocky Mountains. This study documented increases in fall precipitation of 1 to 2% per decade in central and north-central British Columbia and the Queen Charlotte Islands, whereas MWLAP reported an increase of 2% per decade on the coast only.

The two studies found similar seasonal trends in mean temperature, but the present study identified a larger number of significant trends. MWLAP found increases in winter temperature of 1.0 to 1.4°C over the period 1895-1995 on the north coast and in the north-central interior. This study found significant increases of 1.0 to 2.8°C in most regions over approximately the same period. Increases in spring mean temperature reported by MWLAP range from 0.8 to 3.8°C (1895-1995). Corresponding values in this study are 0.8 to 1.2°C. MWLAP found no significant increases in summer temperature in northern British Columbia, except in the far southeast (0.8-1.2°C, 1895-1995). In contrast, this study documented increases of 0.5 to 1.0°C throughout most of the northern British Columbia (1886-2003), but a decrease of 0.7°C in the Yukon-Southern Lakes/Liard Basin (1938-2003). No significant trends in fall mean temperature were reported by MWLAP, whereas this study found positive trends of 0.3 to 0.9°C for more coastal regions (1886-2003) and the Fraser Basin (1895-2003).

This study identified more areas with significant seasonal changes in maximum temperature, but fewer areas with significant mean and minimum temperature changes (i.e., 3-4 regions per season) than MWLAP. Winter trends in the study range from 0.7 to 1.4°C between 1886 and 2003; the lower value applies to the north coast where MWLAP reported a change of 1.9°C between 1895 and 1995. In this study, the dominant trend in spring maximum temperature is negative (-1.7 to -0.9°C, 1886-2003), with the single exception of a positive trend (1.8°C, 1910-2003) in the Boundary Ranges/Yukon Stikine Highland. In contrast, MWLAP reported a northerly spring temperature gradient in the same area of 1.3 to 3.6°C (1895-1995). This study also found significant positive trends (1886-2003) of 0.6 to 0.9°C in maximum summer temperature, a positive trend of 2.1°C in maximum fall temperature in the southeast part of the study area, and a significant negative trend of 0.8 to 2.5°C in maximum fall temperature on the north coast and north-central part of the study area. In contrast, MWLAP found no significant trends in maximum temperature in summer or fall.

Regions with significant trends in minimum winter temperature reported by MWLAP are similar to those found in this study; however, the MWLAP values (2.2 to 2.6°C, 1895-1995) differ from the values in this study (1.2 to 4.3°C, 1886-2003). MWLAP reported positive trends in spring minimum temperatures of 1.2 to 3.9°C (1895-1995), comparable to the values of 1.3 to 4.3°C of this study. Summer minimum temperatures have increased 1.1 to 1.7°C between 1895 and 1995 (MWLAP) and 0.5 to 1.8°C between 1886 and 2003 (this study), with the exception of a decrease of 1.4°C in the central Canadian Rocky Mountains (1963-2003). MWLAP did not report any significant temperature trends in fall, whereas this study found increases of 2.9 to 7.4°C in the central interior and northern Rocky Mountains (1895-2003).

Powell (1965) concluded that precipitation in northern British Columbia has increased more in winter than other seasons, whereas this study found the opposite. Powell (1965) also reported the greatest increase in mean temperature to be in winter, which this study confirms. He reported that the temperature trend at Barkerville is opposite (negative) to that of most climate stations in the study area, which is confirmed by this study. Powell (1965) noted that negative annual temperature trends are accompanied by positive trends in annual precipitation. This pattern is seen at many coastal stations in this study, but it does not hold true in other regions. The trends reported by Powell (1965) and found in this study are similar, with the exception of winter precipitation, regardless of the additional four decades of data; however, the degree of change found in the studies is different.

Zhang et al. (2000) calculated trends in annual and seasonal maximum and minimum temperatures and precipitation in Canada from 1900 to 1998. For northern British Columbia, they found that (1) annual maximum temperature trends are not significant, (2) annual minimum temperature trends are positive, and between 1.5 and 1.75°C; and (3) annual precipitation trends are positive and between 15-25%. Corresponding values determined in this study are -0.9 to 1.1°C, 2.1 to 4.4°C, and -5 to 20%. Seasonal trends reported by Zhang et al. (2000) also differ considerably from those determined in this study. The 1992 and 1995 State of the Environment reports (Gullet and Skinner 1992; Environment Canada 1995) concluded that annual average temperature in northern British Columbia increased 0.8-1.3°C between 1895 and 1995, comparable to the results of this study.

2.5.2 Climate variability

The warm phase of ENSO, or El Niño, is thought to bring warmer and wetter conditions to British Columbia (Bigg 2003). Strong and very strong El Niño years during the study period are 1891, 1899-1900, 1911-1912, 1917, 1925-1926, 1932, 1939-1941, 1957-1958, 1972-1973, 1982-1983, 1992, and 1997 (Bradley and Jones 1995; Bigg 2003). Some evidence of these events is seen here. Many of the graphs of cumulative departure from the mean of annual precipitation show an anomalous spike in 1997, corresponding to the most recent El Niño event (Appendix 4). Other possible El Niño events can be seen in these graphs, although, not consistently. Many graphs of cumulative departure from the mean of annual temperature show an anomalous dip in 1957 (Appendix 4), contrary to what is expected, because El Niño years are thought to bring warmer temperatures to northern British Columbia (Bigg 2003).

Years of anomalous precipitation corresponding to El Niño events can be seen in the baseline climate graphs (Appendix B, CD-Rom-1). 1939, 1992, and 1997 are above-normal precipitation years in most coastal regions, although not elsewhere in the study area. Years of above-normal temperature corresponding to El Niño events can also be seen in the baseline climate graphs, which again are most obvious on the coast. 1997 is the strongest warm year. Other coastal warm years corresponding to El Niño events, in order of decreasing strength, are 1939-1940, 1958, 1926, 1983, and 1900. Of these years, 1939-1941 and 1958 are above-normal warm years in the interior of northern British Columbia.

El Niño is thought to most strongly affect weather in British Columbia in winter, with increases in precipitation and temperature (Bigg 2003). This study found that winter temperatures have increased significantly but winter precipitation has decreased overall. La Niña events are thought to bring cooler and drier conditions to British Columbia (Bigg 2003). Little evidence was found in this study of the strong La Niña events of 1954, 1974, 1988, and 1998. It thus appears that ENSO is not a primary driver of climate in northern British Columbia, or at least not a direct one.

Cool phases of the PDO (1890-1924 and 1947-1976) have alternated with warm phases (1925-1946 and 1977-present) (Mantua and Hare 2002). Climate shifts in the 1920s, 1940s, and 1970s, which are thought to be associated with the PDO, are clearly seen in most graphs showing cumulative departure from mean temperature. Twenty-seven stations show PDO-related temperature shifts at 1921-1929, 1945-1948, and 1975-1979. The shift in the 1970s is the most obvious, likely due to the larger number of climate stations available to record it. The warming trend of the last three decades appears to be declining or levelling off, possibly indicating a switch to a cooling trend.

The warm and cool phases of the PDO are also apparent in the baseline mean temperature graphs. The persistent increase in temperature over the period of record, however, masks the PDO phases. For example, at Fort St. James, the phase shift in the 1970s can be seen, but it is part of a gradual, larger-scale increase in temperature since the 1950s. The PDO may not be the dominant factor driving climate change in northern British Columbia, and natural or anthropogenic warming since the 1950s may have had a greater influence on temperature. Further, the PDO may not influence the climate of all of northern British Columbia. There is no evidence of the PDO, for example, at Barkerville, where temperatures decreased from the early 1900s until the mid-1970s.

Precipitation patterns associated with the cool and warm phases of the PDO are more difficult to recognize in the climate records of northern British Columbia. Mantua and Hare (2002) speculated that the cool phase is associated with wet conditions in British Columbia and the warm phase with dry conditions. Graphs of cumulative departure from the mean for precipitation do not support this hypothesis. Only 15 stations show possible PDO-related precipitation changes, at 1912-1930, 1943-1950, and 1975-1979; the change in the 1970s is the most obvious. Stations near the coast and in northwestern British Columbia (e.g. Masset, Bella Coola, Langara, Cape St. James, Sandspit, Stewart, Dease Lake, and Germansen Landing,) are dry during the cool phase and wet during the warm phase, opposite to the trends suggested by Mantua and Hare (2002). More inland stations and those in northeastern British Columbia (e.g. Telkwa, Ootsa Lake Skins Lake Spillway, Fort St. James, Prince George, McBride, Fort St. John, and Baldonnel) are dry during the warm phase and wet during the cool phase. However, this pattern is not evident at all stations, thus the PDO may not be dominating precipitation trends in northern British Columbia.

PDO has had an effect on temperature and, to a lesser degree, precipitation trends in northern British Columbia. ENSO is also influencing temperature and precipitation in the area, but on a much smaller scale. Because these phenomena are still not fully understood, no attempt is made here to assess the degree to which PDO and ENSO are affecting the study area, if their presence is amplified or masked by natural or anthropogenic climate warming, or how they will affect the climate in northern British Columbia in the future.

2.5.3 Clouds and climate trends

Northern British Columbia has experienced increases in both temperature and precipitation over the period of record. Positive feedbacks have likely affected these changes. Increases in mean temperature often results in increased evaporation, which likely led to greater cloud cover and increased precipitation. The latter, in turn, increased minimum temperatures and decreased maximum temperatures. Day-time cloud cover decreases maximum temperatures, as less short-wave radiation reaches the earth's surface. Night-time cloud cover increases minimum temperatures by trapping long-wave radiation.

Milewska (2005) found negative day-time trends and positive night-time trends in cloudiness in British Columbia. Terrace, for example, experienced a 6.5% increase in average night-time cloud cover over the period 1953-2002. The trends reported by Milewska (2005) are consistent with increases in minimum and maximum temperatures observed in this study at most climate stations in northern British Columbia.

2.5.4 Potential and future work

Climate variability in northern British Columbia may be influenced by other ocean-atmosphere oscillations that are beyond the scope of this study, for example the Arctic Oscillation (AO) and the Madden-Julian Oscillation (MJO). Time series statistics could be used to search for evidence of ocean-atmosphere oscillations in the baseline climate data and thus draw stronger conclusions about the influence of ENSO, PDO, AO, and MJO on the climate of northern British Columbia.

An assessment of snow data would also enhance the results of this study. Trends in the ratio of rain to snow would improve the analysis of the temperature changes that have already been done. The spatial variation of snow in northern British Columbia could also be quantified using the methods presented here. Unfortunately, most of the climate stations in northern British Columbia do not accurately record snow amounts, thus additional data would have to be acquired from snow survey stations operated by the BC Ministry of Water, Land and Air Protection (2005*b*).

2.6 Conclusion

Fourteen of the 15 regions in northern British Columbia have experienced increases in mean temperature since the beginning of the instrumental period (1886-2003). The increases range from 0.2 to 1.3°C. The greatest warming has been in the Skeena/Omineca Mountains (1951-2003). The lone exception to the warming trend in northern British Columbia is the Columbia Highlands/Northern Columbia Mountains/Western Continental region (1888-2003), which shows no significant trend. Annual maximum temperatures have increased in nine regions, decreased in four regions, and remained unchanged in two regions. Only three regions, however, have significant trends in maximum temperatures, and these range from -0.9 to 1.1°C (1888-2003). The greatest increase in maximum temperature is in the Boreal Mountains and Plateaus region (1905-2003), and the greatest decrease is in the Peace River Basin (1916-2003). Annual minimum temperatures have increased in 14 regions, the only exception being the Columbia Highlands/Northern Columbia Mountains/Western Continental region, which has a negative trend that is not significant. Significant increases in minimum temperature range from 2.1 to 4.4°C (1886-2003), with the largest increase in the Fraser Basin (1895-2003). In general, changes in annual minimum temperatures are larger than changes in mean temperatures, and changes in maximum temperatures are less than changes in both minimum and mean temperatures.

Mean temperatures increased in all seasons, over the entire study period, with the largest increases in winter. Significant trends range from 1.0 to 2.8°C in winter, 0.7 to 1.2°C in spring, 0.5 to 1.0°C in summer, and -0.7 to 0.9°C in fall. Maximum temperatures increased in most regions in winter and summer, decreased in spring, and were unchanged in fall. Significant trends are between 0.7 and 1.4°C in winter, -1.7 to 1.8°C in spring, 0.6 to 0.9°C in summer, and -2.5 to 2.1°C in fall. Minimum temperatures increased in all seasons. Significant trends range from 1.2 to 4.3°C in winter, 1.3 to 4.3°C in spring, -1.4 to 1.8°C in summer, and 2.9 to 7.4°C in fall. As in the case of the annual trends, changes in seasonal minimum temperatures are larger than changes in seasonal mean temperatures, and changes in seasonal maximum temperatures are the smallest. The only overall decrease is spring maximum temperature.

Annual precipitation has increased in 12 of the 15 regions in northern British Columbia. Trend values that are significant range from 10.2 to 18.6%, with the largest increase in the Columbia Highlands/Northern Columbia Mountains/Western Continental region (1888-2003). Precipitation increased, over the entire study period, in most regions in spring, summer, and fall, and decreased overall in winter. Significant trends are -24.5 to -41.6% in winter, 15.8 to 27.0% in spring, -18.4 to 23.4% in summer, and 12.5 to 15.5% in fall.

Significant rates of change per decade in annual precipitation range from 1.2 to 1.9%, in annual mean temperature from 0.1 to 0.2°C, in annual maximum temperature from -0.1 to 0.1°C, and in annual minimum temperature from 0.2 to 0.5°C. Significant seasonal changes per decade for precipitation are from -6.2 to -3.7% in winter, 1.7 to 2.9% in spring, -4.5 to 2.8% in summer, and 1.2 to 1.8% in fall. Significant seasonal mean temperature changes per decade range from 0.1 to 0.5°C in winter, 0.1 to 0.2°C in spring, 0.1°C in summer, and -0.1 to 0.1°C in fall. Significant seasonal maximum temperature changes per decade are 0.1°C in winter, -0.2 to 0.2°C in spring, 0.1°C in summer, and -0.4 to 0.2°C in fall. Significant seasonal minimum temperature changes range from 0.1 to 0.5°C in winter, 0.1 to 0.4°C in spring, -0.3 to 0.2°C in summer, and 0.3 to 1.8°C in fall.

The shift in the Pacific Decadal Oscillation from its cool to warm phase in the mid-1970s is seen at most climate stations in northern British Columbia. Stations with the longest records also show regime shifts in the mid-1940s (warm to cool) and the mid-1920s (cool to warm). Some stations, especially those near the Pacific coast, show dry (wet) periods corresponding to the cool (warm) PDO phases, whereas inland stations show the opposite. The El-Niño Southern Oscillation has also affected the climate of northern British Columbia, although to a much smaller degree. These ocean-atmosphere phenomena are contributing to the trends in precipitation and mean temperature documented in this chapter. Trends in cloud cover reinforce observed changes in maximum and minimum temperatures.

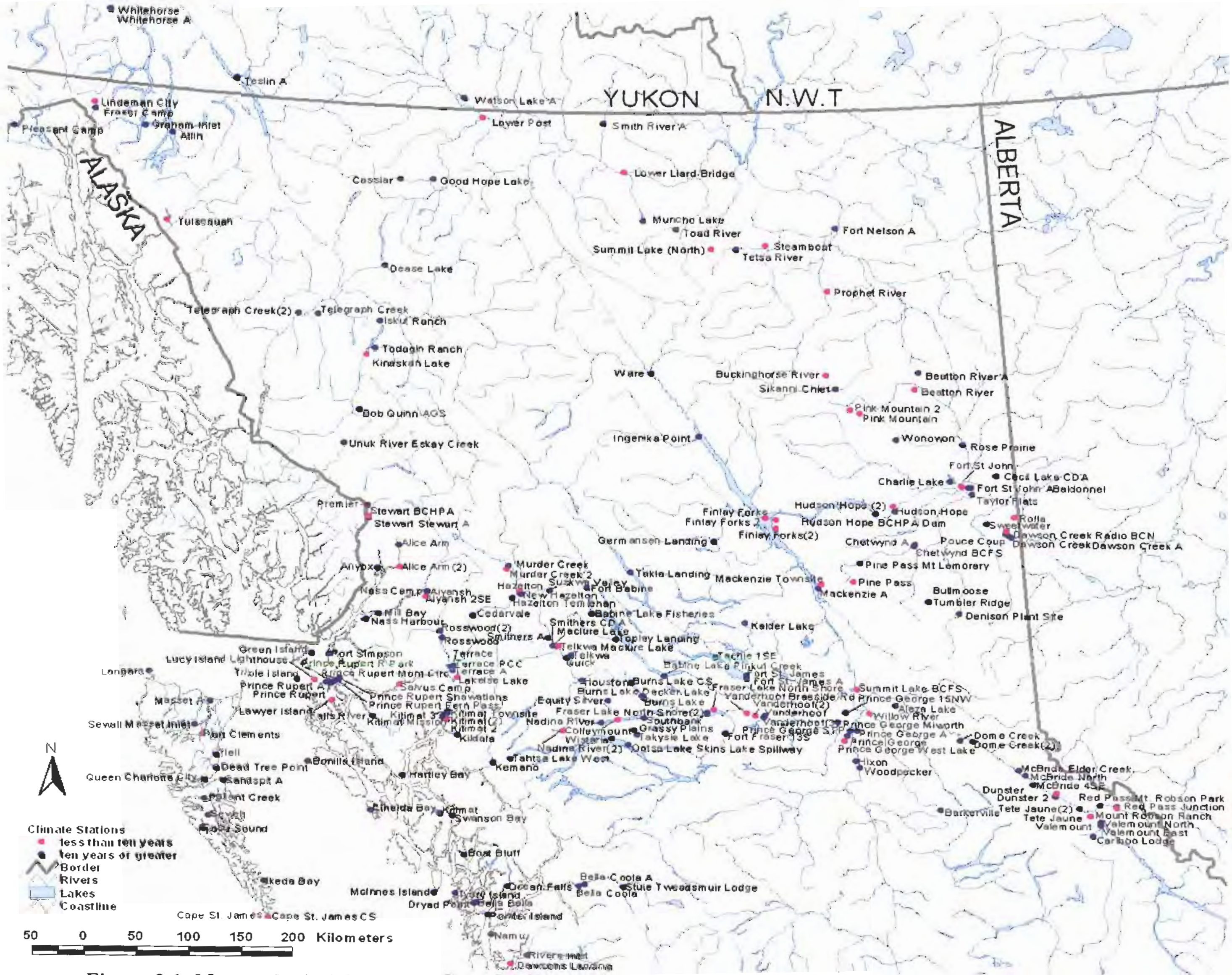

Figure 2.1. Meteorological Service of Canada climate stations in northern British Columbia. (Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

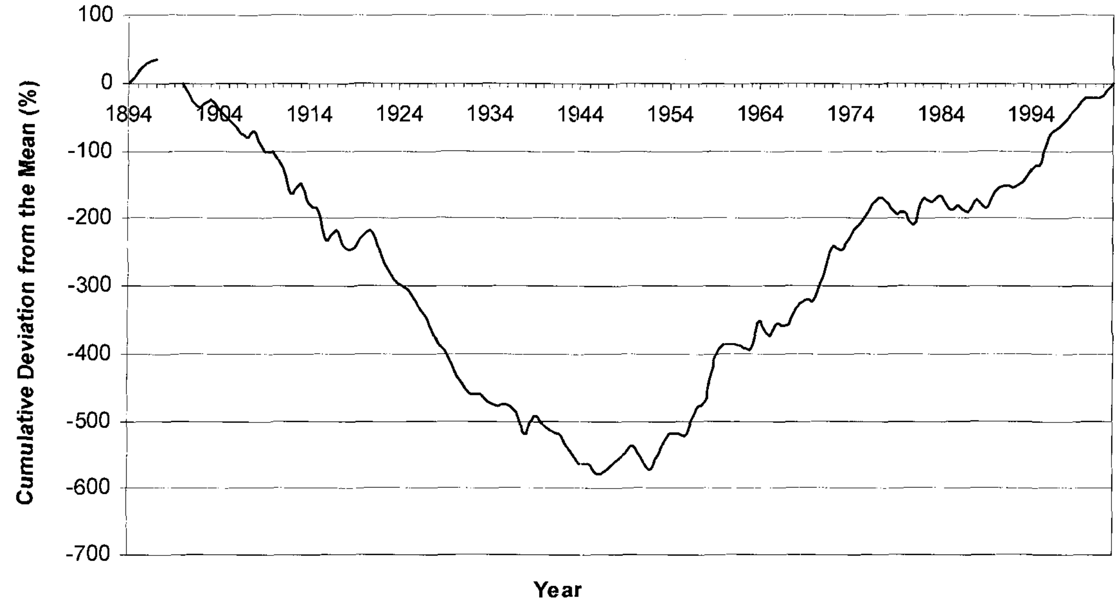

Figure 2.2. Example of a graph of cumulative departure from mean yearly precipitation, Fort St. James.

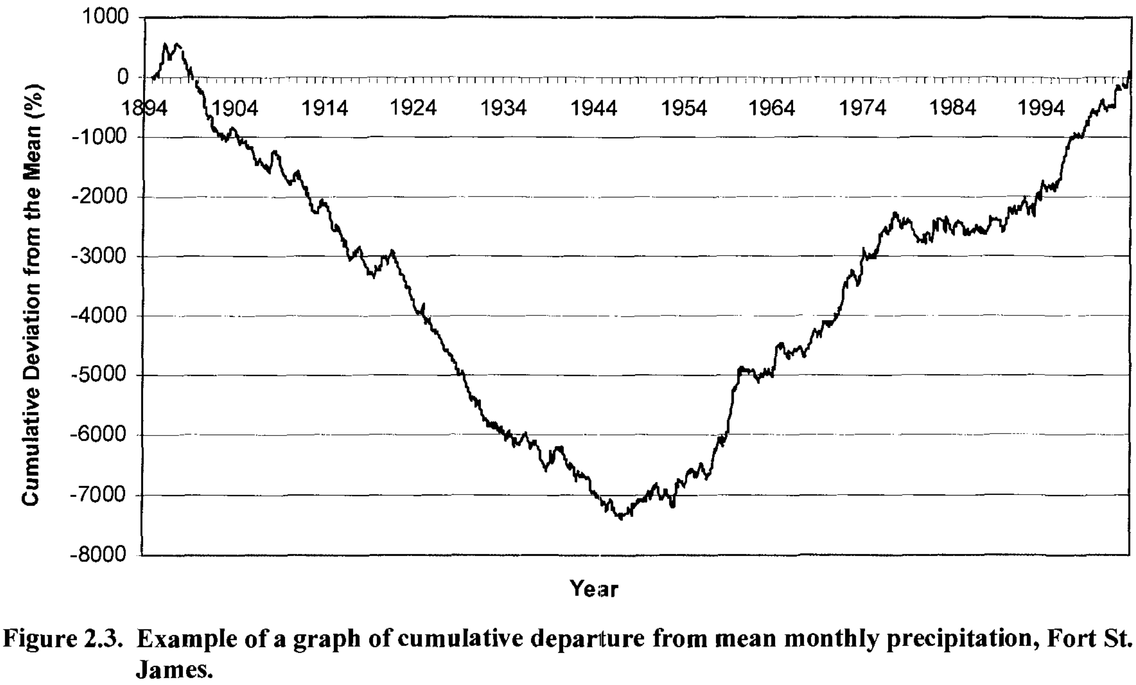

Figure 2.3. Example of a graph of cumulative departure from mean monthly precipitation, Fort St. James.

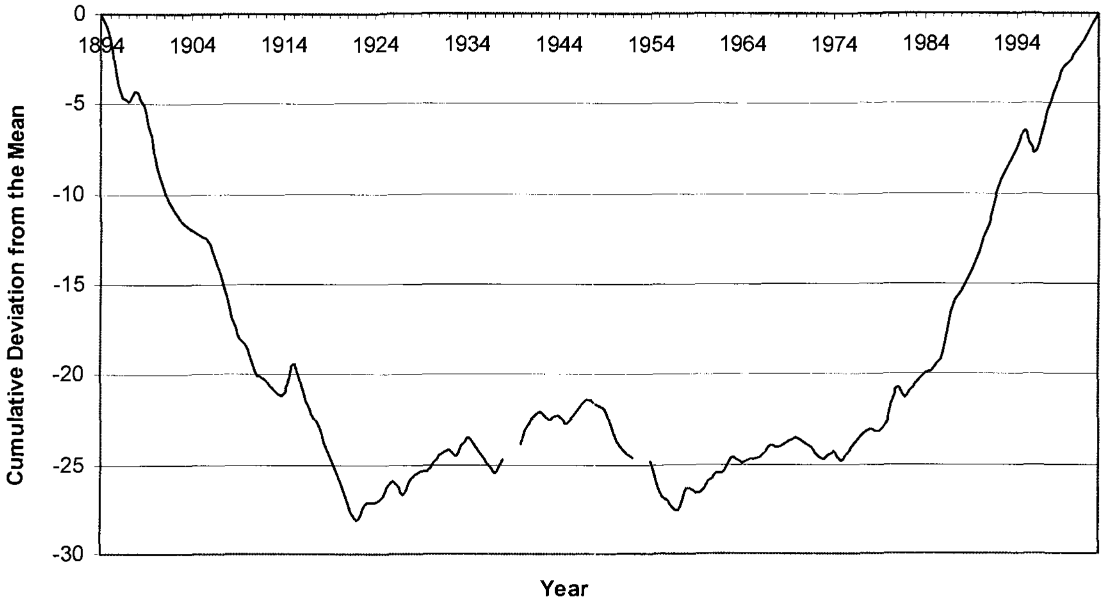

Figure 2.4. Example of a graph of cumulative departure from mean yearly temperature, Fort St. James.

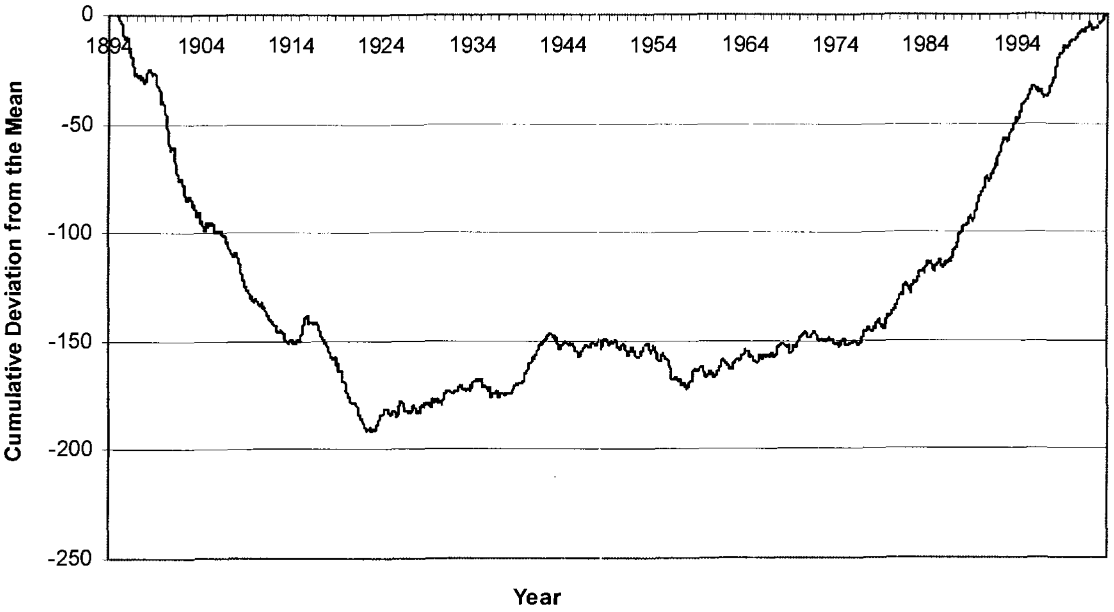

Figure 2.5. Example of a graph of cumulative departure from mean monthly temperature, Fort St. James.

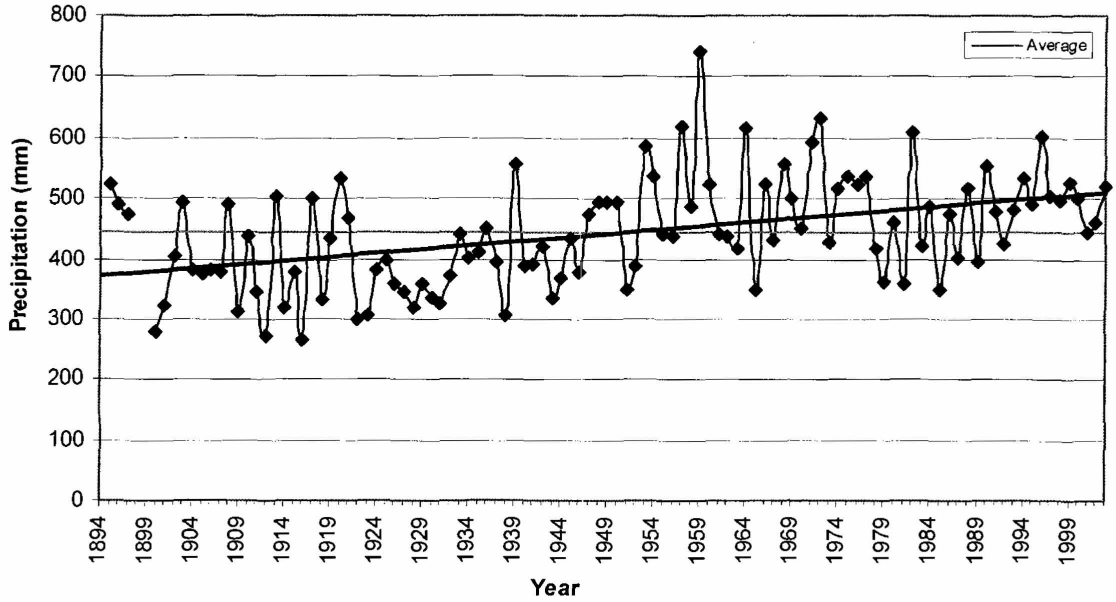

Figure 2.6. Example of a graph of baseline yearly total precipitation, Fort St. James.

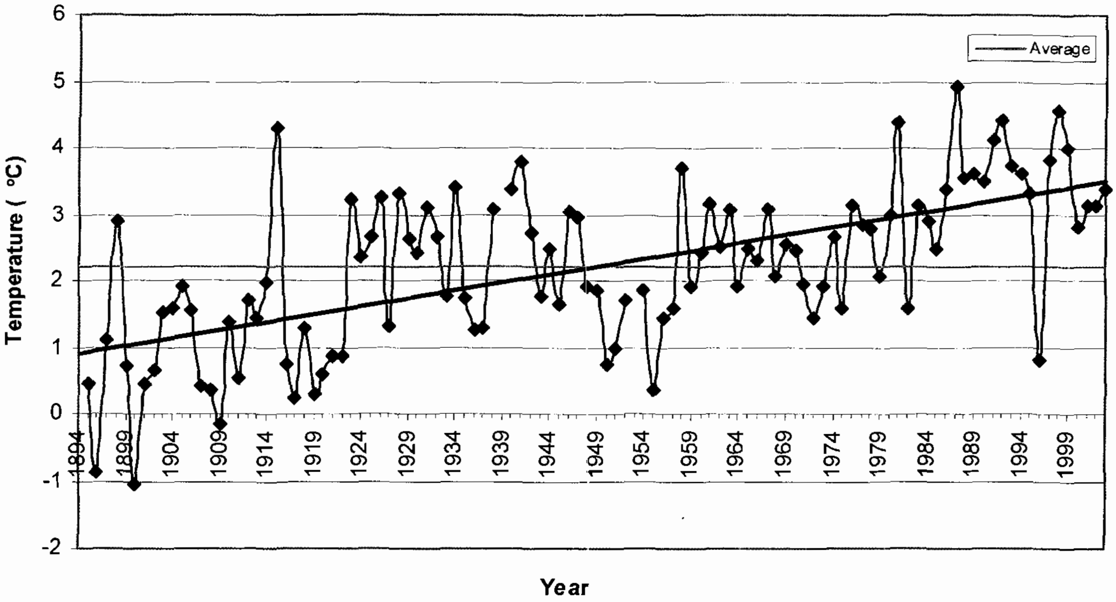

Figure 2.7. Example of a graph of baseline yearly mean temperature, Fort St. James.

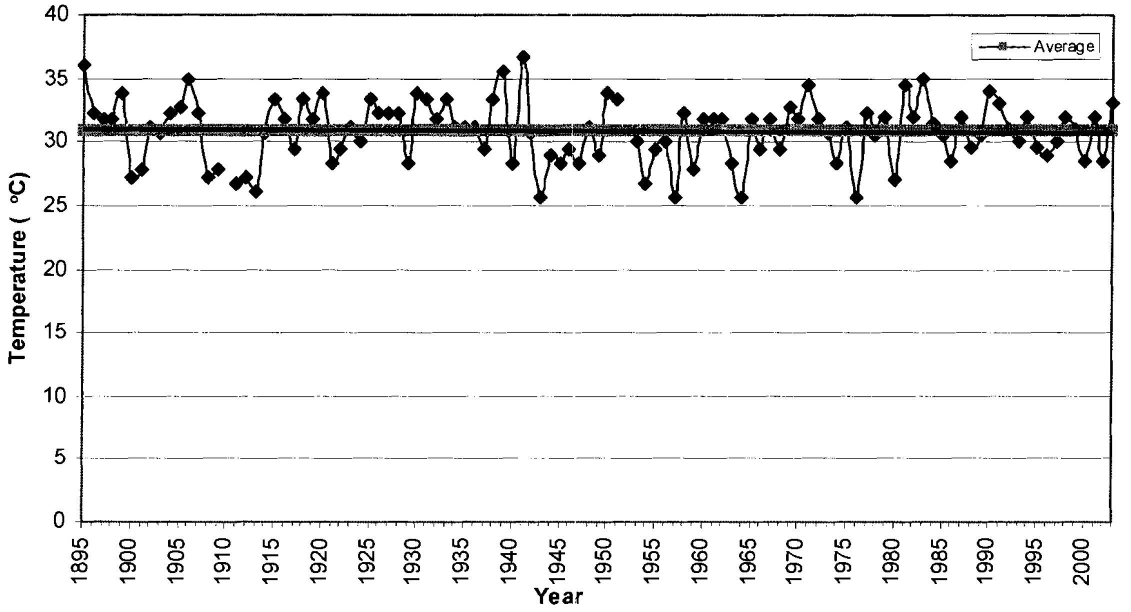

Figure 2.8. Example of a graph of baseline yearly extreme maximum temperature, Fort St. James.

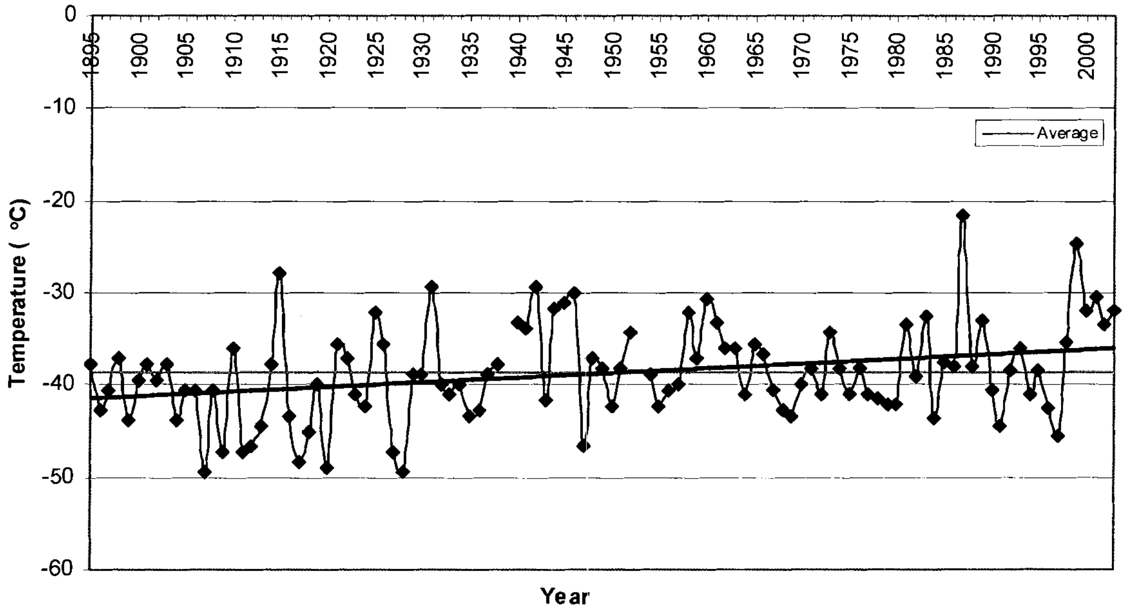

Figure 2.9. Example of a graph of baseline yearly extreme minimum temperature, Fort St. James.

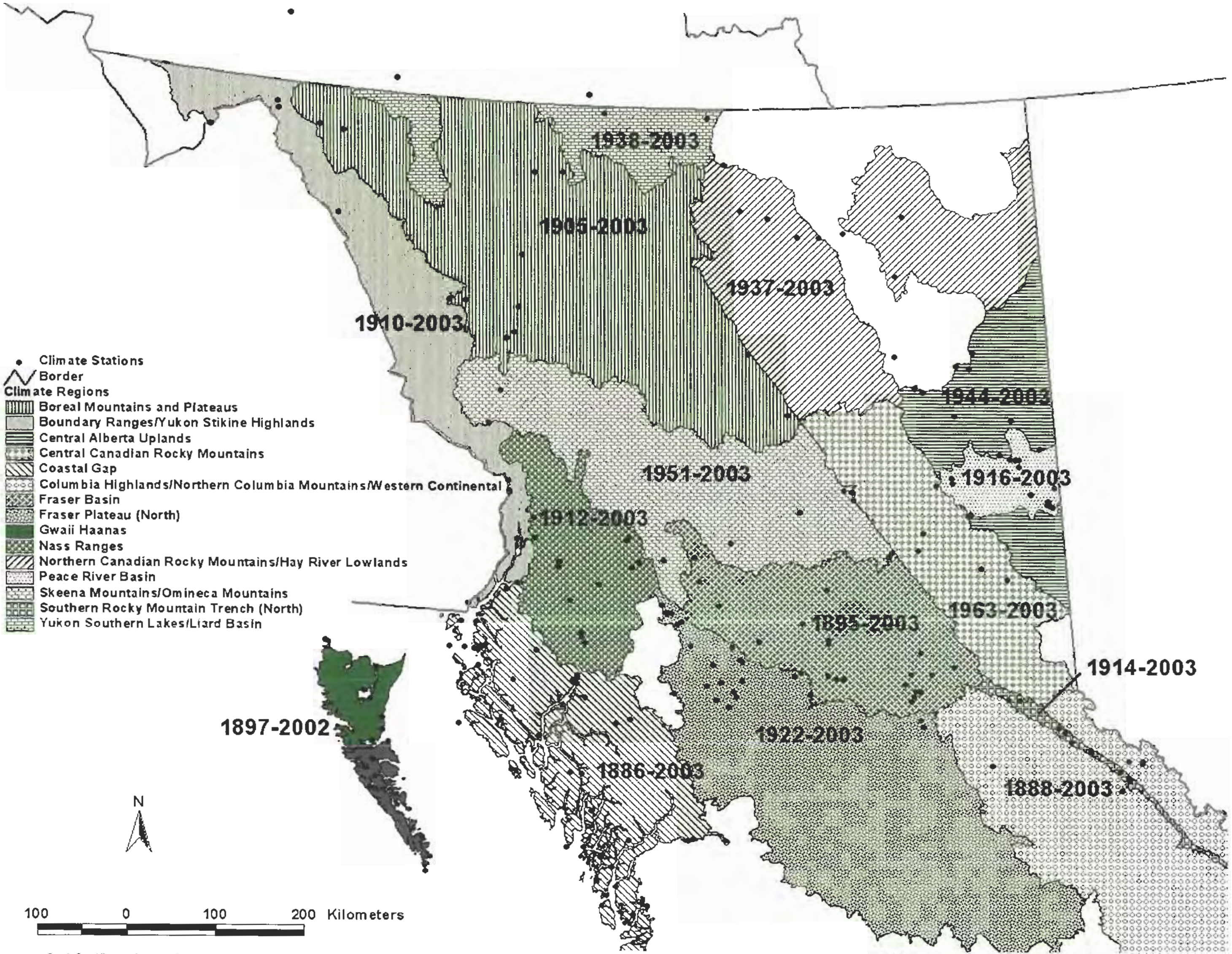

Figure 2.10. Regional groupings of climate stations and years of record. (Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

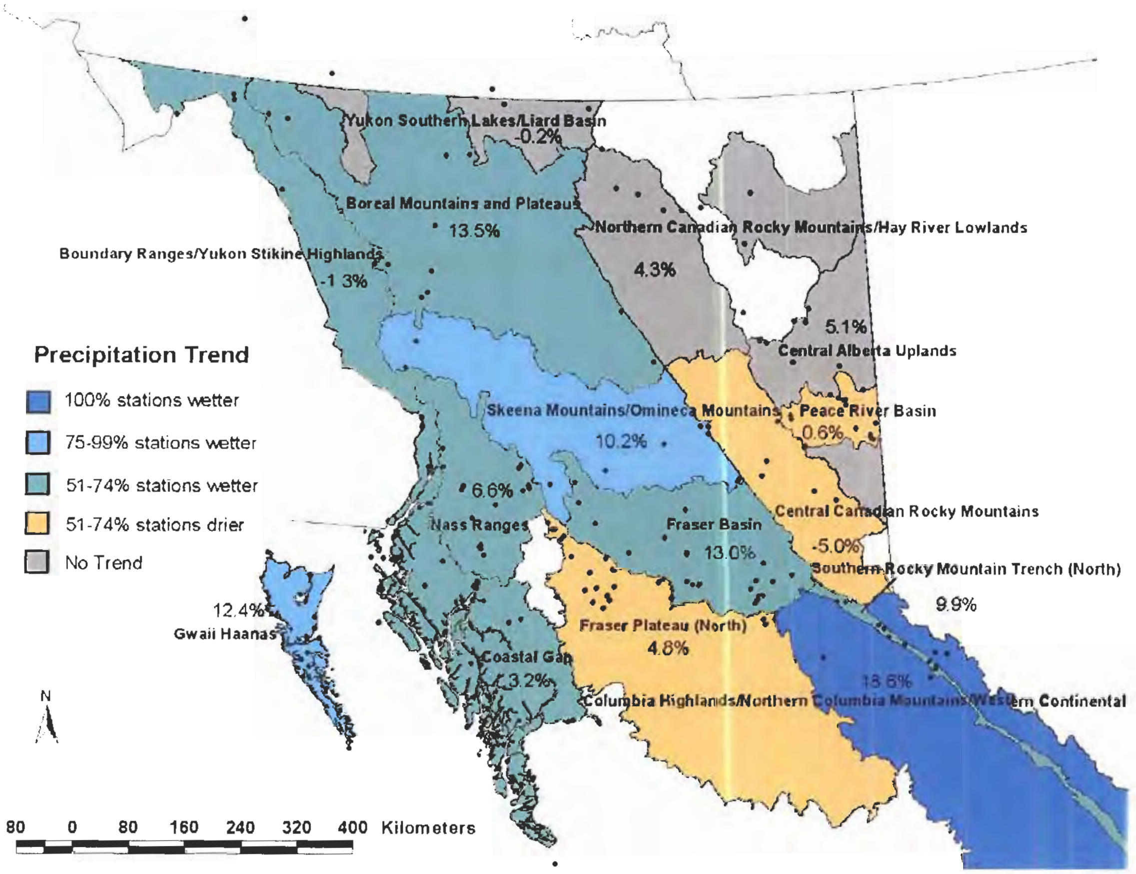

Figure 2.11. Annual total precipitation trends in northern British Columbia.
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

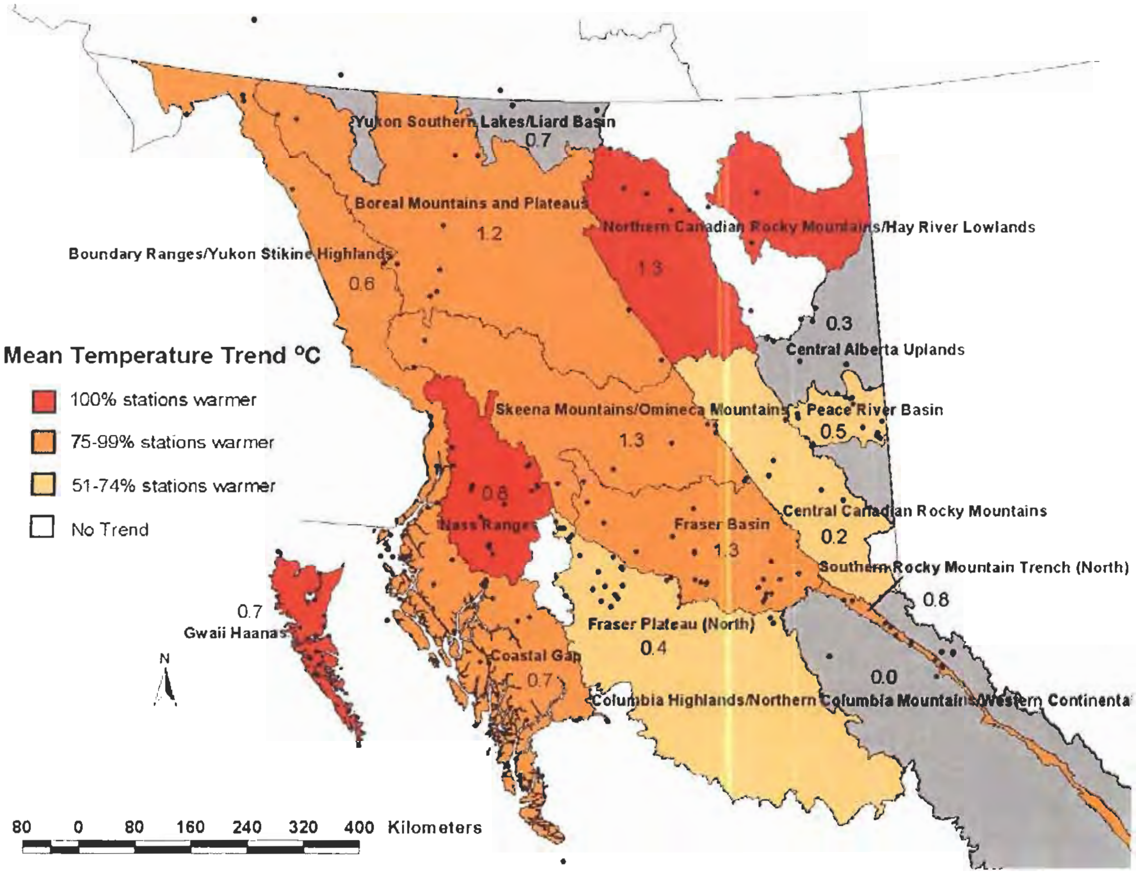

Figure 2.12. Annual mean temperature trends in northern British Columbia.
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

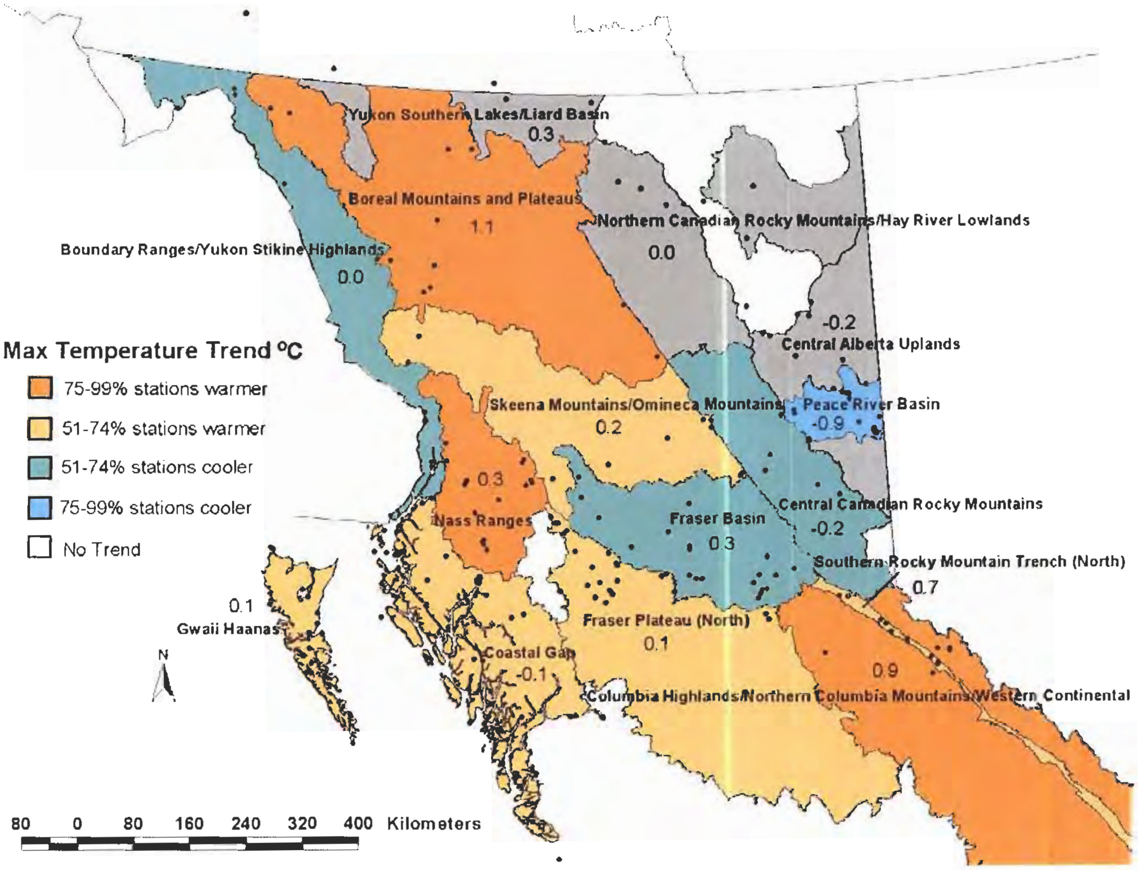

Figure 2.13. Annual maximum temperature trends in northern British Columbia.
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

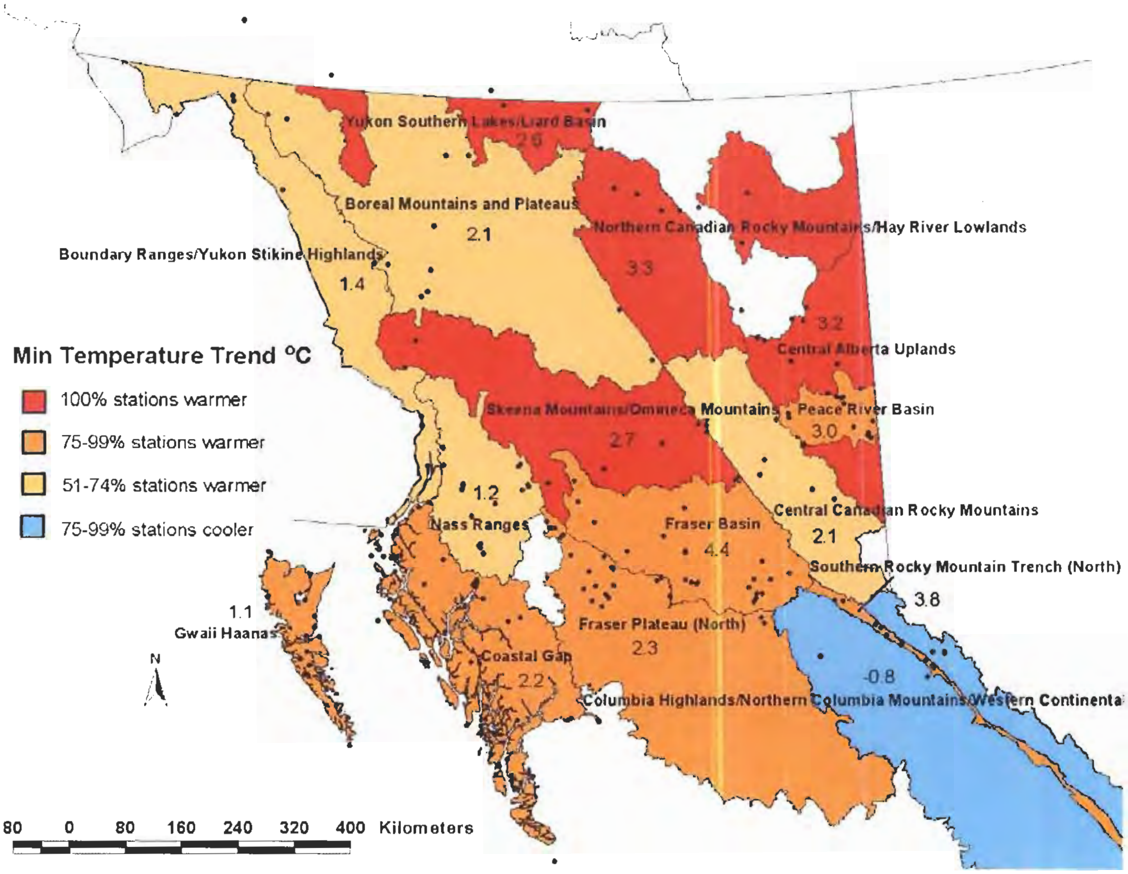

Figure 2.14. Annual minimum temperature trends in northern British Columbia.
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

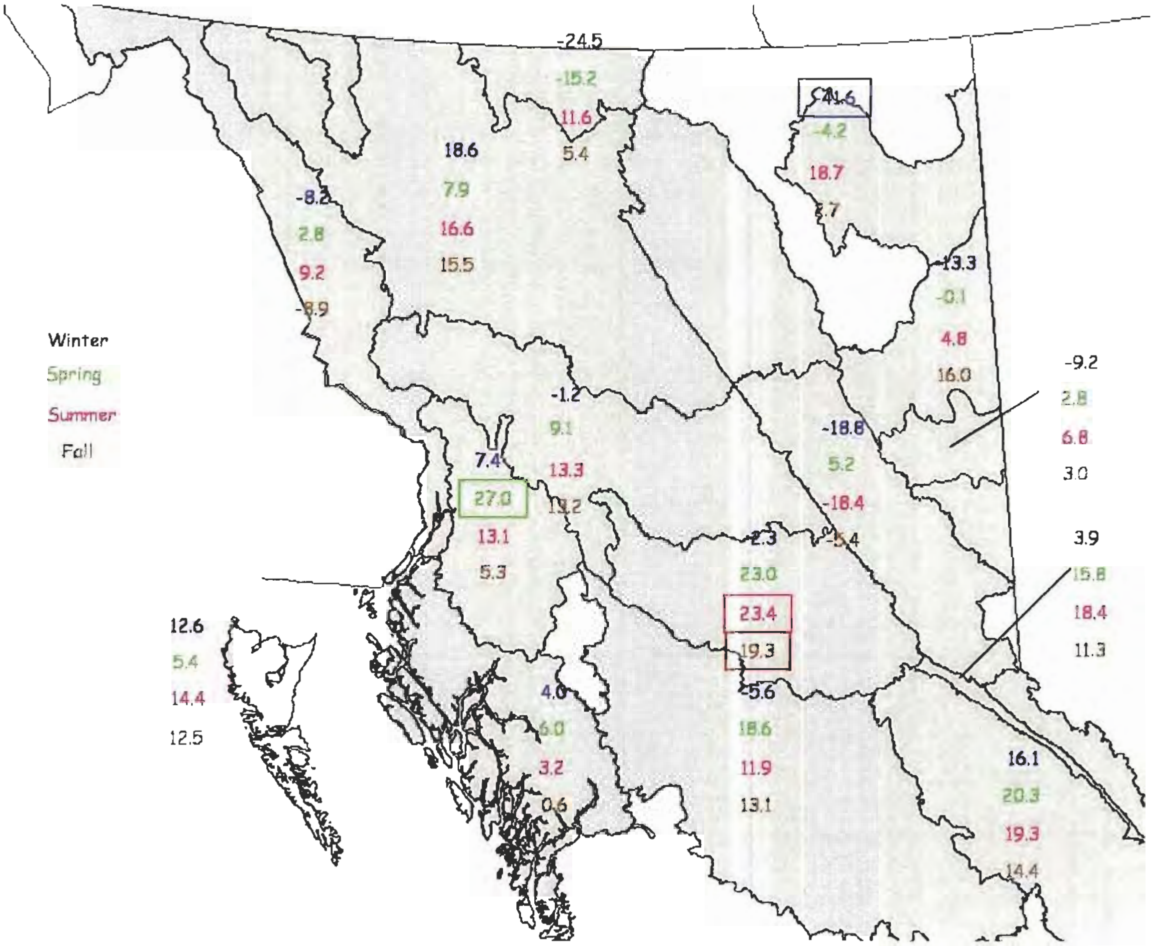

Figure 2.15. Percent change in seasonal precipitation in northern British Columbia.
(Boxes highlight greatest change).
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

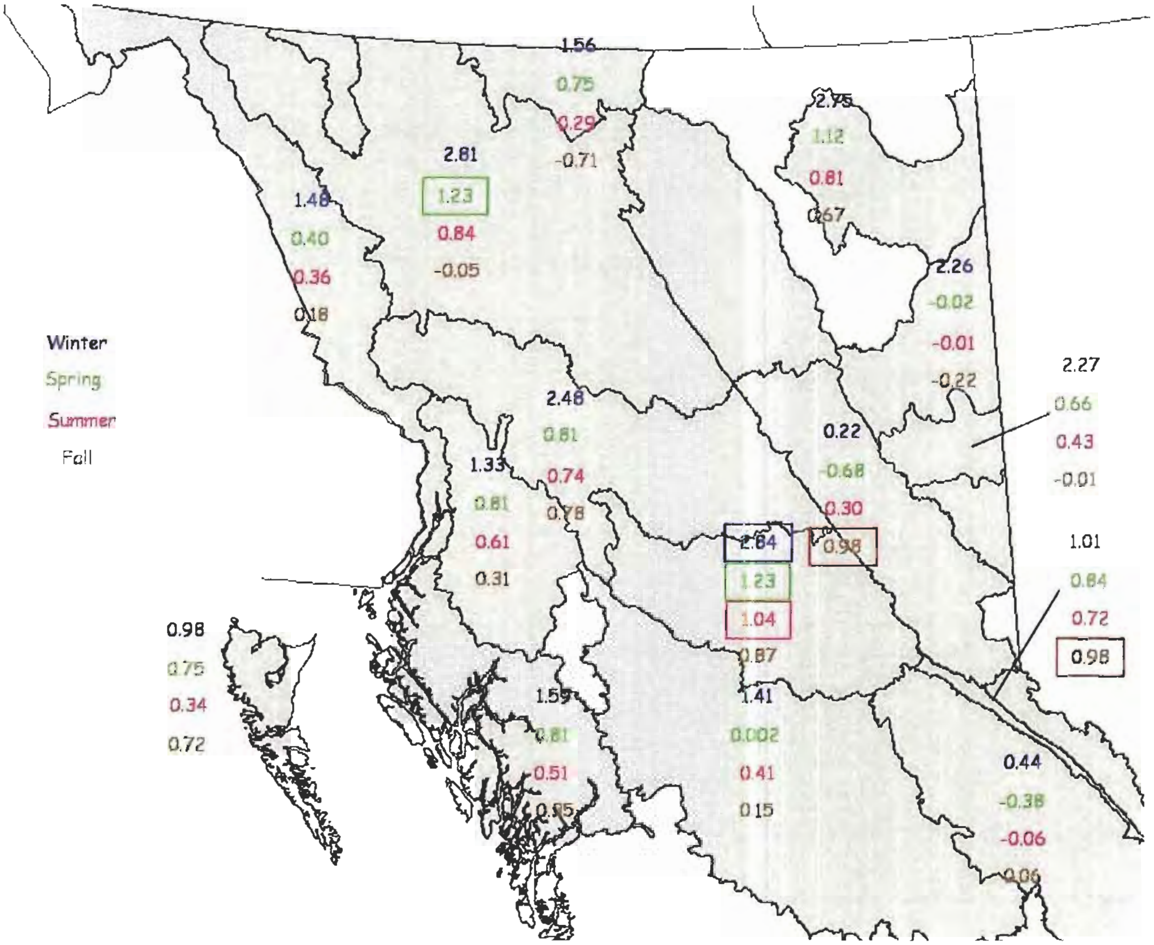

Figure 2.16. Degree Celsius change in seasonal mean temperature in northern British Columbia.
(Boxes highlight greatest change).
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

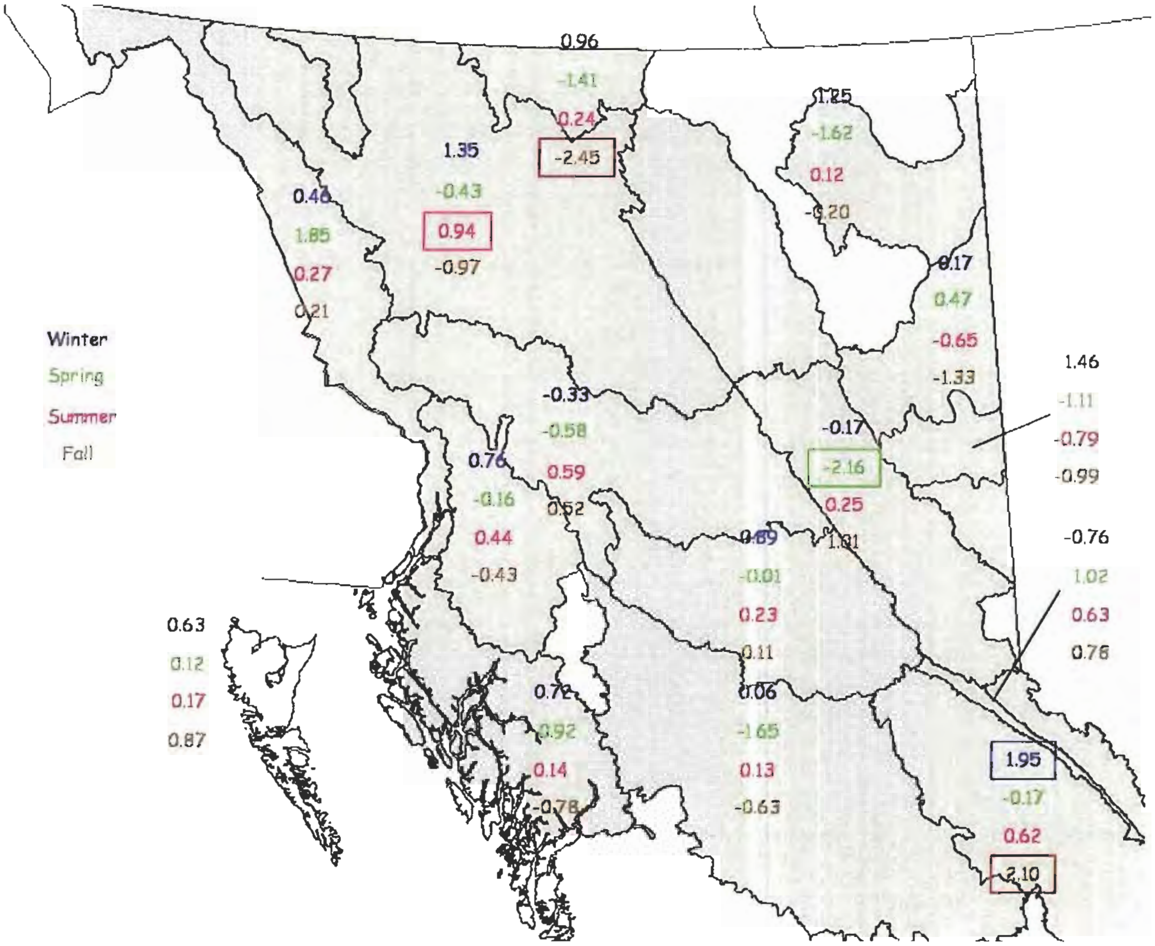

Figure 2.17. Degree Celsius change in seasonal maximum temperature in northern British Columbia. (Boxes highlight greatest change).
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

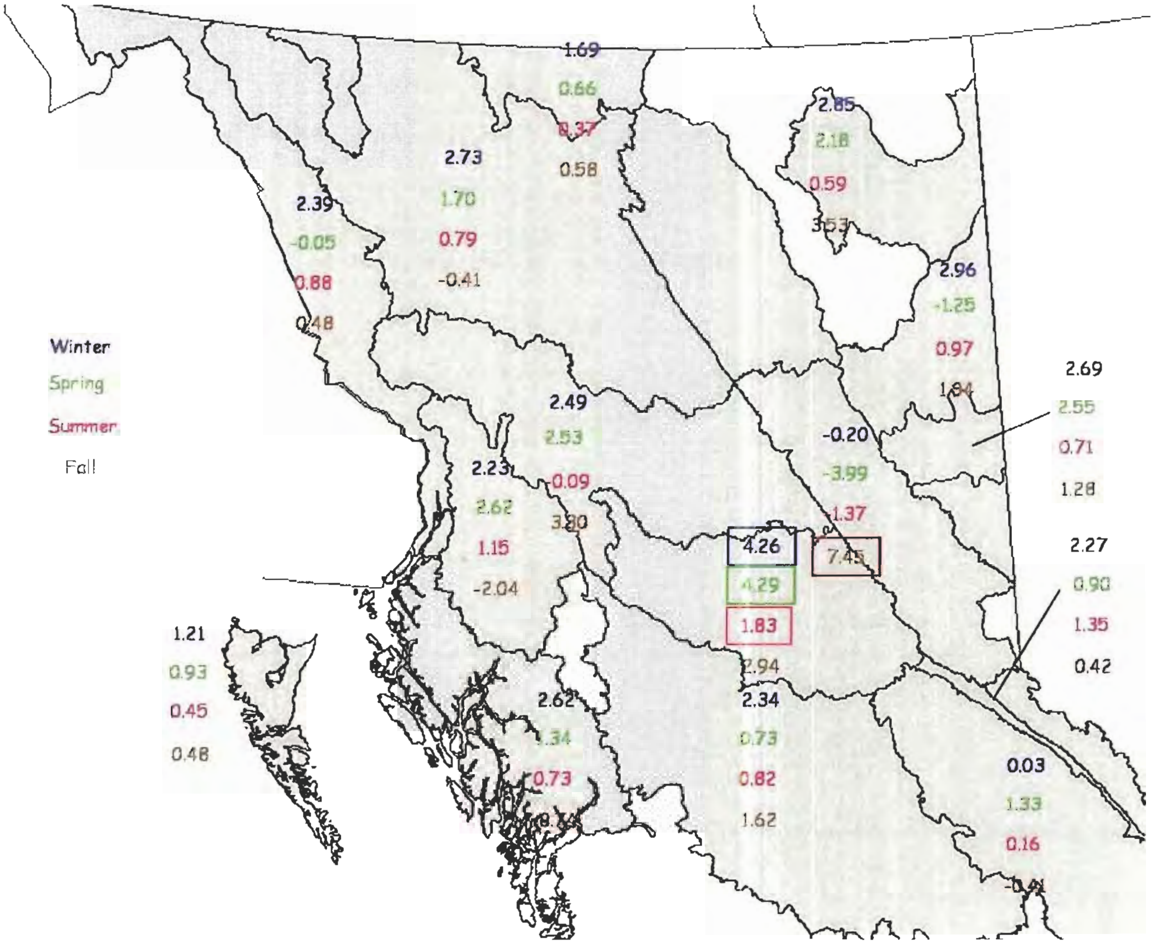

Figure 2.18. Degree Celsius change in seasonal minimum temperature in northern British Columbia. (Boxes highlight greatest change).
(Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

Table 2.1. Regional weighted average annual climate data.

Region	Total Precipitation (mm)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	1803.3	8.0	23.9	-8.7
Boundary Ranges/Yukon Stikine Highlands	1753.1	4.4	29.2	-22.8
Coastal Gap	2589.0	7.4	28.8	-15.0
Nass Ranges	931.8	5.6	32.4	-26.5
Skeena/Omineca Mountains	714.7	1.9	30.0	-35.7
Fraser Plateau	485.5	3.0	30.6	-33.4
Fraser Basin	537.3	3.0	31.0	-37.5
Columbia Highlands-Mtns/Western Continental	928.9	2.1	29.0	-33.0
Southern Rocky Mountain Trench	599.1	4.1	33.2	-37.1
Central Canadian Rocky Mountains	633.9	2.9	30.6	-36.0
Peace River Basin	454.8	1.7	30.8	-40.2
Central Alberta Uplands	496.6	0.2	29.0	-39.8
Northern Rockies/Hay River Lowlands	483.9	-0.6	30.5	-41.3
Yukon Southern Lakes/Liard Basin	354.5	-1.8	29.0	-46.0
Boreal Mountains and Plateaus	404.3	-0.1	28.4	-40.0

Table 2.2. Regional weighted average change in annual climate data.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	**12.4**	**0.7**	0.1	1.1
Boundary Ranges/Yukon Stikine Highlands	-1.3	**0.6**	0.0	1.4
Coastal Gap	3.2	**0.7**	-0.1	**2.2**
Nass Ranges	6.6	**0.8**	0.3	1.2
Skeena/Omineca Mountains	**10.2**	**1.3**	0.2	**2.7**
Fraser Plateau	4.8	0.4	0.1	**2.3**
Fraser Basin	**13.0**	**1.3**	0.3	**4.4**
Columbia Highlands-Mtns/Western Continental	**18.6**	0.0	**0.9**	-0.8
Southern Rocky Mountain Trench	9.9	**0.8**	0.7	**3.8**
Central Canadian Rocky Mountains	-5.0	0.2	-0.2	2.1
Peace River Basin	0.6	0.5	**-0.9**	**3.0**
Central Alberta Uplands	5.1	0.3	-0.2	**3.2**
Northern Rockies/Hay River Lowlands	4.3	**1.3**	0.0	**3.3**
Yukon Southern Lakes/Liard Basin	-0.2	**0.7**	0.3	**2.6**
Boreal Mountains and Plateaus	13.5	**1.2**	**1.1**	**2.1**

Table 2.3. Winter weighted average change in climate.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	12.6	**1.0**	0.6	**1.2**
Boundary Ranges/Yukon Stikine Highlands	-8.2	**1.5**	0.5	2.4
Coastal Gap	4.0	**1.6**	**0.7**	**2.6**
Nass Ranges	7.4	**1.3**	0.8	**2.2**
Skeena/Omineca Mountains	-1.2	**2.5**	-0.3	**2.5**
Fraser Plateau	-5.6	**1.4**	0.1	**2.3**
Fraser Basin	-2.3	**2.8**	**0.9**	**4.3**
Columbia Highlands-Mtns/Western Continental	16.1	0.4	1.9	0.0
Southern Rocky Mountain Trench	3.9	1.0	-0.8	2.3
Central Canadian Rocky Mountains	-18.8	0.2	-0.2	-0.2
Peace River Basin	-9.2	**2.3**	1.5	**2.7**
Central Alberta Uplands	-13.3	**2.3**	0.2	**3.0**
Northern Rockies/Hay River Lowlands	**-41.6**	**2.8**	1.2	**2.8**
Yukon Southern Lakes/Liard Basin	**-24.5**	**1.6**	1.0	**1.7**
Boreal Mountains and Plateaus	18.6	**2.8**	**1.4**	**2.7**

Table 2.4. Spring weighted average change in climate.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	5.4	**0.8**	0.1	0.9
Boundary Ranges/Yukon Stikine Highlands	2.8	0.4	**1.8**	-0.1
Coastal Gap	6.0	**0.8**	**-0.9**	**1.3**
Nass Ranges	**27.0**	**0.8**	-0.2	**2.6**
Skeena/Omineca Mountains	9.1	0.8	-0.6	2.5
Fraser Plateau	**18.6**	0.0	**-1.7**	0.7
Fraser Basin	**23.0**	**1.2**	0.0	**4.3**
Columbia Highlands-Mtns/Western Continental	**20.3**	-0.4	-0.2	1.3
Southern Rocky Mountain Trench	**15.8**	0.8	1.0	0.9
Central Canadian Rocky Mountains	5.2	-0.7	-2.2	-4.0
Peace River Basin	2.8	0.7	-1.1	2.6
Central Alberta Uplands	-0.1	0.0	0.5	-1.3
Northern Rockies/Hay River Lowlands	-4.2	**1.1**	-1.6	2.2
Yukon Southern Lakes/Liard Basin	-15.2	**0.7**	**-1.4**	0.7
Boreal Mountains and Plateaus	7.9	**1.2**	-0.4	**1.7**

Table 2.5. Summer weighted average change in climate.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	**14.4**	0.3	0.2	**0.5**
Boundary Ranges/Yukon Stikine Highlands	9.2	0.4	0.3	**0.9**
Coastal Gap	3.2	**0.5**	0.1	**0.7**
Nass Ranges	**13.1**	**0.6**	0.4	**1.1**
Skeena/Omineca Mountains	13.3	**0.7**	0.6	-0.1
Fraser Plateau	**11.9**	0.4	0.1	**0.8**
Fraser Basin	**23.4**	**1.0**	0.2	**1.8**
Columbia Highlands-Mtns/Western Continental	**19.3**	-0.1	**0.6**	0.2
Southern Rocky Mountain Trench	**18.4**	**0.7**	0.6	**1.3**
Central Canadian Rocky Mountains	**-18.4**	0.3	0.2	**-1.4**
Peace River Basin	6.8	0.4	-0.8	**0.7**
Central Alberta Uplands	4.8	0.0	-0.7	1.0
Northern Rockies/Hay River Lowlands	**18.7**	**0.8**	0.1	0.6
Yukon Southern Lakes/Liard Basin	11.6	0.3	0.2	0.4
Boreal Mountains and Plateaus	**16.6**	**0.8**	**0.9**	**0.8**

Table 2.6. Fall weighted average change in climate.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	**12.5**	**0.7**	0.9	0.5
Boundary Ranges/Yukon Stikine Highlands	-8.9	0.2	0.2	0.5
Coastal Gap	0.6	**0.3**	**-0.8**	0.7
Nass Ranges	5.3	**0.3**	-0.4	-2.0
Skeena/Omineca Mountains	13.2	**0.8**	0.5	**3.3**
Fraser Plateau	**13.1**	0.1	-0.6	1.6
Fraser Basin	**19.3**	**0.9**	0.1	**2.9**
Columbia Highlands-Mtns/Western Continental	14.4	0.1	**2.1**	-0.4
Southern Rocky Mountain Trench	11.3	0.1	0.8	0.4
Central Canadian Rocky Mountains	-5.4	1.0	1.0	**7.4**
Peace River Basin	3.0	0.0	-1.0	1.3
Central Alberta Uplands	16.0	-0.2	-1.3	1.0
Northern Rockies/Hay River Lowlands	2.7	0.7	-0.2	**3.5**
Yukon Southern Lakes/Liard Basin	5.4	**-0.7**	**-2.5**	0.6
Boreal Mountains and Plateaus	**15.5**	-0.1	**-1.0**	-0.4

Table 2.7. Rate of change per decade of annual climate data.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	**1.2**	**0.1**	0.0	0.1
Boundary Ranges/Yukon Stikine Highlands	-0.1	**0.1**	0.0	0.1
Coastal Gap	0.3	**0.1**	0.0	**0.2**
Nass Ranges	0.7	**0.1**	0.0	0.1
Skeena/Omineca Mountains	**1.9**	**0.2**	0.0	**0.5**
Fraser Plateau	0.6	0.1	0.0	**0.3**
Fraser Basin	**1.2**	**0.1**	0.0	**0.4**
Columbia Highlands-Mtns/Western Continental	**1.6**	0.0	**0.1**	-0.1
Southern Rocky Mountain Trench	1.1	**0.1**	0.1	**0.4**
Central Canadian Rocky Mountains	-1.2	0.0	0.0	0.5
Peace River Basin	0.1	0.1	**-0.1**	**0.3**
Central Alberta Uplands	0.9	0.1	0.0	**0.5**
Northern Rockies/Hay River Lowlands	0.6	**0.2**	0.0	**0.5**
Yukon Southern Lakes/Liard Basin	0.0	**0.1**	0.0	**0.4**
Boreal Mountains and Plateaus	1.4	**0.1**	**0.1**	**0.2**

Table 2.8. Rate of change per decade in winter.
(Bold values statistically significant at 95%).

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	1.2	**0.1**	0.1	**0.1**
Boundary Ranges/Yukon Stikine Highlands	-0.9	**0.2**	0.0	0.3
Coastal Gap	0.3	**0.1**	**0.1**	**0.2**
Nass Ranges	0.8	**0.1**	0.1	**0.2**
Skeena/Omineca Mountains	-0.2	**0.5**	-0.1	**0.5**
Fraser Plateau	-0.7	**0.2**	0.0	**0.3**
Fraser Basin	-0.2	**0.3**	**0.1**	**0.4**
Columbia Highlands-Mtns/Western Continental	1.4	0.0	0.2	0.0
Southern Rocky Mountain Trench	0.4	0.1	-0.1	0.3
Central Canadian Rocky Mountains	-4.6	0.1	0.0	0.0
Peace River Basin	-1.0	**0.3**	0.2	**0.3**
Central Alberta Uplands	-2.2	**0.4**	0.0	**0.5**
Northern Rockies/Hay River Lowlands	**-6.2**	**0.4**	0.2	**0.4**
Yukon Southern Lakes/Liard Basin	**-3.7**	**0.2**	0.1	**0.3**
Boreal Mountains and Plateaus	1.9	**0.3**	**0.1**	**0.3**

Table 2.9. Rate of change per decade in spring.
(Bold values statistically significant at 95%).

Region	**Total Precipitation (%)**	**Mean Temperature (°C)**	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**
Gwaii Haanas	0.5	**0.1**	0.0	0.1
Boundary Ranges/Yukon Stikine Highlands	0.3	0.0	**0.2**	0.0
Coastal Gap	0.5	**0.1**	**-0.1**	**0.1**
Nass Ranges	**2.9**	**0.1**	0.0	**0.3**
Skeena/Omineca Mountains	1.7	0.2	-0.1	0.5
Fraser Plateau	**2.3**	0.0	**-0.2**	0.1
Fraser Basin	**2.1**	**0.1**	0.0	**0.4**
Columbia Highlands-Mtns/Western Continental	**1.7**	0.0	0.0	0.1
Southern Rocky Mountain Trench	**1.8**	0.1	0.1	0.1
Central Canadian Rocky Mountains	1.3	-0.2	-0.5	-1.0
Peace River Basin	0.3	0.1	-0.1	0.3
Central Alberta Uplands	0.0	0.0	0.1	-0.2
Northern Rockies/Hay River Lowlands	-0.6	**0.2**	-0.2	0.3
Yukon Southern Lakes/Liard Basin	-2.3	**0.1**	**-0.2**	0.1
Boreal Mountains and Plateaus	0.8	**0.1**	0.0	**0.2**

Table 2.10. Rate of change per decade in summer.
(Bold values statistically significant at 95%).

Region	**Total Precipitation (%)**	**Mean Temperature (°C)**	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**
Gwaii Haanas	**1.4**	0.0	0.0	**0.0**
Boundary Ranges/Yukon Stikine Highlands	1.0	0.0	0.0	**0.1**
Coastal Gap	0.3	**0.0**	0.0	**0.1**
Nass Ranges	**1.4**	**0.1**	0.0	**0.1**
Skeena/Omineca Mountains	2.5	**0.1**	0.1	0.0
Fraser Plateau	**1.4**	0.1	0.0	**0.1**
Fraser Basin	**2.1**	**0.1**	0.0	**0.2**
Columbia Highlands-Mtns/Western Continental	**1.7**	0.0	**0.1**	0.0
Southern Rocky Mountain Trench	**2.0**	**0.1**	0.1	**0.1**
Central Canadian Rocky Mountains	**-4.5**	0.1	0.1	**-0.3**
Peace River Basin	0.8	0.0	-0.1	**0.1**
Central Alberta Uplands	0.8	0.0	-0.1	0.2
Northern Rockies/Hay River Lowlands	**2.8**	**0.1**	0.0	0.1
Yukon Southern Lakes/Liard Basin	1.8	0.0	0.0	0.1
Boreal Mountains and Plateaus	**1.7**	**0.1**	**0.1**	**0.1**

Table 2.11. Rate of change per decade in fall.
(Bold values statistically significant at 95%).

Region	**Total Precipitation (%)**	**Mean Temperature (oC)**	**Maximum Temperature (oC)**	**Minimum Temperature (oC)**
Gwaii Haanas	**1.2**	**0.1**	0.1	0.0
Boundary Ranges/Yukon Stikine Highlands	-0.9	0.0	0.0	0.1
Coastal Gap	0.1	**0.0**	**-0.1**	0.1
Nass Ranges	0.6	**0.0**	0.0	-0.2
Skeena/Omineca Mountains	2.5	**0.1**	0.1	**0.6**
Fraser Plateau	**1.6**	0.0	-0.1	0.2
Fraser Basin	**1.8**	**0.1**	0.0	**0.3**
Columbia Highlands-Mtns/Western Continental	1.2	0.0	**0.2**	0.0
Southern Rocky Mountain Trench	1.3	0.0	0.1	0.0
Central Canadian Rocky Mountains	-1.3	0.2	0.2	**1.8**
Peace River Basin	0.3	0.0	-0.1	0.1
Central Alberta Uplands	2.7	0.0	-0.2	0.2
Northern Rockies/Hay River Lowlands	0.4	0.1	0.0	**0.5**
Yukon Southern Lakes/Liard Basin	0.8	**-0.1**	**-0.4**	0.1
Boreal Mountains and Plateaus	**1.6**	0.0	**-0.1**	0.0

CHAPTER 3 CLIMATE TRENDS ASSOCIATED WITH RECENT LARGE LANDSLIDES IN NORTHERN BRITISH COLUMBIA

3.1 Abstract

Historical climate data are used to assess a connection between climate trends and the more than 30 large landslides that have occurred in the last three decades in northern British Columbia. Much of this region experienced increases in precipitation and temperature in the twentieth century. Many of the landslides in rock are associated with long periods of above-average temperature, whereas those in sediment have occurred during long periods of above-average precipitation. Winter temperatures in this region have increased dramatically, and many of the landslides, regardless of source, occurred after warm winters. Long-term climate trends and short-term climate variability in the region may be preconditioning slopes to fail. However, they may be triggered by other factors, such as rainstorms, rain-on-snow events, and rapid temperature change.

3.2 Introduction

Researchers have postulated a connection between changing climate and an increase in the frequency of landslides in mountain areas (González Díez et al. 1996; Evans and Clague 1997; Schwab et al. 2003). Northern British Columbia has experienced significant climate change in the last century (Chapter 2) and is an area of moderate- to high-relief. These factors, along with the local presence of thick unconsolidated glacial and postglacial sediments, make the region prone to landslides of a variety of types.

In this context, a distinction must be made between landslide triggers and landslide causes. Triggers are events that initiate failure or reactivate an old landslide. They are commonly related to weather and include precipitation, rain-on-snow events, rapid temperature change, and extreme weather (Terlien 1998; Clague 2003). Causes are the factors that predispose slopes to fail and can be climatic, geologic, topographic, or anthropogenic in origin, or more commonly, some combination thereof (Terlien 1998; Clague 2003). An example illustrates the difference between trigger and cause: intense rainstorms commonly "trigger" debris flows (Septer and Schwab 1995), whereas twentieth-century melting of alpine glaciers has debuttressed rock slopes, "causing" some to fail (Evans and Clague 1994).

Climate triggers of landslides depend on the type of landslide (Terlien 1998). Most debris flows are the result of heavy rainfall or snowmelt that mobilizes surface sediments. Many rock falls and topples result from repeated freezing and thawing of water in joints, which produce stresses that exceed the tensile strength of the rock. Slides are common in high-relief, wet areas and often occur during periods of heavy rain, resulting in increased pore-water pressures. Slumps require deep infiltration of water from precipitation. Soil creep can result from seasonal variations in temperature and moisture.

Precipitation is generally the most important cause or trigger of slope failure (van Asch et al. 1999). Rapid runoff may erode slopes and initiate debris flows and debris avalanches, and its potential to do so is dependent on the amount, intensity, and duration of rainfall (Hogan and Schwab 1991; Flageollet et al. 1999). Antecedent soil moisture affects runoff and erosion, because it determines the additional amount of water that the soil can hold (Flageollet et al. 1999). The type of precipitation is also important; heavy wet snow can increase pore-water pressures, and rain-on-snow events can saturate the soil, triggering failure (Jakob and Weatherly 2003). Heavy precipitation or rapid snowmelt can increase streamflow, thus eroding the toes of slopes and decreasing stability (Hogan and Schwab 1991; Guthrie 2002).

Temperature affects slope stability in several ways (Selby 1970; Trenhaille 1998). Higher temperatures can increase evaporation, evapotranspiration, and condensation, which can lead to an increase in cloud cover and may result in an increase in precipitation. Temperature also affects runoff, thus contributing to changes in soil moisture between precipitation events. It also determines whether precipitation falls as rain or snow. The water-absorbing properties of a soil can be altered by temperature changes, especially when the soil is frozen, and ice in soil can raise the soil surface, making it more susceptible to erosion. Snow and glacier melt in alpine areas can debuttress rock slopes and contribute to their failure (Evans and Clague 1997). Landslides at high elevations may be triggered by milder winter or cooler summer temperatures, which increase freeze-thaw activity (Schwab et al. 2003).

Changes in mean climate in northern British Columbia may be increasing the frequency of landslides in the region (Evans and Clague 1997; Geertsema et al. 2006*a*). Temperatures throughout northern British Columbia have increased since the start of climate data collection, with winter and minimum temperatures increasing the most (Chapter 2). Precipitation has also increased, except east of the northern Rocky Mountains. Increases in precipitation have affected areas that are already prone to debris flows, suggesting that debris flows may be increasing in frequency.

Geertsema et al. (2006*a*) have documented 38 large, sudden landslides that have occurred since 1973 in northern British Columbia. All of the landslides have volumes larger than 0.5 Mm^3, run-outs longer than 1 km, or both. Some landslides were catastrophic events that damaged infrastructure and natural habitat. They concluded that these landslides have become more frequent in the past three decades. Here, 34 of the 38 landslides are examined for a climate connection, using annual, seasonal, and monthly trend analysis of precipitation and temperature from the instrumental record.

3.3 Methods

Large landslides were chosen for study for two reasons: (1) their frequency appears to be increasing in northern British Columbia, suggesting a link to climate; and (2) they destroy or damage valuable forest, infrastructure, and fish habitat. The studied landslides (Figure 3.1; Table 3.1) occurred between 1973 and 2003; most of them have been described by Geertsema et al. (2006*a*). Climate data provided by the Meteorological Service of Canada (© Environment Canada, 2005, by permission) were analyzed for the entire period of the instrumental record, 1886-2003 (Chapter 2).

Each landslide was first examined in the context of trends in mean climate conditions in the region in which it is located (Figure 3.1; see also Chapter 2). Climate trends at the nearest climate station to each landslide were then examined. This analysis included examination of (1) graphs of annual and monthly cumulative deviation from the mean of total precipitation and mean temperature, (2) annual, seasonal, and monthly graphs of total precipitation, mean temperature, maximum temperature, and minimum temperature, (3) graphs of daily total precipitation and mean temperature for the five years before the landslide, and (4) composite graphs of daily total precipitation, mean daily temperature, and station-average daily temperature for one year and five months leading up to the slide (where the date of the landslide was specific enough to do so). Due to time constraints and limited data availability, trends in snow were considered only on an anecdotal basis (BC Ministry of Water, Land and Air Protection 2005*b*). Meteorological Service of Canada climate normals and extremes were examined to determine if landslides occurred during extreme events (Environment Canada 2004).

3.4 Results

The 34 landslides were divided into three groups: landslides involving rock (long run-out rockslides); landslides involving sediment (flowslides); and landslides involving both rock and sediment (Geertsema et al. 2006*a*). Landslides within each group were further subdivided on the basis of failure style. Significant climate trends or weather events associated with the landslides are described in the following sections. The climate analysis associated with the landslides is in Appendix C (CD-Rom-1). Antecedent trends and annual, seasonal, monthly, and daily precipitation and temperature conditions associated with each of the landslides are summarized in Tables 3.2 and 3.3.

3.4.1 Landslides involving rock

3.4.1.1 Landslides on rock slopes above glaciers

Seven landslides occurred on rock slopes above glaciers: Howson I and II, North Creek, Frosbisher Glacier I and II, Kshwan Glacier, and Kendall Glacier. Most of the landslides probably initiated as topples or falls and transformed into rock avalanches as they travelled over glaciers (Geertsema et al. 2006*a*).

The Howson I rock slide occurred in 1978. The nearest climate station is Terrace, approximately 50 km west of the landslide. Analysis of the Terrace climate data showed below-normal precipitation and above-normal temperature for 1978. Precipitation had been below normal since 1969 (Figure 3.2). 1978 was the culmination of a long period of below-normal temperature that began in 1963 (Figure 3.3). Fall precipitation in 1978 was above average, and there was an extreme rainfall event (114.8 mm) on October 31, which is the highest daily total rainfall recorded at Terrace. An additional 82 mm of rain fell the following day.

The Howson II rock slide-avalanche occurred at 03:00 PST on September 11, 1999. The time is known precisely because a natural gas pipeline was ruptured, temporarily terminating service to Kitimat, Terrace, and Prince Rupert (Schwab et al. 2003). Data from the Terrace climate station, 50 km west of the landslide, show that 1999 was a year of above-average precipitation and temperature. Annual mean temperature had been increasing since the mid-1970s (Figure 3.3). September had below-average precipitation, but the preceding month had over three times the normal amount. The snowpack in the winter of 1999 was above average with an extreme daily February snowfall on February 11 (113.4 cm). The winter months were warmer than usual, but temperatures were near normal for rest of the year. The ten-day precipitation total prior to the landslide is 37.6 mm. The two weeks prior to the slide were a period of below-average temperatures. The daily data show temperatures slightly above average on the day of the landslide, with no precipitation. Weather satellite images for the week prior to this event were examined for a weather trigger, but none was found (Chapter 4).

The North Creek rock slide occurred in 1986. Analysis of climate data from Cassiar, 50 km northeast of the landslide, shows that 1986 was a year of above-average precipitation and temperature. Annual temperatures had been above normal since 1975. Spring and fall precipitation in 1986 were also above normal, but winter and summer values were below average. March and October precipitation was more than twice normal. Monthly temperatures were above average in the winter of 1986 and near normal the rest of the year. The winter of 1985-1986 was 5-10°C above normal. About 46 mm of precipitation fell on October 5, 1986, which is the highest daily value for the period 1982-1986 (Figure 3.4).

The Frobisher Glacier rock avalanche occurred in 1990. The nearest climate station is Pleasant Camp, approximately 80 km southeast of the landslide. Pleasant Camp reported below-average precipitation and temperature in 1990, but the longer-term trends before and after 1990 were positive (Figure 3.5). The winter of 1989-1990 was cold, but the rest of the year was warmer than usual. Heavy snowfall in late November, followed by above-freezing temperatures in December, indicate the possibility of snowmelt. A second rock avalanche occurred in 1991, a year of above-average precipitation and temperature. August had twice the normal precipitation for the month, February was 4°C warmer than usual, and the remainder of the year had near-average conditions. The highest daily snowfall of the preceding five years (62.8 mm) was recorded on January 31, 1991. Subsequent above-average and above-freezing temperatures in February may have melted some of the snow. The Canadian climate normals at Pleasant Camp include three extreme events in 1991: extreme daily maximum temperature for June (June 20, 29.5°C);

extreme daily snow depth for October (October 1, 15 cm); and extreme daily snow depth for November (November 30, 213 cm).

The Kshwan Glacier rock slide occurred between September 1992 and May 1993. The nearest climate station is Stewart, 25 km northwest of the rock slide. 1992 and 1993 were years of above-average precipitation and temperature, part of positive precipitation and temperature trends that began about 1985 (Figures 3.6 and 3.7). September 1992 had twice the average precipitation for the month, and January and February 1993 also had above-average precipitation. The winter of 1992-1993 was cold, but a warm period with above-freezing temperatures and heavy rainfall occurred in late January and early February. The Canadian climate normals show two extreme events in September 1992: extreme daily September minimum temperature (September 14, -1.2°C); and extreme daily September precipitation (September 28, 85.2 mm).

The Kendall Glacier rock avalanche occurred between July 12 and August 9, 1999, approximately 30 km west of McBride. The climate station at McBride reported above-average precipitation and temperature in 1999. Precipitation and temperature in the winter prior to the landslide were also above normal. About 37 mm of rain was recorded on July 7, the second highest amount in the previous five years. Weather satellite images reveal afternoon convective thunderstorms over the landslide area from August 1 to 7, which is consistent with local reports that the landslide was triggered by a summer cloudburst (Chapter 4).

3.4.1.2 Landslides on sedimentary dip slopes

The Tetsa and Chisca rock avalanches occurred on sedimentary dip slopes of 27° to 36°, respectively, in the foothills of the northern Rocky Mountains (Geertsema et al.

2006*a*). The Testa landslide occurred in May 1988, 5 km northwest of the Testa River climate station. The climate station recorded above-average precipitation and temperature for 1988. Monthly data show above-average precipitation in spring and early summer. January was cold, but February and March were warmer than usual. Above-freezing temperatures were recorded in February and early March. About 37 mm of precipitation, the largest daily amount in 1988, fell on May 28. Canadian climate normals for Fort Nelson, approximately 100 km east of the landslide, show three extreme events in 1988 that may have a bearing on the landslide: extreme daily April snow fall (April 30, 32.2 cm); extreme daily April precipitation (April 30, 25.8 mm); and extreme daily May snow depth (May 1, 32.0 cm).

The Chisca rock avalanche, located approximately 85 km southwest of Fort Nelson, occurred in 1996 (Marten Geertsema, personal communications, 2005). 1996 had above-average precipitation and an average temperature about 1.5°C below normal. Precipitation in winter, summer, and fall was above average, whereas spring precipitation was below average. Temperatures in February were above-average, but monthly mean temperatures for the rest of the year were below or near normal. Temperatures during the winter of 1995-1996 fluctuated from well below zero to well above zero over periods of several days, indicating frequent freeze-thaw cycles (Figure 3.8).

3.4.1.3 Landslides on slopes below slowly deforming mountain tops

The Turnoff Creek and Mosque Mountain rock avalanches are associated with mountaintop spreading in sedimentary rocks (Geertsema et al. 2006*a*). The Turnoff Creek landslide occurred during the fall of 1992, approximately 40 km southwest of the Sikanni Chief climate station. The Sikanni Chief record indicates that 1992 had below-average precipitation and above-average temperature. April and October precipitation was above normal in 1992, but the rest of the months were below. Seasonal temperatures show the winter of 1991-1992 was over 3°C above average, spring over 1.5°C above average, summer was average, and the fall was over 1°C below average and below freezing, which has only occurred a few times in the record. Daily temperatures had been oscillating above and below zero since mid-August until mid-December, indicating prolonged freeze-thaw conditions and prolonged months of precipitation alternating between rain and snow (Figure 3.9).

The Mosque Mountain rock avalanche occurred in the mid-1990s. The nearest climate station is Suskwa Valley, 125 km south of the landslide. 1993 was a year of below-average precipitation and above-average temperature; 1994 had normal precipitation and temperature; 1995 had below-average precipitation and temperature; 1996 had above-average precipitation and a mean temperature about 3°C below normal; and 1997 had above-average precipitation and temperature. Winter temperatures fluctuated above and below freezing throughout the mid-1990s, indicating intense freeze-thaw activity (Figure 3.10). The extreme daily July rainfall in the Canadian climate normals for Suskwa Valley is 56.4 mm, recorded on July 29, 1993. Many other extreme events occurred in the mid-1990s, but the climate record extends back only to 1982.

3.4.1.4 Other landslides in rock

The Verney landslide occurred sometime between July 20, 2001, and July 23, 2002, most likely in June 2002 (Geertsema et al. 2006*a*, *b*). The nearest climate station is Kitimat, approximately 60 km north of the landslide. 2001 was a year of above-average precipitation and below-average temperature, whereas conditions were the opposite in

2002. Monthly precipitation was above-average from August to December 2001 and in May and June 2002. A warm winter was followed by a cold March. The snowpack was likely above average. The nearest snow pillow station at Tahtsa Lake, approximately 90 km northeast of the landslide, recorded 1765 mm of snow water equivalent on May 15, 2002 (mean = 1211 mm). The largest daily total precipitation during the period when the landslide occurred was 61 mm on September 22 and November 9, 2001.

3.4.2 Landslides involving sediments

3.4.2.1 Landslides in glaciomarine sediments

The Mink Creek and Khyex River flowslides occurred in sensitive glaciomarine sediments on British Columbia's north coast (Geertsema et al. 2006*a*). The Mink Creek landslide, located 5 km southwest of Terrace, occurred between December 1993 and January 1994. The Terrace climate station had above-average precipitation and temperature in 1993, part of trends that had persisted since 1986 (Figures 3.2 and 3.3). The winter of 1993-1994 was warm and wet; temperatures were above freezing, and rain was persistent, from December 10 to January 14.

The Khyex River landslide occurred at 00:30 PST on November 28, 2003, approximately 35 km east of Prince Rupert. The precise time of the landslide is known because this landslide severed a natural gas pipeline, which left Prince Rupert and Port Edward without service for 10 days (Schwab et al. 2004*b*). 2003 was a year of below-average precipitation and above-average temperature. Abundant precipitation and cold temperatures in November indicate the possibility of rain-on-snow or wet snow at the site of the landslide. Temperatures were below freezing (-4°C) on November 27, the day before the landslide, and above freezing (4°C) on November 28. About 41 mm of precipitation were recorded at Prince Rupert on November 27, and the ten-day total leading up to the event is 137 mm. Several debris flows and debris avalanches also occurred in the Lachmach watershed, which is adjacent to the Khyex watershed (Schwab et al. 2004*a*). About 214 mm of precipitation fell in the Lachmach watershed between November 23 and 26; 30-60 cm of this precipitation was snow on November 26 (Schwab et al. 2004*a*). Forty millimetres of rain also fell there on November 27 (Schwab et al. 2004*a*). Weather satellite images show that a large cyclonic storm moved slowly through the area for several days around the time of the failure (Chapter 4). The landslide may have been triggered by this precipitation or by bank erosion due to high flow of the Khyex River.

3.4.2.2 Landslides in glaciolacustrine sediments

The Attachie, Inklin, Sharktooth, Halfway, and Flatrock landslides occurred in glaciolacustrine sediments. The Attachie flowslide occurred on May 26, 1973, approximately 45 km west of Fort St. John. It dammed the Peace River for several hours (Geertsema et al. 2006*a*). The Fort St. John climate station recorded above-average precipitation and below-average temperatures for 1973, part of trends that started about 1950 (Figures 3.11 and 3.12). Monthly precipitation and temperature leading up to the landslide were above average. Daily average temperatures were generally above average from mid-March to May. About 16 mm of rain fell on the day of the slide.

The Inklin landslide, located about 60 km southeast of Atlin, occurred in the spring of 1979 (Geertsema et al. 1998). 1979 was a year of above-average precipitation and below-average temperature at Atlin. Temperatures during the three years prior to the slide, however, were warmer than usual. March, May, and June precipitation was above average, but April and the winter of 1978-1979 had below-average precipitation. Monthly average temperatures in December 1978 and March 1979 were warmer than usual. Daily average temperatures in the winter wildly fluctuated about the mean and at times above zero (Figure 3.13). Much of March was above freezing, but temperatures dropped below normal and below freezing near the end of the month, indicating freeze-thaw conditions.

The Sharktooth flowslide occurred in the spring of 1980, approximately 125 km northwest of Dease Lake, the nearest climate station (Geertsema et al. 1998). 1980 was a year of above-average precipitation and below-average temperature. December 1979 and March and May 1980 had above-average precipitation; the intervening months were near normal. January, April, and June had above-average temperatures. 1980 had more days with precipitation than the previous four years. Daily mean temperatures fluctuated from below -20°C to above 0°C through the winter and into mid-March (Figure 3.14).

The Halfway landslide occurred on August 20, 1989, approximately 50 km west of Fort St. John. 1989 was a year of below-average precipitation and above-average temperature. The latter was part of a positive trend that began in 1975 (Figures 3.11 and 3.12). March, May, July, and August had above-average precipitation, and April through August were warmer than usual. The winter of 1988-1989 was also warm. Temperatures were above average from late May to the end of August, and rainfall was frequent. The largest amount of daily precipitation for 1989 fell on August 21 (34 mm); the slide, however, occurred a day earlier.

The Flatrock landslide, which occurred in October 1997, is located 20 km north of Fort St. John. 1997 was a year of above-average precipitation and temperature, trends that began in 1992 and 1975, respectively (Figures 3.11 and 3.12). Most months in 1997, including October, had above-average precipitation; July and September values were twice the normal amount. Monthly mean temperatures in 1997 were generally near average, but September was much warmer than normal. Daily temperatures from mid-September to mid-October fluctuated from far above to far below freezing, indicating frequent freeze-thaw cycles. Snow fell in mid-October, but melted after temperatures rose to 5-10°C and rain began to fall.

3.4.2.3 Landslides involving till

Ten landslides have sources in till: eight at Buckinghorse River and one each at Halden and Scaffold creeks. The precise dates of these landslides are unknown, but all probably occurred in the mid-1990s. The Halden Creek landslide is 60 km southwest of Fort Nelson, the nearest climate station. 1993 was a year of below-average precipitation and above-average temperature. The average temperature for the year was approximately 2°C, whereas the normal average is below freezing. 1994 was a year of average precipitation and above-average temperature; 1995 had near-normal precipitation and temperature; 1996 had above-average precipitation and an average temperature about 1.5°C below normal; and 1997 had about 50% more precipitation than usual and above-average temperature. Seasonal analysis shows that 419 mm of precipitation fell in the summer of 1997, which is more than twice the average summer precipitation and near the annual average (440 mm). The springs of 1993 and 1994 were approximately 3°C warmer than average. The largest daily total precipitation for the period of 1993-1997 occurred on August 7, 1997 (42.8 mm). The mid-1990s had winter temperatures that fluctuated from well below zero to well above zero over periods of several days, indicating frequent freeze-thaw cycles (Figure 3.8).

The nearest climate station to the Scaffold Creek landslide is Muncho Lake, 60 km to the southwest. 1993 to 1997 were years of above-average precipitation at Muncho Lake. Temperatures in 1993 and 1997 were above average, by approximately 2°C and 1°C, respectively. 1994 was slightly warmer than normal; 1995 slightly cooler than normal; and 1996 was approximately 2.5°C cooler than normal. Summers were wetter than usual in the mid-1990s, with especially heavy precipitation in the summer of 1997. The springs of 1993, 1994, and 1995 were warm. The heaviest daily total precipitation for the mid-1990s was 44 mm on June 5, 1995. Daily mean temperatures during the winter of 1996 were very cold, and winter temperatures in the mid-1990s in general fluctuated markedly (Figure 3.15). The Muncho Lake climate normals include many extreme monthly events in the mid-1990s, but the record is relatively short (1970-2003). The record extremes in the mid-1990s include: extreme daily maximum temperature (July 25, 1994, 34.0°C); extreme daily minimum temperature (January 19, 1996, -50.4°C); and extreme daily snow depth (January 18, 1994, 118.0 cm).

The reference station for the Buckinghorse River landslides is Sikanni Chief, about 25 km to the south. 1993, 1995, 1996, and 1997 were years of above-average precipitation, with over 40% more precipitation than usual in 1996. In contrast, 1994 was a normal year in terms of precipitation. 1994, 1995, and 1996 had below-average annual mean temperatures; the average in 1996 was below freezing. Mean temperature in 1993 was more than 1.5°C above normal, and 1997 was warmer than usual too. The summers of 1993-1996 were wetter than average, with 1993 having 60% more precipitation than normal. Precipitation in the summer of 1993 fell mainly in June (257.8 mm compared to the average of 119.5 mm). The fall of 1997 was more than twice as wet as usual; 1993, 1994, and 1995 had warm springs; and 1994 had a warm summer. 63 mm of rain were recorded at Sikanni Chief on June 14, 1995, and 62 mm on July 18, 1996. Daily winter temperatures in the mid-1990s fluctuated from well below average (and below zero) to well above average (and above zero) over the course of several days (Figure 3.16). Permafrost melt is the suspected cause of this landslide (Marten Geertsema, personal communications, 2005). Mean temperatures across northern British Columbia, have been above-average since the mid-1970s.

3.4.3 Landslides involving rock and sediment

3.4.3.1 Rock slide – earth flows

The Muskwa and Muskwa-Chisca landslides are located 60 and 70 km southwest of Fort Nelson, respectively. They likely initiated as a combination of rotational and translational rock slides that transformed into earthflows (Geertsema et al. 2006*a*). The Muskwa slide occurred in 1979, before August 21. That year had below-average precipitation and temperature. Precipitation in most months before the landslide was below average. Mean temperatures for June and August were far above the averages for the months; the remainder of the months in 1979 were below or near normal. Mean daily temperatures during parts of the winter of 1978-1979 were cooler than usual and temperatures throughout the winter and into the spring fluctuated above and below normal, much more than in the rest of the year. Daily temperatures during most of August were above average.

The Muskwa-Chisca landslide occurred in July 2001, probably between July 25 and 28 (Geertsema et al. 2006*a*). Precipitation and temperature in 2001 were above average. The latter is part of a positive temperature trend that began in the mid-1950s.

July had over two times the normal precipitation recorded at the Tetsa River climate station, 30 km to the west, as well as warmer-than-average temperatures. Daily temperatures fluctuated from well above average to below average (and freezing) in the winter and into the spring. Large amounts of rain fell in May, June, and July, including 70 mm on July 18. Weather satellite images indicate that afternoon thundershowers occurred in the area of the landslide from July 21 to 28; the most severe thunderstorm was on July 26 (Chapter 4).

3.4.3.2 Rock slide – debris flows

The Zymoetz River and Harold Price landslides occurred in June 2002. The Zymoetz River landslide happened between 01:15 and 01:30 PST on June 8, approximately 20 km east of Terrace. It ruptured a natural gas pipeline and temporarily dammed the Zymoetz River (Schwab et al. 2003). Data from the Terrace climate station show that 2002 was a year of below-average precipitation and above-average temperature. 2002 is part of a long-term warming trend at Terrace (Figure 3.3). Precipitation in May and June was above normal, as was temperature in June. The winter of 2001-2002 was warmer than usual, as seen in monthly and daily mean temperatures. In contrast, the spring was cooler than usual. Snowpack was above average at the nearest snow pillow station at Tsai Creek, approximately 50 km northeast of the landslide. That station reported 1909 mm of snow water equivalent on June 1, 2002 (mean = 1183 mm). Temperatures fluctuated markedly above and below the average value prior to the landslide, suggesting possible freeze-thaw conditions at high elevations. No precipitation occurred on the day of the landslide. Temperatures were above 20°C, possibly indicating rapid snowmelt.

The Harold Price landslide occurred between June 22 and 24, 2002, approximately 25 km southeast of the Suskwa Valley climate station. 2002 was a year of below-average precipitation and above-average temperature. Most months prior to the landslide, including June, were wetter than usual. Snowpack at the Tsai Creek snow pillow station, approximately 60 km southwest of the landslide, was above average for June 2002. Mean monthly temperatures were above average in the winter, below average in the spring, and average in June. Daily temperatures fluctuated above and below freezing through the winter and into the spring (Figure 3.17). Temperatures were below average, and some precipitation fell at the time of the landslide; neither, however, was unusual. Weather satellite images show an isolated thunderstorm at the site of the landslide on June 23 (Chapter 4). The thunderstorm likely produced localized, heavy rain, which may have triggered the landslide.

3.4.3.3 Rock slide – debris avalanche

The Pink Mountain rock slide-debris avalanche occurred sometime in late June or early July 2002, approximately 150 km northwest of Fort St. John and 20 km northeast of Sikanni Chief, the nearest climate station. The landslide initiated in an area of extensive pre-existing mountaintop deformation (Geertsema et al. 2006*b*). 2002 was a year of below-average precipitation and above-average temperature at Sikanni Chief. Precipitation amounts in the months prior to the landslide were normal. The winter was warm and the spring cold. Snow water equivalent at the Kwadacha snow pillow station, 150 km northwest, was above average on June 1, 2002 (311 mm vs. the mean of 225 mm). Daily mean temperature analysis indicates that temperatures were highly variable through the winter of 2001-2002. About 48 mm of precipitation were recorded between

July 5 and 7. The first week of July had below-average temperatures, possibly with snow at high elevations. Weather satellite images indicate that an inverted trough of low pressure stalled over the area of the landslide from June 30 to July 5, accompanied by heavy rains (Chapter 4).

3.5 Discussion

3.5.1 Annual trends

The year of failure is known for 23 of the 34 landslides. Seventeen of the 23 landslides occurred during years of above-average temperature and thirteen occurred during years of above-average precipitation. Probabilities of landslide occurrence during years of above-average precipitation or temperature are presented and discussed in Appendix 6.

Eleven of the 23 landslides involve rock, of which nine happened in years of above-average temperatures. Most landslides in rock occurred on slopes above glaciers, where the combination of snow and ice loss and infiltration of meltwater into fractures during warm weather may have reduced rock-mass stability. Seven of the eleven landslides involving rock happened during years of above-average precipitation.

Seven landslides with known years of failure occurred in sediment. Five of the seven landslides happened during years of above-average precipitation; four of the seven landslides happened during years with above-average temperature. Greater precipitation increases the probability of failure by raising pore-water pressures in the sediments or by increasing river and creek levels, thus undercutting banks and removing slope material and decreasing slope stability.

The year of failure is known for five landslides involving both rock and sediment. Four of the five landslides happened during years of above-average temperature; four of the five occurred during years of below-average precipitation. These landslides initiated in rock, thus higher temperatures may increase snowmelt and infiltration of water into rock fractures, decreasing slope stability.

One landslide in rock and ten in sediment are dated only to the mid-1990s. Precipitation in 1993 and 1994 was normal, but it was above normal in 1995-1997. Temperature was above average in 1993, 1994, and 1997 but below average in 1995 and 1996.

3.5.2 Seasonal and monthly trends

The dates of 16 landslides are known to a season or month, but the relations to climate are more vague than in the case of annual trends. Nine of the 16 landslides occurred during a season or month with above-average precipitation, and ten of the 16 landslides happened during a season or month with above-average temperatures. Probabilities of landslide occurrence during a season or month of above-average precipitation or temperature are presented and discussed in Appendix 6.

Five of the 16 landslides are in rock. Three of these occurred during a season or month of below-average precipitation and three occurred during a season or month with below-average temperature. Seven of the 16 landslides are in sediment. Of these, five happened during a season or month of above-average precipitation and five during a season or month with above-average temperature. Four of the 16 landslides involved rock and sediment. Three of these happened in a season or month of above-average temperature; no relation was found with precipitation.

Warm winters and winters when temperatures repeatedly fluctuate above and below average, and in most cases above and below freezing, were noted in the seasonal and monthly analyses of most of the landslides. The Howson II, North Creek, Kendall, Turnoff Creek, Verney, Mink Creek, Halfway, Zymoetz, Harold Price, and Pink Mountain landslides occurred after warm winters. The Mosque Mountain, Chisca, Inklin, Scaffold Creek, Halden Creek, Buckinghorse River, Muskwa, and Muskwa-Chisca landslides show an association with highly variable winter temperatures that fluctuated well above and well below normal (and freezing) over a matter of days. The largest increases in temperature in northern British Columbia have been in the winter season (Chapter 2), which is consistent with the observed association of landslides and warm winters. Warm winters, or winters with temperatures that fluctuate above and below freezing, may increase the frequency of large landslides by increasing freeze-thaw activity, rain-on-snow events, heavy wet snow, and early or abnormal snowmelt.

Four large landslides occurred in June 2002: the Zymoetz, Harold Price, Pink Mountain, and Verney events. Two other large landslides also happened in June, but are outside the study area: the McAuley rock slide near Vernon in southern British Columbia (Evans et al. 2003), and a rock slide near Carmacks, Yukon Territory (Crystal Huscroft, personal communication, 2004). It is likely that the six landslides have a climatic cause, possibly the above-average temperatures in British Columbia and Yukon since the mid-1970s. Temperatures in 2002 were generally above average. Snowpacks were above average in June at the nearest snow pillow stations for each of the landslides (no snow data was available for the Yukon). The winter of 2001-2002 was warmer than average and spring of 2002 was colder than normal, which may have delayed melt of the above-average snowpack, producing rapid runoff in June. This situation, warm winter followed by a cool spring, occurred in the past 3-4 years in these areas. The exact triggers of these failures, however, are not known.

3.5.3 Regional trends

Two landslides (North Creek and Sharktooth) occurred in the Boreal Mountains and Plateaus region (Figure 3.1). This region had the largest increase in annual maximum temperature (1.1°C) in the study area, a significant increase in annual minimum temperature (2.1°C), the largest increase in spring mean temperature (1.2°C), and the largest increase in summer maximum temperature (0.9°C). Four landslides (Frobisher I and II, Inklin, and Kshwan) occurred in the Boundary Ranges/Yukon Stikine Highlands region, which has experienced a significant increase in annual mean temperature (0.6°C). Two landslides (Khyex River and Verney) are in the Coastal Gap region, which had significant increases in annual mean temperature (0.7°C) and annual minimum temperature (2.2°C). The Kendall Glacier rock slide-avalanche is in the Columbia Highlands/Northern Columbia Mountains, the region with the largest increases in annual precipitation (18.6%), winter maximum temperature (2.0°C), and fall maximum temperature (2.1°C), and a significant increase in annual maximum temperature (0.9°C). The Howson I, Howson II, Zymoetz, and Mink Creek landslides are in the Nass Ranges region, which experienced a significant increase in annual mean temperature (0.8°C) and the largest increase in spring precipitation (27.0%). Nine landslides are in the Northern Canadian Rocky Mountains region: Scaffold Creek, Tetsa, Chisca, Muskwa, Muskwa-

Chisca, Halden Creek, Buckinghorse River, Pink Mountain, and Turnoff Creek. This region had a large increase in annual minimum temperature (3.3°C) and the largest change in winter precipitation (-41.6%) in northern British Columbia. The Flatrock, Attachie, and Halfway landslides are in the Peace River Basin region, which shows significant trends in annual mean temperature (0.5°C), annual maximum temperature (-0.9°C), and annual minimum temperature (3.0°C). Two slides (Mosque Mountain and Harold Price) are in the Skeena/Omineca Mountain region, which had the largest change in annual mean temperature (1.3°C) and significant increases in annual precipitation (10.2%) and annual minimum temperature (2.7°C).

3.5.4 El Niño and the Pacific Decadal Oscillation

A link probably exists between the landslides in this study and the warm phase of the Pacific Decadal Oscillation (PDO). This phase of the PDO began in the mid-1970s and is responsible for above-average temperatures in northern British Columbia, above-average precipitation in coastal regions, and below-average precipitation in interior regions over the last three decades (Chapter 2). Many of the landslides occurred during years of above-average temperature during the current warm phase of the PDO. However, a definite link is difficult to confirm because data are not available for earlier warm phases.

The most recent, strong El Niños, which are thought to bring warmer and wetter conditions to British Columbia, were in 1972-1973, 1982-1983, 1992, and 1997 (Bigg 2003). The Attachie flowslide occurred during the 1972-1973 El Niño event, the Kshwan Glacier and Turnoff Creek rock slides happened during the 1992 event, and the Flatrock flowslide happened during the 1997 event. Increased temperature and precipitation in an El Niño year may be a factor in these landslides, but the correlation is weak.

3.5.5 Potential and future work

Extension of the record of historic, large landslides to the beginning of the instrumental period in northern British Columbia would enable a better comparison of the frequency of these events with the climate trends and variability documented in Chapter 2. In this study, a strong connection could not be made between landslide events and ocean-atmosphere oscillations because of the short length and small size of the landslide dataset. The use of time series statistical methods could provide information on periods of high or low occurrences of large landslides and how they relate to climate variability. Extension of the landslide dataset also would allow comparison of the effects of the cool and warm phases of the PDO and would provide a more statistically significant sample of landslides for comparison with the ENSO. Only observational comparisons were made in this study; a longer and larger landslide dataset could be statistically correlated with the frequency of strong El Niño or La Niña events. An analysis could also be made of how the PDO and ENSO may be affecting the size of weather systems in northern British Columbia. Potentially, larger weather systems produced by warmer ocean temperatures could bring increased precipitation to the study area, especially on the coast, which would increase the frequency of large landslides.

Additional data could provide more accurate assessments of the causes of landslides in northern British Columbia. Where landslides occurred near rivers or creeks, discharge data from hydrometric stations (Environment Canada 2005) might indicate the possibility that high flows eroded the toes of slopes, thus causing the failures.

Information on ground water levels (BC Ministry of Water, Land and Air Protection 2005*a*) is also useful. Knowledge of the amount and distribution of water in the ground allows better estimates to be made of precipitation amounts that could trigger a landslide. Data on the depth to which variations in temperature can affect rock would also be useful for examining causes of rock failures (Watson et al. 2004). This type of analysis is beyond the scope of this study, but classifying rock failures by rock type might be useful in evaluating the relation between temperature and slope failure. As discussed in Chapter 2, snow data and rain-snow ratios would allow a more complete assessment of the causes of landslides in northern British Columbia.

3.6 Conclusions

Historical climate data from the instrumental record were used to examine the connection between climate trends and 34 recent large landslides in northern British Columbia. Climate may be the cause or trigger of most of the slope failures; however, this relation depends on the landslide type. Most landslides in rock happened in years of above-average temperature or during periods of several years or more of above-average temperatures. Most landslides in sediment happened in years of above-average precipitation or wet periods that lasted at least several years. Some seasonal correlations are inferred, the most obvious being a high likelihood of failure after a winter with above-average or highly variable temperatures that oscillate from well above to well below freezing over short periods. This inferred relation suggests that frequent enhanced freeze-thaw cycles may have reduced the shear strength of slopes.

All landslides examined in this study occurred during the most recent warm phase of the Pacific Decadal Oscillation, and the PDO may have been an important factor in the failures. The climate trends and variability found in this study may have preconditioned already marginally stable slopes to fail, although there are probably contributing non-climatic factors that were not explored in this research. Some of these events may have been triggered by short-term weather systems or storms, but these could not be evaluated because the precise dates of many of the events are unknown. In spite of this complexity, warmer temperatures and changing precipitation patterns are increasing the potential for large landslides in northern British Columbia.

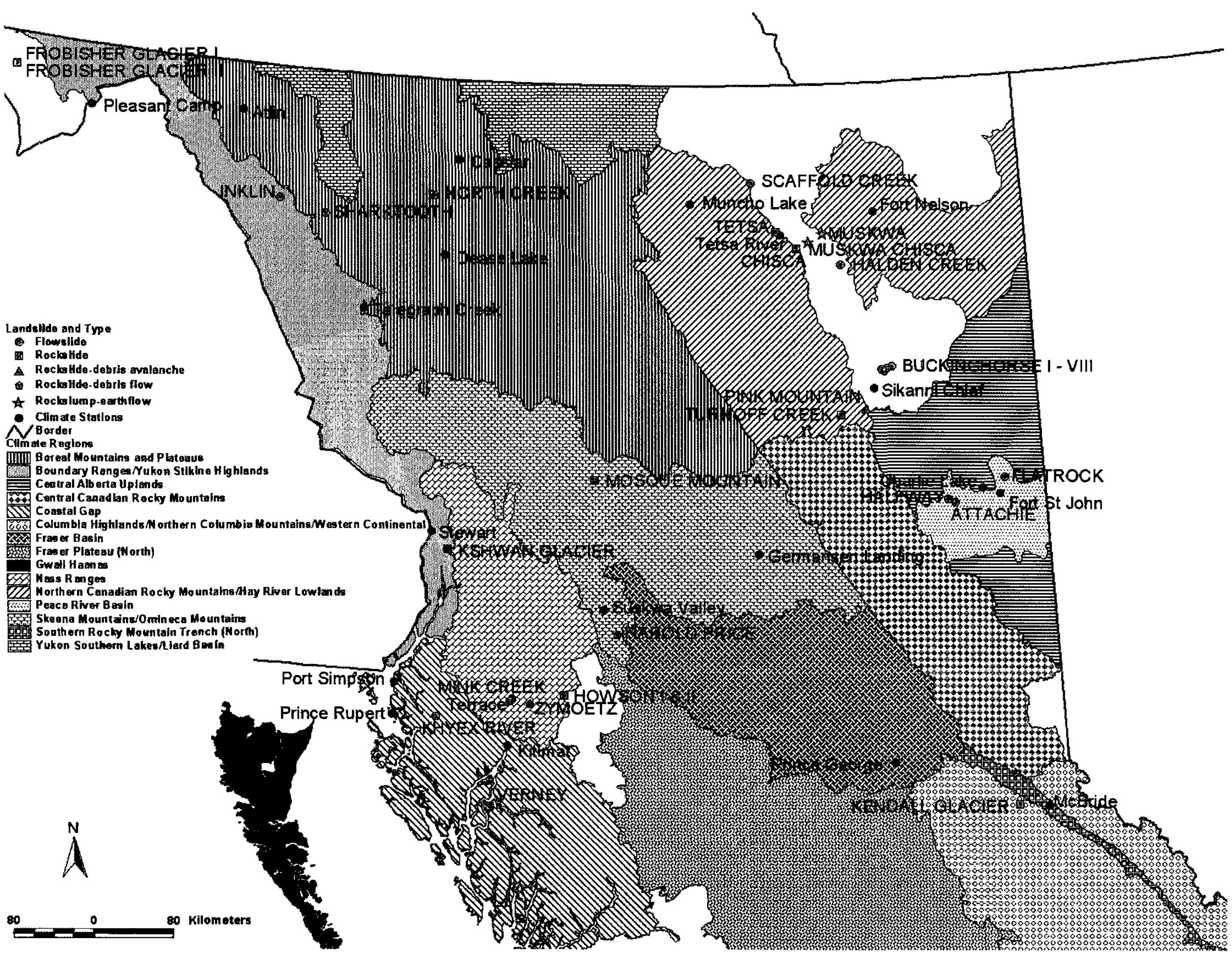

Figure 3.1. Landslides, climate stations, and climate regions in northern British Columbia. (Spatial data source: ftp://ftp.elp.gov.bc.ca/dist/arcwhse/wildlife).

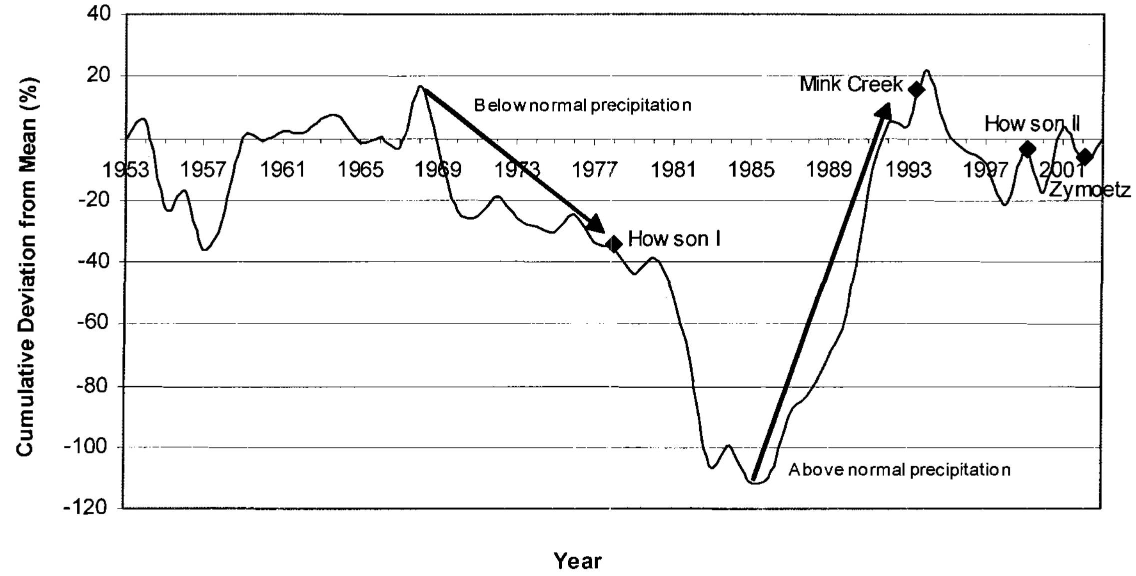

Figure 3.2. Graph of cumulative departure from mean percent precipitation, Terrace.

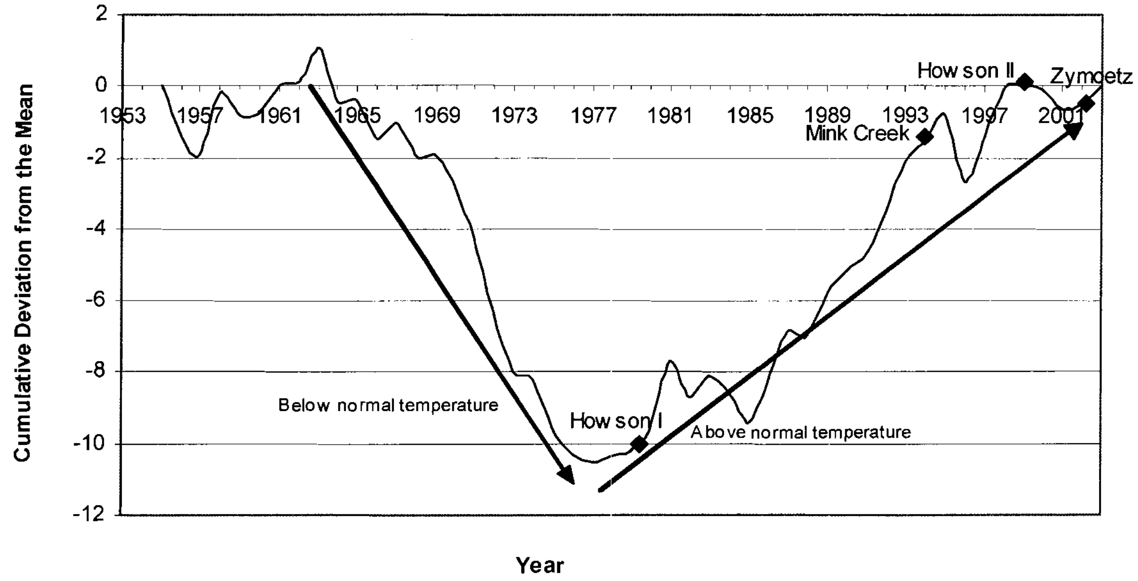

Figure 3.3. Graph of cumulative departure from mean temperature, Terrace.

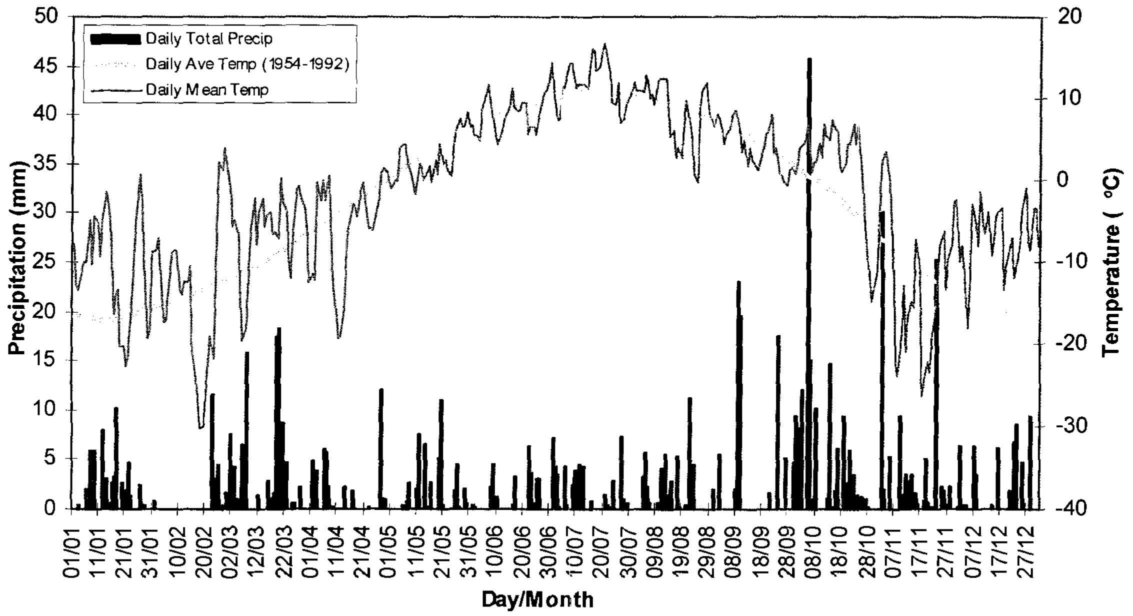

Figure 3.4. Daily climate data for Cassiar, 1986.

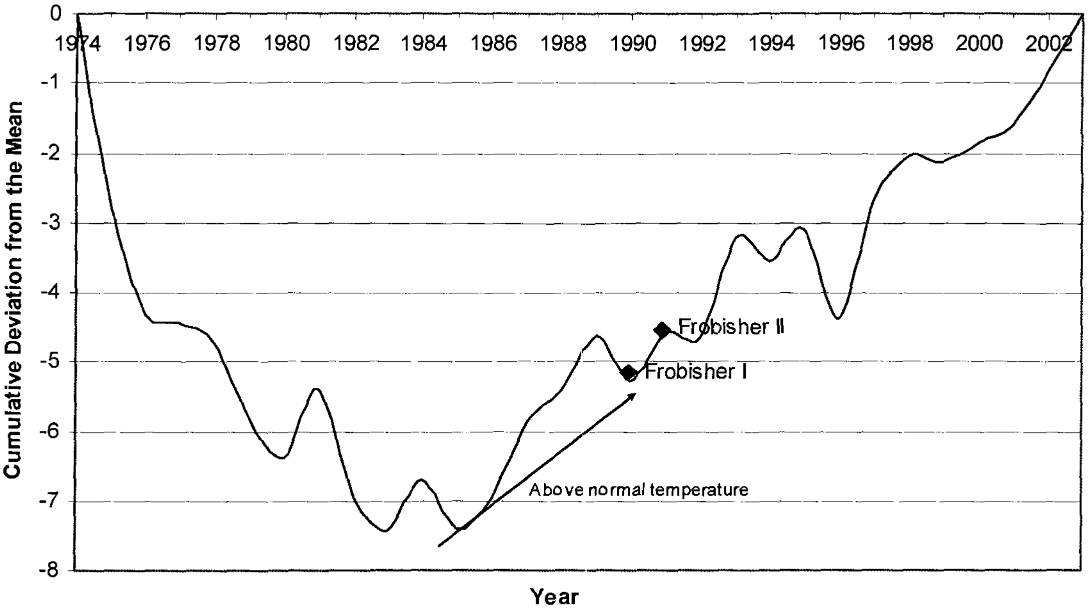

Figure 3.5. Graph of cumulative departure from mean temperature, Pleasant Camp.

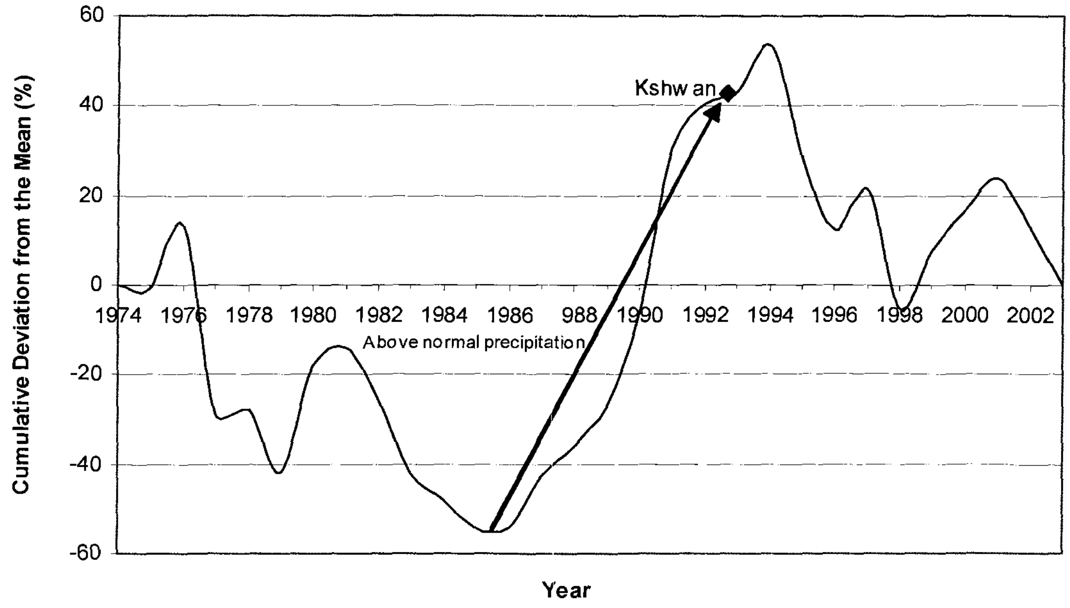

Figure 3.6. Graph of cumulative departure from mean percent precipitation, Stewart.

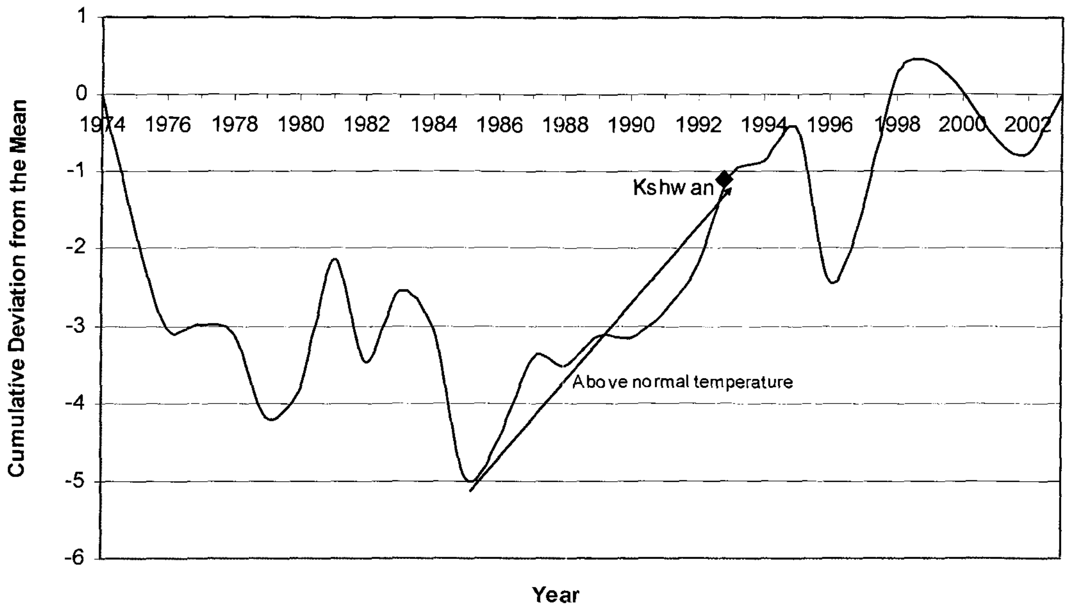

Figure 3.7. Graph of cumulative departure from mean temperature, Stewart.

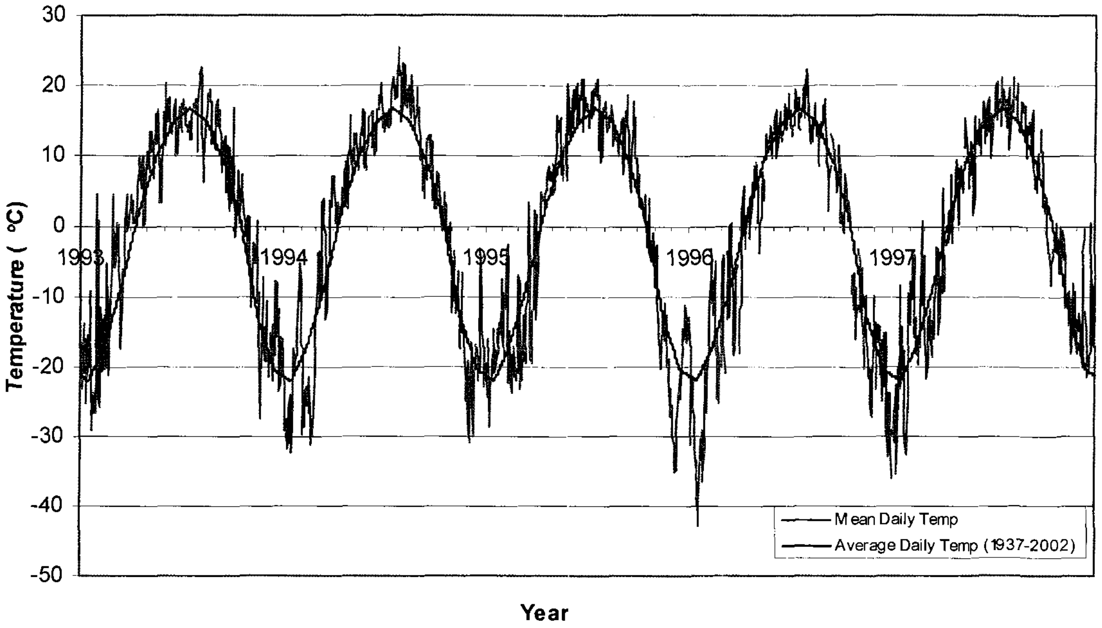

Figure 3.8. Daily temperature data for Fort Nelson, 1993-1997.

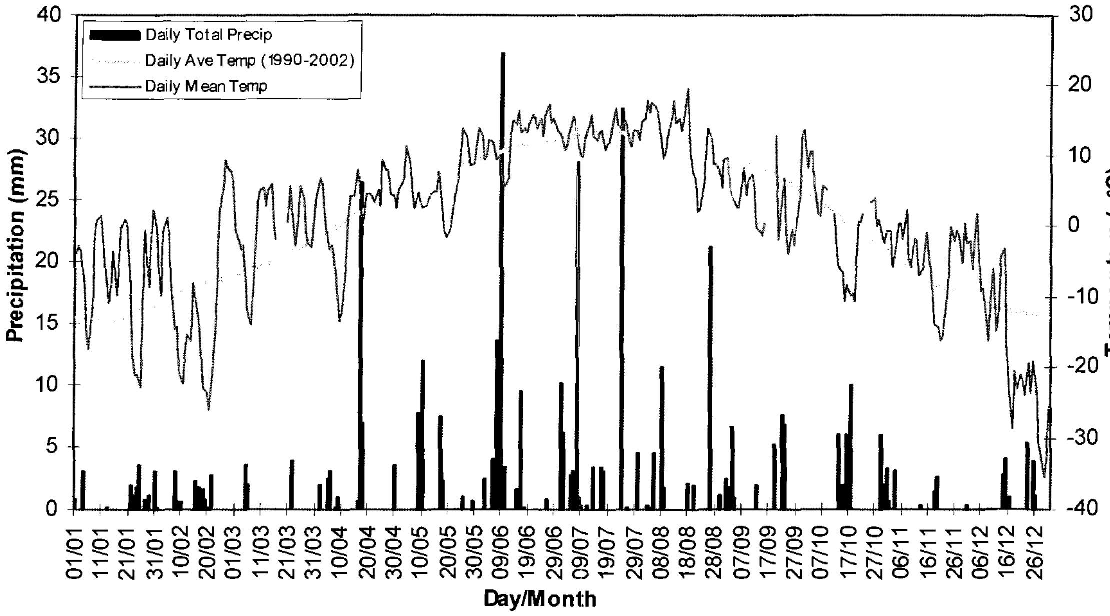

Figure 3.9. Daily climate data for Sikanni Chief, 1992.

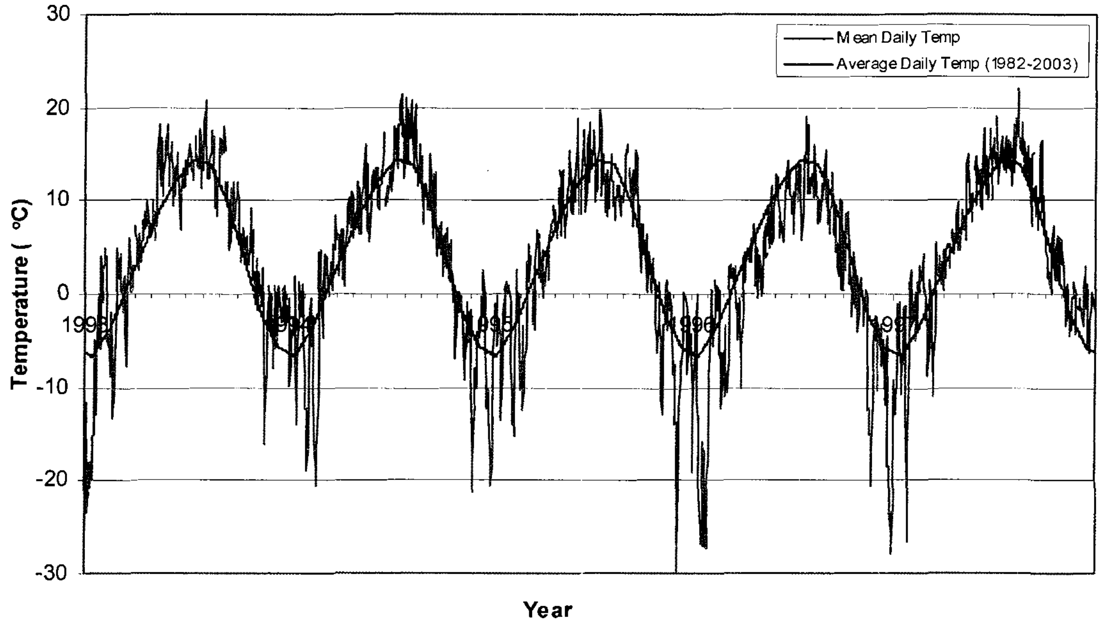

Figure 3.10. Daily temperature data for Suskwa Valley, 1993-1997.

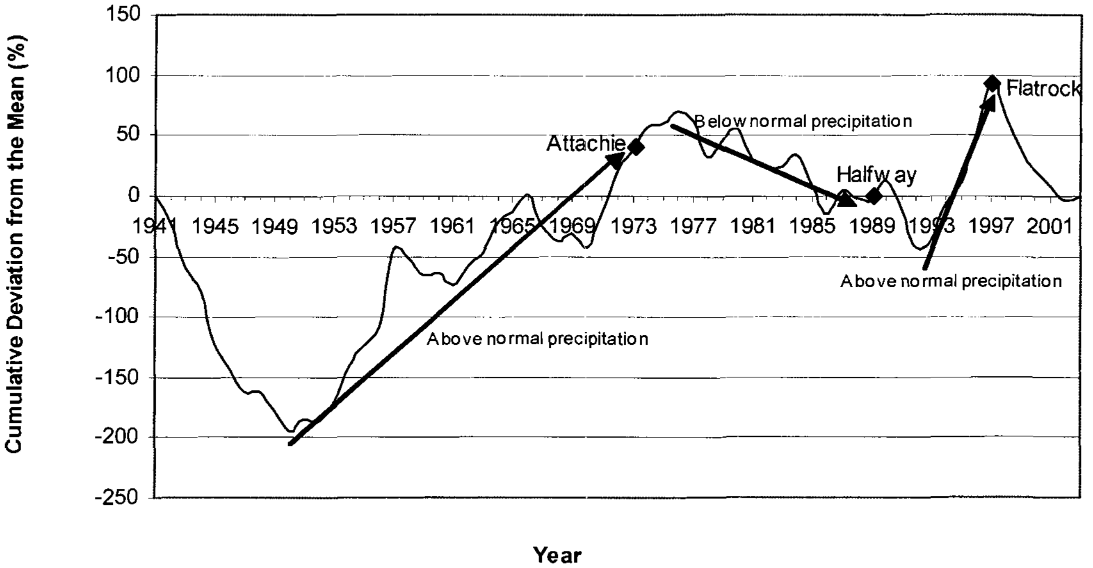

Figure 3.11. Graph of cumulative departure from mean percent precipitation, Fort St. John.

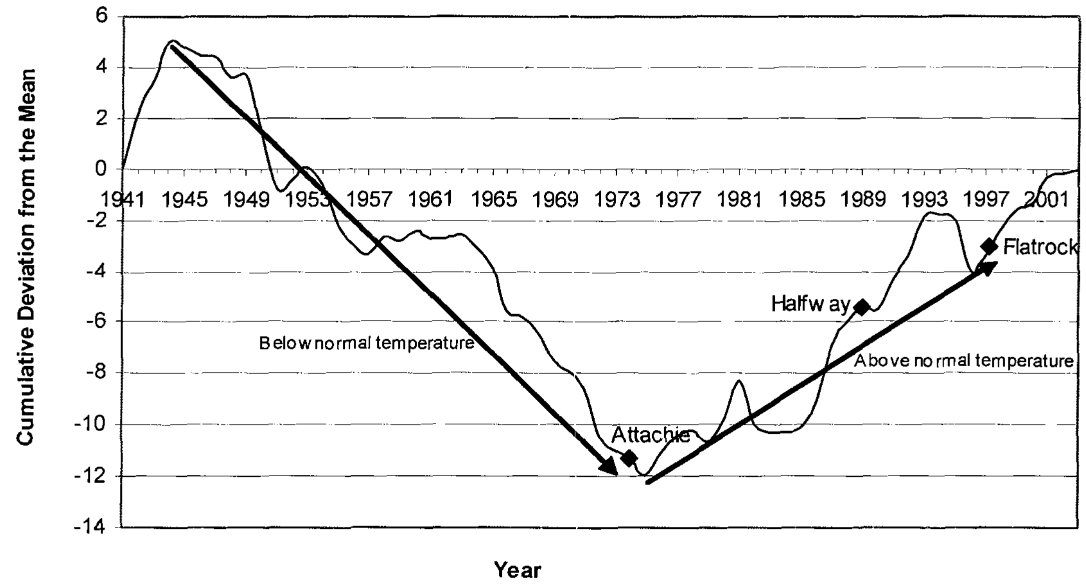

Figure 3.12. Graph of cumulative departure from mean temperature, Fort St. John.

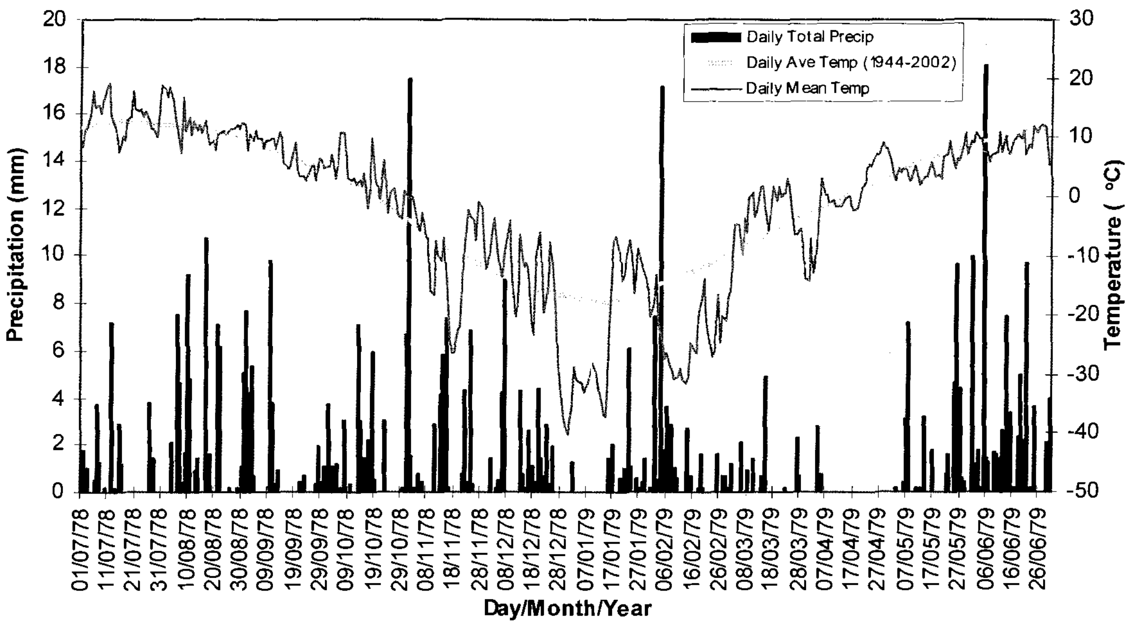

Figure 3.13. Daily climate data for Atlin, July 1978 – June 1979.

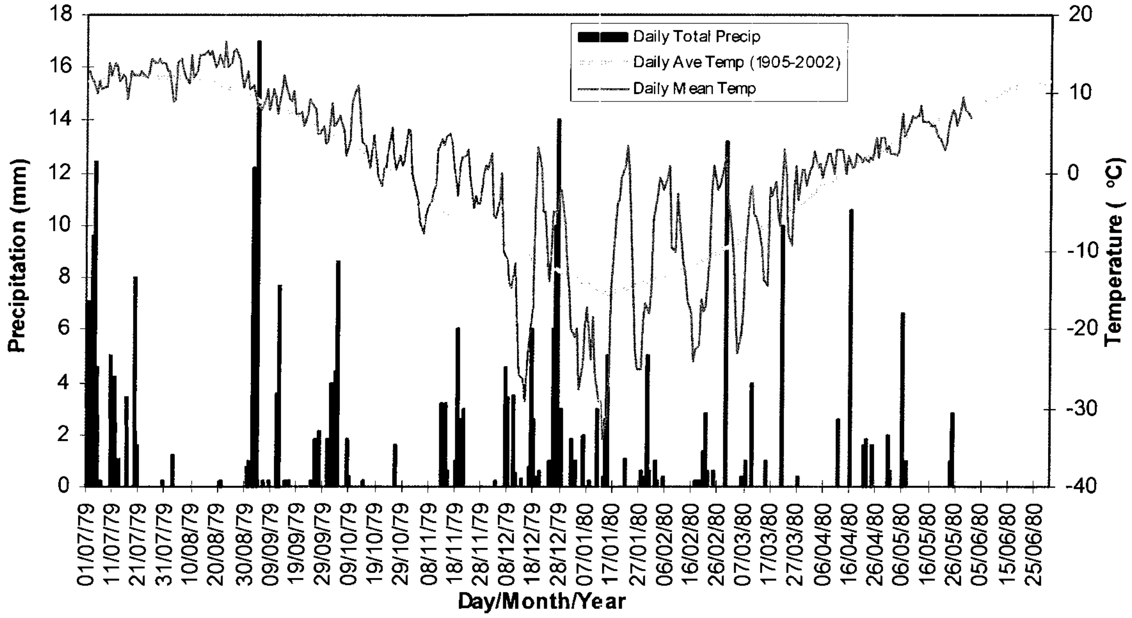

Figure 3.14. Daily climate data for Dease Lake, July 1979 – June 1980.

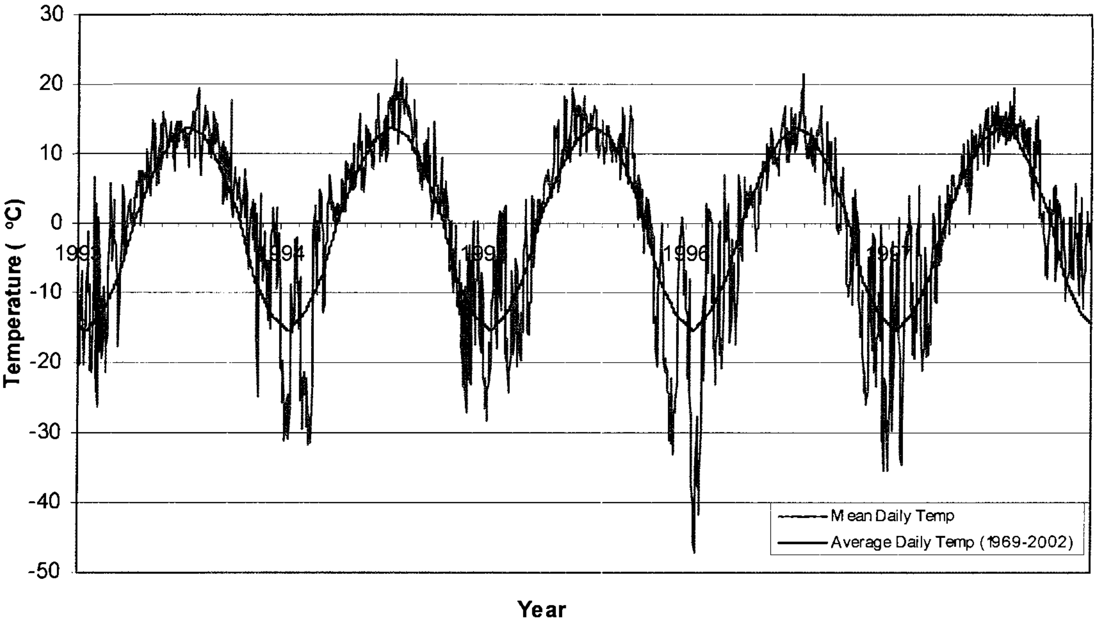

Figure 3.15. Daily temperature data for Muncho Lake, 1993-1997.

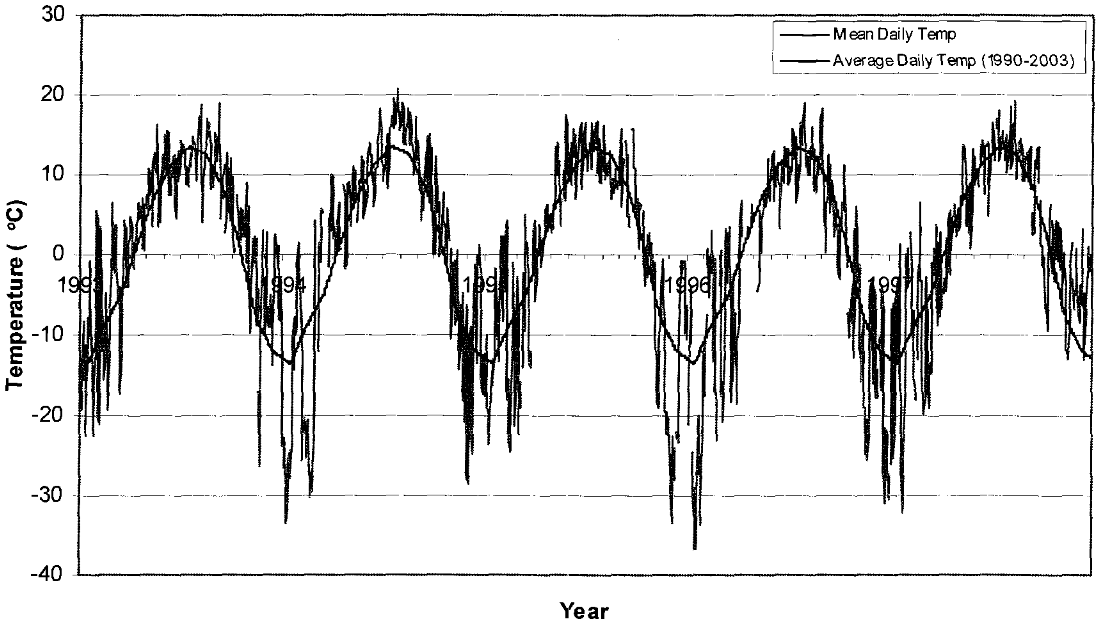

Figure 3.16. Daily temperature data for Sikanni Chief, 1993-1997.

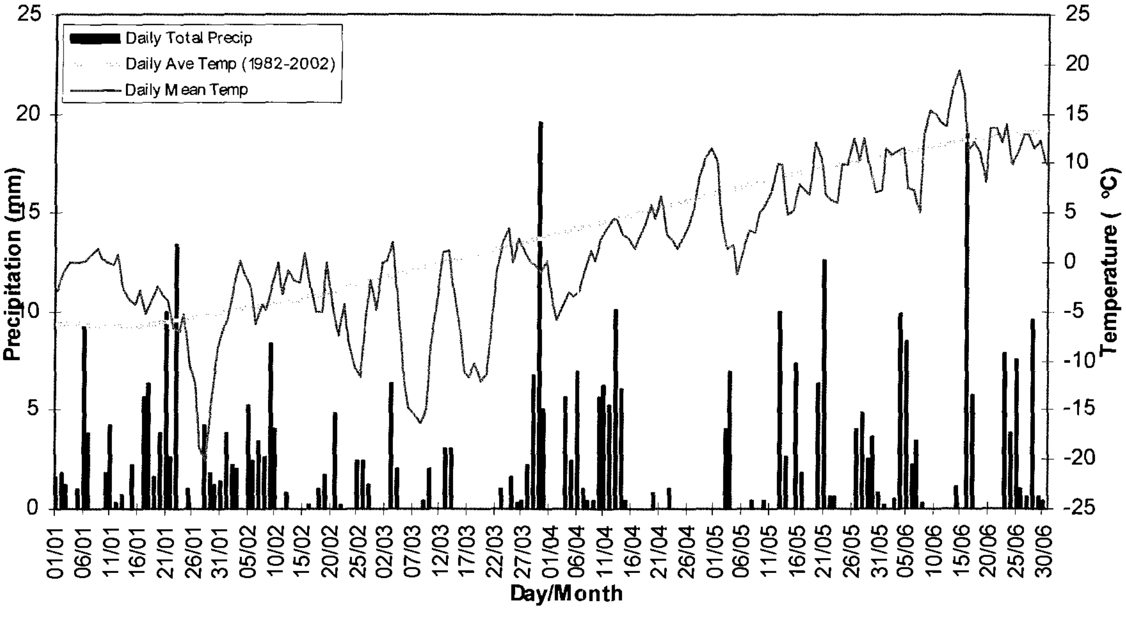

Figure 3.17. Daily climate data for Suskwa Valley, January – June 2002.

Table 3.1. Landslide data.

Location, Fig. 3.1	Date	Landslide Type	Volume (Mm^3)	Length (km)	References
Howson I	1978	Rock slide			Geertsema et al. 2006*a*
North Creek	1986	Rock slide	1-2	2.8	Evans and Clague 1999; Geertsema et al. 2006*a*
Frobisher Glacier I	1990	Rock avalanche		3.1	Evans and Clague 1999; Geertsema et al. 2006*a*
Frobisher Glacier II	1991	Rock avalanche		2.4	Evans and Clague 1999; Geertsema et al. 2006*a*
Kshwan Glacier	September 1992 - May 1993	Rock slide	3.2	2.3	Mauther 1996; Geertsema et al. 2006*a*
Kendall Glacier	July 12 - August 9 1999	Rock avalanche	0.2	1.2	Couture and Evans 2002; Geertsema et al. 2006*a*
Howson II	September 11 1999, 03:00 PST	Rock slide-avalanche	1.5	2.7	Schwab et al. 2003; Geertsema et al. 2006*a*
Testa	May 1988	Rock avalanche		2.0	Geertsema et al. 2006*a*
Chisca	1996	Rock avalanche	1	1.5	Geertsema et al. 2006*a*
Turnoff Creek	Fall 1992	Rock avalanche	4	2.0	Geertsema et al. 2006*a*
Mosque Mountain	mid 1990s	Rock avalanche	5	1.2	Lu et al. 2003; Geertsema et al. 2006*a*
Verney	June 2002	Rock avalanche		0.6	Geertsema et al. 2006*a*
Mink Creek	December 1993 - January 1994	Flowslide	2.5	1.2	Geertsema et al. 2003, 2006*a*
Khyex River	November 28 2003, 00:30 PST	Flowslide	4.7	1.6	Schwab et al. 2004*a,b*; Geertsema et al. 2006*a*
Attachie	May 26 1973	Flowslide	12.4	1.5	Evans et al. 1996; Geertsema et al. 2006*a*
Inklin	Spring 1979	Flowslide	2-3	0.7	Geertsema et al. 1998, 2006*a*
Sharktooth	Spring 1980	Flowslide	3-4	1.2	Bobrowsky and Smith 1992; Geertsema et al. 2006*a*
Halfway	August 20 1989	Flowslide	1.9	0.7	Geertsema et al. 2006*a*
Flatrock	October 1997	Flowslide		0.7	Geertsema et al. 2006*a*
Scaffold Creek	mid 1990s	Flowslide		0.5	Geertsema et al. 2006*a*
Halden Creek	mid 1990s	Flowslide	5	0.6	Geertsema et al. 2006*a*
Buckinghorse I	mid 1990s	Flowslide		1.8	Geertsema et al. 2006*a*
Buckinghorse II	mid 1990s	Flowslide		1.0	Geertsema et al. 2006*a*
Buckinghorse III	mid 1990s	Flowslide		1.8	Geertsema et al. 2006*a*
Buckinghorse IV	mid 1990s	Flowslide		0.7	Geertsema et al. 2006*a*
Buckinghorse V	mid 1990s	Flowslide		1.3	Geertsema et al. 2006*a*
Buckinghorse VI	mid 1990s	Flowslide		0.8	Geertsema et al. 2006*a*
Buckinghorse VII	mid 1990s	Flowslide		1.4	Geertsema et al. 2006*a*
Buckinghorse VIII	mid 1990s	Flowslide		0.7	Geertsema et al. 2006*a*
Muskwa	1979	Rock slide-earthflow	15	2.2	Geertsema et al. 2006*a*
Muskwa-Chisca	July 25-28 2001	Rock slide-earthflow		1.5	Geertsema et al. 2006*a*
Zymoetz	June 8 2002, 01:15-30 PST	Rock slide-debris flow	1.6	4.3	Schwab et al. 2003; Geertsema et al. 2006*a*
Harold Price	June 22-24 2002	Rock slide-debris flow	1.6	4.0	Schwab et al. 2003; Geertsema et al. 2006*a*
Pink Mountain	June 30 - July 6 2002	Rock slide-debris avalanche	1	2.0	Geertsema et al. 2006*a,b*

Table 3.2. **Precipitation at the climate station nearest each landslide.**

Landslide	Date	Antecedent Trend[1]	Annual[1]	Season/Month[1]	10-day Total (mm)	Day (mm)
Howson I	1978	below since 1969	below			
North Creek	1986	above 1985	above			
Frobisher Glacier I	1990	below 1989	below			
Frobisher Glacier II	1991	below since 1989	above			
Kshwan Glacier	September 1992 - May 1993	above since 1986	above			
Kendall Glacier	July 12 - August 9 1999	below 1998	above	below	38	none
Howson II	September 11 1999, 03:00 PST	below since 1995	above	below		
Testa	May 1988	above since 1984	above	above		
Chisca	1996	above 1995	above			
Turnoff Creek	Fall 1992	below 1991	below	below		
Mosque Mountain	mid 1990s	above 1993-1997				
Verney	June 2002	above since 1986	below	above		
Mink Creek	December 1993 - January 1994	above since 1986	above	above		
Khyex River	November 28 2003, 00:30 PST	above since 1986	below	above	137	41
Attachie	May 26 1973	above since 1950	above	above	21	16
Inklin	Spring 1979	above 1978	above	above		
Sharktooth	Spring 1980	above since 1978	above	above		
Halfway	August 20 1989	below since 1977	below	above	22	none
Flatrock	October 1997	above since 1993	above	above		
Scaffold Creek	mid 1990s	above since 1983				
Halden Creek	mid 1990s	above 1993-1997				
Buckinghorse I-VIII	mid 1990s	above 1992-1997				
Muskwa	1979	below 1978	below			
Muskwa-Chisca	July 25-28 2001	below since 1998	above	above	27	
Zymoetz	June 8 2002, 01:15-30 PST	above 2001	below	above	15	none
Harold Price	June 22-24 2002	below since 1998	below	above	36	
Pink Mountain	June 30 - July 6 2002	above since 2001	below	above	50	

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[1] Above or below average station value.

Table 3.3. Temperature at the climate station nearest each landslide.

Landslide	Date	Antecedent Trend[1]	Annual[1]	Season/Month[1]	Week[1]	Day[1]
Howson I	1978	below since 1963	above			
North Creek	1986	above 1985	above			
Frobisher Glacier I	1990	above since 1984	below			
Frobisher Glacier II	1991	above since 1984	above			
Kshwan Glacier	September 1992 - May 1993	above since 1986	above			
Kendall Glacier	July 12 - August 9 1999	above since 1997	above	below		
Howson II	September 11 1999, 03:00 PST	above since 1978	above	below	below	above
Testa	May 1988	above 1987	above	above		
Chisca	1996	above since 1975	below			
Turnoff Creek	Fall 1992	above 1991	above	below		
Mosque Mountain	mid 1990s	below 1993-1997				
Verney	June 2002	above since 1980	above	above		
Mink Creek	December 1993 - January 1994	above since 1986	above	above		
Khyex River	November 28 2003, 00:30 PST	above since 1978	above	below	below	below
Attachie	May 26 1973	below since 1945	below	above	above	below
Inklin	Spring 1979	above since 1976	below	above		
Sharktooth	Spring 1980	above since 1976	below	above		
Halfway	August 20 1989	above since 1976	above	above	above	above
Flatrock	October 1997	above since 1975	above	above		
Scaffold Creek	mid 1990s	above since 1985				
Halden Creek	mid 1990s	above since 1975				
Buckinghorse I-VIII	mid 1990s	below 1993-1997				
Muskwa	1979	above since 1976	below			
Muskwa-Chisca	July 25-28 2001	above since 1976	above	above	above	
Zymoetz	June 8 2002, 01:15-30 PST	above since 1978	above	above	below	above
Harold Price	June 22-24 2002	above since 1976	above	below	below	
Pink Mountain	June 30 - July 6 2002	above since 1997	above	above	below	

[1] Above or below average station value.

CHAPTER 4 INVESTIGATING LANDSLIDE TRIGGERS IN NORTHERN BRITISH COLUMBIA USING WEATHER SATELLITE IMAGERY[1]

4.1 Abstract

Precipitation and temperature conditions responsible for weather-related landslides are commonly assessed from climate station records. In northern British Columbia, however, the climate station network is sparse and observational periods are short, thus it is not always possible to use conventional weather data to evaluate landslide triggers. Digitally archived weather satellite images from Environment Canada were used to provide information on weather conditions at the times of landslides at remote locations in northern British Columbia. Twenty-five well dated landslides that occurred between 1998 and 2004 were studied using this method. Areas of precipitation can be inferred from the satellite images and used to estimate the conditions that may have triggered failure.

4.2 Introduction

Landslides are commonly triggered by unusual weather events, for example intense or prolonged rainstorms, rain-on-snow events, and sudden changes in temperature (Selby 1993; Evans and Clague 1997; van Asch et al. 1999). Heavy rainfall is common in British Columbia's north coast region and is the most important trigger of debris flows and debris avalanches in that region (Septer and Schwab 1995; Schwab 2000). Weather-

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[1] This chapter has been published in the proceedings of the 58th Canadian Geotechnical Conference (authors Vanessa N. Egginton, John J. Clague, and Peter L. Jackson).

related landslides are also common in inland sections of northern British Columbia, particularly areas of mountainous terrain and areas of thick, fine-grained sediments (Geertsema et al. 2006*a*).

Many studies have used climate station data to examine precipitation and temperature conditions at times of landslides (e.g. Caine 1980; Hogan and Schwab 1991; Reid 1998; Cuesta et al. 1999; Jakob and Weatherly 2003). However, difficulties arise in establishing relations between climate conditions and individual landslides when data are missing, the climate station is distant from the landslide, or there is no suitable climate station record at all. Poor or malfunctioning equipment and inappropriate data protocols may further limit the usefulness of climate station data. The climate station network in northern British Columbia is sparse and records are of short duration compared to those from the southern part of the province (BC Ministry of Water, Land, and Air Protection 2002*a*). In addition, the number of climate stations has decreased since the late 1980s. For these reasons, the role of climate in triggering landslides in northern British Columbia cannot be assessed using climate stations records alone.

This chapter presents another, independent method for investigating weather conditions at times of landslides. Satellite images were used to investigate weather conditions for 25 well dated landslides in northern British Columbia between 1998 and 2004 (Figure 4.1). The broader utility of this method in areas with limited instrumental data is discussed.

4.3 Study area

Our study area is the part of British Columbia north of 53°N latitude. It has an extent of approximately 600 000 km^2, includes diverse physiography, and spans a wide range of climate and vegetation zones (Meidinger and Pojar 1991). Elevations range from sea level to over 4000 m, and the region includes many mountain ranges, large plateaus, and river valleys. Climate is controlled by maritime and continental polar air masses with continental arctic air important in winter (Ahrens 1994). Annual precipitation ranges from less than 300 mm to more than 3000 mm, and mean annual temperature ranges from less than -2°C to more than 9°C.

4.4 Methods

4.4.1 Landslide data

Landslides considered in this study range in size from 0.1 ha to 43 ha and include rock slides, debris flows, debris avalanches, and complex landslides (rock slide-debris flow, rock slide-debris avalanche, rock slide-earthflow, and slump-earthflow) (Table 4.1). Information on the landslides was obtained through discussion with personnel of the British Columbia Ministry of Forests, erosion event summary reports (1999-2003), and several publications (Schwab et al. 2003, 2004*a*, 2004*b*; Geertsema and Schwab 2004; Geertsema et al. 2006*a*, *b*). None of the landslides chosen for this study was triggered by human activity. Weather likely played a role in the majority of the failures.

4.4.2 Weather satellite images

Digital satellite images collected by GOES-10, a geostationary infrared weather satellite over Universal Transverse Mercator Zone 10, were obtained from

Meteorological Service of Canada (© Environment Canada, 2005, by permission). Images chosen for analysis cover the areas in which the 25 landslides occurred; most were available at fifteen minute intervals. British Columbia and Yukon infrared images with a red enhancement for cloud top temperatures less than -35°C, plotted lightning strikes from the Canadian Lightning Detection Network with an infrared satellite image background, and infrared in greyscale (256 grey shades) were collected for each landslide. An infrared image measures emitted radiation with a wavelength of 10-12 μm, which corresponds to emission from objects such as Earth's atmosphere and clouds. Warm objects emit more infrared energy than cold objects, allowing discrimination of warm low clouds (appear as grey) from cold high clouds (appear as white) (Ahrens 1994).

Techniques of evaluating cyclogenesis, locations of jet streams, surface fronts, centres of lows, and maximum vorticities were based on the principles developed by Weldon (1979) and Anderson (1987). Storm intensity was inferred by applying a colour scale, which corresponds to cloud-top height based on temperatures. Areas of rainfall were also estimated from the satellite images. Sequential images were acquired and studied for at least a week leading up to the failures to assess antecedent weather conditions and the evolution of specific weather systems. Hourly surface weather observations from nearby climate stations, where available, were examined to aid in the satellite interpretation.

4.4.3 Geographic information systems

ESRI® (Environmental Systems Research Institute) ArcMap 8.3™ was used to geo-reference satellite images to the British Columbia geographical boundary. For georeferencing, a third-order polynomial was generally used for transformation, and images were rectified by cubic convolution and the default cell size. Landslide latitude and longitude was overlaid onto the geo-referenced satellite image using ArcView GIS 3.2™.

4.5 Results

Nine of the 25 landslides are presented here to illustrate a range of storms and weather events that trigger landslides in northern British Columbia. All satellite imagery and hourly climate data associated with each of the 25 landslides are included in Appendix D (CD-Rom-2). Each landslide is briefly described (type, date, location, elevation, volume, length, and estimated damage, where known). Weather conditions at the time and site of the landslides are inferred from the satellite images and compared with what is known from the nearest climate stations. The nine case studies are divided into two categories, landslides that occurred during convective thunderstorms and landslides that occurred during large cyclonic (low pressure) systems.

4.5.1 Landslides during convective thunderstorms

4.5.1.1 Kendall Glacier rock avalanche

The Kendall Glacier rock avalanche occurred between July 12 and August 9, 1999, approximately 30 km northwest of McBride. The landslide has been described by Geertsema et al. (2006*a*). The failure initiated on a rock slope above a glacier and produced about 0.2 Mm^3 of debris that travelled 1.2 km. People in the region speculated that the landslide occurred during a summer cloudburst in early August; however, no rain was recorded at the nearest climate station in McBride. Weather satellite images were examined, along with hourly surface weather observations from the Prince George airport, for the period during which the rock avalanche occurred. The entire period was one of extensive cloud cover and rain showers caused by frontal activity and instability. Convective afternoon thunderstorms were common in the region from August 1 to 7 and lightning was recorded in the hourly observations at the Prince George airport on August 6 and 7 (Figure 4.2). These thunderstorms likely produced isolated and perhaps heavy rainfall at the site of the landslide, but not at the nearest climate station.

4.5.1.2 Muskwa-Chisca rock slide-earthflow

The Muskwa-Chisca rock slide-earthflow occurred between July 25 and 28, 2001 approximately 67 km southwest of Fort Nelson. Details are provided in Geertsema et al. (2006*a*). It initiated as a combination rotational and translational slide in flat-lying shale and sandstone, covered an area of 43 ha, travelled approximately 1.5 km, blocked a stream, and destroyed forest. Local reports indicate that heavy rain may have been the trigger. The nearest climate station, Tetsa River, approximately 30 km to the west, recorded 96.2 mm of rainfall on July 18 and 19, several days before the landslide occurred. Only a small amount of precipitation (<10 mm) fell during the period when the landslide took place. The weather satellite images show that there were several consecutive days of afternoon thunderstorms, likely producing heavy rain in the area from July 21 to 28. The most severe storm occurred on July 26 (Figure 4.3).

4.5.1.3 Gillis Mountain debris slides

The Gillis Mountain debris slides occurred on or about June 16, 2002, approximately 40 km southeast of Germansen Landing. They are thought to have been caused by rain-on-snow and by toe erosion from high flow (Marten Geertsema, personal communication, 2004). Temperatures approaching 30°C, almost 20°C above normal, were recorded at Germansen Landing for several days before the failures, contributing to rapid snowmelt. The high temperatures also contributed to afternoon convective thundershowers seen on the satellite images for June 14 to 16. The largest storm occurred on June 16 (Figure 4.4); 13.8 mm of rain were recorded at the Mackenzie airport, approximately 85 km southeast of the landslide on this day. The storm was associated with the passage of a cold front and included a short period of heavy rain, a sharp decrease in temperatures, and a shift in wind direction.

4.5.1.4 Harold Price rock slide-debris flow

The Harold Price rock slide-debris flow, 35 km northeast of Smithers, occurred between June 22 and 24, 2002. It has been described by Schwab et al. (2003). The landslide initiated at 1723 masl in deeply weathered and highly jointed volcanic bedrock, rubble, and a rock glacier. About 1.6 Mm^3 of debris travelled up to 4 km down-valley; some of the debris temporarily dammed Harold Price Creek. The estimated loss of harvestable timber is $1.6 million. The nearest climate station, at Suskwa Valley, 28 km northwest of the landslide, recorded only a small amount of precipitation between June 22 and 24. The satellite images, however, show a thunderstorm in the area of the landslide on the afternoon of June 23 (Figure 4.5). The storm likely produced heavy, although localized rain. The Smithers airport recorded a distant thunderstorm and associated heavy rains.

4.5.1.5 Legate Creek debris flows

Two debris flows at Legate Creek, approximately 35 km northeast of Terrace, occurred on July 15, 2004, at 19:00 PST and August 27, 2004, at 18:15 PST. Details on the landslides were provided by Jim Schwab (personal communication, 2004). The July 15 debris flow reached Highway 16 and had a total volume estimated at 7000 m^3. Three smaller landslides occurred at high elevation in the Legate Creek watershed on the same day. The August 27 debris flow had a volume of about 15,000 m^3 and deposited a large amount of debris on Highway 16, resulting in its temporary closure. Both debris flows had sources at approximately 1300 masl in highly weathered volcanic bedrock. They were likely triggered by intense thunderstorms. The satellite images showed several days of thunderstorm activity prior to July 15 due to above-average temperatures and an unstable air mass. A thunderstorm occurred when the first debris flow happened (Figure 4.6) and was marked by gusty winds and showers at the Terrace airport. Thunderstorms are also evident on satellite images taken on August 27 at the time of the second debris flow (Figure 4.7). Gusty winds and rain were recorded at the Terrace airport on August 27.

4.5.2 Landslides during large cyclonic storms

4.5.2.1 Khyex River flowslide

The Khyex River flowslide occurred on November 28, 2003 at 00:30 PST. It has been described by Schwab et al. (2004*a*, *b*). It severed the Pacific Northern Gas pipeline 35 km east of Prince Rupert, leaving Port Edward and Prince Rupert without gas for ten days. The landslide occurred in Pleistocene glaciomarine sediments, had a volume of 4.7 Mm^3, and blocked the river for a distance of 1.7 km. It was likely caused by bank erosion and high pore-water pressure. The Prince Rupert and Terrace airports recorded rain and snow showers daily from November 23 to 28. Satellite images show that a large, baroclinic leaf-patterned, low pressure system moved onto the north coast on November 26 and slowly moved through the area at the time of the landslide (Figure 4.8). The ten-day total precipitation leading up to the failure was 137 mm at Prince Rupert, with 41 mm of the total falling the day before the failure. This amount is not unusual for this time of year at Prince Rupert; however, precipitation at the landslide site may have been heavier. Moderate precipitation over several days may have raised the level of Khyex River, eroding the toe of the slope that failed.

4.5.2.2 Prince Rupert debris flows-debris avalanches

As many as 20 debris flows and debris avalanches were reported on the north coast between Prince Rupert and Terrace from November 4 to 6, 2004. Details on the landslides were provided by Jim Schwab (personal communication, 2004). Highway 16, 20 km east of Prince Rupert, was blocked by a debris flow on the night of November 4 near Rainbow Lake. Another debris flow, near Work Channel, severed the Pacific Northern Gas pipeline to Port Edward and Prince Rupert on the afternoon of November 5. A nearly stationary frontal system moved down the coast, prior to the landslide, bringing heavy rains (Figure 4.9). The storm entered the area on the morning of November 3 and culminated November 5 with the passage of a cold front. Precipitation data at the Prince Rupert airport are missing, but at the Terrace airport 11.0 mm, 49.2 mm, and 29.6 mm of rain were recorded for November 3, 4, and 5, respectively.

4.5.2.3 Pink Mountain rock slide-debris avalanche

The Pink Mountain rock slide-debris avalanche occurred in early July 2002, about 150 km northwest of Fort St. John. The landslide has been described by Geertsema et al. (2006*b*). It initiated at 1460 masl, had a volume of 1 Mm^3, and travelled 2 km. The most likely trigger is high pore-water pressure resulting from heavy rainfall and rapid melt of an above-average snowpack. Temperatures at the Sikanni Chief climate station, 23 km northeast of the landslide site, were above normal during June. Rain was recorded daily from June 29 to July 5, totalling 50 mm. Satellite images reveal that an inverted trough of low pressure stalled over the area from June 30 to July 5, accompanied by heavy rains (Figure 4.10).

4.6 Discussion

4.6.1 Case studies

Climate station data were of little value in assessing the relation between weather triggers and landslides for seven of the 25 investigated landslides. The climate stations were either too far from the landslides or the data for the time of interest were missing. Many of the landslides have sources at high elevations, far above the nearest climate station (e.g. Pink Mountain rock slide-debris avalanche, Harold Price rock slide-debris flow, Muskwa-Chisca rock slide-earthflow, Legate Creek debris flows). In these cases, climate data cannot be meaningfully used to assess the landslide triggers. Satellite images, however, provide valuable, although inferential information on weather conditions at the landslide site.

For eight of the 25 landslides, satellite images provide weather information that the nearest climate stations did not record. In seven out of the eight cases, the satellite images confirmed observer or local reports of weather events that may have triggered the landslides (e.g. Kendall Glacier rock avalanche, Muskwa-Chisca rock slide-earthflow, and Legate Creek debris flows). For example, satellite images confirmed a local observer report of a cloudburst over the Kendall Glacier rock avalanche area that was not recorded at the nearest climate station. A local observer reported heavy rains near the Muskwa-Chisca rock slide-earthflow that were not recorded at the nearest climate station. Satellite images showed that thunderstorms, likely associated with heavy precipitation, occurred over the landslide site at the time of the failure but not at the nearest climate station. For the Legate Creek debris flows, the nearest climate station recorded only small amounts of precipitation (1.6 mm on July 15 and 11.2 mm on August 27). In contrast, the satellite images show isolated thundershowers and possible heavy rainfall over the landslide area but not at the climate stations.

The satellite images help constrain the times of many of the studied landslides, including for example the Kendall Glacier rock avalanche, the Harold Price rock slide-debris flow, and the Pink Mountain rock slide-debris avalanche. The images pinpointed days of severe weather that were more likely to trigger landslides than days of fair weather.

Perhaps the greatest value of the satellite images is that they provide weather information that is independent of the climate station data. They also show that it is inadvisable to rely solely on climate data to interpret a weather trigger for a landslide. In several cases, the climate data did not provide any indication of weather favourable for landslides, whereas satellite images suggested otherwise.

Hourly surface weather observations, where available, are useful for studies of climate-triggered landslides. Daily precipitation totals from climate stations, however, provide little indication of the time or intensity of precipitation. Hourly surface observations provide more detail on precipitation intensity and type. For example, the precipitation total at the Fort Nelson airport for one of the days within the failure period of the Muskwa-Chisca rock slide-earthflow was 11.4 mm; however, the hourly surface weather report indicated this entire amount fell within one hour. Hourly data also may be augmented by informative off-hour observations, for example thunderstorms and strong winds. An automatic climate station will not record a thunderstorm, however, an observer recording hourly weather data often will.

4.6.2 Potential and future work

Satellite images can be combined with other information, such as weather radar data, upper air data, and synoptic climatology, to better evaluate weather associated with landslides. Weather (Doppler) radar can provide data on precipitation intensity and the direction of movement of precipitation in the atmosphere within a 200 km radius of the measuring station. Only one weather radar station currently exists in northern British Columbia, at Baldy Hughes, southwest of Prince George. Another weather radar station near Grande Prairie, Alberta, provides information for parts of the Peace River region of northeastern British Columbia.

Upper air stations are radiosonde instrument packages transported by balloon. They measure the vertical profile of temperature, humidity, pressure, and wind to altitudes of about 30 km. There are two upper air stations in northern British Columbia, one at Prince George and the other at Fort Nelson. Two other stations in Whitehorse, Yukon and Annette Island, Alaska, provide information for northwestern British Columbia and the north coast, respectively. Plots (tephigrams) made from the vertical profiles provide information about atmospheric stability and moisture layers, which are important in evaluating thunderstorms. This information, coupled with the satellite imagery, permit a more detailed analysis of the severity of a thunderstorm or may confirm a thunderstorm when a lightning image is not available.

Synoptic climatology methods can be used to locate weather anomalies associated with landslides. Average surface weather patterns (i.e. composites) for days on which landslides occur are examined and compared with a climatological average to evaluate whether or not storms that trigger landslides are abnormal. Weather satellite images alone do not provide information on the significance of weather patterns. Synoptic climatology analysis provides a better understanding of how large cyclonic events develop and the extent to which the conditions are anomalous.

4.7 Conclusion

Weather triggers for 25 well dated landslides from 1998 to 2004 were examined using satellite imagery. The satellite images were brought into a geographic information system to geo-reference the weather images to the landslide locations. The analysis indicated that convective thunderstorms occurred at times of several landslides in summer months. Isolated heavy rains associated with such storms are likely adequate to trigger many landslides, yet they may not be recorded at the nearest climate stations. Significant low pressure systems, seen in satellite images, are associated with several landslides yet, again, the inferred high precipitation was not always recorded at the nearest climate station. Satellite imagery provides more information that is closer in time and space to landslides than climate station data. It is particularly useful for investigating weather triggers of remote landslides where climate station data are sparse and unrepresentative of weather at failure sites. Interpretations made from satellite images can be improved with other weather analysis methods, including weather radar, radiosonde recording of upper air masses, and synoptic climatology. The use of climate station data alone for landslide failure analysis, especially in areas of sparse climate data and high elevation landslides, is inadvisable.

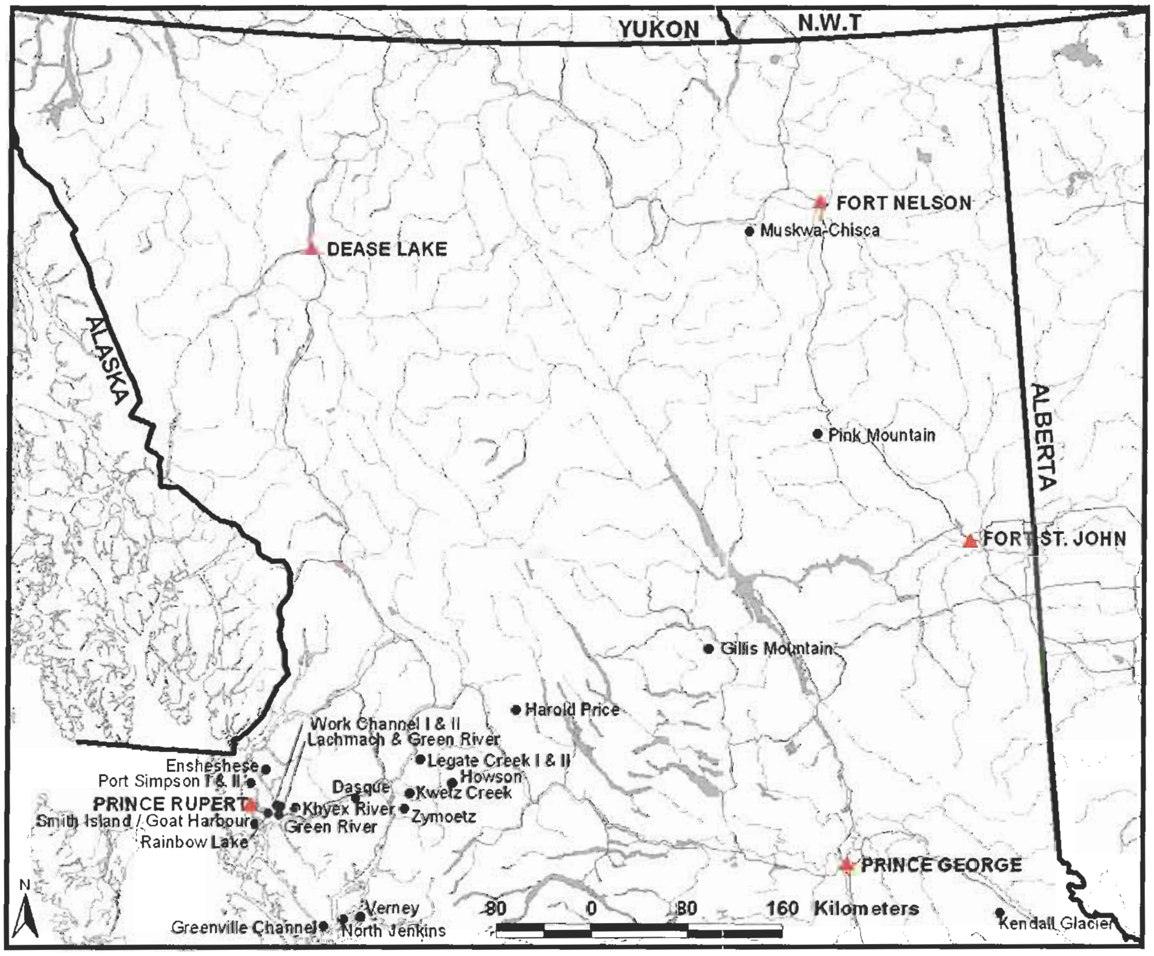

Figure 4.1. Landslides considered in this study, 1998-2004.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

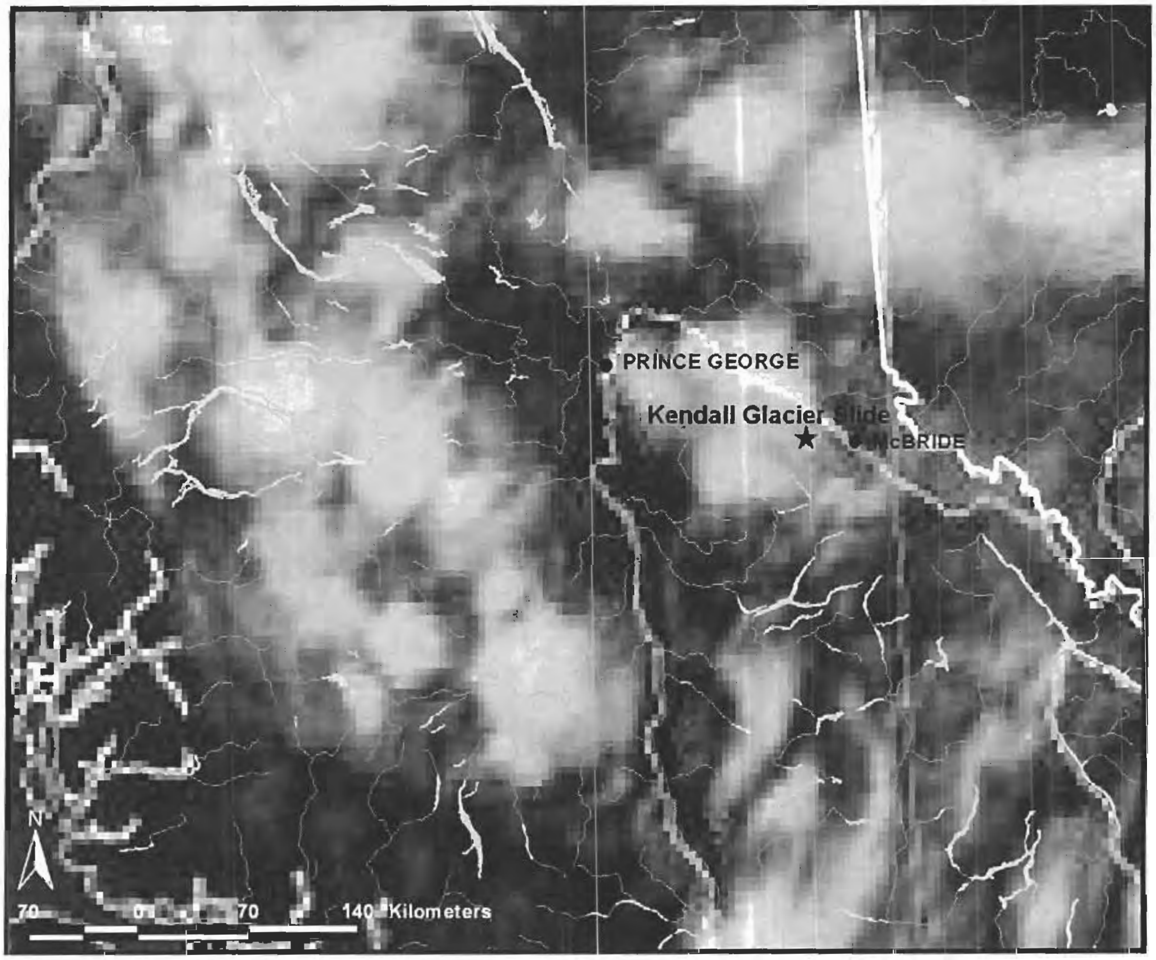

Figure 4.2. Thunderstorm, August 6, 1999, 17:00 PST.
In this infrared greyscale image, black corresponds to a temperature of 33°C and white, a temperature of -65°C. The white cumulus congestus and cumulonimbus clouds indicate convective activity and probable thundershowers.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

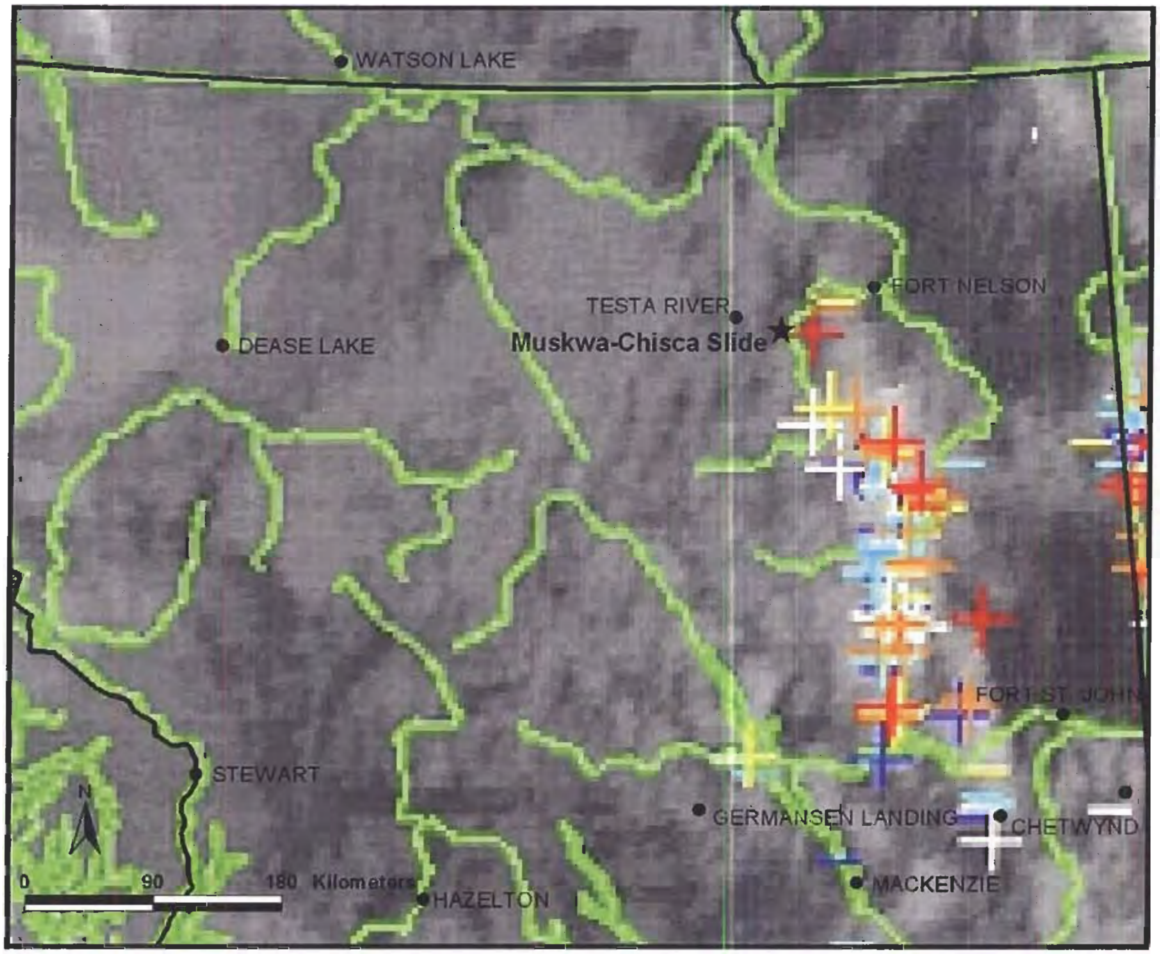

Figure 4.3. Thunderstorm, July 26, 2001, 14:00 PST.
Positive and negative symbols record lightning strikes and the colours are associated with a given time interval. Near the landslide area, the lightning strikes occurred between 13:50 and 14:00 PST.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

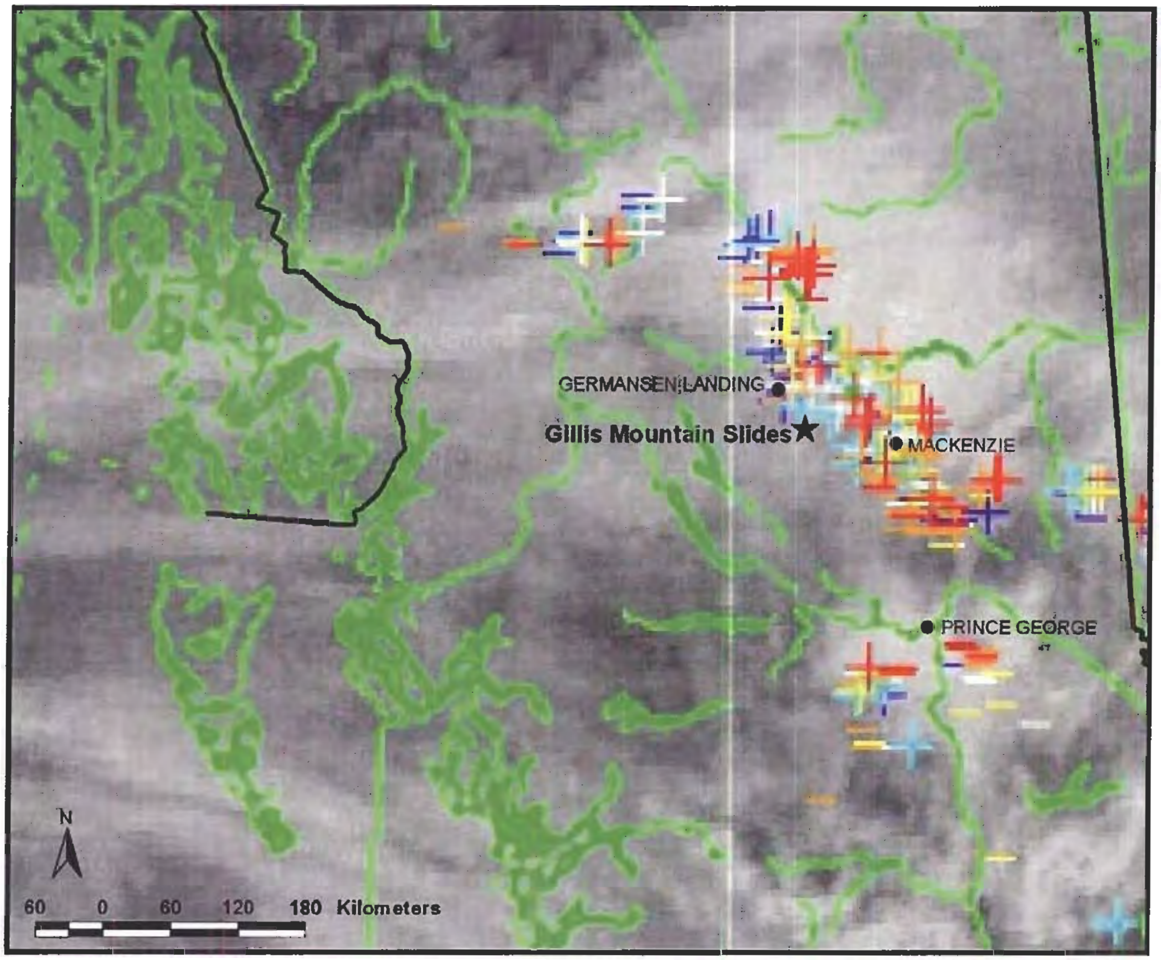

Figure 4.4. Thunderstorm, June 16, 2002, 16:00 PST.
An offshore low pressure system advected warm air into north-central British Columbia, producing convective afternoon thundershowers. Lightning strikes occurred near the landslide area between 15:10 and 15:20 PST.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

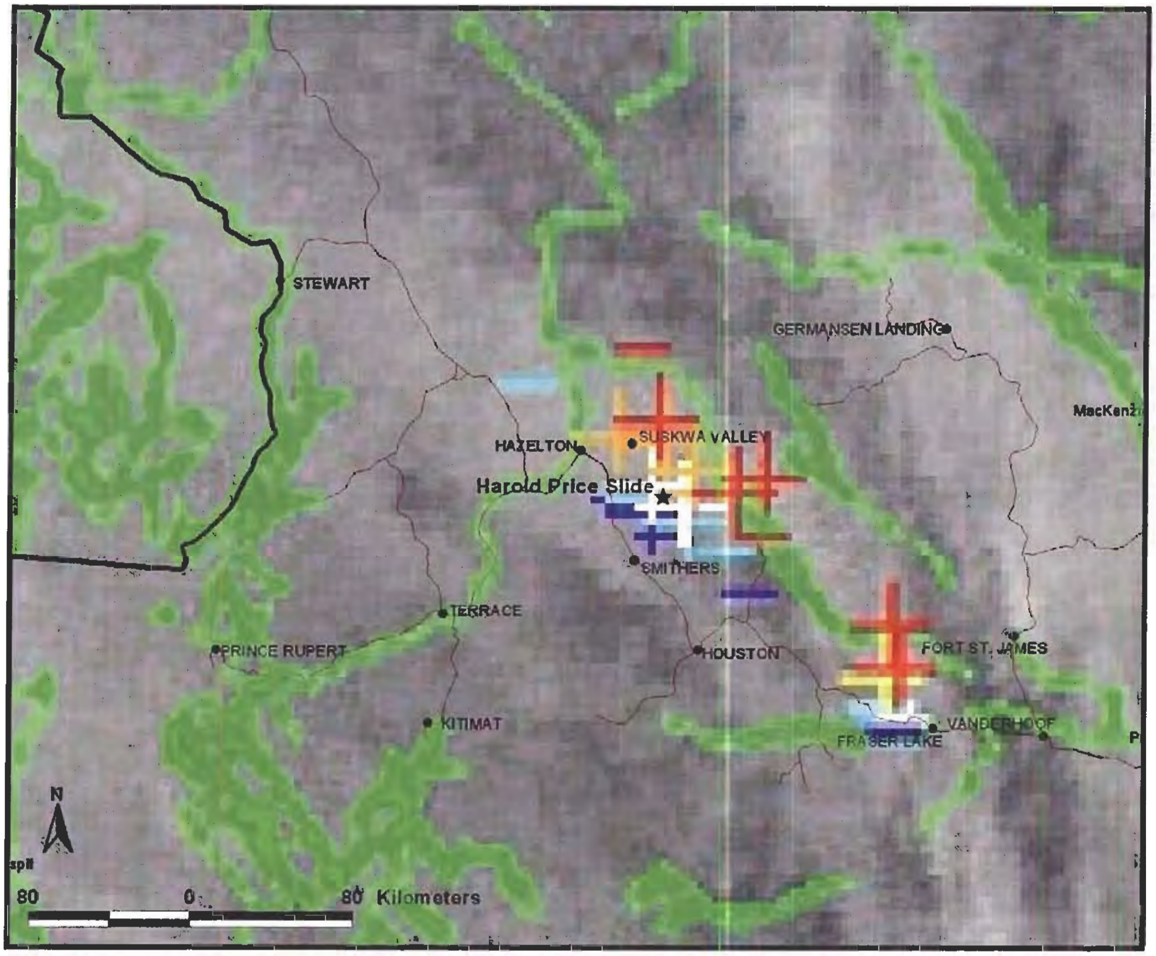

Figure 4.5. Isolated thunderstorm associated with a cold front, June 23, 2002, 13:00 PST. Lightning occurred near the landslide area between 12:10 and 12:30 PST.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

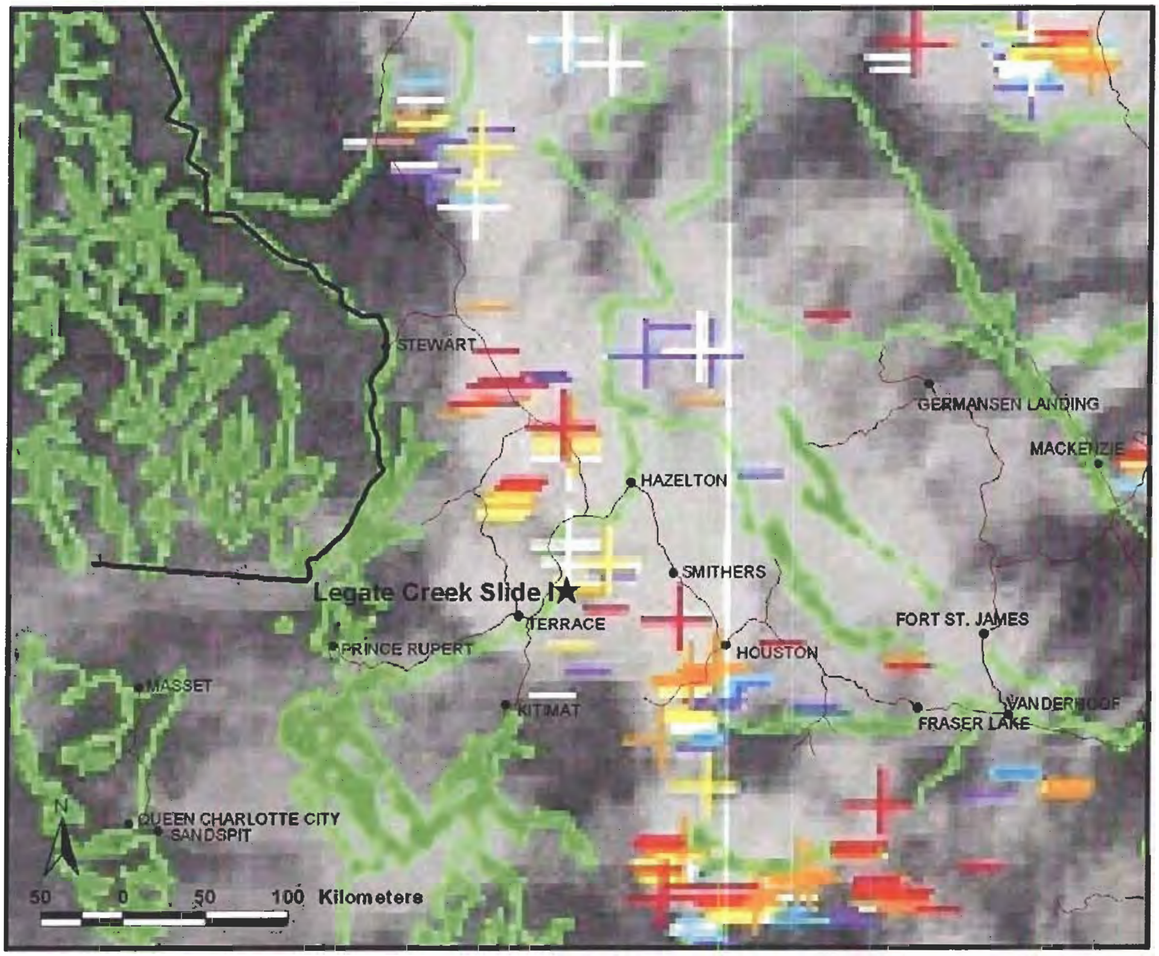

Figure 4.6. Lightning strikes, July 15, 2004, 19:00 PST.
Warm temperatures and instability led to convective activity and thunderstorms. The lightning strikes at Legate Creek occurred between 18:20 and 18:40 PST.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

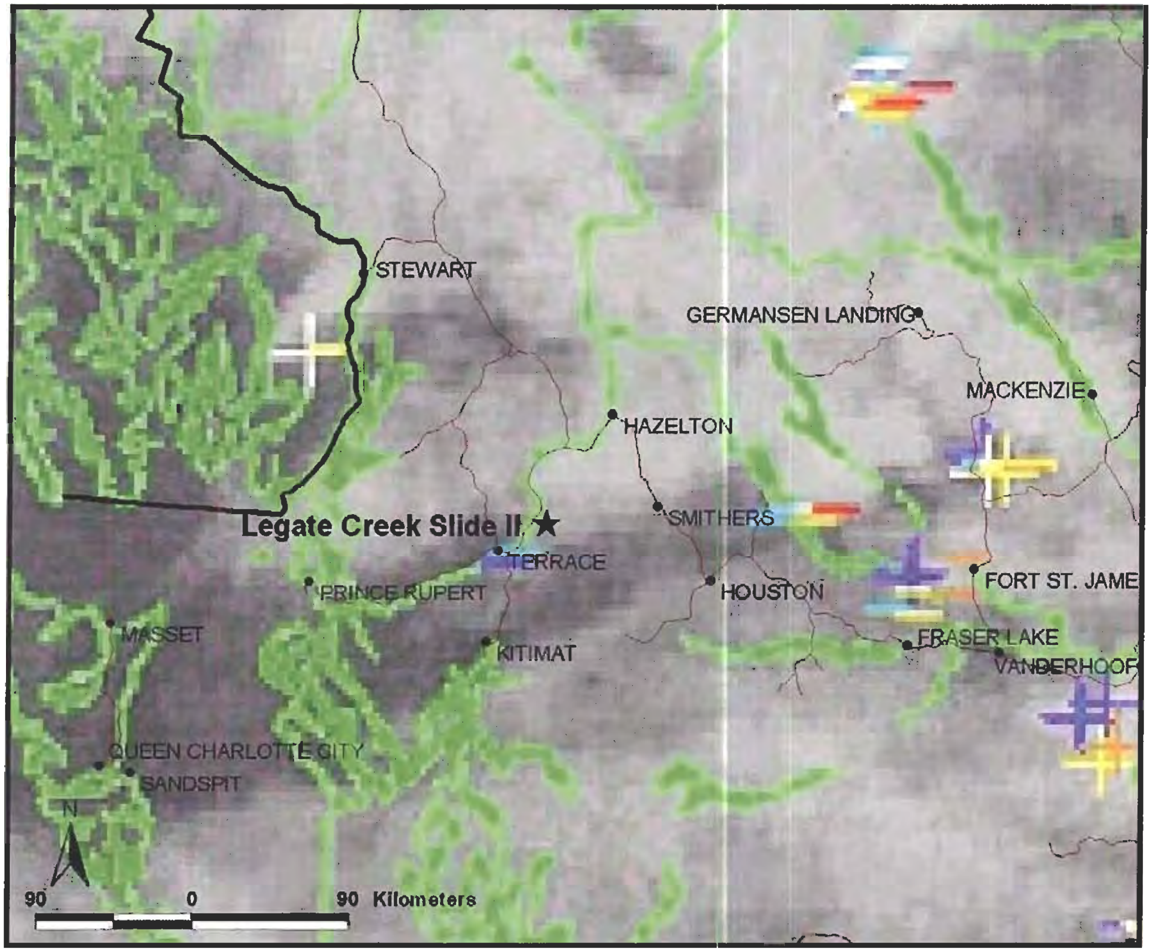

Figure 4.7. Thunderstorms, August 27, 2004, 19:00 PST.
Storms likely from instability and convective activity. Lightning near Legate Creek occurred at 18:00-18:10 PST.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

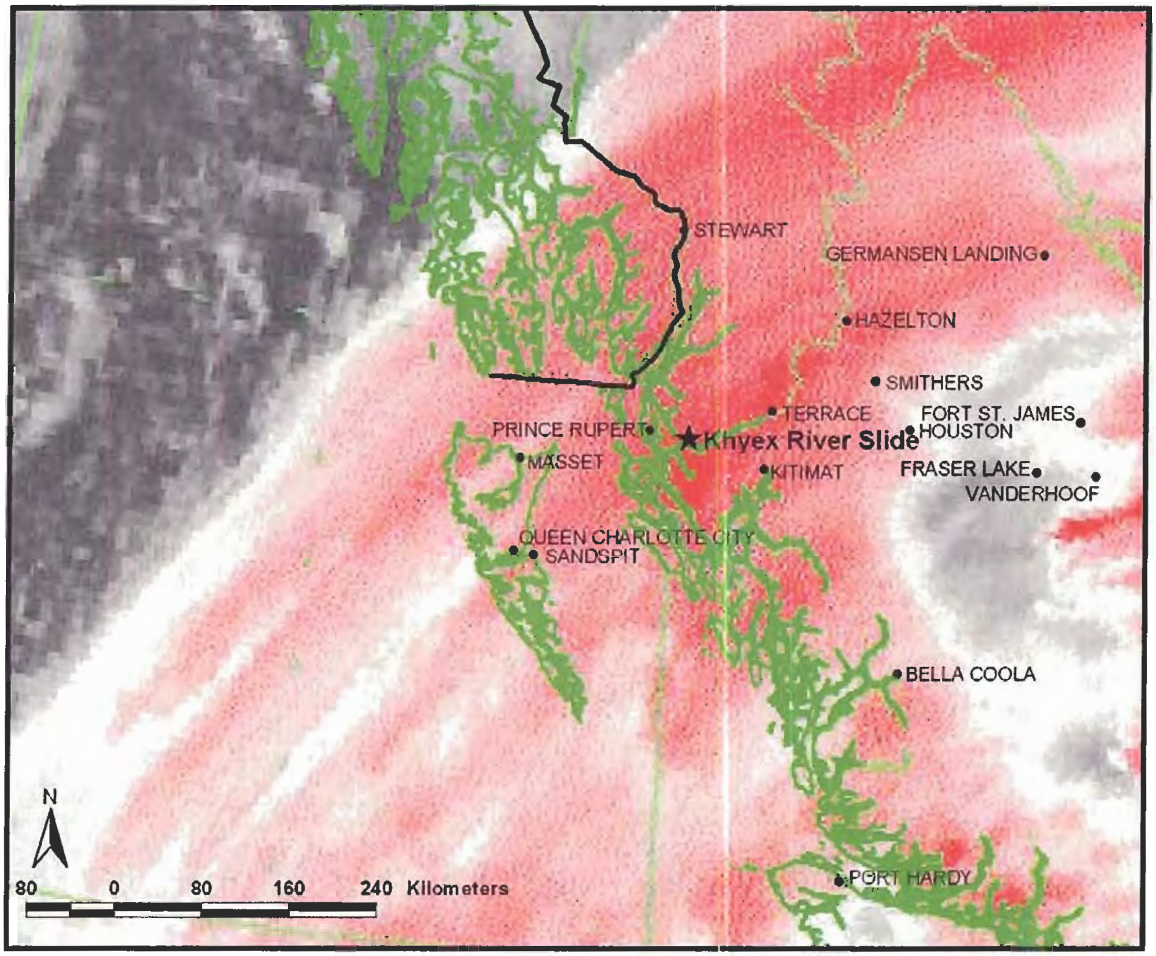

Figure 4.8. Red-enhanced infrared image of the storm on November 27, 2003, 15:30 PST. Cloud tops with temperatures less than -35°C appear red (brightest red corresponds to -57°C and grey to 5°C). The image shows part of the baroclinic leaf pattern that propagated to the northeast across central and northern British Columbia.
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

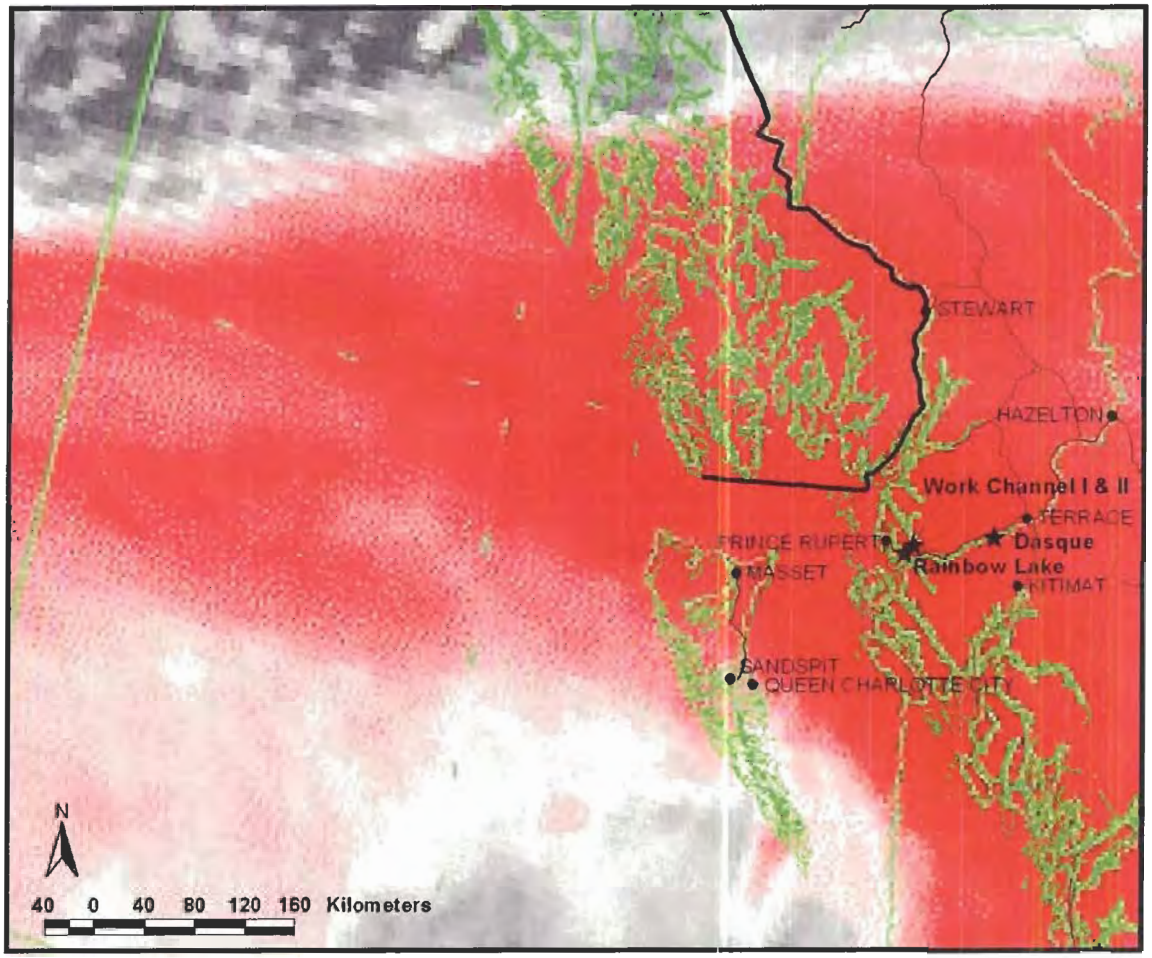

Figure 4.9. Red-enhanced infrared image of the storm on November 4, 2004, 01:30 PST. The lightest red corresponds to cloud tops at -35°C and the darkest red to cloud tops at -67°C. The storm maintained approximately the same position until the afternoon of November 5. (Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

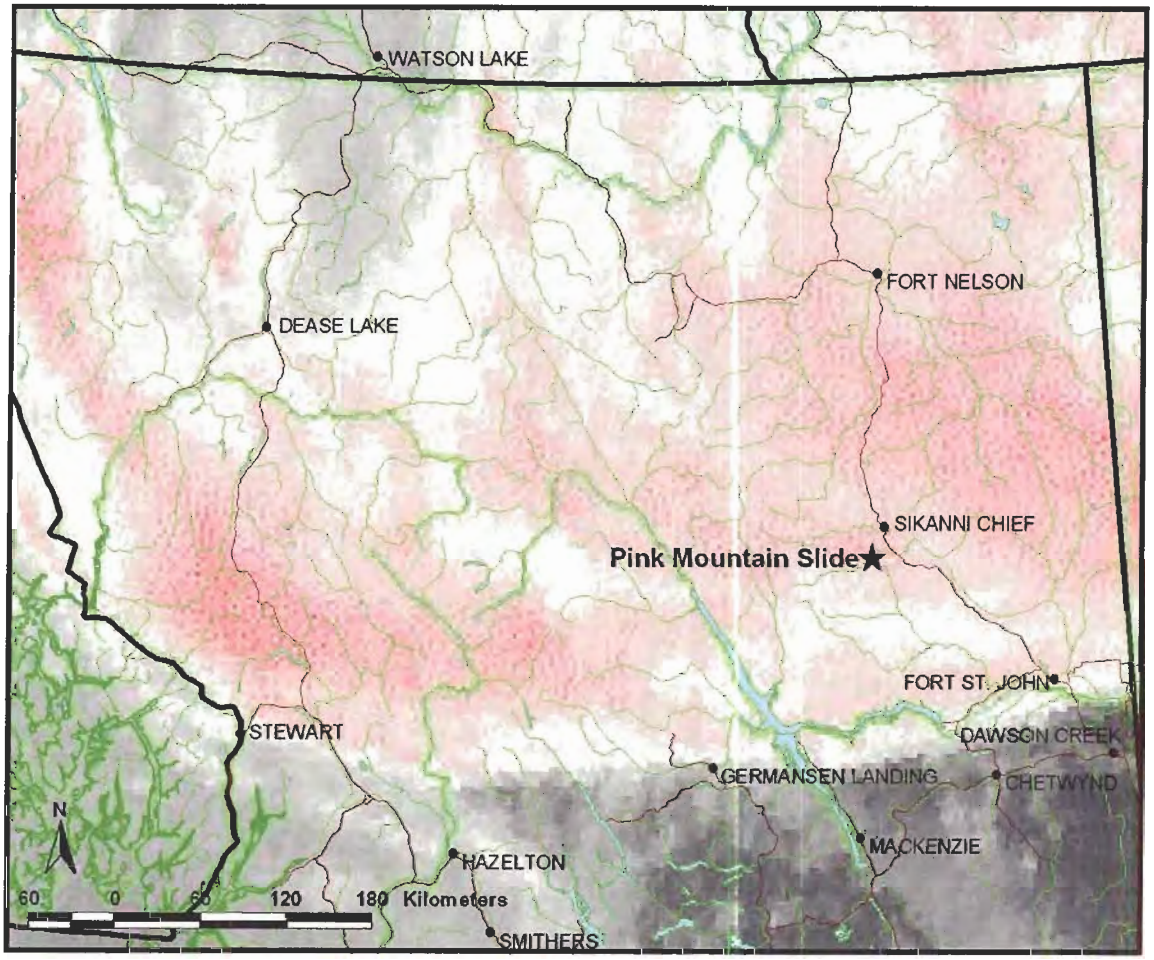

Figure 4.10. Red-enhanced infrared image of anomalous stationary trough, July 1, 2002, 00:00 PST. The highest cloud tops (light red) are estimated at -46°C. The system was associated with heavy rains and heavy rain warnings (Jim Goosen, personal communication, 2004).
(Spatial data source: http://www.em.gov.bc.ca/Mining/Geolsurv/MapPlace/geoData.htm).

Table 4.1. Landslide dates and types.

Name	Date (Time in PST)	Landslide Type
Kendall Glacier	Jul 12-Aug 9, 1999	Rock avalanche
Howson	Sep 11, 1999, 03:00	Rock slide-avalanche
Verney	Jun, 2002	Rock slide
Khyex River	Nov 28, 2003, 00:30	Flowslide
Muskwa-Chisca	Jul 25-28, 2001	Rock slide-earthflow
Zymoetz	Jun 8, 2002, 01:15-30	Rock slide-debris flow
Harold Price	Jun 22-24, 2002	Rock slide-debris flow
Pink Mountain	Jun 30-Jul 6, 2002	Rock slide-debris avalanche
Kwetz Creek	Oct 6, 2004	Slump-earthflow
Legate Creek I	Jul 15, 2004, 23:00	Debris flow
Legate Creek II	Aug 27, 2004, 18:15	Debris flow
Green River	Oct 23-27, 1999	Debris avalanche
Port Simpson I	Sep 18-19, 2002	Debris avalanches/flows
Port Simpson II	Oct 5, 2002	Debris avalanches/flows
North Jenkins	Oct 23-25, 2001	Debris avalanche
Lachmach/Green River	Oct 25, 2003	Debris flows
Gillis Mountain	Jun 16, 2002	Debris slides
Smith Island	Feb 4-8, 2000	Debris avalanche
Goat Harbour	Oct 22, 2000	Debris avalanche
Greenville Channel	Oct 22, 2000	Debris avalanche
Ensheshese	Nov 2, 1999	Debris avalanche
Work Channel I	Nov 5, 2004	Debris flow
Work Channel II	Nov 4-6, 2004	Debris flows
Rainbow Lake	Nov 4, 2004, 21:15	Debris flow
Dasque	Nov 4-6, 2004	Debris flows

CHAPTER 5 CONCLUSIONS

The objectives of this study were outlined as a series of questions: (1) Are there trends in the climate of northern British Columbia that can be extracted from meteorological data? (2) What is the relation between climate variability in the area and the El Niño Southern Oscillation and the Pacific Decadal Oscillation? (3) What meteorological conditions trigger landslides? (4) Are changes in climate responsible for an apparent increase in the frequency of landslides in northern British Columbia? The following paragraphs answer these questions based on the finding of this research.

Trends in climate in northern British Columbia are apparent from an analysis of meteorological data over the instrumental record (Chapter 2). Northern British Columbia has become warmer and wetter in the twentieth century, except east of the Rocky Mountains where climate is drier or shows no significant trends. Mean, maximum, and minimum temperatures have generally increased, minimum temperatures the most and maximum temperatures the least. The only negative temperature trend is spring maximum temperature. Overall, the largest increases in temperature have been in the Fraser Basin. Precipitation has increased at most climate stations, with the largest increases commonly in summer. In contrast, winters overall are drier.

Climate variability in northern British Columbia is related to the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Some strong El Niño events, for example those in 1992 and 1997, are characterized by above-average precipitation or temperature. However, this pattern is not consistent throughout northern

British Columbia, and not all strong El Niño and La Niña events are evident in the climate data. ENSO does not appear to play a strong role in the climate of northern British Columbia, but it does produce significant departures from average climate conditions during strong events. PDO can be seen in mean temperature trends, especially the shift from below-average to above-average temperatures in the 1970s. PDO effects on precipitation patterns are less obvious. Periods of above- and below-normal precipitation at some coastal weather stations correspond, respectively, to the warm and cool phases of the PDO. However, the opposite occurs for some interior stations, and neither trend is consistent for all stations.

Chapters 3 and 4 illustrate different meteorological conditions that can trigger landslides. Conditions that favour landslides include heavy precipitation, warm temperatures, sudden changes in temperature, rain-on-snow, wet snow, thunderstorms, large cyclonic storms, and long periods of above-average temperature or precipitation. Causes of landslides that are related to climate were examined in Chapter 3, and weather triggers of landslides were investigated in Chapter 4. A close relation exists between climate causes and triggers and landslide type. Historic, large landslides in bedrock in northern British Columbia occurred during years or long periods of above-average temperature. In contrast, landslides in unconsolidated sediments occurred during years or long periods of above-average precipitation. Most of the analyzed failures occurred after warm or variable winters. Analysis of weather satellite images (Chapter 4) has shown that convective thunderstorms and large cyclonic storms may have triggered some landslides in the study area in recent years.

Changes in climate documented in this thesis may be responsible for the apparent increase in the frequency of landslides in northern British Columbia. Studies in other areas have demonstrated a connection between climate change and the incidence of landslides. Long-term increases in temperature and precipitation, which are overprinted by shorter-term variability linked to Pacific ocean-atmosphere oscillations, may be preconditioning slopes of marginal stability for failure. Intense or large-scale storms may be the triggers of such failures.

The frequency of landslides in northern British Columbia will probably increase if the climate trends found in this study persist. Similarly, more rapid shifts in the mean state of climate associated with phases of ocean-atmosphere oscillations will alter slope stability. Any increase in landslide incidence in northern British Columbia will adversely affect infrastructure, fish habitat, and forestry.

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APPENDICES

Appendix 1. The *t*-test of slope.

Formulas for the significance test of regression slope (*t*-test of slope) are as follows (Moore and McCabe 1999):

$$t = \frac{b_1}{SE_{b1}}, \qquad H_0 \text{ is } \beta = 0 \tag{1}$$

$$H_a \text{ is } \beta \neq 0$$

where β is the true slope, b_1 is the estimated slope, and SE_{b1} is the standard error in slope.

$$b_1 = r\frac{S_x}{S_y} \tag{2}$$

where S_x is the standard deviation in x, S_y is the standard deviation in y, and r is the correlation.

$$S_x = \sqrt{\frac{1}{n-1}\sum\left(x_i - \bar{x}\right)^2} \tag{3}$$

where x_i is the year or season at time i, $\bar{x}$ is the average time, and n is the number of years of record.

$$S_y = \sqrt{\frac{1}{n-1}\sum\left(y_i - \bar{y}\right)^2} \tag{4}$$

where y_i is the climate parameter at time i and $\bar{y}$ is the average of the climate parameter.

$$SE_{b1} = \frac{S}{\sqrt{\sum\left(x_i - \bar{x}\right)^2}} \tag{5}$$

where S is the standard deviation about the line $= \sqrt{S^2}$ and S^2 is the sum of squares of the residuals divided by n-2.

$$S^2 = \frac{\sum e_i^2}{n-2} \qquad (6)$$

where e_i are the residuals.

$$e_i = y_i - \hat{y} \qquad (7)$$

$$\hat{y} = b_0 + b_1 x_i \qquad (8)$$

where b_0 = the intercept.

$$b_0 = \overline{y} - b_1 \overline{x} \qquad (9)$$

After t was calculated, it was compared to the critical value of t with n-2 degrees of freedom and 0.05 probability (Moore and McCabe 1999). If t-observed is greater than t-critical, H_0 is rejected and the trend is statistically different from zero.

The slope of some climate trends is not statistically different from zero. The data were retained in the regional analysis, however, as small or zero trends are still important and eliminating them would bias the regional data.

Appendix 2. Climate stations regional groups.

1	**Gwaii Haanas**	
	Langara	1936-2001
	Masset A	1897-1968
	Sewall Masset Inlet	1974-2002
	Tlell	1950-1999
	Dead Tree Point	1939-1958
	Queen Charlotte City	1914-1948
	Sandspit A	1945-2003
	Pallant Creek	1980-1998
	Sewell	1973-1990
	Tasu Sound	1963-1984
	Ikeda Bay	1908-1920
	Cape St. James	1925-1998
2	**Boundary Ranges/Yukon Stikine Highland**	
	Premier	1926-1996
	Stewart	1910-1967
	Stewart A	1974-2003
	Anyox	1916-1935
	Alice Arm	1948-1964
	Pleasant Camp	1974-2003
	Fraser Camp	1973-2003
3	**Coastal Gap**	
	Mill Bay	1915-1959
	Nass Harbour	1900-1929
	Green Island	1978-2003
	Port Simpson	1886-1910
	Prince Rupert	1908-1962
	Prince Rupert A	1962-2003
	Prince Rupert R Park	1959-1997
	Prince Rupert Mont Circ	1959-2003
	Prince Rupert Shawantlans	1966-1999
	Triple Island	1989-2002
	Falls River	1931-1992
	Kitimat(2)	1951-1966
	Kitimat Townsite	1954-2003
	Kitimat 2	1966-2003
	Kitimat 3	1988-2003
	Kildala	1966-2000
	Tahtsa Lake West	1951-2000
	Kemano	1951-2003
	Hartley Bay	1973-1996
	Bonilla Island	1960-2003
	Ethelda Bay	1957-1991
	Kitimat	1979-1994
	Swanson Bay	1917-1942
	Boat Bluff	1974-2003
	McInnes Island	1954-2003
	Ocean Falls	1924-1986
	Bella Coola A	1983-2003
	Bella Coola	1895-2002
	Bella Bella	1933-1977
	Dryad Point	1977-2003
	Pointer Island	1977-1989
	Namu	1931-1985
	Rivers Inlet	1893-1943
	Stuie Tweedsmuir Lodge	1932-2003
4	**Nass Ranges**	
	Murder Creek	1973-1994
	Hazelton Temlehan	1973-1997
	New Hazelton	1914-1976
	Aiyansh	1924-1971
	Nass Camp	1974-2003
	Cedarvale	1973-1994
	Rosswood	1927-1946
	Rosswood(2)	1973-1993
	Terrace	1912-1953
	Terrace A	1953-2003
	Terrace PCC	1968-2003
5	**Skeena/Omineca Mountains**	
	Suskwa Valley	1982-2003
	Unuk River Eskay Creek	1989-2003
	Bob Quinn AGS	1977-1994
	Takla Landing	1962-1991
	Germansen Landing	1951-2003
	Mackenzie A	1971-1994
6	**Fraser Plateau - North**	
	Smithers A	1942-2003
	Smithers CDA	1938-1968
	Telkwa	1922-1968
	Maclure Lake	1924-1963
	Quick	1962-1995
	Houston	1957-2003
	Equity Silver	1981-2003
	Burns Lake Decker Lake	1949-1973
	Burns Lake	1969-1990
	Burns Lake CS	1990-2003
	Nadina River	1934-1962
	Southbank	1962-1976
	Grassy Plains	1957-1976
	Takysie Lake	1987-2003
	Wistaria	1926-2003
	Ootsa Lake Skins Lake Spill.	1956-2003

6	**Fraser Plateau - North (cont'd)**	
	Fraser Lake North Shore(2)	1969-2003
	Fort Fraser 13S	1970-1993
	Hixon	1970-2003
	Woodpecker	1934-1945
7	**Fraser Basin**	
	Fort Babine	1944-1975
	Babine Lake Fisheries	1912-1936
	Topley Landing	1965-2003
	Babine Lake Pinkut Creek	1968-2003
	Kalder Lake	1973-1988
	Tachie 1SE	1973-1985
	Fort St. James	1895-2003
	Fort St. James A	1979-1991
	Vanderhoof	1916-1966
	Vanderhoof(3)	1980-2003
	Prince George	1912-1945
	Prince George A	1942-2003
	Prince George STP	1975-2003
	Prince George 15NW	1984-2000
	Prince George Miworth	1984-2002
	Aleza Lake	1952-1980
8	**Columbia Highlands/Northern Columbia Mountains/Western Continental Ranges**	
	Barkerville	1888-2003
	Cariboo Lodge	1975-2003
	Mount Robson Ranch	1975-1992
	Red Pass Junction	1931-1969
9	**Southern Rocky Mountain Trench - North**	
	Dome Creek	1917-1951
	Dome Creek(2)	1970-1995
	McBride 4SE	1922-1980
	McBride Elder Creek	1992-2003
	McBride North	1973-1992
	Dunster	1974-1995
	Tete Jaune(2)	1989-2003
	Valemount	1914-1975
	Valemount East	1970-2003
	Valemount North	1971-1989
10	**Central Canadian Rocky Mountains**	
	Hudson Hope BCHPA Dam	1963-1989
	Pine Pass Mt. Lemoray	1974-2003
	Bullmoose	1982-2003
	Tumbler Ridge	1985-2003
	Denison Plant Site	1982-1998
11	**Peace River Basin**	
	Hudson Hope	1916-2000
	Chetwynd BCFS	1970-1982
	Chetwynd A	1982-2003
	Sweetwater	1932-1945
	Pouce Coup	1926-1939
	Dawson Creek	1950-1963
	Dawson Creek A	1968-2003
	Taylor Flats	1960-2003
	Fort St. John A	1942-2003
	Baldonnel	1927-1993
12	**Central Alberta Uplands**	
	Beatton River A	1944-1967
	Sikanni Chief	1990-2003
	Wonowon	1973-1991
	Rose Prairie	1973-1988
	Cecil Lake CDA	1961-1980
	Charlie Lake	1988-2003
13	**Northern Canadian Rocky Mountains/ Hay River Lowlands**	
	Fort Nelson A	1937-2003
	Muncho Lake	1970-2003
	Toad River	1982-1995
	Tetsa River	1982-2003
14	**Yukon Southern Lakes/Liard Basin**	
	Watson Lake A	1938-2003
	Smith River A	1944-1969
	Whitehorse A	1942-2003
	Teslin A	1943-2003
15	**Boreal Mountains and Plateaus**	
	Graham Inlet	1973-2003
	Atlin	1905-2003
	Good Hope Lake	1973-1986
	Cassiar	1954-1992
	Dease Lake	1944-2003
	Telegraph Creek	1942-1979
	Telegraph Creek (2)	1979-2000
	Iskut Ranch	1976-1994
	Todagin Ranch	1973-1992
	Ware	1966-1987
	Ingenika Point	1972-1984

Appendix 3. Weighted standard deviation and standard error.

Weighted standard deviation and standard error were calculated as follows for all weighted averages and used to test significance of the trends from zero (Bland and Kerry 1998).

First, the weighted sum of squares was calculated:

$$= \frac{\sum\left(w_i\left(x_i^{\,2}\right)\right)}{\frac{\sum w_i}{n}} \qquad (1)$$

where w_i is the weight (number of years of station record), x_i is the station total precipitation (or mean, maximum, or minimum temperature) over its entire record, i is the station, and n is the number of stations with the region.

Second, the following correction factor was subtracted from the weighted sum of squares to obtain the sum of squares about the mean:

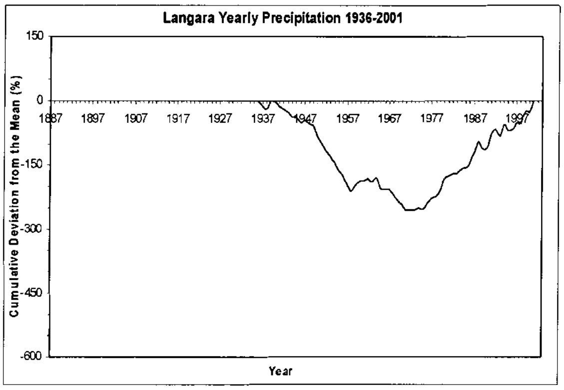
$$n \times \overline{x_w}^{2} \qquad (2)$$

where $\overline{x_w}$ is the weighted average.

Third, the weighted estimate of variance was calculated by dividing the sum of squares about the mean by the degrees of freedom, n – 1. The standard deviation, s, is the square root of the weighted estimate of variance and the standard error is:

$$\frac{s}{\sqrt{n}} \qquad (3)$$

Appendix 4. Graphs of cumulative departure from the mean for stations with more than 50 years of record.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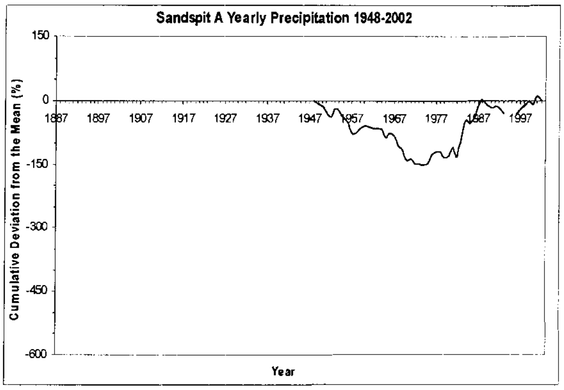
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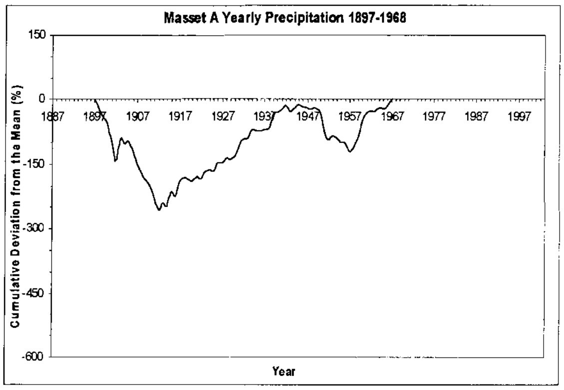
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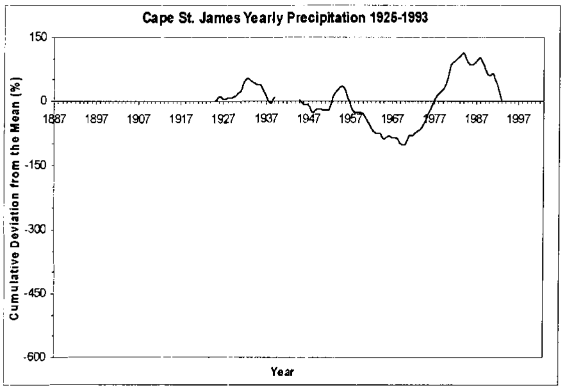
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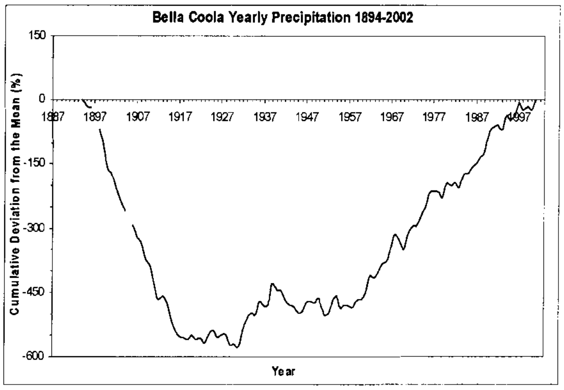
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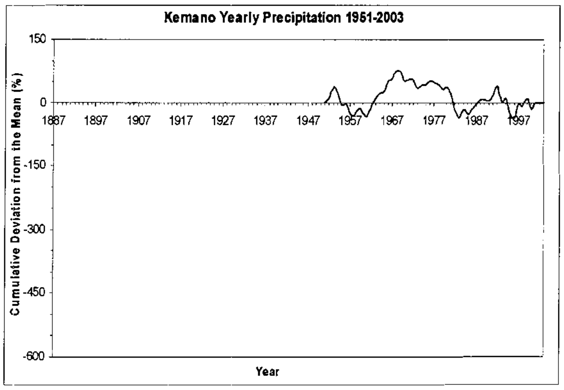
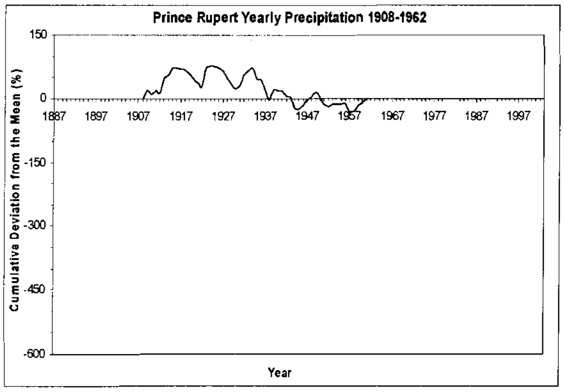

Kemano Yearly Precipitation 1951-2003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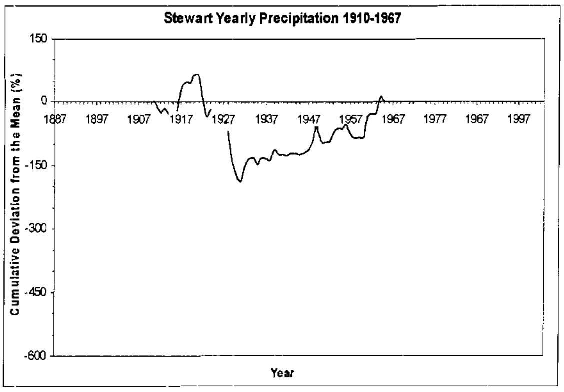
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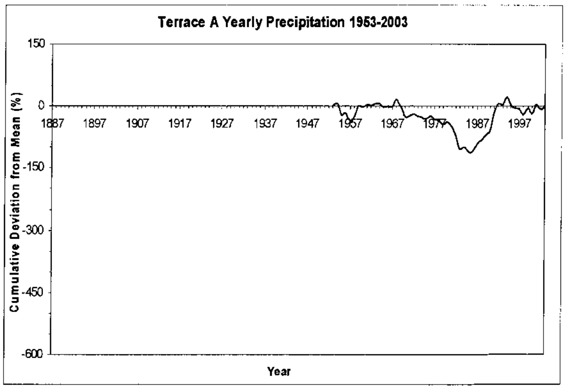
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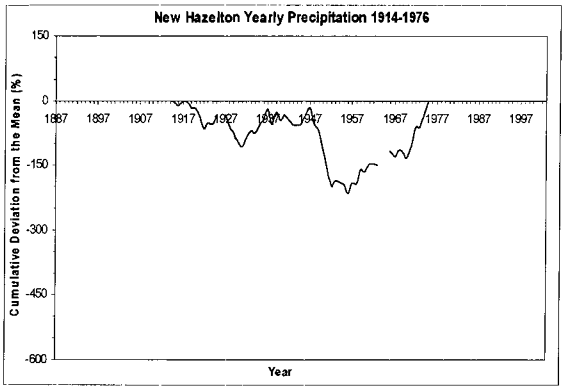
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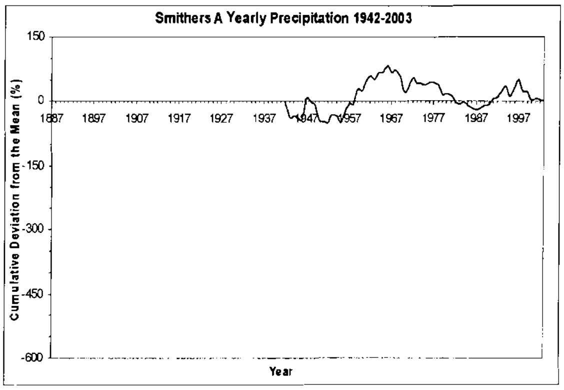
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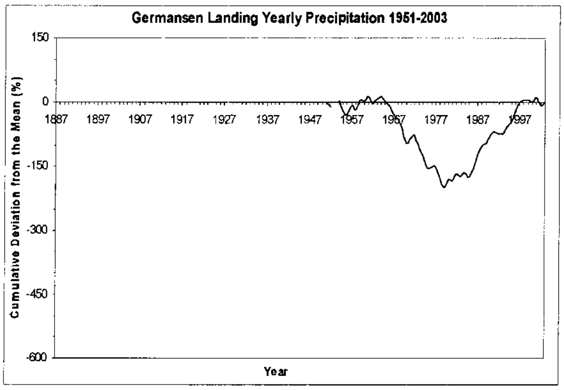
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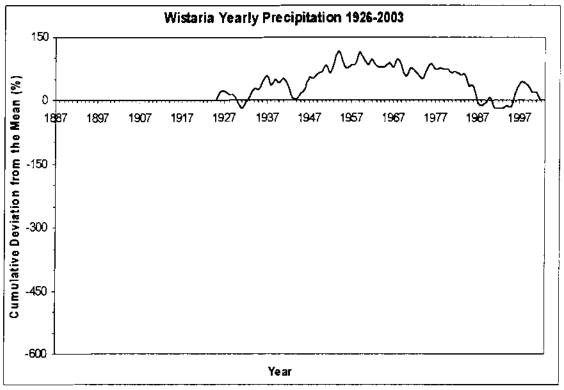
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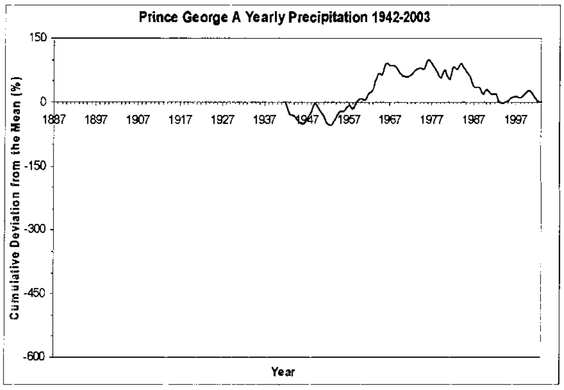
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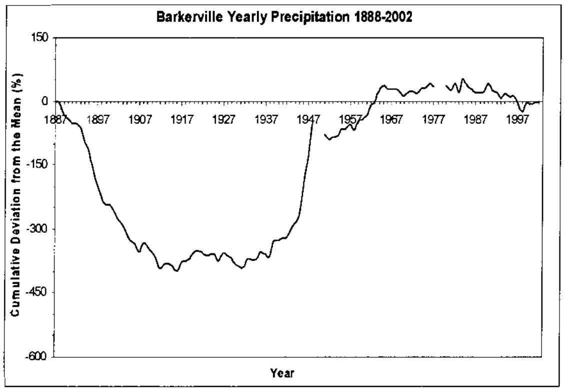
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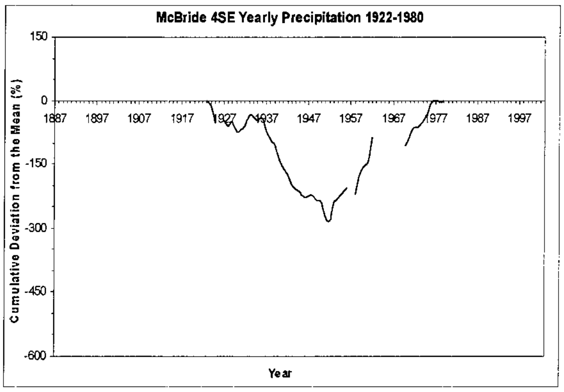
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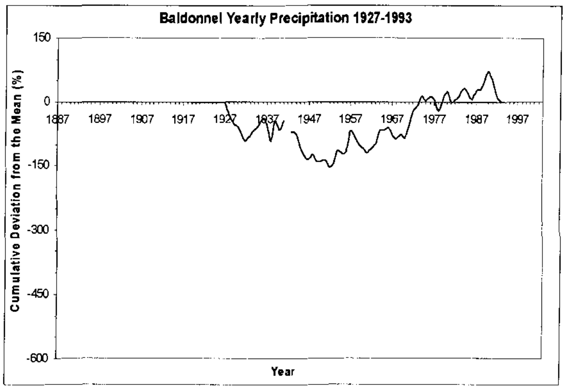
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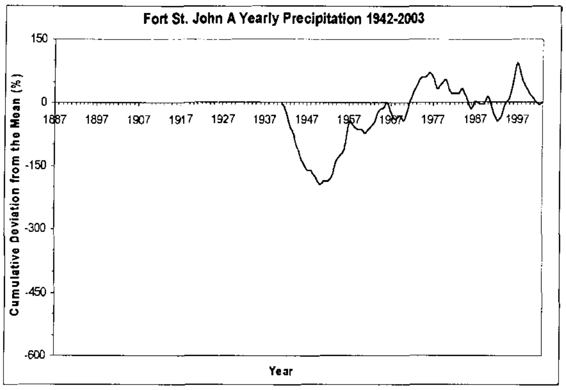
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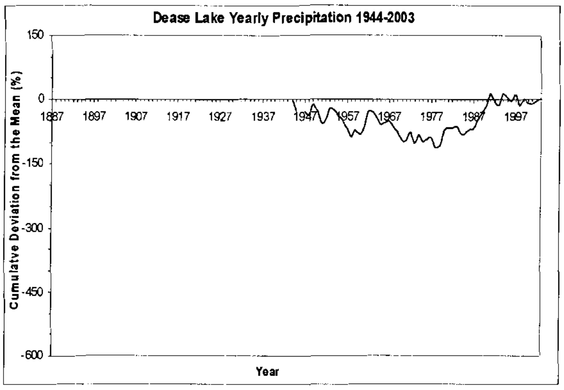
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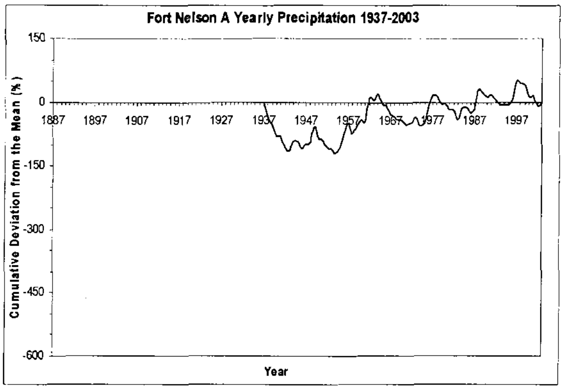
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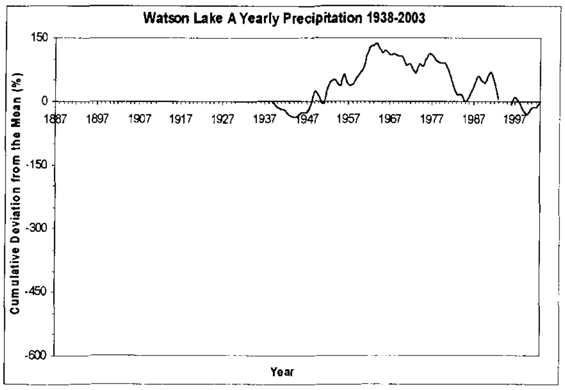
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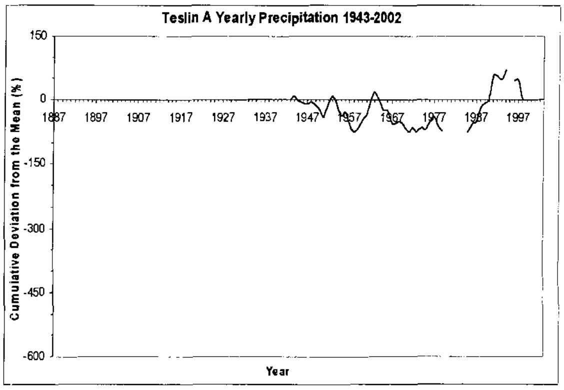
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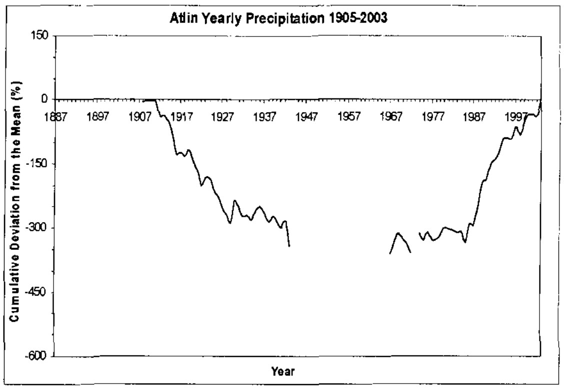
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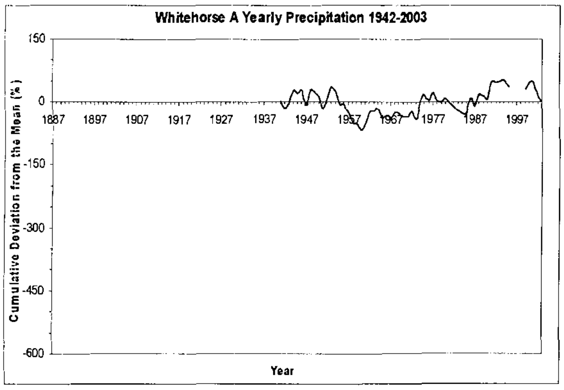
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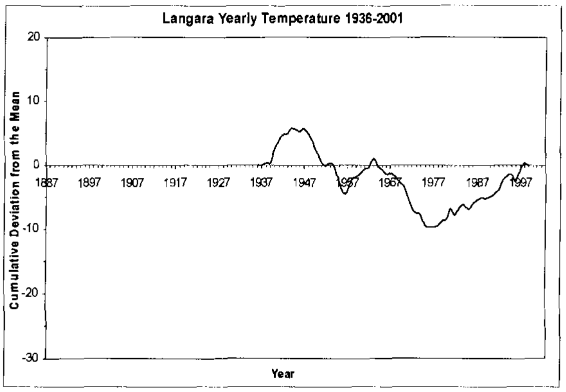
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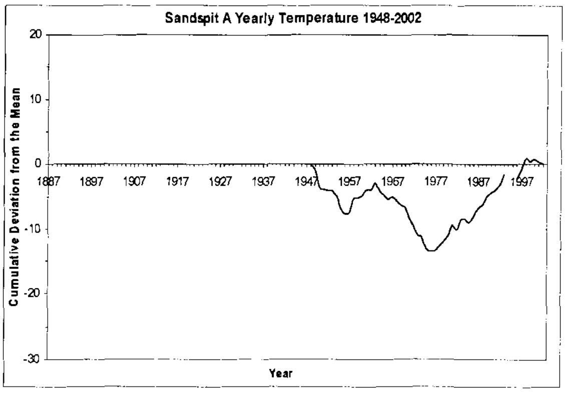
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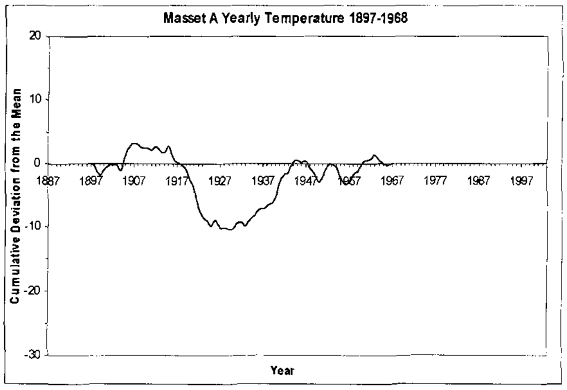
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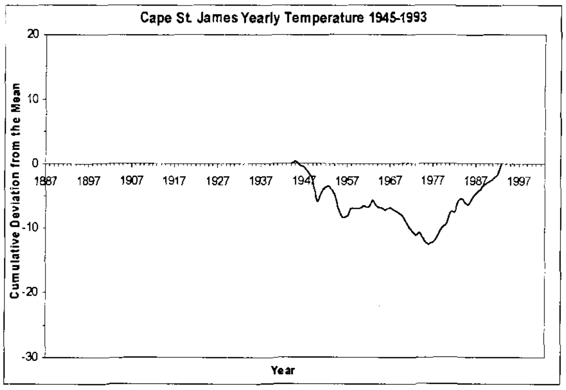
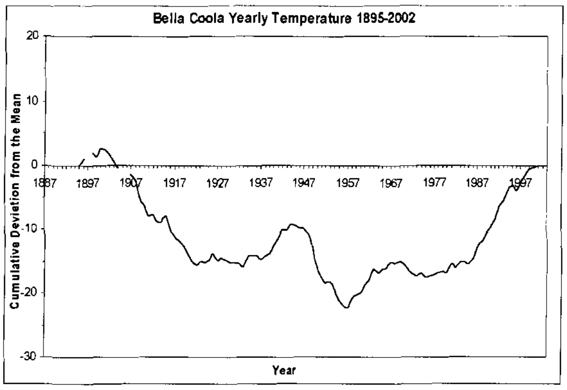
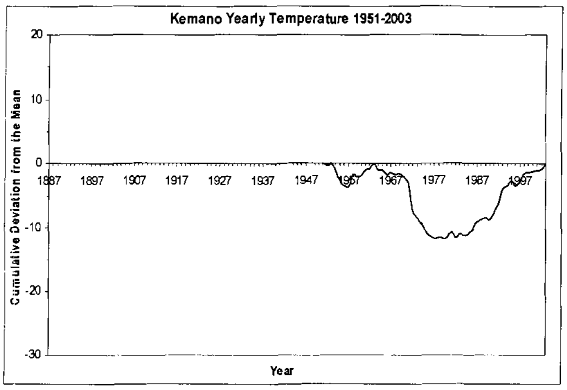

Cape St James Yearly Temperature 1945-1993


Bella Coola Yearly Temperature 1895-2002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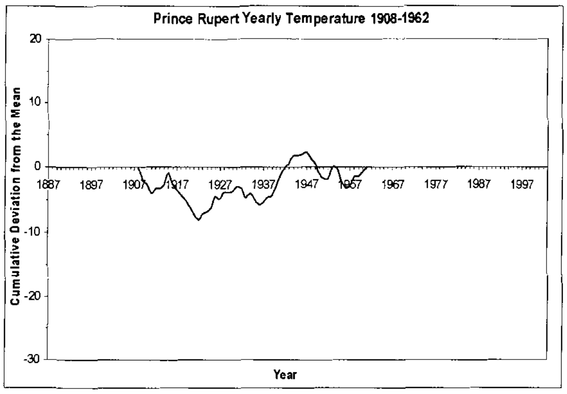
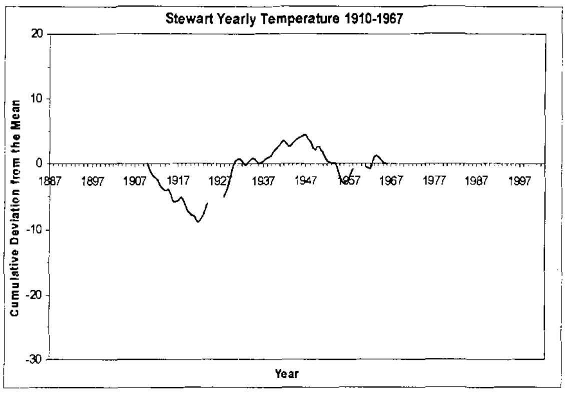

Prince Rupert Yearly Temperature 1908-1962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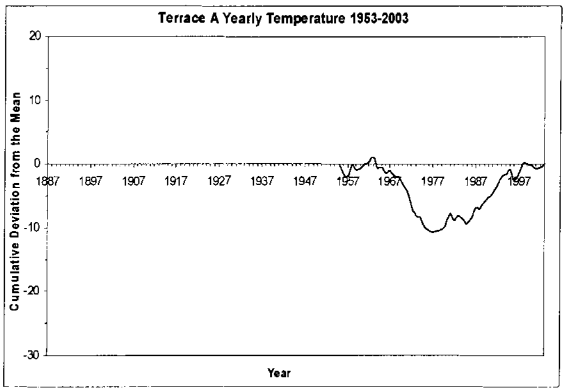

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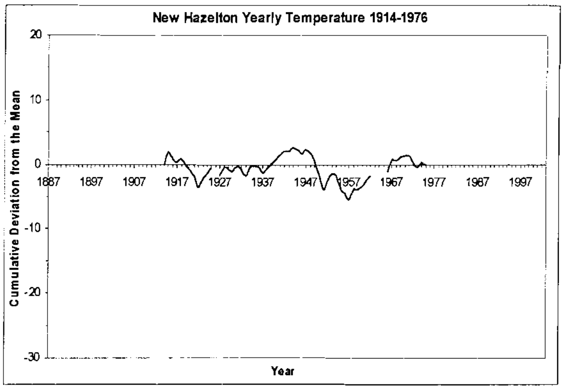

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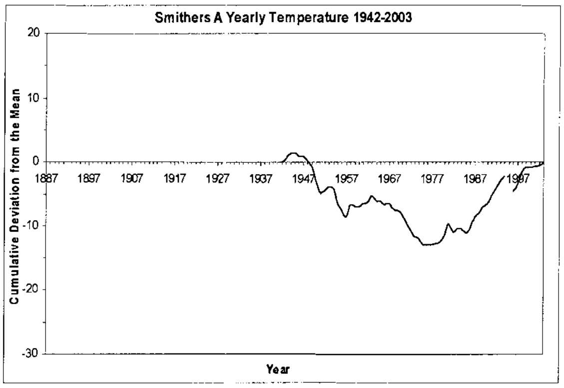
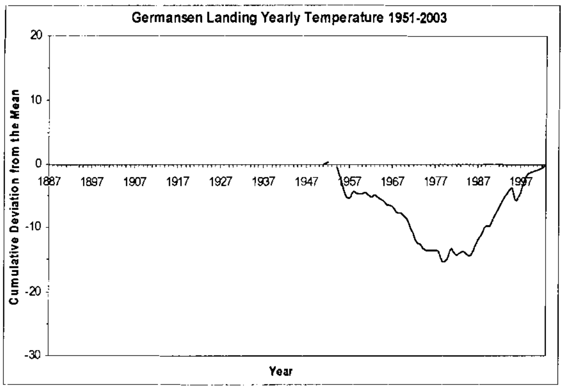


Smithers A Yearly Temperature 1942-2003



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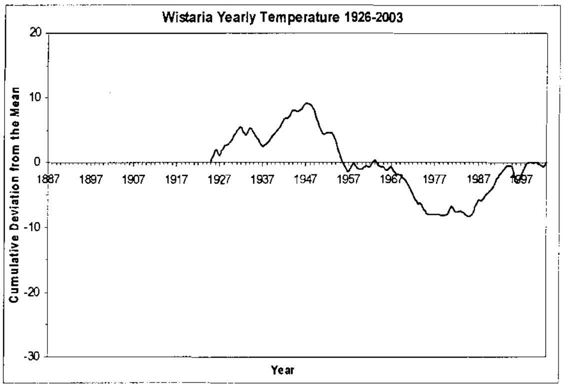

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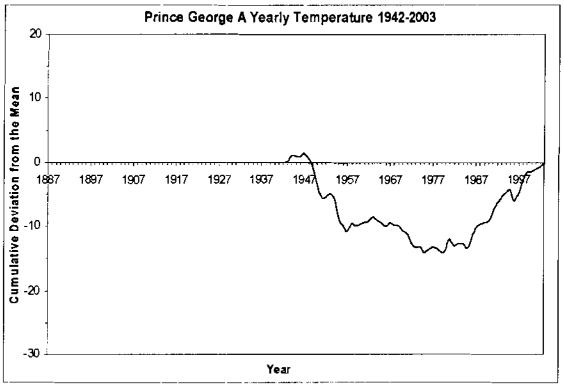
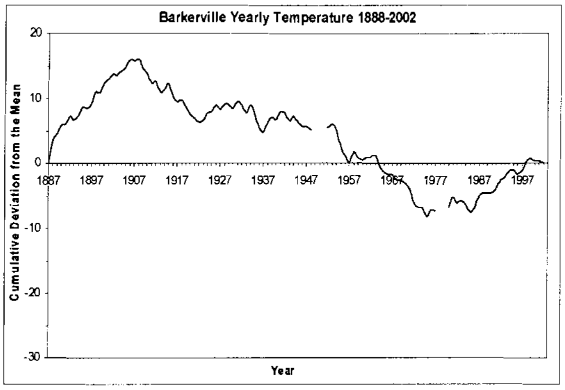
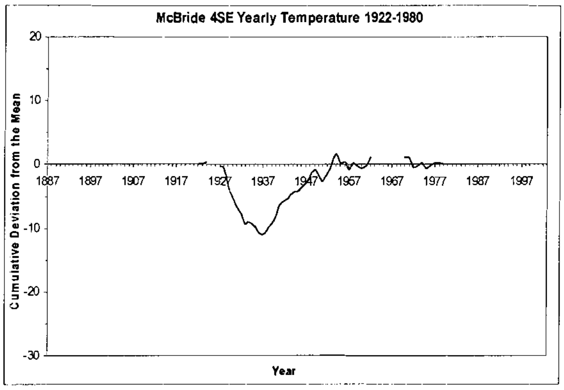


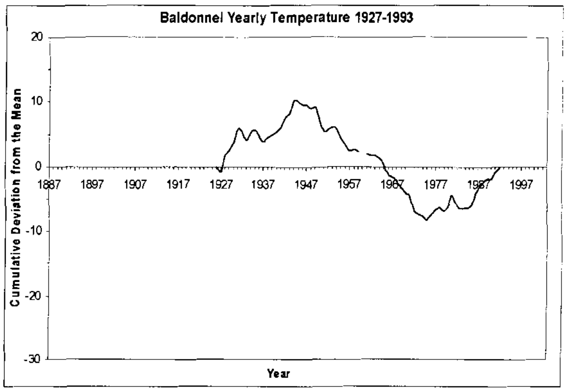
Prince George A Yearly Temperature 1942-2003



Barkerville Yearly Temperature 1888-2002



McBride 4SE Yearly Temperature 1922-1980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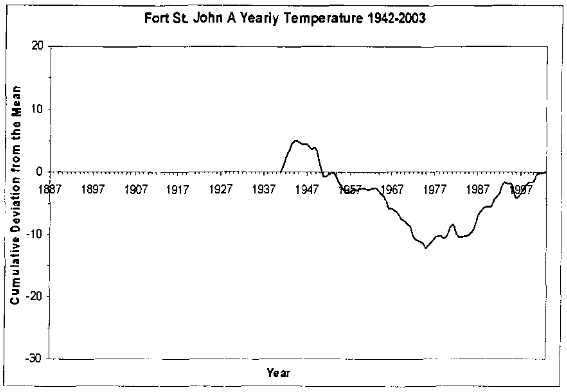
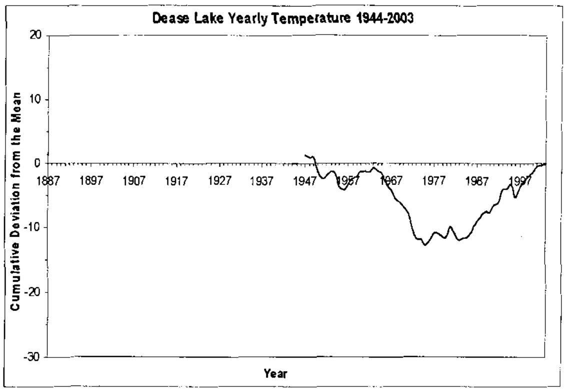
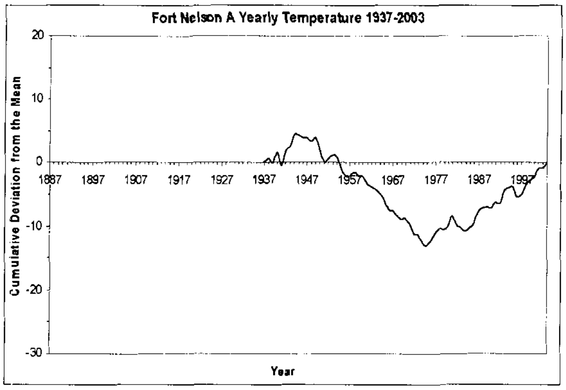
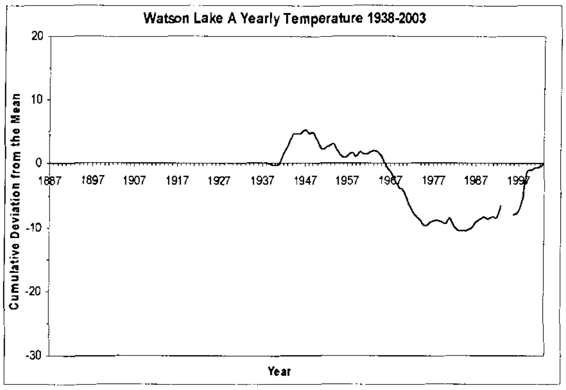
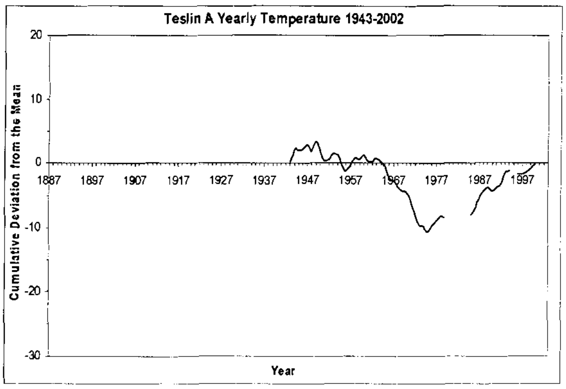
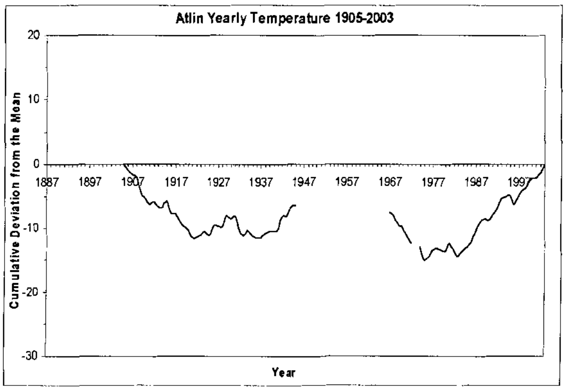

Fort St. John A Yearly Temperature 1942-2003

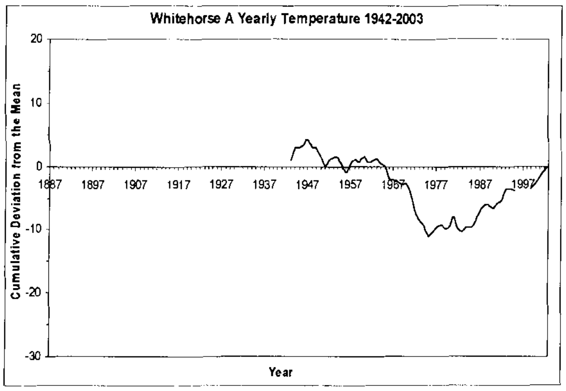

Dease Lake Yearly Temperature 1944-2003


Fort Nelson A Yearly Temperature 1937-2003


Watson Lake A Yearly Temperature 1938-2003


Teslin A Yearly Temperature 1943-2002


Atlin Yearly Temperature 1905-2003


Whitehorse A Yearly Temperature 1942-2003

Appendix 5. Standard errors of weighted average change in climate data.

Annual

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	2.9	0.1	0.5	0.6
Boundary Ranges/Yukon Stikine Highlands	7.6	0.2	0.8	0.9
Coastal Gap	2.6	0.1	0.3	0.5
Nass Ranges	4.1	0.2	0.5	0.9
Skeena/Omineca Mountains	3.1	0.5	1.1	0.6
Fraser Plateau(North)	3.4	0.3	0.4	0.8
Fraser Basin	5.4	0.3	0.4	0.9
Columbia Highlands-Mtns/Western Continental(North)	4.1	0.3	0.3	1.3
Southern Rocky Mountain Trench(North)	6.1	0.2	0.6	1.1
Central Canadian Rocky Mountains	5.9	0.7	0.3	1.4
Peace River Basin	4.8	0.3	0.4	1.2
Central Alberta Uplands	6.7	0.3	0.6	0.8
Northern Rockies/Hay River Lowlands	6.8	0.3	0.4	0.7
Yukon Southern Lakes/Liard Basin	3.3	0.2	0.4	0.8
Boreal Mountains and Plateaus	7.6	0.2	0.4	0.8

Winter

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	6.6	0.2	0.3	0.5
Boundary Ranges/Yukon Stikine Highlands	8.1	0.6	0.8	1.4
Coastal Gap	4.0	0.2	0.3	0.5
Nass Ranges	6.8	0.5	0.6	1.1
Skeena/Omineca Mountains	31.8	0.8	1.3	0.6
Fraser Plateau(North)	6.8	0.5	0.4	0.7
Fraser Basin	9.0	0.8	0.4	0.8
Columbia Highlands-Mtns/Western Continental(North)	13.9	0.6	1.1	0.4
Southern Rocky Mountain Trench(North)	12.5	0.6	0.7	1.3
Central Canadian Rocky Mountains	19.1	1.6	0.6	1.5
Peace River Basin	11.0	0.9	0.8	0.7
Central Alberta Uplands	10.6	0.8	1.3	1.2
Northern Rockies/Hay River Lowlands	15.2	1.0	0.7	1.3
Yukon Southern Lakes/Liard Basin	8.1	0.7	0.5	0.8
Boreal Mountains and Plateaus	12.1	0.6	0.5	0.8

Spring

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	6.1	0.2	0.5	0.5
Boundary Ranges/Yukon Stikine Highlands	10.1	0.5	0.7	1.0
Coastal Gap	3.6	0.2	0.4	0.7
Nass Ranges	4.3	0.2	0.5	0.9
Skeena/Omineca Mountains	51.9	0.9	0.7	2.5
Fraser Plateau(North)	6.9	0.4	0.6	1.2
Fraser Basin	6.9	0.3	0.6	1.4
Columbia Highlands-Mtns/Western Continental(North)	2.6	0.3	0.4	1.0
Southern Rocky Mountain Trench(North)	7.0	0.5	0.8	1.3
Central Canadian Rocky Mountains	23.3	0.6	1.3	2.1
Peace River Basin	8.0	0.5	0.7	1.3
Central Alberta Uplands	8.9	1.3	1.1	3.2
Northern Rockies/Hay River Lowlands	8.0	0.4	0.8	1.2
Yukon Southern Lakes/Liard Basin	11.5	0.3	0.4	0.5
Boreal Mountains and Plateaus	10.5	0.2	0.5	0.7

Summer

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	5.5	0.2	0.5	0.2
Boundary Ranges/Yukon Stikine Highlands	8.4	0.2	0.8	0.4
Coastal Gap	3.5	0.1	0.3	0.3
Nass Ranges	5.4	0.2	0.5	0.3
Skeena/Omineca Mountains	27.1	0.2	0.8	0.5
Fraser Plateau(North)	5.0	0.2	0.3	0.4
Fraser Basin	6.5	0.3	0.3	0.7
Columbia Highlands-Mtns/Western Continental(North)	3.9	0.3	0.2	0.6
Southern Rocky Mountain Trench(North)	7.1	0.2	0.7	0.7
Central Canadian Rocky Mountains	8.0	0.2	0.4	0.5
Peace River Basin	8.0	0.3	0.5	0.3
Central Alberta Uplands	18.6	0.3	0.9	0.5
Northern Rockies/Hay River Lowlands	6.4	0.2	0.7	0.4
Yukon Southern Lakes/Liard Basin	6.7	0.2	0.4	0.4
Boreal Mountains and Plateaus	7.8	0.2	0.4	0.3

Fall

Region	Total Precipitation (%)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
Gwaii Haanas	5.9	0.2	0.4	0.5
Boundary Ranges/Yukon Stikine Highlands	13.2	0.3	0.8	1.1
Coastal Gap	3.4	0.1	0.4	0.4
Nass Ranges	5.2	0.2	0.6	3.4
Skeena/Omineca Mountains	26.5	0.0	1.0	0.9
Fraser Plateau(North)	4.4	0.2	0.9	1.1
Fraser Basin	5.2	0.3	0.3	1.0
Columbia Highlands-Mtns/Western Continental(North)	7.5	0.2	0.4	1.0
Southern Rocky Mountain Trench(North)	6.3	0.2	1.1	0.8
Central Canadian Rocky Mountains	7.9	0.6	0.7	2.2
Peace River Basin	9.5	0.7	1.1	1.6
Central Alberta Uplands	21.1	0.8	1.0	2.9
Northern Rockies/Hay River Lowlands	9.5	0.8	1.2	1.4
Yukon Southern Lakes/Liard Basin	6.7	0.2	0.2	1.3
Boreal Mountains and Plateaus	6.0	0.3	0.4	0.8

Appendix 6. Probabilities of landslide occurrence during years of above-average precipitation or temperature.

Probabilities of landslide occurrence during years (seasons or months) of above-average precipitation or temperature were calculated using binomial probability. If X (random variable) has the binomial distribution $B(n, p)$ with n observations and probability p of success for each observation, the possible values of X are 0, 1, 2, …., n. If k (individual outcomes of X) is any one of these values, the binomial probability is (Moore and McCabe 1999):

$$P(X \geq k) = \binom{n}{k} p^k (1-p)^{n-k} \tag{1}$$

The value of p that was used in this study is 0.5, because there is a 50% chance that precipitation or temperature will be either above or below the average. Equation (1) was used in cases of above-average trends (success) in each category of landslide type to test the probability that there is X to n number of successes, i.e. the probability of X or more landslides occurring in a year or season/month with above-average precipitation or temperature. If the probability is low, the actual probability of a landslide occurring in above-average precipitation or temperature is higher than 50%, thus strengthening the cause-effect hypothesis. It should be noted that "average" precipitation and temperature are defined as the averages for each climate station's record. The results are summarized below:

Above-average Temperature		**Success**	**Occurrences**	**Binomial Probability (%)**
Annual trends	Landslides in rock	9	11	3
	Landslides in sediment	4	7	50
	Landslides in rock/sediment	4	5	19
	Total	17	23	2
Seasonal/monthly trends	Landslides in rock	2	5	81
	Landslides in sediment	5	7	23
	Landslides in rock/sediment	3	4	31
	Total	10	16	23
Above-average Precipitation		**Success**	**Occurrences**	**Binomial Probability (%)**
Annual trends	Landslides in rock	7	11	44
	Landslides in sediment	5	7	23
	Landslides in rock/sediment	1	5	97
	Total	13	23	48
Seasonal/monthly trends	Landslides in rock	2	5	81
	Landslides in sediment	5	7	23
	Landslides in rock/sediment	2	4	69
	Total	9	16	40

The table shows that the probability of landslides during years of above-average temperature is low (2%), as is the probability of landslides in rock during years of above-average temperature is low, 3%, indicating strong relationships. Overall, probabilities are lower at times of above-average temperature than at times of above-average precipitation, indicating that temperature has a greater effect on landslides than precipitation. Probabilities of landslides in a year of above-average temperature are lower than in a season/month of above-average temperature. In contrast, probabilities of landslides in a season/month of above-average precipitation are lower than in a year of above-average precipitation. Turning to annual trends, above-average temperature has more of an effect on landslides in rock and rock/sediment than on landslides in sediment. In contrast, above-average precipitation has more of an effect on landslides in sediment than on landslides in rock and rock/sediment. In the case of seasonal/monthly trends, above-average temperature and precipitation have equal effects on landslides in rock and landslides in sediment. However, above-average temperature has a greater effect on landslides in rock/sediment than above-average precipitation.

Appendix 7. Reference to further appendices.

The following two CD-Roms form part of this work. CD-Rom-1 contains Appendix A, B, C and CD-Rom-2 contains Appendix D, as referred to in the main text. Software required to view the information on CD-Rom-1 is Microsoft® Excel and Microsoft® Word. Software required to view the information on CD-Rom-2 is Microsoft® Internet Explorer, Microsoft® Notepad, and any imaging program with the ability to import Graphical Interchange Format (.gif images). Folders Appendix A, B, C, and D each contain ReadMe files with further information about the data and their sources.

Contents of CD-Roms:

Appendix A: Climate station list, Ch. 2.
Appendix B: Monthly and annual climate station calculations and graphs, Ch. 2.
Seasonal climate station calculations and graphs, Ch. 2.
Appendix C: Climate analysis for each landslide in Ch. 3.
Appendix D: Weather satellite images and surface weather observations for each landslide in Ch. 4.