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Dendroclimatic Studies of White Spruce in the Yukon Territory, Canada

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Geography

DENDROCLIMATIC STUDIES OF WHITE SPRUCE IN THE YUKON TERRITORY, CANADA

(Thesis format: Monograph)

by

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ABSTRACT

An extensive network of 111 white spruce tree-ring chronologies (2983 trees) from treeline sites was developed across the Yukon Territory and adjacent areas of Alaska and British Columbia. Ring-width series from 73 chronologies with adequate signal strength back to 1800 were analysed using correlation and Principal Component analyses. Although 50 chronologies showed a strong common growth pattern over the 1900-1950 period (45.6% of the variance in PC1), PC1 over the 1950-2000 period included only 22 (27.1% of the variance). Correlation with temperature data from the central-north Yukon indicated that 1900-1950 PC1 chronologies showed significant positive relationships to summer (JJA) minimum temperatures and strong negative relationships with prior summer maximum temperatures. Only four of these chronologies retained the positive summer signal for the 1950-2000 period and approximately one third exhibited significant negative responses to spring/summer minimum temperatures during the 1950-2000 period. The loss of positive temperature sensitivity indicates a divergent temperature response in ring-width for most sites throughout the north and central Yukon. Relationships with precipitation showed lower and less significant correlations than temperature.

Analyses of 12 maximum latewood density (MXD) chronologies indicated that nine chronologies have significant relationships with summer maximum or mean temperatures prior to 1950 and six sites, in the central and southern Yukon, retained a slightly weaker but positive summer signal post-1950. Calibration against a regional temperature record (1938-2002) from the southern Yukon indicates that a regional MXD chronology from these six sites captures ca. 39% of the variance of summer (May-August) maximum temperatures. The first, MXD-based, summer maximum temperature reconstruction (1623-2002) was developed for the Yukon Territory. Most of the reconstruction is characterized by high frequency fluctuations with warmer and cooler intervals lasting rarely more than a decade, although the early portion (1630s-1750s) shows a more extended cooler period. This reconstruction showed similarities with the adjacent St. Elias-Wrangell Mountain reconstruction of July-September mean temperatures from Alaska particularly during the 17th and 19th centuries. These results indicate that MXD data are less influenced by divergence and could form the basis for a long temperature reconstruction in the Yukon.

Keywords: dendroclimatology, tree rings, white spruce, maximum latewood density, temperature reconstruction, divergence, Yukon Territory

DEDICATION

This thesis is dedicated in memory of my dear sister, Susan Pitcher (née Morimoto), who passed away unexpectedly during the completion of this research. You are always in my heart.

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CHAPTER ONE

Introduction

1.1 Introduction

Climate change is one of the key environmental issues facing the world today. Though instrumental climate data can provide detailed information regarding recent changes, such records are often relatively short, leading to a need for longer proxy climate records. Various paleoenvironmental techniques are available that can provide useful information regarding climate change at various timescales. Dendroclimatology, the analysis of tree-ring growth and its relation to climate, can be used to study climate change at timescales ranging from years to centuries. By measuring tree-ring parameters such as ring-width or ring-density and determining their statistical relationship with instrumental climate data, dendroclimatological models can be developed enabling reconstruction of past climate conditions. These tree-ring reconstructions can provide long, continuous, annually-resolved proxy climate records that can be used to examine climate variability over longer time periods

1.2 Tree Rings and Northern Environments

Trees growing at or near their ecological limits are generally more sensitive in their responses to changes in their environment (Fritts, 1976). This idea stems from the principle of limiting factors, a fundamental concept in dendrochronology, which states that a biological process, such as growth, cannot proceed faster than is allowed by the most limiting factor (Fritts, 1976). At northern latitudinal and/or high elevation sites, temperature is often the limiting factor to tree growth. In northwestern North America, studies have shown that summer temperatures are a significant control of the growth of northern boreal trees (e.g. Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981; D'Arrigo *et al*., 1992; Szeicz and MacDonald, 1994, 1995). Such studies have primarily focused on white spruce (*Picea glauca* [Moench] Voss), a species that is dominant throughout the northern boreal forest and favourable for dendroclimatic studies due to its longevity (300-600 years).

In their landmark study involving a single white spruce site located in the Northern Yukon (Twisted Tree-Heartrot Hill or ‘TTHH’; 65º20’N 138º20’W), Jacoby and Cook (1981) initiated dendroclimatological research in northwestern Canada. Their work established that trees growing in this northern environment were temperature-sensitive and contained useful information regarding climate variability. Since this key study, tree-ring research in northwestern North America has progressively developed, though much of this work has taken place in Alaska, primarily by scientists at the Lamont-Doherty Earth Observatory (LDEO) at Columbia University (e.g. Jacoby and D’Arrigo, 1995; Jacoby *et al*., 1996; Davi *et al*., 2003; D’Arrigo *et al*., 2005). Within Canada, several studies have involved work in the Northwest Territories (Jacoby and D’Arrigo, 1989; Szeicz and MacDonald, 1994, 1995, 1996; Pisaric *et al*., 2007; D’Arrigo *et al*., 2009; Porter *et al*., 2013). Within the Yukon Territory, dendroclimatological research has been much more limited. Building upon the initial results from TTHH, subsequent research within the northern Yukon has included work by Szeicz and MacDonald (1995), Earles (2008) and Porter and Pisaric (2011). Szeicz and MacDonald (1995) found age-dependent differences in the responses to climate forcing between trees > 100 years old and those < 100 years old. While both age classes exhibited significant positive correlations with summer temperatures in the current growth year, radial growth of older trees showed a negative response to previous year summer temperatures that the younger trees did not (Szeicz and MacDonald, 1995). Earles (2008) and Porter and Pisaric (2011) both found evidence of ‘divergence’ in their tree-ring records. ‘Divergence’ can be characterized as the tendency for tree growth at some previously temperature-limited site to demonstrate a weakening / loss of temperature sensitivity, generally resulting in a growth decline in spite of warming temperatures (D’Arrigo *et al*., 2008). Unlike TTHH (D’Arrigo *et al*., 2004a) or Old Crow (Porter and Pisaric, 2011) in the northern Yukon, studies in the southern Yukon, approximately 500 kilometers further south, have not reported divergence affecting the growth of white spruce. Instead, such studies document increased growth trends with warming temperatures (Pisaric, 2001; Luckman *et al*., 2002; Youngblut and Luckman, 2008). Little is known about the tree-ring temperature relations from sites in the large region between these two study areas.

1.3 Research Objective

Although the previous studies conducted in the Yukon Territory and elsewhere have demonstrated that white spruce can provide high quality, climatically-sensitive tree-ring chronologies, their results have also suggested potential changes in the responses of this species to climate. Available results are geographically limited to small regions in either the northern or southwestern Yukon; little is known regarding the growth trends and responses of spruce for intervening areas. The main goals of this study are to develop an extensive network of ring-width chronologies from white spruce across the Yukon and a smaller network of maximum density chronologies. These chronologies will be used to examine common growth patterns across the Yukon, determine key climate-growth responses and possible changes in these relationships, and to develop one or more regional climate reconstructions for the Yukon that could be used to examine climate variability over the last 300-500 years.

In order to accomplish these goals, several steps are required. The initial phase is to develop an extensive network of ring-width chronologies across this region. This network would provide the opportunity to study patterns of white spruce growth and determine whether regional differences exist within the Yukon. Expanding on the 17 white spruce sites initially sampled in the southwest Yukon in 1999 and 2000 (Luckman *et al*., 2001), additional sampling of white spruce continued until 2005, covering an area between 58° to 68°N and 124° to 141°W within the Yukon Territory and bordering areas in Alaska and northern British Columbia. Developing ring-width chronologies from this collected material, this collection was screened for chronology quality and signal strength. Investigation into the climate signal(s) of these chronologies will be the next phase. To facilitate this endeavour, available instrumental climate data for meteorological stations in the Yukon will be compiled from the Adjusted Historical Canadian Climate Database (AHCCD) and examined for common signals, possibly resulting in the development of regional climate records. These climate data will then be used to examine significant climate-growth responses involving the ring-width chronologies, particularly the strong relationship with summer temperatures. To evaluate the extent of possible divergence or loss of temperature signal in these chronologies, climate-growth responses will be examined over several time periods to determine temporal stability. Results of these analyses will be used to determine suitability for possible development of one or more regional temperature reconstructions.

A similar dendroclimatic analysis was conducted using a smaller series of tree-ring density records. Various studies have shown that tree-ring density (primarily 'maximum latewood density' or MXD) can also provide useful information regarding relationships between tree growth and climate (Polge, 1970; Parker and Henoch, 1971; Schweingruber *et al*., 1978; Schweingruber, 1989; D'Arrigo *et al*., 1992). Since measurement of x-ray densitometry for tree rings is complex and uses specialized equipment that is only available in a few North American tree-ring laboratories, the number of sites processed and analyzed was limited. To supplement this data, additional density records available for the Yukon were obtained from the International Tree-Ring Data Bank (ITRDB) and included in the ring-density network. Similar to the ring-width portion of this study, MXD chronologies were developed from the available density data and analyzed for common growth trends. Using the compiled climate records, climate-growth responses of the density chronologies were determined and also examined for evidence of possible divergence. Results will establish suitability for development of temperature reconstructions.

1.4 Thesis Format

This thesis is presented in traditional monograph format. Chapter 2 includes information regarding the ecological characteristics of white spruce and provides an account of previous dendrochronological research conducted in northwestern North America, including other research conducted while this thesis was in progress. The tree ring-width chronology network is presented in Chapter 3, the quality of the chronologies is evaluated and this database is screened to ensure a high quality network to be used in later analysis. Regional groupings of chronologies are developed based on common growth patterns determined through correlation and principal components analyses. Temporal stability of these patterns is examined by conducting analyses over different time periods. Changes between periods, particularly those involving the 20th century, may be potential indicators of divergence. The available climate data for the Yukon is discussed in Chapter 4 and a series of regional temperature and precipitation records are developed for further analyses. Relationships between these temperature and precipitation records and tree-rings are examined in Chapter 5. Initial analyses into these relationships utilize the regional chronologies from Chapter 3. Results from these early analyses varied and only provided a broad representation of the climate-growth responses. Subsequently, relationships between the regional climate records and each individual site chronology are examined. These relationships are examined for temporal differences, which may suggest potential divergence effects and mapped using GIS software to explore spatial variability in the pattern of these relationships. Chapter 6 describes the development of the smaller MXD chronology network, the evaluation of growth patterns and the climate-growth relationships expressed by these chronologies. A maximum temperature reconstruction representing the south-central Yukon is developed and compared with other regional reconstructions. Chapter 7 summarizes the overall findings of this research, discusses its implications and presents suggestions for future research.

The thesis also contains nine appendices, presenting detailed data and analyses to support the main text. Appendix A provides basic information regarding the 111 white spruce chronologies selected for this study. Detailed statistical and standard dendrochronological measures used to examine the tree-ring chronologies are presented in Appendix B. The next four appendices (C-F) are related to examination of the ring-width climate signals discussed in Chapter 5. Appendix C presents correlations between regional tree-ring chronologies and 12-month averaged data for the ‘northern’ and ‘southern’ regional temperature series. Appendix D provides comprehensive examination of climate-growth responses of individual chronologies found within the six regional ring-width groupings defined in Chapter 3. Appendices E and F outline correlations between seasonal (3-month) temperatures and chronologies for the 1900-1950 and 1951-2000 time periods respectively. Appendix G presents time series plots for the MXD chronologies developed for this study. Statistical measures applied in the model verification process included in the development of the temperature reconstruction are given in Appendix H. Lastly, Appendix I lists the dates and information for major volcanic eruptions (Volcanic Explosive Index (VEI) $\geq$ 4) that occurred between 1623-2002 in support of analyses of possible causes of selected extreme cold years in the summer temperature reconstruction.

CHAPTER TWO

Dendrochronological Studies in Northwestern North America

2.1 Introduction

Instrumental climate observations indicate that the northern latitudes of North America have experienced substantial warming during the 20th century (ACIA, 2004). From 1948-2005, the Yukon Territory experienced an average warming of 2.2°C, the greatest rate of temperature increase in Canada (national average 1.2°C, Prowse *et al*., 2009). However, there are relatively few good instrumental records in the north and most are short (i.e. less than 50-60 years), creating difficulties in studying longer term patterns in climate variability. Proxy climate records provide an opportunity to examine trends on longer timescales. Over the last three decades, the number of paleoclimatic studies in Northwestern Canada has slowly grown, applying diverse proxies such as pollen (Birks, 1980; Cwynar, 1988), chironimids and diatoms (Walker *et al*., 2003; Karst-Riddoch *et al*., 2005), lacustrine sediments (Anderson *et al*., 2005a; 2005b) and ice cores (Holdsworth *et al*., 1995; Fisher *et al*., 2004; 2008). While such studies can provide long-term information regarding climatic and environmental change, such records often lack the fine temporal resolution that tree-ring analysis can provide. Tree-ring analysis can provide continuous, annually resolved terrestrial records corresponding to environmental conditions (Fritts, 1976). Several studies have used tree rings (primarily white spruce) to develop proxy climate data in the Yukon and surrounding regions and will be reviewed below. However, prior to reviewing these data it is important to briefly consider the characteristics of the dominant forest species in this region.

2.2 White Spruce in Northwestern North America

White spruce (*Picea glauca* (Moench) Voss) is a coniferous tree found within the Boreal Forest zone spanning much of northern Canada (Farrar, 1995). Based on pollen frequency curves, Ritchie and MacDonald (1986) date expansion of white spruce into the western interior of Canada at ca. 9500 BP. Presently, in northern regions such as the Yukon Territory, white spruce is commonly the dominant species, often occurring in pure stands on well-drained soils (Scott, 1995). Black spruce (*Picea mariana*), sometimes confused with white spruce, is also found, more commonly in poorly-drained areas (Farrar, 1995). Ritchie (1984) and Wahl *et al*. (1987) indicate that white spruce is intolerant to a high permafrost table and thus is generally found south of the limit of continuous permafrost (approximately 67.5° N). Along the southern Yukon border with British Columbia, white spruce also grows in mixed stands with subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (Kenigsberg, 2005). In areas disturbed by recent wildfire, young white spruce may also be found associated with deciduous species such as white birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) (Ritchie, 1984). As these stands develop, white spruce generally creates shaded conditions which become unfavourable to shade-intolerant species, leading to spruce dominance (Oechel and Lawrence, 1985).

As an evergreen species, white spruce possesses adaptations which aid in its survival and growth at higher latitudes of northwestern North America. Given the harsh winter conditions of such environments (e.g. cold temperatures, aridity, snow/wind abrasion), white spruce's ability to initiate photosynthesis production immediately after snowmelt is advantageous (Bliss, 1985). Retention of photosynthetically viable leaves/needles for periods of a decade or more suggests a conservative demand for soil nutrients by evergreen conifers (Gower and Richards, 1990). Ectotrophic mycorrhizae in their root systems allow conifers to extract nutrients from their own mor litter (Scott, 1995). In their study of water relations at tree line in Alaska, Goldstein *et al*. (1985) indicated that soil temperature can have an impact on the growth of white spruce. It is believed that low soil temperatures increase root resistance to water flow by impeding cell membrane permeability and increasing the viscosity of water (Goldstein *et al*., 1985).

Within northwestern North America, the growth of white spruce has primarily been correlated with warm-season temperatures (Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981; Jacoby and D'Arrigo, 1995; D'Arrigo *et al*., 2005a). In the Yukon, summer temperatures (e.g. average July degree days above 10°C) are considered to be one of the primary controls on growth of white spruce (Daubenmire, 1954).

2.3 Tree-Ring Studies

2.3.1 Early Years

The earliest documented collection of tree-ring material from Alaska and the Yukon was carried out by Giddings (1940, 1942, 1948), and his student Oswalt (1950, 1954). These early studies were developed primarily for archaeological purposes, rather than for the study of past climatic variations. It was not until the 1960s and 1970s that increased interest in climate history grew and the first investigations to explore the dendroclimatic potential of northern species were carried out (Cropper and Fritts, 1981).

The early development of dendroclimatological research in Canada was conducted by researchers from the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona (Luckman and Innes, 1991). Schulman (1947) studied several dry forest stands of Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) at sites in southwest Alberta and British Columbia, similar to moisture-stressed sites in the American Southwest. He found that, like the drought conifers of the Colorado Basin, rainfall was the controlling element in the growth of these trees (Schulman, 1947). During the late 1960s and early 1970s, several of these sites were recollected and included in the first large network of climate-sensitive tree-ring chronologies covering western North America developed by Harold Fritts (Fritts, 1971; Fritts and Shatz, 1975; Fritts and Lough, 1985).

Gordon Jacoby, from the Tree-Ring Laboratory of the Lamont-Doherty Earth Observatory (LDEO) at Columbia University, was the first to highlight the potential of developing temperature reconstructions for northern treeline sites. Jacoby and Cook (1981) developed a 400-year long white spruce ring-width chronology for the Twisted-Tree Heartrot-Hill (TTHH) site located at 65°20′N, 138°20′W in the Yukon Territory. This pivotal study demonstrated that white spruce growing near its northern latitudinal limits was climate-sensitive, responding primarily to summer temperatures. A principal-component time series based on their data showed significant relationships with June-July mean temperatures ($R_a^2 = 0.32$) and June-July total degree-days above 10°C ($R_a^2 = 0.36$) over the period 1921-1965 (Jacoby and Cook, 1981). Subsequently, Jacoby *et al*. (1985) developed a 452-year long reconstruction of June-July total degree days above 10°C for central Alaska and northwestern Canada. In addition to the TTHH Yukon data, white spruce series from Noatak Valley (NW Alaska) and Sheenjek River (NE Alaska) were used in this reconstruction. For the period 1917-1965, 45% of the variance involving total degree-days above 10°C was explained by this regional reconstruction (Jacoby *et al*., 1985).

Concurrently, LTRR researchers John Cropper and Harold Fritts studied ring-width chronologies from the sub-arctic region of North America (Cropper and Fritts, 1981; Cropper, 1982, 1984). While many of these sub-arctic chronologies were deemed of little value for climatic analysis due to limited replication and chronology length (Cropper and Fritts, 1981), a reconstruction was pieced together representing summer anomaly patterns of sea-level pressure over the North Pacific sector for the period 1802-1938 (Cropper, 1982). Positive values, primarily from 1870 to 1920, indicated high pressure over most of Alaska with associated warm weather, while negative values from 1801 to 1860 suggested anomalously cold conditions (Cropper, 1982).

2.3.2 Tree-Ring Densitometry

While dendroclimatic studies involving ring-width data from northwestern North America were growing in number, work involving tree-ring densitometry was slowly developing. This research was initiated in Canada by Marion Parker who joined the Geological Survey of Canada in 1967 from the LTRR (Luckman and Innes, 1991). During his short stay at the Survey (and later at Forintek Canada Corporation in Vancouver) Parker sampled many sites across Canada in an attempt to develop a national tree-ring database. His most important published study was of Engelmann spruce (*Picea engelmannii* Parry) near Peyto Lake, Alberta. Parker and Henoch (1971) reported significant correlations between maximum latewood density (MXD) and August mean maximum temperatures. While this study did not produce a climate reconstruction, it was the first study to assess the dendroclimatic potential of tree-ring density data in northwestern North America.

During the 1980s and 1990s, Fritz Schweingruber from the Swiss Federal Institute for Forest, Snow and Landscape Research (Birmensdorf, Switzerland) pioneered the use of densitometry for dendroclimate work and sampled two extensive tree-ring networks across North America. During the summer of 1984, he sampled 25 sites in British Columbia, Yukon and Alaska as part of a large network spanning the alpine treeline of western North America (Schweingruber, 1988). Subsequently, in 1989, together with Gordon Jacoby, he sampled 44 Canadian sites across the northern treeline from the Yukon to Labrador

(Schweingruber *et al*., 1993). Data from these sampled networks later contributed to a number of dendroclimatic studies at the continental (Schweingruber *et al*, 1991; Briffa *et al*., 1992; Briffa *et al*., 1994) and hemispherical scale (Briffa *et al*., 2002a, 2002b, 2004; Osborn *et al*., 2004) based on ring-width and density data. In their study of northern North America, Briffa *et al*. (1994) developed a series of MXD regional summer half-year (April-September) mean temperature reconstructions, including one for the Alaska and Yukon region covering the period 1760-1983. Based on their results and a comparison with a May-August summer temperature reconstruction from interior Alaska (subsequently published in Jacoby and D'Arrigo, 1995), Briffa *et al*. (1994) indicated that the effects on climate from major volcanic events can vary regionally. While the coldest value in the Jacoby and D'Arrigo (1995) reconstruction occurred in 1783 and was attributed to the eruption of Laki in Iceland, 1810 marked the coldest summer in the Briffa *et al*. (1994) record. It is believed that the 1810 date corresponds to a previously unknown eruption documented by Dai *et al*. (1991).

2.3.3 **Northern North America (LDEO)**

Work by researchers at the LDEO tree-ring lab continued to focus on treeline sites across northern North America. Jacoby and D'Arrigo (1989) developed two annual temperature departure reconstructions using ring-width data from eleven northern boreal sites in Canada and Alaska spanning over 90 degrees of longitude. One reconstruction covered the Arctic (averaged for 64°-90°N), while they also developed one of the earliest reconstructions for the Northern Hemisphere; both series covered the period 1671-1973 (Jacoby and D'Arrigo, 1989). Comparisons between these reconstructions and instrumental hemispheric temperature datasets suggested that such northern tree-ring records were representative of Northern Hemisphere temperatures. In a study involving both ring-width and maximum density data from five northern treeline sites (Coppermine and Hornby sites previously included in Jacoby and D'Arrigo, 1989), D'Arrigo *et al*. (1992) found that maximum latewood density generally exhibited stronger links than ring-width with interannual growing season (summer) temperatures. Ring-width relationships with climate appeared to be more apparent on decadal and longer timescales (Jacoby and D'Arrigo, 1989, 1995). For six thermally stressed sites in northern and interior Alaskan regions, Jacoby *et al*. (1996) found that ring-width corresponded to annual temperatures, while maximum latewood density corresponded primarily to summer temperatures. D'Arrigo *et al*. (1992) suggested that the differential responses of these ring parameters could be applied to develop strategies for extracting the maximum possible information regarding climate from tree rings. Though not contributing any new material specifically from the Yukon, these LDEO studies did confirm the potential for dendroclimatic work at high latitudes in North America.

2.3.4 Northwestern Canada

Within the last twenty years, a growing number of studies have been conducted in the northern Canadian Cordillera, addressing the paucity of dendroclimatic research in the region. Szeicz and MacDonald (1994, 1995, 1996) examined growth dynamics and climatic responses of white spruce at high elevation sites in the northwestern sector of the Northwest Territories (NWT). In 1994 they demonstrated differing, age-dependent growth responses in spruce in three sites located near Norman Wells, NWT. At two sites in the Mackenzie Mountains (Skipping Bullet 64°59′N, 127°34′W; Katherine Creek 64°58′N, 127°29′W), young trees (<200 years old) were found to exhibit significant positive responses to summer temperatures of current growth year but not previous growth year, while older trees (>200 years old) showed little significant response to summer temperatures in the current growing season but strong negative response to spring and previous summer temperatures. At the third site, located in the Franklin Mountains (Discovery Ridge 65°21′N, 126°42′W), the patterns were reversed with young trees displaying negative correlations with current spring temperatures and little response to current or previous summer temperatures, while older trees responded significantly with June and sometimes July temperatures (Szeicz and MacDonald, 1994). Analyses of standard and age-dependent models used to estimate June-July mean temperatures from 1909 to 1989 indicated that the age-dependent models performed slightly better than the standard models. While these results challenged the common assumption in dendroclimatic analyses that relationships between climate and radial growth are independent of tree age once the biological growth function is removed (Fritts and Guiot, 1990), Szeicz and MacDonald (1994) were quick to point out that their study was based on a relatively small sample of sites and that their results were site specific. In their later 1996 study on the Campbell Dolomite Upland near Inuvik, NWT, they found little difference in climate responses with tree age. Their response function analysis indicated a strong positive relationship with early spring precipitation, and they reconstructed a 930-year (AD 1064-1992) record of February-May precipitation. This reconstruction was significant, not only for its extensive length, but also because it was the first dendrohydrological record developed in northwestern Canada.

In research examining Holocene environmental change at the subarctic alpine treeline in northern British Columbia and southern Yukon, Pisaric (2001) utilized several proxy indicators, including pollen and stomate analysis, as well as tree-ring analysis. Using tree-ring data from Stone Mountain in British Columbia plus Lapies Pass and Macmillan Pass in the Yukon, he found that *Picea glauca* growth responded most strongly to summer temperatures, similar to previous dendroclimatic studies in northwest Canada. Both standard and age-dependent modeling were employed though results showed no clear improvement with the age-dependent models. Using standard modeling, Pisaric (2001) developed a ring-width reconstruction of June-July mean temperature extending back to AD 1733.

The University of Western Ontario (UWO) sampling programme in the Yukon began in 1999 as an exploration of the dendroclimatic potential of ring-width chronologies from sites in the southwest Yukon and adjacent areas in northern British Columbia. The initial work was supported by the Meteorological Service of Canada and grew out of previous research conducted on low-elevation moisture-sensitive sites in British Columbia and Alberta (Watson *et al.*, 2000; Luckman and Youngblut, 2000; Luckman *et al.*, 2001, 2002). Initial sampling in the SW Yukon / NW British Columbia showed that ring-width chronologies from upper elevation sites were strongly correlated with summer temperatures, whereas the lower elevation sites yielded chronologies that were distinct from adjacent treeline sites (Luckman *et al.*, 2002). Based on this early work, Youngblut and Luckman (2008) published a June-July maximum temperature reconstruction based on seven sites in the southwest Yukon. This ring-width reconstruction, which extended back to1684 AD, explained 46.6% of the climatic variation over the 1946-1995 calibration period (Youngblut and Luckman, 2008). These chronologies did not exhibit reduced sensitivity of tree growth to temperature during the late 20th century.

Kenigsberg (2005) studied a network of 26 subalpine fir (*Abies lasiocarpa*) sites from the southern Yukon/northern British Columbia. He noted that while this species displayed correlations with summer temperatures similar to spruce, subalpine fir also exhibited distinct correlations with autumn-early winter temperatures (Kenigsberg, 2005).

Sampling of the Yukon network of spruce sites continued through to 2005 and the northernmost part of the network was examined by Earles (2008). This work focused on 23 treeline sites along the Dempster Highway in the northern Yukon (61°-68°N) and showed evidence of reduced sensitivity to temperatures in the growth patterns of white spruce during the 20th century. Several sites which exhibited positive relationships with summer temperatures in the 1900-1950 period showed much weaker or negative relationships with summer temperatures over the 1951-2000 period. Detailed examination of ring-width data from three highly replicated sites showed distinctive 'sub-populations' of trees at these sites with trees responding either negatively, positively or neutrally to summer temperatures within the same site. Results from these studies highlight the complexity found in growth responses for treeline sites across Northwestern Canada.

2.4 Divergence

2.4.1 The Divergence Phenomenon

The most commonly reported mode of climate response of northern boreal forest trees is increased growth with warmer temperatures (e.g. Garfinkel and Brubaker, 1980). However, there has been suggestion of a loss in temperature sensitivity among some high-latitude trees experienced during the latter half of the 20th century, an occurrence termed 'divergence'. Divergence is defined as the tendency for tree growth at some previously temperature-limited sites to show a weakening in temperature response in recent decades, with divergence being expressed as a loss in climate sensitivity and/or a divergence in trend (D'Arrigo *et al*., 2008). The first study to note this phenomenon was Jacoby and D'Arrigo (1995) working with five alpine and latitudinal treeline sites in Alaska. Their initial expectation was that ring-widths from these white spruce sites would favourably reflect the increasing temperatures of the 20th century, however their analyses showed a deterioration in the relationship between ring-width growth and temperature in the middle to late 1970s (Jacoby and D'Arrigo, 1995). They hypothesized that this change in response was related to moisture stress due to warming in Alaska (Jacoby and D'Arrigo, 1995).

Barber *et al*. (2000) conducted a study involving 20 closed canopy white spruce stands in the interior boreal forest zone of Alaska. Unlike the treeline sites examined by Jacoby and D'Arrigo (1995), these stands were thought to be less responsive to temperature due to their site types. Examination of their tree-ring data (raw ring-widths) with a combined temperature and precipitation index also showed evidence of divergence, with greatest declines in temperature sensitivity exhibited by the most rapidly growing white spruce (Barber *et al*., 2000). They also suggested that under recent climate warming, moisture stress likely had become an important limiting factor.

In a study of eight Alaskan sites at or near treeline and representing a variety of locations and topography, Lloyd and Fastie (2002) found that after ca. 1950, warmer temperatures were associated with decreased tree growth in all regions but the wettest in the Alaska Range. Since decreased ring-width growth was more prevalent on drier sites, they concluded that the increased warming of these forests was accompanied by drought stress which impacted tree growth (Lloyd and Fastie, 2002).

D'Arrigo *et al*. (2004a) demonstrated a weakening in temperature-growth response in the Yukon in their update of the Twisted Tree-Heartrot Hill (TTHH) site. Originally touted as the classic temperature-sensitive site (i.e. Jacoby and Cook, 1981), D'Arrigo *et al*. (2004a) showed that when the positive temperature-ringwidth relationship for the period 1900-1964 was used to predict ring-widths for the 1900-2000 period, the model over predicted growth compared with actual ring-widths. This divergence was also attributed to a change in response from temperature to moisture sensitivity (D'Arrigo *et al*., 2004a).

While many studies have concluded that moisture stress resulting from increasing temperatures is likely the main reason for the divergence phenomenon, other possible explanations have been suggested. Based on analysis of tree-growth data from trees sampled from more than 300 locations spread across the Northern Hemisphere, Briffa *et al*. (1998) found that decadal trends between wood density and summer temperatures increasingly diverged during the second half of the 20th century. While not discrediting soil moisture stress, they point out the apparent widespread synchroneity of the phenomenon suggested a hemispheric-scale influence. They mention higher UV-B levels or decreased solar radiation receipts (increased optical depth) may be involved (Briffa *et al.*, 1998b).

2.4.2 **Divergence and MXD**

Many of the studies exhibiting the divergence phenomenon have been based on tree ring-width data. Studies involving maximum density data have shown contrasting results with regards to the divergence issue. As noted, Briffa *et al.* (1998) detected divergence involving maximum density and summer temperatures within their Northern Hemisphere network of high latitude sites, similar to the diverging response exhibited by ring-widths. In studies on the Seward Peninsula of Alaska, D'Arrigo *et al*. (2004b, 2005) found evidence of divergence in both their maximum density and ring-width data. While exhibiting a strong relationship with May-August mean temperatures during the early half of the 20th century, D'Arrigo *et al*. (2004b) indicated a decrease in positive correlation with density beginning ca. 1950 which became most noticeable after ca. 1970. Similarly, a loss of positive temperature response ca. 1970 was noted with the ring-width data for these western Alaskan sites (D'Arrigo *et al*., 2005). In contrast, Davi *et al*. (2003) in a study of 14 treeline sites in the Wrangell Mountain region of southeastern Alaska, found that although their ring-width composite series exhibited a decrease in growth beginning around 1970, their maximum density composite series did not show a decrease in sensitivity to increasing temperatures of recent decades. Presently, it is unclear as to the exact reasons for the inconsistency regarding divergence and maximum density responses.

2.4.3 **Divergence Within Tree Stands**

Several studies have indicated that divergence does not necessarily affect all individuals at the stand-level, but rather "sub-populations" of positive and negatively responding trees (responders) can exist within a tree stand (Wilmking *et al*., 2004, 2005; Driscoll *et al*., 2005; Pisaric *et al*., 2007; Earles, 2008; Porter and Pisaric, 2011, Porter *et al*., 2013). While positive responders maintain increasing growth trends in response to warming during the 20th century, negative responders appear to lose sensitivity to warming temperatures and exhibit a decrease in growth. In their study of 13 treeline sites in the

Brooks and Alaska Mountain Ranges, Wilmking *et al*. (2004) found opposing growth responses (pre-1950 vs. post-1950) existed in all their sampled sites. They also discovered that there was no clear relationship between growth responses and landscape position (i.e. floodplain, north- or south-facing upland stands) within a site (Wilmking *et al*., 2004). Driscoll *et al*. (2005) observed diverging sub-populations in two of their four study sites located in Lake Clark National Park in southern Alaska. While two sites (Lake Telaquana and Lower Twin Lake) exhibited positive correlations with April-July temperatures during the second half of the 20th century, the other two sites (Fish Trap Lake and Portage Lake) each contained sub-populations of positive- and negative-responders (Driscoll *et al*., 2005). Microsite differences, influencing local moisture conditions, were considered as a possible explanation for these results (Driscoll *et al*., 2005). Extending their earlier research, Wilmking *et al*. (2005) examined eight forest stands situated across the circumpolar North and discovered that their divergent growth trends in Alaska were not just a local or regional phenomenon but appeared to exist on a much larger, hemispherical scale.

2.4.4 **Evidence of Divergence in Canada**

Within Canada, the divergence 'sub-population' phenomenon has been documented in stands located in the Mackenzie Delta, Northwest Territories (Pisaric *et al*., 2007; Porter *et al*., 2013) as well as in northern Yukon (Earles, 2008; Porter and Pisaric, 2011). Examining ring-width growth responses from nine sites in the eastern Mackenzie Delta, Pisaric *et al*. (2007) identified both positive- and negative-responders in their samples. Unlike previous studies, divergence between growth trends of the sub-populations was found to begin ca. 1930 (Pisaric *et al*., 2007). This earlier onset of divergence was also identified in a 23-site white spruce ring-width network sampled in the Old Crow Flats region of the northern Yukon (Porter and Pisaric, 2011). Negative responders exhibited strongest correlations with maximum July temperatures while positive responders correlated strongest with minimum June temperatures (Porter and Pisaric, 2011). Further research in the Mackenzie Delta region by Porter *et al*. (2013) yielded evidence of divergence occurring within the low-frequency growth trends of the region as early as ca. 1900. With the addition of 19 new sites, Porter *et al*. (2013) indicated that divergence in the Mackenzie Delta occurred in two phases. The first phase, between

1900-1950, saw tree growth overestimate summer temperatures, while the second phase followed when tree growth underestimated temperatures (Porter *et al*., 2013). It was suggested that the growth surge of the early period was due to a thickening of the permafrost active layer under warming conditions which released water and nutrients resulting in augmented growth. Increased warming-related stress in the late 20th century may have countered this benefit, resulting in patterns of depressed growth (Porter *et al*., 2013).

It is evident from the various divergence studies mentioned that this phenomenon is quite complex, not only with respect to its timing and ring parameters it affects, but also with the (sub-) populations it impacts. Common amongst these studies is the fact that divergence has primarily influenced tree growth at higher northern latitudes. Results from lower northern latitudes (i.e. lack of divergence in SW Yukon (Youngblut and Luckman, 2008)) suggest that spatial variability may exist. In the next chapter, an extensive network of ring-width sites throughout the Yukon will be developed. This network will be used to examine growth patterns and responses to climate, perhaps leading to a better documentation of the potential distribution of divergence across this region.

CHAPTER THREE

The Development of a White Spruce Ring-Width Chronology Network within the Northern Canadian Cordillera

3.1 Introduction

This chapter summarizes the development of a ring-width chronology network derived from white spruce sampled primarily within the Yukon Territory, with a small number of bordering sites in Alaska, the Northwest Territories, and northern British Columbia, Canada. Site selection, sampling procedures and chronology development will be discussed. The dendrochronological quality of the chronologies making up the network will be examined, and patterns of common variation within the network will be identified through the use of correlation analysis and principal component analysis (PCA). Although previous studies (e.g. Jacoby and Cook, 1981; Cropper, 1984; Szeicz and MacDonald, 1995; Pisaric, 2001; Earles, 2008; Youngblut and Luckman, 2008) have examined white spruce in the Yukon, they have often focused on single sites, or have been limited in their geographical scope. This study develops a more geographically-extensive tree-ring network based on many newly-developed site chronologies. This study will provide the opportunity to study spatial and temporal patterns of variations in white spruce growth across the entire Yukon, allowing earlier studies to be placed within a larger regional context.

3.2 Previous Work

A recent search of the International Tree-Ring Database (ITRDB), an online depository for global tree-ring data, provided a listing of only 11 individual ring-width chronology sites for white spruce throughout the entire Yukon Territory. While this may represent only those data voluntarily made available to the public, it does suggest the relatively small amount of tree-ring research focused on this region, compared with other areas of North America. As noted above, a small number of tree-ring studies have been conducted elsewhere in the Canadian North, but in most cases the geographical scope of these studies have been limited to a single site or small localized grouping of sites.

Much of the earliest documented collection of tree-ring material from northwestern North America involves the work of Giddings (1940, 1942, 1948), and his student Oswalt (1950, 1954). These early studies, focused primarily in Alaska, were developed solely for archaeological dating purposes and generally consisted of small numbers of samples.

During the 1960s and 1970s, Hal Fritts and associates from the Laboratory of Tree-Ring Research (LTRR), University of Arizona conducted sampling throughout North America, including the Arctic. While many of these materials were dated and processed into raw chronologies, the data were often not fully analyzed for information on climate (e.g. the chronology collection from Western Canada and Mexico published by Drew (1975)). It was not until the early 1980s when Cropper was at the LTRR that chronologies from the North American Arctic were studied for their dendroclimatic potential (Cropper and Fritts, 1981; Cropper, 1982, 1984).

Gordon Jacoby, from the Tree-Ring Laboratory at the Lamont-Doherty Earth Observatory (LDEO) at Columbia University, was the first to highlight the potential of developing temperature reconstructions for northern treeline sites. Jacoby and Cook (1981) developed a 400-year white spruce ring-width chronology for the Twisted-Tree Heartrot-Hill (TTHH) site at 65° N in the Yukon Territory. This paramount study indicated for the first time that spruce growing near its northern limits responded primarily to summer temperatures, and exhibited patterns similar to long-term temperature trends for the Northern Hemisphere. Building upon the results from TTHH, Jacoby and D'Arrigo (1989) developed two temperature reconstructions from a collection of northern boreal treeline sites in Canada and Alaska, spanning over 90 degrees of longitude. Comparisons between the reconstructed annual temperatures and temperature datasets covering the Northern Hemisphere indicated that the selected tree-ring records were representative of Northern Hemisphere temperatures.

Fritz Hans Schweingruber from the Institute for Forest, Snow and Landscape Research in Birmensdorf, Switzerland, was also instrumental in developing tree-ring collections from North America during the 1980s. Having developed dendroclimatic studies in Europe, Schweingruber extended his interests to include material from the alpine timberline of western North America (Schweingruber, 1988). In 1984, as part of this western North America network, Schweingruber collected samples from 25 sites in British

Columbia, Yukon and Alaska (Schweingruber et al., 1993). In 1989, he sampled 44 additional sites across Canada, to form a longitudinal transect of the northern conifer zone from Alaska to Labrador (Schweingruber et al., 1993). Research from these collections focused on the densitometric chronologies and their relationship to climate, though ring-width data were also examined (Briffa et al., 1992; Schweingruber et al., 1993; Briffa et al., 1994). Further studies using this data have gone on to address climate variability at even larger hemispherical scales (e.g. Briffa et al., 2002a, 2002b; Briffa et al., 2004).

Within the last two decades, a limited number of studies have been conducted in the northern Canadian Cordillera, addressing the paucity of dendroclimatic research in the region. In the northwestern sector of Northwest Territories, research focused on high elevation sites found positive relationships between *Picea glauca* growth and mean summer temperatures (Szeicz and MacDonald, 1994; 1995), as well as late winter-spring precipitation (Szeicz and MacDonald, 1996). Pisaric (2001) also found *Picea glauca* responded strongly with summer temperatures at three high elevation tree-ring sites located in northeastern British Columbia and southeastern Yukon. Luckman *et al*. (2002) reported the first findings of a project which explored the dendroclimatic potential of ring-width chronologies from a small collection of sites concentrated in southwestern Yukon. Analyses showed that chronologies from upper elevation sites were strongly correlated with summer temperatures, whereas lower sites near Kluane Lake yielded chronologies that had a distinctly different signal from adjacent treeline sites (Luckman *et al*., 2002). Subsequently, Youngblut and Luckman (2008) developed a June-July maximum temperature reconstruction, extending back to 1684, from seven high-elevation upper treeline sites in the southwest Yukon. Subsequent sampling by the UWO group (see below) developed the database on which this thesis is based. In a parallel study, Kenigsberg (2005) completed a network of subalpine fir (*Abies lasiocarpa*) sites from the same area of northwestern Canada. He noted that while this species displayed correlations with summer temperatures similar to spruce, subalpine fir also exhibited distinct correlations with autumn-early winter temperatures (Kenigsberg, 2005). Recently, Earles (2008) studied a group of white spruce sites from the UWO network in the northern Yukon and determined that their relationships to summer temperatures varied between the first and second halves of the 20th century, indicating an apparent “divergence” response for these trees at high latitude. Jacoby and D'Arrigo (1995) first noted this "divergence" response in a study of white spruce in Alaska. They theorized that the weakening temperature sensitivity of the trees during the latter half of the 20^{th} century was potentially due to increased moisture stress related to pronounced warming (Jacoby and D'Arrigo, 1995). D'Arrigo *et al*. (2008) provide a comprehensive review of the "divergence" issue.

While these previous studies have involved white spruce from specific locations in the Yukon, they provided only small, localized views of tree growth. This current study will provide a larger, more comprehensive examination of white spruce growth patterns over the Yukon Territory, and thus a broader context for these earlier studies.

3.3 Characteristics of the Study Area

Sites sampled for this study represent an area of ca 400 000 km^2, between 58° to 68°N and 124° to 141°W within the Yukon Territory and bordering areas. In areas above 68°N latitude, which include the Northern British Mountains and Arctic Coastline regions of the Yukon, spruce forest cover diminishes and accessibility becomes a major limitation, thus this part of the Yukon is not included in this study. The major forest regions represented within the selected study area consist essentially of Boreal Forest and Tundra. This extensive study area involves a wide range of topographic and climatic conditions. A series of major reports, which describe the physiography, climate and ecological characteristics of the Yukon (Bostock (1948), Wahl *et al*. (1987), Smith *et al*. (2004)), are the basis for the following overview. As topography and climate are intricately linked within the Yukon, the climatic regions outlined by Wahl *et al*. (1987) form the basis for the recognition of most regional divisions of the Yukon (Figure 3.1) outlined below.

3.3.1 St. Elias-Coastal Mountains

The St. Elias-Coastal Mountains located in the south-west corner of the Yukon Territory act as a formidable barrier between the Pacific Coast and the interior regions of

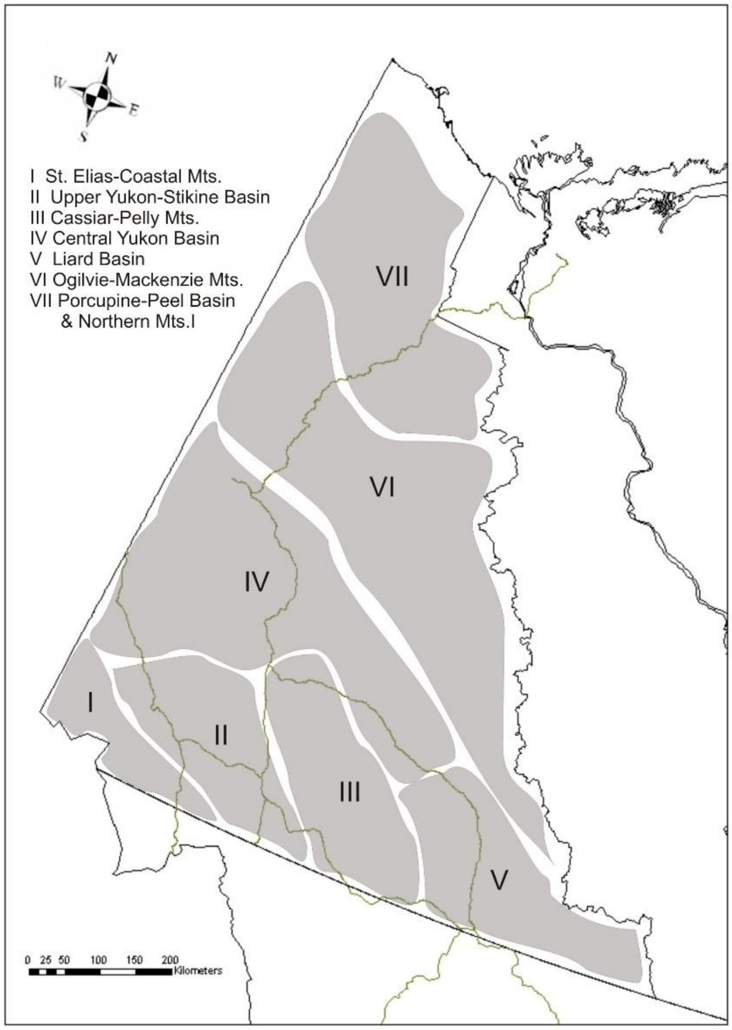


Figure 3.1 Regional climatic divisions of the Yukon Territory (adapted from Wahl *et al*. (1987)).

the Yukon. With mean elevations ranging between 2000-3000 m asl and scattered peaks topping 4000-5000 m asl (Smith *et al*., 2004), these mountains provide an effective topographical divide between the wet maritime climate of the coast and the more continental climate of the interior. Annual total precipitation amounts decrease from approximately 4000 mm on the coast side to under 300 mm on the continental side (Wahl *et al*., 1987). The temperature regime of this region is complex as a result of the elevational variations within the mountain ranges and its proximity to the Pacific Ocean. Due to the storminess of the Gulf of Alaska, this region can encounter moderate to strong winds, often funneled through well-defined valleys. Treeline in this region is close to 1080 m asl (Smith *et al*., 2004) and only the major valleys are forested

3.3.2 **Upper Yukon-Stikine Basin**

The Upper Yukon-Stikine Basin is located between the St. Elias-Coast Mountains and the Cassiar-Pelly Mountains found further east. This 'basin' is actually a rough highland plateau ranging in elevation from 900-1500 m asl with individual mountains reaching up to 2000m asl (Wahl *et al*., 1987). The Shakwak Trench lies along the western boundary of this region. This valley formed a large trough where the ice from the Pleistocene glaciers of St. Elias Mountains coalesced and spread outward through gaps in the ranges to the north and east. As a consequence, it has been heavily scoured in its narrower parts and elsewhere mantled by widespread drift deposits (Bostock, 1948). Due to the rain shadow effect of the St. Elias-Coast Mountains, this region has relatively low amounts of annual precipitation, ca. 200-300mm/year (Wahl *et al*., 1987). The temperature regime is considered continental, showing large variability on both a daily and seasonal basis. Much of this region lies above treeline (situated approximately 1200 m asl) (Smith *et al*., 2004).

3.3.3 **Cassiar-Pelly Mountains**

The Cassiar-Pelly Mountains form a secondary topographic barrier in the southern portion of the Yukon Territory that extends northwestward from the Cassiar Mountains of north-central British Columbia to the Pelly Mountains over south-central Yukon. Elevations in these mountains range between 1000-2000 m asl, with occasional peaks reaching 2500 m asl (Wahl *et al*., 1987). These mountains form a second significant barrier to weather systems east of the St. Elias and Coast Mountains, resulting in increased precipitation amounts (mean annual values of 500-650 mm) (Wahl *et al*., 1987). The higher elevations also experience cooler summers and less severe winters. Treeline in this region lies between 1350-1500 m asl (Smith *et al*., 2004).

3.3.4 **Central Yukon Basin**

The Central Yukon Basin is essentially a northward extension of the Yukon-Stikine Basin, distinguished from the latter by its lower elevations. Its climatic regime also differs from the Yukon-Stikine Basin due to the reduced influence of the Gulf of Alaska. Precipitation is relatively moderate, with mean annual values of approximately 400 mm (Wahl *et al*., 1987). Mean annual temperatures are around -4°C, though extreme temperatures are evident in this region. The coldest temperature in North America (-62.8°C) was recorded at Snag while Mayo has the highest recorded temperature in the Yukon of 36.1°C (Smith *et al*., 2004). Treeline in this vast area varies between 1200-1500m asl, with lower values found in the west rising gradually to the northeastern portions of the region (Smith *et al*., 2004). One of the distinguishing features of the Central Yukon Basin is that it contains one of the few areas in northwestern Canada that remained relatively unglaciated during the last glaciation. As part of easternmost Beringia, the western portion of the Basin (sometimes known as the Klondike Plateau) features deep V-shaped valleys and extensive colluvial (and gold bearing) surface deposits (Smith *et al*., 2004).

3.3.5 **Liard Basin**

The Liard Basin in the southeastern Yukon Territory is characterized primarily by its low-lying, broad plains reaching elevations less than 900m asl (Smith *et al*., 2004). Moderate precipitation (400-600 mm annually) and relatively long, warm summers in this region result in good forest growth. Most of the Liard Basin lies below treeline.

3.3.6 **Ogilvie-Mackenzie Mountains**

The Ogilvie-Mackenzie Mountains region lies along the southern half of the Yukon-Northwest Territories border, and extends westward along the 65th parallel. It includes the Ogilvie and Mackenzie Ranges and the Selwyn Mountains. Elevations range from 1500-2000m asl in the Ogilvie and Selwyn Mountains, up to 2500-3000m in the Mackenzies (Wahl *et al*., 1987). The westward arm of this region is often considered to separate central Yukon from northern Yukon (Smith *et al*., 2004). Due to its extreme topography, this region experiences moderate to heavy orographic precipitation ranging from 500mm to greater than 700mm annually (Wahl *et al*., 1987). The Mackenzie Mountains are a significant barrier that reduces the penetration of shallow layers of cold arctic air into the central and southern Yukon, often resulting in moderate winters (Smith *et al*., 2004). Treeline ranges from approximately 900m in the Ogilvies to 1200m in the Mackenzie and Selwyn Mountains (Smith *et al*., 2004). Like the Klondike Plateau in the Central Yukon Basin to the west, the Ogilvie Mountains were largely ice-free during the most recent glaciation as the Richardson and Mackenzie mountains restricted the westward penetration of the Laurentide Ice Sheet (Smith *et al*., 2004).

3.3.7 Porcupine-Peel Basin and Northern Mountains

These two regions represent the most northerly areas sampled for this study. The Porcupine-Peel Basin is a combination of flat plains and plateau, bordered to the east by the Richardson Mountains which form the southern leg of the Northern Mountains region. Elevations in the Porcupine-Peel Basin range between 300-600m asl, while peaks in the Richardson Mountains can reach over 1600m asl (Smith *et al*., 2004). Winters are usually prolonged and cold, while summers are short and variable, reflecting the northern latitudinal nature of these regions. The Ogilvie Mountains to the south act as an effective barrier to moisture from the Pacific, resulting in light precipitation amounts on the order of 200-300mm annually (Wahl *et al*., 1987). Treeline in these northern regions is generally found ca. 600m asl (Zoltai and Pettapiece, 1973).

3.4 Tree-Ring Sampling

Sampling was conducted by UWO tree-ring lab personnel between 1999 and 2005 to study the dendroclimatic potential of white spruce tree-ring chronologies within the northern Canadian Cordillera. Sampling was carried out primarily on a reconnaissance basis as few data on stand age or structure were available to guide site selection. Proximity to treeline, lack of natural disturbance and accessibility were primary considerations in site selection. The geographical pattern of sample sites generally reflected the available road network throughout the region, though seven sites located within the Wernecke Mountain range in central-eastern Yukon were accessed by float plane in order to extend the network into this remote region (Figure 3.2).

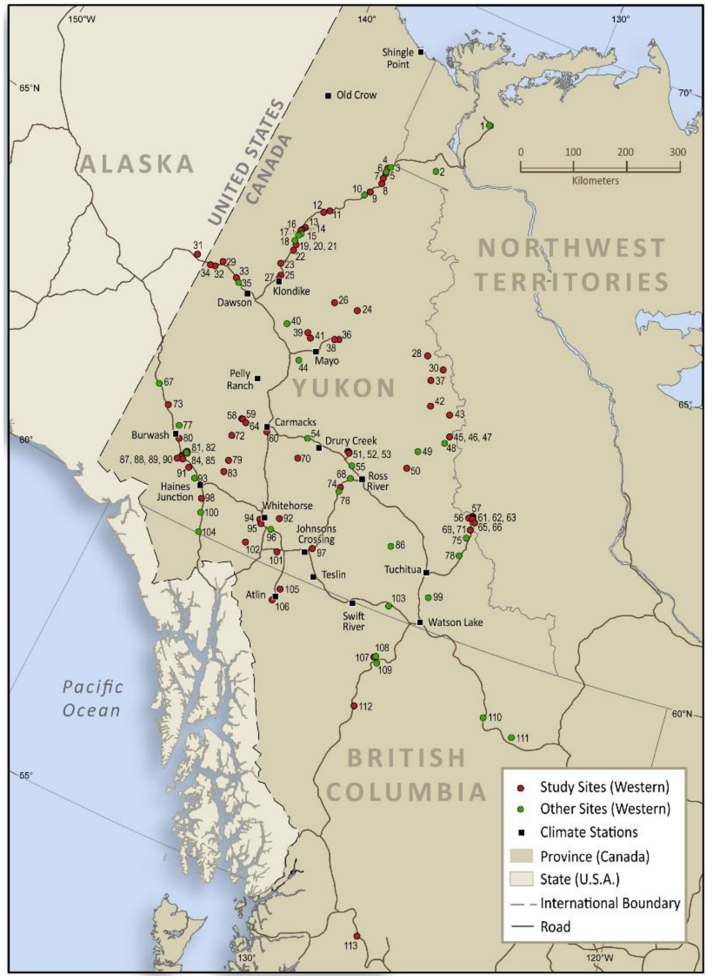


Figure 3.2 Geographical distribution of the 111 white spruce (Picea glauca) sites sampled by UWO. The 73 sites analyzed in this study (red circles) and those sites which were screened out (green circles) (Section 3.6.2) are marked along with Yukon climate stations (black squares). Site numbers shown correspond to site information in Appendix A.

At each site, preliminary coring trials and field counts were used to assess the potential length of record. If these data indicated a relatively young stand (usually less than 100-150 years) coring was generally abandoned after ca. 10-12 trees had been sampled. These limited core collections were retained for measurement and analysis. At sites with longer records, coring continued until ca. 20-30 trees had been sampled. At sites where trees appeared to be significantly older, larger numbers of cores were often taken for ring-width analysis. Several sites that exhibited advanced tree ages were also revisited in subsequent field seasons to update sample holdings and gather additional material for possible densitometric analyses. In total, UWO personnel sampled 111 white spruce sites between 1999 and 2005. Samples were usually collected at breast height and duplicate cores 90° apart or greater were taken from each tree. At some sites, complete diameter cores were taken from trees given their narrow diameter. Core samples were stored in individual drinking straws and labeled for identification purposes before transport back to the tree-ring laboratory for analysis.

Sample sites were primarily pure, open grown stands of white spruce with understory often including groundcover such as *Ledum groenlandicum* (Labrador tea), *Cladina rangiferina* (reindeer moss), or *Hylocomium splendens* (stairstep moss). In six cases (Rock Glacier, Szeicz, Jade City, Rancheria, Rancheria Mt., Tagish), white spruce was found in mixed stands with subalpine fir (*Abies lasiocarpa*). Such instances were limited to locations in the southern Yukon, where the natural ranges of these two species overlap. A network of 23 *Abies* chronologies has been analysed in Kenigsberg (2005).

3.5 Chronology Development

Increment core samples collected from each site were processed using standard dendrochronological techniques (Stokes and Smiley, 1968; Fritts, 1976). Cores returned from the field were allowed to air dry to prevent mould development, placed on mounting boards, and sanded with progressively finer sandpapers to aid in distinguishing individual tree rings. Ring-widths were measured to the nearest 0.001mm using either a Velmex Unislide Traversing Measuring system or Tree Ring Increment Measuring (TRIM) system, utilizing Measure J2X software. To ensure that measured samples were properly dated, ring-width series were crossdated utilizing COFECHA computer software (Holmes, 1983). Those cores or portions of cores that did not crossdate properly were excluded from use in chronology development. In cases where sites were re-sampled in multiple field seasons, data samples were combined to produce updated records.

Tree-ring series often exhibit a biological decreasing growth trend with increasing age, as net primary productivity is progressively spread around an increasing ring circumference (Fritts, 1976; Briffa, 1995). Since this age-related growth trend is considered to be due to non-climatic causes, standardization procedures are commonly used to remove this trend. As part of the chronology development process for each site, each measured series was standardized using the computer program ARSTAN (Cook, 1985). For this study, ARSTAN version 40c_win (2006) was utilized. Each series was standardized either by fitting a modified negative exponential curve, a Hugershoff curve, a linear trend line of negative slope, or a horizontal line through the mean of the series. The interactive detrending feature in ARSTAN allowed the viewing of raw measurements and trial curve fits for each series, allowing the selection of growth curve to be applied. By dividing the measured series by the appropriately fitted growth curve, the resultant transformed values were presented as tree-ring indices. These standardized indices of individual trees were then averaged within ARSTAN using biweight robust estimates to generate a mean standard chronology for each sample site (Fritts, 1976). By averaging data series in the creation of a mean chronology, non-common variability or ‘noise’ can be reduced (Fritts, 1976; Briffa, 1995). ARSTAN also generated a mean residual chronology for each sample site. The difference between a standard and residual chronology is that all autocorrelation has been stripped from the series within the residual chronology, while the standard chronology still possesses autocorrelation (Speer, 2010). As a result, the residual chronology highlights the high frequency, interannual variability inherent in the tree-ring data; while the standard chronology provides a view of the lower frequency, longer-term variability.

Both the COFECHA and ARSTAN software programs used in the development of the site chronologies additionally provided information regarding several statistical characteristics, useful in examining the quality of the chronologies. These measures included: average mean sensitivity (MS), first-order autocorrelation (1AC), mean series intercorrelation (r), mean inter-tree correlation (RBAR), and expressed population signal (EPS) (See Appendix B for a brief explanation of these measures).

3.6 Chronology Results

3.6.1 Entire Collection

In total, 111 site chronologies were produced from the UWO collection as potential candidates for inclusion in the ring-width network for this study. In constructing these UWO chronologies, 2983 individual white spruce trees were sampled, producing 5566 core series, and resulting in a total of 1 150 290 tree rings being measured and chronologically dated. This collection represents the largest grouping of white spruce ring-width chronologies currently available for the Yukon Territory and bordering areas (see Appendix A).

The mean chronology length for the entire collection was 343 years, ranging from 74 years (Deadwood) to 1089 years (Landslide). The extraordinary length of the Landslide record was the result of assembling crossdated material from both living and dead trees at this site next to Kluane Lake (Luckman *et al*., 2002; Van Dorp, 2004). Almost all other chronologies in this current study were developed from samples obtained from live standing trees. In total, 100 chronologies, or 90.1% of this full collection, had raw chronology lengths greater than 200 years in length. Of these, 32 chronologies (28.8% of the collection) were longer than 400 years. Six chronologies (5.4% of the collection) were over 500 years long (Figure 3.3a).

The average tree (and core) sample depth for the entire collection was 26 trees (50 cores), ranging from 4 (Rock Glacier Spruce, Rancheria Spruce, and Yukon Crossing Spruce) to 84 trees (Tombstone Mountain) (Figure 3.3b), and between 7 (Yukon Crossing Spruce) and 161 cores (Landslide) (Figure 3.3c). Mean series segment length was 200 years, with a minimum of 62 years (Deadwood) and a maximum of 339 years (Burwash). In terms of age distribution of trees, the collection as a whole exhibited a unimodal distribution with 51.3% of the collection consisting of trees greater than 200 years (Table 3.1). This is quite noteworthy, given that in northern latitudes, finding trees older than 200 years was thought to be considered rare due to fire disturbance and also because spruce generally has a low resistance to trunk rot in old age (Schweingruber, 1988).

Table 3.1 Age class distribution of trees in UWO *Picea glauca* collection.

	<50	50-99	100-149	150-199	200-299	300-399	400-499	>500
total count	88	453	979	1198	2042	672	120	14
percentage	1.6	8.1	17.6	21.5	36.7	12.1	2.2	0.3

Although the majority of sites in the collection displayed unimodal tree age-class distributions, a small number of sites appeared to exhibit bimodal distributions (i.e. Campbell Upland, Rock River, Tsiivii Creek, Airstrip Eagle Plains, Mt. Jeckell, Distincta East, Tombstone Mountain, North Klondike River, Emerald Lake, Wheaton River)

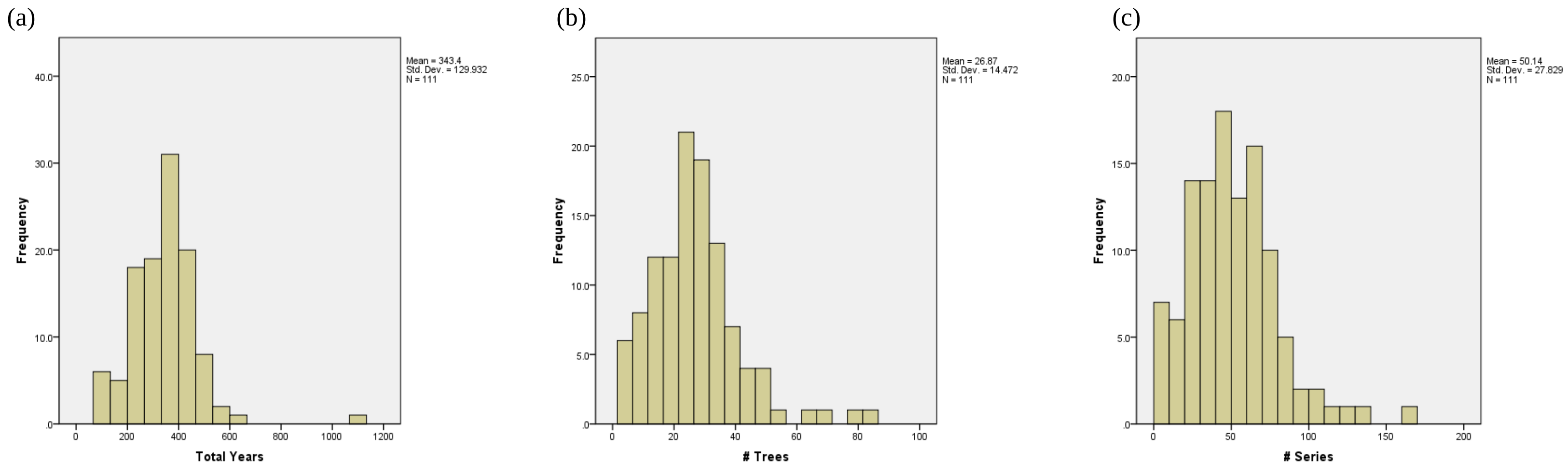


Figure 3.3 Distribution of (a) raw chronology lengths, (b) sample depth of trees, and (c) sample depth of core series, of the entire UWO *Picea glauca* collection.

(Figure 3.4). Such distributions suggest stand disturbance due to natural causes (usually due to past fires) and more than one generation of trees.

Mean sensitivity (MS) values for the standard chronologies of the collection ranged from 0.096 (Little Hyland) to 0.273 (Jackson Point), with an overall collection mean of 0.148. This average value is similar to other spruce collections; for example, mean sensitivity of 0.155 for a collection from Alaska and northwestern Canada (Cropper, 1982), as well as a mean sensitivity value of 0.140 derived from three sites in northern British Columbia and southern Yukon (Pisaric, 2001). Although most sites showed MS values centered about the collection mean, nine sites located mainly near Kluane Lake in the southwestern portion of the Yukon appeared to form a subpopulation, exhibiting mean sensitivity values greater than 0.200 (subpopulation average of 0.246) (Figure 3.5a). These nine sites were: Extra Point (0.216), Aishihik (0.228), Donjek (0.232), Cultus Bay (0.236), Landslide (0.247), Fox Point (0.256), Bullion Creek (0.259), Yukon Crossing Spruce (0.264), and Jackson Point (0.273).

The mean sensitivity values for the residual chronologies of the collection had a higher overall mean of 0.169, with a minimum value of 0.116 (Tungsten and Little Hyland) and a maximum value of 0.306 (Jackson Point). While the majority of the values were below 0.200, eleven residual chronologies exhibited higher mean sensitivity values (Figure 3.6a). With a calculated mean of 0.268, these eleven sites were: Midway Lake (0.224), Donjek (0.227), Telluride (0.235), Aishihik (0.259), Extra Point (0.263), Cultus Bay (0.275), Yukon Crossing Spruce (0.278), Landslide (0.283), Fox Point (0.294), Bullion Creek (0.299), and Jackson Point (0.306). With the exception of Midway Lake, in the far north of the Yukon, and Yukon Crossing, with low sample depth, this group of sites is mainly from the Kluane region in the southwestern Yukon. Higher mean sensitivity in both high frequency (residual chronologies) and low frequency (standard chronologies) signals suggest that these sites represent a distinctive sub-population from the rest of the Yukon Territory.

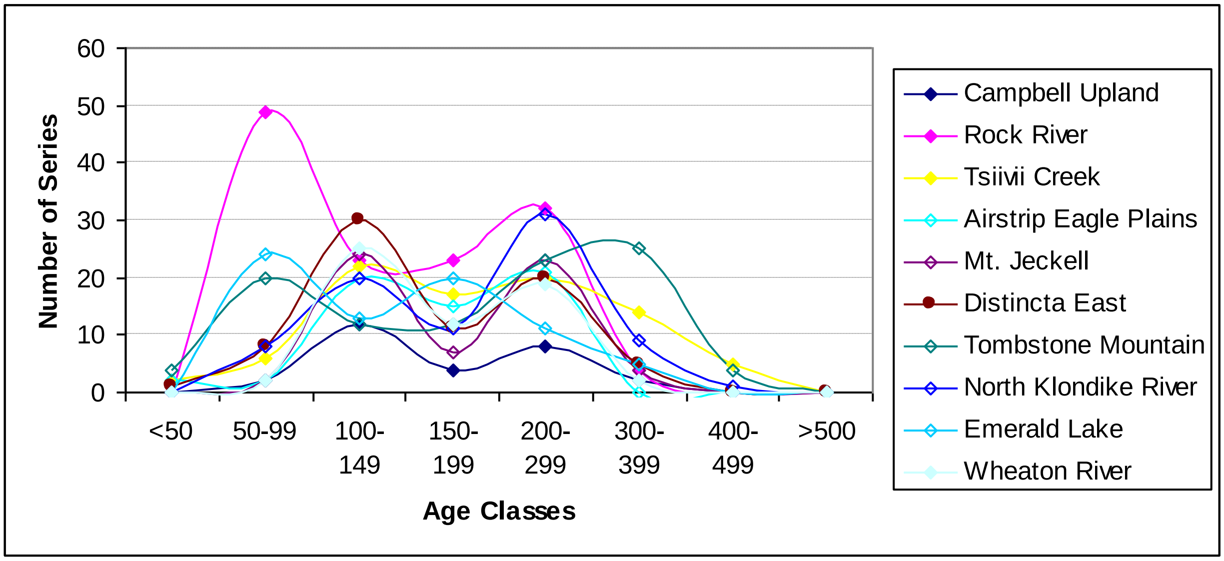


Figure 3.4 Sites within the UWO *Picea glauca* collection exhibiting bimodal age distributions.

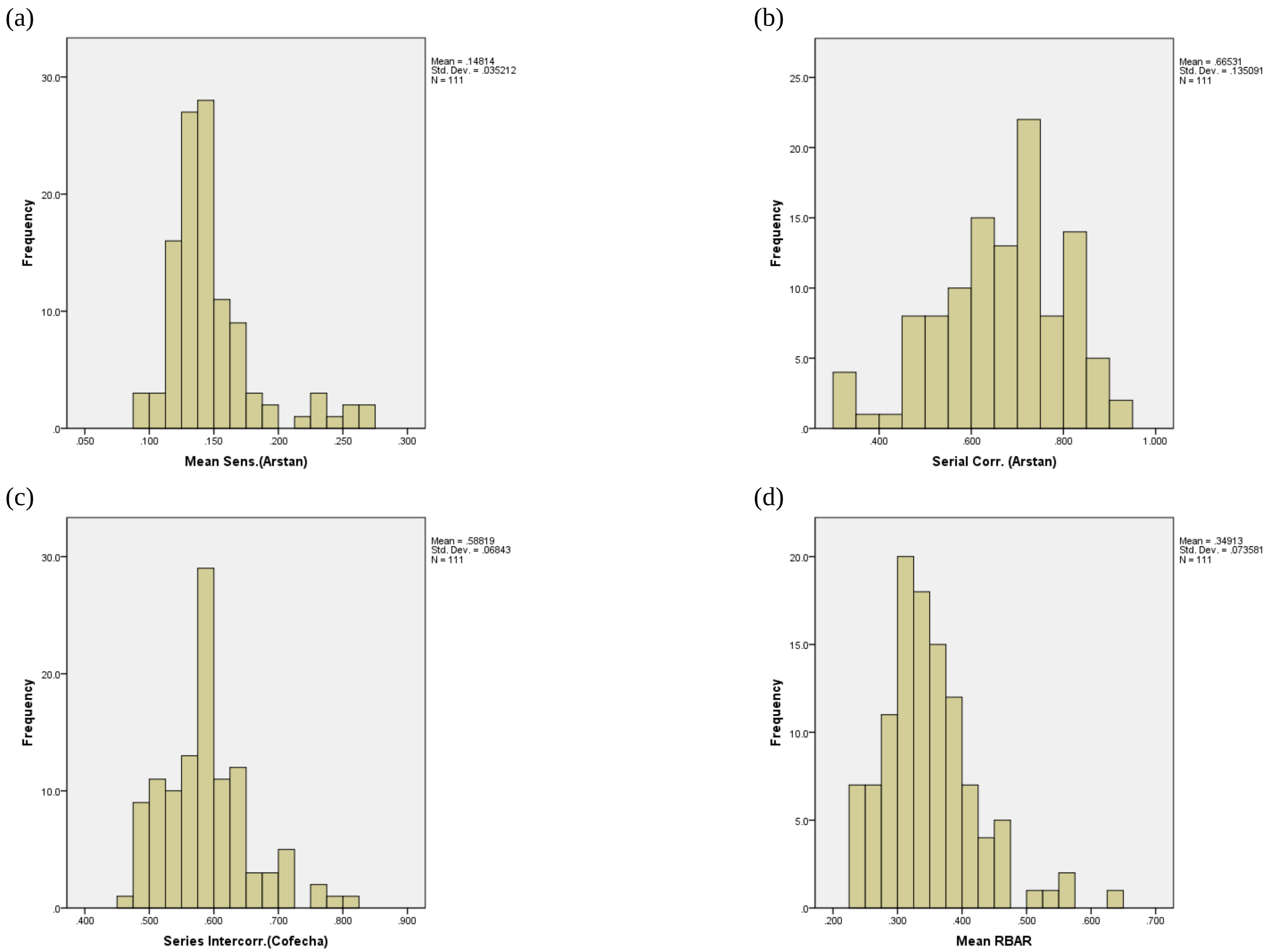


Figure 3.5 Tree-ring statistical characteristics of standard chronologies. Distributions of (a) mean sensitivity values, (b) serial correlation (or first-order autocorrelation (1AC)) values, (c) series intercorrelation (r) values, and (d) mean RBAR values.

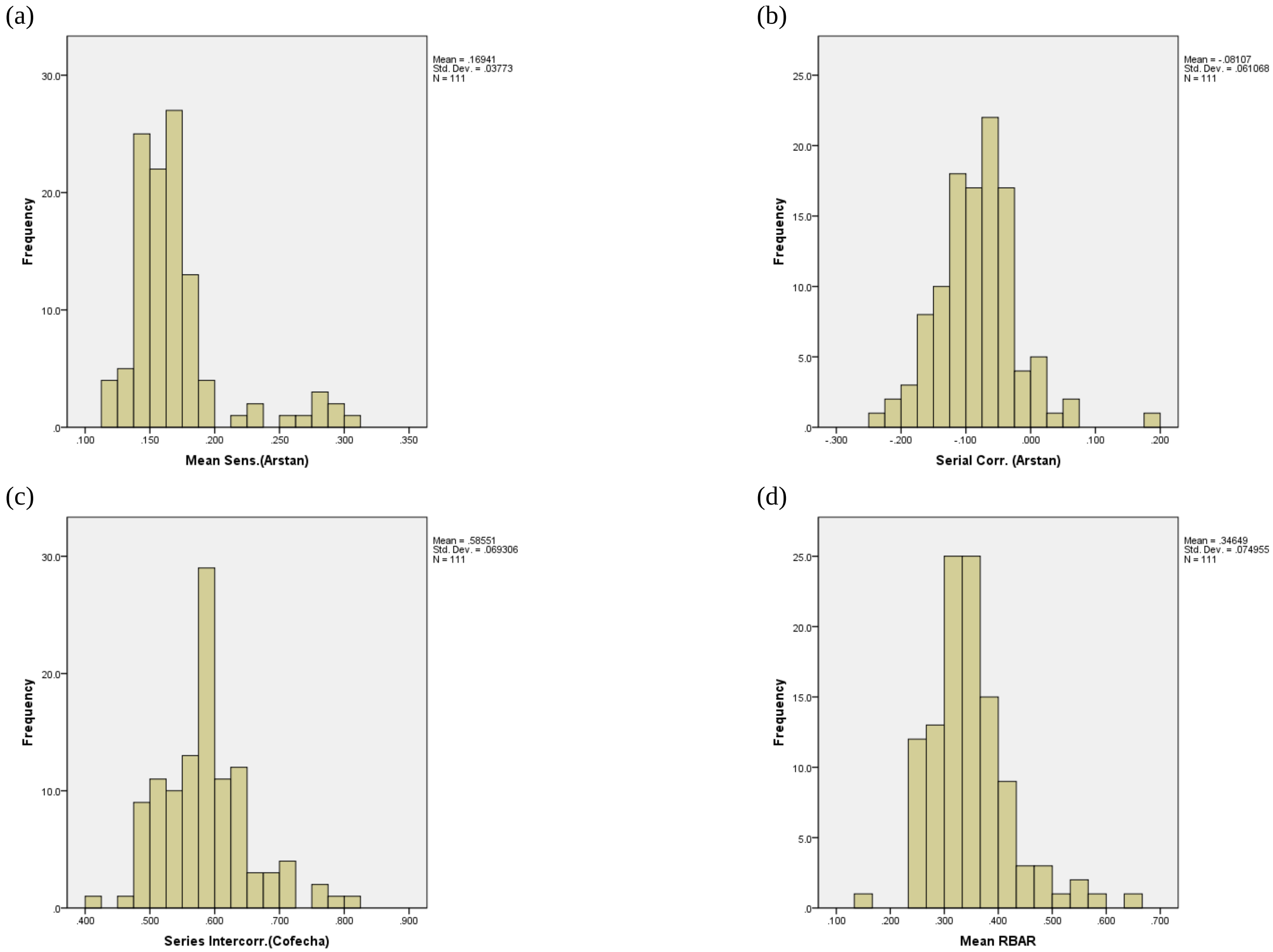


Figure 3.6 Tree-ring statistical characteristics of residual chronologies. Distributions of (a) mean sensitivity values, (b) serial correlation (or first-order autocorrelation (1AC)) values, (c) series intercorrelation (r) values, and (d) mean RBAR values.

First-order autocorrelation (1AC) values for the standard chronologies of the collection ranged from 0.309 (Aishihik) to 0.948 (Aina), with an overall mean value of 0.665 (Figure 3.5b). This average was slightly higher, though comparable, with mean first-order autocorrelation values from other spruce collections (e.g. 1AC value of 0.62 (Cropper and Fritts, 1981) and 0.657 (Pisaric, 2001)). Those sites with higher 1AC values indicate chronologies which contain considerable persistence in ring-width from one year to the next. First-order autocorrelation values of the residual chronologies ranged from -0.230 (Rancheria Mountain Spruce) to 0.186 (Buttle Creek), with an overall mean value of -0.081 (Figure 3.4b). As residual chronologies reflect the interannual variability inherent in the high frequency signals of chronologies, and since most autocorrelation is removed in their development (Speer, 2010), these lower autocorrelation values of the residual chronologies are not surprising.

Mean series intercorrelation (r) value for standard chronologies of the tree-ring collection was 0.588, ranging from 0.467 (Interfluve) to 0.807 (Aishihik) (Figure 3.5c). Values for residual chronologies were similar with an average value of 0.586, registering a low of 0.416 (Muncho Lake Slope) and high of 0.807 (Aishihik) (Figure 3.6c). Sites exhibiting higher series intercorrelation were primarily found in the southern portions of the Yukon (e.g. Bullion Creek (0.763), Yukon Crossing Spruce (0.764), Jackson Point (0.781) and Aishihik (0.807)) (Figure 3.7). Not surprisingly, results for RBAR showed similar patterns to series intercorrelation. RBAR values ranged from 0.234 (Engineers Creek) to 0.641 (Yukon Crossing Spruce) with an overall collection mean of 0.349 for standard chronologies (Figure 3.5d), while residual chronology RBAR values spanned from 0.163 (Muncho Lake Slope) to 0.641 (Yukon Crossing Spruce) with a mean of 0.346 (Figure 3.6d). The mean RBAR value of the standard chronologies of this collection is comparable with other studies (e.g. mean inter-tree correlation of 0.355 (Pisaric, 2001)).

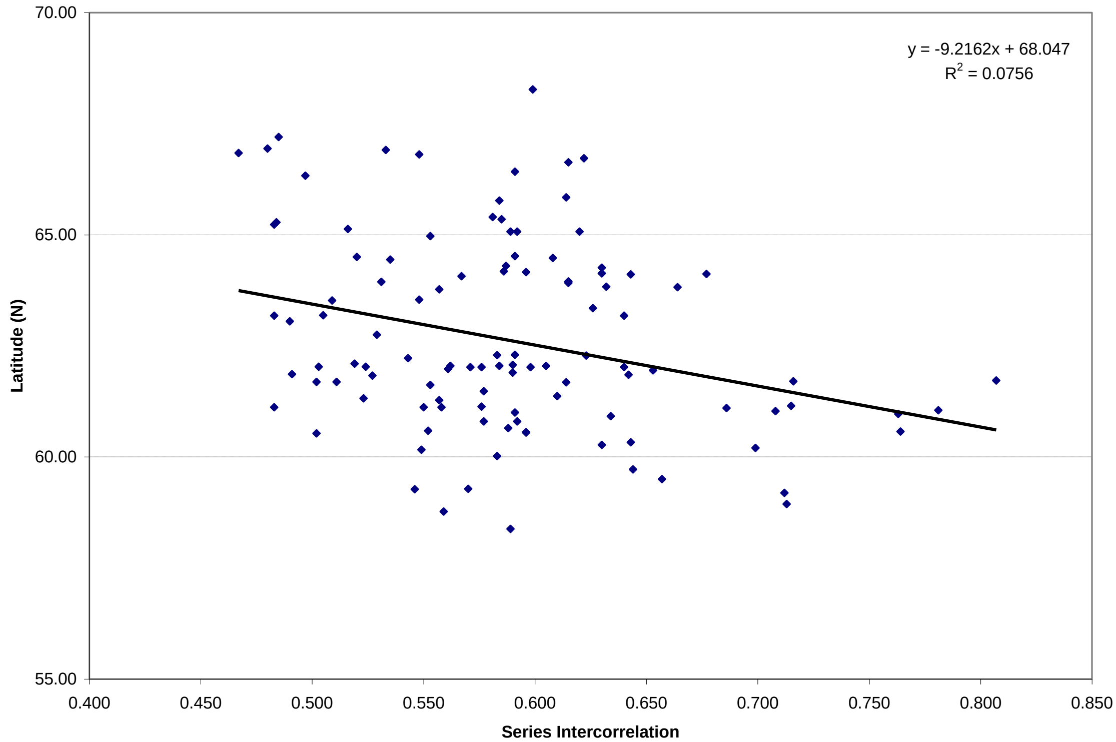


Figure 3.7 Relationship between mean series intercorrelation and latitude for standard chronologies in the UWO *Picea glauca* collection (n=111). Sites exhibiting higher series intercorrelation were located at lower latitudes (r = -0.275, significant at 95% confidence level).

The earliest portions of most chronologies are poorly replicated and the usable, EPS defined chronologies are often much shorter than the oldest trees at a site. The longest chronology meeting the 0.85 criterion was Landslide which extended back to 1135 AD. The next longest chronology, based solely on living material, had an EPS value going back to 1512 AD (Burwash). In total, 65.8% (73 chronologies) of the collection had EPS values extending back beyond 1800 AD (Figure 3.8a & 3.8b). Interestingly, the seven longest EPS defined chronologies of the collection (Landslide, Burwash, Faro, Monarch, Webber Creek, Telluride, Gray Mountain) were all from the southwestern region of the Yukon, an indication of the longevity of trees in this part of the territory. Unfortunately, several site chronologies exhibited poor EPS results within the latter portions of their records (Figure 3.8a & 3.8b). These sites included: Triangle, MacMillian Pass West, Mt. Sheldon, Little Salmon, Buttle Creek, Mt. Cook, Rock Glacier Spruce, Fox Point, Rancheria Spruce, Spruce Beetle, Yukon Crossing Spruce, and Szeicz . In most of these cases, low sample

Chronology Lengths/EPS (Sites 1-56)

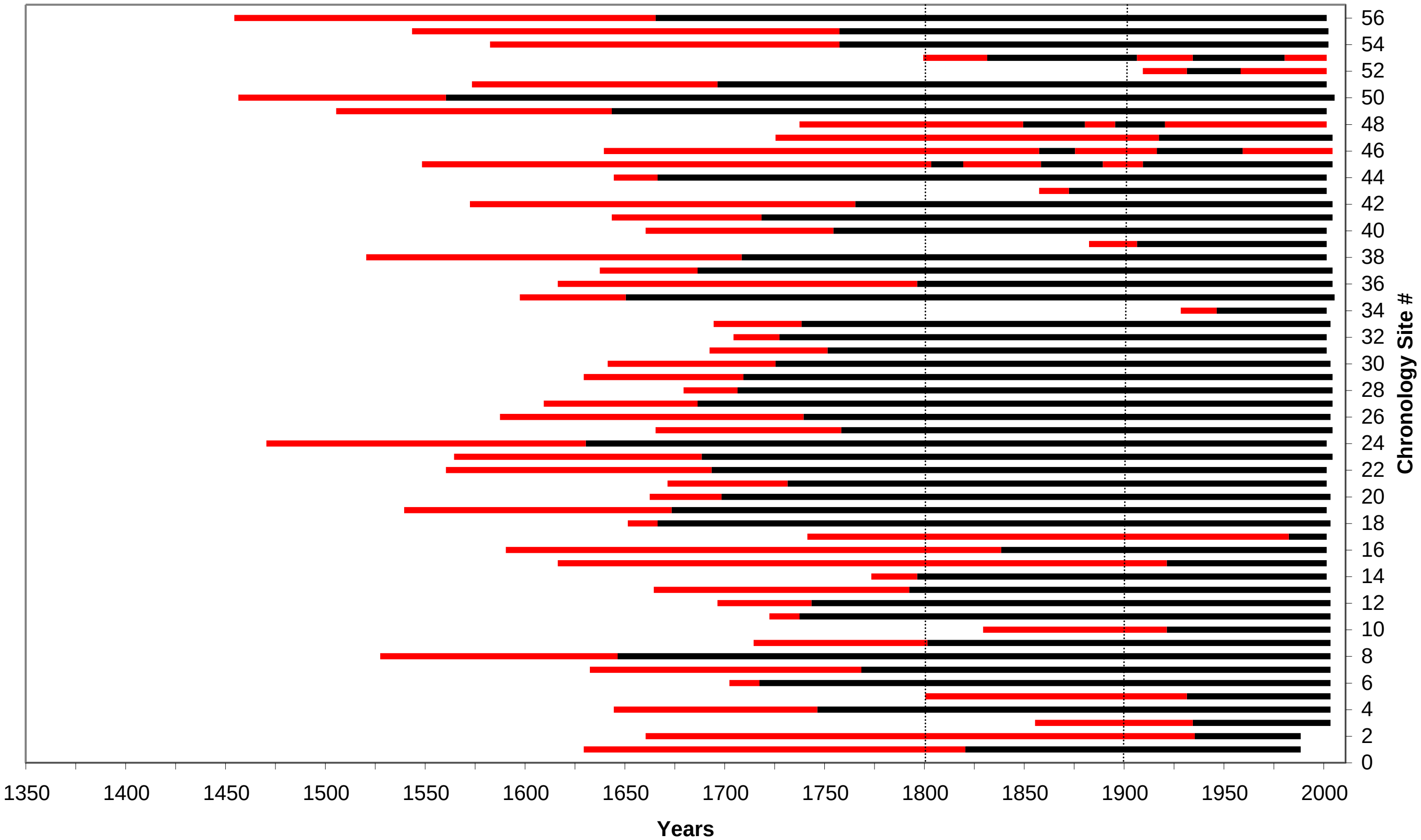


Figure 3.8a Summary for sites 1-56 (site numbers/names listed in Appendix A) showing chronology lengths and the portion of the chronologies which meet the EPS > 0.85 criterion (indicated in black). Red denotes intervals of the chronology where EPS < 0.85 for longer than 10 consecutive years.

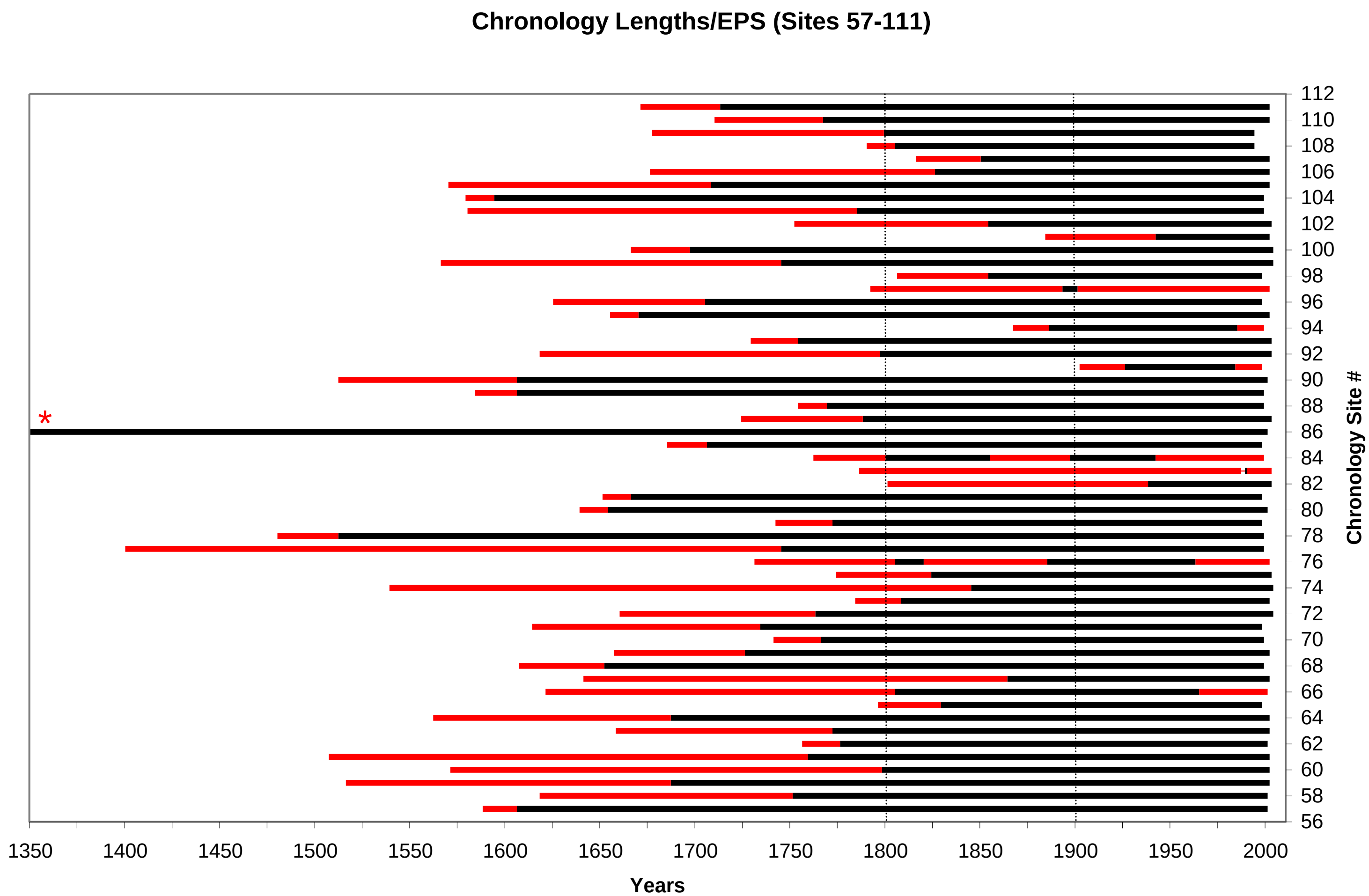


Figure 3.8b Summary for sites 57-111 (site numbers/names listed in Appendix A) showing chronology lengths and the portion of the chronologies which meet the EPS > 0.85 criterion (indicated in black). Red denotes intervals of the chronology where EPS < 0.85 for longer than 10 consecutive years. * Site 87 (Landslide) had EPS > 0.85 extending back to 1135 AD.

replication was the contributing factor to their poor performance.

3.6.2 Screening Chronologies for Network Inclusion

The 111 chronologies developed in this study represent the single largest collection of tree-ring records of ring-width for the Yukon. Each individual chronology describes the radial growth trend for a tree stand at a particular location over a period of time (Schweingruber, 1996). By assembling a network of chronologies, it is possible to characterize radial growth trends within a broader geographical area. By utilizing a network, it is possible to examine both spatial and temporal variability of signals contained in the tree-ring records. The chronologies developed in this study vary in both length and quality and, in order to look at regional patterns of growth over time, there is an inevitable trade-off between maximizing the period of time for analysis while maintaining a reasonable geographical distribution of chronologies. It is therefore necessary to screen this database to select those chronologies with adequate quality and length to provide the most useful information for examining variability in growth patterns of white spruce. The primary consideration of chronology quality is signal strength, followed by the length of the chronology over which that signal strength is maintained. Since a key objective of this study is to examine the geographical patterns in spruce growth, it is also important to maintain the spatial distribution of sites within the network. In order to accommodate both these temporal and spatial considerations, two network datasets were developed. The smaller dataset focused on chronologies exhibiting longer acceptable lengths, while the second dataset maintained a larger number of chronologies to examine conditions over the 20th century. Since EPS assesses the common signal of a chronology and its change due to sample depth and intercore correlation, chronologies were screened mainly based on EPS values.

Examination of the plots of chronology lengths for the entire collection showed that EPS acceptable lengths varied significantly (Figure 3.8a & 3.8b). While acceptable EPS values extending back in time formed the primary focus of the screening process, EPS results of the late 20th century were also a consideration. While most chronologies maintained acceptable EPS values until the late 20th century, thirteen chronologies exhibited poor EPS results during this later period (Table 3.2). These poor EPS results were mainly due to limited sample depth, ranging from 4 to 19 trees. Many of these sites were those where initial sampling indicated that the trees were young or limited numbers of spruce were present and thus sampling was terminated after the collection of a small number of samples. In other cases, sample collection was conducted for purposes other than climate analysis. For example, samples at Extra Point and Fox Point were collected to date beach formations (Luckman, *pers. comm.*) and were limited to the small number of trees necessary to provide a reasonable estimate of the age of the surface. In the two cases of MacMillian Pass West and Rancheria Spruce, additional collections were made from sites within a kilometer and correlations of ≥ 0.8 between records during the 20th century allowed combination of these collections to form composite site chronologies with adequate sample replication and signal strength. Based on these poor late 20th century EPS results, eleven of these chronologies were removed from further analyses. Four chronologies with end dates prior to 1995 and relatively poor signal strengths (i.e. Campbell Upland, Midway Lake, Muncho Lake Slope and Summit Lake North) were also removed from further analyses. Since most of the data in the ITRDB for Yukon white spruce often had end dates from the 1970s and 1980s, this material was not used for analysis. However, due to its historical significance in Yukon tree-ring research, TTHH (Twisted Tree-Heartrot Hill) was included in the analysis in order to evaluate how it compares with the network. An updated record for TTHH, extending to 2000, was used (Earles, 2008).

In a further reduction of sample site numbers, closely proximal sample collections at Distincta, Big Bend and Eagle were combined to form single composite chronologies, similar to MacMillian Pass and Rancheria.

Table 3.2 UWO chronologies exhibiting poor EPS results during the late 20th century. EPS values shown in table indicate portions of the chronologies meeting EPS > 0.85 threshold criteria.

Site #	Site Name	Latitude(N)	Longitude(W)	# Series	# Trees	Start Date	End Date	EPS > 0.85
17	Triangle	65.13	138.37	18	12	1741	2001	1982-2001
46	MacMillian Pass West	63.18	130.15	17	8	1639	2004	1857-1875; 1916-1959
48	Mt. Sheldon	62.75	131.03	16	8	1737	2001	1849-1880; 1895-1920
52	Little Salmon	62.22	134.83	9	5	1909	2001	1931-1958
53	Buttle Creek	62.10	133.00	20	13	1799	2001	1831-1906; 1934-1980
66	Mt. Cook	61.90	132.87	19	11	1621	2001	1805-1965
76	Rock Glacier Spruce	61.37	128.35	8	4	1731	2002	1805-1820; 1885-1963
82	Extra Point	61.13	138.45	8	8	1801	2003	1938-2003
83	Fox Point	61.12	138.42	8	8	1786	2003	1987-1989
84	Rancheria Spruce	61.10	130.67	8	4	1762	1999	1800-1855; 1897-1942
91	Spruce Beetle	60.80	137.78	27	19	1902	1998	1926-1984
94	Yukon Crossing Spruce	60.57	134.68	7	4	1867	1999	1886-1985
97	Szeicz	60.53	128.84	9	5	1792	2002	1893-1901

Dataset 1 – EPS1800

Given the primary goal of examining the widest spatial distribution for the longest time interval, the primary dataset used in this thesis contains those chronologies from the UWO data set with acceptable EPS values extending back to 1800 AD. Eighteen additional sites were removed from the network because the acceptable EPS lengths ended in the 19th century (Table 3.3). Data from a site at Lapies Pass was added to the dataset to improve representation from the eastern Yukon. This site, situated midway along the North Canol Road in the eastern Yukon, provided coverage in this part of the network, replacing the nearby Mt. Sheldon site in the UWO network. Dr. M. Pisaric from Brock University (*pers. comm.*) provided data for the Lapies Pass site. In total, Dataset 1 (to be further referred to as the EPS1800 dataset) consists of 73 site chronologies (Table 3.4) and includes 65.7% of the chronologies in the UWO *Picea glauca* collection.

Dataset 2 – EPS1900

The EPS1800 dataset sacrificed site numbers and distribution in order to maximize temporal coverage, Dataset 2 (further referred to as EPS1900) was developed to maintain a larger number of sites to investigate potential changes during the 20th century. Earles (2008) showed that several sites in the northern Yukon exhibited 'divergent' growth responses in relation to summer temperatures during the latter half of the 20th century. By utilizing a broader geographical network of sites, it will be possible to examine whether this phenomenon was localized or not. The 84 chronologies (74.8% of the UWO data set) with acceptable EPS values for the 20th century were retained (Table 3.5 indicates the additional sites found in EPS1900, not included in EPS1800 dataset). This EPS1900 dataset is focused on the 20th century.

Table 3.3 Sites removed during the screening process in the formation of EPS1800 dataset. "Comp" indicates composite chronology.

Site #	Site Name	Latitude (N)	Longitude (W)	# Series	# Trees	First Year	Last Year	EPS > 0.85
3	Richardson Mountain	66.94	136.26	32	25	1855	2003	1934
5	Interfluve	66.84	136.35	42	24	1800	2003	1931
10	Corbett Hill	66.33	136.73	45	24	1829	2003	1921
15	Engineers Creek	65.28	138.25	26	19	1616	2001	1921
16	Talus	65.23	138.33	24	16	1590	2001	1838
34	Deadwood	64.07	139.52	31	16	1928	2001	1946
39	Pup 65	63.82	137.25	26	13	1882	2001	1906
43	Hungry Mountain	63.35	136.28	62	32	1857	2001	1872
47	Dewhurst Creek	63.05	130.25	28	17	1725	2004	1917
65	Koidern	61.95	140.37	34	17	1796	1998	1829
73	Little Hyland	61.69	128.33	41	24	1784	2002	1808
74	Rose River	61.62	133.06	31	15	1539	2004	1845
75	Duke Terrace	61.48	139.08	30	28	1774	2003	1824
98	St. Elias Lake	60.33	137.08	21	12	1806	1998	1854
Comp	Rancheria Combined	60.16	130.50	17	9	1762	2002	1891
102	Tatshenshini	60.02	136.87	56	25	1752	2003	1854
106	Troutline Creek	59.28	129.83	43	25	1676	2002	1826
107	Jade City Spruce	59.19	129.67	16	10	1816	2002	1850

Table 3.4 Site chronologies comprising EPS1800 dataset.

Site #	Site Name	Latitude (N)	Longitude (W)	Elevation (m)	# Series	# Trees	First Year	Last Year	Total Years	EPS > 0.85
4	Rock River	66.91	136.35	500	131	68	1644	2003	360	1746
6	Mt. Cronin	66.81	136.34	579	46	24	1702	2003	302	1717
7	Vadzaih Kan Creek	66.72	136.34	691	61	31	1632	2003	372	1768
8	Tsiivii Creek	66.63	136.31	685	86	37	1527	2003	477	1646
9	Airstrip Eagle Plains	66.42	136.58	705	60	30	1714	2003	290	1801
11	Scriver Creek	65.84	137.67	848	111	66	1722	2003	282	1737
12	Ogilvie Ridge	65.77	137.85	811	64	34	1696	2003	308	1743
13	Mt. Jeckell	65.40	138.23	600	60	31	1664	2003	340	1792
14	Sappers Hill	65.35	138.30	640	66	36	1773	2001	229	1796
15	TTHH (Updated)	65.33	138.33	915	69	64	1459	2000	542	1624
19-21	Distincta Combined	65.07	138.25	945	199	88	1539	2003	465	1671
22	Blackstone River	64.97	138.25	865	52	29	1671	2001	331	1731
23	Black City	64.68	138.45	1004	20	13	1560	2001	442	1693
24	Carpenter Lake	64.52	135.10	1100	49	26	1564	2004	441	1688
25	Tombstone Mountain	64.50	138.25	1006	100	84	1470	2001	532	1630
26	Worm Lake	64.48	136.00	1125	48	27	1665	2004	340	1758
27	North Klondike River	64.44	138.26	975	80	44	1587	2003	417	1739
28	Bonnet Plume Lake	64.30	132.03	1130	56	33	1609	2004	396	1686
29	Clinton Creek	64.26	140.39	1050	65	34	1679	2004	326	1706
30	Misty Lake	64.18	131.30	1241	60	33	1629	2004	376	1709
31	Jack Wade	64.16	141.36	961	101	50	1641	2003	363	1725
32	Swede Dome	64.13	140.58	990	39	24	1692	2001	310	1751
33	Empire Creek	64.12	139.68	1080	30	16	1704	2001	298	1727
34	Big Gold Creek	64.11	140.75	1078	60	32	1694	2003	310	1738
36	Wernecke	63.95	135.28	1254	86	48	1597	2005	409	1650
37	Einarson Lake	63.94	131.57	1124	40	23	1616	2004	389	1796
38	Galena	63.92	135.42	1204	55	30	1637	2004	368	1687
39	Barlow Dome	63.83	136.42	1160	77	37	1520	2001	482	1708

41	Highet Creek	63.77	136.25	1235	34	20	1660	2001	342	1754
42	Emerald Lake	63.54	131.23	1130	73	33	1643	2004	362	1718
43	Keele Lake	63.52	130.45	1184	75	42	1572	2004	433	1765
45-47	MacMillian Pass Combined	63.18	130.16	1180	76	43	1548	2004	457	1663
50	Lapie Pass (Pisaric)	62.42	131.17	1490	28	17	1654	1995	342	1766
51	Anvil Mine	62.30	133.33	1175	50	25	1505	2001	497	1643
52	Faro	62.29	133.28	1205	83	44	1456	2005	550	1560
53	Mt. Mye	62.28	133.27	1205	41	20	1573	2001	429	1696
56	Nahanni Spruce	62.07	128.38	1150	63	33	1582	2002	421	1757
57	Divide Spruce	62.05	128.37	1156	56	25	1543	2002	460	1757
58	Nansen Creek	62.05	137.22	1115	49	27	1454	2001	548	1665
59	Webber Creek	62.05	137.17	1340	78	46	1588	2001	414	1606
60	Mt. Berdoe	62.03	136.23	1170	35	23	1618	2001	384	1751
61-62	Big Bend Combined	62.03	128.35	1310	74	41	1516	2002	487	1686
63	Campsite	62.02	128.49	1240	45	25	1507	2002	496	1759
64	Victoria Creek	62.02	137.03	1050	51	29	1756	2001	246	1776
65	NWT Pass	62.02	128.36	1355	37	20	1658	2002	345	1772
66	Tungsten	61.98	128.25	1145	78	39	1562	2002	441	1687
70	Eagle Twelve	61.85	134.85	1130	78	40	1607	1999	393	1652
69,71	Eagle Combined	61.84	128.30	1170	75	47	1641	2002	362	1748
72	Aishihik	61.72	137.28	975	59	31	1741	1999	259	1766
73	Donjek	61.70	139.75	750	56	29	1614	1998	385	1734
74	Lapie Lakes	61.69	133.07	1083	42	25	1660	2004	345	1763
79	Sandpit	61.32	137.00	1000	65	33	1400	1999	600	1745
80	Burwash	61.28	138.88	840	79	37	1480	1999	520	1512
81	Cultus Bay	61.15	138.43	805	41	21	1742	1998	257	1772
82	AINA	61.12	138.40	825	40	22	1639	2001	363	1654
83	Canyon Lake	61.12	136.98	900	43	22	1651	1998	348	1666
87	Jackson Point Good	61.05	138.52	830	77	36	1685	1998	314	1706
88	Landslide Main	61.03	138.50	800	161	78	913	2001	1089	1135
89	Pipeline	61.00	138.44	814	45	29	1724	2003	280	1788
90	Bullion Creek	60.97	138.62	820	58	28	1754	1999	246	1769
91	Telluride	60.92	138.13	1400	89	50	1584	1999	416	1606

92	Gray Mountain	60.80	134.57	1140	92	49	1512	2001	490	1606
94	Mt. McIntyre	60.65	135.17	1232	51	25	1618	2003	386	1797
95	Coal Lake Road	60.59	135.07	1070	47	28	1729	2003	275	1754
97	Big Salmon	60.56	133.13	1190	94	54	1655	2002	348	1670
98	Kathleen Lake	60.55	137.27	750	62	27	1625	1998	374	1705
101	Tagish	60.27	134.18	1167	70	40	1566	2004	439	1745
102	Wheaton River	60.20	135.29	1032	60	34	1666	2004	339	1697
105	MacDonald Lake	59.72	133.58	950	36	19	1580	1999	420	1785
106	Monarch	59.50	133.68	1400	64	30	1579	1999	421	1594
107	Cassiar	59.27	129.83	1225	53	27	1570	2002	433	1708
112	Tanzilla Butte (UWO/Laval)	58.38	129.86	1166	123	34	1710	2002	293	1767
113	Smithers Ski 2	54.77	127.25	1280	29	20	1671	2002	332	1713

Table 3.5 Additional site chronologies in the EPS1900 dataset.

Site #	Site Name	Latitude (N)	Longitude (W)	Elevation (m)	# Series	# Trees	First Year	Last Year	Total Years	EPS > 0.85
17	Talus	65.23	138.33	720	24	16	1590	2001	412	1838
44	Hungry Mountain	63.35	136.28	990	62	32	1857	2001	145	1872
67	Koidern	61.95	140.37	800	34	17	1796	1998	203	1829
75	Little Hyland	61.69	128.33	1207	41	24	1784	2002	219	1808
76	Rose River	61.62	133.06	1085	31	15	1539	2004	466	1845
77	Duke Terrace	61.48	139.08	785	30	28	1774	2003	230	1824
100	St. Elias Lake	60.33	137.08	925	21	12	1806	1998	193	1854
86,103	Rancheria Combined	60.16	130.50	1325	17	9	1762	2002	241	1891
104	Tatshenshini	60.02	136.87	883	56	25	1752	2003	252	1854
108	Troutline Creek	59.28	129.83	1245	43	25	1676	2002	327	1826
109	Jade City Spruce	59.19	129.67	1316	16	10	1816	2002	187	1850

3.7 Network Evaluation

3.7.1 Methods of Evaluation

In order to study the tree-ring chronology network for possible common patterns, correlation matrix analysis and principal components analysis were performed on the EPS1800 dataset. Correlation matrix analysis is a technique often used to highlight commonality within a dataset. It also allows for the identification of anomalous chronologies within a network. Principal Components Analysis (PCA) is used to identify groups of inter-correlated variables quantitatively within a dataset. It also provides a method of reducing a large number of variables into a smaller collection of orthogonal components. By reducing the large number of site chronologies down to several key component groups, principal component analysis allows for easier examination of common signals within the network (Richman, 1986).

Correlation analyses between the 73 site chronologies retained in the EPS1800 dataset were performed on both standard and residual chronology data in order to provide measures of commonality involving both the low-frequency and high-frequency ranges of the data respectively. Sites with records ending before 2004 had correlations based on a slightly shorter period. Additionally, these analyses were performed over several time intervals in order to examine whether the relationships between sites varied over time.

PCA was initially performed on the common period of 1800-1995, followed by analyses over the time intervals 1800-1899, 1900-1995, 1900-1949, and 1950-1995.

3.7.2 Correlation Matrix Analysis

The network mean correlation between all 73 standard chronologies for the entire 1800-2004 time period was 0.346, with a range from 0.121 (Smithers Ski 2) to 0.476 (Webber Creek). For the residual chronologies, the network mean correlation value was 0.440, with individual site values between 0.132 (Mt. Jeckell) to 0.573 (Anvil Mine). The stronger inter-site correlations of the residual chronologies suggest that the high frequency, year-to-year variability found within the chronologies plays a major role in the common signals found within the network. The lower correlation values of the standard chronologies are a reflection of reduced commonality due to lower frequency, longer-term patterns.

The EPS1800 residual chronology correlation matrix showed several regional groupings of sites within the network that exhibited high inter-site correlations (0.500 or greater), as well as a number of poorly correlated sites (Figure 3.9). The poorly correlated sites within the entire network were: Mt. Jeckell, Aishihik, Donjek, Burwash, Cultus Bay, AINA, Jackson Point Good, Landslide Main, Pipeline, Bullion Creek, Kathleen Lake and Smithers Ski 2. Mean network correlation values for these sites ranged between 0.132 (Mt. Jeckell) to 0.337 (Pipeline). Both Mt. Jeckell and Smithers Ski 2 did not show any significant correlation results with other sites in the network and appear to be anomalous sites within the network. Though displaying poor relationships with the rest of the network, Jackson Point, Landslide Main, Pipeline and Bullion Creek have a high inter-site correlation of 0.739 (Figure 3.10), and also show strong relationships with Burwash, Cultus Bay and AINA. These seven sites are all located around the southern end of Kluane Lake in southwestern Yukon. The spatial concentration of these sites and their poor correlation with other sites in the network, suggests that trees in this area of the Yukon are responding differently to climate, or experience a different local climate, than most other sites in the Yukon.

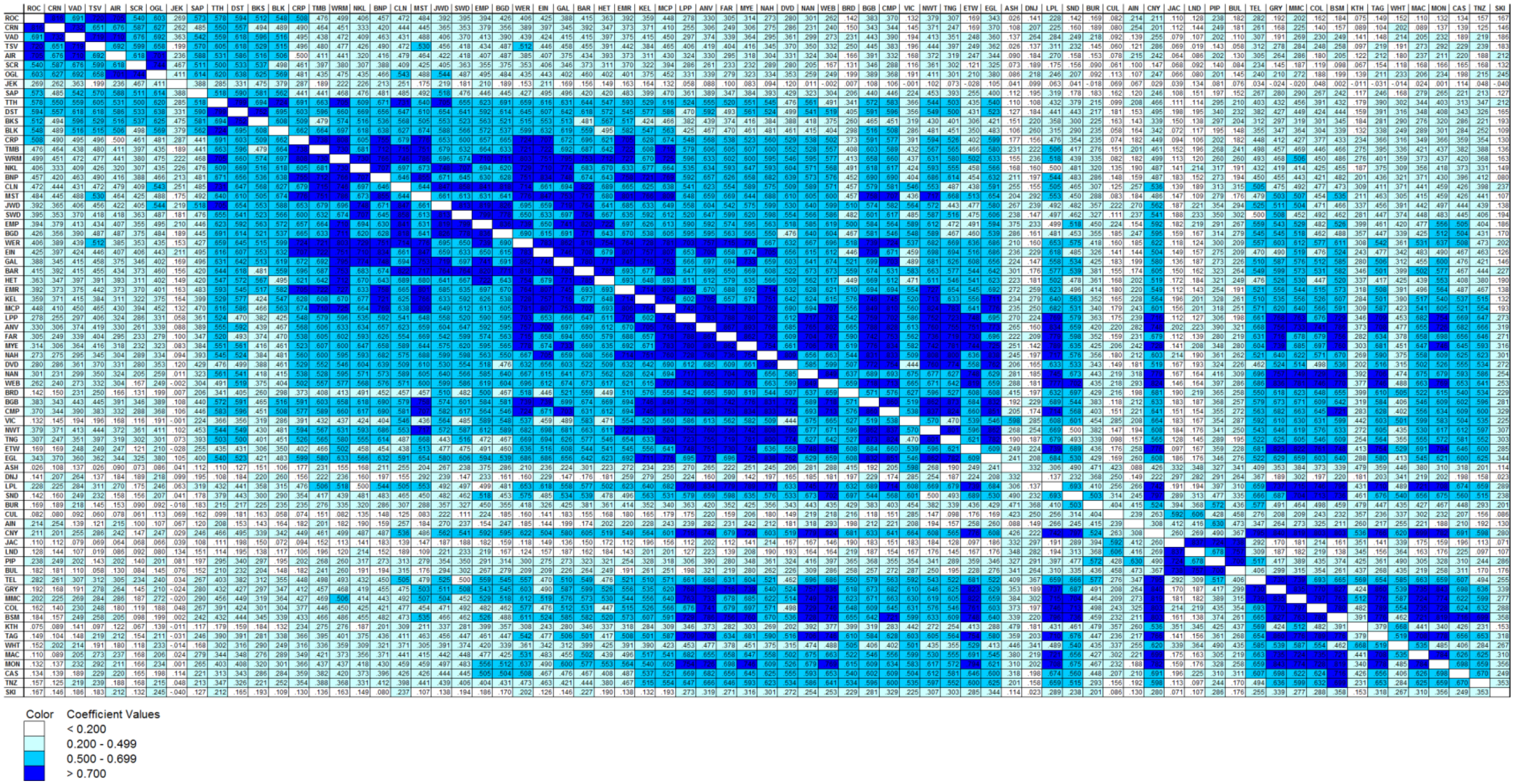


Figure 3.9 Correlation matrix for the residual chronologies of the EPS1800 dataset. Sites are arranged from north to south (site codes listed in Appendix A). Correlation values <0.200 coloured white, 0.200-0.499 pale blue, 0.500-0.699 light blue, and >0.700 dark blue.

Correlations												
	Mt. Jeckell	Aishihik	Donjek	Burwash	Cultus Bay	AINA	Jackson Point Good	Landslide Main	Pipeline	Bullion Creek	Kathleen Lake	Smithers Ski 2
Mt. Jeckell		.041	.099	-.018	.069	.067	.039	.134	.081	.076	-.011	-.040
Aishihik	.041		.332	.471	.423	.088	.332	.348	.327	.341	.479	.114
Donjek	.099	.332		.368	.250	.149	.297	.282	.291	.264	.181	.023
Burwash	-.018	.471	.368		.404	.415	.394	.368	.572	.436	.479	.201
Cultus Bay	.069	.423	.250	.404		.239	.592	.606	.428	.458	.357	.086
AINA	.067	.088	.149	.415	.239		.412	.416	.630	.473	.260	.130
Jackson Point Good	.039	.332	.297	.394	.592	.412		.837	.724	.738	.351	.071
Landslide Main	.134	.348	.282	.368	.606	.416	.837		.678	.757	.345	.107
Pipeline	.081	.327	.291	.572	.428	.630	.724	.678		.700	.425	.286
Bullion Creek	.076	.341	.264	.436	.458	.473	.738	.757	.700		.437	.176
Kathleen Lake	-.011	.479	.181	.479	.357	.260	.351	.345	.425	.437		.153
Smithers Ski 2	-.040	.114	.023	.201	.086	.130	.071	.107	.286	.176	.153	

Color	Coefficient Values
	< 0.200
	0.200 - 0.499
	0.500 - 0.699
	> 0.700

Figure 3.10 Correlation matrix of residual chronology sites which displayed poor relationships to most sites within the EPS1800 dataset network.

Removing these poorly correlated sites from the EPS1800 residual chronology matrix and collapsing the matrix highlights the main regional groupings (Figure 3.11). The most highly correlated sites within the matrix formed four prominent regional groupings within the network, along with the Kluane grouping (Figure 3.12). The sites in the first group, representing the northern portion of the network, were: Rock River, Mt. Cronin, Vadzaih Kan Creek, Tsiivii Creek, Airstrip Eagle Plains, Scriver Creek, Ogilvie Ridge, Sappers Hill, TTHH, Distincta Combined, Blackstone River, and Black City. With a mean within-group correlation of 0.608, these sites followed a northeast-southwest transect running along the Dempster Highway in northern Yukon between 64.5º-67º N. A second regional group representing the southern portion of the network has a within-group mean correlation of 0.710 and consists of 12 sites at Lapie Lakes, Sandpit, Canyon Lake, Telluride, Gray Mountain, Mt. McIntyre, Coal Lake Road, Big Salmon, Tagish, Wheaton River, MacDonald Lake, and Monarch. Though situated in the southwestern Yukon, these sites show no relationship with the ‘Kluane’ group mentioned earlier and are south or east of the Kluane area. These sites also showed strong correlations with Lapies Pass, Anvil Mine, Faro, Mt. Mye, Nansen Creek, and Webber Creek in the south-central Yukon, roughly paralleling 62º N. These sites comprised part of the south-central Yukon regional grouping that also included MacMillian Pass Combined, Nahanni Spruce, Divide Spruce,

	ROC	CRN	VAD	TSV	AIR	SCR	OGL	SAP	TTH	DST	BKS	BLK	CRP	TMB	WRM	NKL	BNP	CLN	MST	JWD	SWD	EMP	BGD	WER	EIN	GAL	BAR	HET	EMR	KEL	MCP	LPP	ANV	FAR	MYE	NAH	DVD	NAN	WEB	BRD	BGB	CMP	VIC	NWT	TNG	ETW	EGL	LPL	SND	CNY	TEL	GRY	MMC	COL	BSM	TAG	WHT	MAC	MON	CAS	TNZ	SKI
ROC		.816	.691	.720	.705	.540	.603	.573	.578	.594	.512	.548	.508	.476	.499	.406	.457	.472	.484	.392	.395	.394	.426	.406	.425	.388	.415	.363	.392	.359	.448	.278	.330	.305	.314	.273	.280	.301	.262	.142	.383	.370	.132	.379	.307	.169	.343	.228	.142	.211	.282	.192	.202	.162	.184	.149	.152	.110	.132	.134	.157	.167
CRN	.816		.732	.651	.676	.587	.627	.485	.550	.557	.494	.489	.490	.464	.451	.333	.420	.444	.445	.365	.353	.379	.356	.389	.397	.345	.392	.347	.373	.371	.410	.255	.306	.249	.306	.275	.286	.231	.240	.150	.343	.344	.145	.371	.247	.169	.370	.225	.160	.201	.261	.168	.225	.140	.157	.104	.202	.089	.137	.139	.125	.146
VAD	.691	.732		.719	.710	.676	.692	.542	.559	.618	.596	.516	.495	.438	.472	.409	.463	.431	.488	.406	.370	.413	.390	.439	.424	.415	.415	.397	.375	.415	.450	.297	.374	.339	.364	.295	.361	.299	.273	.231	.443	.390	.194	.413	.351	.248	.360	.284	.249	.255	.307	.191	.269	.230	.249	.148	.214	.205	.232	.189	.219	.186
TSV	.720	.651	.719		.692	.599	.658	.570	.605	.618	.529	.515	.496	.480	.477	.426	.490	.472	.530	.456	.418	.434	.487	.512	.446	.458	.455	.391	.442	.384	.465	.406	.419	.404	.416	.345	.370	.350	.332	.250	.445	.383	.196	.444	.397	.249	.362	.311	.232	.286	.312	.278	.284	.248	.258	.219	.191	.273	.292	.229	.239	.183
AIR	.705	.676	.710	.692		.618	.701	.588	.531	.586	.516	.506	.500	.411	.441	.320	.416	.479	.464	.422	.418	.407	.487	.385	.407	.375	.434	.393	.373	.311	.430	.324	.330	.295	.318	.304	.331	.324	.304	.166	.391	.332	.168	.372	.319	.247	.344	.270	.158	.242	.305	.264	.286	.180	.205	.212	.180	.237	.211	.220	.188	.212
SCR	.540	.587	.676	.599	.618		.744	.511	.500	.533	.537	.498	.461	.397	.380	.307	.388	.409	.425	.405	.363	.355	.375	.353	.406	.346	.373	.311	.370	.322	.394	.286	.261	.233	.232	.289	.280	.205	.167	.131	.346	.288	.116	.361	.302	.121	.325	.175	.156	.147	.234	.145	.187	.119	.098	.154	.118	.168	.166	.165	.168	.132
OGL	.603	.627	.692	.658	.701	.744		.614	.620	.638	.625	.569	.481	.435	.475	.435	.466	.543	.488	.544	.487	.495	.484	.435	.443	.402	.460	.402	.401	.375	.452	.331	.339	.279	.323	.334	.353	.259	.249	.199	.389	.368	.191	.411	.301	.210	.380	.246	.207	.247	.240	.210	.272	.188	.199	.211	.233	.206	.234	.198	.215	.245
SAP	.573	.485	.542	.570	.588	.511	.614		.518	.590	.581	.562	.441	.441	.468	.476	.481	.485	.492	.518	.476	.446	.445	.427	.495	.496	.420	.420	.483	.399	.470	.361	.389	.347	.384	.393	.429	.323	.304	.206	.440	.446	.224	.453	.393	.255	.400	.319	.178	.246	.267	.280	.290	.267	.242	.246	.168	.279	.265	.221	.213	.127
TTH	.578	.550	.559	.605	.531	.500	.620	.518		.799	.694	.724	.691	.663	.705	.609	.671	.731	.640	.705	.655	.623	.691	.659	.616	.631	.644	.547	.593	.529	.616	.524	.555	.520	.551	.545	.476	.561	.491	.341	.572	.583	.366	.544	.503	.435	.540	.432	.379	.466	.403	.432	.456	.391	.432	.390	.302	.344	.403	.313	.347	.212
DST	.594	.557	.618	.618	.586	.533	.638	.590	.799		.752	.695	.603	.596	.660	.669	.656	.647	.610	.654	.641	.592	.614	.645	.607	.642	.618	.572	.545	.577	.586	.470	.592	.493	.561	.524	.499	.541	.519	.405	.591	.596	.356	.549	.500	.431	.523	.441	.443	.495	.382	.427	.449	.424	.444	.391	.316	.348	.408	.343	.326	.165
BKS	.512	.494	.596	.529	.516	.537	.625	.581	.694	.752		.608	.509	.479	.574	.516	.536	.568	.505	.553	.523	.563	.521	.515	.553	.513	.481	.567	.517	.424	.466	.382	.439	.374	.416	.384	.388	.418	.375	.260	.465	.451	.319	.430	.401	.306	.421	.358	.300	.339	.312	.297	.319	.301	.345	.281	.290	.276	.320	.286	.221	.193
BLK	.548	.489	.516	.515	.506	.498	.569	.562	.724	.695	.608		.662	.664	.697	.618	.638	.627	.674	.588	.566	.572	.537	.599	.632	.619	.559	.495	.582	.547	.563	.425	.467	.470	.461	.481	.461	.415	.404	.298	.516	.508	.286	.481	.451	.350	.483	.315	.290	.342	.355	.347	.364	.304	.339	.338	.249	.289	.301	.284	.252	.109
CRP	.508	.490	.495	.496	.500	.461	.481	.441	.691	.603	.509	.662		.738	.808	.605	.755	.679	.776	.653	.600	.657	.665	.724	.707	.672	.696	.621	.705	.628	.674	.548	.568	.538	.523	.560	.529	.538	.502	.373	.591	.577	.391	.594	.526	.402	.599	.476	.354	.449	.448	.412	.427	.377	.433	.366	.316	.349	.366	.359	.354	.130
TMB	.476	.464	.438	.480	.411	.397	.435	.441	.663	.596	.479	.664	.738		.730	.681	.712	.715	.751	.679	.632	.664	.633	.721	.722	.692	.687	.642	.722	.608	.710	.579	.606	.605	.607	.600	.552	.528	.557	.408	.603	.589	.432	.567	.565	.466	.580	.506	.417	.461	.498	.457	.469	.446	.466	.395	.336	.421	.437	.382	.388	.136
WRM	.499	.451	.472	.477	.441	.380	.475	.468	.705	.660	.574	.697	.808	.730		.730	.766	.746	.786	.696	.674	.710	.711	.803	.751	.795	.753	.712	.727	.670	.725	.596	.633	.602	.600	.595	.546	.595	.577	.413	.658	.660	.437	.631	.580	.502	.633	.518	.439	.499	.493	.468	.506	.450	.486	.401	.359	.373	.437	.420	.368	.163
NKL	.406	.333	.409	.426	.320	.307	.435	.476	.609	.669	.516	.618	.605	.681	.730		.707	.697	.673	.748	.707	.694	.620	.729	.710	.774	.683	.670	.633	.677	.664	.535	.634	.593	.647	.593	.604	.571	.568	.491	.618	.617	.424	.593	.555	.458	.566	.500	.481	.487	.432	.419	.414	.425	.455	.375	.309	.356	.418	.373	.331	.149
BNP	.457	.420	.463	.490	.416	.388	.466	.481	.671	.656	.536	.638	.755	.712	.766	.707		.646	.855	.671	.645	.630	.628	.751	.834	.748	.674	.643	.758	.721	.769	.592	.657	.626	.658	.682	.639	.573	.576	.452	.690	.690	.404	.686	.614	.454	.632	.544	.483	.487	.450	.455	.443	.421	.482	.436	.321	.371	.430	.396	.412	.080
CLN	.472	.444	.431	.472	.479	.409	.543	.485	.731	.647	.568	.627	.679	.715	.746	.697	.646		.644	.847	.858	.841	.818	.714	.661	.694	.822	.689	.665	.625	.638	.541	.623	.554	.589	.575	.509	.589	.571	.457	.579	.581	.546	.553	.487	.438	.591	.505	.465	.536	.505	.475	.492	.477	.473	.411	.371	.441	.459	.426	.398	.237
MST	.484	.445	.488	.530	.464	.425	.488	.492	.640	.610	.505	.674	.776	.751	.786	.673	.855	.644		.661	.613	.631	.641	.776	.847	.753	.717	.680	.801	.766	.809	.648	.659	.669	.644	.688	.610	.605	.600	.457	.758	.707	.436	.717	.668	.513	.654	.553	.450	.486	.479	.503	.507	.454	.535	.463	.305	.415	.459	.426	.441	.107
JWD	.392	.365	.406	.456	.422	.405	.544	.518	.705	.654	.553	.588	.653	.679	.696	.748	.671	.847	.661		.813	.819	.826	.695	.659	.719	.764	.641	.685	.633	.649	.558	.604	.542	.575	.599	.530	.640	.599	.510	.574	.582	.564	.572	.443	.477	.580	.492	.482	.562	.525	.511	.504	.471	.466	.456	.391	.442	.497	.444	.439	.138
SWD	.395	.353	.370	.418	.418	.363	.487	.476	.655	.641	.523	.566	.600	.632	.674	.707	.645	.858	.613	.813		.799	.778	.650	.633	.697	.764	.667	.635	.592	.612	.520	.647	.599	.620	.598	.554	.566	.586	.482	.601	.617	.485	.587	.516	.475	.606	.497	.462	.541	.500	.508	.452	.492	.462	.447	.374	.448	.483	.445	.406	.194
EMP	.394	.379	.413	.434	.407	.355	.495	.446	.623	.592	.563	.572	.657	.664	.710	.694	.630	.841	.631	.819	.799		.836	.739	.650	.741	.820	.722	.697	.626	.613	.590	.592	.574	.595	.563	.518	.585	.619	.500	.584	.564	.589	.612	.472	.491	.594	.499	.518	.592	.559	.543	.529	.482	.526	.461	.420	.477	.556	.505	.404	.186
BGD	.426	.356	.390	.487	.487	.375	.484	.445	.691	.614	.521	.537	.665	.633	.711	.620	.628	.818	.641	.826	.778	.836		.690	.615	.691	.771	.643	.670	.538	.605	.595	.595	.563	.565	.550	.476	.640	.604	.467	.581	.546	.548	.589	.467	.460	.539	.481	.453	.595	.545	.545	.518	.462	.488	.447	.339	.425	.512	.504	.431	.170
WER	.406	.389	.439	.512	.385	.353	.435	.427	.659	.645	.515	.599	.724	.721	.803	.729	.751	.714	.776	.695	.650	.739	.690		.783	.862	.818	.754	.764	.728	.781	.703	.757	.715	.778	.667	.632	.667	.696	.518	.739	.724	.537	.682	.669	.636	.686	.653	.575	.622	.557	.603	.612	.577	.611	.542	.361	.531	.637	.508	.473	.202
EIN	.425	.397	.424	.446	.407	.406	.443	.495	.616	.607	.553	.632	.707	.722	.751	.710	.834	.661	.847	.659	.633	.650	.615	.783		.746	.708	.679	.807	.757	.807	.653	.700	.658	.674	.705	.656	.615	.612	.446	.739	.671	.459	.698	.694	.516	.686	.618	.485	.504	.470	.490	.519	.476	.524	.477	.342	.483	.490	.467	.463	.126
GAL	.388	.345	.415	.458	.375	.346	.402	.496	.631	.642	.513	.619	.672	.692	.795	.774	.748	.694	.753	.719	.697	.741	.691	.862	.746		.780	.771	.745	.716	.753	.666	.697	.694	.733	.659	.603	.641	.674	.521	.699	.703	.489	.681	.626	.608	.656	.558	.534	.580	.510	.587	.576	.512	.585	.506	.312	.455	.600	.476	.421	.146
BAR	.415	.392	.415	.455	.434	.373	.460	.420	.644	.618	.481	.559	.696	.687	.753	.683	.674	.822	.717	.764	.764	.820	.771	.818	.708	.780		.785	.693	.677	.702	.647	.699	.650	.669	.608	.522	.673	.673	.559	.674	.631	.583	.663	.577	.544	.642	.577	.539	.605	.549	.599	.573	.531	.582	.501	.399	.502	.577	.467	.444	.227
HET	.363	.347	.397	.391	.393	.311	.402	.420	.547	.572	.567	.495	.621	.642	.712	.670	.643	.689	.680	.641	.667	.722	.643	.754	.679	.771	.785		.693	.648	.693	.611	.612	.579	.635	.566	.509	.562	.617	.449	.669	.612	.471	.611	.546	.541	.623	.502	.478	.519	.476	.526	.530	.447	.520	.417	.425	.439	.553	.408	.380	.190
EMR	.392	.373	.375	.442	.373	.370	.401	.483	.593	.545	.517	.582	.705	.722	.727	.633	.758	.665	.801	.685	.635	.697	.670	.764	.807	.745	.693	.693		.714	.806	.705	.670	.688	.692	.714	.632	.628	.621	.510	.694	.694	.554	.727	.654	.545	.692	.623	.496	.549	.521	.556	.544	.515	.573	.508	.391	.496	.564	.487	.467	.138
KEL	.359	.371	.415	.384	.311	.322	.375	.399	.529	.577	.424	.547	.628	.608	.670	.677	.721	.625	.766	.633	.592	.626	.538	.728	.757	.716	.677	.648	.714		.764	.602	.705	.657	.671	.751	.642	.624	.615	.576	.746	.745	.520	.713	.633	.556	.711	.640	.563	.564	.510	.535	.556	.526	.607	.501	.390	.517	.540	.537	.515	.132
MCP	.448	.410	.450	.465	.430	.394	.452	.470	.616	.586	.466	.563	.674	.710	.725	.664	.769	.638	.809	.649	.612	.613	.605	.781	.807	.753	.702	.693	.806	.764		.742	.768	.718	.783	.760	.690	.694	.707	.556	.849	.810	.560	.824	.783	.641	.776	.682	.531	.601	.571	.620	.640	.566	.591	.587	.423	.541	.605	.521	.554	.193
LPP	.278	.255	.297	.406	.324	.286	.331	.361	.524	.470	.382	.425	.548	.579	.596	.535	.592	.541	.648	.558	.520	.590	.595	.703	.653	.666	.647	.611	.705	.602	.742		.783	.788	.780	.728	.612	.717	.783	.542	.759	.702	.586	.752	.723	.748	.695	.769	.579	.716	.661	.768	.763	.676	.729	.709	.453	.682	.754	.669	.647	.273
ANV	.330	.306	.374	.419	.330	.261	.339	.389	.555	.592	.439	.467	.568	.606	.633	.634	.657	.623	.659	.604	.647	.592	.595	.757	.700	.697	.699	.612	.670	.705	.768	.783		.867	.893	.768	.685	.765	.802	.665	.788	.828	.613	.760	.755	.751	.773	.834	.659	.748	.668	.756	.733	.741	.786	.708	.477	.655	.726	.682	.666	.319
FAR	.305	.249	.339	.404	.295	.233	.279	.347	.520	.493	.374	.470	.538	.605	.602	.593	.626	.554	.669	.542	.599	.574	.563	.715	.658	.694	.650	.579	.688	.657	.718	.788	.867		.862	.736	.609	.704	.767	.590	.742	.753	.562	.736	.719	.730	.696	.779	.598	.679	.631	.716	.678	.679	.756	.634	.378	.658	.698	.656	.646	.271
MYE	.314	.306	.364	.416	.318	.232	.323	.384	.551	.561	.416	.461	.523	.607	.600	.647	.658	.589	.644	.575	.620	.595	.565	.778	.674	.733	.669	.635	.692	.671	.783	.780	.893	.862		.754	.661	.706	.781	.619	.776	.834	.582	.742	.781	.744	.725	.789	.635	.728	.604	.739	.685	.697	.760	.681	.451	.647	.746	.645	.593	.316
NAH	.273	.275	.295	.345	.304	.289	.334	.393	.545	.524	.384	.481	.560	.600	.595	.593	.682	.575	.688	.599	.598	.563	.550	.667	.705	.659	.608	.566	.714	.751	.760	.728	.768	.736	.754		.809	.656	.663	.544	.831	.833	.509	.808	.800	.636	.838	.717	.576	.603	.521	.640	.622	.571	.670	.590	.375	.558	.609	.625	.623	.301
DVD	.280	.286	.361	.370	.331	.280	.353	.429	.476	.499	.388	.461	.529	.552	.546	.604	.639	.509	.610	.530	.554	.518	.476	.632	.656	.603	.522	.509	.632	.642	.690	.612	.685	.609	.661	.809		.585	.599	.507	.772	.754	.444	.760	.774	.558	.762	.633	.533	.519	.462	.524	.514	.498	.536	.516	.315	.502	.526	.555	.534	.272
NAN	.301	.231	.299	.350	.324	.205	.259	.323	.561	.541	.418	.415	.538	.528	.595	.571	.573	.589	.605	.640	.566	.585	.640	.667	.615	.641	.673	.562	.628	.624	.694	.717	.765	.704	.706	.656	.585		.849	.637	.689	.693	.675	.677	.627	.748	.629	.745	.673	.779	.696	.757	.749	.729	.728	.706	.474	.675	.679	.593	.586	.254
WEB	.262	.240	.273	.332	.304	.167	.249	.304	.491	.519	.375	.404	.502	.557	.577	.568	.576	.571	.600	.599	.586	.619	.604	.696	.612	.674	.673	.617	.621	.615	.707	.783	.802	.767	.781	.663	.599	.849		.659	.718	.713	.665	.671	.642	.819	.659	.777	.702	.824	.686	.836	.781	.746	.770	.746	.488	.663	.769	.653	.641	.253
BRD	.142	.150	.231	.250	.166	.131	.199	.206	.341	.405	.260	.298	.373	.408	.413	.491	.452	.457	.457	.510	.482	.500	.467	.518	.446	.521	.559	.449	.510	.576	.556	.542	.665	.590	.619	.544	.507	.637	.659		.571	.576	.627	.596	.527	.608	.608	.632	.697	.681	.550	.618	.623	.648	.655	.610	.505	.522	.615	.540	.534	.229
BGB	.383	.343	.443	.445	.391	.346	.389	.440	.572	.591	.465	.516	.591	.603	.658	.618	.690	.579	.758	.574	.601	.584	.581	.739	.739	.699	.674	.669	.694	.746	.849	.759	.788	.742	.776	.831	.772	.689	.718	.571		.860	.519	.862	.873	.684	.832	.689	.544	.633	.579	.673	.671	.609	.642	.584	.406	.546	.609	.602	.596	.281
CMP	.370	.344	.390	.383	.332	.288	.368	.446	.583	.596	.451	.508	.577	.589	.660	.617	.690	.581	.707	.582	.617	.564	.546	.724	.671	.703	.631	.612	.694	.745	.810	.702	.828	.753	.834	.833	.754	.693	.713	.576	.860		.538	.837	.824	.660	.851	.714	.568	.641	.563	.682	.663	.645	.721	.628	.402	.556	.634	.609	.600	.329
VIC	.132	.145	.194	.196	.168	.116	.191	.224	.366	.356	.319	.286	.391	.432	.437	.424	.404	.546	.436	.564	.485	.589	.548	.537	.459	.489	.583	.471	.554	.520	.560	.586	.613	.562	.582	.509	.444	.675	.665	.627	.519	.538		.570	.470	.539	.546	.608	.601	.664	.592	.610	.630	.631	.599	.603	.501	.599	.583	.504	.535	.225
NWT	.379	.371	.413	.444	.372	.361	.411	.453	.544	.549	.430	.481	.594	.567	.631	.593	.686	.553	.717	.572	.587	.612	.589	.682	.698	.681	.663	.611	.727	.713	.824	.752	.760	.736	.742	.808	.760	.677	.671	.596	.862	.837	.570		.801	.596	.862	.669	.500	.608	.543	.646	.619	.576	.633	.605	.435	.530	.617	.612	.597	.307
TNG	.307	.247	.351	.397	.319	.302	.301	.393	.503	.500	.401	.451	.526	.565	.580	.555	.614	.487	.668	.443	.516	.472	.467	.669	.694	.626	.577	.546	.654	.633	.783	.723	.755	.719	.781	.800	.774	.627	.642	.527	.873	.824	.470	.801		.621	.782	.679	.493	.565	.522	.625	.605	.546	.609	.564	.355	.555	.572	.581	.552	.303
ETW	.169	.169	.248	.249	.247	.121	.210	.255	.435	.431	.306	.350	.402	.466	.502	.458	.454	.438	.513	.477	.475	.491	.460	.636	.516	.608	.544	.541	.545	.556	.641	.748	.751	.730	.744	.636	.558	.748	.819	.608	.684	.660	.539	.596	.621		.609	.739	.689	.776	.681	.823	.822	.761	.748	.754	.529	.691	.794	.646	.600	.285
EGL	.343	.370	.360	.362	.344	.325	.380	.400	.540	.523	.421	.483	.599	.580	.633	.566	.632	.591	.654	.580	.606	.594	.539	.686	.686	.656	.642	.623	.692	.711	.776	.695	.773	.696	.725	.838	.762	.629	.659	.608	.832	.851	.546	.862	.782	.609		.684	.530	.608	.522	.629	.659	.603	.640	.580	.413	.545	.621	.600	.625	.344
LPL	.228	.225	.284	.311	.270	.175	.246	.319	.432	.441	.358	.315	.476	.506	.518	.500	.544	.505	.553	.492	.497	.499	.481	.653	.618	.558	.577	.502	.623	.640	.682	.769	.834	.779	.789	.717	.633	.745	.777	.632	.689	.714	.608	.669	.679	.739	.684		.693	.742	.659	.737	.715	.746	.796	.710	.489	.721	.708	.674	.659	.289
SND	.142	.160	.249	.232	.158	.156	.207	.178	.379	.443	.300	.290	.354	.417	.439	.481	.483	.465	.450	.482	.462	.518	.453	.575	.485	.534	.539	.478	.496	.563	.531	.579	.659	.598	.635	.576	.533	.673	.702	.697	.544	.568	.601	.500	.493	.689	.530	.693		.797	.666	.687	.704	.713	.736	.676	.540	.656	.675	.560	.515	.238
CNY	.211	.201	.255	.286	.242	.147	.247	.246	.466	.495	.339	.342	.449	.461	.499	.487	.487	.536	.486	.562	.541	.592	.595	.622	.504	.580	.605	.519	.549	.564	.601	.716	.748	.679	.728	.603	.519	.779	.824	.681	.633	.641	.664	.608	.565	.776	.608	.742	.797		.795	.840	.819	.803	.803	.766	.620	.699	.782	.691	.598	.280
TEL	.282	.261	.307	.312	.305	.234	.240	.267	.403	.382	.312	.355	.448	.498	.493	.432	.450	.505	.479	.525	.500	.559	.545	.557	.470	.510	.549	.476	.521	.510	.571	.661	.668	.631	.604	.521	.462	.696	.686	.550	.579	.563	.592	.543	.522	.681	.522	.659	.666	.795		.730	.739	.693	.665	.654	.585	.663	.659	.607	.494	.255
GRY	.192	.168	.191	.278	.264	.145	.210	.280	.432	.427	.297	.347	.412	.457	.468	.419	.455	.475	.503	.511	.508	.543	.545	.603	.490	.587	.599	.526	.556	.535	.620	.768	.756	.716	.739	.640	.524	.757	.836	.618	.673	.682	.610	.646	.625	.823	.629	.737	.687	.840	.730		.835	.770	.827	.860	.539	.735	.843	.698	.636	.339
MMC	.202	.225	.269	.284	.286	.187	.272	.290	.456	.449	.319	.364	.427	.469	.506	.414	.443	.492	.507	.504	.452	.529	.518	.612	.519	.576	.573	.530	.544	.556	.640	.763	.733	.678	.685	.622	.514	.749	.781	.623	.671	.663	.630	.619	.605	.822	.659	.715	.704	.819	.739	.835		.797	.763	.776	.587	.724	.774	.622	.599	.277
COL	.162	.140	.230	.248	.180	.119	.188	.267	.391	.424	.301	.304	.377	.446	.450	.425	.421	.477	.454	.471	.492	.482	.462	.577	.476	.512	.531	.447	.515	.526	.566	.676	.741	.679	.697	.571	.498	.729	.746	.648	.609	.645	.631	.576	.546	.761	.603	.746	.713	.803	.693	.770	.797		.780	.789	.554	.735	.728	.624	.632	.288
BSM	.184	.157	.249	.258	.205	.098	.199	.242	.432	.444	.345	.339	.433	.466	.486	.455	.482	.473	.535	.466	.462	.526	.488	.611	.524	.585	.582	.520	.573	.607	.591	.729	.786	.756	.760	.670	.536	.728	.770	.655	.642	.721	.599	.633	.609	.748	.640	.796	.736	.803	.665	.827	.763	.780		.776	.462	.721	.819	.716	.699	.358
TAG	.149	.104	.148	.219	.212	.154	.211	.246	.390	.391	.281	.338	.366	.395	.401	.375	.436	.411	.463	.456	.447	.461	.447	.542	.477	.506	.501	.417	.508	.501	.587	.709	.708	.634	.681	.590	.516	.706	.746	.610	.584	.628	.603	.605	.564	.754	.580	.710	.676	.766	.654	.860	.776	.789	.776		.519	.708	.778	.656	.653	.318
WHT	.152	.202	.214	.191	.180	.118	.233	.168	.302	.316	.290	.249	.316	.336	.359	.309	.321	.371	.305	.391	.374	.420	.339	.361	.342	.312	.399	.425	.391	.390	.423	.453	.477	.378	.451	.375	.315	.474	.488	.505	.406	.402	.501	.435	.355	.529	.413	.489	.540	.620	.585	.539	.587	.554	.462	.519		.535	.485	.406	.284	.267
MAC	.110	.089	.205	.273	.237	.168	.206	.279	.344	.348	.276	.289	.349	.421	.373	.356	.371	.441	.415	.442	.448	.477	.425	.531	.483	.455	.502	.439	.496	.517	.541	.682	.655	.658	.647	.558	.502	.675	.663	.522	.546	.556	.599	.530	.555	.691	.545	.721	.656	.699	.663	.735	.724	.735	.721	.708	.535		.784	.626	.625	.310
MON	.132	.137	.232	.292	.211	.166	.234	.265	.403	.408	.320	.301	.366	.437	.437	.418	.430	.459	.459	.497	.483	.556	.512	.637	.490	.600	.577	.553	.564	.540	.605	.754	.726	.698	.746	.609	.526	.679	.769	.615	.609	.634	.583	.617	.572	.794	.621	.708	.675	.782	.659	.843	.774	.728	.819	.778	.485	.784		.698	.659	.356
CAS	.134	.139	.189	.229	.220	.165	.198	.221	.313	.343	.286	.284	.359	.382	.420	.373	.396	.426	.426	.444	.445	.505	.504	.508	.467	.476	.467	.408	.487	.537	.521	.669	.682	.656	.645	.625	.555	.593	.653	.540	.602	.609	.504	.612	.581	.646	.600	.674	.560	.691	.607	.698	.622	.624	.716	.656	.406	.626	.698		.670	.249
TNZ	.157	.125	.219	.239	.188	.168	.215	.213	.347	.326	.221	.252	.354	.388	.368	.331	.412	.398	.441	.439	.406	.404	.431	.473	.463	.421	.444	.380	.467	.515	.554	.647	.666	.646	.593	.623	.534	.586	.641	.534	.596	.600	.535	.597	.552	.600	.625	.659	.515	.598	.494	.636	.599	.632	.699	.653	.284	.625	.659	.670		.353
SKI	.167	.146	.186	.183	.212	.132	.245	.127	.212	.165	.193	.109	.130	.136	.163	.149	.080	.237	.107	.138	.194	.186	.170	.202	.126	.146	.227	.190	.138	.132	.193	.273	.319	.271	.316	.301	.272	.254	.253	.229	.281	.329	.225	.307	.303	.285	.344	.289	.238	.280	.255	.339	.277	.288	.358	.318	.267	.310	.356	.249	.353	

Color	Coefficient Values
white	< 0.200
pale blue	0.200 - 0.499
light blue	0.500 - 0.699
dark blue	> 0.700

Figure 3.11 Correlation matrix for the residual chronologies of the EPS1800 dataset, with poorly performing sites removed. Sites are arranged from north to south (site codes listed in Appendix A). Correlation values <0.200 coloured white, 0.200-0.499 pale blue, 0.500-0.699 light blue, and >0.700 dark blue.

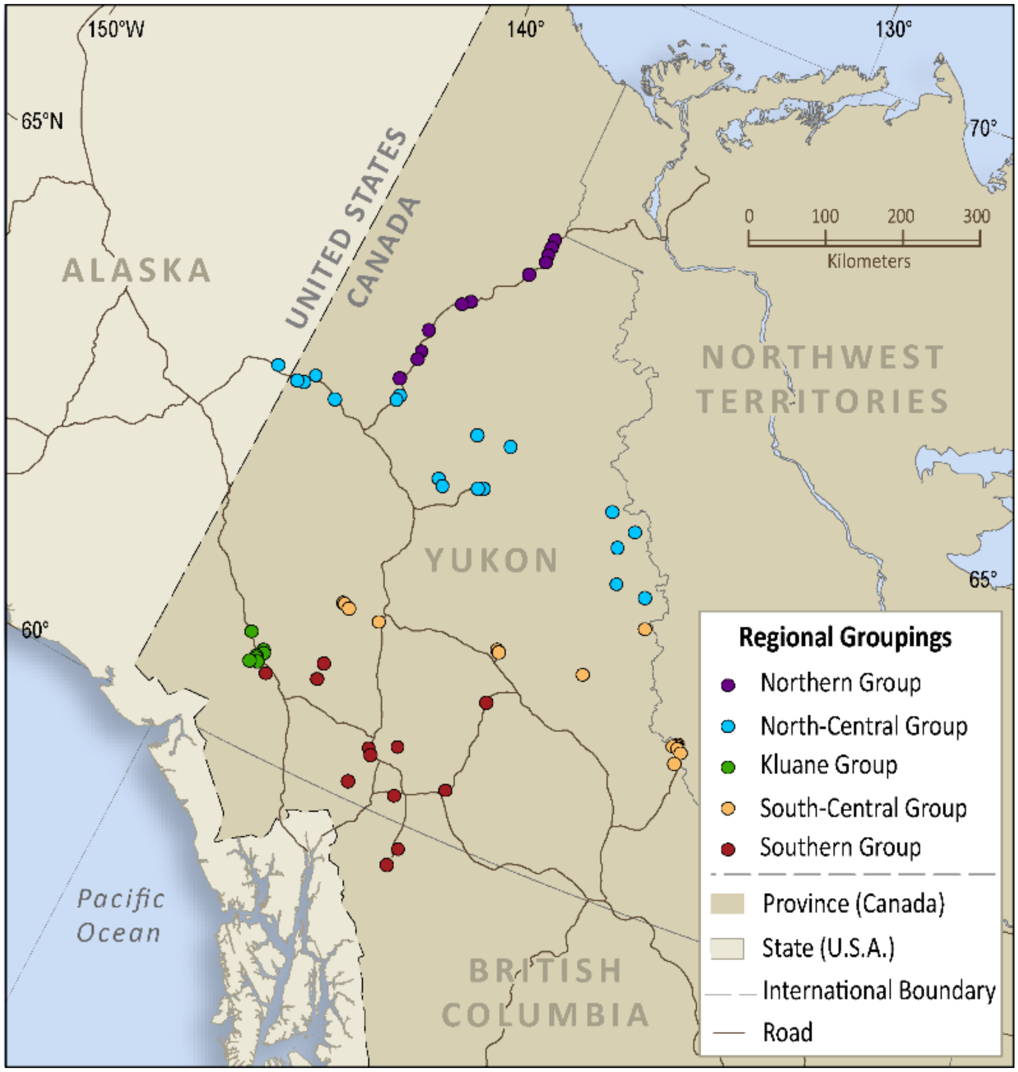


Figure 3.12 Geographical distribution of most highly correlated sites found in the EPS1800 residual chronology correlation matrix, forming five regional groupings.

Mt. Berdoe, Big Bend Combined, Campsite, Victoria Creek, NWT Pass, Tungsten, and Eagle Combined. With a within-group mean correlation of 0.711, this southern-central group represented an area across the central Yukon from Carmacks to the eastern border with the Northwest Territories. The fourth regional grouping, which represented the northern half of the central portion of the matrix, consisted of 18 sites at Carpenter Lake, Tombstone, Worm Lake, North Klondike River, Bonnet Plume Lake, Clinton Creek, Misty Lake, Jack Wade, Swede Dome, Empire Creek, Big Gold Creek, Wernecke, Einarson Lake, Galena, Barlow Dome, Highet Creek, Emerald Lake, and Keele Lake. This northern-central group had a mean correlation value of 0.712. The dividing line between this northern group and the southern group within the central portion of the network was approximately 63º N. Both the north and south-central groups cover a broad area of the Yukon stretching from the Top of the World Highway at the Alaska-Yukon border in the west to remote sites in the Wernecke and Selwyn Mountain ranges in the east.

The correlation matrix of the standard chronologies for the EPS1800 dataset showed relatively similar patterns to the residual chronology correlation matrix (Figure 3.13), but the groupings are not as cohesive and visually pronounced as those in the residual chronology matrix. The northern and southern are visible in the standard chronology matrix, and display strong relationships within their respective groupings. Interestingly, several sites in the northern regional group also showed strong correlations with sites located further east. For example, the Rock River and Black City sites along the Dempster Highway exhibit high correlations with Carpenter Lake and Worm Lake, several hundred kilometers to the east within the Wernecke Mountain range. While strong inter-site correlations exist within the central portion of the standard chronology matrix, the distinction between the northern-central and southern-central groupings of sites is not as clearly defined in the standard chronologies matrix. Mt. Jeckell and Smithers Ski 2 again appear anomalous sites and the ‘Kluane’ sites form a distinct, separate group.

Correlation analyses of the EPS1800 dataset were conducted for both residual and standard chronologies over four different periods (1800-2004, 1900-2004, 1900-1949, and 1950-2004) to determine possible changes over time. Overall, the residual chronologies exhibited higher mean network correlation values than standard chronologies for all four time intervals examined (Table 3.6). This is most likely due to the stronger common high frequency, interannual variability in the residual chronologies, whereas the standard chronologies contain lower frequency, longer-term variability which may complicate patterns. The mean correlation values show similar temporal patterns for both chronology networks over the four time periods. There is a slight improvement in mean network values from the 1800-2004 to 1900-2004 intervals, primarily focused in the central portion of the network. However, the most significant change is the strong increase in inter-site

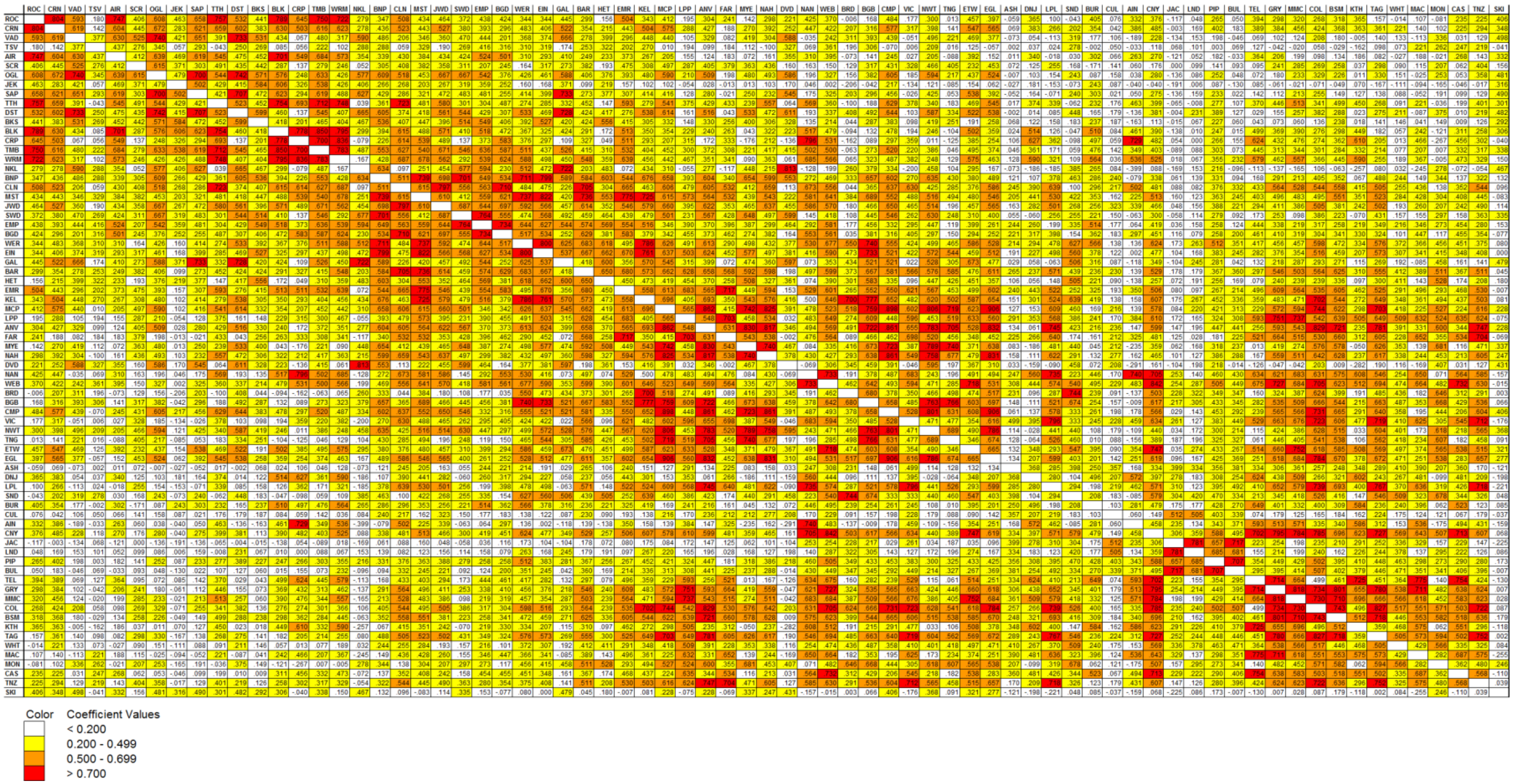


Figure 3.13 Correlation matrix for the standard chronologies of the EPS1800 dataset. Sites are arranged from north to south (site codes listed in Appendix A). Correlation values <0.200 coloured white, 0.200-0.499 yellow, 0.500-0.699 orange, and >0.700 red.

Table 3.6 Mean network correlation values for various time periods analyzed. In all periods, mean network values of the residual chronologies were higher than corresponding standard chronologies.

	Standard Chronologies	Residual Chronologies
1800 - 2004	0.346	0.440
1900 - 2004	0.375	0.455
1900 - 1949	0.503	0.519
1950 - 2004	0.322	0.393

correlations over the 1900-1949 time interval in both the residual and standard chronologies, particularly in the central and southern portions of the network. Mean network correlation values for this interval are 0.519 (residual chronologies) and 0.503 (standard chronologies). Mean correlations for the 1950-2004 period are the lowest of the four trials (0.393 and 0.322 respectively). These poorer correlations in the latter half of the 20^{th} century suggest the possibility of "divergence" in these chronologies, possibly due to a loss of temperature sensitivity, as first described by Jacoby and D'Arrigo (1995).

3.7.3 Principal Components Analysis

Examination of the chronologies using correlation analyses provided useful insight into the relationships between chronologies across the network, and highlighted those sites that exhibited strong common signals as well as anomalous sites within the network. The application of Principal Components Analysis (PCA) to the data provided a further method to identify quantitatively major groups of inter-correlated chronologies within the network. Essentially, PCA identifies vectors in the data along which variance is maximized (Daultrey, 1976). By projecting the original data upon these vectors and measuring the variance, 'components' are constructed representing the mean dominant variance in the data. These components are weighted according to the amount of total variance that they describe, such that the first component accounts for the maximum possible variance, the second component accounts for as much of the remaining variance as possible while being uncorrelated with the first component, and so forth (Daultrey, 1976). A varimax orthogonal rotation technique was utilized to ensure that the resulting components were unrelated and that the variance in each component was maximized (Shaw and Wheeler, 1985). In quantitatively identifying groups of inter-correlated chronologies in the network, PCA also potentially provides the additional benefit of reducing the large number of chronologies to a smaller number of orthogonal components.

3.7.3.1 *PCA – EPS1800 Residual Chronologies*

Principal component analysis was conducted on the EPS1800 dataset using a common period of 1800-1995. In the PCA of the 73 residual chronologies, eight components were identified with eigenvalues greater than 1 (Table 3.7) explaining nearly 75.8% of the common variance within the residual chronology network. The first component (Res-PC1) represents the dominant regional signal, and explained 48.8% of the common variance. Table 3.8 shows the factor loadings of each residual chronology upon each principal component. Twenty-four of the 73 residual chronologies loaded most heavily on the first component. Most of these chronologies correspond to those identified as the southern and south-central portions of the network identified in the correlation analysis. Figure 3.14a maps the loading scores of each residual chronology on the first component, clearly showing a strong spatial pattern of this principal component focused on the south-central Yukon. The second principal component (Res-PC2) explained 9.8% of the variance and 21 residual chronologies loaded most strongly on this component, which corresponded to the north-central portion of the network of the correlation analysis as is clearly shown in Figure 3.14b. The ten residual chronologies loading most heavily on Res-PC3 account for approximately 5.8% of the common variance and represent the regional signal of the northern sites located along the Dempster Highway (Figure 3.14c). Res-PC4 loads most heavily on six chronologies in the eastern Yukon near the Yukon-NWT border (Figure 3.14d) with ca. 3.4% of the common variance. However all of these sites also load strongly on Res-PC1 (0.427-0.539) and were grouped with the south-central portion of the tree-ring network (Res_PC1) in the correlation analysis. The eight chronologies of Res-PC5 essentially comprise the "Kluane" group (Figure 3.14e). The remaining higher-order principal components (Res-PC6, Res-PC7, and Res-PC8) represent sites that were categorized as anomalous within the correlation analyses. Each of these components explained less than 2% of the variance found within the residual chronology network.

Table 3.7 Principal component analysis results for the 73 residual chronologies of EPS1800 dataset over the period 1800-1995.

Component	Eigenvalue	% of Variance	Cumulative %
1	35.608	48.778	48.778
2	7.129	9.765	58.543
3	4.265	5.842	64.386
4	2.498	3.421	67.807
5	1.996	2.735	70.542
6	1.415	1.938	72.480
7	1.276	1.748	74.228
8	1.123	1.538	75.766

Table 3.8 Factor loadings of the residual chronologies in the EPS1800 dataset.

	Component							
	1	2	3	4	5	6	7	8
Gray Mountain	.872	.236	.086	.095	.119	.034	-.049	.047
Big Salmon (UWO/Laval)	.852	.229	.076	.169	.077	.052	.039	.041
Tagish	.848	.159	.070	.104	.077	.086	.031	.030
Monarch	.845	.226	.065	.101	.064	.062	.068	.093
Eagle Twelve	.843	.231	.097	.132	.069	-.014	-.083	-.077
Coal Lake Road	.841	.204	.082	.054	.183	.053	-.006	.002
Canyon Lake	.834	.301	.096	-.005	.211	.121	-.046	.022
Mt McIntyre	.828	.224	.161	.097	.118	.155	-.113	-.042
Webber Creek	.800	.399	.098	.129	.096	-.013	-.067	-.032
MacDonald Lake	.798	.153	.091	.081	.083	.163	.075	.065
Lapie Lakes	.775	.253	.114	.288	.136	.003	.020	.006
Nansen Creek	.735	.422	.139	.120	.131	-.003	-.077	-.029
Lapie Pass	.726	.347	.177	.297	.010	.034	-.016	-.023
Cassiar	.719	.169	.031	.225	.143	.073	.141	.131
Sandpit	.719	.263	.040	.056	.236	.205	.042	-.028
Anvil Mine	.719	.403	.177	.350	.134	-.060	.016	.036
Telluride	.706	.255	.181	-.002	.285	.230	-.145	-.060
Faro	.702	.387	.149	.336	.029	-.046	.047	-.059
Tanzilla Butte (UWO/Laval)	.698	.137	.067	.289	.007	-.011	.143	.187
Mt. Mye	.694	.411	.166	.365	.086	-.066	.017	.018
Mt. Berdoe	.624	.302	.012	.179	.146	.200	-.008	.088
Victoria Creek	.588	.377	-.005	.070	.103	.410	-.037	.153
Campsite	.572	.402	.212	.553	.092	-.048	.004	.076
Wheaton River	.493	.170	.138	.014	.361	.378	-.209	.058
Clinton Creek	.291	.803	.297	.009	.113	.045	.035	.211
Jack Wade	.324	.780	.249	.022	.153	.097	.109	.105
Empire Creek	.349	.775	.210	.012	.096	.242	.058	.176
Swede Dome	.313	.758	.212	.076	.142	-.001	.072	.228
Barlow Dome	.411	.749	.221	.121	.068	.101	-.060	.116
Big Gold Creek	.361	.748	.258	-.039	.111	.075	.022	.173
Worm Lake	.288	.745	.312	.223	.064	.021	-.058	-.120
North Klondike River	.265	.733	.191	.238	.109	-.034	.112	-.056
Galena	.421	.717	.194	.243	.077	-.008	.039	-.102
Highet Creek	.346	.680	.196	.190	.114	.065	-.061	.029
Wernecke	.480	.675	.238	.258	.029	.010	-.034	-.088
Carpenter Lake	.224	.675	.373	.248	.023	.048	-.046	-.122
Tombstone Mountain	.279	.670	.302	.232	.102	.056	-.031	-.137
Bonnet Plume Lake	.278	.662	.287	.403	.055	.059	.042	-.199
TTHH	.262	.634	.538	.083	.062	-.114	.107	.009
Einarson Lake	.349	.632	.265	.429	.032	.106	.058	-.160
Emerald Lake	.415	.629	.225	.369	.046	.148	-.015	-.108
Misty Lake	.322	.627	.339	.428	.011	.093	-.055	-.227
Black City	.166	.565	.496	.149	.030	.006	.179	-.195
Keele Lake	.429	.529	.187	.443	.114	.100	.024	-.115
MacMillian Pass Combined	.488	.513	.284	.499	.077	.067	-.064	-.098
Vadzaih Kan Creek	.115	.186	.832	.135	.043	.111	.037	-.019
Mt. Cronin	.013	.213	.817	.110	.127	.037	-.174	-.023
Airstrip Eagle Plains	.128	.221	.817	.025	.045	.018	-.065	.104
Rock River	.037	.272	.808	.084	.121	-.072	-.129	-.027
Tsiivii Creek	.180	.269	.771	.106	-.029	-.033	-.042	.015
Ogilvie Ridge	.069	.319	.769	.067	.005	.106	.206	.180
Scriver Creek	.024	.190	.741	.128	.008	.107	.250	.055
Sappers Hill	.126	.322	.591	.161	.061	.045	.291	.012
Distincta Combined	.287	.520	.570	.098	.124	-.084	.227	-.032
Blackstone River	.182	.440	.567	.032	.099	.037	.335	.037
Tungsten	.527	.307	.196	.639	.039	-.001	.000	.052
Divide Spruce	.427	.357	.175	.615	.094	.014	.088	.119
Nahanni Spruce	.524	.407	.126	.600	.106	.022	.069	.103
NWT Pass	.512	.390	.242	.593	.064	.121	-.021	.123
Big Bend Combined	.539	.406	.261	.578	.089	.004	-.046	.041
Eagle Combined	.510	.397	.202	.575	.104	.056	-.028	.179
Landslide Main	.051	.065	.006	.097	.884	.109	.143	.011
Jackson Point Good	.038	.040	.006	.118	.880	.136	.083	-.017
Bullion Creek	.175	.138	.046	.038	.829	.067	-.005	.081
Pipeline	.299	.127	.156	.047	.813	.023	-.079	.065
AINA	.226	.085	.168	-.047	.616	-.244	-.243	-.073
Cultus Bay	.165	.019	.018	.009	.600	.308	.232	-.006
Burwash	.421	.175	.060	.037	.469	.315	-.148	-.012
Kathleen Lake	.406	.173	.029	-.113	.411	.384	-.212	.075
Aishihik	.285	.126	-.024	-.012	.280	.726	.038	.100
Donjek	.140	.003	.222	.130	.220	.592	.030	-.280
Mt. Jeckell	-.066	.148	.366	-.004	.077	-.018	.699	-.100
Smithers Ski 2	.310	-.045	.202	.152	.101	-.037	-.096	.676

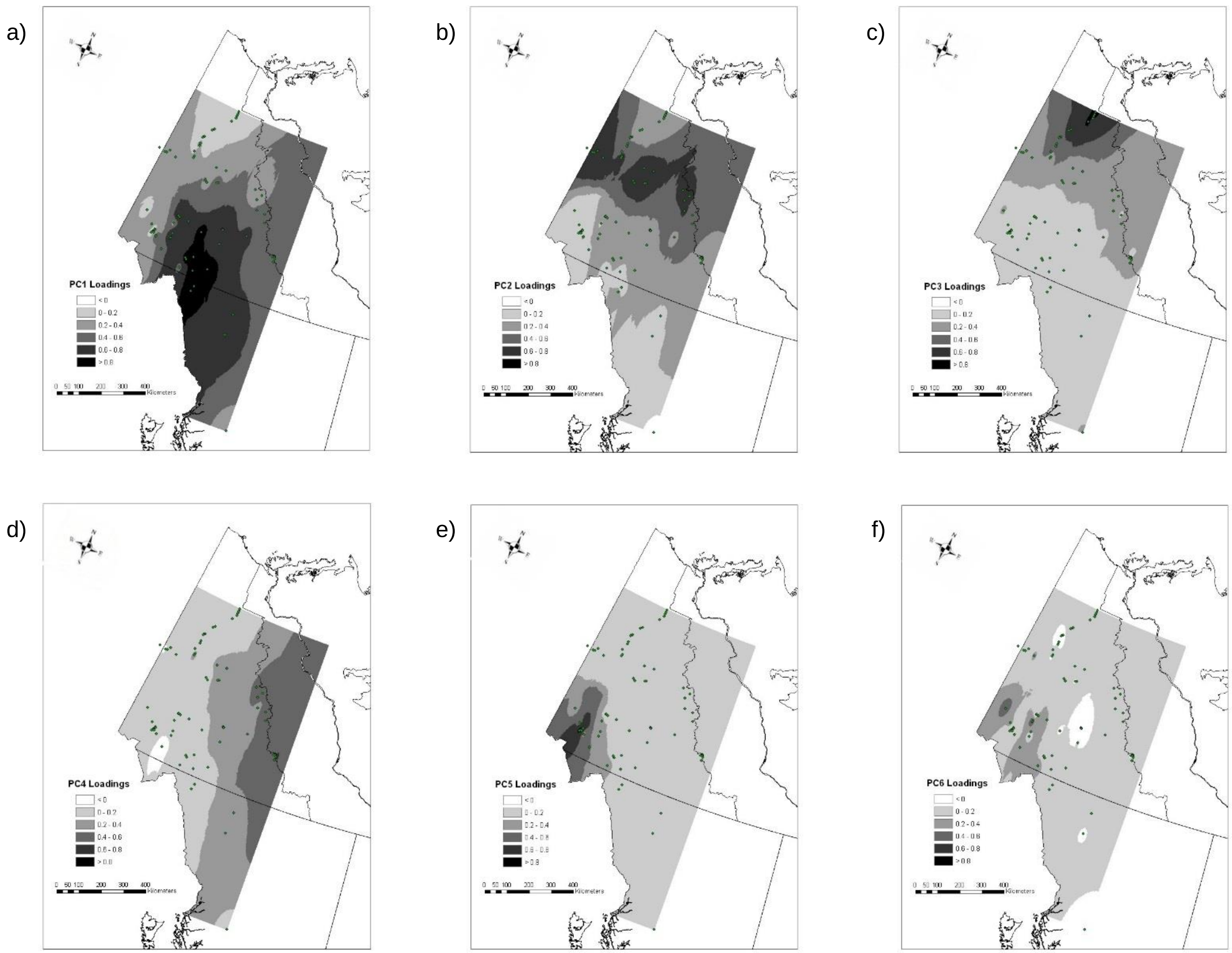


Figure 3.14 Mapped component scores of the first six principal components (a – f) of the 73 EPS1800 residual chronologies, using ArcGIS (v.9.3) Loading values <0 coloured white, 0-0.2 greyscale (20%), 0.2-0.4 greyscale (40%), 0.4-0.6 greyscale (60%), 0.6-0.8 greyscale (80%) and >0.8 black.

Several chronologies in this PCA analysis have strong loadings on more than one PC (Table 3.8). The eastern chronologies in Res-PC4 load strongly on Res-PC1 and Campsite, between NWT Pass and Eagle sites, loads marginally higher on Res-PC1 than on Res_PC4. However, the MacMillian Pass, Keele, Bonnet Plume, Einarson and Misty Lake sites further north along the Yukon/NWT border load most heavily on Res-PC2 and only between 0.499-0.403 on Res-PC4 indicating a stronger link to the central-north portion of the network. This suggests that, in addition to the north-south differentiation of the central group, there is also a significant east-west component

The PCA loading matrix also highlights the distinctiveness of the chronologies loading on Res-PC3 and Res-PC5 representing the northern sites along the Dempster Highway, and the Kluane region in southwestern Yukon. With minor exceptions, (Burwash and Kathleen Lake in the south and Distincta and Blackstone River in the north) these chronologies did not load heavily on the other Res-PCs. While the analysis of the component loading scores provided a method to identify regional groupings of chronologies based on highest score values, it is apparent that additional information regarding relationships or patterns involving the chronologies can also be gleaned from the values in the matrix.

Time series plots of the first six principal components of the residual chronologies clearly exhibited significant interannual variability, a characteristic common of residual chronologies (Figure 3.15). The time series record of Res-PC1, representing almost half of the total variance within the network showed several interesting patterns along with the underlying record of interannual variability. Between 1870-1900 and also from 1910-1930, the Res-PC1 record showed periods of much less variability relative to the rest of the record (Figure 3.15a). Res-PC6, representing less than two percent of the network variance, also showed a period of reduced variability from approximately 1890-1910. Since these time periods are offset, it is difficult to determine whether they are associated with each other. Since these periods of reduced variability were not recorded in the time series of other components, it suggests that the probable cause was limited to the regions represented by these principal components. Another distinctive trait of the Res-PC1 record was the period of sustained increasing growth found in the late 20th century (Figure 3.15a). From the mid-1980s onward, Res-PC1 showed continuously increasing growth, possibly in response to

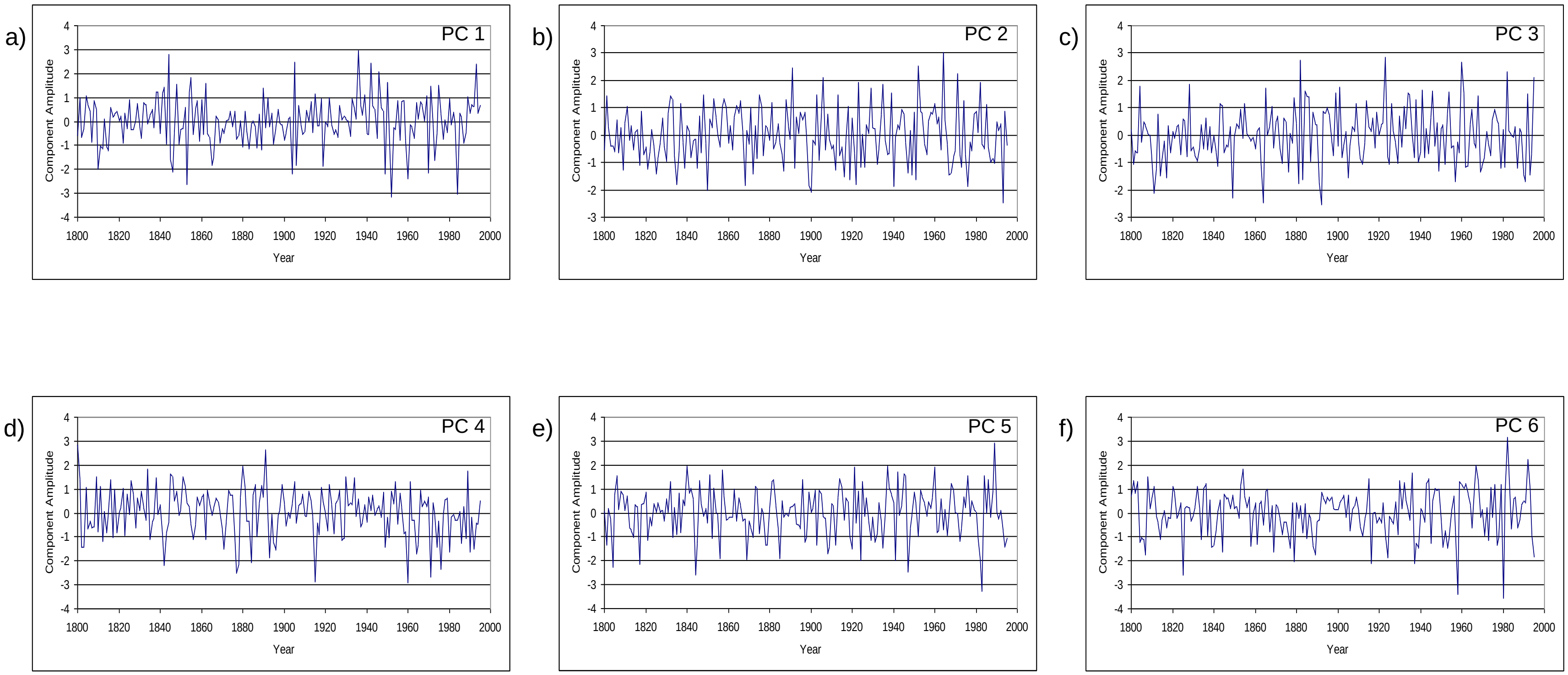


Figure 3.15 Time series plots of the first six Res-PCs (a – f) from PCA of the residual EPS1800 chronologies.

favourable environmental conditions such as increasing temperatures. None of the other principal components exhibited this increased growth to such a degree.

3.7.3.2 ***PCA – EPS1800 Standard Chronologies***

PCA of the standard chronologies, like the results of the correlation analyses, showed that the spatial patterns of the standard chronologies were not as cohesive and clear as their residual counterparts. While principal components characterizing the northern sites along the Dempster Highway (Std-PC3) and the 'Kluane' sites in southwestern Yukon (Std-PC6) were easily distinguished, the spatial patterns of the other standard chronology components exhibited more variation than the residual chronology components (Figure 3.16).

The PCA of the EPS1800 standard chronologies identified eleven principal components with eigenvalues greater than 1. These eleven components explained a total of 85.2% of the common variance contained within the network of standard chronologies (Table 3.9). Factor loadings of each standard chronology upon each principal component are shown in Table 3.10. The first principal component (Std-PC1) explained 39.4% of the network variance, with 19 of the 73 standard chronologies loading most strongly on this component. The second principal component (Std-PC2) had 16 chronologies load most heavily on it, and involved 12.5% of the common variance. Unlike the first two PCs of the residual chronologies, which appeared to show a north-south difference in the dominant regional signals, the spatial patterns represented by Std-PC1 and Std-PC2 appear to reflect a more east-west distinction within the network (Figure 3.16a and 3.16b). As previously mentioned, Std-PC3 focused primarily on the chronologies of the northern Yukon along the Dempster Highway, explaining ca. 9.9% of the network variance. Surprisingly, the Mt. Jeckell and Smithers Ski 2 standard chronologies loaded strongly on this third principal component with the sites from the northwest of the area sampled. Results from the correlation analyses and PCA of the residual chronologies had suggested that these two sites were anomalies within the network, showing very little association with the regional tree-ring signals within the Yukon. The fourth and fifth principal components of the standard chronologies appeared to represent signals within the central portion of the

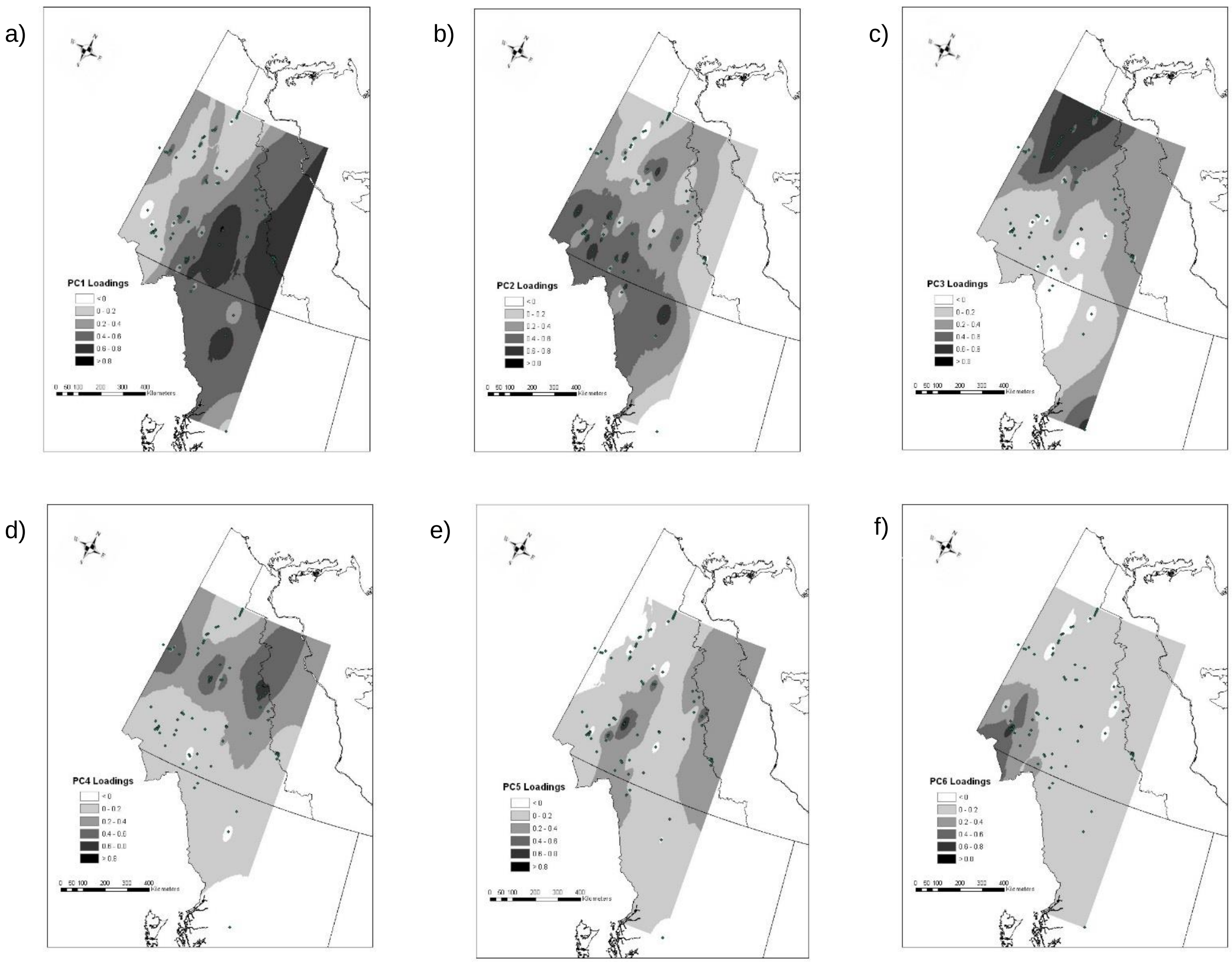


Figure 3.16 Mapped component scores of the first six principal components (a – f) of the 73 EPS1800 standard chronologies. Loading values <0 coloured white, 0-0.2 greyscale (20%), 0.2-0.4 greyscale (40%), 0.4-0.6 greyscale (60%), 0.6-0.8 greyscale (80%) and >0.8 black.

Table 3.9 Principal components analysis results of the 73 standard chronologies of the EPS1800 dataset over the period 1800-1995.

Component	Eigenvalue	% of Variance	Cumulative %
1	28.790	39.439	39.439
2	9.133	12.511	51.950
3	7.211	9.878	61.827
4	4.151	5.687	67.514
5	3.149	4.313	71.828
6	2.493	3.414	75.242
7	1.858	2.545	77.787
8	1.703	2.333	80.120
9	1.612	2.208	82.328
10	1.118	1.532	83.859
11	1.008	1.381	85.240

Table 3.10 Factor loadings of the standard chronologies in the EPS1800 dataset.

	Component										
	1	2	3	4	5	6	7	8	9	10	11
Anvil Mine	.882	.150	.189	.156	.162	.145	.147	-.032	.011	-.076	-.030
Nahanni Spruce	.841	.103	.249	.193	-.009	.055	.035	-.001	-.137	.115	.158
MacMillian Pass Combined	.807	.142	.349	.203	.274	.055	-.088	-.011	-.072	.018	.119
Eagle Combined	.803	.237	.323	.048	.234	.059	-.140	.052	-.123	-.046	.120
Campsite	.800	.159	.455	.096	.124	.058	.042	-.030	-.200	-.070	.059
Mt. Mye	.796	-.169	.164	.235	.149	.060	.252	.251	.041	.020	-.117
NWT Pass	.768	-.064	.330	.139	.253	.014	.192	.137	.057	.105	.025
Tungsten	.760	-.096	-.051	.238	.253	.126	-.188	.244	-.055	-.018	-.102
Tanzilla Butte (UWO/Laval)	.744	.398	.051	-.018	-.004	.081	.096	-.017	.269	-.004	.088
Lapie Lakes	.728	.438	-.182	.214	-.032	.172	-.052	-.241	.092	-.027	-.137
Tagish	.724	.439	-.025	.070	.251	.110	.124	.037	.165	.039	-.071
Coal Lake Road	.723	.457	.089	-.021	.333	.174	.105	-.055	-.027	-.063	-.085
Faro	.704	.390	-.025	.210	-.227	-.049	.112	.118	.183	.218	-.088
Big Salmon (UWO/Laval)	.696	.461	.082	.082	.070	.116	-.055	.215	-.120	-.051	-.043
Victoria Creek	.668	.520	-.098	.080	.046	.095	-.049	-.175	.059	.244	-.100
Big Bend Combined	.610	.141	.098	.369	.519	.134	.051	.158	.113	-.028	.070
Emerald Lake	.563	.392	.282	.443	.006	-.055	-.107	.045	.010	.231	.058
Monarch	.550	.024	-.031	.029	.446	.152	.171	.544	.168	-.014	.051
Clinton Creek	.516	.438	.352	.393	-.286	.077	.039	-.167	.021	.058	.023
Telluride	.118	.880	.125	.070	.073	.081	.106	.059	-.020	.126	-.143
AINA	.074	.794	.070	-.083	-.261	.162	-.155	-.226	.086	-.121	.207
Kathleen Lake	.111	.768	.101	.061	.033	.202	-.213	.086	-.319	.080	-.019
Cassiar	.220	.758	-.033	.073	.185	.113	.228	.138	.133	.056	.016
MacDonald Lake	.319	.748	-.174	.152	.000	.149	.079	.067	.203	.116	-.190
Nansen Creek	.365	.726	.122	.207	.004	.183	-.078	-.346	-.005	-.105	.118
Carpenter Lake	.019	.716	.394	.281	-.220	.016	-.095	-.316	-.108	-.093	.132
Mt McIntyre	.490	.698	.131	-.028	.168	.092	-.219	.210	-.048	.050	.130
Gray Mountain	.555	.698	.035	.039	.046	.091	.000	.238	-.036	.060	-.006
Donjek	-.086	.688	.196	.152	.064	.112	-.276	-.124	-.067	.319	-.041
Canyon Lake	.429	.684	.156	.026	.320	.238	.103	.110	.032	-.064	.024
Webber Creek	.372	.666	.162	.240	.292	.183	.233	.049	.193	-.002	.132
Worm Lake	.133	.587	.545	.433	-.043	.029	-.122	-.052	-.187	-.104	.100
Burwash	-.078	.572	.243	.233	.248	.156	.288	-.038	-.399	-.003	-.274
Lapie Pass	.489	.544	-.020	.297	.050	-.016	-.094	.416	.147	.112	.146
Eagle Twelve	.341	.512	.415	.022	.383	.046	.032	.356	-.034	-.087	.281
Rock River	.135	.316	.830	.070	-.073	-.013	-.055	-.126	-.053	-.079	.001
Sappers Hill	.031	.081	.807	.096	.255	-.003	.121	.082	.048	-.091	.079
Ogilvie Ridge	.345	-.027	.802	.141	.075	-.032	.089	-.030	.284	.064	-.002
Vadzaih Kan Creek	.165	-.139	.789	.047	.305	-.004	.019	.180	.179	.059	-.063
Airstrip Eagle Plains	-.062	.275	.785	.144	-.067	-.017	.085	-.011	.292	.028	.008
Black City	.056	.478	.750	.170	-.128	-.085	.081	-.134	-.157	.030	.084
Distincta Combined	.306	-.106	.746	.168	.319	.144	.050	.052	.053	-.056	.035
Mt. Cronin	.242	.352	.737	.012	.148	.054	-.160	-.110	.055	-.097	-.080
Tombstone Mountain	.139	.349	.722	.324	-.100	.012	.235	-.102	-.079	-.002	.175
Mt. Jeckell	-.107	-.049	.686	.203	-.168	-.038	.029	.001	-.183	.162	-.188
TTHH	.377	.355	.646	.147	-.324	-.017	-.224	-.068	-.134	.012	.139
Smithers Ski 2	.168	-.198	.627	-.275	-.037	.044	.278	.339	-.198	-.198	-.005
Galena	.165	-.005	.621	.257	.467	-.008	.147	.308	-.123	-.013	.192
Blackstone River	.193	-.123	.576	.465	-.074	.084	.025	.124	.030	.109	-.383
Scriver Creek	.484	-.090	.497	.019	-.062	.008	-.368	.000	.354	.257	-.123
Jack Wade	.433	.280	.450	.433	-.006	.068	.234	-.274	.128	.101	.244
Misty Lake	.422	.325	.263	.665	.241	.021	-.148	-.090	.071	.066	.027
Highet Creek	.209	-.028	.223	.660	.229	.103	.057	.499	.049	-.066	-.012
Einarson Lake	.429	.166	.232	.651	.397	.026	.068	-.025	.071	.017	-.141
Bonnet Plume Lake	.409	.010	.374	.634	.268	-.008	.214	-.061	.057	.118	-.006
Big Gold Creek	.211	.391	.247	.626	-.173	.064	.229	-.087	.164	.082	.070
Barlow Dome	.561	.228	.157	.595	.070	.141	-.052	.175	.074	.014	.066
Wernecke	.310	.332	.256	.561	.494	.160	.141	-.007	-.013	-.129	-.059
Empire Creek	.122	.283	.414	.560	.104	.008	.482	.096	.141	.175	-.104
Mt. Berdoe	.366	.068	-.024	.030	.835	.183	-.045	.046	.011	.020	-.013
Sandpit	.270	.150	.021	.171	.724	.242	.080	.232	.175	.128	-.026
Keele Lake	.497	.252	.270	.314	.588	.111	.080	-.161	.033	-.039	-.029
Landslide Main	.035	.081	.091	-.018	.200	.859	.052	.132	.029	.159	.116
Jackson Point Good	.043	.189	-.210	.080	.050	.854	-.092	-.020	.068	.178	-.046
Bullion Creek	.288	.309	-.076	.027	.064	.792	-.018	.017	.038	-.086	-.073
Pipeline	.226	.355	.230	.098	.184	.737	.052	.001	-.084	-.005	-.094
Swede Dome	.405	-.009	.449	.342	-.017	-.016	.590	-.002	.177	.067	-.124
North Klondike River	-.005	-.280	.550	.324	.398	-.005	.558	.059	-.008	-.024	.019
Divide Spruce	.172	-.249	.471	.107	.411	.020	.502	.054	.184	.145	.254
Wheaton River	.320	.356	-.026	.059	.264	.319	-.068	.472	.008	.082	-.149
Tsiivii Creek	-.046	-.020	.221	.285	.230	.104	.123	.052	.790	-.038	-.011
Aishihik	.078	.337	-.107	.060	.141	.292	.030	.070	-.032	.634	-.154
Cultus Bay	.150	.020	.076	.091	-.083	.517	.091	-.059	.004	.590	.231

network (Figure 3.16d and 3.16e), drawing some similarity to Res-PC2, though obviously not weighted as dominantly. Std-PC4 and Std-PC5 explained 5.7% and 4.3% of the network variance respectively. The sixth principal component of the standard chronologies corresponded to the ‘Kluane’ group in southwestern Yukon (Figure 3.16f), explaining 3.4% of the common variance. The remaining higher-order PCs (Std-PC7 through Std-PC11), while identified as separate components, had chronologies that also loaded strongly, but not highest, on the higher order PCs. As a result, it was difficult to determine whether these higher-order components actually characterized small isolated pockets of sites with separate signals. Each of these higher-order components explained ≤ 2.6% of the overall variance in the standard chronology network.

The principal component time series of the standard chronologies display long term, low frequency patterns. The time series plots of the first six principal components of the standard chronologies suggest that several different regional signals exist within the tree-ring network (Figure 3.17a-f). Since common, long-term, low frequency signals across sites are often associated with climate, these standard chronology principal component series are important for studying past variations in climate. Each principal component time series was plotted against the standard chronologies that loaded most strongly on that component, in order to examine how representative the regional PC series was to the original standard chronologies. These comparisons indicated that the principal component time series did not always clearly represent the patterns found in the constituent standard chronologies. In several cases the PC series either under-represented or over-represented the growth patterns of the standard chronologies.

Examination of the PC time series (Figure 3.17) indicated that almost all the PC series showed a strong decrease in the component values in the late 20th century that might be consistent with possible “divergence” in the tree-ring series at these sites. Only PC2 showed a positive growth trend in the late 20th century. However, comparison of the Std-PC2 time series with the standard chronologies that load most heavily on it (Figure 3.18), show a large discrepancy post-1950. Although the PC2 series shows a continuously increasing trend, the majority of the standard chronologies loading on that component showed relatively neutral growth trends over that period. It appears that these

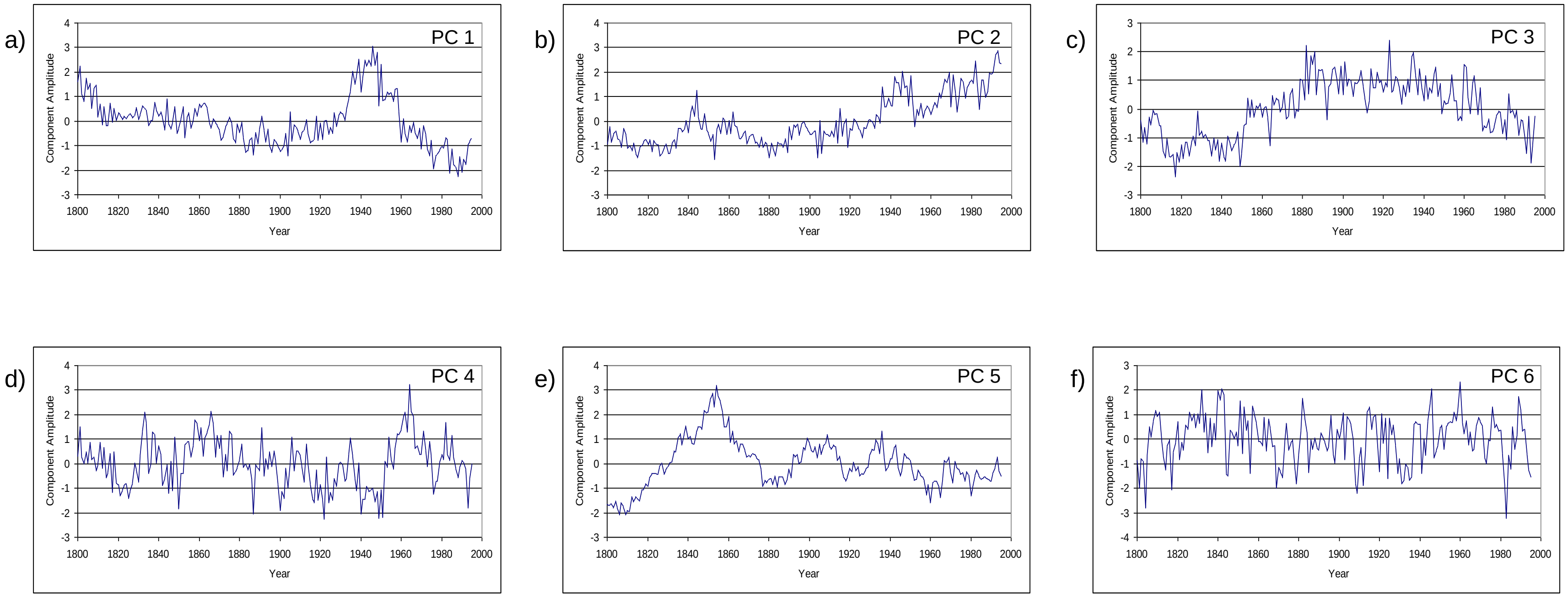


Figure 3.17 Time series plots of the first six Std-PCs (a – f) from PCA of the standard EPS1800 chronologies.

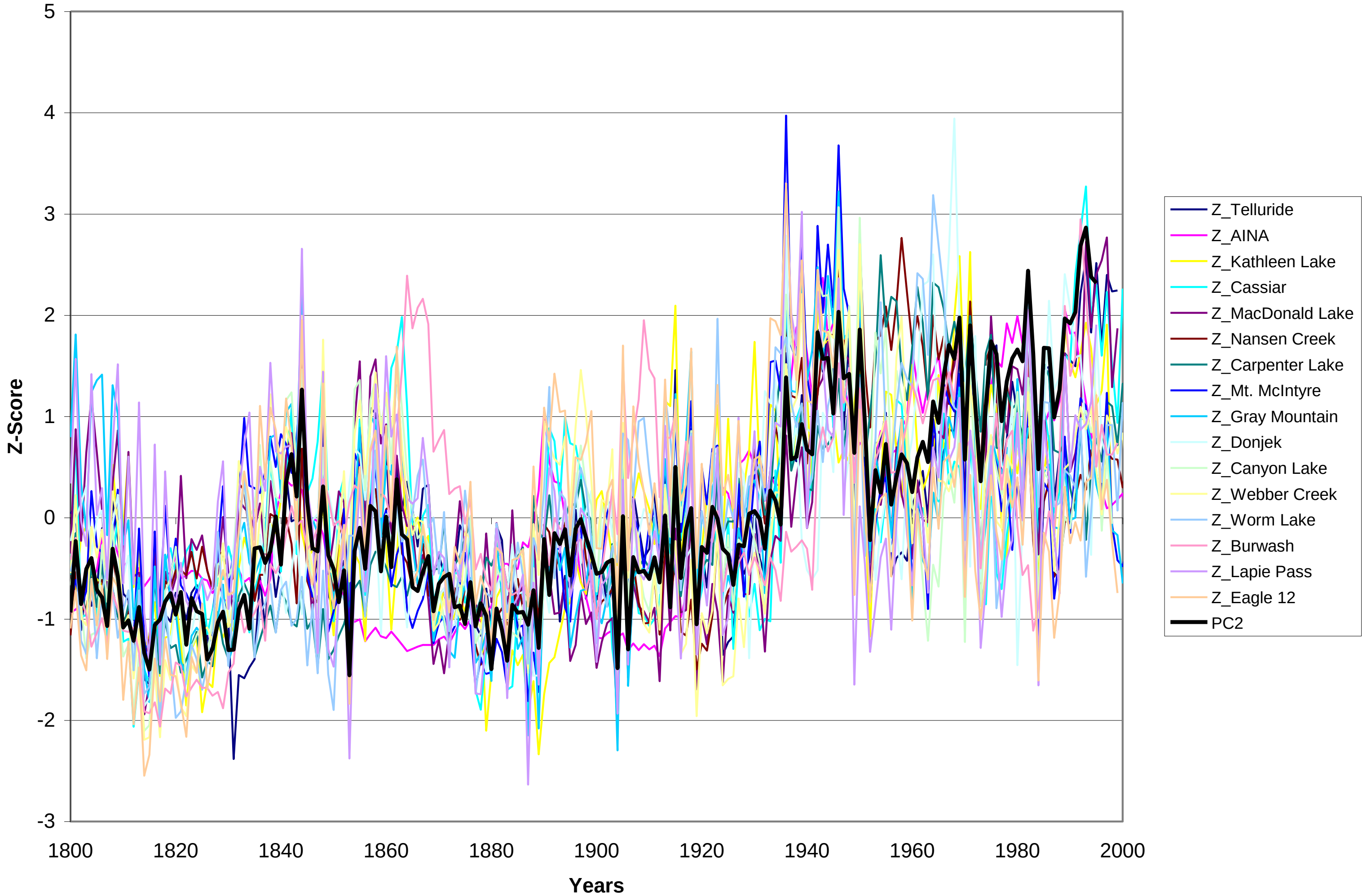


Figure 3.18 Comparison of Std-PC2 (black solid line) with z-scores of individual standard chronologies of sites loading strongest on that component.

incongruities are likely the result of the calculation process of the PCA. As noted earlier, PCA develops components by attempting to maximize variance within the data in a stepwise fashion. The first principal component measures as much of the common variance in the data as possible, while the second component then tries to account for as much of the remaining variance after the first component is removed, and so forth with each higher-order component. Each component is constrained by the fact that it must be orthogonal from the previous ones. In the standard chronology PCA the time series of Std-PC1 showed a dramatic and sustained decrease in the last half of the 20th century (Figure 3.17a). With the removal of that portion of the variance captured in Std-PC1, the processing of the remaining variance in the data likely resulted in the elevated trend seen in Std-PC2 post-1950 (Figure 3.17b). Therefore, although PCA shows merit as a powerful tool for analyzing data variance and quantitatively identifying groups of inter-correlated data, caution must be used when considering its application as an interpretative tool.

The representativeness of the PC is particularly critical as the available climate data for the Yukon are primarily restricted to the period after 1950 and it is important to have a representative tree-ring series for climate calibration studies. Three potential series options were compared to determine which best represented the standard chronologies comprising each of the regional groupings. The first option was the PC time series produced by the initial PCA of the standard chronologies. The second option involved regional time series based on the quantitative groupings of the PCA, created by calculating an averaged (MEAN) series from the group of individual standard chronologies that loaded strongest on each component. The third option was regional time series developed by running secondary PCAs restricted to only those chronologies that loaded strongest on each component. Mean correlations of the chronologies loading strongest on each component against the three options indicated that the MEAN time series provided the most representative record, at both the entire record scale as well the period representing the last half of the 20th century (Table 3.11). Therefore, the averaged time series were used to study trends in the tree-ring series.

Table 3.11 Mean correlations of loaded sites on each component with (i) original PC time series, (ii) averaged (MEAN) regional time series, and (iii) secondary PCA time series restricted to chronologies of each regional component (RPCA).

	1800-2005			1950-2005		
	PC	MEAN	RPCA	PC	MEAN	RPCA
PC1 sites	0.720	0.799	0.508	0.771	0.790	0.709
PC2 sites	0.690	0.775	0.577	0.400	0.589	0.466
PC3 sites	0.692	0.739	0.505	0.748	0.763	0.711
PC4 sites	0.619	0.827	0.829	0.704	0.839	0.845
PC5 sites	0.715	0.893	0.892	0.221	0.773	0.769
PC6 sites	0.811	0.882	0.884	0.798	0.862	0.873
Average	*0.708*	*0.819*	*0.699*	*0.607*	*0.769*	*0.729*

Figure 3.19 shows averaged time series of the groups of chronologies loading on each of the first six PCs of the STD PCA. The mean series of the Std-PC1 grouping, primarily consisting of sites representing the eastern half of the Yukon, showed a decreasing trend early in the 19th century, which was followed by a slight recovery between 1820 and 1870. In the 20th century, this record shows high growth from 1930 to 1950 and a continuous decline through the last half of the century. The Std-PC2 sites mainly found in the southwestern Yukon shows two different periods of sustained growth. Throughout the 19th and first quarter of the 20th century, growth appeared relatively stable at moderate levels with only a slight improvement during the mid 1800s. Between 1920 and 1940 the record shows increasing growth and after a sharp drop in the 1950s retains relatively high growth thereafter. Between 1800 and 1950, these first two principal components show similar patterns (correlation value of 0.618) but differ greatly post-1950 (correlation value of -0.388). The Std-PC3 sites, mainly along the Dempster Highway show low growth in the first half of the 19th century and gradual improvement from 1850 to 1900. It maintains variable but relatively high growth until 1960s and decreases thereafter. The mean series of the Std-PC4 grouping, generally representing the central portion of the Yukon, showed less low frequency trend relative to the three previous components with relatively low growth in the 1820s, 1840s, 1920s and 1950s and higher growth in the early 1830s, 1860s, 1930s and 1960s. The mean of Std-PC5 sites is dominated by the significant increase

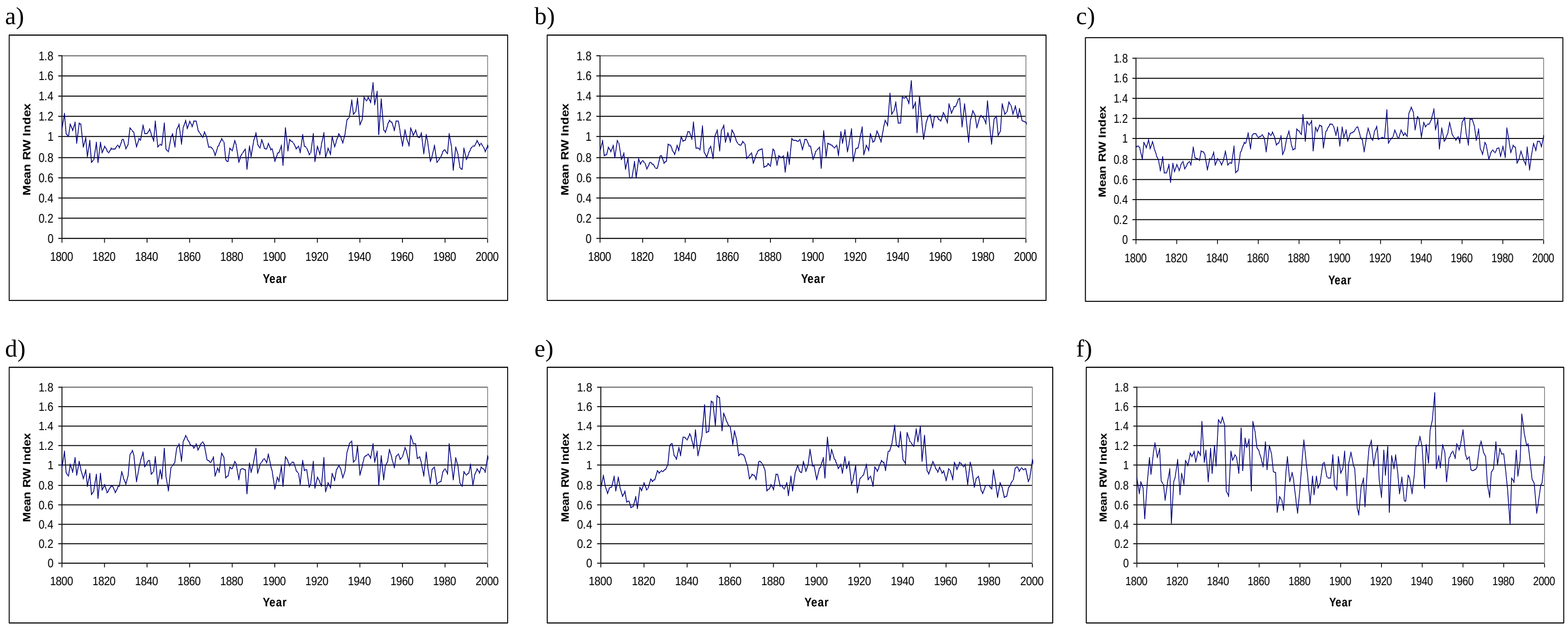


Figure 3.19 Mean time series of the standard chronologies loading on the first six PCs (a – f) of the standard chronologies of the EPS1800 dataset.

in growth from 1810-1854 and subsequent decline until the 1880s. Shorter periods of higher growth occurred ca 1890-1910 and 1930-1950. Post-1950, the record shows a decreasing trend until ca. 1990 and a slight recovery in the last decade. Std-PC6, the 'Kluane' displays relatively limited low frequency trend in its time series though averaging lower values between the 1860s to the 1940s. A sharp drop in the record appeared in 1983, but was short lived.

3.7.3.3 *PCA Temporal Analysis*

In order to determine whether possible temporal changes in the component loadings of the chronologies existed, PCA was also conducted on the data over several different time intervals. In addition to the initial 1800-1995 common period, analyses of the EPS1800 dataset were also performed using 1800-1899, 1900-1995, 1900-1949, and 1950-1995 time periods. Component loading results of these analyses indicated that the PC loadings of the residual chronologies exhibited more temporal stability than the standard chronologies (Figure 3.20). Similarly, an examination of the variance explained by the principal components over the different time periods clearly showed that the residual chronologies were more consistent over time relative to the standard chronologies, especially in the case of PC1 representing the dominant signal within the network (Table 3.12). To some extent it is not the actual components which are important in the following discussion but rather the pattern of loadings, e.g. the northern groups all show the same unique pattern of loading, as do the Kluane sites. It is not important whether this is PC3 or PC4 but that there is a group which all show a 3-4-3-3-4 pattern, just as there are many sites which show a 2-2-2-2-2 or 1-1-1-1-1 pattern, or 5-5-4-4-5 (Kluane).

Regional groupings of the residual chronologies, earlier identified from the loadings of the PCA conducted over the 1800-1995 common period, remained relatively consistent over the various time intervals. One exception to this was a small number of sites (Nahanni Spruce, Divide Spruce, Big Bend Combined, NWT Pass, Tungsten, and Eagle Combined) which initially loaded most strongly on PC4 over the 1800-1995 time period (i.e. they are a subgroup of 1-1-1-1-1 that show a 4-3-1-1-3 pattern). All located near the northern end

STANDARD CHRONOLOGIES

SITE NAME	1800_2005	1800_1899	1900-2005	1900-1949	1950-2005
Rock River	3	1	4	4	4
Mt. Cronin	3	1	4	1	4
Vadzaih Kan Creek	3	1	4	4	4
Tsiivii Creek	9	1	8	5	4
Airstrip Eagle Plains	3	1	4	4	4
Scriver Creek	3	6	4	1	4
Ogilvie Ridge	3	1	1	1	4
Mt. Jeckell	3	1	6	8	2
Sappers Hill	3	1	1	7	4
TTHH (Updated)	3	1	2	1	2
Distincta Combined	3	1	1	2	1
Blackstone River	3	1	2	6	2
Black City	3	1	2	1	2
Carpenter Lake	2	1	2	1	2
Tombstone Mountain	3	1	2	1	2
Worm Lake	2	1	2	2	2
North Klondike River	7	1	1	5	2
Bonnet Plume Lake	4	1	2	1	2
Clinton Creek	1	3	2	1	2
Misty Lake	4	3	2	1	2
Jack Wade	3	1	2	1	2
Swede Dome	7	1	1	1	1
Empire Creek	4	1	2	1	6
Big Gold Creek	4	1	2	2	2
Wernecke	4	2	2	1	2
Einarson Lake	4	2	2	1	2
Galena	3	1	6	2	2
Barlow Dome	4	3	2	1	2
Highet Creek	4	8	6	2	2
Emerald Lake	1	3	2	1	2
Keele Lake	5	2	1	1	1
MacMillian Pass Combined	1	3	1	1	1
Lapie Pass (Pisaric)	2	3	3	1	3
Anvil Mine	1	3	1	1	1
Faro	1	3	3	1	3
Mt. Mye	1	3	1	1	1
Nahanni Spruce	1	3	1	1	1
Divide Spruce	7	1	1	5	1
Nansen Creek	2	2	2	1	1
Webber Creek	2	2	3	1	3
Mt. Berdoe	5	2	1	1	1
Big Bend Combined	1	2	1	1	1
Campsite	1	3	1	1	1
Victoria Creek	1	3	3	1	6
NWT Pass	1	3	1	1	1
Tungsten	1	3	1	1	1
Eagle Twelve	2	2	1	1	3
Eagle Combined	1	3	1	1	1
Aishihik	10	7	3	3	7
Donjek	2	10	9	9	9
Lapie Lakes	1	3	2	1	1
Sandpit	5	2	3	1	3
Burwash	2	1	7	6	5
Cultus Bay	10	4	9	3	7
AINA	2	* 5 (4)	3	1	5
Canyon Lake	2	2	3	1	1
Jackson Point Good	6	4	5	3	5
Landslide Main	6	4	5	3	5
Pipeline	6	4	5	3	5
Bullion Creek	6	4	5	3	5
Telluride	2	2	3	1	3
Gray Mountain	2	3	3	1	3
Mt. McIntyre	2	2	3	1	3
Coal Lake Road	1	2	1	1	1
Big Salmon	1	3	1	1	1
Kathleen Lake	2	3	3	1	3
Tagish	1	2	3	1	1
Wheaton River	8	8	3	1	3
MacDonald Lake	2	3	3	1	3
Monarch	1	2	1	1	3
Cassiar	2	2	3	1	3
Tanzilla Butte (UWO/Laval)	1	3	3	1	1
Smithers Ski 2	3	1	1	* 7 (3)	1

RESIDUAL CHRONOLOGIES

SITE NAME	1800_2005	1800_1899	1900-2005	1900-1949	1950-2005
Rock River	3	4	3	3	4
Mt. Cronin	3	4	3	3	4
Vadzaih Kan Creek	3	4	3	3	4
Tsiivii Creek	3	4	3	3	4
Airstrip Eagle Plains	3	4	3	3	4
Scriver Creek	3	4	3	3	4
Ogilvie Ridge	3	4	3	3	4
Mt. Jeckell	7	7	7	6	* 10 (4)
Sappers Hill	3	4	3	8	4
TTHH (Updated)	2	2	3	2	4
Distincta Combined	3	4	3	2	4
Blackstone River	3	2	3	3	4
Black City	2	2	3	2	4
Carpenter Lake	2	2	2	2	3
Tombstone Mountain	2	2	2	2	2
Worm Lake	2	2	2	2	2
North Klondike River	2	2	2	2	2
Bonnet Plume Lake	2	2	2	2	3
Clinton Creek	2	2	2	2	2
Misty Lake	2	2	2	2	3
Jack Wade	2	2	2	2	2
Swede Dome	2	2	2	2	2
Empire Creek	2	2	2	2	2
Big Gold Creek	2	2	2	2	2
Wernecke	2	2	2	2	2
Einarson Lake	2	2	2	2	3
Galena	2	2	2	2	2
Barlow Dome	2	2	2	2	2
Highet Creek	2	2	2	2	2
Emerald Lake	2	2	2	2	2
Keele Lake	2	3	2	2	3
MacMillian Pass Combined	2	3	1	2	3
Lapie Pass (Pisaric)	1	1	1	1	1
Anvil Mine	1	1	1	1	1
Faro	1	1	1	1	1
Mt. Mye	1	1	1	1	1
Nahanni Spruce	4	3	1	1	3
Divide Spruce	4	3	1	1	3
Nansen Creek	1	1	1	1	1
Webber Creek	1	1	1	1	1
Mt. Berdoe	1	1	1	1	1
Big Bend Combined	4	3	1	2	3
Campsite	1	3	1	1	3
Victoria Creek	1	6	1	1	1
NWT Pass	4	3	1	1	3
Tungsten	4	3	1	1	3
Eagle Twelve	1	1	1	1	1
Eagle Combined	4	3	1	1	3
Aishihik	6	6	4	1	6
Donjek	6	5	5	7	7
Lapie Lakes	1	1	1	1	1
Sandpit	1	1	1	1	1
Burwash	5	5	6	1	5
Cultus Bay	5	5	4	4	6
AINA	5	9	4	1	5
Canyon Lake	1	1	1	1	1
Jackson Point Good	5	5	4	4	5
Landslide Main	5	5	4	4	5
Pipeline	5	5	4	4	5
Bullion Creek	5	5	4	4	5
Telluride	1	1	1	1	1
Gray Mountain	1	1	1	1	1
Mt. McIntyre	1	1	1	1	1
Coal Lake Road	1	1	1	1	1
Big Salmon	1	1	1	1	1
Kathleen Lake	5	5	6	5	8
Tagish	1	1	1	1	1
Wheaton River	1	5	1	1	8
MacDonald Lake	1	1	1	1	1
Monarch	1	1	1	1	1
Cassiar	1	1	1	1	1
Tanzilla Butte (UWO/Laval)	1	1	1	1	1
Smithers Ski 2	8	8	8	9	1

Figure 3.20 Principal component loadings of EPS1800 chronologies over different time intervals. Component numbers with asterisk denote negative loading on component, with component number of most positive loading given in brackets. Sites are arranged from north to south.

Table 3.12 Percentage of variance explained within the network by each principal component over the time periods analyzed.

STANDARD CHRONOLOGIES

	% Variance Explained				
Component	1800-1995	1800-1899	1900-1995	1900-1949	1950-1995
PC1	19.972	24.523	24.847	45.614	27.159
PC2	16.309	20.507	20.290	10.188	20.304
PC3	15.451	18.353	17.123	7.437	13.766
PC4	7.945	5.812	5.936	6.716	8.963
PC5	7.034	4.081	5.277	6.692	5.972
PC6	5.224	3.121	4.663	5.328	3.373
PC7	3.500	2.811	2.714	3.618	3.246
PC8	3.347	2.496	2.553	2.803	2.766
PC9	2.774	2.294	2.130	1.658	2.690
PC10	2.138	2.050	1.715		1.890
PC11	1.546	1.984			

RESIDUAL CHRONOLOGIES

	% Variance Explained				
Component	1800-1995	1800-1899	1900-1995	1900-1949	1950-1995
PC1	25.321	22.272	29.560	31.258	23.290
PC2	19.054	16.845	18.789	25.031	16.448
PC3	11.109	10.777	13.514	9.864	13.540
PC4	6.912	9.994	6.628	6.897	13.224
PC5	6.814	7.974	3.788	2.731	6.784
PC6	2.886	2.899	3.409	2.575	3.330
PC7	1.922	2.482	1.925	2.267	2.510
PC8	1.748	2.263	1.765	1.988	2.448
PC9		1.699		1.887	2.031
PC10		1.636		1.732	2.021

of the Nahanni Range Road in southeastern Yukon, these sites appear to represent a separate signal. During the 1800-1899 period, these sites loaded on PC3, but when examined over the later 1900-1995 and 1900-1949 time intervals, these sites shifted onto PC1 suggesting that during this time they shared in the larger dominant signal within the network. During the 1950-1995 time period, these sites showed another shift in their component loading, ending up on PC3. Several additional sites exhibited a similar shift during this latter time period. Carpenter Lake, Bonnet Plume Lake, Misty Lake, Einarson Lake, and Keele Lake (sites all situated in the Wernecke Mountains of eastern Yukon) along with MacMillian Pass Combined, loaded strongly on PC2 during the four earlier time intervals, but shifted to PC3 during the 1950-1995 time period. Also showing a change in component loading during the late 20th century, the block of sites comprising the regional grouping in the northern Yukon (along the Dempster Highway) exhibited a shift from PC3 to PC4. Results from the 1800-1899 analysis period though, showed that these sites also loaded on PC4 during this earlier period. Overall, the principal component loading results of the residual chronologies indicate that several distinct regional groupings do exist within the network, and that these groupings are relatively stable over time. While some sites showed a minor change from one component to the next during the analyses, only a select few showed a larger shift in component loading during the 1950-1995 period. These sites represented an area along the eastern margin of the tree-ring network, suggesting that perhaps this part of the network was more vulnerable to changes in growth during the latter half of the 20th century. It should also be noted that some sites showed relatively unique and different patterns (e.g. Jeckell, Donjek, Aina, Kathleen Lake Smithers).

While the PCA results of the residual chronologies clearly displayed several regional groupings within the network, which appeared to be relatively stable over time, the corresponding results involving the standard chronologies were more complex and exhibited less temporal stability. Though the general nature of the regional groupings shown by the residual chronologies was detectable within the standard chronology temporal matrix, several key differences were observed. The first major difference was that the component loading pattern of the 1800-1995 time interval appeared quite different from those reflected in the other time intervals of the matrix. For example, in the 1800-1995 interval nearly all of the northern Yukon sites found along the Dempster Highway loaded on Std-PC3 as a cohesive group. During the 1800-1899 period, these sites loaded on Std-PC1 as a solid group. In the subsequent time periods though, this group showed a noticeable split, with the northern half primarily loading on Std-PC4 while the southern half loaded on the first and second components, associated more with the central portion of the network. Similarly, a group of sites, which loaded together on Std-PC4 in the 1800-1995 time period, showed a distinct shift to the more dominant first and second principal components in the subsequent time intervals. It appears that certain regional patterns may have existed in the past which are not clearly reflected in the patterns found in the network during the 20th century.

Another key pattern, which stood out in the temporal analysis of the standard chronology PCA results, was the higher coherence in Std-PC1 across the network during the 1900-1949 time interval. Fifty of the 73 standard chronologies loaded onto the first principal component during this time period representing the dominant signal. As noted in Table 3.12, Std-PC1 explained 45.6% of the variance within the network during the 1900-1949 interval, a value much greater compared to the other time periods. It is evident that during the first half of the 20th century, a significant portion of the white spruce population in the Yukon shared a common growth response as reflected by the standard chronologies.

3.8 Summary

The 111 UWO *Picea glauca* sites examined in this chapter represent the single largest collection of white spruce tree-ring data for the Yukon Territory and its bordering areas. Collectively, the 2983 individual trees sampled in this study provide geographical coverage extending from the northern reaches of the Dempster Highway near the Arctic Circle to below the territory's southern border with British Columbia, and from the western boundary with Alaska to the eastern border along the Northwest Territories. While raw chronology lengths for these sites ranged from 74 years to 1089 years, over half of the entire collection (51.3%) had lengths greater than 200 years. This is significant given that for northern latitudes, finding trees older than 200 years was thought to be considered quite rare due to fire disturbance and also because spruce generally has a low resistance to trunk rot in old age (Schweingruber, 1988). Surprisingly, 5.4% of the collection actually reached ages extending beyond 500 years.

Mean RBAR and series intercorrelation values (average of 0.349 and 0.588 respectively for the standard chronologies, and 0.346 and 0.586 respectively for the residual chronologies) indicate strong common signals within the chronologies of this collection. Average mean sensitivity values of 0.148 for the standard chronologies, and 0.169 for the residual chronologies, show that considerable interannual variability also exists within these chronologies. These statistics suggest that these chronologies have considerable dendrochronological potential for the examination of variations in growth, both in the low frequency, longer term signals of standard chronologies, as well as the high frequency, short term signals of residual chronologies.

In order to establish a high quality network for this study the initial chronologies were screened based on chronology length and signal strength. As EPS assesses the common signal of a chronology and its change over time, screening of the 111 site chronologies was primarily based on their EPS results. Particular attention was paid to chronology quality in the early portions of the chronologies, where sample depth is a common problem. In a few cases, low sample replication in the most recent part of the chronologies resulted in their removal from further study. Screening of the collection resulted in the creation of two data sets comprised of chronologies with EPS values extending back beyond 1800AD (73 chronologies) and 1900AD (84 chronologies).

Common patterns within the EPS1800 dataset network (73 sites) were evaluated using correlation analysis and principal component analyses. Mean correlation between the 73 chronologies over the 1800-2004 period was 0.346 for the standard chronologies, and 0.440 for the residual chronologies. The stronger inter-site correlations of the residual chronologies suggest that the high frequency, interannual variability of these chronologies play an important role in the common signals found in the network. The correlation matrix of the residual chronologies showed four main regional groupings within the network. Geographically, these groupings separated into a) a northern group representing 7 sites along the Dempster Highway, b) a southern group comprised of 11 sites primarily found in southwestern Yukon, c) a south-central group involving 18 sites in both the central and southeastern Yukon, and d) a north-central group of 18 sites that included remote sites found in the Wernecke and Selwyn Mountain ranges. The correlation matrix also highlighted a sub-population of sites located around Kluane Lake in southwestern Yukon, which correlated well amongst themselves, but not with the rest of the network. The correlation matrix of the standard chronologies showed similar regional patterns to the residual chronologies, though not as cohesive and visually pronounced. This latter observation was especially noted in the central portion of the Yukon. Site inter-correlations over varying time periods, conducted to determine temporal stability of network relationships, indicated that the residual chronologies exhibited higher mean network correlations over all time intervals studied. Correlation results of the 1900-1949 time period were significantly greater (0.503 and 0.519 respectively) compared with the other time intervals (means 0.348 and 0.429) in both standard and residual chronologies. The subsequent low mean network correlations during the 1950-2004 time period suggest the possibility of 'divergence' within the chronologies of the network.

Results of the principal component analysis of the EPS1800 residual chronologies essentially verified the regional groupings identified in the earlier correlation analysis. Component loading scores quantitatively recognized the south-central and north-central regional groupings of sites, as well as the northern group along the Dempster Highway and the distinct grouping of the 'Kluane' sites in the southwestern Yukon. The PCA results also showed that several chronologies could have strong loadings on more than one principal component, revealing additional relationships within the network. While the correlation analysis of the residual chronologies showed a north-south differentiation within the central portion of the network, the PCA suggested that an east-west element was also identifiable. Sites located along the Yukon-NWT border in southeastern Yukon were identified in the PCA as loading separately from those in the south-central portion of the network, a distinction which the correlation analysis did not identify. Results of the standard chronology PCA clearly identified the regional groupings representing sites along the Dempster Highway, and those surrounding Kluane Lake, but the spatial patterns of the other principal components exhibited more variability than the residual chronology components. Examination of the temporal stability of the PCA results showed that the PC loadings of the residual chronologies exhibited greater consistency than the standard chronologies over the different time intervals studied. Noteworthy, the PCA results for the standard chronologies, during the 1900-1949 time interval, was highlighted by the domination of PC1 across a large portion of the network. This result, combined with the dramatic increase in inter-site correlations within the correlation analysis for the same time interval, indicates that a strong, shared common signal existed over much of the network in the past.

While PCA proved to be a powerful tool for analyzing data variance and quantitatively identifying groups of inter-correlated data, it was discovered that caution must be taken when considering its application as an interpretative tool. A comparison of the component time series produced by the PCA against the actual chronologies of those sites loading on the component indicated that the time series might not necessarily show the actual patterns represented in the chronologies. This is likely a result of the stepwise computational processes involved with PCA to maximize variance within the data. Each component produced by the PCA is constrained by the fact that it must be orthogonal from the previous ones. In order to establish records which truly represented the patterns of the site chronologies, comparisons were made between original ‘network’ PC time series, ‘regional’ PC time series (produced by PCA limited to only those sites which loaded on the specific component), and a ‘mean’ time series produced by averaging the chronologies of sites based on the PC groupings (rather than the PC scores themselves). Results indicated that the ‘mean’ time series provided the most representational record.

It is evident from the analyses conducted on the ring-width chronology network of this study that several distinct regional signals exist within the Yukon. Given the extensive spatial coverage of these chronologies and the varying physiographical landscape, this result is not surprising. While the residual chronologies showed greater temporal stability relative to the standard chronologies, in both the correlation and principal component analyses, each set of chronologies displayed these regional signals. These regional variations in the patterns of tree-ring growth may be a reflection of the physiographical landscape but it is important to also consider the effect that climate and its variability may have on the patterns of tree growth. In the next chapter, variations in climate and the associated growth responses will be investigated.

CHAPTER FOUR

Yukon Climate Data

4.1 Introduction

The major goal of this research is to examine tree-ring series from across the Yukon and their potential to reconstruct past climate variation within the Yukon. Relationships between tree growth and climate are therefore vital to this project. However, prior to examining these relationships, it is important to evaluate the quality and length of the available climate records from the Yukon. As this region has large differences in latitude, topography, and atmospheric circulation patterns, it is important to identify whether there are strong spatial differences and therefore regional variations in these data. This chapter examines the available temperature and precipitation records for the Yukon obtained from the Adjusted Historical Canadian Climate Database (AHCCD) and spatial variation of these data across the Yukon.

4.2 Climate Data

The climate of the Yukon and surrounding regions of northwestern North America is in large part a reflection of the interplay between Pacific maritime air masses and Polar arctic air masses (Ritchie, 1984). Two primary regional climates have been defined for Yukon, the continental subarctic climate and the arctic coastal climate (Ritchie, 1984). The sites of the white spruce chronologies used in this study all fall within the continental subarctic regional climate zone.

Instrumental climate records for the Yukon are relatively short and sparsely distributed (Table 4.1). Few climate records extend prior to 1945, the main exception being Dawson with a climate record extending back to 1898. This length reflects the timing of the Klondike gold rush and its effect on settlement patterns in the Yukon (Duerden, 1971). Most of the remaining climate records in the region begin during the mid-20th century, contemporaneously with the construction of the Alaska Highway through the Yukon in 1942-3, as well as the development of the DEW Line in the 1950s (Wahl *et al*., 1987).

Table 4.1 Long homogenized climate records for the Yukon stations in the Adjusted Historical Canadian Climate Database (AHCCD) version 2010. Canadian Climate Normals (*) 1971-2000 values were obtained from Environment Canada – National Climate Data & Information Archive. Climate normals marked (†) are calculated from AHCCD records for 1971-2000 or for the periods [a] 1967-1994, [b] 1945-1985, and [c] 1974-2000 . The record for Atlin, BC (‡) has no data between 1943-1974.

Site Name	Latitude (N)	Longitude (W)	Elevation (m)	Temperature (years)	Precipitation (years)	Clim. Normals * 1971-2000 (Temp.) °C	Climate Normals * 1971-2000 (Precip.) mm
Komakuk Beach	69.62	140.20	13	1959-2010	1959-1992	-11	161.3
Shingle Point	68.95	137.22	49	1958-2010	1959-1993	-9.9	253.9
Old Crow	67.57	139.83	251	1952-2008	1969-2002	-9.0	265.5
Klondike	64.45	138.22	960	n/a	1966-2003	n/a	479.2 †
Dawson	64.05	139.13	370	1898-2010	1902-2002	-4.4	324.4
Mayo	63.62	135.87	504	1925-2010	1925-2003	-3.1	312.9
Pelly Ranch	62.82	137.37	454	1955-2010	1955-2002	-3.9	310.3
Drury Creek	62.20	134.38	609	n/a	1970-2003	n/a	388.3 †
Carmacks	62.10	136.30	525	n/a	1964-2003	n/a	302.7 †
Ross River	61.98	132.45	698	n/a	1967-1994	n/a	274.4 † [a]
Burwash	61.37	139.05	807	1967-2008	1967-2002	-3.8	279.7
Tuchitua	60.93	129.22	724	n/a	1967-2003	n/a	505.6 †
Haines Junction	60.75	137.50	596	1945-2010	1945-1985	-2.4 †	306.0 † [b]
Whitehorse	60.72	135.07	706	1943-2010	1942-2003	-0.7	267.4
Johnsons Crossing	60.48	133.30	690	n/a	1964-1995	n/a	376.2
Teslin	60.17	132.75	705	1944-2010	1944-2002	-1.2	343.3
Watson Lake	60.12	128.82	690	1939-2010	1939-2003	-2.9	404.4
Swift River	60.00	131.18	891	n/a	1967-2003	n/a	556.2 †
Atlin (B.C.)	59.57	133.70	674	1910-2010 ‡	1910-2010 ‡	0.7 † [c]	369.8 † [c]

Temperature and precipitation data used in this study were obtained through the Adjusted Historical Canadian Climate Database (AHCCD) Version 2010 provided by the Climate Monitoring and Data Interpretation Division, Climate Research Branch, Meteorological Service of Canada. These data have been 'adjusted' or 'homogenized' so as to remove variations introduced by non-climatic factors such as changes in site location and exposure, instrumentation and measuring procedures (Metcalfe *et al*., 1997; Vincent, 1998; Mekis and Hogg, 1999; Vincent and Gullett, 1999). These data include monthly maximum, mean and minimum temperatures plus monthly total precipitation for climate stations. In total, eighteen climate stations in the Yukon have precipitation data, of which eleven also have temperature data available (Figure 4.1). Data for Atlin, British Columbia was also included as a supplementary site due to its proximity to the Yukon/BC border and its long record. Individual missing values within the AHCCD records were subsequently estimated by calculating the overall monthly mean value from remaining available data for that station.

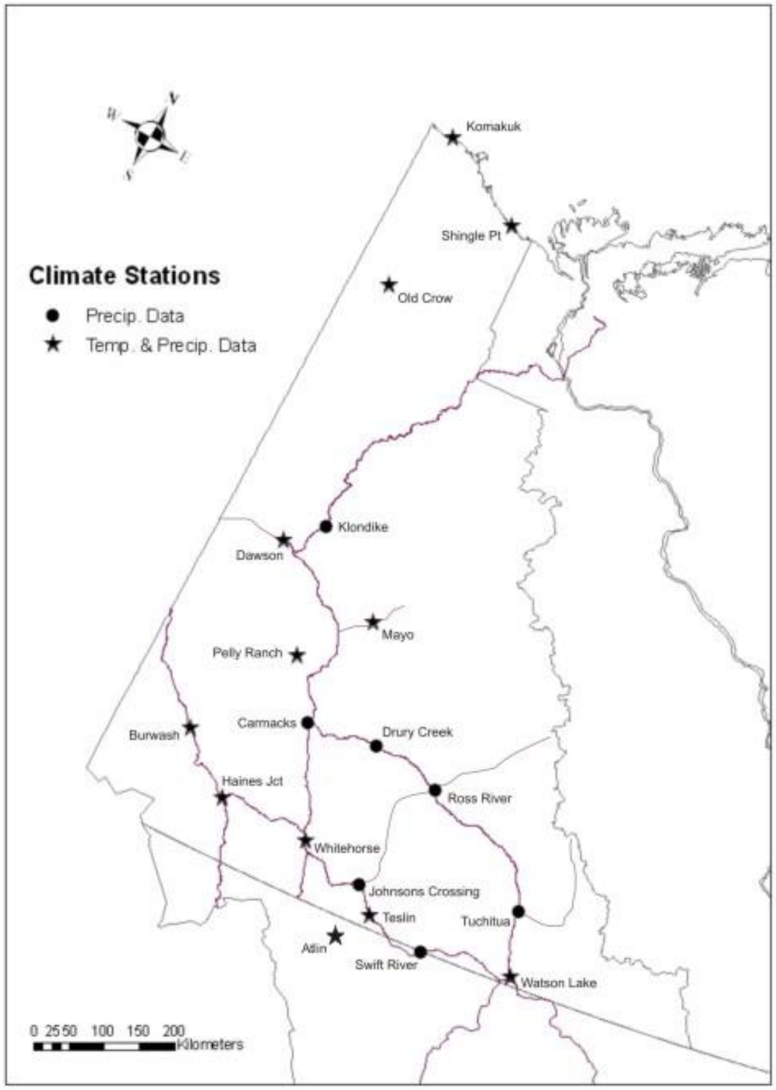


Figure 4.1 Map showing locations of the AHCCD climate stations in the Yukon and bordering area.

4.3 Analysis of the Temperature Data

Monthly maximum, mean and minimum temperature data for the available climate stations were extracted from the AHCCD. Annual and seasonal (e.g. summer, JJA) records were calculated from the monthly data for each of the temperature variables. These data were analyzed using correlation and principal component analyses to determine possible common patterns of variability within the data.

Results of the correlation analyses revealed several key observations regarding Yukon climate. Firstly, correlation matrices for each temperature variable (maximum, mean, minimum) indicated that most of the records were highly correlated with each other. Many dendroclimatological studies have reported a significant positive relationship between ring-width and summer temperatures for high-latitude areas (e.g. Briffa *et al*., 1990; Szeicz and MacDonald, 1995, D'Arrigo *et al*., 2006; Youngblut and Luckman, 2008) and therefore this period was elected for more detailed analysis. The correlation matrix of summer maximum temperatures for the Yukon (Table 4.2) shows numerous inter-site correlation values of 0.700 or greater. These strong correlations revealed a distinct separation of the Yukon temperature stations into two discernible groupings. The three most northern stations (Komakuk, Shingle Point and Old Crow) were strongly correlated but showed much weaker correlations with stations situated further south. The remaining eight temperature stations, located within the central and southern Yukon, formed a second (and more extensive) grouping of sites displaying high correlation values. Correlation analyses of the other temperature variables (mean, minimum and seasonal values) showed similar results, distinguishing the northern stations from those stations further south. Inter-site correlation values for summer minimum temperatures were lower than those found for other temperature variables, particularly amongst the southern stations (highest correlation within the southern group was between Whitehorse and Haines Junction (0.836)), however records were statistically significant at the 0.05 level.

Table 4.2 Inter-site correlations of summer maximum temperatures for Yukon climate stations. Correlation periods varied due to differences in length of record for each station (N). All correlations were statistically significant at the 0.01 level.

	Komakuk	ShinglePt	OldCrow	Dawson	Mayo	PellyRanch	Burwash	HainesJct	Whitehorse	Teslin	WatsonLk
Komakuk		.923	.811	.520	.611	.544	.518	.476	.494	.498	.557
ShinglePt	.923		.851	.534	.603	.576	.541	.515	.549	.556	.580
OldCrow	.811	.851		.620	.643	.630	.659	.589	.614	.602	.584
Dawson	.520	.534	.620		.925	.921	.811	.761	.748	.695	.589
Mayo	.611	.603	.643	.925		.957	.876	.820	.836	.785	.709
PellyRanch	.544	.576	.630	.921	.957		.886	.847	.876	.796	.718
Burwash	.518	.541	.659	.811	.876	.886		.890	.930	.828	.806
HainesJct	.476	.515	.589	.761	.820	.847	.890		.921	.881	.757
Whitehorse	.494	.549	.614	.748	.836	.876	.930	.921		.908	.841
Teslin	.498	.556	.602	.695	.785	.796	.828	.881	.908		.871
WatsonLk	.557	.580	.584	.589	.709	.718	.806	.757	.841	.871	
N	52	53	57	113	86	56	42	66	68	67	72

0.700-0.799   0.800-0.899   0.900-0.999

Results from principal component analyses (PCA) of the temperature data support division of climate stations into two groups. PCA loading scores for summer maximum temperatures showed that the stations situated in central and southern Yukon loaded strongest on the first principal component, while those stations located in the far north loaded on the second principal component (Table 4.3). PCA results for the other temperature variables displayed a similar loading pattern. Examination of the percentage variance explained by each component within the PCA results for maximum, mean and minimum summer temperatures indicates the strong similarities between these temperature records, though recording relatively weaker relationships exhibited within the summer minimum temperature record (Table 4.4).

Table 4.3 PCA loadings for summer maximum temperature. The common period of analysis was 1967-2008. Total variance explained by the first two PCs was 86.8% (PC1: 74.6%, PC2: 12.2%)

	Component	
	1	2
Whitehorse	.924	.281
HainesJct	.907	.258
Burwash	.898	.316
PellyRanch	.889	.313
Mayo	.884	.358
Teslin	.859	.303
Dawson	.831	.309
WatsonLk	.753	.406
Komakuk	.257	.931
ShinglePt	.303	.921
OldCrow	.408	.799

Table 4.4 Percent variance in PCA analyses for annual and summer temperature variables (common period of analysis 1967-2008). PC1 represents the central/southern climate group. PC2 represents the northern climate group.

	% Variance Explained		
	PC1	**PC2**	**Total**
Annual - Max Temp	77.2	14.2	91.4
Annual - Mean Temp	77.9	14.9	92.8
Annual - Min Temp	76.5	16.2	92.7
Summer - Max Temp	74.6	12.2	86.8
Summer - Mean Temp	77.9	11.6	89.5
Summer - Min Temp	69.6	11.9	81.5

These correlation and PCA results of the temperature data support the description made by Ritchie (1984) that there are two distinctly different climate regimes in the Yukon, the arctic coastal regime and the continental subarctic regime. Given that the network of tree-ring data used in this study is located primarily within the continental subarctic zone, further examination of the climate data will focus on the grouping of climate stations in the central and southern Yukon (i.e. Dawson, Mayo, Pelly Ranch, Burwash, Haines Junction, Whitehorse, Teslin, and Watson Lake).

An examination of the mean inter-site correlations between each of the stations in the central/southern grouping for each temperature variable showed that mean temperatures exhibited the strongest relationships for both annual and summer records, though maximum temperatures showed nearly similar results (Table 4.5). Mean inter-site correlations for minimum temperatures were lower, suggesting weaker relationships, especially in the case of summer temperatures. In all cases, the Whitehorse temperature records showed the strongest mean inter-site correlations with the other stations in the grouping, while the Watson Lake records consistently exhibited the weakest correlations. These results may reflect the position of these climate stations within the network. Whitehorse is situated centrally within the group of stations, while Watson Lake is found on the eastern margin. Detailed examination of the inter-site correlations (Table 4.2) shows that Watson Lake correlates most strongly with Teslin and Whitehorse, the two nearest stations, and weakest with Dawson, the most distant station. Whitehorse's strongest correlations were with neighbouring stations of Haines Junction, Burwash and Teslin, while weakest correlations were with the furthest stations Watson Lake and Dawson.

Table 4.5 Mean inter-site correlations of temperature variables between each climate station and all others within the central/southern Yukon group. Periods of analysis varied due to differences in length of each record (N). Dark grey highlighting marks the strongest mean correlation, light grey indicates the weakest correlation. The stations are ordered from north (l) to south (r).

	Dawson	Mayo	Pelly Ranch	Burwash	Haines Jct	Whitehorse	Teslin	Watson Lake	Average
Annual - Max Temp	0.8623	0.8959	0.8972	0.9012	0.8963	0.9249	0.8911	0.8485	0.8897
Annual - Mean Temp	0.8893	0.9169	0.9108	0.9230	0.9019	0.9362	0.8968	0.8558	0.9038
Annual - Min Temp	0.8755	0.8984	0.8911	0.8982	0.8647	0.9207	0.8708	0.8266	0.8808
Summer - Max Temp	0.7786	0.8440	0.8572	0.8609	0.8395	0.8656	0.8233	0.7558	0.8281
Summer - Mean Temp	0.7943	0.8253	0.8499	0.8579	0.8325	0.8611	0.8316	0.7741	0.8283
Summer - Min Temp	0.6828	0.6810	0.7043	0.6510	0.6612	0.7270	0.6304	0.6093	0.6684
N	113	86	56	42	66	68	67	72	

Closer examination of the correlation matrix for summer maximum temperatures (Table 4.6) shows an interesting pattern among the stations indicating two sub-populations that exhibit higher inter-site correlations. Dawson, Mayo and Pelly Ranch correlated strongly, defining a northern sub-population, while Burwash, Haines Junction, Whitehorse and Teslin formed a southern sub-population. Summer mean and minimum temperature correlations exhibited similar results, though inter-site correlations for minimum temperatures were slightly weaker (i.e. highest inter-site correlation of minimum temperatures was only 0.879 [Dawson-Mayo]). PCA results (common period

Table 4.6 Inter-site correlations of summer maximum temperature for the South and Central Yukon (data as for Table 4.2). Correlation periods varied due to the differences in length of records (N).

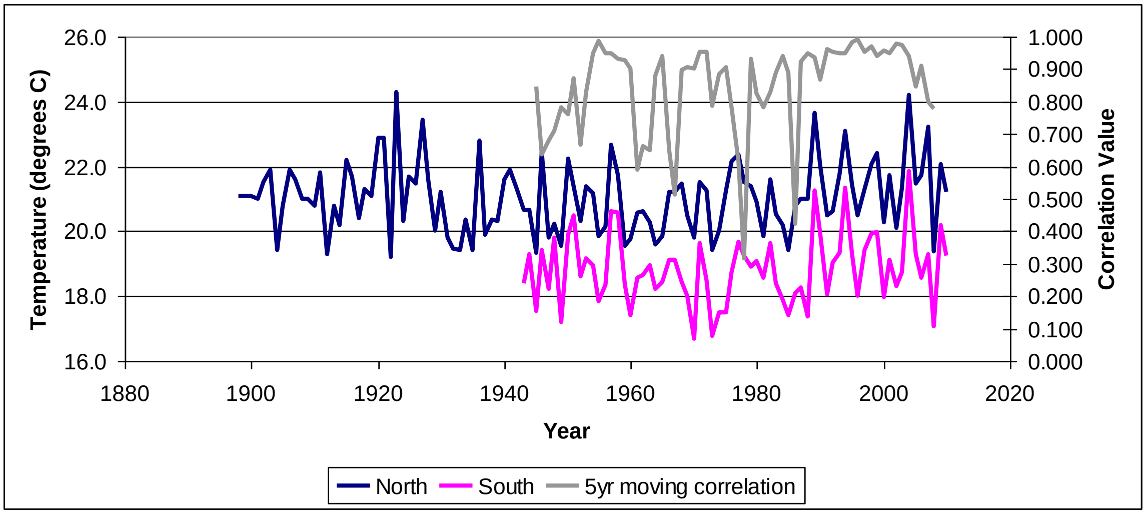
	Dawson	Mayo	PellyRanch	Burwash	HainesJct	Whitehorse	Teslin	WatsonLk
Dawson		.925	.921	.811	.761	.748	.695	.589
Mayo	.925		.957	.876	.820	.836	.785	.709
PellyRanch	.921	.957		.886	.847	.876	.796	.718
Burwash	.811	.876	.886		.890	.930	.828	.806
HainesJct	.761	.820	.847	.890		.921	.881	.757
Whitehorse	.748	.836	.876	.930	.921		.908	.841
Teslin	.695	.785	.796	.828	.881	.908		.871
WatsonLk	.589	.709	.718	.806	.757	.841	.871	
N	113	86	56	42	66	68	67	72
		0.700-0.799			0.800-0.899			0.900-0.999

1967-2000) of the stations did not differentiate between the sub-populations, as all of the stations loaded on a single principal component for all summer temperature variables.

The inter-site correlations of summer temperatures at Dawson also shows a north-south gradient (Table 4.6). As Dawson provides the longest continuous climate record within the Yukon, its relationship with other stations is of interest when possibly testing changes in the climate signal in the tree-ring chronologies over the 20th century. This pattern may represent a latitudinal difference found within the summer temperatures of the Yukon.

Time series plots of the temperature records indicated differences in summer temperatures between the climate stations. The northern stations exhibit summer temperatures that are a 1-2ºC warmer than stations located further south. Based on the composition of the sub-population groupings of Table 4.6, two composite temperature series (a 'northern' series and a 'southern' series) were developed for comparison of the temperature variables. These composite series were created by standardizing the individual temperature records (converting to z-scores) and averaging the records of those stations within each sub-population. These z-scores were converted back to original units using the mean and standard deviation of the average series (Jones and Hulme, 1996). The time series plot for summer maximum temperatures clearly shows a difference in absolute temperature values of approximately 2 ºC between the northern and southern sub-populations (Figure 4.2a). A 5-year moving window was used to examine changes in correlations between the two sub-populations. While there are a few periods of low correlations, much of the record showed strong correlations (0.800 or greater) between the two sub-populations (e.g. post-1990). Periods in the record marked by considerably reduced correlation included: 1961-63, 1967, 1978 and 1986.

(a)



(b)

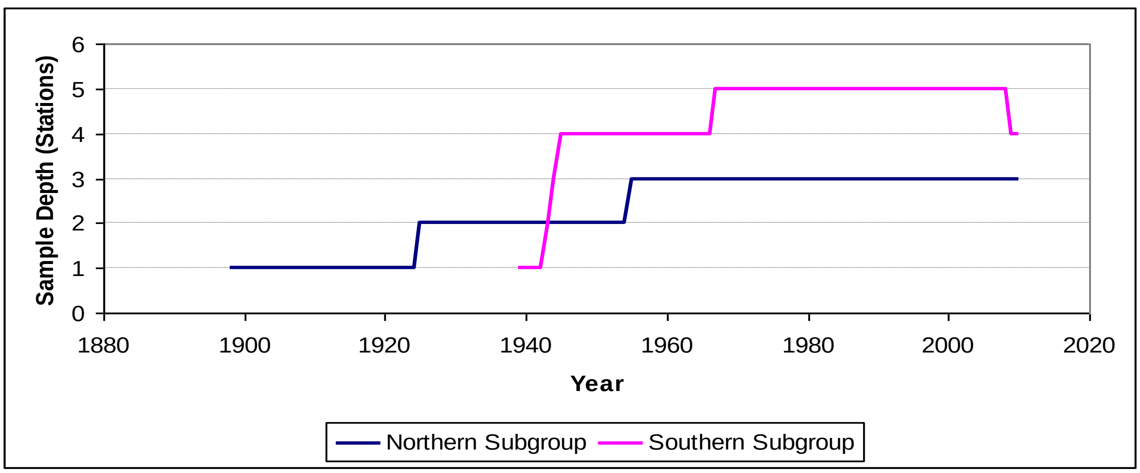
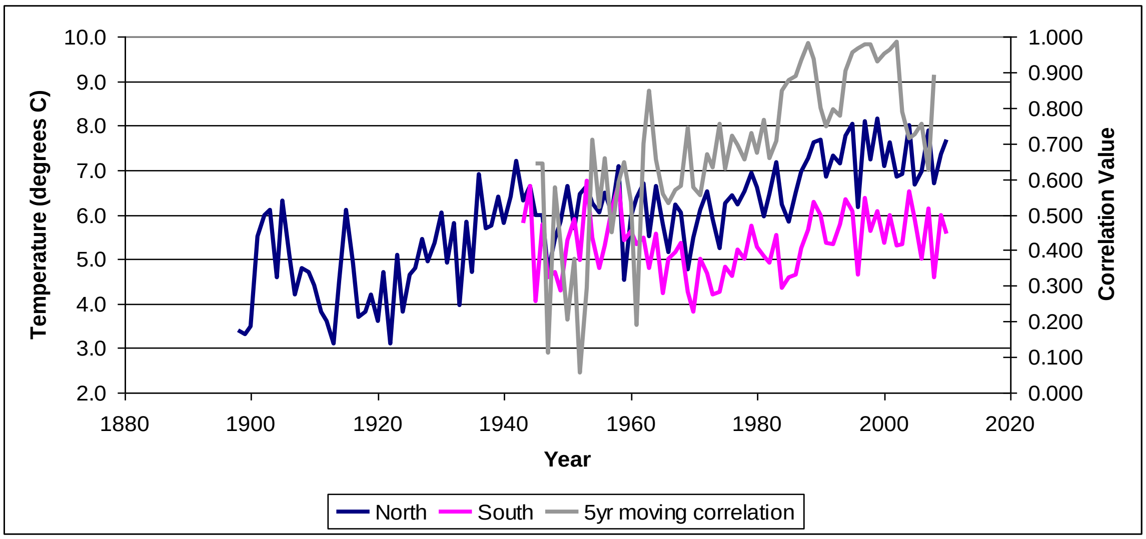


Figure 4.2 Regional summer maximum temperature records. (a) Time series plots with a 5-year moving window to show changes in correlations over time. (b) Number of stations in each sub-population.

Examination of the time series plot for summer minimum temperatures (Figure 4.3a) indicates that the northern and southern sub-populations had relatively similar absolute values prior to ca. 1960, but that the northern sites warmed more and at a greater rate thereafter. While summer minimum temperatures for the southern sub-population remained relatively stable (with individual cold years in the early 1970s and late 1980s), minimum temperatures of the northern sub-population showed a progressive rise. Difference between these two regional records over time is shown in Figure 4.3b.

(a)



(b)

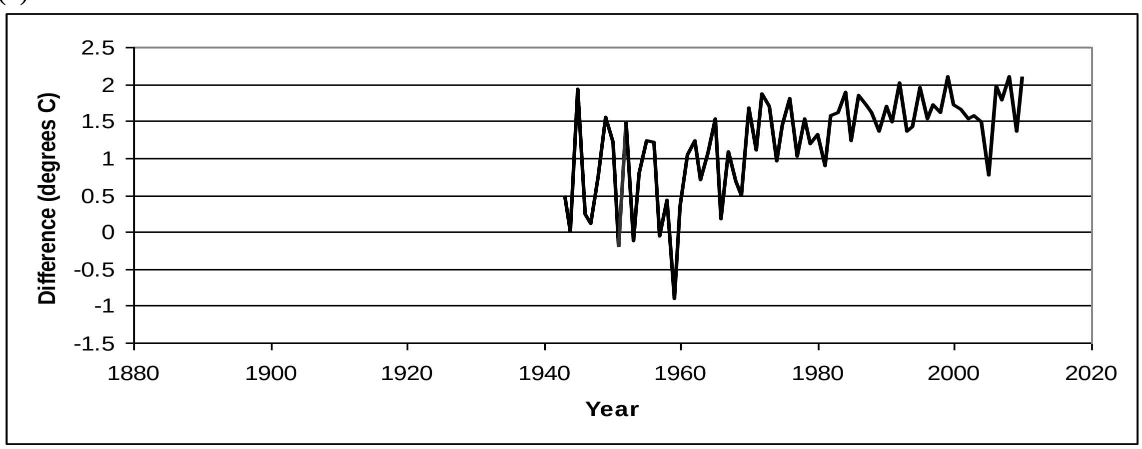


Figure 4.3 Regional summer minimum temperature series. (a) Time series plots. A 5-year moving window was used to show changes in correlations over time. (b) Difference (north-south) between the two records highlighting the relative increase in summer minimum temperature for the northern sites compared to the relatively stable trend of the southern sub-population.

PCA analysis of these seven stations over the 1955-1961 period (the Burwash record does not cover this period) identified two separate principal components corresponding to the two sub-populations observed in the correlation matrix.

Based on the PCA and correlation analyses of the temperature data from the climate stations of the Yukon, it is evident that there are differences in the temperature records between these stations. The far north stations are representational of an arctic coastal climate regime (as defined by Ritchie (1984)). Further south, data from the temperature stations represent a continental subarctic climate regime (Ritchie, 1984). Analyses of the southern data suggest that two sub-populations exist within this subarctic regime. The distinguishing factor which appears to differentiate these two sub-populations lies within their summer temperature records. Stations located in the southern Yukon (i.e. Burwash, Haines Junction, Whitehorse and Teslin) have records that indicate relatively stable summer minimum temperatures over the lengths of their records, while stations in the central portion of the Yukon (i.e. Dawson, Mayo and Pelly Ranch) show increasing summer minimum temperatures over time. It is apparent that within the Yukon subarctic, summer minimum temperatures do not vary consistently. In addition, maximum temperatures of the northern stations are generally 1-2ºC higher than the southern stations. Given the results from the analyses of the temperature data, subsequent investigations into the climate-growth relationships with Yukon tree-ring records will use climate records representing the two sub-populations detected in the temperature data. These two regional records are 1898-2010 for the northern group of stations and 1939-2010 for the southern stations.

4.4 Analyses of Precipitation Climate Data

4.4.1 Annual Precipitation

Monthly precipitation data available for 18 climate stations in the Yukon (Table 4.1) were extracted from the AHCCD, and annual total precipitation records were developed. Using correlation and principal component analyses, these data were analyzed for possible common patterns of variability.

Mean annual total precipitation for the 18 stations was 357.7mm, ranging from 176.0 mm at Komakuk on the Arctic Ocean coast to 566.9 mm at Swift River near the Yukon-British Columbia border. Examination of the monthly distribution of precipitation for these stations shows a marked summer maximum, with much drier winter and spring seasons (Figure 4.4). Maximum precipitation occurs in July (Table 4.7) at the majority of stations (12/18). The most northern sites (Komakuk Beach, Shingle Point and Old Crow) exhibited peaks later in August. Three southern sites showed slight differences from the regional pattern, Swift River (September), Haines Junction (October) and Klondike (August) exhibited maxima that were slightly greater than July. Wahl *et al.* (1987) noted that the sites with fall maxima may rely on fall cyclonic activity, just as much as summer convection processes, for precipitation.

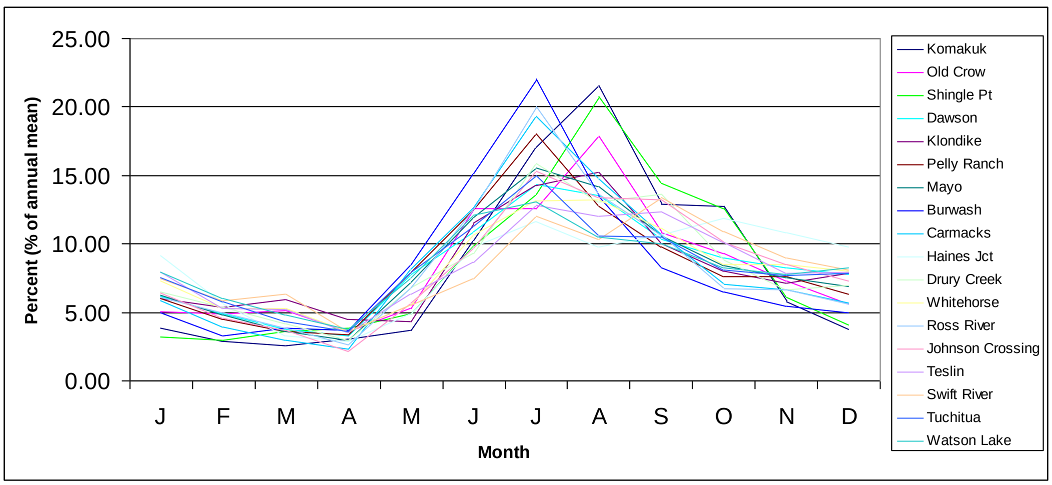


Figure 4.4 Mean monthly total precipitation (as a percentage of annual mean) for climate stations in the Yukon.

Table 4.7 Mean monthly distribution of total precipitation (data as for Figure 4.4). Values are given as a percentage of annual mean. Grey highlights indicate maximum values.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Komakuk	3.83	2.89	2.55	3.06	3.71	10.25	17.04	21.58	12.91	12.70	5.73	3.76
Old Crow	5.08	4.88	5.14	3.60	5.25	12.56	12.62	17.83	10.83	9.31	7.31	5.59
Shingle Pt	3.20	2.96	3.63	3.88	4.87	9.85	13.64	20.79	14.43	12.57	6.11	4.07
Dawson	6.18	4.89	3.76	3.30	7.77	10.89	14.33	13.56	10.37	8.96	8.25	7.76
Klondike	5.98	5.35	5.91	4.48	4.34	11.51	14.26	15.24	10.01	8.00	7.09	7.82
Pelly Ranch	6.02	4.48	3.57	3.34	7.92	12.52	18.03	12.75	9.80	7.59	7.64	6.33
Mayo	6.28	4.78	3.62	2.98	7.24	11.93	15.51	14.17	10.62	8.42	7.54	6.93
Burwash	4.99	3.31	3.83	3.65	8.46	15.11	22.05	13.45	8.26	6.46	5.44	4.99
Carmacks	5.86	3.94	2.95	2.30	8.19	12.68	19.27	14.76	10.62	7.09	6.63	5.71
Haines Jct	9.17	5.58	3.28	2.90	4.88	9.75	11.65	9.74	10.62	11.83	10.81	9.79
Drury Creek	6.49	5.34	4.16	2.97	6.80	9.28	15.90	13.07	13.62	8.79	6.63	6.94
Whitehorse	7.26	5.26	5.31	3.58	5.53	10.62	13.18	13.17	11.10	8.48	8.50	8.00
Ross River	6.06	4.99	3.84	2.64	6.79	12.50	20.01	13.59	10.65	6.70	6.65	5.58
Johnson Crossing	6.41	4.59	3.65	2.17	5.73	9.69	15.27	13.39	13.22	10.11	8.46	7.30
Teslin	7.91	5.33	5.22	3.50	6.34	8.65	12.85	12.03	12.30	10.06	7.89	7.92
Swift River	7.47	5.81	6.36	3.64	5.51	7.42	12.01	10.35	13.40	10.93	8.99	8.11
Tuchitua	7.52	5.77	4.30	3.57	7.89	11.32	14.96	10.54	10.54	8.05	7.69	7.84
Watson Lake	7.93	5.97	4.82	3.79	7.56	12.08	13.08	10.46	10.03	8.25	7.74	8.27

Time series plots of total precipitation for the individual stations highlight the interannual variability inherent in these records. The mean of these records suggest intermittent dry periods during the 1930s and 40s and particularly in the 1950s, followed by a short period of increased precipitation during the early 1960s, before a return to more stable conditions from the mid 1960s through to the late 1980s (Figure 4.5). Station records were marked by individual years of peak precipitation (e.g. 1991 and 2000) as well as significant drier years (e.g. 1969, 1989 and 1998). On a seasonal basis, time series of summer (June-August) total precipitation (not shown) indicated increased moisture in the early 1960s, followed by distinctly drier summers during the mid-1960s and early 1970s. The summers of 1989, 1998 and 2004 recorded quite low precipitation values. Time series of autumn (September-November) total precipitation (not shown), the next greatest seasonal distribution of moisture in the Yukon, was highlighted by periods of increased precipitation during the early 1970s and early 1990s.

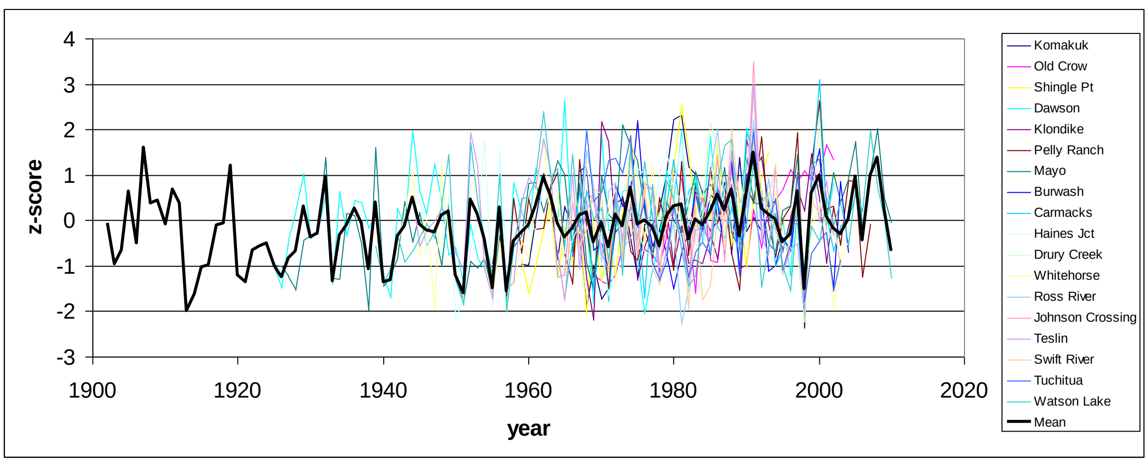


Figure 4.5 Time series plots of total annual precipitation for Yukon climate stations. Values were standardized by converting to z-scores.

Correlation analyses of the annual precipitation records suggested three possible regional groupings within the Yukon (Table 4.8). Stations in the south-east Yukon (Drury Creek, Whitehorse, Ross River, Johnson Crossing, Teslin, Swift River, Tuchitua and Watson Lake) exhibited strong positive correlations with each other, with a mean inter-site correlation of 0.537. In the central Yukon, a second grouping included Dawson, Klondike, Pelly Ranch, Mayo, Burwash and Carmacks. Mean inter-site correlation of these stations was 0.389. Relative proximity between stations appeared to be a factor in the strength of these correlations. Stations located in the far north (Komakuk, Old Crow and Shingle Point) correlated with each other but much more weakly with the rest of the stations across the Yukon. Haines Junction showed few significant relationships with other records, possibly reflecting its proximity to the St. Elias Mountains and the influence of a rain shadow.

Table 4.8 Correlations of annual precipitation between Yukon climate stations. Correlation periods varied due to differences in length of records (N).

	Komakuk	OldCrow	ShinglePt	Dawson	Klondike	PellyRanch	Mayo	Burwash	Carmacks	HainesJct	DruryCk	Whitehorse	RossRiver	JohnsonCr	Teslin	SwiftRiver	Tuchitua	WatsonLk
Komakuk		.354	.697	-.018	-.215	.080	-.004	-.462	.215	.225	-.195	-.114	-.421	.017	-.051	.027	-.483	-.115
OldCrow	.354		.392	-.041	.076	.116	.042	-.132	.134	.416	-.049	-.071	-.169	.199	.088	.204	-.077	.188
ShinglePt	.697	.392		-.206	-.172	.100	-.109	-.388	.048	.285	-.078	.012	-.237	.118	-.151	-.082	-.403	-.307
Dawson	-.018	-.041	-.206		.563	.416	.489	.300	.241	-.019	.408	.145	-.094	-.179	.115	.296	.379	.185
Klondike	-.215	.076	-.172	.563		.224	.331	.108	.183	-.430	.077	-.015	-.037	.071	.109	.263	.155	.059
PellyRanch	.080	.116	.100	.416	.224		.617	.478	.532	.241	.424	.116	-.121	.018	.044	.134	.055	-.014
Mayo	-.004	.042	-.109	.489	.331	.617		.488	.341	.179	.336	.212	-.133	-.243	.113	.080	.191	.278
Burwash	-.462	-.132	-.388	.300	.108	.478	.488		.517	.168	.516	.518	.276	.339	.368	.174	.369	.252
Carmacks	.215	.134	.048	.241	.183	.532	.341	.517		.280	.668	.464	.108	.411	.316	.260	.097	.054
HainesJct	.225	.416	.285	-.019	-.430	.241	.179	.168	.280		.076	.348	-.140	.311	.227	.256	-.224	.439
DruryCk	-.195	-.049	-.078	.408	.077	.424	.336	.516	.668	.076		.587	.593	.558	.488	.309	.321	.242
Whitehorse	-.114	-.071	.012	.145	-.015	.116	.212	.518	.464	.348	.587		.563	.720	.640	.437	.636	.515
RossRiver	-.421	-.169	-.237	-.094	-.037	-.121	-.133	.276	.108	-.140	.593	.563		.520	.536	.223	.528	.372
JohnsonCr	.017	.199	.118	-.179	.071	.018	-.243	.339	.411	.311	.558	.720	.520		.846	.608	.414	.507
Teslin	-.051	.088	-.151	.115	.109	.044	.113	.368	.316	.227	.488	.640	.536	.846		.688	.534	.710
SwiftRiver	.027	.204	-.082	.296	.263	.134	.080	.174	.260	.256	.309	.437	.223	.608	.688		.529	.581
Tuchitua	-.483	-.077	-.403	.379	.155	.055	.191	.369	.097	-.224	.321	.636	.528	.414	.534	.529		.498
WatsonLk	-.115	.188	-.307	.185	.059	-.014	.278	.252	.054	.439	.242	.515	.372	.507	.710	.581	.498	
N	34	34	34	101	38	53	86	38	42	41	34	63	29	32	59	37	37	72
Significance			negative			positive			positive									
			95% level			95% level			99% level									

Correlation analysis of summer (June-August) total precipitation (not shown) showed a similar pattern to the annual records. While exhibiting the three regional groups previously mentioned, values among the south-east Yukon grouping showed slightly weaker correlations during the summer season. Mean inter-site correlation dropped to 0.495. Correlations between the three far north stations were stronger for the summer period, all recording positive correlations significant at the p=0.01 level.

Principal component analysis was initially conducted using the precipitation records from all 18 climate stations over the 1970-1985 common period. Results indicated the data loaded on six principal components which explained 83.4% of the total variance (Table 4.9). The three far north stations loaded together on PC2, while the stations of the south-east and central Yukon (identified in the correlation analyses) were spread over several components. The south-east Yukon stations loaded primarily on PC1 and PC4, appearing to separate based on latitudinal location. Central Yukon stations loaded across PC3, PC5 and PC6. Several stations showed anomalous patterns, for example, Haines

Junction loaded on PC2 with the three far north stations. Again, this may reflect the potential influence of a rain shadow effect leading to its loading with drier, northern stations. Ross River loads most strongly on PC2 but negatively – the next highest and positive loading is on PC4, grouping this record with similar sites in the central Yukon. Tuchitua, situated in the south-east Yukon, loaded most strongly on PC3 though it exhibited a relatively high score on PC1 which would link it with similar south-east stations.

Table 4.9 PCA loadings of annual precipitation for all Yukon climate stations over the 1970-1985 period. Shading indicates highest positive loadings on each component.

	Component					
	1	2	3	4	5	6
Teslin	.912	-.164	-.024	.160	.012	-.109
JohnsonCr	.847	.109	-.207	.189	-.215	.188
WatsonLk	.839	.039	.052	-.080	.105	-.293
SwiftRiver	.771	.227	.432	-.053	.057	.058
ShinglePt	-.088	.786	-.277	-.015	-.307	.081
RossRiver	.268	-.775	-.140	.310	.069	-.148
OldCrow	.329	.739	.144	.220	.058	-.377
Komakuk	.039	.735	-.157	.174	-.392	.280
HainesJct	.201	.691	-.313	.109	.148	.058
Dawson	-.023	.011	.886	.299	.181	.246
Klondike	.030	-.361	.808	-.216	-.184	-.100
Tuchitua	.442	-.278	.576	-.184	.253	-.285
Carmacks	.067	.269	-.053	.798	-.141	-.006
DruryCk	-.009	-.159	.060	.767	.266	.154
Burwash	.110	-.211	-.357	.144	.842	.143
Mayo	-.091	-.046	.375	.042	.803	.013
PellyRanch	-.023	.138	.050	.153	.160	.927
Whitehorse	.358	-.061	-.019	.586	.139	-.612
%Variance	23.0	21.0	12.6	11.7	7.9	7.2

The common period of analysis was extended to 1967-1995 by removing the records for Drury Creek (start date 1970) and Haines Junction (end date 1985) and the three stations in the far north. The revised PCA (29 years) identified four main components, explaining 76.2% of the total variance (Table 4.10). The loading indicates a more geographically cohesive pattern with the seven stations in the southeast Yukon (south of 62ºN and east of 135ºW) loading on PC1. Dawson, Klondike and Mayo loaded highest on PC2 forming a central-northern regional grouping. Carmacks and Pelly Ranch, located in the central Yukon, load most strongly on PC4 whereas Burwash is the only chronology loading most strongly on PC3, possibly suggesting a unique pattern. Figure 4.6 displays plots of each of the principal components along with their member station records.

Table 4.10 PCA loadings for annual total precipitation for selected Yukon climate stations (1967-1995). Shading indicates highest positive loadings on each component.

	Component			
	1	2	3	4
Teslin	.935	-.025	-.024	.067
JohnsonCr	.832	-.105	.039	.366
WatsonLk	.772	.079	-.013	-.191
Whitehorse	.769	-.079	.235	.305
SwiftRiver	.760	.332	-.313	.093
Tuchitua	.692	.363	.323	-.322
RossRiver	.645	-.222	.396	-.086
Dawson	-.021	.872	.176	.257
Klondike	.193	.833	-.158	.045
Mayo	-.210	.605	.563	.026
Burwash	.270	.038	.791	.288
Carmacks	.185	.211	.138	.837
PellyRanch	-.274	.418	.367	.495
%Variance	34.6	18.1	12.1	11.4

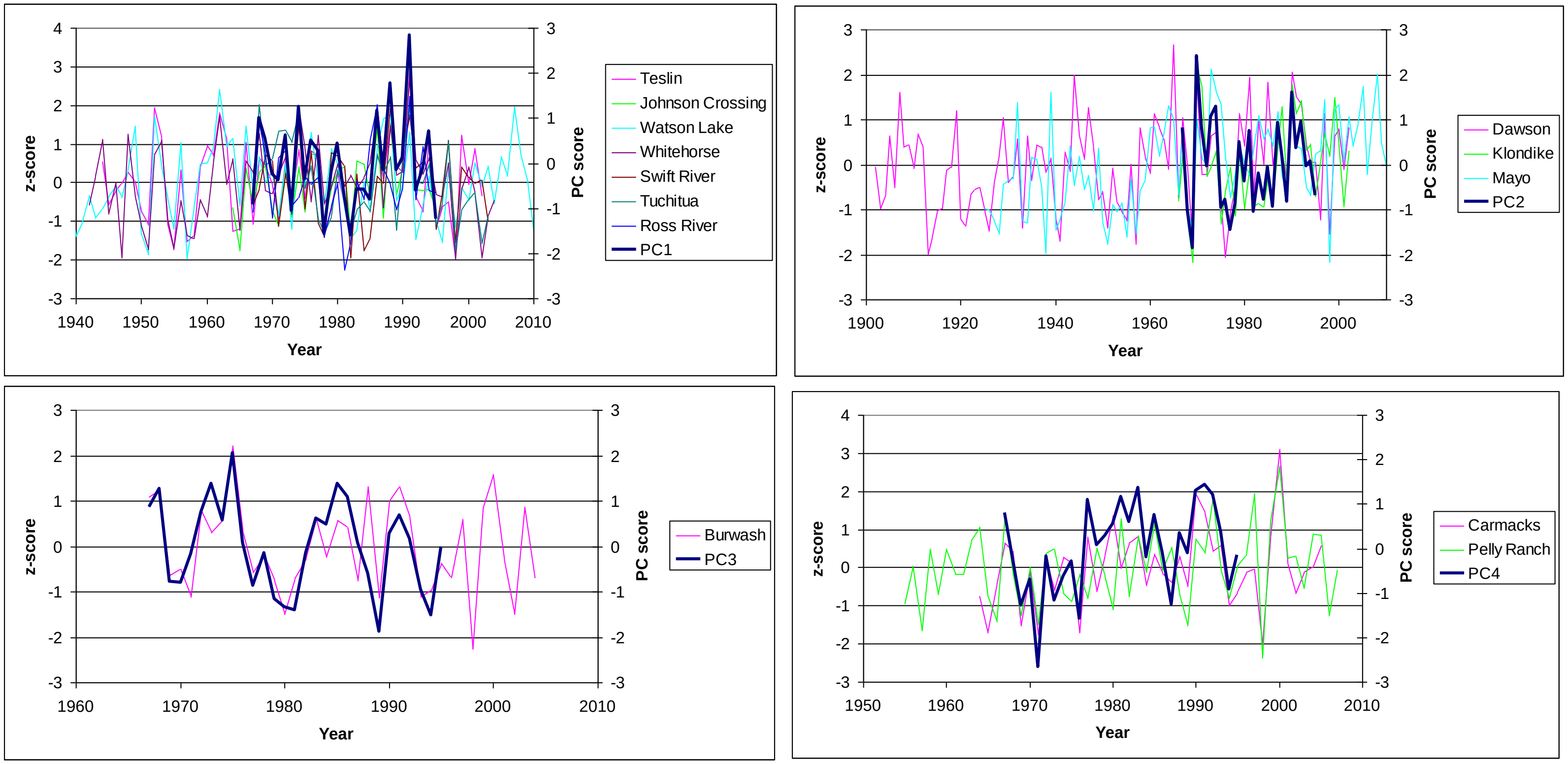


Figure 4.6 Time series plots of principal components and annual precipitation records for the Yukon. PC1 (upper left) represents southeast Yukon grouping. PC2 (upper right) represents northern Yukon grouping. PC3 (lower left) represents southwest Yukon (i.e. Burwash) grouping. PC4 (lower right) represents central Yukon grouping.

Time series plots of these four principal components demonstrated the variability between these regional series (Figure 4.7). PC1 and PC2 express over 52% of the total variance of the data, showed opposing patterns especially during the early portions of their records (i.e. 1967-77). PC2 showed a distinct increase in 1970 which was not evident in any of the other series. PC3, representing mainly the Burwash record, demonstrated noticeable dissimilarities from the other components in 1975 and 1979-82 PC4 showed a period of relatively suppressed precipitation during the first half of the 1970s followed by an increase post-1976 lasting until 1987. Not until ca. 1989 do all four component series appear to show similar trends, with increased precipitation during the early 1990s followed by general declines (PC1 showed a slight rise in 1993-94 but continued to decline in 1995).

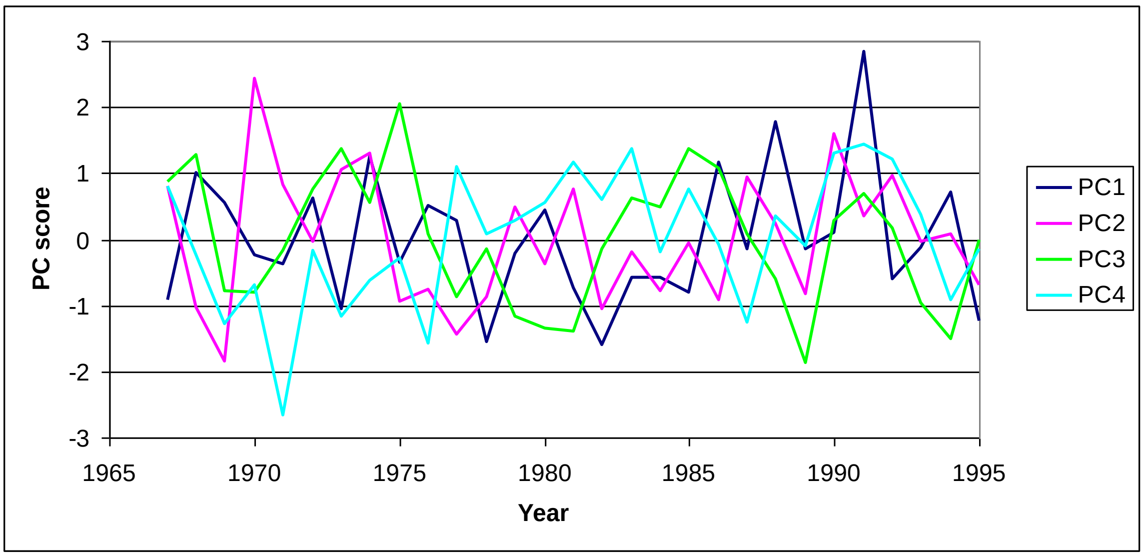


Figure 4.7 Time series plot of annual precipitation principal components resulting from PCA of selected Yukon climate stations (common period 1967-1995).

Based on the isolated loading result of Burwash in this PCA and the variations between the PC3 (Burwash) time series and the other principal components, additional examination of the Burwash record was conducted. Given its location on the lee-side of the St. Elias and Wrangell Mountain Ranges in southwestern Yukon and southeastern Alaska, the precipitation record of the Burwash station may be influenced by a rain shadow effect. There is a relatively long, though incomplete precipitation record for Atlin (located in northern British Columbia) in the lee of the mountains and approximately 350 and 250 km southeast of Burwash and Haines Junction, respectively. Its climate record extends from 1910 to 2010 with a gap of 30 years between 1944 and 1973. The early part of this record is the only replicate for the early Dawson record (1902-2002). Correlations involving Burwash, Dawson, Atlin1910 (1910-1943) and Atlin1974 (1974-2010) indicated that Burwash correlates much better with Dawson (0.300) and Atlin1974 (0.219) total annual precipitation records than with the closest station at Haines Junction (0.168). During the summer season though, when stations receive the greatest percentage of precipitation (see Figure 4.4), Burwash correlates highest with Haines Junction (0.421) followed by Atlin1974 (0.275), compared to Dawson (0.144). It is quite possible that the Burwash record is affected by a rain shadow effect caused by the St. Elias and Wrangell Mountains, similar to conditions experienced by Haines Junction and Atlin. With respect to the early period (1910-1943) shared by the Dawson and early Atlin records, annual precipitation correlated better (0.141) than summer precipitation (-0.111), though both relationships were quite weak.

4.4.2 **Summer Precipitation**

PCA involving summer (June-August) season precipitation for the 29 year long data subset identified three principal components, explaining 70.5% of the total variance within the data (Table 4.11). Loading scores indicated more cohesive regional groupings. Summer PC1 comprised stations representing the southern Yukon and is similar to PC1 from the annual data. Summer PC2 included stations located in the central Yukon (PC4 of the annual PCA), plus Mayo and Burwash. Summer PC3 consisted of Dawson and Klondike plus Tuchitua, which loaded on PC1 in annual PCA. While loading highest alongside the two northern stations, Tuchitua also showed a strong loading score on summer PC1 which would associate it with similarly located stations in the southern Yukon. Figure 4.8 shows each of the summer season principal components plotted along with their member station records.

Table 4.11 PCA loadings of June-August precipitation for selected Yukon climate stations (common period 1967-1995). Shading indicates highest positive loadings on each component.

	Component		
	1	2	3
Teslin	.889	.051	-.030
JohnsonCr	.863	.203	.034
WatsonLk	.831	-.197	-.081
SwiftRiver	.776	.100	.266
Whitehorse	.710	.190	-.269
RossRiver	.693	.014	-.075
PellyRanch	-.149	.846	-.063
Mayo	-.035	.753	.181
Carmacks	.267	.714	.202
Burwash	.540	.670	.038
Dawson	-.195	.209	.873
Klondike	-.071	.138	.827
Tuchitua	.586	-.104	.669
%Variance	35.3	18.8	16.4

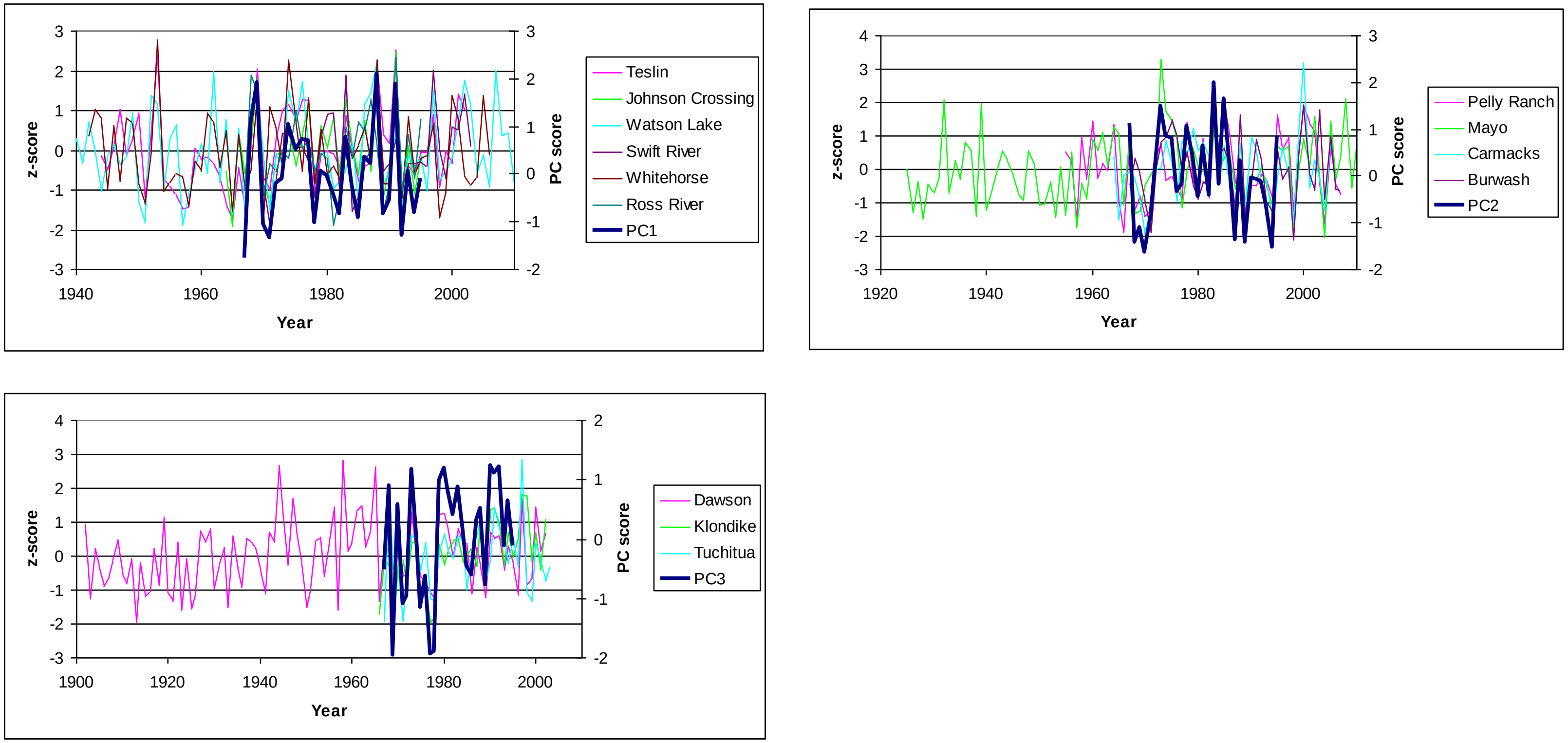


Figure 4.8 Time series plots of principal components and summer (June-August) precipitation records. PC1 (upper left) represents southern Yukon grouping. PC2 (upper right) represents central Yukon grouping. PC3 (lower left) represents northern Yukon grouping.

As with the annual precipitation principal components, the time series plots of summer season principal components are characterized by considerable variability over time (Figure 4.9). While the three PCs may show some limited agreement during certain periods (e.g. early 1970s) or years (e.g. 1983 and 1989), these series primarily highlight the regional differences in summer precipitation trends found in the Yukon.

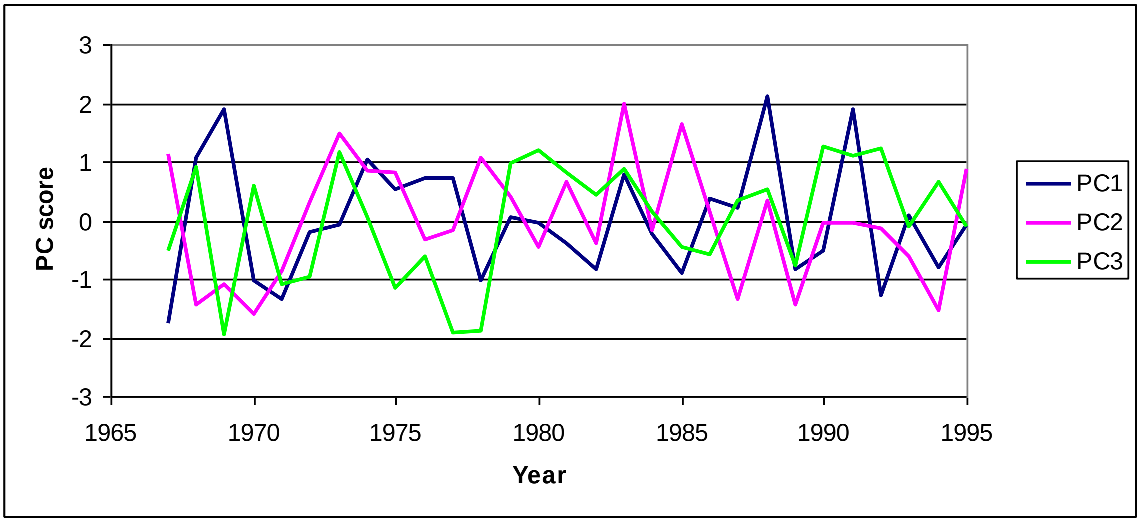


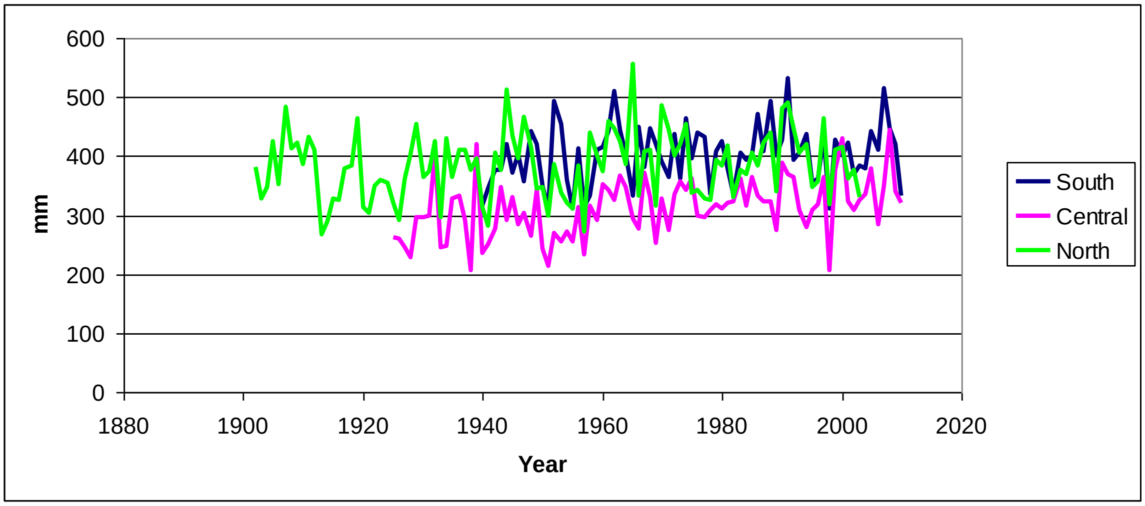
Figure 4.9 Time series plot of principal components of summer (June-August) precipitation of selected Yukon climate stations (common period 1967-1995).

As the largest proportion of annual precipitation occurs during summer months (see Figure 4.4), the PCA results for the summer precipitation records were used to guide the development of the regional precipitation series representing the Yukon. Based on the summer precipitation PCA, three regional series were constructed corresponding to the 'southern' Yukon (sites loading on PC1), the 'central' Yukon (sites loading on PC2), and the 'northern' Yukon (sites loading on PC3). Similar to the regional temperature series constructed previously, regional precipitation series were developed by standardizing (z-scores) the individual precipitation records, averaging together those records in each regional group, and then transforming each averaged series to original units (Jones and Hulme, 1996).

Total annual precipitation varied between the three regional series, with the 'central' series consistently showing lower amounts (Figure 4.10a). Mean value for the 'central' series was 311.7 mm, compared to 384.1 mm for the 'northern' series and 402.2

mm for the ‘southern’ series. On a seasonal basis, the differences between the ‘central’ series and the other two regional series were most apparent during autumn and winter (Table 4.12). Standardizing each series into z-scores to remove these differences in absolute amounts produced regional series that highlighted trends over time (Figure 4.10b). Throughout the 1940s and 1950s, precipitation values showed an overall decrease followed by a sharp recovery in the early 1960s. During the 1970s and 1980s, series exhibited relatively little trend (though the ‘northern’ and ‘southern’ series did experience drier years in 1978 and 1982). All three regional series showed a rise in precipitation culminating in peak values in 1990-91. Values declined sharply through the 1990s, reaching a low in 1998 before rebounding during the early 2000s. While these standardized series displayed some general shared trends over time, each record possesses distinct periods or individual years that differentiated them. For example, the ‘northern’ series exhibited greater precipitation during the mid- to late-1940s relative to the other two regional series. Similarly, the ‘northern’ series show a dramatic peak in 1965, while both the ‘central’ and ‘southern’ series recorded large reductions in precipitation that year (Figure 4.10).

a)



b)

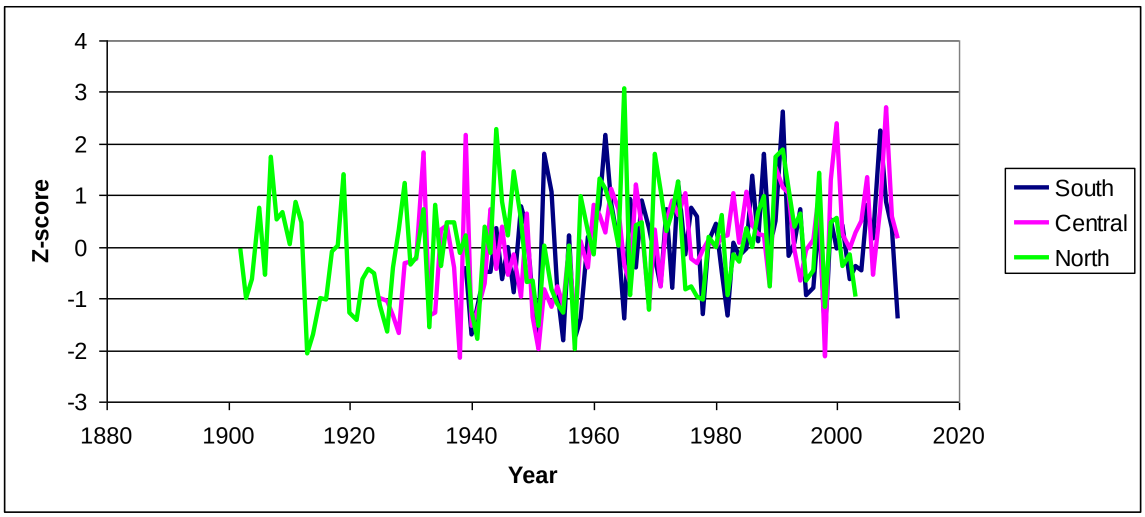


Figure 4.10 Time series plots of regional annual precipitation series for the Yukon, groupings based on PCA of summer precipitation 1967-1995. Precipitation series shown as (a) absolute amounts indicate 'central' series is drier. Annual precipitation series standardized as (b) z-scores highlight trends over time that are more similar.

Table 4.12 Mean total precipitation values (in mm) of the three regional time series records, separated into seasons.

	Annual	Spring	Summer	Autumn	Winter
Southeast	402.2	61.8	143.4	112.5	84.4
North	384.1	58.0	151.8	101.7	72.4
South	311.7	44.6	140.1	76.9	50.1

4.5 Relationship between Temperature and Precipitation

From the analyses in this chapter, it is evident that both temperature and precipitation within the Yukon vary both spatially and temporally. Correlations between temperature and precipitation records were calculated for those climate stations (except the far north sites) with data for both variables. Data for Atlin, B.C. were also included due to its long record (1910-1942, 1974-2010). As almost half the yearly precipitation occurs in June, July and August (Figure 4.4), which also corresponds to the general growing season for trees at higher northern latitudes, focus was placed on studying correlations for summer months. Results of the correlation calculations are shown in Table 4.13.

Table 4.13 Correlations between temperature and precipitation records for Yukon climate stations (plus Atlin, B.C. – early & late records). Positive correlations are in orange, negative correlations in black. Values in bold are statistically significant at the 95% level. Correlations for individual summer months were calculated, along with seasonal summer (June-August) and winter (December-February) for comparisons.

	Dawson	Mayo	PellyRanch	Burwash	HainesJct	Whitehorse	Teslin	WatsonLk	Atlin	Atlin
	1902-2002	1925-2010	1955-2007	1967-2007	1945-1985	1943-2004	1944-2002	1939-2010	1910-1943	1974-2010
JunMaxT_JunPrecip	**-0.507**	**-0.424**	**-0.373**	**-0.367**	**-0.331**	**-0.277**	**-0.343**	**-0.544**	-0.134	-0.210
JunMeanT_JunPrecip	**-0.370**	**-0.326**	-0.200	-0.290	-0.248	-0.215	-0.235	**-0.405**	-0.075	-0.177
JunMinT_JunPrecip	-0.102	-0.122	0.100	-0.049	-0.092	-0.087	-0.006	-0.136	0.028	-0.073
JulMaxT_JulPrecip	**-0.407**	**-0.467**	**-0.549**	**-0.625**	**-0.367**	**-0.474**	**-0.574**	**-0.479**	-0.105	**-0.382**
JulMeanT_JulPrecip	-0.110	**-0.228**	-0.248	**-0.412**	-0.250	**-0.347**	**-0.432**	**-0.344**	-0.041	-0.302
JulMinT_JulPrecip	**0.305**	0.146	0.232	0.057	0.040	-0.068	-0.070	-0.010	0.079	-0.124
AugMaxT_AugPrecip	**-0.412**	**-0.452**	**-0.582**	**-0.416**	**-0.315**	**-0.531**	**-0.581**	**-0.601**	-0.243	**-0.397**
AugMeanT_AugPrecip	-0.126	**-0.247**	**-0.317**	-0.259	-0.192	**-0.506**	**-0.415**	**-0.508**	-0.254	-0.311
AugMinT_AugPrecip	**0.256**	0.135	0.266	0.117	0.104	**-0.348**	-0.086	-0.202	-0.235	-0.025
SummerMaxT_SummerPrecip	**-0.472**	**-0.414**	**-0.499**	**-0.539**	0.000	**-0.306**	**-0.326**	**-0.483**	-0.091	-0.193
SummerMeanT_SummerPrecip	-0.142	-0.207	-0.194	**-0.346**	0.072	-0.235	-0.154	**-0.370**	-0.097	-0.139
SummerMinT_SummerPrecip	**0.254**	0.090	0.270	0.125	0.147	-0.084	0.097	-0.111	-0.068	-0.125
WinterMaxT_WinterPrecip	0.045	0.165	-0.010	-0.006	0.173	-0.133	-0.172	**-0.247**	-0.145	-0.144
WinterMeanT_WinterPrecip	0.040	0.157	-0.017	-0.022	0.173	-0.159	-0.182	**-0.243**	-0.125	-0.150
WinterMinT_WinterPrecip	0.032	0.147	0.002	-0.036	0.175	-0.183	-0.184	**-0.236**	-0.108	-0.155

Significant negative correlations existed between maximum temperature and total monthly precipitation for each of the summer months across all the Yukon climate stations. While the later portion of the Atlin record (1974-2010) showed significant negative correlations between maximum temperature and monthly precipitation for July and August, correlations for the early portion of the record (1910-1943) were non-significant and weaker relative to the other stations. Seasonally, the inverse relationship between summer maximum temperature and summer precipitation was evident for all of the Yukon stations except for Haines Junction. This anomalous result was surprising since individually each summer month exhibited significant inverse relationships. Possibly, the individual monthly data for

Haines Junction contained greater variability than the other sites, such that when averaged together to obtain a seasonal value, the result was non-significant. Correlations between winter temperatures and precipitation were not significant for all sites except Watson Lake, which showed significant negative correlations between winter precipitation and all three winter temperature variables. This may be due in part to the fact that Watson Lake receives substantially more winter precipitation than the other stations (mean value of 105.8 mm for Watson Lake compared to an averaged mean of 64.3 mm for the other Yukon stations).

4.6 Conclusions

Long-term climate records for the Yukon are relatively limited. There are only 11 temperature and 18 precipitation records available for the region in the Adjusted Historical Canadian Climate Database (AHCCD). Most of these climate records do not begin until the 1940s or later. Correlation and principal component analyses of these data have been conducted to develop regional patterns of precipitation and temperature across the Yukon.

The longest available temperature records in the Yukon are from Dawson (1898) and Mayo (1925), the remaining stations have records beginning between 1939-1967. Ritchie (1984) and correlation analyses identify two broad regions – an arctic “coastal” regime (Komakuk Beach, Shingle Point and Old Crow) and a more southerly continental subarctic climate within which all the forest sites are located. Based on primarily summer temperatures, this subarctic group was further subdivided into northern and southern groups and regional temperature series (minimum, mean and maximum) were developed. The northern record covers the period from 1898-2010 and the southern record from 1939-2010. Both regional series of summer maximum temperatures show similar interannual patterns over their common period, i.e. relatively warm conditions during the 1940s and 50s, followed by colder temperatures in the 1960s and 70s, before a return to warmer temperatures by the 1990s. Although the trends are similar, the northern record exhibits summer maximum temperatures which are consistently 1-2ºC warmer than those of the southern series. Summer minimum temperatures also show differences between these records. Summer minimum temperatures were similar prior to ca. 1960 (e.g. cooler conditions in the late 1940s), but the northern record subsequently displays an increasing warming trend which exceeds the southern record in magnitude and rate. It is clear that the

Yukon experiences regional differences in temperatures, both in absolute values and change over time, and must be recognized in their influence on tree growth.

Precipitation in the Yukon is also characterized by regional variability. Data from the 18 climate stations showed that 29.8-50.6% of annual precipitation occurs during the summer season (June-August). The majority exhibits maximum monthly percentages in July, though the northern stations (Komakuk Beach, Shingle Point, Old Crow and, to a lesser extent, Klondike) have peak precipitation in August. Three of the southern sites (Swift River, Haines Junction and Teslin) showed slight differences from the other southern stations. Swift River and Haines Junction experienced peak precipitation during September and October, respectively; while the percentages for Teslin were relatively even over the summer months. Correlation and principal component analyses of the data, based mainly on summer precipitation, suggested the identification of four Yukon regional groupings: the "arctic stations" (Komakuk Beach, Shingle Point and Old Crow) and the southeastern, southern and northern groups in the central and southern Yukon. As none of the forest sites examined fell within the "arctic" regime only three regional precipitation series were created: a northern series (Dawson, Klondike and Tuchitua) from 1902-2003, a central series (Pelly Ranch, Mayo, Carmacks and Burwash) from 1925-2010, and a southern series (Teslin, Johnson Crossing, Watson Lake, Swift River, Whitehorse and Ross River) from 1939-2010. Total annual precipitation amounts for the central series were consistently lower than either of the other two regional records, driven mainly by less precipitation during autumn and winter. With respect to trends over time, the three regional series generally exhibited similar patterns. The 1950s were characterized by lower precipitation, followed by a dramatic rise in the early 1960s. From the mid-1960s through the 1980s, precipitation remained relatively stable but increased during the early 1990s. While displaying these overall patterns, each regional series experienced individual years in which precipitation values differed considerably from the other series. With regards to relationships between temperature and precipitation, there appears to be a strong inverse relationship between maximum temperatures and precipitation during summer months in the Yukon.

It is clear from the analyses of the Yukon climate data that they are characterized by regional variability in both temperature and precipitation. In studying white spruce growth across the Yukon, it will be important to consider how this variability in climate is reflected in the tree-growth patterns.

CHAPTER FIVE

Investigation of Climate-Growth Responses in White Spruce Network of the Yukon

5.1 Introduction

In Chapter 3, ring-width growth patterns within the white spruce tree-ring network were examined and several regional growth patterns were distinguished. This chapter investigates climate-growth relationships in these white spruce chronologies. Correlations between the tree-ring records and climate records were used to determine possible relationships between tree growth and climate variables. These investigations took place at increasingly detailed levels. The initial analyses investigate relationships between the regional PC-based chronologies developed in Chapter 3 and regional climate records. Secondly, relationships between climate variables and individual chronologies within each PC were investigated and finally the response of individual chronologies to selected climate variables were mapped across the network. The relationships between tree growth and temperature were analyzed first followed by relationships between tree growth and precipitation.

5.2 Temperature-Tree Growth Relationships

5.2.1 Analytical Methods - Introduction

To investigate climate-growth relationships for sites within the tree-ring network, a series of exploratory correlation analyses were conducted. These analyses used several data sets examining the relationships in more detail.

- Analyses were first performed utilizing the regional tree-ring records developed in Chapter 3. Since these regional records represented groupings of sites which expressed common growth patterns over the last 200 years, the study of correlations between temperature series and these tree-ring records could be used to examine whether varying responses to climate could explain differences in regional growth patterns. Since none of the tree-ring sites included in this study are located in the far northern reaches of the Yukon, climate data from Komakuk, Shingle Point and

Old Crow were not utilized in the investigation of climate-tree growth relationships. Using the methodology outlined by Jones and Hulme (1996), two regional climate series were established for each of the temperature variables (maximum, mean and minimum temperature). The 'northern' temperature series (Dawson, Mayo and Pelly Ranch) covered the period 1898-2010, while the 'southern' temperature series (Burwash, Haines Junction, Whitehorse and Teslin) extended from 1939 to 2010. Given published discussions regarding 'divergence', temporal stability of the climate signal was also a concern. In order to investigate temporal changes in climate-growth responses, additional correlation analyses were independently conducted for the first and second halves of the 20th century to allow comparisons of the response between time periods. These analyses could only be carried out using the "northern "record that covered the whole 20th century.

- Correlation analyses between temperature series and the individual chronologies within each regional tree-ring grouping were conducted to determine if climate-growth responses were similar amongst sites in each group, or whether there was variation in response within each regional grouping.
- Individual chronology responses were analyzed for temporal changes over the 20th century and for potential differences between the 'northern' and 'southern' climate records.
- Based on the correlation results, strongest relationships were mapped to examine potential geographical patterns expressed by the climate-growth responses.

5.2.2 Climate-Growth Responses – Regional Chronologies

Cambial tree growth is limited to a short time window (4-6 weeks) at high latitudes although other processes such as photosynthesis and root growth may continue beyond the growing season (Fritts, 1976). Climate conditions such as a mild winter and spring temperatures may provide opportunities for earlier initiation of growth activity, while severe conditions in fall and winter may adversely influence growth in subsequent growth seasons. In consideration of such effects, correlations between tree-ring records and monthly temperature variables covered a 36 month period (current growth year, previous year, and two years prior). Correlations were also performed using 3-month aggregated (seasonal) temperature data and 12 month (annual) temperature data to examine whether such data captured the relationships between climate and growth processes more effectively, resulting in potentially stronger climate-growth relationships.

5.2.2.1 ***Correlation Between Regional Chronologies and Monthly Temperatures***

These correlation analyses used the monthly temperature data from the two regional temperature records (1900-2003 and 1939-2003) and the six regional tree-ring records (Tables 5.1 and 5.2). There were a much greater number of statistically significant correlation values (p=0.05) with regional chronologies for the ‘northern’ temperature series compared with the ‘southern’ record (Tables 5.1 and 5.2). Also, the numbers of positive correlations were greater than negative correlations for each of the three temperature variables examined, with both sets of regional temperature data. However, the correlation values were somewhat lower than those found in other studies involving white spruce at high latitudes (e.g. Jacoby and D’Arrigo, 1995; Bégin *et al*., 2000; D’Arrigo *et al*., 2004a).

Although each regional tree-ring record exhibited a number of significant correlations with monthly temperatures over the 36 month period, certain results were common across several regions. There are significant positive correlations with current year June temperatures (both maximum and mean temperature) with both the ‘northern’ climate record (Table 5.1) and ‘southern’ climate record (Table 5.2). In the case of the ‘northern’ correlations, all regional tree-ring chronologies except for the Dempster record showed significant positive relationships with current June maximum temperature, while significant relationships with current June mean temperature existed for all groups except the Eastern Yukon and Dempster regions. All regional chronologies except Kluane showed significant positive correlations with current June temperatures (maximum and mean temperatures) of the ‘southern’ climate record. The lack of significant June

Table 5.1 Correlations between the monthly 'northern' temperature series and regional tree-ring records over the 1900-2003 period. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue. Values >0.250 or <-0.250 (bolded) are statistically significant at p=0.01. Labels of growth year months include current, previous (e.g. pJan) and two years prior (e.g. ppJan).

	Maximum Temperature							Mean Temperature							Minimum Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan																					
ppFeb		0.24							0.23							0.21					
ppMar			-0.21							-0.22							-0.22				
ppApr		0.24							0.24							0.23					
ppMay																					
ppJun																**0.29**					
ppJul										**-0.27**						0.22	**-0.29**				
ppAug					-0.21											**0.27**					
ppSep						0.19										0.21					
ppOct	**0.27**		0.22		0.24			**0.26**		0.20	0.20	0.24			0.25	0.20		0.21	0.23		
ppNov																					
ppDec																					
pJan																					
pFeb																					
pMar		**0.33**				**0.27**			**0.29**				0.25			0.25				0.21	
pApr									0.20							0.21					
pMay																	-0.22				
pJun				**-0.32**						**-0.28**	**-0.28**						**-0.35**				
pJul	-0.23	-0.22	**-0.36**	**-0.43**	-0.24	**-0.27**		-0.21		**-0.44**	**-0.32**	-0.25	-0.22			0.22	**-0.34**				
pAug																0.25	-0.22				
pSep																					
pOct			0.21		0.21							0.20									
pNov																					
pDec																					
Jan						0.20							0.20								
Feb																					
Mar			-0.23							-0.23							-0.22				
Apr			-0.25	**-0.27**	-0.20					**-0.27**	**-0.26**	-0.22					**-0.26**	-0.22	-0.23		
May						0.20											-0.20				
Jun	0.20	0.22		0.20	0.24	0.20			**0.30**		0.23	0.21	0.20			**0.34**		0.21			
Jul									**0.30**							**0.36**	-0.20				
Aug				-0.20	-0.22							-0.20				**0.26**					
Sep									0.21				0.19			**0.32**				0.25	
Oct						0.24							0.20								
Nov																					
Dec																					
# positive	2	4	2	1	3	6	*18*	1	7	1	2	3	5	*19*	1	15	0	2	1	2	*21*
# negative	1	1	4	4	4	1	*15*	1	0	6	3	3	1	*14*	0	0	10	1	1	0	*12*

Table 5.2 Correlations between the monthly 'southern' temperature series and regional tree-ring records over the 1939-2003 period. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue. Values >0.315 or <-0.315 (bolded) are statistically significant at p=0.01.

	Maximum Temperature							Mean Temperature							Minimum Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan																					
ppFeb		0.27							0.26												
ppMar																					
ppApr		0.29							0.26												
ppMay																					
ppJun																		0.29			
ppJul																					
ppAug																					
ppSep																					
ppOct		0.26							0.30							0.31					
ppNov																					
ppDec																					
pJan																					
pFeb																					
pMar		**0.37**							**0.40**							**0.41**					
pApr																					
pMay																					
pJun																					
pJul		-0.28				**-0.32**			-0.29				-0.30								
pAug																					
pSep																					
pOct																					
pNov																					
pDec																					
Jan																					
Feb																					
Mar			-0.25	-0.31							-0.26										
Apr	**-0.35**		**-0.40**	**-0.44**	**-0.36**			-0.28		-0.31	**-0.42**	**-0.33**						**-0.37**	-0.29		
May																					
Jun	**0.36**	**0.51**	0.26	0.31	**0.38**			**0.34**	**0.45**	0.25	0.28	**0.35**			0.26	0.29			0.24		
Jul																					
Aug																					
Sep																					
Oct																					
Nov																					
Dec																					
# positive	1	5	1	1	1	0	9	1	5	1	1	1	0	9	1	3	0	1	1	0	6
# negative	1	1	2	2	1	1	8	1	1	1	2	1	1	7	0	0	0	1	1	0	2

correlations between the ‘northern’ temperature record and the Dempster regional tree-ring record (and its presence with the ‘southern’ climate record) was unexpected considering that the ‘northern’ record is from climate stations in closer proximity to the Dempster sites. Significant negative relationships between the regional tree-ring records and previous July temperatures (both maximum and mean temperatures) were evident in the correlations with the ‘northern’ climate series, but only for the SW Yukon and Kluane regions with the ‘southern’ climate series. Current April temperatures (maximum and mean temperatures) of the ‘southern’ record showed strong negative relationships with 4 of the 6 regional tree-ring records but only between 3 of the regional tree-ring records and the ‘northern’ climate data. With respect to minimum temperatures, relationships between the regional tree-ring records and the ‘northern’ climate series indicated that trees in the SW Yukon region responded positively to summer/early-fall minimum temperatures in both the current growth year and two years prior (positive relationships during the intermediate year were limited to pMAR-pAPR and pJUL-pAUG). The Dempster regional record showed negative correlations with minimum temperatures during the spring and summer months of the current and previous growth years. Correlations with the ‘southern’ climate series showed very few significant relationships with minimum temperatures.

These results are similar to those one would expect based on previous studies. The significant positive responses with current June (summer) temperatures are characteristic of trees located at cold, northern latitudes (e.g. Briffa *et al*., 1990, Bégin *et al*., 2000). Negative responses with previous July (summer) temperatures have also been documented for high-latitude sites (e.g. Garfinkel and Brubaker, 1980; Szeicz and MacDonald, 1996). The correlations with the monthly temperature data were relatively weak, thus correlations with aggregated, seasonal temperature data were conducted.

5.2.2.2 ***Correlation Between Regional Chronologies and Seasonal Temperature Data***

Correlation analyses using 3-month aggregated climate data (Tables 5.3 and 5.4) tended to highlight differences in climate-growth responses between regions, rather than relationships shared across the regions. The negative relationship between tree growth

Table 5.3 Correlations between three month averaged 'northern' temperature series and regional tree-ring records over the 1900-2003 period. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue. Values >0.250 or <-0.250 (bolded) are statistically significant at p=0.01.

	Maximum Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan-ppMar		0.22					
ppFeb-ppApr		**0.31**					
ppMar-ppMay		0.23					
ppApr-ppJun		0.22					
ppMay-ppJul							
ppJun-ppAug							
ppJul-ppSep				-0.21			
ppAug-ppOct							
ppSep-ppNov							
ppOct-ppDec							
ppNov-pJan							
ppDec-pFeb							
pJan-pMar		**0.27**					
pFeb-pApr		**0.30**					
pMar-pMay		**0.31**					
pApr-pJun							
pMay-pJul			-0.25	**-0.35**			
pJun-pAug	-0.21	-0.23	**-0.29**	**-0.42**	-0.25		
pJul-pSep				-0.25	-0.22		
pAug-pOct							
pSep-pNov							
pOct-pDec							
pNov-Jan						0.19	
pDec-Feb							
Jan-Mar							
Feb-Apr							
Mar-May			**-0.27**	-0.21			
Apr-Jun						0.22	
May-Jul		0.23				0.25	
Jun-Aug						0.22	
Jul-Sep							
Aug-Oct						0.25	
Sep-Nov							
Oct-Dec							
# positive	0	8	0	0	0	5	*13*
# negative	1	1	3	5	2	0	*12*

	Mean Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan-ppMar		0.20					
ppFeb-ppApr		**0.28**					
ppMar-ppMay		0.21					
ppApr-ppJun		**0.27**					
ppMay-ppJul		0.23					
ppJun-ppAug			-0.20				
ppJul-ppSep			-0.23				
ppAug-ppOct		0.20					
ppSep-ppNov							
ppOct-ppDec							
ppNov-pJan							
ppDec-pFeb							
pJan-pMar		**0.26**					
pFeb-pApr		**0.29**					
pMar-pMay		**0.31**					
pApr-pJun							
pMay-pJul			**-0.35**	**-0.26**			
pJun-pAug			**-0.40**	**-0.30**	-0.23		
pJul-pSep			-0.23		-0.20		
pAug-pOct							
pSep-pNov							
pOct-pDec							
pNov-Jan						0.19	
pDec-Feb							
Jan-Mar							
Feb-Apr							
Mar-May			**-0.30**	-0.22			
Apr-Jun							
May-Jul		**0.32**				0.23	
Jun-Aug		**0.31**				0.23	
Jul-Sep		**0.28**				0.23	
Aug-Oct						**0.27**	
Sep-Nov							
Oct-Dec							
# positive	0	12	0	0	0	5	*17*
# negative	0	0	6	3	2	0	*11*

	Minimum Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan-ppMar							
ppFeb-ppApr		0.24					
ppMar-ppMay			-0.20				
ppApr-ppJun		**0.29**					
ppMay-ppJul		**0.29**					
ppJun-ppAug		**0.33**	-0.23				
ppJul-ppSep		**0.31**	-0.23				
ppAug-ppOct	0.21	**0.31**		0.20			
ppSep-ppNov							
ppOct-ppDec							
ppNov-pJan							
ppDec-pFeb							
pJan-pMar		0.23					
pFeb-pApr		**0.27**					
pMar-pMay		**0.28**	-0.20				
pApr-pJun			-0.25				
pMay-pJul			**-0.38**				
pJun-pAug		0.21	**-0.38**				
pJul-pSep		**0.29**	-0.23				
pAug-pOct		0.24					
pSep-pNov							
pOct-pDec							
pNov-Jan							
pDec-Feb							
Jan-Mar							
Feb-Apr							
Mar-May			**-0.30**	-0.21			
Apr-Jun			-0.23				
May-Jul		**0.34**					
Jun-Aug		**0.40**					
Jul-Sep		**0.42**	-0.24			0.20	
Aug-Oct		0.25				0.24	
Sep-Nov							
Oct-Dec							
# positive	1	16	0	1	0	2	*20*
# negative	0	0	11	1	0	0	*12*

Table 5.4 Correlations between three month averaged 'southern' temperature series and regional tree-ring records over the 1939-2003 period. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue. Values >0.315 or <-0.315 (bolded) are statistically significant at p=0.01.

	Maximum Temperature							Mean Temperature							Minimum Temperature						
	East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane		East YK	SW YK	Dempster	Central N	Central S	Kluane	
ppJan-ppMar																					
ppFeb-ppApr		0.26																			
ppMar-ppMay																					
ppApr-ppJun		0.28							0.27												
ppMay-ppJul																					
ppJun-ppAug																					
ppJul-ppSep																					
ppAug-ppOct																					
ppSep-ppNov																					
ppOct-ppDec																					
ppNov-pJan						0.25															
ppDec-pFeb																					
pJan-pMar		**0.33**							**0.34**							**0.33**					
pFeb-pApr		**0.37**							**0.39**							**0.40**		0.26			
pMar-pMay		**0.34**							**0.38**							**0.38**					
pApr-pJun																					
pMay-pJul																					
pJun-pAug																					
pJul-pSep																					
pAug-pOct																					
pSep-pNov																					
pOct-pDec																					
pNov-Jan						0.24							0.24								
pDec-Feb																					
Jan-Mar																					
Feb-Apr	-0.27			-0.28	-0.28							-0.24									
Mar-May			**-0.35**	**-0.44**						-0.27	**-0.41**							**-0.36**	-0.25		
Apr-Jun																					
May-Jul	0.31	**0.40**			0.27			0.25	**0.34**												
Jun-Aug		0.30							0.27												
Jul-Sep																					
Aug-Oct																					
Sep-Nov																					
Oct-Dec																					
# positive	1	7	0	0	1	2	*11*	1	6	0	0	0	1	*8*	0	3	0	1	0	0	*4*
# negative	1	0	1	2	1	0	*5*	0	0	1	1	1	0	*3*	0	0	0	1	1	0	*2*

and previous July maximum temperatures (Table 5.1) is seen as pJUN-pAUG (Table 5.3) as negative correlations with the northern record in all regional chronologies except Kluane. This significant previous summer negative response was absent in the correlations with the southern climate record (Table 5.4). Significant correlations with current summer temperatures of the northern record were fewer compared to the monthly correlations, with only the SW Yukon and Kluane regions exhibiting positive results (Table 5.3). Seasonal correlations involving the SW Yukon record also showed significant positive responses with winter/early spring temperatures (January through May) of the previous growth year for both the northern and southern climate records, and also two years prior with the northern record. The Kluane tree-ring record was characterized by positive relationships with late spring and summer temperatures of the northern climate record during the current growth year (Table 5.3) but not with the southern record. The Dempster region also displayed differences between the two regional temperature records. Significant negative responses were found with summer temperatures (e.g. pJun-pAug) of the northern record, but did not appear in the results with the southern record. While some seasonal response patterns were similar between the northern and southern climate records (e.g. SW Yukon responses), several regional responses differed between the two records. A greater number of significant correlations were found with the northern climate record versus the southern record.

Statistically significant results from the correlation analyses using aggregated 12-month temperature data were dominated by positive relationships (see Appendix C). The only significant negative correlations were between the 'northern' climate series current year minimum temperature and the Dempster regional tree-ring record (-0.20), and the 'southern' series current year maximum temperature and the Central-Northern regional record (-0.25). The positive correlations between 12-month temperatures and the tree-ring records were limited to the SW Yukon and Kluane regional records. The SW Yukon record exhibited significant correlations with temperatures throughout growth year two years prior, and up to November of the previous growth year. The Kluane record displayed significant correlations from the growth period two years prior up to June of the previous growth year in both maximum and mean temperatures. It also showed positive correlations spanning from August of the previous growth year to the end of the current growth year.

However, maximum correlation for any 12-month period for these two regional chronologies was 0.30 (i.e. less than 10% of the explained variance).

From these preliminary analyses, it is evident that climate-growth responses vary across the network. While some responses are quite dominant across the regional tree-ring records (e.g. the negative responses with previous July maximum temperature of 'northern' temperature series), other responses appear to be more regionally specific (e.g. the negative responses to 'northern' spring minimum temperatures of the Dempster region). Although results of analyses using 3-month (seasonal) climate data did not necessarily yield substantially stronger values relative to single month data, the seasonal results do emphasize the major signals within the regional climate-growth responses.

5.2.3 Temporal Changes in the Climate-Growth Response

Changes in climate-growth responses, primarily declines in temperature sensitivity during the late 20th century (termed 'divergence' effects, D'Arrigo *et al*., 2008, see Chapter 2) have been detected in various tree-ring studies from northern latitude locations. It is possible that the relatively poor correlation results of the analyses earlier in this study reflect some temporal instability in these relationships. Earles (2008) demonstrated significant differences in the relationships between ring-width and summer temperatures over the first and second halves of the 20th century for sites along the Dempster Highway. Several sites in that study exhibited positive relationships with summer temperatures at Dawson in the 1900-1950 period but had much weaker or negative relationships over the 1951-2000 period (Earles, 2008). In light of this occurrence, the climate-growth responses of the sites in this more extensive study were examined for potential changes over time. Utilizing the length of the 'northern' climate series, correlations between the 'northern' temperature series (maximum, mean and minimum temperatures) and the regional tree-ring records were calculated separately for the 1900-1949 and 1950-2000 periods to look for possible evidence of changes in the climate-growth response.

Examination of the pattern of monthly correlations over these two time periods showed major differences in climate-growth responses (Table 5.5). Significant correlations during the 1900-1950 period were dominated by positive relationships particularly for mean and minimum temperatures during late spring months (May and

Table 5.5 Correlations between the regional tree-ring series and the northern monthly temperature series for the 1900-1949 (Pre1950) and 1950-2000 (Post1950) time periods. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue.

Maximum Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan													
ppFeb											0.30		
ppMar													
ppApr				0.42									
ppMay													
ppJun													
ppJul								-0.34					
ppAug													
ppSep													
ppOct				0.34				0.34					
ppNov													
ppDec													
pJan	0.29		0.30										
pFeb													
pMar	0.29			0.42							0.38		
pApr													
pMay													
pJun							-0.38	-0.30					
pJul			-0.31		-0.38	-0.47	-0.46	-0.46	-0.34		-0.35		
pAug							-0.35		-0.33				
pSep													
pOct			0.29										
pNov													
pDec													
Jan										-0.42	0.30		
Feb													
Mar		-0.32				-0.29		-0.34					
Apr						-0.39		-0.46					
May	0.29	-0.30	0.32			-0.35		-0.47		-0.36	0.33		
Jun				0.32			0.31						
Jul													
Aug									-0.31				
Sep													
Oct											0.32		
Nov													
Dec													
# positive	3	0	3	4	0	0	1	1	0	0	5	0	*17*
# negative	0	2	1	0	1	4	3	6	3	2	1	0	*23*

Mean Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan													
ppFeb													
ppMar													
ppApr				0.38									
ppMay	0.32		0.29		0.35		0.33						
ppJun													
ppJul		-0.30				-0.30		-0.38					
ppAug													
ppSep													
ppOct				0.32				0.30					
ppNov													
ppDec													
pJan													
pFeb													
pMar				0.40							0.37		
pApr													
pMay													
pJun						-0.30	-0.31	-0.33					
pJul					-0.31	-0.49	-0.30	-0.49					
pAug													
pSep													
pOct	0.29		0.29										
pNov													
pDec													
Jan										-0.41			
Feb													
Mar		-0.38				-0.31		-0.38					
Apr		-0.34				-0.43		-0.49		-0.31			
May	0.31	-0.33	0.30			-0.42		-0.53	0.38	-0.40			
Jun	0.30		0.33		0.31		0.39		0.36		0.34		
Jul							0.30						
Aug													
Sep											0.33		
Oct											0.30		
Nov													
Dec													
# positive	4	0	4	3	2	0	3	1	2	0	4	0	*23*
# negative	0	4	0	0	1	6	2	6	0	3	0	0	*22*

Minimum Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan													
ppFeb													
ppMar													
ppApr				0.32									
ppMay	0.33				0.37		0.46		0.37				
ppJun	0.34						0.33		0.36				
ppJul								-0.29				-0.29	
ppAug	0.30				0.40		0.30						
ppSep													
ppOct				0.29									
ppNov													
ppDec													
pJan													
pFeb													
pMar				0.38							0.35		
pApr						-0.31							
pMay						-0.35		-0.29					
pJun		-0.33				-0.33		-0.30					
pJul						-0.32		-0.34					
pAug													
pSep													
pOct													
pNov													
pDec													
Jan										-0.41			
Feb													
Mar		-0.42				-0.32		-0.39		-0.31			
Apr		-0.38				-0.43		-0.48		-0.34			
May		-0.34				-0.46		-0.55	0.39	-0.41			
Jun	0.36		0.36				0.41		0.45		0.34		
Jul	0.34		0.33				0.37		0.40				
Aug													
Sep	0.37		0.41						0.34		0.36		
Oct													
Nov													
Dec													
# positive	6	0	3	3	2	0	5	0	6	0	3	0	*28*
# negative	0	4	0	0	0	7	0	7	0	4	0	1	*23*

June) of the current growth year. Positive responses were also noted with May temperatures (mean and minimum) two years prior, though regional differences existed. Significant negative responses with previous July maximum temperatures were noted in all regions except the Eastern Yukon, whereas similar negative responses with mean July temperatures were limited to the Dempster and Central-North Yukon regions. The negative responses with previous July temperatures (maximum and mean) for the Dempster and Central-North Yukon regions were the only climate-growth responses that were statistically significant and similar over both time periods examined.

Although correlations during the earlier time period indicated a general dominance of positive relationships with temperatures, results for the 1950-2000 time period were dominated by negative or non-significant relationships (Table 5.5). Statistically significant negative responses with current year spring months (March, April and May) were recorded for all three temperature variables in all regions except the SW Yukon and Kluane regions. As noted previously, negative relationships with previous June and July maximum and mean temperatures were evident in the Dempster and Central-North regions. Significant correlations with minimum temperatures in these two regions showed an earlier onset, with negative responses occurring with previous May temperature (and previous April in the Dempster region). Significant positive responses during the 1950-2000 period were limited to the SW Yukon region (previous March, October two years prior, and April two years prior, for all three temperature variables) and Central-North Yukon (October two years prior for maximum and mean temperatures). Climate-growth correlations using seasonal (aggregated 3-month) temperatures (Table 5.6) emphasized the major relationships found in the monthly correlations, further highlighting the dominance of significant positive correlations during the 1900-1950 period and negative correlations over the 1950-2000 period. Further analyses will concentrate on relationships using seasonal climate data.

Table 5.6 Correlations between the seasonal (3-month) 'northern' temperature series and regional tree-ring records over the 1900-1949 (Pre1950) and 1950-2000 (Post1950) periods. Statistically significant correlations (p=0.05) are shown, positive relationships in red and negative relationships in blue.

Maximum Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan-ppMar	0.31		0.35								0.30		
ppFeb-ppApr			0.31								0.35		
ppMar-ppMay													
ppApr-ppJun					0.33						0.29		
ppMay-ppJul													
ppJun-ppAug													
ppJul-ppSep													
ppAug-ppOct													
ppSep-ppNov													
ppOct-ppDec													
ppNov-pJan													
ppDec-pFeb													
pJan-pMar	0.32		0.33										
pFeb-pApr				0.32									
pMar-pMay	0.31		0.29	0.33									
pApr-pJun													
pMay-pJul						-0.39	-0.35	-0.38					
pJun-pAug	-0.35		-0.37		-0.42	-0.32	-0.54	-0.36	-0.42		-0.30		
pJul-pSep					-0.32		-0.41		-0.35				
pAug-pOct													
pSep-pNov													
pOct-pDec													
pNov-Jan										-0.30			
pDec-Feb										-0.31			
Jan-Mar		-0.32								-0.38			
Feb-Apr		-0.31						-0.37					
Mar-May		-0.41				-0.46		-0.56		-0.36			
Apr-Jun						-0.39		-0.45			0.35		
May-Jul			0.32			-0.33	0.33	-0.38			0.36		
Jun-Aug				0.31									
Jul-Sep													
Aug-Oct											0.33		
Sep-Nov													
Oct-Dec													
# positive	3	0	5	3	1	0	1	0	0	0	6	0	*19*
# negative	1	3	1	0	2	5	3	6	2	4	1	0	*28*

Mean Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan-ppMar			0.31										
ppFeb-ppApr											0.32		
ppMar-ppMay													
ppApr-ppJun	0.30		0.30		0.35		0.31				0.30		
ppMay-ppJul	0.34		0.32				0.30		0.30				
ppJun-ppAug													
ppJul-ppSep													
ppAug-ppOct													
ppSep-ppNov													
ppOct-ppDec													
ppNov-pJan													
ppDec-pFeb													
pJan-pMar			0.29										
pFeb-pApr				0.29									
pMar-pMay	0.33		0.29	0.29		-0.33			0.31				
pApr-pJun						-0.32							
pMay-pJul						-0.43		-0.41					
pJun-pAug					-0.32	-0.38	-0.35	-0.39					
pJul-pSep													
pAug-pOct													
pSep-pNov													
pOct-pDec													
pNov-Jan													
pDec-Feb										-0.30			
Jan-Mar		-0.34		-0.30				-0.29		-0.38			
Feb-Apr		-0.36						-0.39					
Mar-May		-0.47				-0.48		-0.58		-0.40			
Apr-Jun		-0.30				-0.43		-0.49			0.35		
May-Jul	0.38		0.40		0.32	-0.35	0.43	-0.41	0.45		0.39		
Jun-Aug					0.33		0.31				0.36		
Jul-Sep											0.38		
Aug-Oct											0.41		
Sep-Nov													
Oct-Dec													
# positive	4	0	6	2	3	0	4	0	3	0	7	0	*29*
# negative	0	4	0	1	1	7	1	7	0	3	0	0	*24*

Minimum Temperature

	EasternYK_PC1		SW_YK_PC2		Dempster_PC3		CentralNorthYK_PC4		CentralSouthYK_PC5		Kluane_PC6		
	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	Pre1950	Post1950	
ppJan-ppMar													
ppFeb-ppApr													
ppMar-ppMay													
ppApr-ppJun	0.31				0.32		0.36		0.33				
ppMay-ppJul	0.39		0.32		0.31		0.42		0.42				
ppJun-ppAug	0.37		0.32		0.31		0.33		0.36				
ppJul-ppSep	0.34		0.29										
ppAug-ppOct	0.38		0.35						0.31				
ppSep-ppNov													
ppOct-ppDec													
ppNov-pJan													
ppDec-pFeb													
pJan-pMar													
pFeb-pApr													
pMar-pMay	0.32					-0.37			0.35				
pApr-pJun		-0.30				-0.38		-0.33	0.29				
pMay-pJul		-0.33				-0.43		-0.39					
pJun-pAug						-0.34		-0.32					
pJul-pSep													
pAug-pOct	0.33		0.32										
pSep-pNov													
pOct-pDec													
pNov-Jan													
pDec-Feb										-0.30			
Jan-Mar		-0.36		-0.31				-0.32		-0.39			
Feb-Apr		-0.40						-0.40		-0.30			
Mar-May		-0.49				-0.47		-0.56		-0.42			
Apr-Jun		-0.37				-0.43		-0.50		-0.35			
May-Jul	0.40	-0.29	0.38			-0.34	0.42	-0.40	0.53		0.30		
Jun-Aug	0.40		0.42		0.34		0.42		0.47		0.36		
Jul-Sep	0.42		0.46				0.33	-0.33	0.43		0.39		
Aug-Oct	0.36		0.39					-0.29	0.32		0.41		
Sep-Nov													
Oct-Dec													
# positive	11	0	9	0	4	0	6	0	10	0	4	0	*44*
# negative	0	7	0	1	0	7	0	10	0	5	0	0	*30*

5.2.4 Relationships Between Individual Chronologies and Temperatures

The exploratory correlation analyses between the regional tree-ring records and the ‘northern’ and ‘southern’ regional climate records provided a broad representation of the climate-growth responses of white spruce throughout the Yukon. However, the results were weaker than anticipated. It was thought that regional aggregation of the tree-ring series might possibly be masking differences in response between the individual chronologies within each region. Therefore, further correlation analyses were undertaken between individual site chronologies and the climate records to obtain a more detailed picture of these climate-growth responses. Correlations with the ‘northern’ climate record were split over two time periods (1900-1950 and 1950-2000) to identify possible changes in response during the 20th century. However, given differences between the “northern’ and “southern” climate series and differences in both the geographical distribution of climate stations and tree-ring sites, a comparative analysis was also undertaken correlating each site with the ‘southern’ series over the same 1950-2000 period. The pattern of climate-growth correlations of the individual chronologies were examined within each of the regional groupings defined by the PCA in Chapter 3 to allow comparison with the regional-scale correlation patterns. Seasonal (aggregated 3-month) temperature responses were examined as they provided a clearer illustration of the key major patterns represented in the ‘noisier’ monthly correlations.

5.2.4.1 *Differences in Climate Responses of Chronologies Within Regional Groupings*

Analysis of the climate responses of individual chronologies within the regional groupings defined by the 1800-2000 PCA revealed major differences in the climate-tree ring relationships between individual chronologies within each region. While regional level correlation patterns provided a record of the most dominant climate-growth relationships, chronology level correlations highlighted variations in tree responses within each region. For example, at the regional scale, correlations (pre-1950 period) involving June-August maximum temperatures of the previous growth year were significantly negative for all regions (Table 5.6). At the individual chronology level though, results showed differences (see Appendix D). Table 5.7 provides an interpretative key for the subsequent tables displaying individual chronology level climate responses. For the

Central-North Yukon region, all eight individual chronologies exhibited significantly negative responses (at $p \leq 0.01$ level) with pre-1950 previous June-August maximum temperatures of the 'northern' record. For the Southwest Yukon group though, only six of 16 chronologies showed negative responses (at $p \leq 0.01$ level). While the strong previous summer negative correlation pattern was recorded in each region of the Yukon, the degree to which the individual chronologies within each region reflected this pattern varied.

Comparisons of the climate-growth relationships between minimum, mean and maximum temperatures and the individual chronologies of each region not only highlighted differences in chronology responses within regions, but also demonstrated variations between the temperature variables. For example, correlations between seasonal (3-month) temperatures and the individual chronologies of the Eastern Yukon group (19 chronologies) demonstrated a significant positive signal with pre-1950 current summer (June-August) minimum temperatures in a majority of the chronologies (Table 5.8a) but little response to current summer maximum temperatures (Table 5.8c). While some responses were shared between temperature variables (e.g. negative signal with current spring temperatures), others appeared to be more limited.

Table 5.7 Interpretative key for tables indicating individual chronology level climate response correlations. Vertical column at left indicates aggregated 3-month periods (i.e. rows) represented in growth years 'Current', 'Prior' and '2x Prior'. Chronologies are identified by 3-digit site codes (listed in Appendix A) along top row. Second row indicates time period (Pre-1950 or Post-1950) and climate record (North or South series) used for correlations as marked by A, B, C. Coloured blocks indicate statistically significant correlations (POSITIVE: red = 99% significance level, yellow = 95% significance level; NEGATIVE: dark blue = 99% significance level, light blue = 95% significance level).

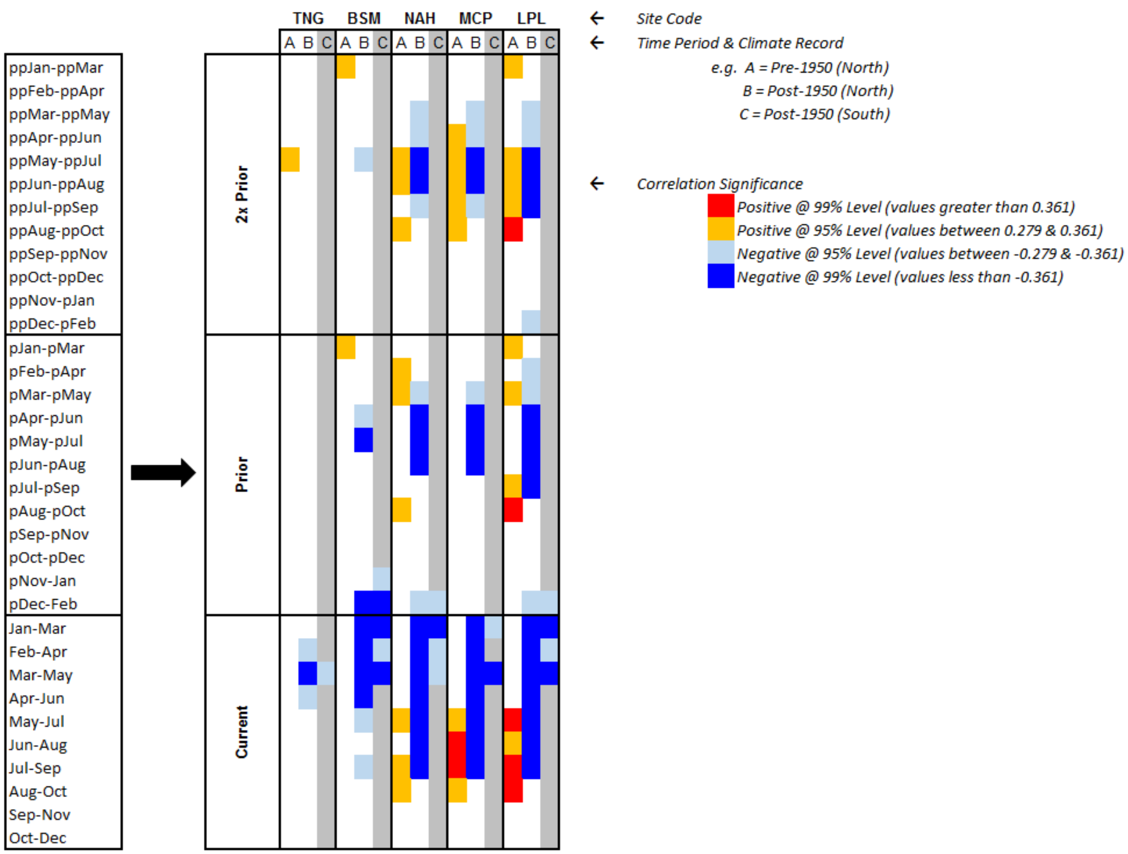


Table5.8 Correlation between seasonal (3-month) temperatures and individual chronologies of the Eastern Yukon region. Correlations with (a) minimum temperatures, (b) mean temperatures, and (c) maximum temperatures. Statistically significant relationships are highlighted. Negative relationships in light blue (0.05 level) or dark blue (0.01 level). Positive relationships in yellow (0.05 level) or red (0.01 level). Results for each chronology are in three columns for pre- and post-1950 periods ('northern' record) and post-1950 for the 'southern' record (grey shading). Note that the positioning of chronologies (columns) within the table is primarily based on the similarity in the response pattern rather than geographical location of the chronology sites.

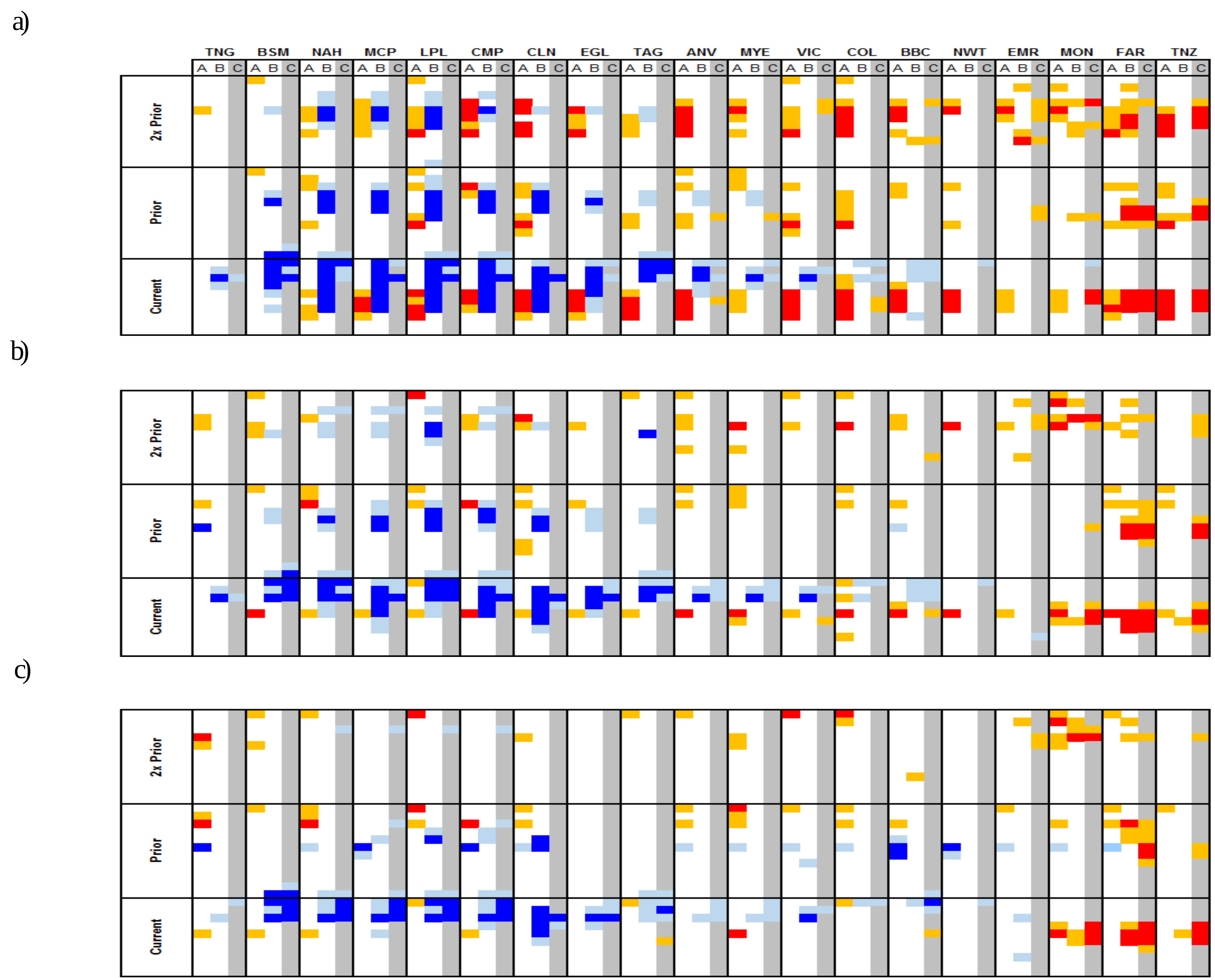


Table 5.9 summarizes the results of correlations between temperature variables and tree-ring variables for each region. Although this table does not identify the specific season of these correlations it clearly indicates that there are significant changes in the pattern of correlations and there is a larger number of significant correlations with minimum temperatures compared with mean and maximum temperatures. Significant positive correlations dominated during the pre-1950 period, whereas significant negative correlations were more apparent during the post-1950 period. Each region displays this opposing temporal pattern for both minimum and mean temperatures, except for the Southwest Yukon where positive correlations dominated both pre-1950 and post-1950 relationships for all three temperature variables. Correlation patterns with maximum temperatures showed varying results. While the Eastern Yukon and Kluane regions displayed opposite correlation patterns between time periods, the maximum temperature results for the Dempster and Central-North Yukon regions showed significant negative correlations outnumbering positive correlations for both pre- and post-1950 periods. In almost all cases, except maximum temperatures with the Eastern Yukon, there are a greater number of significant correlations with the northern than the southern temperature record after 1950.

Further examination of these correlation patterns, similar to the results illustrated in Table 5.8, was carried out for each region and the detailed results are given in Appendix D. These results are summarized in Table 5.10 which compares the major climate-growth responses found in the network between the regional and individual chronology levels. In some cases the chronology-level results appear to agree quite well with the regional-scale responses (e.g. Eastern Yukon pre-1950 results). For most cases though, the chronology-level results suggest considerable variation in the responses within each region. Moreover, similar response patterns were found in some chronologies from different regions. Therefore the analysis of these patterns on the basis of regional groupings was abandoned; further analyses of climate-growth relationships was focused on the response of individual chronologies across the entire network rather than the response of chronologies within regions.

Table 5.9 Summary of the number of significant correlations between temperature variables and the individual chronologies within each region. The number of significant correlations for 3-month maximum, mean and minimum temperatures are shown for the pre- and post-1950 periods of the Northern climate data and post-1950 for the Southern record (> 1950 S). The correlations are calculated for 32 three month intervals, (Oct-Dec of the current growth year to Jan-Mar two years prior). The maximum number of trials is 32 times the number of chronologies in that region. The total number of significant correlations in each category are tabulated and also given as a percentage for comparative purposes (each region has a different number of chronologies = n).

		Minimum Temperature					Mean Temperature					Maximum Temperature			
Eastern YK		**< 1950**	**> 1950**	**> 1950 S**	**Total**		**< 1950**	**> 1950**	**> 1950 S**	**Total**		**< 1950**	**> 1950**	**> 1950 S**	**Total**
(PC1)	NEG (p=0.05)	0	**136**	**38**		NEG (p=0.05)	2	**100**	**46**		NEG (p=0.05)	18	**50**	**49**	
n=19	POS (p=0.05)	**180**	23	37		POS (p=0.05)	**83**	16	32		POS (p=0.05)	**54**	16	26	
	# signif values	180	159	75	414	# signif values	85	116	78	279	# signif values	72	66	75	213
					(21.36%)					*(14.4%)*					*(10.99%)*
Southwest YK															
(PC2)	NEG (p=0.05)	0	45	20		NEG (p=0.05)	7	39	21		NEG (p=0.05)	20	32	24	
n=16	POS (p=0.05)	**124**	**60**	**53**		POS (p=0.05)	**81**	**51**	**58**		POS (p=0.05)	**70**	**55**	**60**	
	# signif values	124	105	73	302	# signif values	88	90	79	257	# signif values	90	87	84	261
					(18.50%)					*(15.75%)*					*(15.99%)*
Dempster															
(PC3)	NEG (p=0.05)	4	**102**	**14**		NEG (p=0.05)	13	**91**	**30**		NEG (p=0.05)	**20**	**70**	**38**	
n=15	POS (p=0.05)	**36**	5	9		POS (p=0.05)	**22**	2	5		POS (p=0.05)	17	2	3	
	# signif values	40	107	23	170	# signif values	35	93	35	163	# signif values	37	72	41	150
					(11.11%)					*(10.65%)*					*(9.80%)*
Central North YK															
(PC4)	NEG (p=0.05)	0	**58**	**15**		NEG (p=0.05)	9	**57**	**20**		NEG (p=0.05)	**22**	**48**	**26**	
n=8	POS (p=0.05)	**44**	4	7		POS (p=0.05)	**22**	3	6		POS (p=0.05)	10	3	5	
	# signif values	44	62	22	128	# signif values	31	60	26	117	# signif values	32	51	31	114
					(15.69%)					*(14.34%)*					*(13.97%)*
Central South YK															
(PC5)	NEG (p=0.05)	0	**14**	6		NEG (p=0.05)	0	**12**	**7**		NEG (p=0.05)	**4**	**8**	**7**	
n=3	POS (p=0.05)	**21**	2	**10**		POS (p=0.05)	**7**	1	**7**		POS (p=0.05)	**4**	1	6	
	# signif values	21	16	16	53	# signif values	7	13	14	34	# signif values	8	9	13	30
					(17.32%)					*(11.11%)*					*(9.80%)*
Kluane															
(PC6)	NEG (p=0.05)	0	**8**	0		NEG (p=0.05)	1	**3**	1		NEG (p=0.05)	1	**2**	2	
n=4	POS (p=0.05)	**37**	0	**6**		POS (p=0.05)	**35**	0	**3**		POS (p=0.05)	**27**	0	**3**	
	# signif values	37	8	6	51	# signif values	36	3	4	43	# signif values	28	2	5	35
					(12.50%)					*(10.54%)*					*(8.58%)*

Table 5.10 Summary of major climate-growth response signals in the network at regional level and individual chronology level.

REGIONS	REGIONAL LEVEL SIGNALS	CHRONOLOGY LEVEL SIGNALS
Eastern Yukon (19 chronologies)	<u>Pre-1950</u> Strong positive correlations with summer minimum and mean temperatures	<u>Pre-1950</u> 17/19 chronologies showed positive relationship with summer minimum temperature; 18/19 chronologies showed positive relationship with summer mean temperature
	<u>Post-1950</u> Significant negative correlations with current spring temperatures	<u>Post-1950</u> 14/19 chronologies showed strong negative correlations with current spring temperatures (negative signal extended into summer months with 'northern' record, 'southern' record limited to spring months)
Southwest Yukon (16 chronologies)	<u>Pre-1950</u> Strong positive correlations with current spring/summer temperatures and previous spring maximum and mean temperatures	<u>Pre-1950</u> 3/16 chronologies showed strong positive correlations with spring/summer temperatures (current, previous & 2-yrs prior); 13/16 chronologies showed negative response to previous summer maximum temperatures
	<u>Post-1950</u> Negative correlations with current winter (Jan-Mar) mean and minimum temperatures; positive correlations with previous spring maximum and mean temperatures	<u>Post-1950</u> 3/16 chronologies showed strong negative correlations with current and previous spring temperatures of 'northern' record; negative correlations with spring temperatures of 'southern' record were limited to current growth year (3/16)
Dempster (15 chronologies)	<u>Pre-1950</u> Strong negative correlations with previous summer maximum and mean temperatures; positive correlation with current summer mean and minimum temperatures; positive correlations with spring temperatures 2-yrs prior	<u>Pre-1950</u> 9/15 chronologies showed strong negative correlations with previous summer maximum temperatures; 7/15 chronologies showed positive correlations with current summer mean temperatures
	<u>Post-1950</u> Strong negative correlations with current spring and previous summer temperatures	<u>Post-1950</u> 12/15 chronologies showed strong negative correlations with current spring and previous summer temperatures ('northern' and 'southern' records)

Table 5.10 (cont'd) Summary of major climate-growth response signals in the network at regional level and individual chronology level.

REGIONS	REGIONAL LEVEL SIGNALS	CHRONOLOGY LEVEL SIGNALS
Central-North Yukon (8 chronologies)	Pre-1950 Strong negative correlations with previous summer maximum and mean temperatures; positive correlation with current summer temperatures	Pre-1950 6/8 chronologies showed negative correlations with previous summer maximum temperatures (3/8 with previous summer mean temperature); 5/8 chronologies showed positive correlations with current summer maximum temperature
	Post-1950 Strong negative correlations with early half (Jan-June) temperatures of current growth year; negative correlation with previous summer temperatures	Post-1950 7/8 chronologies showed negative correlations with current spring/summer temperatures ('northern' and 'southern' records); 6/8 chronologies showed negative correlations with previous summer maximum temperatures ('northern' record)
Central-South Yukon (3 chronologies)	Pre-1950 Strong negative correlations with previous summer maximum temperature; positive correlation with current late spring/early summer mean and minimum temperatures	Pre-1950 2/3 chronologies showed negative correlations with previous summer maximum temperature; 3/3 chronologies showed positive correlations with current summer minimum and mean temperatures
	Post-1950 Negative correlation with previous winter/current early spring temperatures	Post-1950 2/3 chronologies showed negative correlations with previous winter/current early spring temperatures ('northern' and 'southern' record)
Kluane (4 chronologies)	Pre-1950 Strong positive correlations with current spring/summer temperatures; negative correlation with previous summer maximum temperature	Pre-1950 All 4 chronologies showed positive correlations with current spring/summer temperatures; 1/4 chronologies showed negative correlation with previous summer mean and maximum temperature
	Post-1950 No significant ($p \leq 0.05$) correlations	Post-1950 1/4 chronologies showed negative correlation with previous summer temperatures of 'northern' record; 1/4 chronology showed negative correlation with previous summer maximum temperature of 'southern' record

5.2.5 Regrouping of Chronologies based on PCA for 1900-1950 (PCAE) and 1951-2000 (PCAL) Ring-Width Data

The response patterns of individual chronologies within the PCs defined over the 1800-2000 record indicate that the climate-growth relationships of white spruce within the Yukon are variable. Each of the PCA-defined groupings examined showed several distinctive sub-groups of response patterns which were not anticipated and similar patterns were noted between chronologies in different regional groupings. This suggested that the chronologies within these regional chronology groupings did not show a homogeneous response to climate. The regional grouping of chronologies was based on PCA over the entire 1800-2000 period. However, PCA analysis of the chronologies in Chapter 3 (e.g. Figure 3.20) indicated that the chronologies grouped differently depending on the period selected for PCA analysis. Therefore, to investigate climate response patterns in more detail, new PCA groupings of the chronologies were constructed using only the ring-width records from the period of the instrumental climate record. Given the significant differences in response over the 20th century these analyses were undertaken separately for the 1900-1950 (PCAE) and 1951-2000 (PCAL) portions of the ring-width records.

The PCAE analysis (Table 5.11) showed a strong common pattern with 50 of the 73 standard chronologies (45.6% of variance) loading most strongly on the first principal component (PCE1), sharing common variance in their growth patterns. Examining the climate-growth responses for these chronologies showed strong and coherent signals (Table 5.12). The most evident response was the strong positive correlations between growth and current spring/summer minimum temperatures (May through September). Of the 50 chronologies, 44 displayed positive correlations (significant at p=0.05) within these months. The six chronologies that did not were on the outer portions of the network, Tungsten to the east, Big Salmon to the south, and Mt. Cronin, Ogilvie Ridge, TTHH and Scriver Creek on the northern part of the Dempster Highway. The peripheral nature of these locations may explain their weaker correlation results – all showed positive though non-significant correlations with current summer temperatures. Forty-two of these 50 chronologies also exhibited significant positive correlations (p=0.05) with spring/summer minimum temperatures two years prior.

Table 5.11 PCA loadings of standard chronologies for the 1900-1950 (PCAE) time period.

	Component								
	1	2	3	4	5	6	7	8	9
Victoria Creek	.963	.052	.128	.006	.117	.008	.130	-.008	.028
Lapie Lakes	.955	-.073	.136	.050	.023	.020	.181	-.068	.017
Anvil Mine	.955	.113	.163	.091	.102	.061	.040	-.017	-.064
Tagish	.942	.024	.155	.093	.116	-.079	-.025	-.108	.115
Nansen Creek	.938	.078	.123	.068	.087	-.048	.226	-.061	.051
Faro	.937	.167	.136	.143	.083	.038	.084	-.073	.005
Eagle Combined	.932	.220	.025	.102	.124	.048	.126	.052	.056
Tanzilla Butte (UWO/Laval)	.919	.055	.089	.118	.195	-.176	-.023	.012	.060
Coal Lake Road	.918	-.041	.212	-.039	.199	.190	.109	-.035	-.002
Campsite	.907	.224	.089	.144	.164	.154	-.012	.042	-.003
Nahanni Spruce	.904	.315	.118	.129	.009	.079	-.047	.000	.040
Keele Lake	.896	.285	-.006	.144	.139	.022	.134	.085	.022
MacDonald Lake	.895	.090	.264	.045	.041	.229	.043	-.124	.101
MacMillian Pass Combined	.892	.303	-.015	.167	.156	-.039	.123	.041	-.007
Mt McIntyre	.877	.242	.213	.085	.076	.036	-.048	-.028	.225
AINA	.874	-.077	.163	.089	-.173	-.289	.084	-.178	-.090
Gray Mountain	.872	.166	.270	.050	-.096	.130	-.205	-.032	.082
Clinton Creek	.859	.181	.209	.201	.145	.142	.144	.002	-.152
Carpenter Lake	.854	.218	.023	.273	-.041	-.164	.212	-.084	.005
Webber Creek	.830	.125	.241	.010	.433	.126	.009	-.053	-.003
Cassiar	.828	.026	.373	.114	.038	.153	-.187	-.030	.116
Telluride	.827	.169	.280	.052	.001	.286	-.111	.046	.115
Canyon Lake	.824	.138	.387	.066	.109	.109	-.176	-.094	.143
NWT Pass	.814	.218	.029	.136	.340	.272	.130	.011	.035
Emerald Lake	.793	.382	-.092	.113	.157	.049	.334	-.128	-.007
Jack Wade	.792	.322	.062	.111	.334	-.129	.239	.078	-.042
Mt. Mye	.776	.332	.277	.165	.015	.277	-.090	-.169	-.086
Swede Dome	.776	.213	.251	.027	.310	.261	.172	.129	-.157
Lapie Pass	.771	.468	.115	.153	.105	-.112	-.075	-.020	.124
Wernecke	.760	.430	.095	.154	.255	.239	-.132	.187	-.089
Big Salmon (UWO/Laval)	.746	.107	.232	.132	-.146	.203	-.080	-.408	.141
Eagle Twelve	.737	.490	.135	.094	.099	-.047	-.108	.018	.226
Einarson Lake	.716	.381	-.063	.164	.286	.023	.388	-.015	-.018
Black City	.712	.197	.006	.289	.394	.190	.154	.225	-.195
Big Bend Combined	.712	.455	.052	.159	.331	.155	-.030	.214	.005
Misty Lake	.707	.479	-.142	.259	.254	-.006	.136	.133	.013
Mt. Cronin	.693	.066	.146	.483	-.106	-.174	.178	-.279	-.134
Tombstone Mountain	.681	.382	.099	.378	.253	.102	-.073	-.057	-.217
Bonnet Plume Lake	.676	.485	-.043	.206	.402	-.001	.101	.105	-.017
Tungsten	.672	.415	.037	.269	-.213	.298	-.179	.111	.032
Ogilvie Ridge	.658	.125	-.002	.486	.344	-.185	.077	.168	.029
Monarch	.631	.292	.334	.056	.119	.434	-.247	-.098	.223
Barlow Dome	.618	.552	.223	.190	.232	.180	.154	.015	-.024
Sandpit	.600	.335	.290	-.060	.305	.089	-.092	-.071	.281
Mt. Berdoe	.597	.275	.054	-.174	.527	.331	.239	.022	.093
TTHH	.583	.450	.084	.507	-.051	-.249	.136	-.176	-.059
Kathleen Lake	.581	.237	.275	-.175	-.119	.040	.079	.051	.169
Scriver Creek	.573	.223	.048	.532	.025	-.360	.123	.277	.081
Empire Creek	.563	.469	.097	.125	.394	.390	.110	.134	.007
Wheaton River	.479	.148	.433	-.010	.346	.368	-.193	-.077	.039
Galena	.208	.890	-.015	.237	.039	-.064	.046	.064	.077
Highet Creek	.209	.870	.062	.066	.151	.213	.005	.070	.023
Big Gold Creek	.487	.636	.127	.269	.176	.138	.263	.058	.032
Worm Lake	.596	.624	.055	.329	-.037	.147	.164	.052	-.088
Distincta Combined	.175	.572	.167	.506	.445	.153	.120	.048	-.038
Landslide Main	.088	.081	.906	.088	.049	-.074	-.065	.045	-.067
Jackson Point Good	.202	.034	.872	.100	-.064	.011	.090	.044	.158
Bullion Creek	.480	-.037	.785	.041	-.010	.134	.041	-.102	-.153
Pipeline	.497	.036	.725	.039	.028	.220	-.171	-.018	-.106
Cultus Bay	.068	.212	.576	.025	.424	-.287	.004	.361	.216
Aishihik	.448	-.039	.560	-.053	.215	.351	.032	-.134	.281
Airstrip Eagle Plains	.170	.115	.222	.841	.081	.038	.089	-.025	.019
Vadzaih Kan Creek	.041	.307	-.068	.823	.080	.078	-.116	.211	.126
Rock River	.282	.181	.072	.616	.020	-.218	.342	-.400	-.161
Tsiivii Creek	.186	.087	-.015	.326	.851	-.167	.156	.024	.022
Divide Spruce	.275	.105	.106	-.019	.821	.291	.142	-.028	.071
North Klondike River	-.148	.444	.004	-.064	.610	.502	-.041	.194	-.239
Burwash	.172	.132	.134	-.094	.095	.891	.005	.128	-.024
Blackstone River	.056	.337	-.043	.470	.177	.529	.356	.114	.167
Sappers Hill	.063	.094	-.047	.222	.283	.076	.804	-.052	.053
Smithers Ski 2	-.219	-.149	.415	.201	.016	.277	-.499	-.433	-.016
Mt. Jeckell	-.236	.251	.100	.189	.071	.281	-.014	.787	-.011
Donjek	.480	.153	.135	.326	.065	.013	.352	.074	.528
% Variance	45.614	10.188	7.437	6.716	6.692	5.328	3.618	2.803	1.658

This group also showed significant negative correlations (39 of the 50 chronologies) between growth and previous summer (pJune-pAugust) maximum temperatures (p=0.05) (Table 5.12). The chronologies which did not share in this relationship were situated either in the far north (Mt. Cronin, TTHH, Scriver Creek) or in the southwest Yukon (Lapie Lakes, Tagish, Tanzilla Butte, AINA, Cassiar, Canyon Lake, Big Salmon, Sandpit).

Table 5.13 shows the climate-growth responses of these chronologies for the 1951-2000 period and clearly demonstrates the marked difference in climatic response of these chronologies over the two time periods (Table 5.12 vs Table 5.13). Though many chronologies exhibited a shift to negative responses for the 1951-2000 period, five chronologies (Faro, MacDonald Lake, Cassiar, Telluride and Lapie Pass) appeared to retain strong positive signals (Table 5.13). These positive responses likely represent relationships with local, site-specific conditions rather than regional conditions as these sites are situated in different regions of the Yukon.

Table 5.12 Correlations between seasonal (3-month) temperatures and ring-width for the 50 chronologies in PC1E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positve=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). The positioning of chronologies (columns) within the table is based on their loadings on PC1E with the highest values on the left.

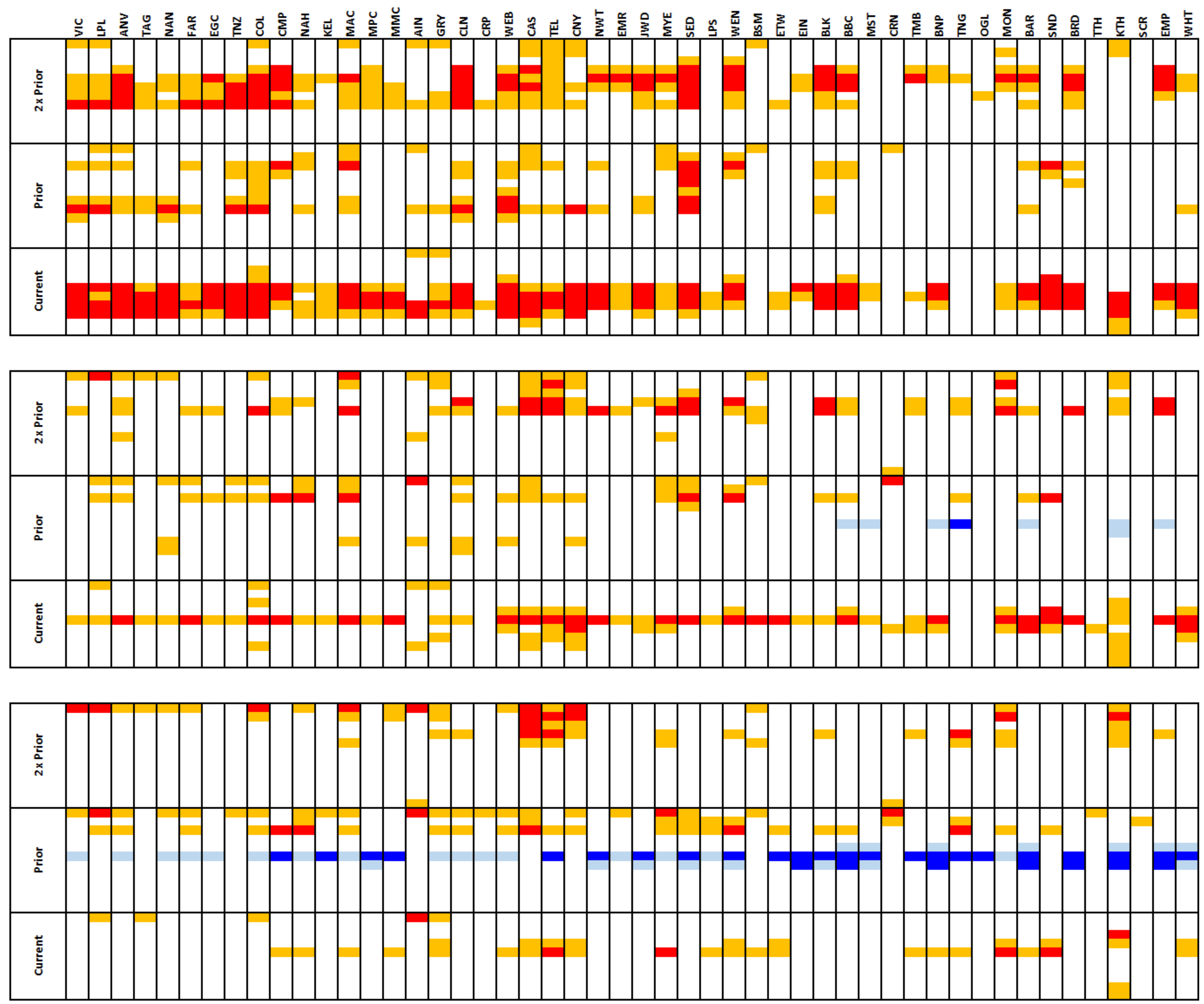
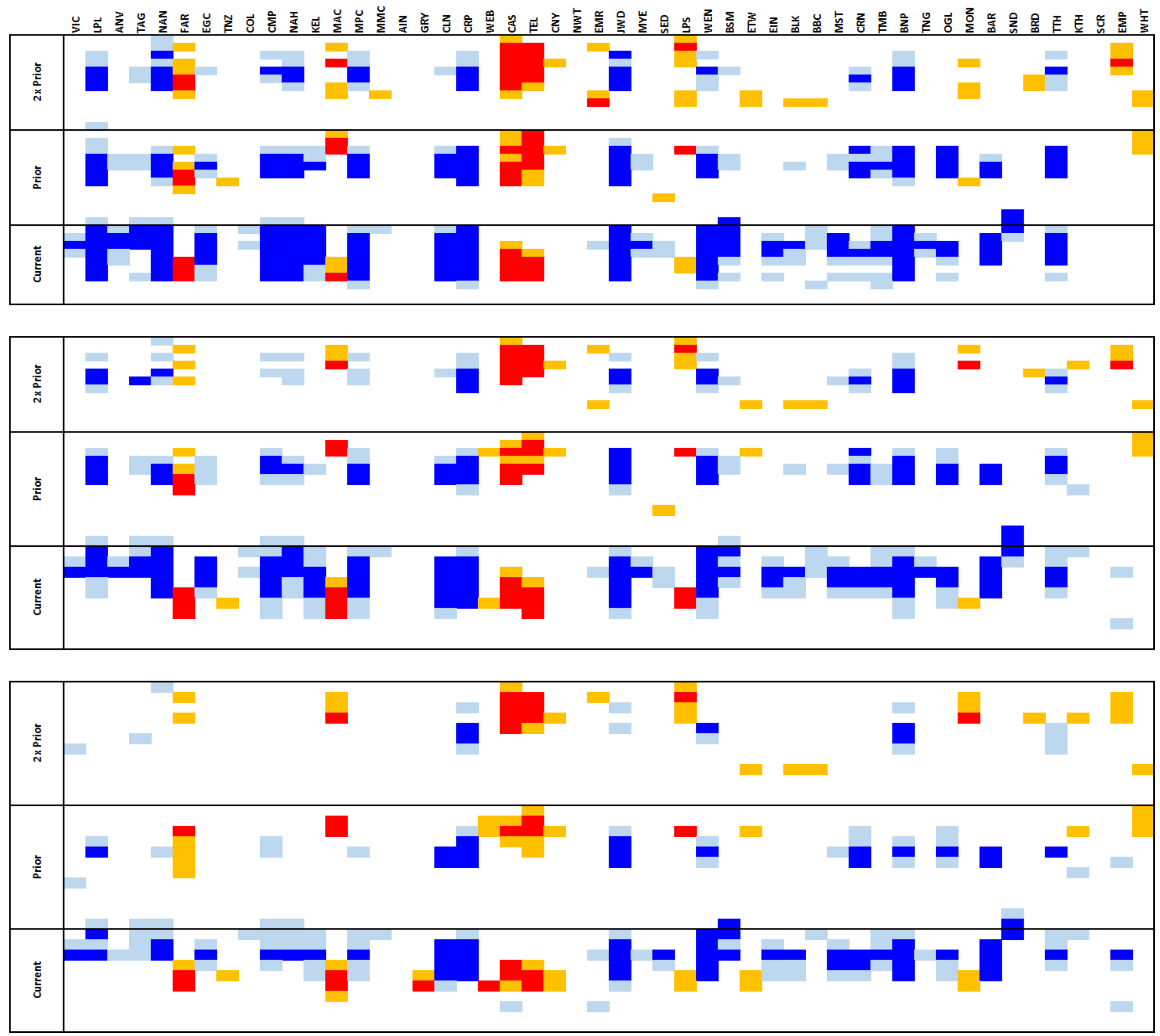


Table 5.13 Correlations between seasonal (3-month) temperatures (northern record) and ring-width for the 50 PC1E chronologies over the 1951-2000 period. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). The positioning of chronologies (columns) within the table is based on their loadings on PC1E with the highest values on the left.



Climate-growth responses of the chronologies loading on PC2E through PC9E were mixed (see Appendix E). The five chronologies on PC2E (Galena, Highet Creek, Big Gold Creek, Worm Lake, and Distincta Combined) are all in the northern part of the network and displayed significant negative correlations with previous summer (pMay through pSeptember) maximum temperatures, but failed to consistently show the strong positive correlations with current spring/summer minimum temperatures that was so evident with the PC1E chronologies. The six chronologies loading on PC3E are all from the Kluane area (Landslide, Jackson Point, Bullion Creek, Pipeline, Cultus Bay, and Aishihik) with an opposite signal to PC2E, i.e. significant positive correlations with current spring/summer minimum temperatures but lacking strong negative correlations with previous summer maximum temperatures. Airstrip Eagle Plains, Vadziah Kan Creek, and Rock River from the Dempster Highway all load on PC4E and showed relatively few significant responses, the only consistent one being negative correlations with previous summer temperatures. Tsiivii Creek and North Klondike, found along the Dempster Highway, together with Divide Spruce (eastern Yukon) loaded on PC5E and showed similar responses to PC1E, dominated by strong positive correlations with summer minimum temperatures and negative correlations with previous summer maximum temperatures. The response results of the remaining higher-order PCs were more random, suggesting individual, possibly site controls on the climate-growth relationships of these chronologies. For the 1900-1950 period, it is evident that PC1E clearly represents the most dominant regional pattern and that PC2E-PC5E are primarily regional variants. Responses of the PC1E chronologies with temperatures of the northern climate record were dominated by positive correlations for the 1900-1950 period (Table 5.12), while displaying primarily negative results over the 1950-2000 period (Table 5.13). Correlations with the southern climate record (not shown) resulted in very similar response patterns, though correlations were generally weaker.

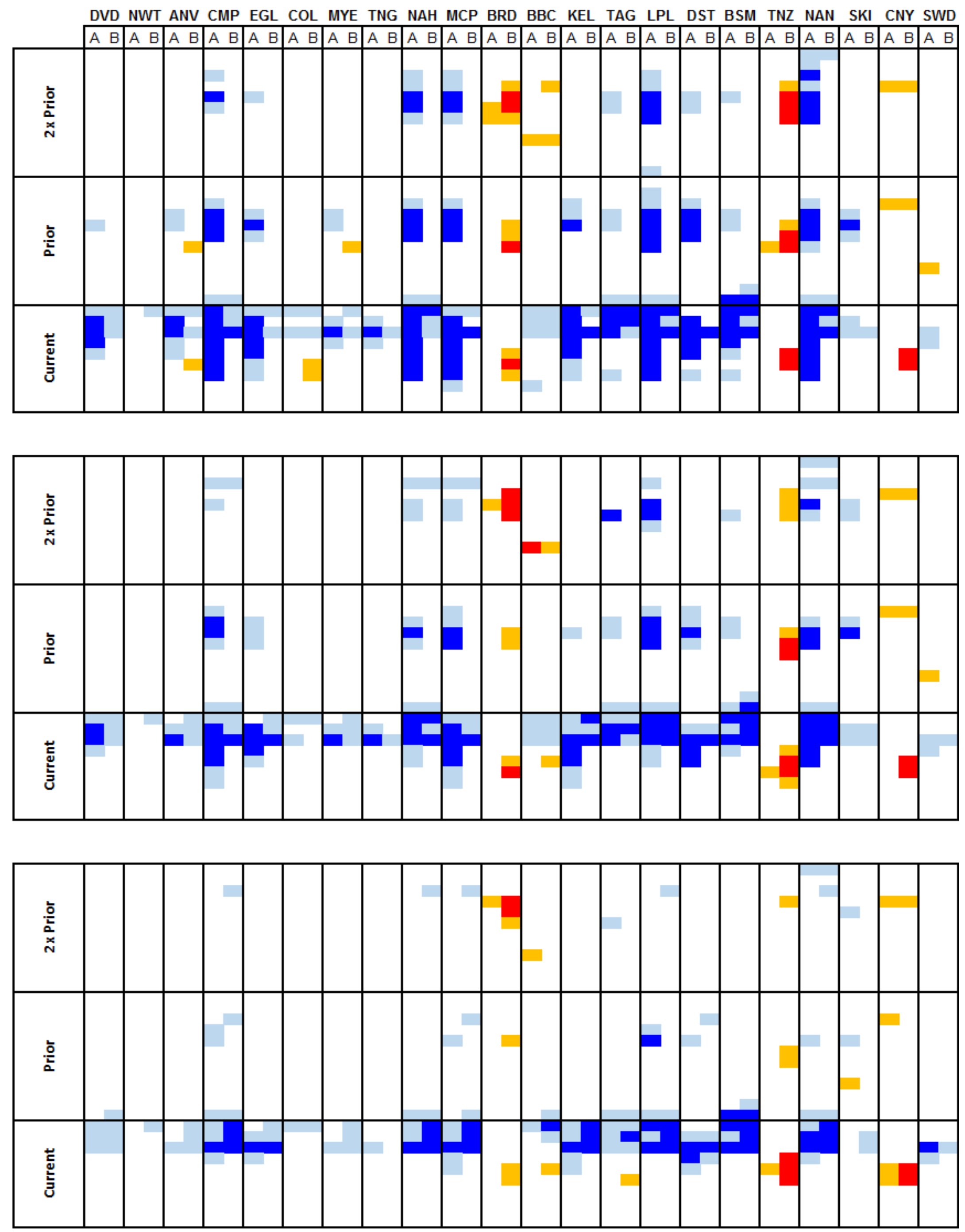
PCA based on ring-widths for the 1951-2000 period (PCAL) showed a greater diversity of patterns (Table 5.14). PC1L includes 22 of the 73 standard chronologies representing only 27.1% of the variance. These PC1L chronologies are all located in the southern half of the network, with the exceptions of Distincta and Swede Dome (northern Yukon). These chronologies clearly indicated negative relationships between growth and

Table 5.14 PCA loading scores of standard chronologies for the 1951-2000 time period (PCAL).

	Component									
	1	2	3	4	5	6	7	8	9	10
Divide Spruce	.940	.160	.042	.139	.068	.043	.060	-.016	-.075	-.091
NWT Pass	.918	.081	.198	.179	-.069	.038	-.093	-.130	-.027	-.011
Anvil Mine	.906	.306	.008	.139	.057	.044	.042	.188	-.037	-.002
Campsite	.899	.356	-.051	.111	.052	-.016	.021	-.099	-.061	.085
Eagle Combined	.893	.298	.012	.203	-.001	.139	-.053	-.017	.033	.053
Coal Lake Road	.883	.029	.300	.118	.013	.033	.141	.157	-.024	.096
Mt. Mye	.872	.349	.122	.207	-.034	.060	-.063	.102	-.012	.099
Tungsten	.871	.265	.077	.114	.089	.021	-.096	.042	-.062	-.257
Nahanni Spruce	.868	.411	-.035	.036	.117	-.021	.139	.035	-.043	-.072
MacMillian Pass Combined	.836	.454	-.041	.213	.045	-.048	-.007	-.102	-.034	.037
Mt. Berdoe	.791	.054	.321	.049	-.029	.227	.149	.315	.068	.004
Big Bend Combined	.777	.224	.302	.087	.012	-.098	-.245	-.111	-.117	-.235
Keele Lake	.754	.562	-.001	.212	-.040	-.032	.080	-.004	.110	-.023
Tagish	.743	.023	.515	.025	.032	.096	.156	-.078	-.044	.170
Lapie Lakes	.738	.469	.109	.073	.080	-.171	.266	.034	-.204	-.011
Distincta Combined	.727	.416	-.082	.404	-.031	-.036	.037	-.045	-.179	.173
Big Salmon (UWO/Laval)	.723	.415	.444	-.082	-.109	-.032	.096	-.039	.049	.136
Tanzilla Butte (UWO/Laval)	.714	.078	.358	.071	-.017	.112	-.030	.514	-.049	.013
Nansen Creek	.688	.465	.104	.018	.235	-.151	.255	-.078	-.304	.069
Smithers Ski 2	.648	.336	.136	.215	.120	.100	-.227	-.120	.040	.353
Canyon Lake	.616	-.200	.573	.141	.004	.193	-.099	-.099	-.332	-.012
Swede Dome	.553	.280	.016	.327	-.074	.440	-.319	.005	-.227	.198
Galena	.112	.884	.274	.021	.057	.027	-.071	-.117	.092	.156
Highet Creek	-.081	.884	.237	.073	.009	.165	-.026	.142	.136	.029
Worm Lake	.212	.857	.085	.269	-.046	.177	-.124	.096	.104	-.041
Wernecke	.458	.820	.088	.137	.063	-.016	.080	-.095	.128	.035
Clinton Creek	.352	.819	-.037	.217	-.001	.258	.034	.005	-.163	.134
Barlow Dome	.408	.783	-.007	.207	-.066	.308	-.035	-.057	-.051	.041
Misty Lake	.456	.766	.087	.261	-.064	-.021	-.197	-.058	.170	-.121
Einarson Lake	.444	.756	.075	.242	-.034	.062	.013	.170	-.010	-.148
Carpenter Lake	.360	.722	-.076	.295	.001	-.123	.098	-.325	-.036	-.211
Jack Wade	.519	.719	-.143	.235	.038	.067	.087	-.167	-.224	.111
Bonnet Plume Lake	.531	.714	.076	.177	-.093	-.159	.104	-.176	.127	-.092
Mt. Jeckell	-.048	.714	-.186	.301	-.065	-.269	.229	.320	.100	-.029
North Klondike River	.608	.703	-.168	.191	.026	-.040	-.023	-.073	-.102	.128
Tombstone Mountain	.557	.691	.018	.277	.049	-.008	.035	.003	.078	-.119
Black City	.332	.678	.059	.442	-.010	-.144	-.079	.028	.168	.163
TTHH	.558	.655	.015	.335	-.059	-.135	.137	.071	-.181	-.017
Blackstone River	.233	.648	.004	.416	.073	-.026	.321	.222	-.149	.016
Big Gold Creek	.364	.634	.185	.242	.097	.360	-.098	-.015	-.371	-.071
Emerald Lake	.272	.632	.252	.352	-.122	.247	-.212	.122	.205	-.246
MacDonald Lake	.044	-.047	.921	-.033	.063	-.084	.003	.050	-.042	.007
Mt McIntyre	.266	.204	.876	-.003	.034	-.010	.136	-.005	.077	.065
Telluride	-.238	-.159	.854	.034	.081	.135	.025	.032	.101	-.117
Gray Mountain	.355	-.072	.825	-.037	.019	.020	-.061	-.180	-.113	.178
Lapie Pass	-.115	.289	.806	-.034	-.010	.089	-.188	.233	.102	-.204
Eagle Twelve	.396	.209	.791	.009	.104	-.157	-.182	.177	-.074	.003
Sandpit	.146	.204	.782	-.168	-.060	-.001	.352	-.082	.077	.166
Wheaton River	.008	-.004	.762	.226	.070	.113	.022	-.214	.140	-.120
Monarch	.563	.110	.706	.040	-.075	.087	-.025	.228	-.040	.177
Cassiar	.007	-.154	.644	-.099	-.033	.399	-.099	.515	.084	-.197
Faro	.402	.023	.637	.013	-.160	-.028	-.230	.390	.117	.082
Kathleen Lake	.014	.113	.635	-.060	.329	.158	.330	.022	.047	-.401
Webber Creek	.578	.088	.603	-.093	.146	.227	-.026	.071	-.238	-.019
Vadzaih Kan Creek	.368	.201	.042	.809	.027	.034	-.038	.082	-.031	-.060
Scriver Creek	.182	.418	-.094	.801	-.023	-.013	.064	.090	-.023	-.076
Airstrip Eagle Plains	.051	.396	.118	.777	.228	-.053	.000	-.079	-.024	-.122
Mt. Cronin	.133	.304	-.136	.745	.002	.055	.088	-.306	.135	.242
Rock River	.436	.362	-.217	.710	-.085	.168	.010	-.009	-.024	.117
Tsiivii Creek	-.078	.181	.320	.696	-.120	.093	-.277	.110	.130	-.297
Ogilvie Ridge	.440	.496	-.115	.655	-.071	.082	-.020	.009	-.056	.090
Sappers Hill	.304	.450	.005	.654	-.135	.056	-.062	-.004	-.060	.278
Pipeline	.224	.183	-.045	.088	.880	.001	.038	-.046	-.067	.015
Landslide Main	-.098	-.212	-.041	.001	.864	-.154	.109	-.104	.007	-.009
Jackson Point Good	.057	-.287	.106	-.146	.862	.005	.075	-.076	.180	.040
AINA	-.488	.187	.283	-.069	.715	-.169	-.077	.013	-.024	.039
Bullion Creek	.335	.112	.033	.148	.691	.330	.137	.315	-.022	-.185
Burwash	.129	.083	.316	-.067	.599	.155	.392	.373	.272	.023
Empire Creek	-.071	.537	.316	.234	-.174	.651	-.048	.065	-.071	-.088
Victoria Creek	.556	.179	.350	.045	-.010	.610	.172	.139	.135	.071
Cultus Bay	.252	-.043	-.029	-.025	.392	-.067	.750	-.035	.084	-.039
Aishihik	-.264	.132	.382	-.078	.199	.349	.504	-.045	.387	.019
Donjek	-.256	.208	.149	.076	.160	-.012	.118	.027	.786	-.014
% Variance	27.159	20.304	13.766	8.963	5.972	3.373	3.246	2.766	2.690	1.890

climate (Table 5.15) compared to the overwhelming positive responses from 1900-1950. The strongest correlation with the northern climate record during the post-1950 period was a negative response to minimum temperatures during the first half of current growth year (January through July), with 18 of the 22 chronologies recording significant negative correlations (p=0.05) during these months. Strong negative correlations were also found with spring/summer minimum temperatures of previous years (one and two years prior), though fewer chronologies recorded this pattern. Significant negative correlations during the early half of current growth year were also evident with mean and maximum temperatures, though significant negative responses with maximum temperature during prior years were noticeably absent. Correlations with the southern climate record for the 1951-2000 period exhibited similar negative responses for the current growth year, but over a shorter seasonal window (January through May) (Table 5.15). Unlike the northern record, significant negative correlations with spring/summer temperatures during prior years were absent with the southern record. A small number of PC1L chronologies exhibited positive correlations with the southern record. Mt. Berdoe, Tanzilla Butte and Canyon Lake (located in SW Yukon/NW B.C) displayed strong positive correlations with summer temperatures during the 36-month analysis window. This pattern was strongest with summer minimum temperatures, but was also visible in correlations with summer mean and maximum temperatures (especially during current year values). While these three chronologies did not share in the negative climate-growth responses which characterized the majority of the PC1L chronologies, their annual growth patterns were similar leading to their loading on PC1L.

Table 5.15 Correlations between seasonal (3-month) temperatures and ring-width for the 22 PC1L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom).



Climate-growth responses of the chronologies loading on PC2L through PC9L are shown in Appendix F. Responses of the 19 chronologies loading on PC2L were also dominated by significant negative correlations primarily focused on spring/summer temperatures. Similar to patterns witnessed with PC1L, negative correlations with spring/summer temperatures of the northern record were most evident during the current growth year with fewer chronologies exhibiting similar seasonal responses in prior years. Unlike the PC1L results in which significant correlations with the southern climate record were absent during prior years, several PC2L chronologies displayed strong correlations with prior spring mean and maximum temperatures of the southern record. Carpenter Lake, Jack Wade, Bonnet Plume Lake, Mt. Jeckell and North Klondike River exhibited significant negative correlation values (p=0.05) between pMarch and pJune. This pattern did not appear in the relationships with minimum temperature.

The 13 chronologies loading on PC3L for the 1951-2000 period were characterized by significant positive correlations, especially with spring and summer temperatures (Table 5.16). MacDonald Lake, Telluride, Lapie Pass, Cassiar and Faro exhibited such correlations throughout the 36-month analysis window. These strong relationships were seen in the correlations with both the northern and southern climate records. Maintaining the summer temperature signal that was so prevalent during the early half of the century, these PC3L sites are primarily located in the southern Yukon or northern B.C. Many of these chronologies were included in an early Southwest Yukon reconstruction chronology (Luckman *et al*., 2002). The Sandpit chronology exhibited a very different response from the other PC3L chronologies showing a strong negative correlation with previous winter/spring (pNovember to April) temperatures. Response results of the chronologies loading on PC4L through PC9L for the 1951-2000 time period were more scattered indicating poorer regional climate-growth signals amongst their chronologies.

5.2.6 **Correlation Patterns Across the Network**

Table 5.17 summarizes the most prominent climate-growth temperature relationships across the entire network, indicating the number of the 73 chronologies that exhibit statistically significant relationships with maximum, mean and minimum

Table 5.16 Correlations between seasonal (3-month) temperatures and ring-width for the 13 PC3L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom).

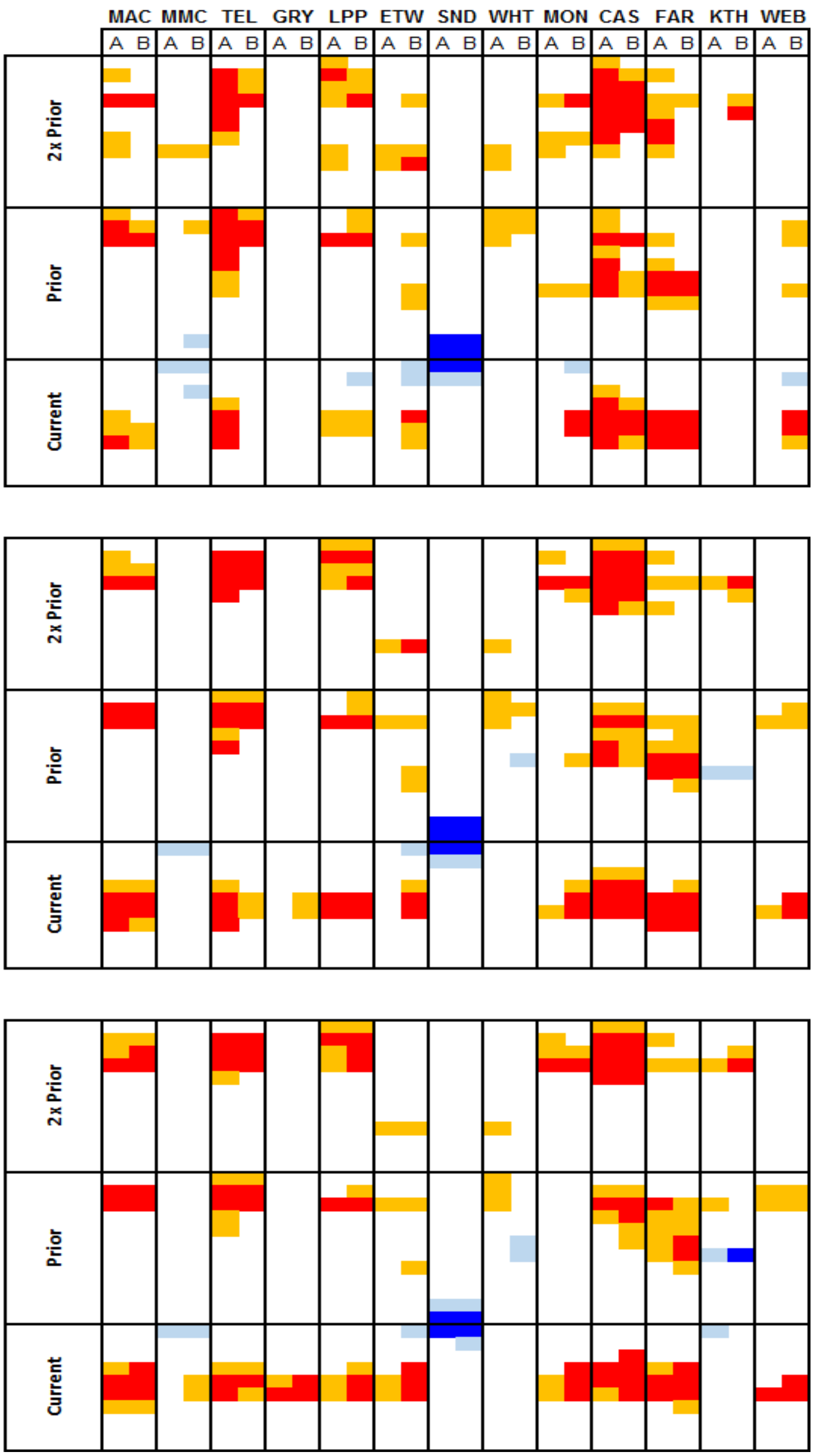


Table 5.17 Summary of the relationships between the 73 ring-width chronologies and 3-month temperatures. The number of significant relationships ($p \leq 0.05$) are shown for minimum, mean and maximum temperatures for the northern (1900-1950 and 1950-2000) and southern (1950-2000) regional series. Colours indicate the percentage of sites correlating significantly.

	MINIMUM TEMPERATURE						MEAN TEMPERATURE						MAXIMUM TEMPERATURE					
	1900-1950 (North)		1950-2000 (North)		1950-2000 (South)		1900-1950 (North)		1950-2000 (North)		1950-2000 (South)		1900-1950 (North)		1950-2000 (North)		1950-2000 (South)	
	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg	Pos	Neg
ppJan-ppMar	14		2	1		1	18	1	2	1	2	1	22	2	2	1	2	1
ppFeb-ppApr	8		8	1	3		10		9		4		13		9		5	
ppMar-ppMay	7		5	14	4		7		6	11	6	9	7		7	5	8	11
ppApr-ppJun	30		9	8	19		24		10	3	16		18		11		15	
ppMay-ppJul	44		5	19	12		34		4	16	10		10		3	7	7	1
ppJun-ppAug	39		5	16	6		3		2	15	3		1			6	1	
ppJul-ppSep	26		7	12	3		1			7		1				4		1
ppAug-ppOct	32		9		2		4							1	1			
ppSep-ppNov	1		6		5				5		3			1	4		1	
ppOct-ppDec																		
ppNov-pJan											1		1				1	
ppDec-pFeb	1		1	1			2		1				3					
pJan-pMar	9		4		4		16		2		3		25		2		1	
pFeb-pApr	7		5	3	7		7		5		7		10		5		6	
pMar-pMay	26		7	21	7		25		9	16	8	7	24		10	8	7	13
pApr-pJun	12		2	29		1	1		3	22	3	3		1	4	10	3	7
pMay-pJul	6	2	4	34	4	1		9	4	32	5	3		13	2	23	3	6
pJun-pAug	4	1	4	20	6	1		15	3	23	6	5		52	1	15	3	5
pJul-pSep	14	1	6	7	12			6	2	5	3	3		27	1	2	2	4
pAug-pOct	26		2	1	3		6			1	2	2				2	2	2
pSep-pNov	4		2	2		2	2		1	1		2			1	2		2
pOct-pDec			1		1				1						1			
pNov-Jan			1	1		3				1		2				1		2
pDec-Feb				8		7		1		7		7		1		7		10
Jan-Mar	3			25		25	5			23		25	6	1		22		28
Feb-Apr	1			33		17	1			33		27				27		33
Mar-May	2		1	42		34	3		1	43	1	39	2			39	1	38
Apr-Jun	10		2	38	1	10	15		3	33	6	9	14		4	27	8	9
May-Jul	47		6	29	11	3	57		6	28	14	3	32		11	20	15	2
Jun-Aug	51		6	15	15		23		9	10	15		4		10	2	14	
Jul-Sep	50		5	23	7	1	11		3	6	3			2	1		2	
Aug-Oct	31			6			9			1		1	3			3		
Sep-Nov	3				1		2				1		1					
Oct-Dec	1					1	1					1	1				2	1

	>70%	60%	50%	40%	30%	20%
POSITIVE						
NEGATIVE						

temperatures for the northern (1900-1950 and 1950-2000) and southern (1950-2000) regional records. As a general observation, the overall pattern of the numbers of significant correlations were minimum > mean > maximum temperatures and 1900-1950N > 1950-2000N > 1950-2000S. During the 1900-1950 period almost all of the statistically significant relationships with minimum temperatures were positive and were primarily associated with summer temperatures during the current growth year and two years prior. More than 70% of the chronologies exhibited significant ($p \leq 0.05$) positive correlations with June-August minimum temperatures and May-July mean temperatures, and 32 chronologies (43.8% of the network) showed significant positive correlations with May-July maximum temperature. Greater than 60% of the chronologies also showed significant positive correlations with May-July and July-September of the current growth year. Strong positive results with summer minimum and mean temperatures were also present in the climate-growth relationships two years prior (i.e. ppMay-ppJuly). Correlation results during the prior growth year showed fewer positive responses. Significant negative correlations with pJune-pAugust maximum temperatures were exhibited by 52 chronologies (71.2% of the network), while 15 chronologies (20.5% of the network) showed significant negative correlations with pJune-pAugust mean temperatures.

Results for the 1950-2000 period showed a scattering of positive significant relationships for all three temperature variables and both climate data sets but were dominated by strong negative correlations, mainly associated with spring/early-summer temperatures. Correlations between chronologies and the northern climate record showed a greater number of significant values than with the southern climate record, especially in responses involving the previous growth year and two years prior (Table 5.17). Both the northern and southern climate records exhibited large numbers of significant negative correlations with winter and spring temperatures of the current growth year. Correlations with current March-May temperatures were the most prominent with 47% or more of the network chronologies expressing this spring signal across the three temperature variables with stronger correlation to the northern rather than the southern record. Results with the southern climate record did show positive correlations with spring temperatures during the current growth year and two years prior (i.e. June-August and ppApril-ppJune) but these positive responses were expressed in less than 25% of the network chronologies.

In general, the early period exhibited very strong positive response patterns particularly with minimum temperatures. During the later period, significant negative correlations became dominant, which also included responses with mean and maximum temperatures. Correlations with temperatures of the northern climate record tended to be greater than those with the southern record.

5.2.6.1 ***Spatial Patterns of Temperature-Growth Responses***

The above analyses show contrasting growth responses to temperatures over the 20th century. Although there is a strong coherent signal in the early record, the relationships change and become more variable in the latter half of the century. This section explores the spatial pattern of these relationships by mapping selected correlation patterns across the network using ArcGIS (version 9.3) for significant seasons identified in the previous analyses.

One of the key seasonal temperature responses was the ‘summer’ (May-July) signal. For all three temperature variables of the northern record, this ‘summer’ signal clearly exhibited positive relationships over the network for the 1900-1950 period (Figure 5.1). Relationships with minimum and mean temperatures were generally stronger compared to maximum temperatures. The strongest correlation ($r>0.361$, $p\leq 0.01$) with mean temperatures showed the most coherent spatial pattern, dominating the central and

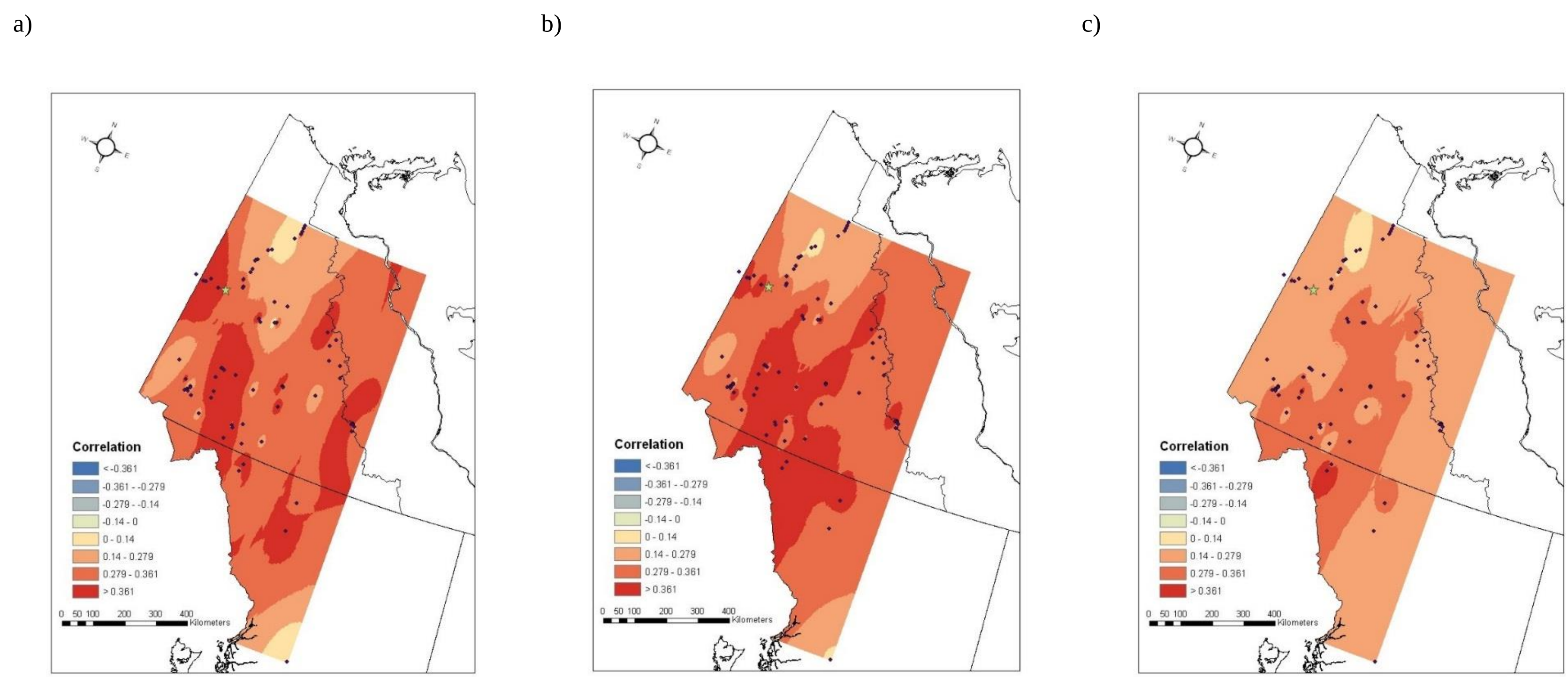


Figure 5.1 Comparison of the correlation patterns of May-July ('summer') (a) minimum, (b) mean, and (c) maximum temperatures of the northern record with ring-width over the 1900-1950 period. Values greater than +/- 0.361 are significant at p=0.01, while values greater than +/- 0.279 are significant at p=0.05.

southern parts of the network (Figure 5.1b). Surprisingly, the weakest correlations were associated with sites located along the northern portion of the Dempster Highway that are some of the closest sites to the Dawson and Mayo climate stations. Examination of the ‘summer’ mean temperature signal across the 20^{th} century showed a notable change in responses (Figure 5.2). While relationships in the earlier half of the century were characterized by positive responses, correlations over the 1950-2000 period showed a marked weakening, with strong negative relationships dominating much of the northern portion of the network. Sites in the southern half of the Yukon showed mainly non-significant values that trended from slightly negative to slightly positive to the south with a few sites in Northern British Columbia retaining a significant ($r>0.279$, $p\leq0.05$) positive relationship (Figure 5.2b).

Comparison of the ‘summer’ mean temperature signal between the ‘northern’ and ‘southern’ climate records over the latter half of the 20^{th} century showed variations in the strength of correlations. Correlations with the ‘northern’ record displayed significantly negative values across the north with mainly neutral values in the Southern Yukon (Figure 5.3a), whereas results with the ‘southern’ record showed a neutral response in the north with weakly positive or significantly positive values in the south (Figure 5.3b). Comparing the ‘summer’ signal across all three temperature variables for the 1950-2000 period, results from the ‘northern’ climate series (Figure 5.4 a-c) showed the area of significantly negative correlations found across the northern half of the network was greatest with minimum temperatures and became progressively less with mean and maximum temperatures, respectively. Conversely, the ‘southern’ climate maps (Figure 5.4 d-f) showed an increase in significantly positive correlations in the southern half of the network. In both cases however, the pattern remains similar.

Another strong signal found within the network was the relationship between ring-width and ‘spring’ (March-May) temperatures. Correlations with ‘spring’ (March-May) mean temperature of the northern record for the 1900-1950 period were mainly weakly positive with higher, though still non-significant, values to the south (Figure 5.5a). The Dempster chronologies in the north are slightly different and exhibit slightly negative ($r = -0.14$-0.00) correlation values (Figure 5.5a). Comparison between the three temperature variables and ring-widths over the 1900-1950 period (not shown) suggested very little

a) b)

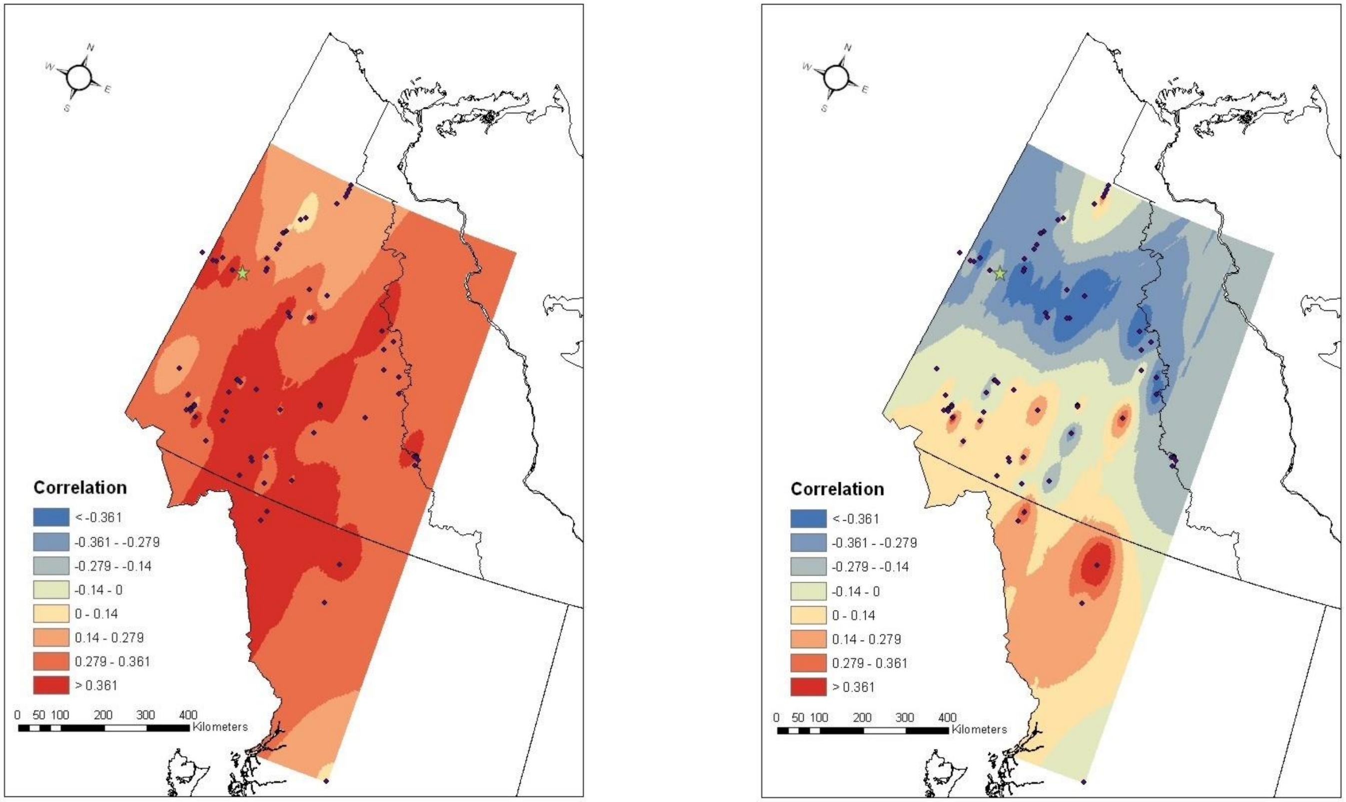


Figure 5.2 Comparison of the correlation patterns between May-July ('summer') mean temperatures of the northern record and ring-width for the (a) 1900-1950 and (b) 1950-2000 periods. Values greater than +/- 0.361 are significant at p=0.01, while values greater than +/- 0.279 are significant at p=0.05.

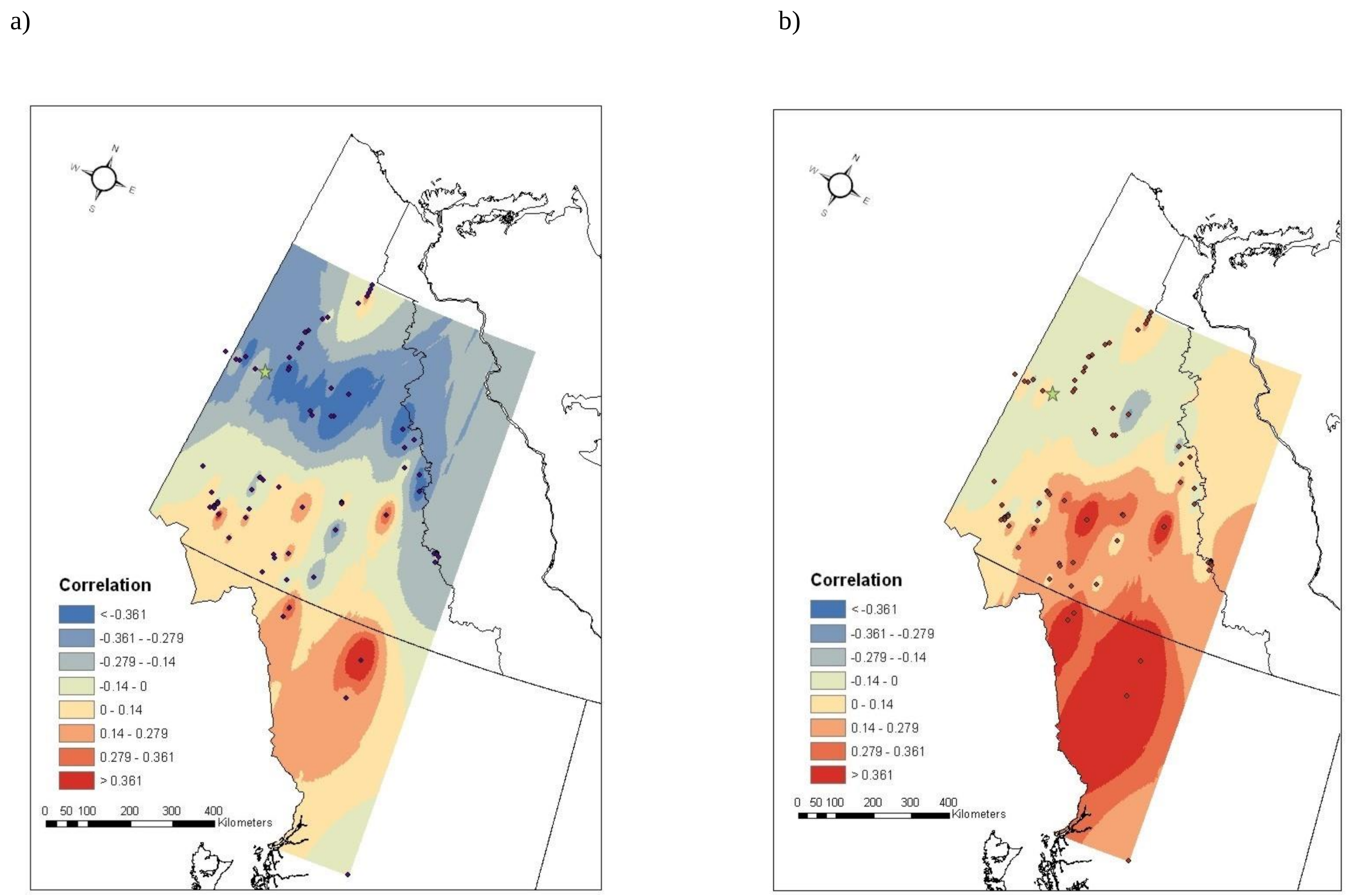


Figure 5.3 Comparison of the correlation patterns between ring-width and the 1950-2000 (a) 'northern' and (b) 'southern' summer (May-July) mean temperature records. Values greater than +/- 0.361 are significant at p=0.01 level, while values greater than +/- 0.279 are significant at p=0.05 level.

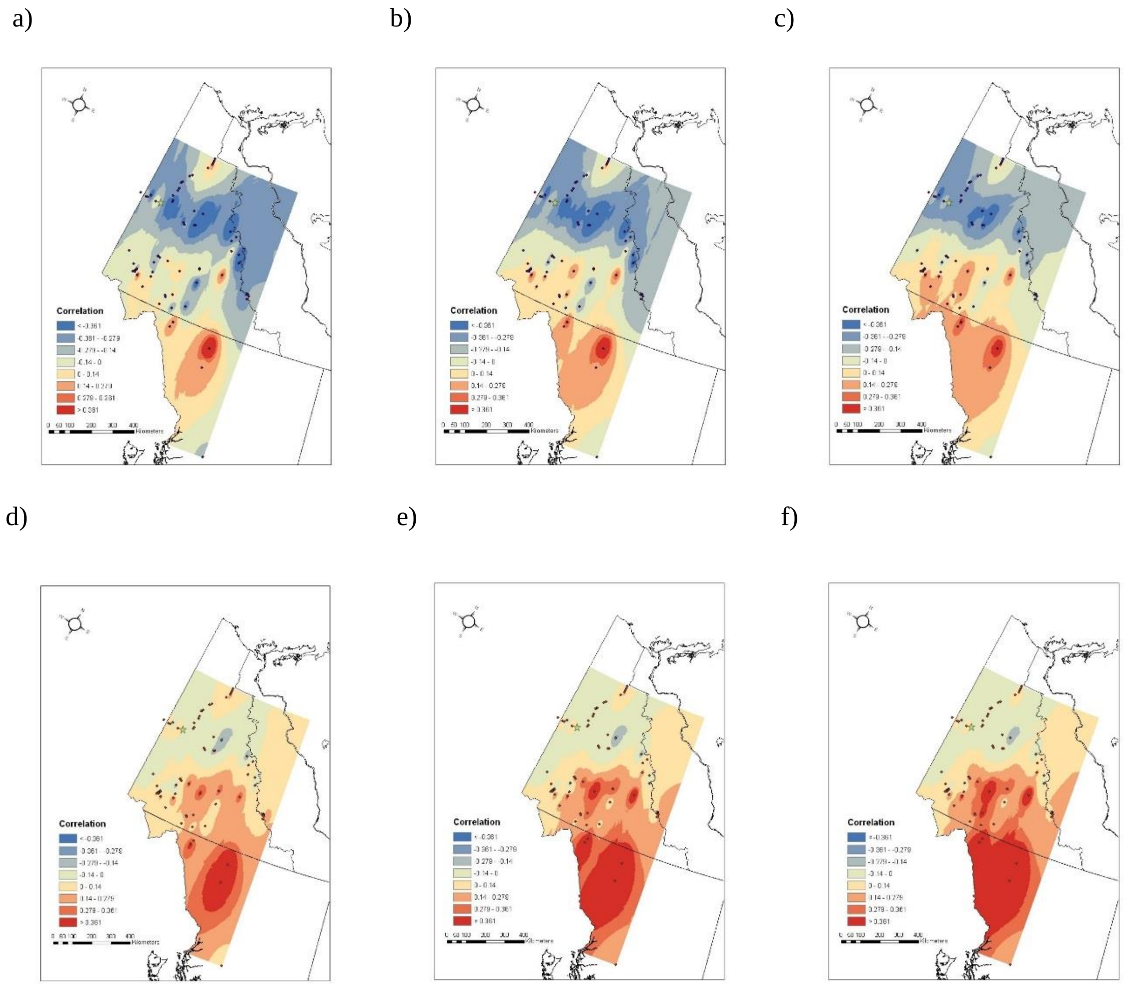


Figure 5.4 Correlation patterns of ring-width and May-July ('summer') (a) minimum, (b) mean, (c) maximum temperatures of the 'northern' climate record for the 1950-2000 period, and (d) minimum, (e) mean, (f) maximum temperatures of the 'southern' climate record for the 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01, while values greater than +/- 0.279 are significant at p=0.05.

a) b)

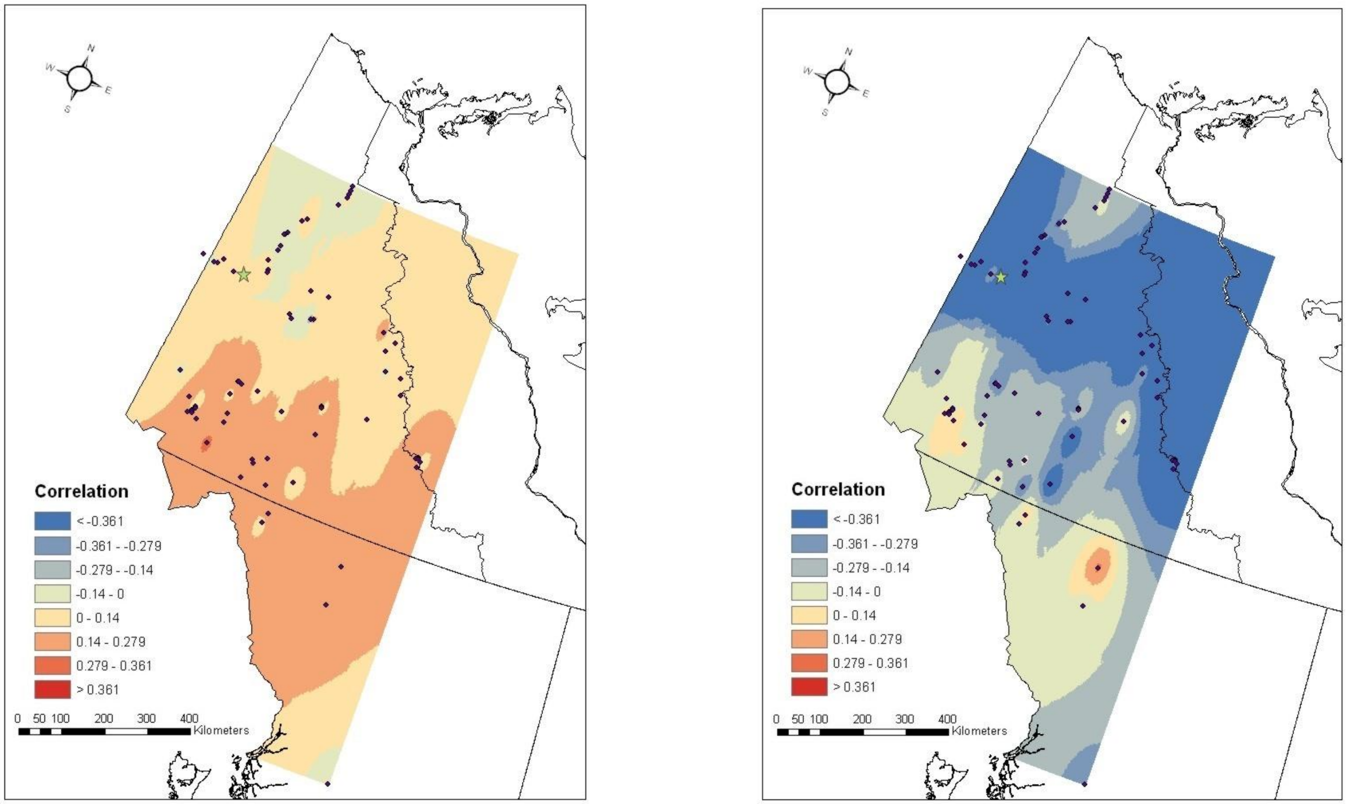


Figure 5.5 Comparison of the correlation patterns between March-May ('spring') mean temperatures of the northern record and ring-width between a) 1900-1950 period and b) 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01, while values greater than +/- 0.279 are significant at p=0.05.

a) b)

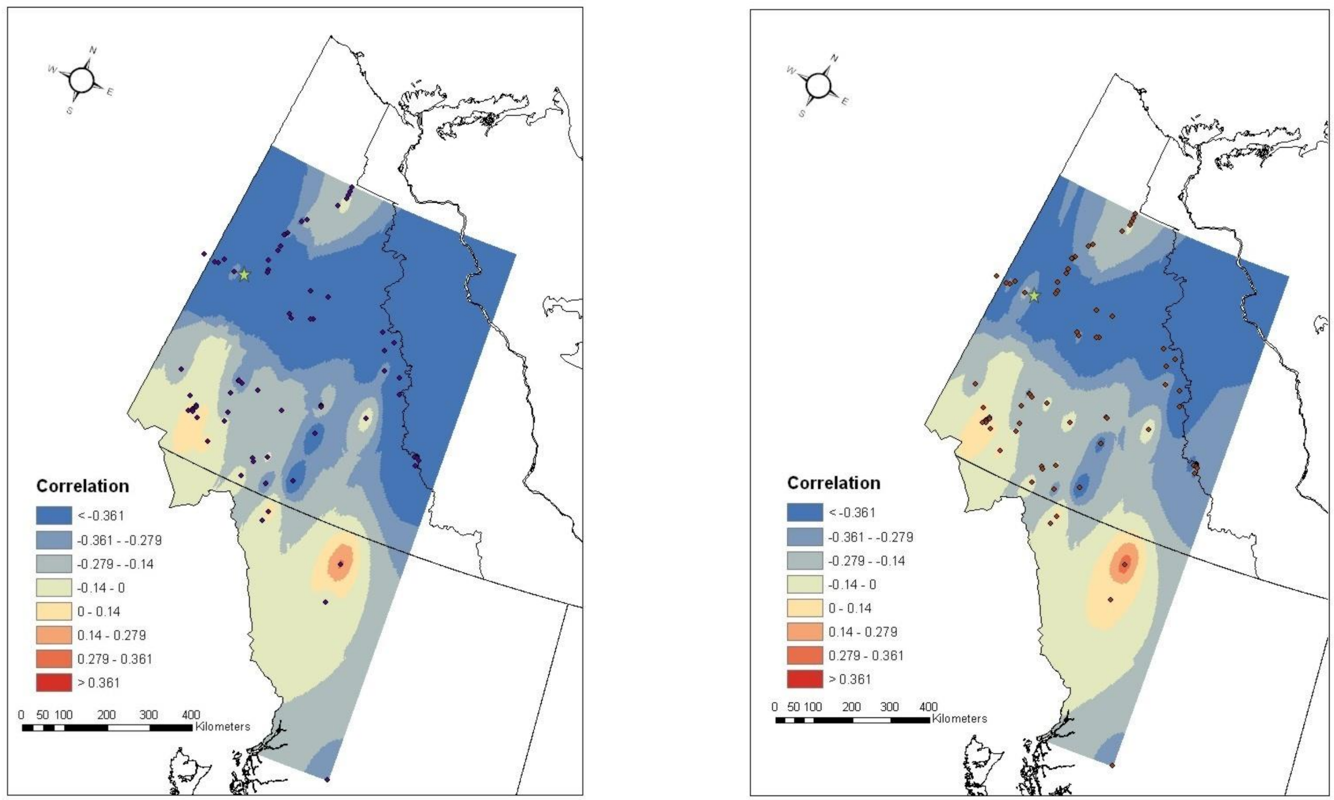


Figure 5.6 Comparison of the correlation patterns between ring-width and the (a) 'northern' and (b) 'southern' 1950-2000 spring (March-May) mean temperature records. Values greater than +/- 0.361 are significant at p=0.01 level, while values greater than +/- 0.279 are significant at p=0.05 level.

variation in the spatial patterns of correlations. Spring (March-May) mean temperature correlations with the northern record over the 1950-2000 period (Figure 5.5b) were almost all negative with only two small pockets of 'weak' positive correlations, one found in the south-west Kluane region and the other near Cassiar in northern British Columbia. Unlike the 'summer' signal, there is little discernable difference in the post-1950 correlation patterns of the 'northern' and 'southern' climate records (Figure 5.6 a & b). Both showed significantly negative values covering much of the northern half of the network and non-significant negative values in the south with a few isolated weakly positive relationships.

Maps of the geographical patterns of responses to 'summer' and 'spring' temperatures clearly demonstrated the variability inherent in these seasonal responses. Temporally, changes in the response for both spring and summer temperatures occur during the 20th century; positive correlations characterize relationships during the first half of the century and negative correlations dominate the second half. During the earlier period, the 'summer' signal showed much stronger (i.e. statistically significant) and regionally extensive positive correlations across the network in comparison to the 'spring' signal which exhibited more neutral values. For the latter half of the century, both seasonal responses displayed strong, significant negative correlations across the northern portions of the network, while maintaining moderately positive relationships in the south. The most dramatic shifts in seasonal correlations appear to be in the responses of chronologies found in the northern half of the network, while relationships in the south exhibit more stability.

5.3 Precipitation-Tree Growth Relationships

5.3.1 Introduction

Several studies have highlighted significant relationships between temperature and tree growth at high latitudes in northwestern North America (e.g. Jacoby and Cook, 1981; Jacoby and D'Arrigo, 1989; Szeicz and MacDonald, 1995; Davi *et al.*, 2003; Youngblut and Luckman, 2008; Porter and Pisaric, 2011). Similar research discussing relationships with precipitation are more limited (e.g. Garfinkel and Brubaker, 1980; Szeicz and MacDonald, 1996; Chavardés *et al.*, 2012; Griesbauer and Green, 2012). In this study, correlation analyses were performed between the tree-ring chronologies and the three regional precipitation series developed in Chapter 4 to investigate potential relationships between precipitation and tree growth in the Yukon.

5.3.2 Correlation Analyses

The analyses of tree-ring-temperature responses indicated that these relationships varied between chronologies and over time. Therefore, the analyses of precipitation-tree-ring relationships focused on the responses of the individual chronologies rather than regional chronologies or the regional groupings developed in Chapter 3. In addition, the analysis was focused on possible differences in response over the two halves of the 20th century using the long ‘northern’ precipitation record, plus studies of the relationships post-1950 with the shorter ‘central’ and ‘southern’ regional precipitation records.

5.3.2.1 *Analyses Using the Northern Precipitation Record*

Examination of precipitation-growth relationships between the two halves of the 20th century used the ‘northern’ regional precipitation record as it was the only precipitation series to span the time periods. Correlation results indicated distinct differences in significant responses between the 1900-1950 and 1950-2000 periods (Table 5.18). During the 1900-1950 period, two regional responses are apparent: a strong positive correlation with previous summer precipitation (pMay-pJuly and pJune-pAugust) and a strong negative correlation with previous early spring (pFebruary-pApril) precipitation. Fifty-two of the 73 chronologies (71.2% of the network) exhibited significant ($p \leq 0.05$) positive correlations with previous June-August precipitation. Most of these chronologies (46 of the 52) loaded on the first principal component (PC1E) of the 1900-1950 ring-width PCA (Table 5.19a). The other six chronologies were Big Gold Creek (PC2E), Bullion Creek, Aishihik (PC3E), Rock River (PC4E) and Divide Spruce (PC5E). This response to summer precipitation is also seen for the two overlapping three month periods namely pMay-pJuly (49/73=67.1%) and pJuly-pSeptember (28/73=38.4%)

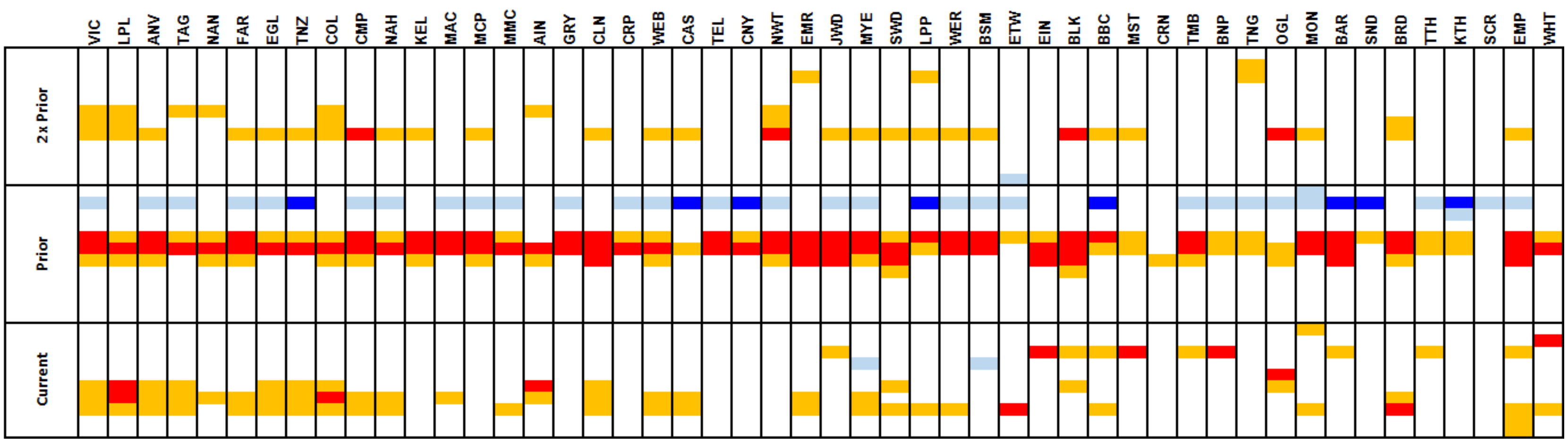
Table 5.18 Summary of the relationships between the 73 ring-width chronologies and 3-month precipitation totals for the 'northern' (1900-1950 and 1950-2000) regional precipitation records. Colours indicate the percentage of sites in the network correlating significantly (p≤0.05).

	1900-1950 (North)		1950-2000 (North)	
	Pos	Neg	Pos	Neg
ppJan-ppMar			1	9
ppFeb-ppApr	1		2	9
ppMar-ppMay	5			18
ppApr-ppJun		1	3	
ppMay-ppJul			3	
ppJun-ppAug	8	1	2	
ppJul-ppSep	6	1	1	1
ppAug-ppOct	30			1
ppSep-ppNov	1		1	29
ppOct-ppDec			3	21
ppNov-pJan			2	19
ppDec-pFeb		2	5	1
pJan-pMar		3	6	2
pFeb-pApr		43	2	1
pMar-pMay		1	1	12
pApr-pJun				1
pMay-pJul	49		4	
pJun-pAug	52		5	
pJul-pSep	28		5	
pAug-pOct	2		6	
pSep-pNov		2	8	1
pOct-pDec			5	1
pNov-Jan		2	4	2
pDec-Feb			3	1
Jan-Mar	3		3	16
Feb-Apr	5		1	8
Mar-May	23			5
Apr-Jun	2	4		5
May-Jul	1	1	1	1
Jun-Aug	12		5	
Jul-Sep	20		1	
Aug-Oct	28			
Sep-Nov	1		3	32
Oct-Dec	1		2	13

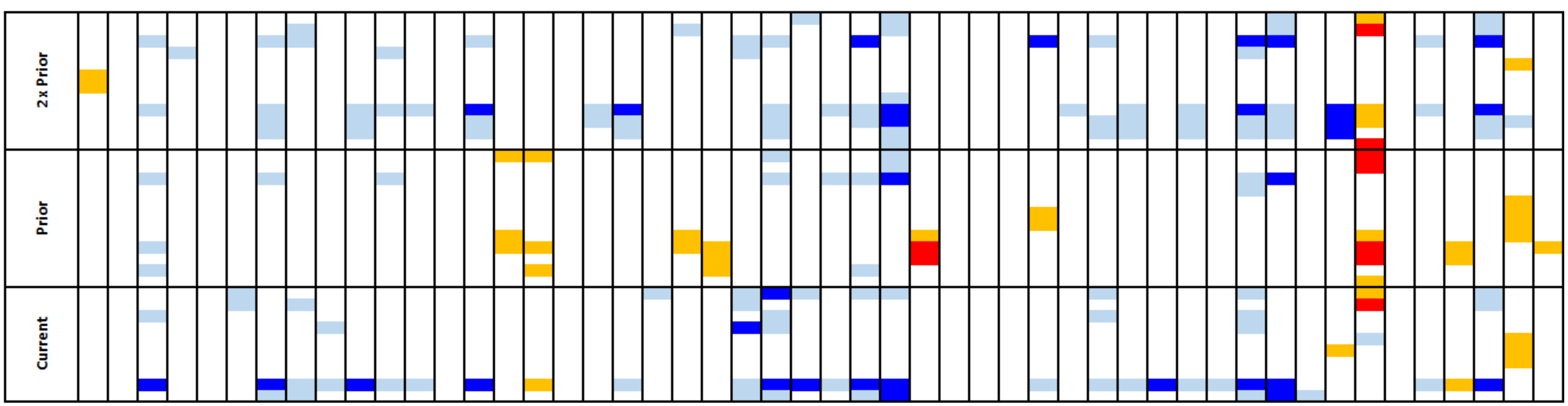
	>70%	60%	50%	40%	30%	20%
POSITIVE						
NEGATIVE						

Table 5.19 Precipitation-growth responses of the 50 chronologies loading on PC1E for the 1900-1950 time period. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for the 'northern' regional precipitation series for (a) 1900-1950 and (b) 1950-2000. The positioning of chronologies (columns) within the table is based on their loadings on PC1E with the highest values on the left.

a)



b)



(Table 5.18). This would appear to be a strong regional signal with correlation values of up to 0.57 for pMay-pJuly. Just under half of the chronologies (30/73) show a weaker, more scattered relationship with August-October precipitation two years prior and between 20-30% of the chronologies show relationships with spring and late summer precipitation in the current growth year.

The strong negative response involving previous early spring (pFebruary-pApril) precipitation during the 1900-1950 period was exhibited by 43 of the 73 chronologies (58.9% of the network). Similar to the summer response, most of the chronologies exhibiting this negative spring signal (36 of the 43) loaded on PC1E (Table 5.19a). The seven other chronologies were Highet Creek, Big Gold Creek, Worm Lake (PC2E), Landslide, Aishihik (PC3E), Vadzaih Kan Creek (PC4E) and Donjek (PCE9).

Climate-growth responses of the 1950-2000 period differed considerably from the earlier period (see Tables 5.19a and 5.19b) Few chronologies (5 chronologies or less, representing less than 7% of the network) displayed the strong positive correlations with previous summer precipitation that were so prevalent during the first half of the 20th century. The negative prior spring (pFeb-pApril) signal found in the earlier period was only found in a single chronology (Swede Dome) from the 1950-2000 responses. The largest numbers of significant correlations for the latter time period were negative and focused primarily on autumn precipitation, two years prior and surprisingly September-November of the current growth year (32/73=43.8%, Table 5.18). These 32 chronologies were distributed across PC1L (16 chronologies), PC2L (9 chronologies) and PC4L (7 chronologies). Significant negative correlations with autumn precipitation two years prior (ppSeptember-ppNovember) were evident in 29 of 73 chronologies (39.7% of network, Table 5.18). Interestingly, significant negative correlation with autumn precipitation during the intermediary growth year (pSeptember-pNovember) was limited to a single chronology, Anvil Mine.

The correlation results obtained using the northern regional precipitation series for the first and second halves of the 20th century suggest that growth responses to precipitation varied over time and seasonality. While relationships during the 1900-1950 period were characterized by positive responses with previous summer precipitation and negative responses with previous early spring precipitation in a majority of the chronologies, relationships during the 1950-2000 period were primarily dominated by negative responses associated with late autumn precipitation.

5.3.2.2 *Comparison of Tree-Ring Responses to the Three 1950-2000 Precipitation Series*

Three regional precipitation series were developed for the latter half of the 20th century and it is possible that these regional series may be more appropriate to evaluate the later precipitation-tree-ring relationships across parts of the network. Table 5.20 summarizes the pattern of correlations for three-month precipitation periods between the three precipitation series.

Although all three precipitation series show a scattering of positive correlations with precipitation, the pattern varies between precipitation series and the only relationship seen in greater than 20% of the chronologies is for prior spring (pFebruary-pApril) with the ‘southern’ precipitation series. The correlation results for these three regional records are dominantly negative and differ in seasonal pattern between the three series. Significant negative correlations with ppMarch-ppMay and ppSeptember-ppNovember precipitation are found with the ‘northern’ and ‘central’ precipitation series but are not seen with the ‘southern’ series (Table 5.20). Strong though slightly different negative responses with current year spring precipitation (April-June and May-July) occurred with the ‘southern’ and ‘central’ series but were rare with the ‘northern’ series.

Comparison of growth responses between the three regional precipitation series revealed two unique significant responses: (a) the positive correlations with pFebruary-pApril precipitation of the ‘southern’ series, and (b) the negative correlations with current September-November precipitation of the ‘northern’ series. The pFebruary-pApril response to the ‘southern’ record was found with 23.3% (17/73) of the tree-ring chronologies but only 2 chronologies were correlated with the ‘northern’ and none with the ‘central’ records. The significant negative correlations with current September-November precipitation of the ‘northern’ series (43.8% of the chronologies, 32/73) are only found for two sites with the ‘central’ record and there are no significant correlations with the ‘southern’ record.

Table 5.20 Summary of relationships between the 73 ring-width chronologies and 3-month precipitation totals for 'northern', 'central' and 'southern' regional precipitation record for the 1950-2000 period. Colours indicate the percentage of sites in the network correlating significantly (p≤0.05).

	1950-2000 (North)		1950-2000 (Central)		1950-2000 (South)	
	Pos	Neg	Pos	Neg	Pos	Neg
ppJan-ppMar	1	9	4	7	2	
ppFeb-ppApr	2	9	5	10	7	2
ppMar-ppMay		18	1	20	6	
ppApr-ppJun	3			6	3	
ppMay-ppJul	3			14	3	4
ppJun-ppAug	2			8	1	
ppJul-ppSep	1	1		11	4	1
ppAug-ppOct		1		11	2	1
ppSep-ppNov	1	29	2	16	2	1
ppOct-ppDec	3	21	2	4	1	
ppNov-pJan	2	19	4	4	1	
ppDec-pFeb	5	1	2	4	1	
pJan-pMar	6	2	1	5	3	
pFeb-pApr	2	1			17	2
pMar-pMay	1	12		5	2	7
pApr-pJun		1		14	2	
pMay-pJul	4			9	4	5
pJun-pAug	5			3		3
pJul-pSep	5		1	2	1	9
pAug-pOct	6		2	2	3	
pSep-pNov	8	1	9	1	11	2
pOct-pDec	5	1	13		3	
pNov-Jan	4	2	6		3	3
pDec-Feb	3	1	3		1	3
Jan-Mar	3	16	2	3	2	4
Feb-Apr	1	8	3	1	9	1
Mar-May		5	2	13	1	6
Apr-Jun		5	2	25		19
May-Jul	1	1		16		29
Jun-Aug	5			6		3
Jul-Sep	1				1	2
Aug-Oct				1		
Sep-Nov	3	32	3	2	5	
Oct-Dec	2	13		1	5	

	>70%	60%	50%	40%	30%	20%
POSITIVE						
NEGATIVE						

5.3.2.3 *Spatial Patterns of Precipitation Climate-Growth Responses*

It appears from the above analyses that correlations with precipitation are generally weak, variable and differ between the regional precipitation series used. The maps in the following section examine the spatial patterns of these correlations to evaluate whether some of these differences reflect spatial differences in precipitation across the region and over time.

Examination of responses across the 20th century using the ‘northern’ precipitation record showed significant previous summer and early spring relationships for the first half of the century but not the second half. Figure 5.7a shows that almost all chronologies showed a significant positive relationship with pJune-pAugust precipitation of the ‘northern’ series before 1950. However, results from sites along the Dempster Highway (some of the closest to the meteorological stations) and in the Kluane-Burwash area, though showing positive relationships, were not statistically significant. Unsurprisingly Smithers, the most southerly site in the network, exhibited a very weak negative correlation. Most sites showed neutral or positive correlations with the June-August post-1950 northern precipitation record but these results were not statistically significant (Figure 5.7b).

a) b)

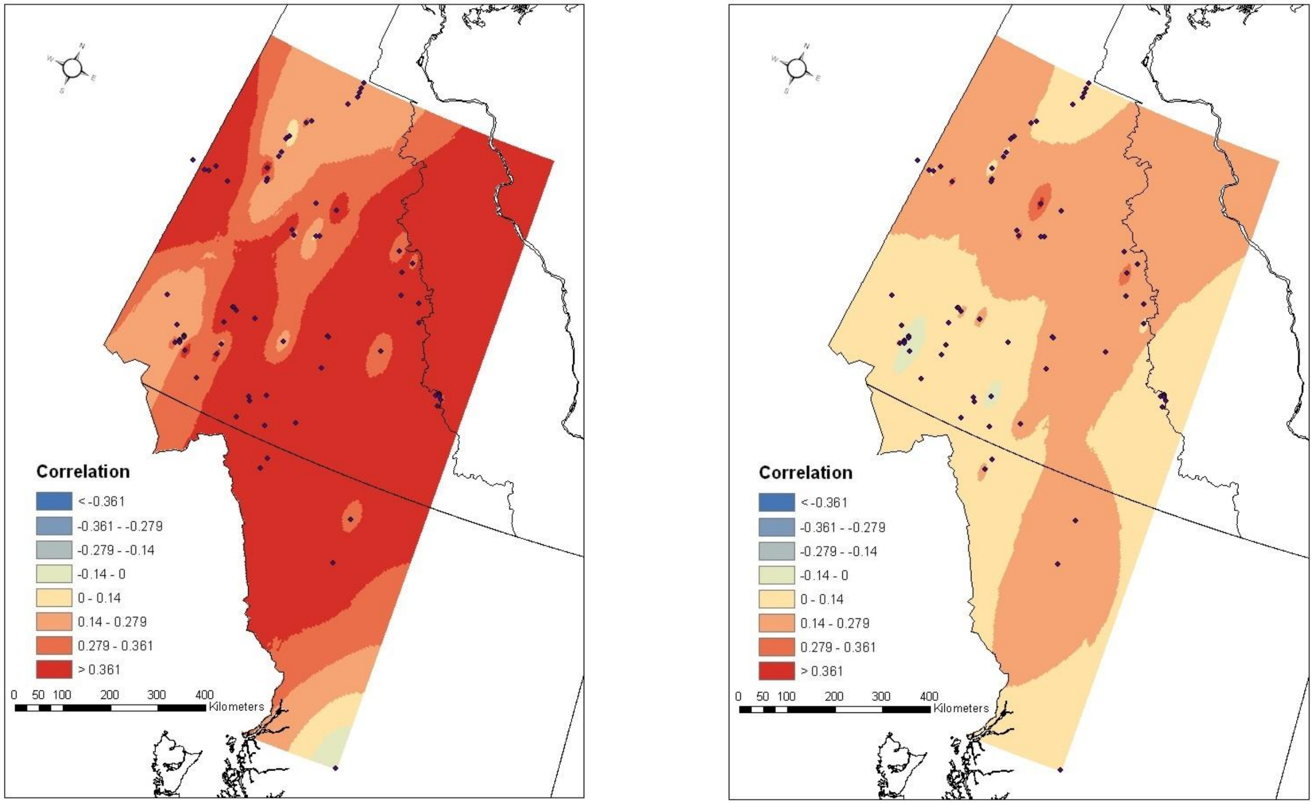


Figure 5.7 Comparison of the correlation between previous summer (June-August) precipitation of the 'northern' precipitation record and ring-width for a) 1900-1950 and b) 1950-2000 periods. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

Mapping of the correlations between previous early spring (pFebruary-pApril) precipitation of the ‘northern’ series and the tree-ring chronologies demonstrated that the entire network showed negative responses during the pre-1950 period, with significant ($p \leq 0.05$) correlations covering much of the central and southern Yukon (Figure 5.8a). Again, the weakest correlations are for northern sites along the Dempster Highway and around Kluane Lake. Only three scattered sites show significant correlations post 1950 (two positive, one negative) and most are weakly correlated (Figure 5.8b). Sites along the Dempster Highway and several of those situated in the eastern half of the network still exhibited negative correlations, though much weaker and non-significant relative to pre-1950 values (Figure 5.8b). Portions of the network in the central-interior and southwest Yukon actually showed positive correlations with pFebruary-pApril precipitation for the 1950-2000 period (Figure 5.8b) although not statistically significant. This represents a distinct change in the climate-growth responses between the first and second halves of the 20th century.

Analyses for the three regional precipitation series post 1950 showed different seasonal relationships between tree-rings and precipitation (Table 5.20). Figures 5.8-5.10 map the spatial pattern of some of the more prominent seasonal relationships to determine whether these reflect regionally based patterns of response within the tree-ring network. The most dominant relationship with the ‘northern’ series was the negative response with current fall (September-November) precipitation (Figure 5.9). These significant negative correlations were concentrated in the northern and eastern portions of the network, while chronologies in the southwest demonstrated weakly positive correlations (Figure 5.9a). Most correlations with the ‘central’ and ‘southern’ precipitation series (Figures 5.9b and 5.9c respectively) were weaker and not statistically significant, showing a reduction in the spatial extent of negative correlations. However, positive if non-significant correlations were evident in the southwest for all three precipitation series, with the strongest relationships with the ‘southern’ precipitation series.

Significant negative correlations with spring precipitation of the current growth year were the strongest post-1950 responses of the ‘central’ and ‘southern’ precipitation series. Strongest correlations with the ‘central’ series were with current April-June precipitation, whereas correlations with current May-July were stronger with the

a) b)

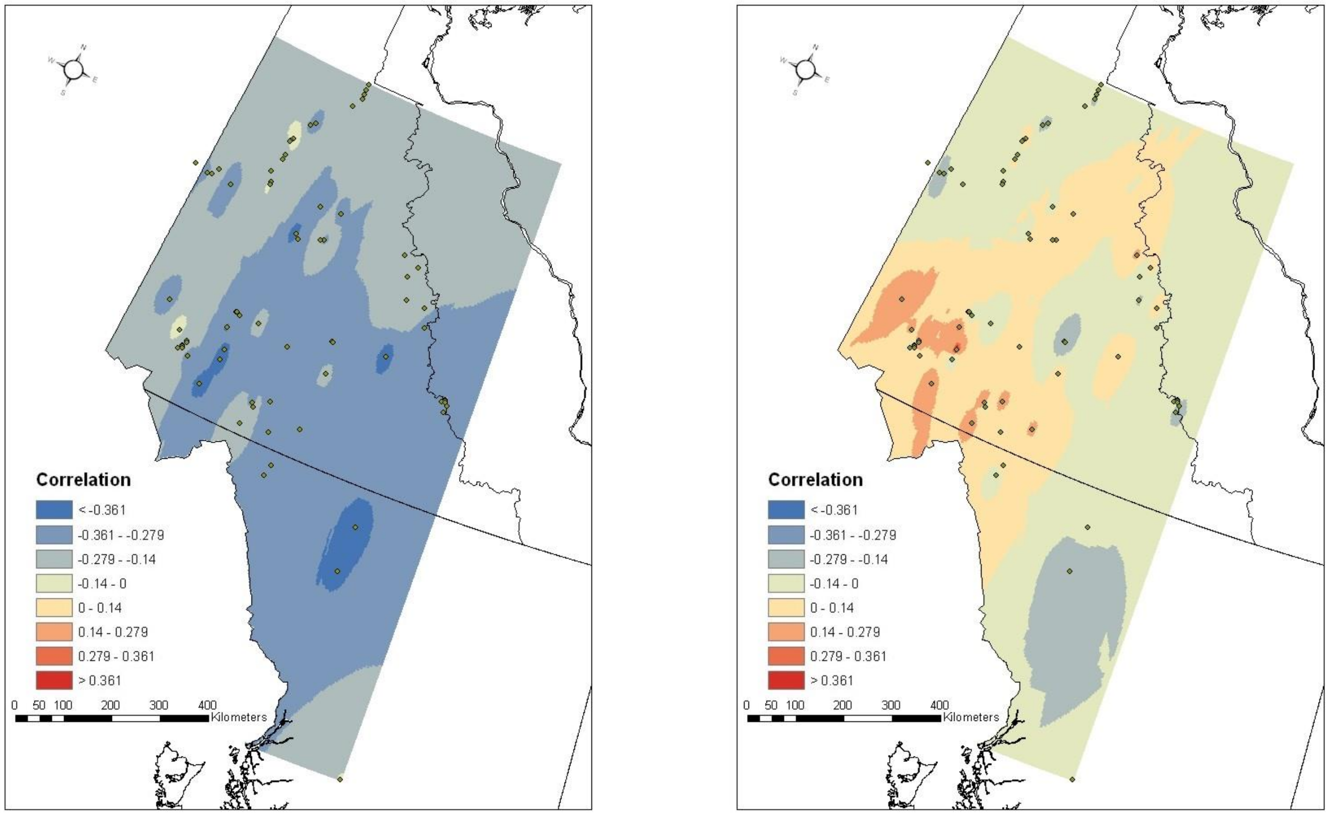


Figure 5.8 Comparison of the correlation between previous early spring (February-April) precipitation of the 'northern' precipitation record and ring-width for a) 1900-1950 and b) 1950-2000 periods. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

a) b) c)

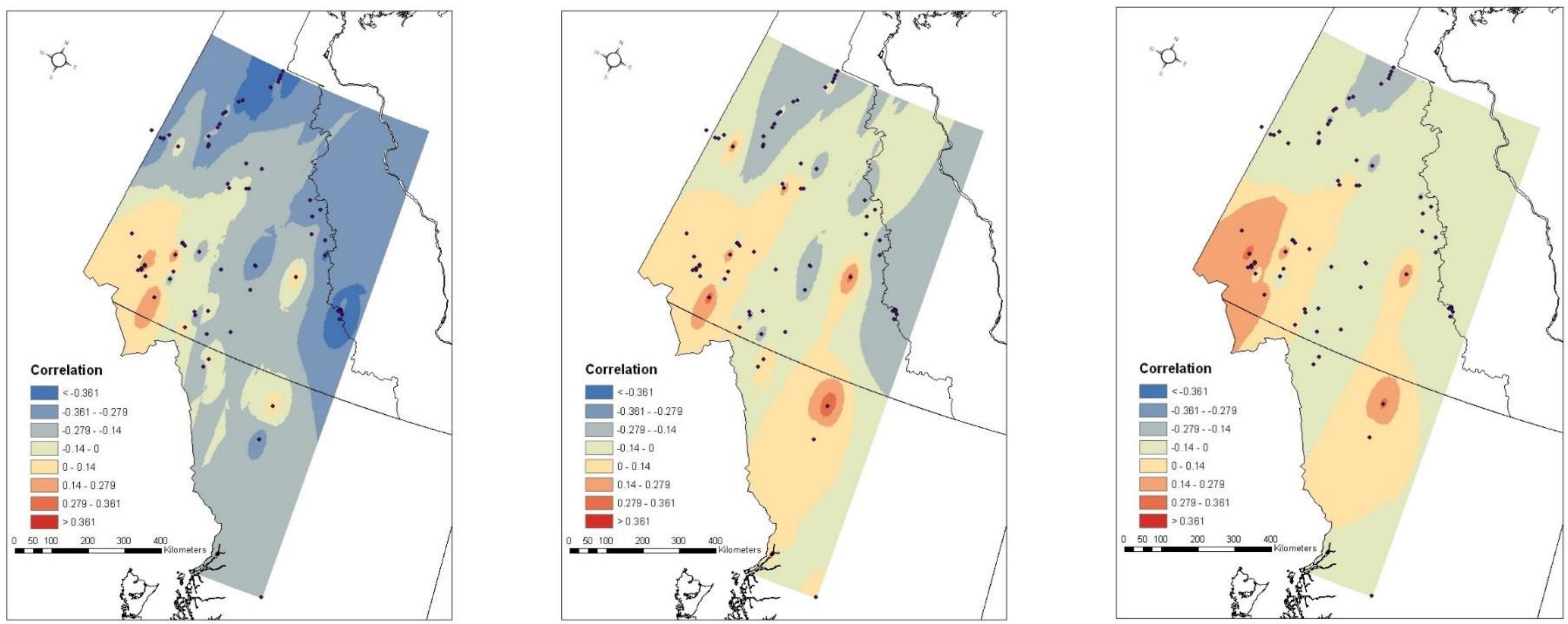


Figure 5.9 Comparison of the correlation patterns between ring-width and September-November (autumn) precipitation for the a) 'northern', b) 'central', and c) 'southern' regional precipitation records for the 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

a) b) c)

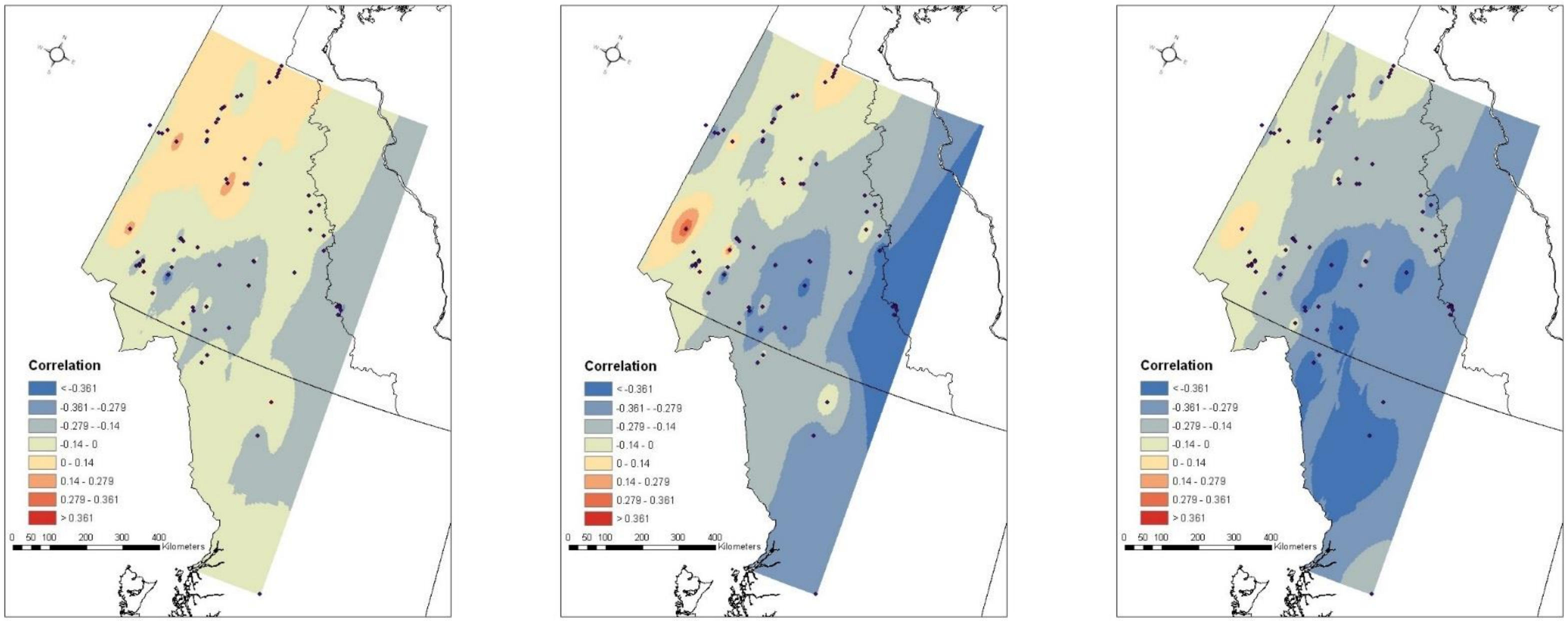


Figure 5.10 Comparison of the correlation patterns between ring-width and April-June (early spring) precipitation for the a) 'northern', b) 'central', and c) 'southern' regional precipitation records for the 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

'southern' series. Maps of the correlations for April-June precipitation (Figure 5.10) showed an east-west gradient across the chronology network, with stronger negative responses found in the east and neutral to slightly positive correlations in the west. Correlation patterns for May-July precipitation (Figure 5.11) were similar to the April-June results, though positive correlations between the 'northern' series and chronologies in the northwest portion of the network were slightly stronger for this later spring window (Figure 5.11a). For both of these periods the strongest correlations were found in the eastern part of the network.

Contrary to the predominantly negative correlations of the post-1950 responses, the 'southern' series showed significant positive correlations with pFebruary-pApril precipitation. Mapping of this response (Figure 5.12c) indicated that the significant positive correlations were concentrated in the northern portion of the network, involving chronologies along the Dempster Highway and in the Wernecke Mountains of central-north Yukon, the most distant sites from the 'southern' climate stations. Correlations between chronologies and pFebruary-pApril precipitation of the 'northern' and 'central' series (Figure 5.12a and 5.12b) did not show any statistically significant responses although the sites in the southwest Yukon (positive to negative) and the Dempster Highway (slightly negative to significantly positive) changed the sign of the relationship between the northern and southern pFebruary-pApril precipitation records.

a) b) c)

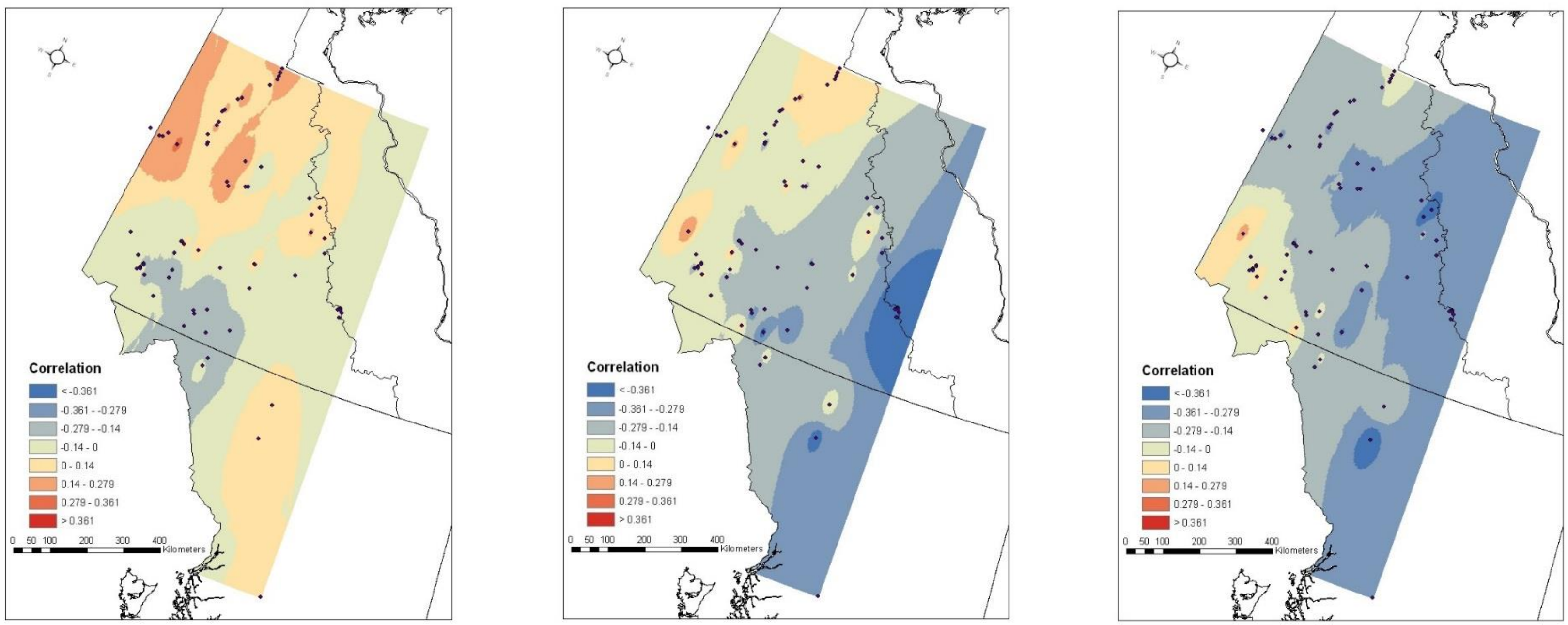


Figure 5.11 Comparison of the correlation patterns between ring-width and May-July (late spring) precipitation for the a) 'northern', b) 'central', and c) 'southern' regional precipitation records for the 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

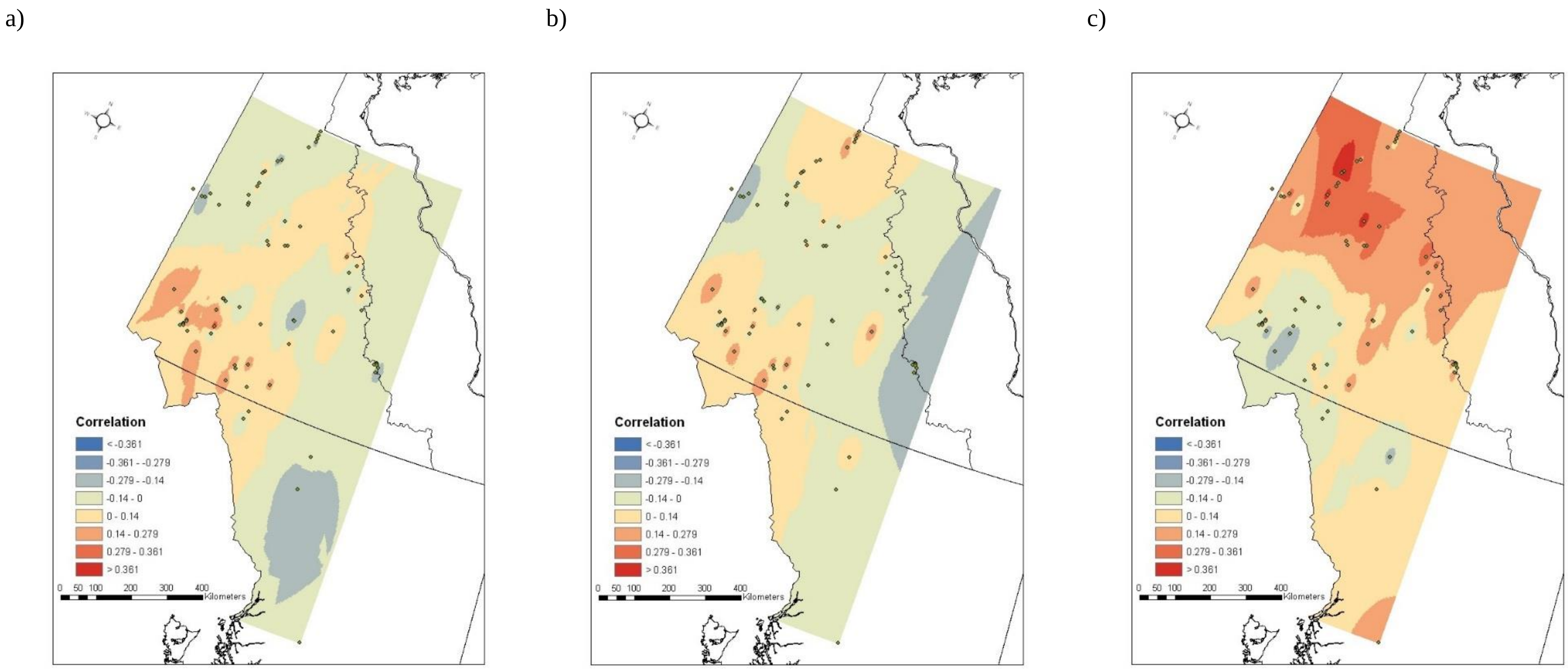


Figure 5.12 Comparison of the correlation patterns between ring-width and previous February-April precipitation for the a) 'northern', b) 'central', and c) 'southern' regional precipitation records for the 1950-2000 period. Values greater than +/- 0.361 are significant at p=0.01. Values greater than +/- 0.279 are significant at p=0.05.

5.4 Conclusions

Evaluation of the climate-growth responses of white spruce in the Yukon Territory has demonstrated the complexity inherent in these relationships. Given the geographical extent of the region and its topographical features, such variations are not altogether unexpected. However ‘divergence’ effects involving temperature relationships, reported for some northern latitude sites, are also a contributing factor to the complicated climate-growth relationships. Through the use of correlation functions to quantify the relationships between climate and interannual growth, key significant responses were determined.

5.4.1 Temperature-Growth Relationships

Previous studies reported strong relationships between summer temperatures and ring-width growth for high-latitude regions (e.g. Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981; Szeicz and MacDonald, 1995; Youngblut and Luckman, 2008). Initial analyses in the current study examined correlations between two regional temperature series (1900-2003 and 1939-2003) and six regional tree-ring chronologies developed by averaging 73 chronologies selected on the basis of PCA over the 1800-2000 period. The correlation results of these regional series with monthly temperature data indicated that while some responses were common across the regional chronologies, other responses appeared to be more regionally specific. The strong summer temperature relationship reported in previous studies was exhibited by the regional chronologies of the current study. A significant positive signal with current June maximum temperature was recorded by all the regional chronologies (except Dempster chronology) in the correlations with the northern climate series. Against the southern series, all but the Kluane chronology displayed significant positive correlations with current June maximum and mean temperatures. These correlations were generally stronger with the southern temperature record than the northern record. The current study also revealed strong negative correlations with previous July temperatures of the northern record. This signal was the most widespread across the regional groups with all regional chronologies exhibiting significant values with previous July maximum temperature, while all but the Southwest Yukon chronology also displaying strong negative correlations with previous July mean temperature. Against the southern temperature record though, only the Southwest Yukon and Kluane chronologies indicated significant negative correlations with previous July temperatures. Negative responses with current April temperatures of both the northern and southern climate records were displayed by the Dempster, Central-North Yukon and Central-South Yukon regional chronologies, with stronger correlation values occurring with the southern series.

Correlation analyses involving 3-month averaged (seasonal) temperature data emphasized the major relationships exhibited by the regional chronologies by removing many of the weaker, isolated correlation values derived from the single-month analyses. Against the northern climate record, the strong negative relationship with previous summer temperatures was again evident, with all but the Kluane regional chronology exhibiting significant ($p \leq 0.05$) negative correlations with pJune-pAugust maximum temperatures. Against the southern record, none of the regional chronologies showed significant correlations with previous summer temperatures. Negative responses with current spring (March-May) temperatures, with both the northern and southern climate records, were recorded by the Dempster and Central North regional chronologies. The analyses with 3-month averaged temperature data did highlight distinct positive responses exhibited by the Southwest Yukon and Kluane regional chronologies. Both regional chronologies displayed significant ($p \leq 0.05$) positive correlations with current spring/summer temperatures of the northern record. The Southwest Yukon chronology further displayed strong positive relationships with early year (i.e. January through May) temperatures during the previous two growth years. This pattern was particularly evident in the responses with the northern record, though correlation values with the southern record during the prior year were found to be stronger.

Utilizing the length of the northern climate record which spanned the entire 20th century, correlations with the regional chronologies were separated into 1900-1950 and 1950-2000 time periods. Results from this analysis revealed that significant ($p \leq 0.05$) relationships during the early period were primarily positive, while most significant responses for the later period were negative. An exception to this pattern was the strong negative relationship with previous summer (pJune-pAugust) maximum temperatures during the 1900-1950 period. All six regional chronologies displayed significant negative correlations with pJune-pAugust maximum temperatures (Table 5.6). The Dempster and

Central-North Yukon chronologies continued to exhibit this significant negative signal with summer temperatures (maximum and mean) in the 1950-2000 period. Significant correlations during the current growth year appeared to show the most dramatic change with most regional chronologies displaying positive relationships with spring/summer (May-July) temperatures during the first half of the century, only to be replaced by negative responses during the second half. The only chronology not to exhibit any significant negative correlations during the 1950-2000 period was the Kluane chronology.

Examination of the temperature versus ring-width relationships for the individual chronologies within each PCA-defined regional grouping indicated that strong differences in response patterns occurred between chronologies within these groups and, in addition, similar response patterns occurred for some chronologies included in different regional groupings. The PCA used to define these regional groupings was based on the period from 1800-2000 and these groupings may reflect similarities or differences between chronologies from the period prior to the instrumental climate record. Therefore additional analyses of climate-growth responses of individual chronologies were carried out using chronology groupings based on PCA using ring-widths covering the 1900-1950 and 1950-2000 periods of the instrumental climate records.

PCA results using ring-width chronologies for the first and second halves of the 20th century indicated strong differences in chronology groupings compared with those from the 1800-2000 analysis and also between the two time periods (compare Table 3.20 with Tables 5.11 and 5.14). PCA for the 1900-1950 period indicated a strong common growth pattern with 50 of the 73 chronologies loading on the first principal component (PC1E). However, only 22 chronologies loaded on the first PC (PC1L) of the 1950-2000 period, indicating more diverse post-1950 responses of these chronologies. Therefore examination of the relationships between individual tree-ring chronologies and seasonal 3-monthly averaged temperatures were undertaken separately for both intervals using the ‘northern’ temperature record. Results were also examined for the post-1950 period using the ‘southern’ temperature series.

The most dominant temperature response amongst the chronologies during the 1900-1950 period was a positive relationship with current summer temperatures. Over 78% (57 of 73 chronologies) exhibited significant ($p \leq 0.05$) positive correlations with current May-July mean temperature with a mean correlation value of 0.31. Mapping of this signal (Figure 5.1a) indicated that the strongest correlations were concentrated in the central-southern portion of the Yukon, while weaker values were found in the north along the Dempster Highway. Correlations with May-July minimum temperatures showed a more scattered pattern of significant values, while relationships with maximum temperature showed similar spatial patterns to mean temperature but with weaker values (mean correlation of 0.25). Many sites also showed significant correlations with current June-August minimum temperature with almost 70% (51/73) of chronologies showing significant positive responses with a mean correlation of 0.33. Only 23 chronologies displayed significant correlations with June-August mean temperature (mean value of 0.24), and 4 chronologies with June-August maximum temperature (mean correlation of 0.09). The significant response to minimum temperatures, particularly early in the summer season, may be a result of warmer temperatures extending the growing season of white spruce (Porter *et al*., 2013). A strong positive response with May-July minimum temperatures two years prior (ppMay-ppJuly) was also witnessed. Just over 60% (44/73) of chronologies exhibited this positive relationship with a mean correlation value of 0.30. This was stronger than the results with ppMay-ppJuly mean temperature (34/73 chronologies; mean value of 0.25) or maximum temperature (10/73 chronologies; mean correlation of 0.15). A strong negative relationship with previous June-August maximum temperatures was recorded by over 71% (52/73) of chronologies (mean value of -0.33). This signal is not dominant in the responses with previous June-August mean temperature (15/73 chronologies; mean value of -0.19) or minimum temperature (1/73 chronologies; mean correlation of 0.08). Warm summer temperatures during the previous growth year may limit carbohydrates reserved for following growing season (Griesbauer and Green, 2012). These results are consistent with other studies of white spruce in neighbouring Alaska (e.g. Barber et al., 2000; Lloyd and Fastie, 2002).

Analyses of the 1950-2000 temperature-growth responses were dominated by negative relationships. Many of the chronologies which exhibited strong positive responses during the early half of the 20th century (PC1E group) display significant negative responses during the second half (Tables 5.12 and 5.13). The most dominant response during this later time period was a strong negative relationship with current spring (March-

May) temperatures of the 'northern' record with 59% (43/73) of the chronologies showing significant correlations ($p \leq 0.05$) with an average value of -0.29. These negative correlations were primarily from sites located in the northern half of the network (Figure 5.3b). This supports findings by Pisaric *et al*. (2007), Earles (2008) and Porter and Pisaric (2011) indicating shifts from positive to negative responses between the two halves of the 20th century for sites in northwestern Canada. Within the current study, significant negative relationships were also recorded with March-May temperatures of the 'northern' record for the post-1950 period (minimum temperature: 42/73 chronologies; mean temperature: 43/73 chronologies; maximum temperature: 39/73 chronologies). Both the 'northern' and 'southern' temperature series displayed relatively similar negative spring (March-May) responses during the current growth year, both in terms of numbers of significant correlations (Table 5.17) as well as in spatial patterns (Figures 5.6a and 5.6b). While the responses during the 1950-2000 period were dominated by negative relationships, 13 chronologies managed to maintain positive relationships with summer temperatures. Eight of these chronologies (MacDonald Lake, Telluride, Lapie Pass, Eagle 12, Monarch, Cassiar, Faro and Webber Creek) loaded together on PC3L and were primarily located in the southern Yukon and northern B.C. These chronologies exhibited significant positive correlations with summer temperatures (especially June-August maximum temperatures) of both the "northern" and "southern" climate series. The remaining chronologies (Mt. Berdoe, Tanzilla Butte, Canyon Lake [PC1L]; Tsivii Creek [PC4L]; and Bullion Creek [PC5L]) exhibited positive correlations with summer temperatures of the "southern" record. Maps of the post-1950 responses to summer temperature clearly showed positive correlations concentrated in the southern portion of the network for both the "northern" and "southern"records, with maximum temperature correlations of the "southern" record being the most widespread (Figure 5.4).

5.4.2 **Precipitation-Growth Relationships**

This study is the first comprehensive attempt to examine precipitation-growth relationships across the Yukon Territory. The tree-ring response to precipitation also showed changes over the 20th century. During the 1900-1950 period, many sites show a strong positive correlation with previous summer (pJune-pAugust) precipitation and a strong negative relationship with previous early spring (pFebruary-pApril) precipitation. The strong prior summer response was registered by over 71% (52/73) of the chronologies in the network with a mean correlation value of 0.34. These significant correlations covered most of the network, with slightly weaker (non-significant) positive correlations appearing in the north along the Dempster Highway and in the southwest corner of the Yukon (Figure 5.7a). The significant negative response with previous early spring (pFebruary-pApril) precipitation was exhibited by 59% (43/73) of the tree-ring chronologies with a network average value of -0.27. These significant ($p \leq 0.05$) negative correlations extended across the central and southeastern portions of the network, with strongest correlations ($\geq$ -0.361) appearing in small areas in northern B.C., eastern and southwestern Yukon (Figure 5.8a).

Correlations with precipitation for the 1950-2000 period were much weaker than those of the earlier period, with fewer significant correlations in the network (Table 5.20). Negative relationships dominated. Although some spatial patterns are present in the response maps for this later period, most correlations were not statistically significant ($p \geq 0.05$). Three regional precipitation records are available for the post-1950 period and the correlation patterns vary with the precipitation record used. The strongest post-1950 relationships were negative relationships with autumn (September-November) of the northern record in the current growth year and two years prior. However, these autumn correlations were displayed by less than 44% of the chronologies in the network and were concentrated in the northern and eastern portions of the network (Figure 5.9a). Autumn correlations with the ‘central’ and ‘southern’ precipitation series were non-significant (Figures 5.9b and 5.9c). However, although not statistically significant, correlations with September-November precipitation in the southwest corner of the Yukon were consistently positive for the 1950-2000 period, regardless of the regional precipitation series examined. This differs from the results of Charvadés *et al*. (2012) which documented negative correlations with previous growing season precipitation for spruce in the southwest Yukon after 1977. This contrasting response for the southwest Yukon may reflect moisture requirements for growth during the current growth year in the rain shadow of the St. Elias Mountains. Significant negative correlations with current spring (April-June and May-July) precipitation were evident in relationships with the ‘central’ and ‘southern’ precipitation records respectively. These spring signals were not seen in correlations with the 'northern' precipitation record, suggesting some difference between the regional records. These significant spring correlations, represented by 34-40% of the network chronologies, were primarily restricted to small pockets found in the eastern half of the network (Figures 5.10 and 5.11).

5.4.3 Implications for Climate Reconstruction

The examination of climate-tree growth relationships in the Yukon clearly indicates that these relationships are complex. Many of the sites examined in this thesis clearly demonstrate a divergent response to climate over the 20th century. Significant responses for both temperature and precipitation not only show evidence of spatial variations across the network and between climatic variables, but also exhibit changes over time. Results indicate that chronologies in the northern portion of the network experienced the most dramatic changes in relationships to temperature over the 20th century, shifting from primarily positive responses to summer temperatures during the first half of the century to negative responses in the second half. Relationships involving precipitation, though weaker, also indicate changes in response during the latter half of the 20th century. Such complexities and changes in the climate-growth responses of white spruce to temperature and precipitation create significant challenges for the development of regional climate reconstructions from spruce ring-width records for the Yukon.

A primary initial goal of this research was to use this tree-ring network to develop one or more long regional temperature reconstructions for the Yukon following the earlier successful work by Youngblut (Luckman *et al*., 2002). The lack of a consistent temperature signal in most of the chronologies violates one of the primary underpinnings of dendroclimatology, namely the principle of uniformitarianism (Fritts, 1976). Several potential mechanisms have been proposed to explain the divergence phenomenon but none has, as yet, been comprehensively accepted (D'Arrigo *et al*., 2008)

There are, nevertheless, a number of potential ways to develop a reconstruction from these data. One strategy would be to calibrate the reconstruction based only on the pre-1950 responses. This process would avoid the loss of signal experienced during the second half of the 20th century, though problems with verification of the model(s) would arise due to the short pre-1950 instrumental climate records for the Yukon. Verification is commonly conducted by splitting the full calibration period into two sub-periods; calibrating on one sub-period and using the other sub-period to verify against (Fritts and Guiot, 1990). By eliminating the post-1950 period, this split-period verification approach would be limited to only those stations with climate data extending back to the beginning of the 20th century (i.e. essentially just the Dawson record (1898), the Mayo record only goes back to 1925). Another issue with this strategy is that it assumes that response changes are limited to the post-1950 period. While this study determined that response differences existed between the pre- and post-1950 periods, it has not established when each signal began exhibiting changes. Pisaric *et al*. (2007) actually detected divergence effects beginning as early as AD 1900 in the Mackenzie Delta region.

Another potential approach would be to select only those chronologies in the network which exhibit consistent, stable climate-growth responses over the 20th century. While this would circumvent the issue of temporal shifts in responses and provide adequate calibration-verification period lengths, the sparse number of chronologies exhibiting such responses is an issue. Only 5 chronologies (Faro, MacDonald Lake, Cassiar, Telluride, Tsiivii Creek) display significant ($p \leq 0.05$) positive correlations with summer (June-August) minimum temperatures of the 'northern' climate record for both halves of the 20th century. While MacDonald Lake, Cassiar and Telluride are found in the southern portion of the network, Faro is situated in the central Yukon and Tsiivii Creek is located along the Dempster Highway in the northern Yukon, making it quite difficult to develop a 'regional' reconstruction. Pisaric *et al*. (2007) and Earles (2008) found that individual sites sometimes contained sub-populations within-stand which exhibited contrasting responses. While many trees exhibited negative temperature-growth trends during the latter half of the 20th century, some tree series continued the positive trends experienced during the first half of the century. By individually selecting those trees exhibiting diverging trends and excluding them from the chronology, it may be possible to increase the number of site chronologies usable for a reconstruction. In their development of a temperature reconstruction for the Mackenzie Delta region, Porter *et al*. (2013) applied such an approach but rather than excluding divergent series totally they excluded only the divergent portions of each tree series. Such an approach would require detailed examination of the changes in response to determine when exactly the loss of signal could be detected. Due to the extremely large number of individual trees in the network, this procedure was not conducted in the current study. Youngblut and Luckman (2008) did develop a summer maximum temperature reconstruction for the southwest Yukon. Fortunately, this region is one of the few areas in the Yukon in which chronologies did not exhibit significant 'divergent' shifts from strongly positive responses to strongly negative responses, as seen in the PC3L responses of this study.

Each of these strategies possesses inherent challenges which would be problematic in the development of a climate reconstruction based on the ring-width data. An additional possibility would be to examine another temperature sensitive parameter from the tree-ring chronologies. Prior studies have shown that tree-ring density (in particular, maximum latewood density (MXD)) can be useful for temperature reconstructions (e.g. Parker and Henoch, 1971; Schweingruber *et al*., 1978; Briffa *et al*., 1988). Therefore 15 densitometric chronologies were also developed as part of this study. Chapter 6 will explore the possibility of obtaining stronger temperature-density relationships from these chronologies that could be used to reconstruct past temperatures in this region.

CHAPTER SIX

Development of White Spruce Tree-Ring Density Network Within the Yukon Territory, Canada

6.1 Introduction

Although the majority of studies of tree-ring climate relationships have used ring-width parameters, variations in tree-ring density have also provided important information regarding relationships between tree growth and climate (Polge, 1970; Parker and Henoch, 1971; Schweingruber *et al*., 1978; Schweingruber, 1989; D'Arrigo *et al*., 1992). X-ray densitometry determines the variations of wood density within annual growth rings by measuring the optical transparency of x-ray films of the tree-ring samples. Maximum latewood density (MXD) has been found to correlate significantly with temperature, particularly summer temperatures (Parker and Henoch, 1971; Briffa *et al*., 1992; Jacoby and D'Arrigo, 1995). In the present study, tree-ring density was measured from a subset of tree-ring sample sites in the Yukon network and combined with six previously sampled density chronologies available from the International Tree-Ring Data Bank (ITRDB). This chapter discusses the development and assessment of these maximum density tree-ring chronologies, evaluates the tree-ring density/climate relationships and develops a summer temperature reconstruction from these data.

6.2 Previous Work

The first studies of tree-ring density characteristics are attributed to Hubert Polge (Polge, 1963). Using his x-ray densitometric method, Polge (1970) demonstrated that crossdating of tree rings could be conducted with greater precision by examining ring-density rather than the commonly studied ring-width. Ring-width is related to cell numbers and cell-enlargement, whereas ring-density is related to cell size and cell-wall thickness (Schweingruber and Briffa, 1996). Parker and Henoch (1971) demonstrated the dendroclimatic potential of tree-ring density data in their study of Engelmann spruce near Peyto Lake, Alberta. Their work showed that MXD was significantly correlated with mean maximum air temperatures for the month of August (Parker and Henoch, 1971). Schweingruber *et al*. (1978) developed one of the first climate reconstructions based on

MXD data. In their study of Swiss alpine trees, they found a significant relationship between summer temperatures and MXD and also concluded that minimum density data possessed little significant information regarding climate (Schweingruber *et al*., 1978).

Two key figures in the research of northern North American tree-ring densitometry are Fritz Schweingruber and Gordon Jacoby. Based at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) Laboratory in Birmensdorf, Switzerland, Fritz Schweingruber and his colleagues are responsible for several extensive tree-ring networks which extend across the Northern Hemisphere. Portions of his western North American network (Schweingruber, 1988; Briffa *et al*., 1992) and northern North American network (Schweingruber *et al*., 1993; Briffa *et al*., 1994) include sites from the Yukon and British Columbia. Results from his research indicated that MXD chronologies generally exhibit strong positive relationships with spring and late summer temperatures (Schweingruber *et al*., 1993) and usually show strong common variance over large areas (Schweingruber, 1988; Schweingruber and Briffa, 1996). Densitometric research conducted by Gordon Jacoby and his associates at the Lamont-Doherty Earth Observatory (LDEO) Tree-Ring Laboratory at Columbia University, New York have primarily targeted northern latitudinal and/or elevational tree-line sites, where trees are growing at temperature-defined limits of forest growth (Jacoby and D'Arrigo, 1995). Their research has included sites in the Northwest Territories and Nunavut (D'Arrigo *et al.*, 1992; D'Arrigo and Jacoby, 1993; D'Arrigo *et al*., 2009) and Alaska (Jacoby and D'Arrigo, 1995; Davi *et al*., 2003; D'Arrigo *et al*., 2004b). Their work has shown that ring-width and MXD parameters can respond to and record temperatures of different seasons even within the same trees (D'Arrigo *et al*., 1992; Jacoby and D'Arrigo, 1995).

The issue of divergence, the weakening of temperature sensitivity in recent decades, has been documented in many northern North American ring-width studies (see Chapter 2). Studies involving MXD data have shown contrasting results with regards to this phenomenon. Briffa *et al*. (1998; 2004) have indicated divergence between MXD and increasing summer temperatures for sites at high northern latitudes. D'Arrigo *et al*. (2004b) encountered divergence with their density data, showing a decrease in positive correlations with summer temperatures starting around 1950 and becoming more prevalent after 1970. In contrast, Davi *et al*. (2003) in their study of elevational treeline sites in the Wrangell

Mountains of southeastern Alaska did not find a decrease in temperature sensitivity with their MXD data, though they did document divergence in their ring-width data. Presently, it is unclear as to the exact reasons for this inconsistency with the density response.

6.3 Sampling & Chronology Development

6.3.1 Introduction

In 1984, Fritz Schweingruber sampled five sites in the Yukon and northernmost British Columbia for ring-width and density chronologies as part of the North American data set in his Northern Hemisphere network (Schweingruber, 1988). Cores from these five sites were processed at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) laboratory in Birmensdorf, Switzerland. An additional site (Campbell Dolomite) was sampled by Julian Szeicz in 1993 and later also processed by Schweingruber. Ring-width and density data for these sites were obtained from the ITRDB (Table 6.1). In addition, duplicate sample collections were obtained by UWO field parties from several sites during tree-ring sampling in 2003 and 2004 using standard collection protocols (see Chapter 3). The measurement of x-ray densitometry for tree rings is complex and uses expensive equipment that is only available in a few North American tree-ring laboratories. Nine sites from the UWO network were selected for density analysis based on their length of record and the spatial distribution of suitable sites. These samples were processed at laboratories in Quebec or New York. A summary of the site characteristics is given in Table 6.1.

Table 6.1 Tree-ring density chronology sites. Data from sites marked with asterisk (*) were obtained from the International Tree-Ring Data Bank (ITRDB). Sites have been arranged from north to south.

Site Name	Code	Process	Sampled	Lat. (N)	Long. (W)	Elev. (m)	# Series	# Cores	# Trees	First Yr.	Last Yr.	Total Yrs.
Campbell Dolomite *	SCH2	WSL	1993	68.27	133.33	1200	10	10	10	1560	1992	433
Rock River	Y4Z	LAVAL	2004	66.91	136.35	500	51	17	12	1668	2003	336
North Klondike	YK4	LAVAL	2004	64.44	138.26	975	41	17	15	1653	2003	351
Divide	Y3D	LDEO	2003	62.05	128.37	1156	12	12	8	1613	2002	390
Tungsten	YT3	LDEO	2003	61.98	128.25	1145	19	18	15	1622	2002	381
Donjek *	SCH4	WSL	1984	61.67	139.67	750	29	29	15	1585	1983	399
Watson Lake *	SCH6	WSL	1984	60.97	128.83	750	23	23	12	1742	1983	242
Whitehorse (Gray Mt.)	YG1	LAVAL	2001	60.80	134.57	1140	161	26	16	1522	1999	478
Big Salmon	YC0	LAVAL	2000	60.56	133.13	1190	139	35	16	1723	1999	277
Monarch	YP0	LAVAL	2000	59.50	133.68	1400	134	18	11	1581	1999	419
Cassiar (UWO)	YG3	LDEO	2003	59.27	129.83	1225	29	28	19	1575	2002	428
Cassiar *	SCH1	WSL	1984	59.08	129.92	900	22	22	11	1817	1983	167
Summit Lake *	SCH5	WSL	1984	58.67	124.67	1260	24	24	13	1770	1983	214
Tanzilla Butte	YX3	LAVAL	2003	58.38	129.86	1166	57	16	11	1724	2002	279
Dease Lake *	SCH3	WSL	1984	58.33	129.92	1200	24	24	12	1757	1983	227

6.3.2 **Sample Preparation**

X-ray densitometric data for UWO samples were developed at either the Tree-Ring Laboratory at the Centre d'études Nordiques, Université Laval (Sainte-Foy, Quebec, Canada) or the Tree-Ring Laboratory at the Lamont-Doherty Earth Observatory (LDEO) of Columbia University (Pallisades, New York, USA). Preparation of core samples for x-ray irradiation differed between these two laboratories. The density data for six chronology sites were developed by the Laval Tree-Ring Laboratory following procedures outlined by Schweingruber (1989). Using a twin-blade saw, thin (1250 μm) laths were obtained from core samples for irradiation. To maintain correct perpendicular orientation to the wood fibres, short overlapping saw cuts of samples were often required resulting in large numbers of short sample segments for each individual core. This resulted in between 2 and 11 segments per core. At the LDEO Tree-Ring Laboratory, core samples for three chronology sites were processed, after instruction, by the author and Michael Kenigsberg using a microtome sample preparation approach (Thetford *et al*., 1991; Davi *et al*., 2003). This technique resulted in thinner (300 μm) microsections of samples. These microsections were longer (often complete core lengths) and resulted in smaller numbers of sample series. At both labs the resultant samples underwent similar irradiation to produce x-ray film images of the samples.

An x-ray densitometer (Dendro-2003, Walesch Electronics) was used to determine the wood density of tree-rings by measuring the optical transparency along each sample image on the x-ray films. Before each measurement, the densitometer was calibrated using a calibration wedge imaged on the same film to establish a standard optical reference. The optical values were then converted to wood density values using the calibration results. The ring parameters obtained from the densitometer were: ring-width, earlywood width, latewood width, minimum (earlywood) density and maximum (latewood) density. The most common density variable used in dendroclimatic studies is maximum latewood density (MXD). MXD is a ring parameter based on the highest density of the cells formed at the end of the growing season (Parker and Jozsa, 1973; Schweingruber, 1989). Previous studies have shown that MXD typically integrates local to regional-scale warm-season temperatures on annual to multidecadal time scales (e.g. Parker and Henoch, 1971; Briffa *et al*., 1992; Schweingruber *et al*., 1993; Jacoby and D'Arrigo, 1995; Wilson and Luckman, 2003). Therefore MXD values were examined in this study.

As mentioned earlier, many of the increment core samples processed by the Laval Tree-Ring Laboratory were cut into short segments prior to irradiation and subsequent measurement of x-ray images by the densitometer. While data from these short segments could be developed into chronologies, interpretation of low-frequency variations from such chronologies would be severely limited. According to the 'segment length curse', the longest period of information derived from a composite chronology is limited by the lengths of individual series being analyzed (Cook *et al*., 1995). This is of particular concern when series are broken into short fragments (the 'many fragments curse' (Sheppard *et al*., 1997)). To minimize this issue, density data of the short segments were re-assembled into complete time series before MXD chronologies could be developed. In order to date these segments correctly, ring-width measurements of the segments derived from the densitometer (alongside maximum density) were crossdated against ring-width data of the cores measured using traditional dendrochronological techniques (Stokes and Smiley, 1968; Yamaguchi, 1991) to verify ages. Once arranged in chronological order, density data of the segments were examined for anomalies (e.g. 'jumps' in the absolute values between segments). As segments were often cut on angles, overlapping sections would result in small numbers of annual rings being measured twice (segments on either side of the cut). For adjacent segments where there were obvious differences in absolute values, a shift constant was developed based on the mean difference between values for the overlapping rings. Using this constant, the segment exhibiting a "jump" was shifted to align mean values with the remaining segments of that core. Figure 6.1 shows an example of a core in which a segment exhibits a "jump" in density. Once aligned, values of overlapping sections (i.e. duplicate measurements) were averaged to create a single core series.

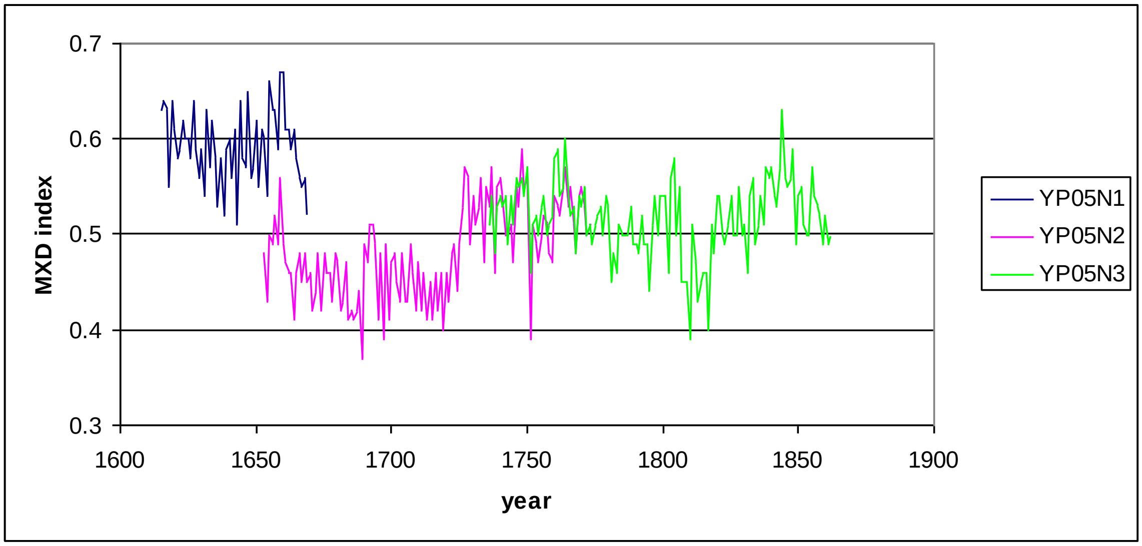


Figure 6.1 Plot of MXD for three segments of core YP05N from the Monarch (YP0) site. The mean difference between segments YP05N1 and YP05N2 for the overlap period 1653-1669 was calculated (0.12) and used as a "shift constant" to align YP05N1 segment with the remaining core segments. Values for overlapping sections (e.g. 1736-1774) were then averaged to develop a single core series.

6.3.3 Chronology Development

MXD chronology development followed similar procedures to those for ring-width chronologies (i.e. crossdating of core series, standardization/detrending and construction of mean site chronologies) using the computer software programs COFECHA (Holmes, 1983) and ARSTAN (Cook, 1985). Compared to ring-width data, standardization of maximum density series is generally simpler as latewood density tends to show less reaction to local ecological (non-climatic) changes, and because the age trend is usually simpler and less pronounced (Schweingruber and Briffa, 1996). Negative exponential or linear regression functions were used to standardize the core series density data. Previous studies, e.g. Schweingruber *et al*., 1978, have shown that the common signal in MXD data is usually stronger than that in ring-width series and therefore fewer samples are generally required to attain adequate signal strength. The number of trees (cores) processed per site for density examination ranged from 8 (12) [Divide site] to 19 (29) [Cassiar (UWO) site]. [*There are two Cassiar chronologies in the MXD network: the first, collected by Fritz Schweingruber in 1984, will hereafter be referred to as Cassiar, while the second one collected by UWO in 2003 at a different adjacent site will be identified as Cassiar (UWO)*]. As the construction of chronologies uses absolute values transformed to dimensionless indices with stabilized variance, comparisons of density data from different processing laboratories is possible.

6.4 Chronology Results

Fifteen MXD standard chronologies were developed from core series density data. Time series plots of the chronologies are shown in Appendix G. Total chronology lengths varied from 167 years (Cassiar) to 478 years (Whitehorse/Gray Mountain). Summary statistics for the MXD chronologies are shown in Table 6.2. Samples processed by the Laval Tree-Ring Laboratory displayed shorter mean segment lengths (mean 106 years after reassembly) while chronologies developed from the microtomed samples at the LDEO laboratory were longer with an average mean segment length of 242 years.

Table 6.2 Summary statistics for MXD chronologies. Sites are arranged from north to south. Single values for EPS indicate the date after which EPS>0.85 continuously. Multiple values indicate only those periods where EPS>0.85.

Site Name	Process	First Yr.	Last Yr.	# Cores	Mean Segment Length	Mean Index	Std. Dev.	Series Intercorr. (r)	Mean Sensitivity	Serial Corr. (1AC)	Mean RBAR	EPS>0.85
Campbell Dolomite *	WSL	1560	1992	10	166	1.000	0.077	0.612	0.080	0.144	0.401	1778
Rock River	LAVAL	1668	2003	17	74	0.997	0.072	0.565	0.074	0.178	0.381	1746
North Klondike	LAVAL	1653	2003	17	96	0.996	0.050	0.484	0.047	0.222	0.271	1832-1849;1945-1964
Divide	LDEO	1613	2002	12	291	0.992	0.070	0.530	0.050	0.553	0.319	1638-1661;1678-1714;1835-1856
Tungsten	LDEO	1622	2002	18	213	0.995	0.060	0.606	0.054	0.336	0.446	1742
Donjek *	WSL	1585	1983	29	172	0.991	0.071	0.504	0.043	0.723	0.260	1762
Watson Lake *	WSL	1742	1983	23	140	0.990	0.064	0.543	0.050	0.463	0.342	1838
Whitehorse (Gray Mt.)	LAVAL	1522	1999	26	117	0.984	0.142	0.451	0.141	0.240	0.301	1605
Big Salmon	LAVAL	1723	1999	35	43	0.996	0.061	0.490	0.066	0.105	0.283	1796
Monarch	LAVAL	1581	1999	18	255	0.989	0.059	0.431	0.057	0.291	0.375	1633
Cassiar	LDEO	1575	2002	28	221	0.979	0.083	0.504	0.069	0.368	0.274	1685
Cassiar *	WSL	1817	1983	22	136	0.998	0.054	0.659	0.050	0.293	0.452	1836
Summit Lake *	WSL	1770	1983	24	146	0.993	0.051	0.549	0.048	0.286	0.342	1884
Tanzilla Butte	LAVAL	1724	2002	16	50	1.000	0.069	0.523	0.072	0.095	0.357	1802-1853;1900-1934;1965-1972
Dease Lake *	WSL	1757	1983	24	167	0.995	0.068	0.712	0.077	-0.021	0.396	1793
Overall Mean					152	0.993	0.070	0.544	0.065	0.285	0.347	

Series intercorrelation ranged from 0.484 (North Klondike) to 0.712 (Dease Lake) with an overall mean value of 0.544. For comparison, Wilson (1999) calculated an average series intercorrelation value of 0.741 for a network of Engelmann spruce MXD chronologies in southern British Columbia. The Yukon results suggest that the MXD chronologies of the current study show a weaker common signal. The series intercorrelation statistic measures only high frequency variation in the data (low frequency trends are removed during its calculation by the COFECHA software).

RBAR (or running $\bar{r}$) is a running correlation between series within a chronology and considered a good measure of common signal strength through time (Cook *et al*., 2000). While series intercorrelation involves correlations between all core segments over all intervals in a chronology (thus including within- and between-tree correlations), the moving correlation of RBAR focuses only on between-tree correlations (Briffa, 1995). RBAR for the MXD chronologies had a mean value of 0.347, with a minimum of 0.260 (Donjek) and maximum of 0.452 (Cassiar), suggesting that the chronologies maintained a relatively good common signal over time.

Mean sensitivity is a traditional measure of chronology quality devised at the Laboratory of Tree-Ring Research (LTRR) at the University of Arizona. Initially developed for ring-width analysis of moisture sensitive chronologies, mean sensitivity expresses the difference between two successive values in a ring-width series by means of percentages (Schweingruber, 1989; see Chapter 3, Appendix B). Mean sensitivity values of the MXD chronologies are low, ranging between 0.043 (Donjek) to 0.080 (Campbell Dolomite). The 0.141 value for Whitehorse/Gray Mountain is noticeably larger than the other sites of the network, as is the standard deviation for MXD values. The reason for this difference is not known but reflects the considerably higher variability of MXD values in this chronology (see Appendix G). Traditional interpretation of the low site mean sensitivity values in the network would suggest that the chronologies have low interannual variability and would not therefore be useful indicators of interannual variations in temperatures. However, MXD has been found to be a good measure of summer temperatures (Parker and Henoch, 1971; Schweingruber *et al*., 1978). These low mean sensitivity values for MXD data reflect the data characteristics. Unlike ring-width values, which can vary widely from one year to the next, MXD values commonly exhibit little dispersion of values from the mean which therefore results in a low mean sensitivity statistic (Wilson, 1999). Table 6.3 shows the differences in standard deviation and mean sensitivity found between the maximum density and ring-width data for the chronologies. The low mean sensitivity value reflects the fact that the year to year variation in MXD is relatively small compared to the mean value when compared to similar statistics derived for a ring-width series. Wilson (1999) also calculated a low average mean sensitivity value of 0.12 for his Engelmann spruce MXD network in southern British Columbia. Bunn *et al*. (2013) discussed the use of mean sensitivity as a useful statistic in dendrochronology. They also note that mean sensitivity is dependent on the variance of the actual variable measured and that the magnitude of the variance is usually related to the nature of the variable itself. Considering that the difference in the maximum density of adjacent rings is a small fraction of the total density value, and that mean sensitivity is highly dependent on the magnitude of difference between adjacent rings, it is not surprising that the MXD chronologies exhibit low mean sensitivity values.

Table 6.3 Standard deviation and mean sensitivity values for MXD and RW chronologies. Sites are arranged from north to south.

	MXD		RW	
Site Name	**Std. Dev.**	**Mean Sens.**	**Std. Dev.**	**Mean Sens.**
Campbell Dolomite	0.077	0.080	0.224	0.185
Rock River	0.072	0.074	0.178	0.124
North Klondike	0.050	0.047	0.152	0.129
Divide	0.070	0.050	0.278	0.117
Tungsten	0.060	0.054	0.218	0.109
Donjek	0.071	0.043	0.282	0.176
Watson Lake	0.064	0.050	0.231	0.134
Whitehorse (Gray Mt.)	0.142	0.141	0.210	0.141
Big Salmon	0.061	0.066	0.197	0.127
Monarch	0.059	0.057	0.204	0.145
Cassiar (UWO)	0.083	0.069	0.163	0.105
Cassiar	0.054	0.050	0.167	0.115
Summit Lake	0.051	0.048	0.179	0.140
Tanzilla Butte	0.069	0.072	0.180	0.138
Dease Lake	0.068	0.077	0.192	0.144
Overall Mean	0.070	0.065	0.204	0.135

A better indication of year to year variability in these chronologies is the mean value for serial correlation (or first order autocorrelation 1AC) for the MXD chronologies (mean 0.285, see Table 6.2). The low autocorrelation values of the MXD chronologies indicate that each annual density value is independent of the value for the previous year. While the mean sensitivity values of the chronologies suggested little interannual variability in the density data, the low autocorrelation values clearly indicate that each year's value is independent of the value for the previous year. This would indicate that this statistic is a much better measure of year to year variability in MXD data than the traditional mean sensitivity values. Wilson (1999) had an average 1AC value of 0.46 for his Engelmann spruce MXD chronologies.

The Expressed Population Signal (EPS) is used to assess the common signal in a chronology and an EPS threshold of 0.85 has commonly been used to define chronology lengths with sufficiently high common signal strength for climate analyses (Wigley *et al.*, 1984, see Chapter 3). The results in Table 6.2 indicate that three MXD chronologies have obvious problems with signal strength indicating a poor correlation between the component tree-ring series. The North Klondike, Divide and Tanzilla Butte MXD chronologies exhibit limited periods in which acceptable EPS values were maintained. All three sites had a relatively low number of cores (17, 12 and 16 cores respectively) which is a contributory factor to the weak EPS values. The average number of cores for the other sites is 22 cores. Therefore these three chronologies were excluded from further analyses within the network. The Campbell Dolomite chronology has only 10 cores and shows a period of reduced EPS between 1889-1942 but acceptable signal strength back to 1778. Since this northern site represents an underrepresented area in the network, it was retained in the network analyses. Twelve chronologies have acceptable EPS values back to 1884, with eight extending prior to 1795. The Gray Mountain (Whitehorse) chronology maintains signal strength back to 1605.

6.5 Network Evaluation

While the twelve retained MXD chronologies have acceptable signal strength extending back to at least the late 19th century, climate records for the Yukon Territory are only available for the 20th century. Since the primary goal in examining the MXD network is to evaluate relationships between tree-ring density and climate, evaluation of the MXD chronologies will focus primarily on periods within the 20th century.

The full densitometric chronologies for the 15 sites are shown in Appendix E. Most extend back several centuries and will be briefly reviewed prior to detailed evaluation of the relationships over the 20th century. Ten-year smoothing splines were added to highlight lower frequency trends in these chronologies. Records indicate a period of decreasing MXD values during the latter half of the 17th century. Conditions during this time were known to be cold, in part due to reduced solar activity known as the Maunder Minimum (Rind *et al*., 2004). MXD values during the 18th and 19th centuries were generally stronger and more stable, though records show a common short episode of lower density growth ca. 1810 (also coinciding with the Dalton solar minimum). Many of the chronologies exhibit other short-lived decreases in density (e.g. ca. 1601, 1643, 1699, 1959). Years of extremely low tree-ring density have been linked to changes in temperature due to major volcanic eruptions (Briffa *et al*., 1998a; D’Arrigo and Jacoby, 1999; Davi *et al*., 2003). Several of the low density departures seen in these Yukon chronologies follow known volcanic events (e.g. 1600 Huaynaputina, Peru (Briffa *et al*., 1998a); 1641 Awu, Indonesia (D'Arrigo and Jacoby, 1999); 1959 Kilauea, Hawaii (Macdonald, 1962)) indicating that although some parts of the chronologies have low signal strength they still contain important climatic information. Such influences are discussed further in Section 6.7. During the 20th century, chronologies generally showed increasing density over the first quarter of the century followed by a gradual decrease. Growth over the last three decades showed varying results. The Campbell Dolomite and Whitehorse/Gray Mountain chronologies exhibited decreasing density whereas others (e.g. Rock River and Cassiar (UWO)) appeared to show slight increases. As several of the chronologies ended in 1983, it was difficult to determine which pattern was more dominant.

6.5.1 **Evaluation of the 20th Century Records**

Examination of the MXD chronology network for common patterns was conducted through correlation matrix analyses and principal components analyses. Both sets of analyses were performed for the 1900-2000 period (or slightly shorter intervals when limited by chronology length) and separately for 1900-1950 and 1950-2000[1] to investigate possible changes in the pattern of relationships over time.

6.5.2 **Correlation Matrix Analyses**

Correlation analysis of the MXD chronologies indicated the presence of strong relationships within the network (Table 6.4). For the 1900-2000 period, the mean correlation for each site with all others (mean value) ranged from 0.233 (Donjek) to 0.523 (Dease Lake) with an overall network correlation value of 0.404 (Table 6.4a). Individual correlation values (≥ 0.400) within the matrix suggested two main regional groupings. The largest group consists of sites located primarily in the central and southern portions

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[1] The WSL chronologies only extend to 1983, limiting the common period for analyses in some cases.

Table 6.4 Correlation matrices of MXD chronologies in the 20th century. The analyses are based on their common intervals within the periods (a) 1900-2000, (b) 1900-1950, and (c) 1950-2000 periods. Values significant at p≤0.01 level are coloured based on the strength of correlation.

a)

	Campbell Dolomite	Rock River	Tungsten	Gray Mountain	Big Salmon	Monarch	Cassiar (UWO)	Cassiar	Dease Lake	Watson Lake	Summit Lake	Donjek
Campbell Dolomite		.549	.412	.331	.307	.252	.341	.223	.337	.159	.162	.154
Rock River	.549		.479	.369	.321	.404	.318	.376	.317	.075	.330	.348
Tungsten	.412	.479		.632	.550	.364	.679	.470	.550	.428	.431	.277
Gray Mountain	.331	.369	.632		.764	.504	.568	.481	.723	.446	.307	.286
Big Salmon	.307	.321	.550	.764		.592	.635	.494	.736	.495	.165	.235
Monarch	.252	.404	.364	.504	.592		.593	.593	.560	.135	.182	.244
Cassiar (UWO)	.341	.318	.679	.568	.635	.593		.694	.700	.469	.417	.285
Cassiar	.223	.376	.470	.481	.494	.593	.694		.680	.350	.517	.187
Dease Lake	.337	.317	.550	.723	.736	.560	.700	.680		.511	.403	.237
Watson Lake	.159	.075	.428	.446	.495	.135	.469	.350	.511		.238	.002
Summit Lake	.162	.330	.431	.307	.165	.182	.417	.517	.403	.238		.304
Donjek	.154	.348	.277	.286	.235	.244	.285	.187	.237	.002	.304	
N	93	101	101	100	101	100	101	84	84	84	84	84
Mean	0.279	0.322	0.454	0.466	0.460	0.380	0.492	0.443	0.502	0.301	0.287	0.233

> 0.600 .400-.599 .200-.399

b)

	Campbell Dolomite	Rock River	Gray Mountain	Big Salmon	Monarch	Cassiar (UWO)	Cassiar	Dease Lake	Tungsten	Watson Lake	Summit Lake	Donjek
CampbellDolomite		.467	.244	.205	.291	.267	.192	.259	.352	.223	.099	.250
RockRiver	.467		.451	.401	.338	.507	.279	.327	.513	.395	.172	.279
GrayMountain	.244	.451		.812	.732	.765	.721	.762	.670	.584	.262	.441
BigSalmon	.205	.401	.812		.700	.704	.655	.728	.589	.680	.162	.471
Monarch	.291	.338	.732	.700		.665	.507	.602	.446	.438	.017	.307
Cassiar(UWO)	.267	.507	.765	.704	.665		.670	.595	.781	.643	.352	.526
Cassiar	.192	.279	.721	.655	.507	.670		.721	.529	.649	.462	.412
DeaseLake	.259	.327	.762	.728	.602	.595	.721		.514	.552	.373	.386
Tungsten	.352	.513	.670	.589	.446	.781	.529	.514		.531	.432	.383
WatsonLake	.223	.395	.584	.680	.438	.643	.649	.552	.531		.468	.343
SummitLake	.099	.172	.262	.162	.017	.352	.462	.373	.432	.468		.239
Donjek	.250	.279	.441	.471	.307	.526	.412	.386	.383	.343	.239	
N	51	51	51	51	51	51	51	51	51	51	51	51
Mean	0.236	0.350	0.546	0.512	0.431	0.541	0.489	0.494	0.487	0.469	0.254	0.367

c)

	Campbell Dolomite	Rock River	Gray Mountain	Big Salmon	Monarch	Cassiar (UWO)	Cassiar	Dease Lake	Tungsten	Watson Lake	Summit Lake	Donjek
Campbell Dolomite		.617	.448	.444	.186	.410	.245	.440	.462	.164	.193	.063
Rock River	.617		.301	.306	.385	.233	.300	.380	.463	.063	.297	.356
Gray Mountain	.448	.301		.724	.253	.323	.449	.674	.551	.227	.538	.159
Big Salmon	.444	.306	.724		.593	.564	.610	.763	.475	.181	.348	.062
Monarch	.186	.385	.253	.593		.528	.594	.628	.257	.124	.119	.108
Cassiar (UWO)	.410	.233	.323	.564	.528		.768	.866	.569	.486	.469	-.029
Cassiar	.245	.300	.449	.610	.594	.768		.811	.499	.560	.413	-.063
Dease Lake	.440	.380	.674	.763	.628	.866	.811		.567	.505	.534	.120
Tungsten	.462	.463	.551	.475	.257	.569	.499	.567		.392	.530	.116
Watson Lake	.164	.063	.227	.181	.124	.486	.560	.505	.392		.464	-.214
Summit Lake	.193	.297	.538	.348	.119	.469	.413	.534	.530	.464		.280
Donjek	.063	.356	.159	.062	.108	-.029	-.063	.120	.116	-.214	.280	
N	34	51	50	50	50	51	34	34	51	34	34	34
Mean	0.328	0.304	0.408	0.455	0.333	0.474	0.477	0.561	0.433	0.288	0.355	0.087

of the network. Characterized by inter-site correlations reaching values greater than 0.600, this group includes: Gray Mountain, Big Salmon, Monarch, Cassiar (UWO), Cassiar, Tungsten and Dease Lake. The second group of sites consists of Campbell Dolomite and

Rock River in the northern Yukon. Though not exhibiting correlation values quite as high as the previous group, these northern sites did share strong correlations between themselves which differentiated them from the rest of the network. The Tungsten chronology, located in the eastern Yukon, displayed moderate correlation with both of these groups and was most strongly correlated with the Cassiar (UWO) and Gray Mountain chronologies. The Summit Lake and Watson Lake chronologies in the south-eastern corner of the network displayed moderate correlations (≥0.400) with the chronologies of the southern grouping and the Tungsten chronology. The Donjek chronology was weakly correlated with most other chronologies in the network.

Correlation analysis over the 1900-1950 period generally exhibited an increase in the strength of relationships between chronologies (Grand mean = 0.462 compared with 0.404). Correlations between chronologies in the central portion of the network showed the greatest increases, with Gray Mountain and Big Salmon reaching values over 0.800 (Table 6.4b). The Watson Lake and Tungsten chronologies displayed noticeably stronger correlations with chronologies in the network during this early period. The correlation between the two northernmost chronologies was slightly weaker though still statistically significant ($p \leq 0.01$). The Rock River chronology showed moderate increases in the strength of the relationships with chronologies in the central portion of the network. In contrast, the Campbell Dolomite chronology only correlated significantly ($p \leq 0.01$) with Rock River during this period. The Donjek chronology showed stronger correlations for the 1900-1950 period, but was still the most weakly correlated overall (Table 6.4b).

Correlation analysis of the MXD chronologies over the 1950-2000 period (Table 6.4c) showed a substantial weakening of relationships between most chronologies in the network in comparison with the earlier half of the 20th century. Mean correlation for the network dropped to 0.379 for this period. Correlations between chronologies in the central portion of the matrix showed fewer statistically significant results ($p \leq 0.01$ level), while chronologies in the south (e.g. Cassiar sites) displayed slightly weaker relationships. Correlations with Dease Lake improved slightly for this period. Chronologies such as Cassiar (UWO), Monarch and Gray Mountain that exhibited strong correlations (> 0.600) during the 1900-1950 period, showed much lower correlations over the 1950-2000 period. Summit Lake had better correlations post-1950 compared with pre-1950 particularly with sites in the east and south (e.g. Tungsten, Cassiar (UWO) and Dease Lake). The Donjek chronology showed no significant ($p \leq 0.01$) correlations during the 1950-2000 period, and actually exhibited negative correlations with Watson Lake, Cassiar (UWO), and Cassiar which was unprecedented among the correlation analyses previously conducted. Correlation values in the northern portion of the network showed stronger relationships than those witnessed during the earlier 1900-1950 period.

Based on the series of correlation analyses, it is evident that strong relationships occur between some sites within the network and two main regional groupings can be tentatively identified. The largest of these groups consisted of chronologies located in the central and southern portion of the Yukon (and neighboring northern British Columbia), while those chronologies located in the northern Yukon formed a smaller group. Although there are variations in the strength of these relationships over the two halves of the twentieth century, the underlying pattern remained. Correlations during the 1900-1950 period showed the strongest values, particularly between the central and southern chronologies. Relationships during the 1950-2000 period were generally weaker between many sites, except for the two northern chronologies, which were more strongly correlated.

6.5.3 **Principal Components Analyses**

Results of principal components analyses (PCA) complement the findings of the correlation analyses identifying regional groupings within the network. Results for the full 1900-1983 period (Table 6.5a) and early 1900-1950 period (Table 6.5b) are very similar and show three principal components, whereas the later 1950-1983 period indicates four components with different groupings (Table 6.5c). PC1 explains approximately 50% of the total variance in all three analyses with the strongest result appearing in the 1900-1950 analysis interval. Big Salmon, Monarch, Dease Lake, Cassiar (UWO) and Cassiar consistently load on PC1 in each time period, forming a coherent group. Rock River and Campbell Dolomite, the two most northerly sites in the network, always load on the same PC although Tungsten and Gray Mountain are also in PC2 in the post-1950 period (Table 6.5c). Summit Lake, the most easterly site, consistently loads on PC3 either singly (Table 6.5b) or with one other site, whereas Donjek exhibits three different combinations.

Based on these results, it is evident that there are changes in the correlation patterns between the two halves of the 20th century. There is a core group of five chronologies which always load on PC1, but four chronologies drop from PC1 post-1950. Gray Mountain drops out of this group in the post-1950 period and comparison of this chronology with a mean composite series developed from the five “core” chronologies (“Mean Composite Series” or MCS) reveals a disconnect beginning in the early 1970s (Figure 6.2). Prior to this break, there is a strong stable correlation between the two series (Figure 6.2a). The greatest difference between the two records appears during the late-1970s and early-1980s, after which the relationship shows a moderate recovery. Based on this correlation pattern and the fact that it is the second and third strongest chronology score in PC1 of the other two intervals, the post-1970 part of the Gray Mountain was truncated and this chronology was subsequently combined with the other south/central chronologies. The Tungsten MXD chronology also changed loading from PC1 in the 1900-1950 PCA to PC2 of the 1950-2000 PCA. Comparison with the MCS record indicates a relatively strong though more variable relationship prior to 1970 with periods of weaker correlation during the early 1920s and late 1940s (Figure 6.3). However, similar to Gray Mountain, there is a breakdown of the relationship in the late-1970s and early-1980s though subsequent recovery took longer and is weaker than at Gray Mountain. This major deterioration, common to both Tungsten and Gray Mountain, is likely the reason why both chronologies shift from PC1 to PC2 between the two time periods. Though Tungsten loaded highest on PC2 during the 1950-2000 period, it also exhibited a strong loading score on PC3, which included the eastern sites in the network (Watson Lake and Summit Lake). Given its eastern geographical position in the network, along with its strong loading score on PC3, the Tungsten chronology was grouped with the other eastern sites.

Table 6.5 Principal component analyses of the MXD chronologies. Results are shown for (a) 1900-1983 (20th century), (b) 1900-1950 and (c) 1950-1983 periods.

(a)

	Component			Total
	1	2	3	
Variance Explained	48.6%	11.2%	8.7%	68.5%
Big Salmon	.841	.309	-.027	
Dease Lake *	.831	.169	.245	
Gray Mountain	.772	.350	.129	
Cassiar (UWO)	.763	.327	.320	
Watson Lake *	.743	-.187	.015	
Cassiar *	.640	.099	.501	
Tungsten	.608	.411	.305	
Monarch	.561	.418	.132	
Rock River	.163	.796	.324	
Campbell Dolomite *	.196	.784	-.014	
Summit Lake *	.243	-.013	.866	
Donjek *	.003	.372	.589	

(b)

	Component			Total
	1	2	3	
Variance Explained	53.0%	10.1%	9.6%	72.7%
Big Salmon	.895	.169	.103	
Gray Mountain	.882	.226	.169	
Monarch	.843	.225	-.185	
Dease Lake *	.783	.112	.289	
Cassiar (UWO)	.744	.360	.320	
Cassiar *	.726	.045	.480	
Watson Lake *	.593	.185	.515	
Tungsten	.522	.481	.427	
Donjek *	.427	.297	.257	
Campbell Dolomite *	.077	.845	.006	
Rock River	.265	.783	.120	
Summit Lake *	.076	.064	.936	

(c)

	Component				Total
	1	2	3	4	
Variance Explained	49.8%	13.6%	10.4%	8.5%	82.3%
Monarch	.914	.116	-.080	.090	
Big Salmon	.818	.426	.129	.049	
Dease Lake *	.739	.279	.516	.066	
Cassiar *	.724	.094	.526	-.112	
Cassiar (UWO)	.655	.387	.499	-.107	
Campbell Dolomite *	.150	.908	.057	-.105	
Rock River	.228	.818	.012	.281	
Tungsten	.239	.627	.516	.076	
Gray Mountain	.410	.594	.355	.201	
Watson Lake *	.140	.020	.827	-.296	
Summit Lake *	.105	.191	.785	.418	
Donjek *	.022	.107	-.037	.936	

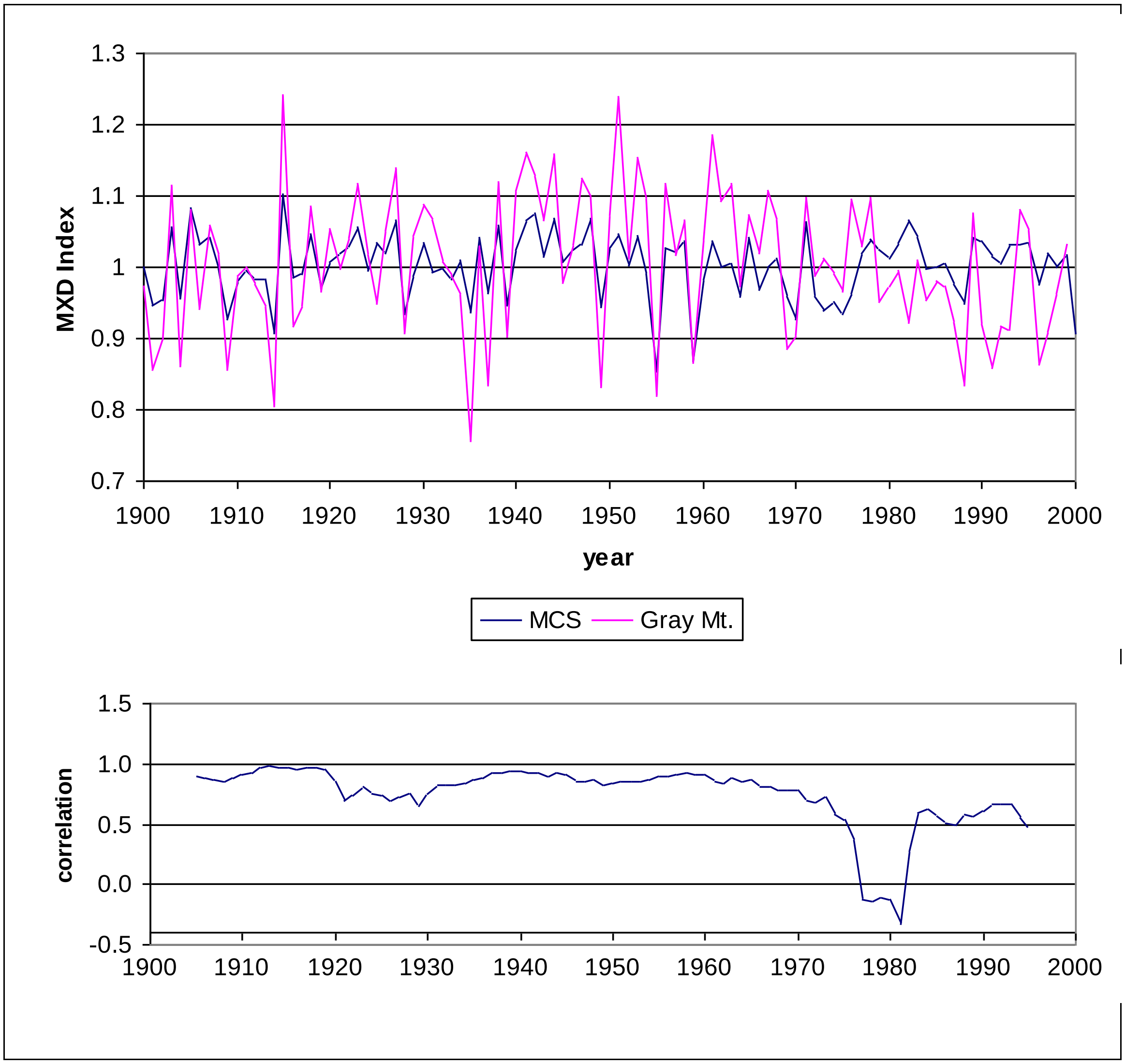

Figure 6.2 Comparison of Gray Mountain MXD chronology and Mean Composite Series (MCS) over the 20th century. Patterns between the two records are similar prior to ca. 1970 but differ subsequently. A 10-year moving correlation between the two series verifies the separation between the records.

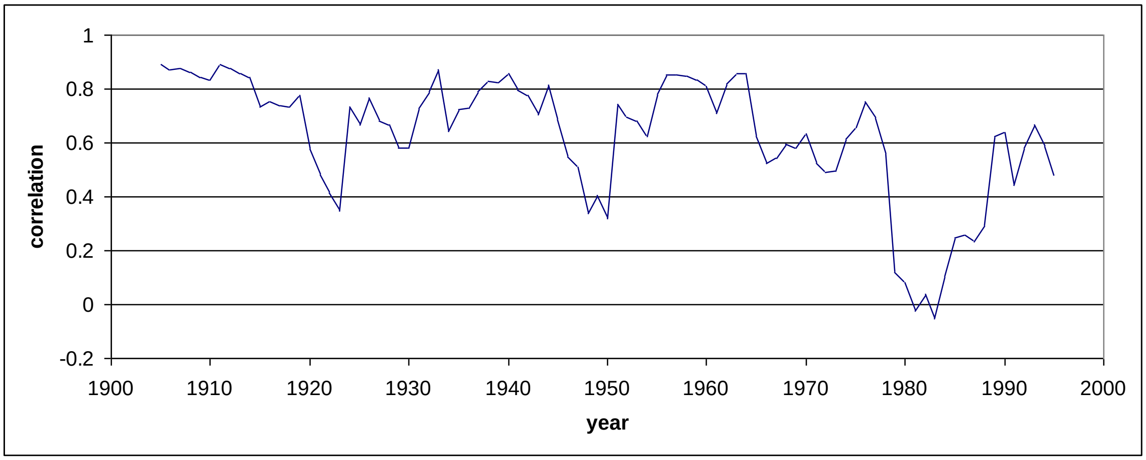

Figure 6.3 A 10-year moving correlation between Tungsten MXD chronology and Mean Composite Series (MCS) over the 20th century.

The other two chronologies that dropped from PC1 post-1950 were Watson Lake and Donjek. Unlike Gray Mountain and Tungsten, which showed relatively strong correlations with the MCS series until the late-1970/early-1980 period, Watson Lake and Donjek showed increasingly poor correlations during the 20th century. Initially exhibiting strong correlations in the 1920s, relationships for both chronologies progressively deteriorated (Figure 6.4). Though Watson Lake exhibited a partial recovery in correlations with MCS during the late-1950s and early-1960s, this was short-lived and subsequently correlations weakened. For the 1950-2000 PCA, Watson Lake shifted to PC3 alongside Summit Lake, while Donjek loaded uniquely on PC4.

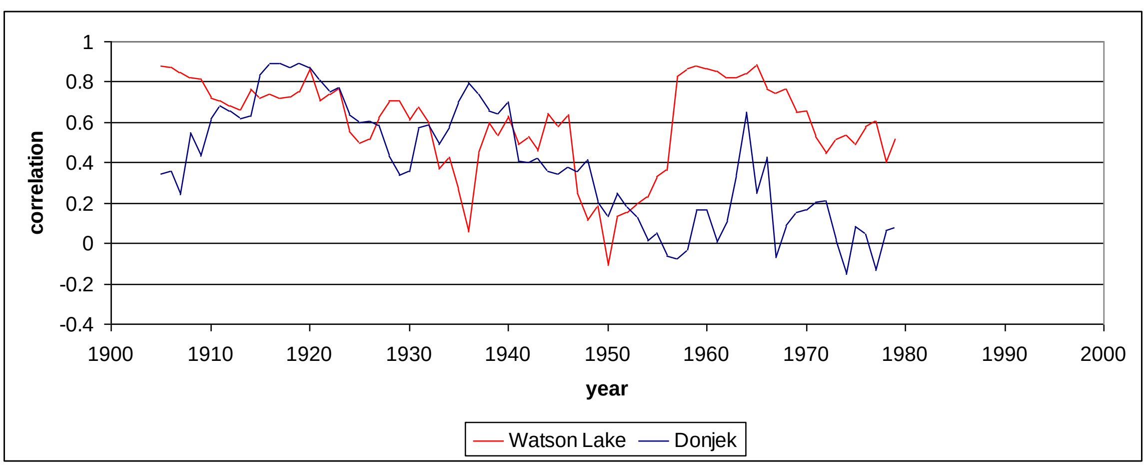

Figure 6.4 A 10-year moving correlation between the Mean Composite Series (MCS) and (i) Watson Lake (red) and (ii) Donjek (blue) MXD chronologies over the 20th century.

The results of the PCA and correlation analyses indicate that the MXD chronologies could be arranged into three regional groups: (i) a south-central group involving Big Salmon, Monarch, Dease Lake, Cassiar (UWO), Cassiar and Gray Mountain, (ii) a northern group consisting of Campbell Dolomite and Rock River, and (iii) an eastern group made up of Watson Lake, Summit Lake and Tungsten. The next section will examine the climate-growth relationships of these MXD chronologies.

6.6 MXD-Climate Relationships

Correlation analyses were conducted between MXD data and temperatures over a 36 month period from January two years prior to December of the growth year using the single month and aggregated “seasonal” climate variables as discussed in Chapter 4.

6.6.1 Temperature

Correlations between the 12 individual MXD chronologies and regional temperature records showed strong positive relationships between MXD and summer temperatures. Table 6.6 summarizes the number of chronologies in the MXD network that exhibited statistically significant ($p \leq 0.05$) positive correlations with single month temperature variables. The majority of these significant correlations were with current year temperatures, and no or few correlations with prior summer months, confirming observations of earlier studies (Schweingruber *et al*., 1993; Briffa *et al*., 1994) that MXD values strongly reflect conditions in the growth year. The largest numbers of correlations were concentrated in summer months. For the pre-1950 period, 7 of 12 chronologies exhibited significant responses with current July maximum temperatures (and also May maximum temperatures). For the post-1950 period, relationships with current August temperatures dominated with 8 of 12 chronologies displaying significant positive correlations with August mean temperatures of the northern climate record and all three August temperature variables of the southern climate record.

The earlier network evaluation established a ‘core’ group of five south-central chronologies that are highly correlated and represent nearly 50% of the total variance within the network. Examination of the temperature-growth relationships focuses primarily on these chronologies. Table 6.7 summarizes mean correlations of these five chronologies with single month, three-month and four-month seasons. Mean correlations with aggregated temperature data yielded the strongest results and likely represent the effective climate window influencing tree growth. For the pre-1950 period, the highest mean correlation was with May-August mean temperatures (r=0.48) of the northern climate record. Relationships during the post-1950 period were stronger than those of the earlier period. For the second half of the 20^{th} century, the highest mean correlation was with May-August maximum temperatures (r=0.62) of the southern climate record. The best result with the northern climate record was with May-August mean temperatures (r=0.53).

The MXD chronologies generally maintained positive relationships with temperatures in both halves of the 20^{th} century, unlike many of the RW chronologies (see Chapter 5) that demonstrated significant shifts in their responses to summer temperatures in the latter half of the 20^{th} century. The MXD chronologies of the ‘core’ group are from the southernmost parts of the tree-ring network least affected by the ‘divergence’ effect seen in the ring-width data.

Table 6.6 Number of MXD chronologies (out of total 12) exhibiting significant positive correlations (p≤0.05) with single month temperature variables.

		1900-1950 North Climate Record			1950-2000 North Climate Record			1950-2000 South Climate Record		
		Max Temp	Mean Temp	Min Temp	Max Temp	Mean Temp	Min Temp	Max Temp	Mean Temp	Min Temp
Two Years Prior	ppJAN				1	1	1		1	1
	ppFEB									
	ppMAR									
	ppAPR									
	ppMAY									
	ppJUN	4	7	6						
	ppJUL		3				2		1	1
	ppAUG	1	5	1						
	ppSEP									
	ppOCT									
	ppNOV	1								
	ppDEC		1	2						
Previous Year	pJAN	3	3	2						
	pFEB				2	4	4	3	2	1
	pMAR			1			1		1	1
	pAPR	2	2	2					1	2
	pMAY						1			
	pJUN									
	pJUL									
	pAUG							1	1	
	pSEP						4			
	pOCT	1	1	1						
	pNOV							1	1	
	pDEC									
Current Year	JAN	3	4	5	1	1	1	1	1	1
	FEB									
	MAR	1	1	2	2	2	1	1	1	1
	APR		1	1						
	MAY	7	6	1	2	3	3	2	2	2
	JUN	5	6	6	1	1	2	1	1	1
	JUL	7	6	3	2	2	2	3	3	1
	AUG	2	6	4	6	8	6	8	8	8
	SEP		1	2						
	OCT						2		1	1
	NOV						1			
	DEC									

Table 6.7 Summary of mean correlations between the 'core' group of five south-central chronologies and (a) single month, (b) aggregated 3-month and (c) aggregated 4-month temperature variables. Values highlighted in grey indicate the strongest correlations. The temperature records are as defined in Chapter 5.

a)

	MAX			MEAN			MIN		
	1900	1950N	1950S	1900	1950N	1950S	1900	1950N	1950S
JAN	0.17	0.10	0.06	0.18	0.10	0.06	0.19	0.11	0.06
FEB	0.03	0.06	-0.06	0.03	0.06	-0.02	0.03	0.06	0.01
MAR	0.24	0.18	0.17	0.21	0.19	0.16	0.19	0.18	0.15
APR	0.17	0.21	0.18	0.17	0.15	0.13	0.16	0.10	0.08
MAY	0.35	0.26	0.27	0.33	0.29	0.29	0.22	0.29	0.28
JUN	0.26	0.09	0.13	0.32	0.18	0.14	0.33	0.30	0.14
JUL	0.31	0.22	0.41	0.34	0.30	0.40	0.20	0.30	0.26
AUG	0.27	0.37	0.43	0.30	0.42	0.44	0.19	0.35	0.39
SEP	0.14	0.05	0.10	0.17	0.10	0.09	0.16	0.17	0.05
OCT	0.10	-0.06	0.12	0.10	0.01	0.13	0.10	0.09	0.13
NOV	0.00	0.14	0.17	-0.01	0.16	0.17	-0.01	0.22	0.16
DEC	0.00	-0.03	-0.07	0.00	-0.01	-0.06	0.00	0.01	-0.05
Mean	0.17	0.13	0.16	0.18	0.16	0.16	0.15	0.18	0.14

b)

	MAX			MEAN			MIN		
	1900	1950N	1950S	1900	1950N	1950S	1900	1950N	1950S
JAN-MAR	0.21	0.14	0.06	0.20	0.15	0.08	0.19	0.16	0.09
FEB-APR	0.20	0.18	0.10	0.19	0.17	0.11	0.17	0.16	0.11
MAR-MAY	0.34	0.28	0.28	0.31	0.25	0.25	0.26	0.22	0.20
APR-JUN	0.37	0.27	0.26	0.36	0.26	0.23	0.29	0.23	0.18
MAY-JUL	0.42	0.33	0.41	0.44	0.40	0.38	0.32	0.43	0.28
JUN-AUG	0.38	0.40	0.59	0.43	0.52	0.56	0.31	0.48	0.38
JUL-SEP	0.34	0.31	0.47	0.37	0.40	0.45	0.24	0.44	0.33
AUG-OCT	0.23	0.16	0.30	0.23	0.21	0.29	0.18	0.24	0.23
SEP-NOV	0.08	0.11	0.20	0.07	0.16	0.20	0.07	0.23	0.18
OCT-DEC	0.03	0.04	0.08	0.03	0.09	0.09	0.03	0.16	0.09
Mean	0.26	0.22	0.28	0.26	0.26	0.26	0.21	0.27	0.21

c)

	MAX			MEAN			MIN		
	1900	1950N	1950S	1900	1950N	1950S	1900	1950N	1950S
JAN-APR	0.24	0.17	0.10	0.23	0.17	0.10	0.22	0.17	0.10
FEB-MAY	0.26	0.22	0.16	0.23	0.21	0.15	0.20	0.19	0.14
MAR-JUN	0.40	0.29	0.30	0.37	0.28	0.27	0.30	0.25	0.22
APR-JUL	0.43	0.32	0.40	0.41	0.31	0.33	0.30	0.28	0.22
MAY-AUG	0.45	0.46	0.62	0.48	0.53	0.55	0.33	0.51	0.39
JUN-SEP	0.37	0.33	0.52	0.42	0.46	0.48	0.30	0.52	0.33
JUL-OCT	0.32	0.22	0.43	0.30	0.27	0.40	0.21	0.29	0.30
AUG-NOV	0.14	0.20	0.29	0.12	0.23	0.27	0.09	0.28	0.23
SEP-DEC	0.05	0.05	0.09	0.05	0.10	0.10	0.05	0.17	0.09
Mean	0.30	0.25	0.32	0.29	0.28	0.29	0.22	0.29	0.22

Table 6.8 shows the responses of the individual chronologies to aggregated mean summer temperatures of the northern climate record over the twentieth century. The ‘core’

group of south-central chronologies maintains significant positive correlations throughout the 20th century, with only Gray Mountain exhibiting a loss of signal post 1950. Correlations for the other chronologies in the network show mixed results. Campbell Dolomite and Tungsten show increases during the post-1950 period (though Campbell remains non-significant), while Rock River and Watson Lake both showed weakening responses. Donjek exhibits a shift to a significant negative response for the post-1950 period and Summit Lake shows no relationship in either period.

Table 6.8 Correlations of individual chronologies with aggregated 4-month mean temperatures of northern climate record for 1900-1950 (upper) and 1950-1983 (lower) time periods.

1900-1950	Big Salmon	Monarch	Cassiar (UWO)	Cassiar (SCH)	Dease Lake	Gray Mountain	Campbell Dolomite	Rock River	Watson Lake	Summit Lake	Tungsten	Donjek
Jan-Apr	0.15	0.14	0.39	0.29	0.17	0.34	-0.23	-0.02	0.36	0.15	0.28	0.06
Feb-May	0.18	0.16	0.32	0.31	0.20	0.28	-0.22	-0.05	0.35	0.02	0.16	-0.01
Mar-Jun	0.39	0.29	0.43	0.42	0.31	0.35	-0.21	0.04	0.46	0.14	0.24	0.26
Apr-Jul	0.43	0.46	0.53	0.36	0.28	0.37	0.00	0.32	0.47	0.08	0.25	0.45
May-Aug	0.56	0.43	0.56	0.41	0.42	0.46	0.16	0.49	0.52	0.02	0.29	0.45
Jun-Sep	0.53	0.42	0.55	0.35	0.27	0.45	0.16	0.49	0.41	-0.09	0.28	0.46
Jul-Oct	0.34	0.25	0.46	0.25	0.20	0.29	0.01	0.35	0.19	0.00	0.31	0.35
Aug-Nov	0.17	0.14	0.28	0.06	-0.04	0.09	-0.15	0.14	0.25	0.04	0.30	0.08
Sep-Dec	0.09	0.07	0.14	0.00	-0.05	0.08	-0.18	0.13	0.21	-0.05	0.13	0.04
Mean	0.32	0.26	0.41	0.27	0.20	0.30	-0.07	0.21	0.36	0.04	0.25	0.24
1950-1983												
Jan-Apr	0.05	0.02	0.27	0.29	0.22	-0.07	0.08	0.10	0.49	0.23	0.32	-0.19
Feb-May	0.14	0.12	0.29	0.29	0.20	-0.14	-0.04	-0.05	0.44	0.15	0.30	-0.25
Mar-Jun	0.23	0.21	0.37	0.32	0.27	-0.16	0.00	-0.19	0.35	0.12	0.16	-0.34
Apr-Jul	0.34	0.34	0.33	0.30	0.25	-0.09	-0.06	-0.15	0.12	-0.01	0.08	-0.35
May-Aug	0.56	0.42	0.60	0.55	0.53	0.15	0.29	0.07	0.36	0.05	0.30	-0.45
Jun-Sep	0.56	0.44	0.44	0.39	0.48	0.19	0.33	0.09	0.07	-0.03	0.38	-0.11
Jul-Oct	0.26	0.24	0.27	0.35	0.22	0.29	0.22	0.38	0.14	0.04	0.51	0.07
Aug-Nov	0.20	0.08	0.29	0.38	0.21	0.22	0.06	0.24	0.05	0.05	0.38	-0.15
Sep-Dec	0.05	0.02	0.12	0.19	0.11	0.05	0.03	0.14	-0.11	0.19	0.30	0.09
Mean	0.26	0.21	0.33	0.34	0.28	0.05	0.10	0.07	0.21	0.09	0.31	-0.19

The strongest relationship between the 'core' group of chronologies and regional climate records was the correlation with post-1950 May-August maximum temperatures of the southern temperature series. Responses of the individual chronologies within this group exhibited variability in the strength of the summer signal, ranging from r=0.54 (Monarch) to r=0.66 (Big Salmon and Dease Lake). The mean response of the five core chronologies was used in measuring the strongest seasonal response. The sites were subsequently grouped into three regional chronologies based on the correlation and PCA analyses. Unlike the earlier MCS record which averaged the five 'core' raw chronologies, each new regional composite chronology was created by averaging the z-scores of the indices of the individual chronologies and then converting these averaged z-scores back to indices using the grand mean and standard deviation for each group. The South-Central Regional Series

(SCRS) was developed from the Big Salmon, Monarch, Cassiar (UWO), Cassiar, Dease Lake and truncated Gray Mountain chronologies. The Northern Regional Series (NRS) combined the Campbell Dolomite and Rock River chronologies, while an Eastern Regional Series (ERS) consisted of the Watson Lake, Summit Lake and Tungsten chronologies. Correlations between these regional series and the climate records confirmed that the most consistent and strongest relationship was between SCRS and May-August temperatures (Table 6.9). The strongest correlation (r=0.69) was between SCRS and May-August maximum temperatures of the Southern Climate Record for the post-1950 period. This relationship appears to hold the greatest potential for development of a MXD temperature reconstruction.

Since the SCRS record was developed by averaging the total lengths of six individual site chronologies, each with different absolute length and length of acceptable EPS signal strength (Figure 6.5), the signal strength of the SCRS series is variable. All six individual chronologies have acceptable EPS values back to 1836, the EPS cutoff for Cassiar. Five sites have adequate EPS values back to the 1790s when the EPS cutoffs for Big Salmon (1796) and Dease Lake (1793) occur. Prior to 1793, the SCRS chronology is primarily represented by Gray Mountain, Cassiar (UWO) and Monarch. Using COFECHA (Holmes, 1983), moving correlations between the six chronologies were calculated for 20-year segments lagged 10 years. Using average segment correlations between chronologies as a measure of common growth signal, the chronologies showed strong segment correlations back to at least 1640 with a mean value of r=0.74. Although this approach provides insight into the common signal of the chronologies in the SCRS record, it does not provide a conventional measure of signal strength. To address this issue, a secondary regional record was developed combining the MXD data for samples from the six sites into a single chronology. This composite “bulk” chronology contains 239 series (104 cores, 69 trees) with a mean segment length of 103 years. Mean sensitivity for this record was 0.093, and first-order autocorrelation was 0.186. The chronology extended from 1522-2002 (481 years) with EPS values exceeding 0.85 after 1623. By combining the MXD data and creating a single bulk chronology (BULK), a conventional EPS measure was obtained and the chronology considerably lengthened.

Table 6.9 Correlations of the three regional MXD series with aggregated 4-month current year temperatures. Maximum correlation values are highlighted in grey.

PRE-1950

Series	Period	SCRS	NRS	ERS
1900-1950 Mean Temp. (North Climate Series)	Jan-Apr	0.27	-0.13	0.34
	Feb-May	0.27	-0.15	0.21
	Mar-Jun	0.42	-0.09	0.34
	Apr-Jul	0.46	0.20	0.32
	May-Aug	0.55	0.39	0.33
	Jun-Sep	0.49	0.39	0.24
	Jul-Oct	0.34	0.23	0.22
	Aug-Nov	0.13	0.01	0.26
	Sep-Dec	0.06	-0.01	0.13
1900-1950 Max Temp. (North Climate Series)	Jan-Apr	0.28	-0.10	0.35
	Feb-May	0.30	-0.07	0.22
	Mar-Jun	0.46	0.02	0.32
	Apr-Jul	0.49	0.34	0.27
	May-Aug	0.52	0.45	0.21
	Jun-Sep	0.44	0.39	0.09
	Jul-Oct	0.36	0.27	0.15
	Aug-Nov	0.16	0.03	0.22
	Sep-Dec	0.06	0.03	0.12

POST-1950

Series	Period	SCRS	NRS	ERS	Series	Period	SCRS	NRS	ERS
1950-1983 Mean Temp. (North Climate Series)	Jan-Apr	0.19	0.12	0.37	1950-1983 Mean Temp. (South Climate Series)	Jan-Apr	0.11	0.11	0.34
	Feb-May	0.22	-0.03	0.32		Feb-May	0.16	-0.04	0.30
	Mar-Jun	0.27	-0.09	0.23		Mar-Jun	0.27	-0.18	0.21
	Apr-Jul	0.31	-0.09	0.06		Apr-Jul	0.35	-0.14	0.14
	May-Aug	0.59	0.20	0.23		May-Aug	0.63	0.09	0.36
	Jun-Sep	0.50	0.22	0.13		Jun-Sep	0.54	0.08	0.35
	Jul-Oct	0.30	0.34	0.24		Jul-Oct	0.46	0.28	0.43
	Aug-Nov	0.29	0.18	0.18		Aug-Nov	0.34	0.07	0.26
	Sep-Dec	0.13	0.09	0.19		Sep-Dec	0.13	-0.05	0.17
1950-1983 Max. Temp. (North Climate Series)	Jan-Apr	0.20	0.15	0.39	1950-1983 Max. Temp. (South Climate Series)	Jan-Apr	0.10	0.12	0.33
	Feb-May	0.25	0.02	0.37		Feb-May	0.16	-0.05	0.28
	Mar-Jun	0.30	-0.08	0.26		Mar-Jun	0.29	-0.21	0.16
	Apr-Jul	0.33	-0.07	0.07		Apr-Jul	0.42	-0.16	0.12
	May-Aug	0.51	0.12	0.19		May-Aug	0.69	0.09	0.37
	Jun-Sep	0.35	0.15	0.00		Jun-Sep	0.57	0.13	0.29
	Jul-Oct	0.25	0.31	0.14		Jul-Oct	0.48	0.31	0.37
	Aug-Nov	0.26	0.15	0.14		Aug-Nov	0.36	0.08	0.24
	Sep-Dec	0.07	0.06	0.14		Sep-Dec	0.12	-0.08	0.14

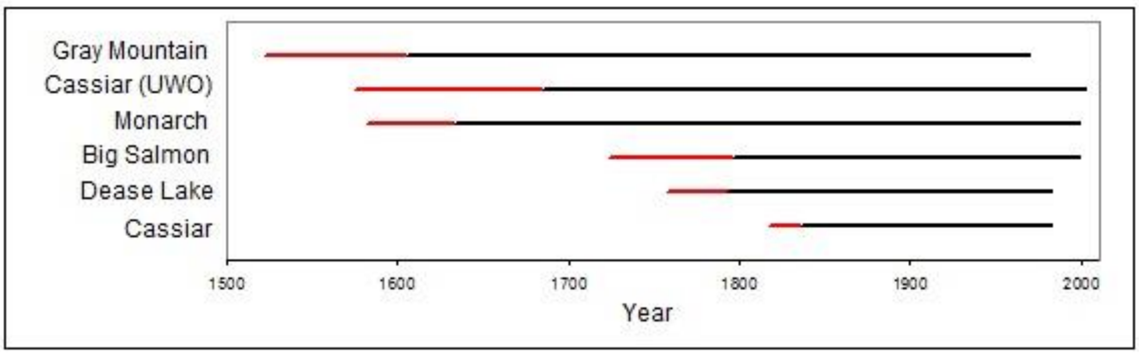

Figure 6.5 Plot showing the lengths of the individual MXD chronologies used in the development of the regional SCRS chronology. Portions shown in black indicate acceptable EPS (≥0.85) values while portions in red indicate unacceptable values.

6.6.2 Precipitation

Correlation analyses between the MXD chronologies and the three regional precipitation records indicated mixed results and significant responses with precipitation were sporadic. Table 6.10 summarizes the number of MXD chronologies that exhibited statistically significant ($p \leq 0.05$) correlations with single month precipitation totals. For the 1900-1950 period, six of the 12 MXD chronologies exhibited significant ($p \leq 0.05$) negative correlations with previous December of the northern precipitation record (the only regional record covering this time period). Five of these six chronologies (Big Salmon, Monarch,

Table 6.10 Number of MXD chronologies (out of total 12) exhibiting significant correlations (p≤0.05) with single month total precipitation. For the 1900-1950 period, correlations were calculated only with the northern precipitation record as the other two regional precipitation records did not cover this period.

		1900-1950			1950-1983					
		Total Precipitation			Total Precipitation					
		North			North		Central		South	
		Pos	Neg		Pos	Neg	Pos	Neg	Pos	Neg
Two Years Prior	**ppJAN**		1							
	ppFEB	4				5		4	1	
	ppMAR	2							3	
	ppAPR					2		4		
	ppMAY									1
	ppJUN		1							
	ppJUL				3					
	ppAUG									
	ppSEP									
	ppOCT		1						1	
	ppNOV		1		1					
	ppDEC									
Previous Year	**pJAN**									
	pFEB		5							
	pMAR		3						4	
	pAPR		1				1			
	pMAY						4			
	pJUN								1	
	pJUL	1				1				
	pAUG									
	pSEP		1		4					
	pOCT					4		1		
	pNOV	1								
	pDEC		6			1				
Current Year	**JAN**						1		1	
	FEB								1	
	MAR	2						1	1	
	APR							1	1	
	MAY				7					1
	JUN		2		1				1	
	JUL									1
	AUG				1					2
	SEP				1					
	OCT						2		2	
	NOV									
	DEC						2			

Cassiar (UWO), Cassiar, Gray Mountain) were from the 'core' group found in the south-central Yukon, with a mean correlation value of r=-0.34. The sixth chronology was Tungsten (-0.32). For the 1950-1983 time period, correlations were calculated against all three regional precipitation records (northern, central and southern records). The most dominant response for the later time period was a significant ($p \leq 0.05$) positive correlation with current May of the northern precipitation record for the six chronologies of the south-central 'core' group plus Tungsten (mean r=0.49). The three eastern chronologies (Watson Lake, Summit Lake and Tungsten) showed a positive response with previous March of the southern regional precipitation record (1950-1983) with a mean correlation value of 0.42. Rock River showed a similar response (r=0.46).

Correlations were also conducted with aggregated ('seasonal') precipitation data but results did not show improvement. For the 1900-1950 period, only four chronologies (Cassiar, Cassiar (UWO),Gray Mountain and Tungsten) exhibited significant correlations with previous December-current February precipitation (mean r=-0.32). Significant positive correlations with current spring precipitation (April-June) of the northern record during the 1950-1983 period were limited to four chronologies (Gray Mountain, Campbell Dolomite, Rock River and Tungsten) with a mean correlation value of r=0.43.

These correlation results suggest that precipitation may influence MXD development in white spruce in certain regions of the network. However, these precipitation relationships do not appear to be time stable across the 20th century and are much weaker for seasonalized data. Although a strong negative response to previous December precipitation was dominant in the early half of the century, it is not present in the relationships with the regional precipitation records post 1950. Similarly, the strong positive relationship with current May precipitation of the northern record during the 1950-1983 period was not evident in the responses of the earlier 1900-1950 period.

6.7 Climate Reconstruction

6.7.1 Development of Reconstruction

Results of the previous section demonstrated significant correlations between the MXD chronologies in the south-central Yukon and summer temperatures, particularly May-August maximum temperatures of the southern regional temperature record for the post-1950 period. Based on this strong relationship, two dendroclimatic reconstructions were developed using the SCRS and BULK chronologies. Using stepwise multiple linear regression, statistical models representing the temperature-growth relationships were constructed for the common period between the MXD chronologies and instrumental climate record. This process is referred to as *calibration* (Fritts, 1976; Fritts and Guiot, 1990). The reliability of the models are then assessed by calculating statistics which measure the degree of similarity between estimates of climate made from the models and corresponding instrumental data for periods independent of the calibration, a procedure known as *verification* (Gordon, 1982; Fritts and Guiot, 1990). Since the tree-ring chronologies extend back prior to the instrumental climate record, the statistical models or *transfer functions* (Fritts and Guiot, 1990) can be applied to reconstruct past variations in temperature based on past variations in the tree-ring record.

In developing a reconstruction, certain assumptions and limitations exist which should be recognized. One of the key assumptions involving the calibration process is that the relationship to be modeled is assumed to be time stable (Fritts and Guiot, 1990). To address this matter, the current reconstructions focused strictly on the composite records developed from the core group of six south-central sites in the Yukon. These site chronologies all exhibit significant positive correlations with summer temperatures for both the first and second halves of the 20th century indicating temporal stability of the relationship. Assumptions related to the use of multiple linear regressions were also considered. Parametric tests assume that data are normally distributed. For this study the southern regional temperature series and all six standard chronologies were tested for normality using the Kolmogorov-Smirnov test (Shaw and Wheeler, 1985). All series were found to be normally distributed though Monarch and Cassiar (UWO) were slightly negatively skewed at the 95% confidence limit. Autocorrelation is another concern in multiple linear regressions as values of predictor data must be independent of each other. While ring-width chronologies often show high first-order autocorrelation (1AC), MXD chronologies generally exhibit low 1AC. Autocorrelation values for the MXD chronologies of this study were low (see Table 6.2). As a precaution, the predictor series chronology was lagged forward one year so that the climate of the previous year could also be modeled (Fritts, 1976). Regression models may be accepted if there is no autocorrelation in the residual series of the regression (Shaw and Wheeler, 1985). The Durbin-Watson (DW) test is used to test the residual series of the calibration models. DW values range from 0 to 4, with 2 denoting zero correlation while 0 represents perfect positive correlation and 4 perfect negative correlation (Shaw and Wheeler, 1985).

The common period available for calibration of the MXD models with the southern regional temperature record was 1939-2002. This period was split into two sub-periods (1939-1970 (EARLY) and 1972-2002 (LATE)). Two calibration-verification trials were carried out using step-wise regression between May-August maximum temperature of the instrumental record as the predictand in the calibration and the SCRS (and BULK record) and the SCRS (and BULK) record lagged forward one year (SCRS1, BULK1) as predictors[2]. The regression was performed on each of the two sub-periods and the relationships verified using the other half (Table 6.11). Additional verification trials were carried out comparing the reconstructed 1939-2002 temperature record with the independent northern instrumental record for 1898-2002 period.

The results of the calibration and verification trials are plotted in Figures 6.6 and 6.7. In most respects the results for the two analyses are very similar. Calibration of the SCRS (BULK) models on the early and late periods explained 44.7% (43.0%) and 39.2% (37.7%) of the variance, respectively. Results of the Durbin-Watson tests did not clearly indicate significant correlation ($\alpha = 0.01$) within the residuals of the models suggesting acceptance of the models (Draper and Smith, 1998). The EARLY calibration models showed good agreement with the instrumental record in the verification process ($r = 0.676$ (SCRS), $r = 0.670$ (BULK)), though the models underestimate the warm temperatures of 1957 and 1958 by an average of 1.28 °C (Figure 6.6a) or 1.30°C (Figure 6.7a). The LATE

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[2] Predictor chronologies are generally lagged forward so that the affect of the previous year's climate may also be modelled (Fritts, 1976).

calibration models showed slightly weaker correlation with the instrumental record (r = 0.642 (SCRS), r = 0.630 (BULK)) during verification, also exhibiting difficulty in reconstructing the temperature peaks of 1989, 1994 and 1998 (Figures 6.6b and 6.7b). The LATE models underestimated these peaks by an average of 1.67 °C in SCRS and 1.70°C in BULK. Underestimation of extreme events is a common occurrence with tree-ring-based reconstructions (Fritts, 1976; Fritts and Guiot, 1990). The reduction of error (RE) verification statistic (see Appendix F) indicates whether a regression model provides a better estimate than simply using the mean of the instrumental data of the calibration period and is a highly sensitive measure of reliability (Fritts and Guiot, 1990). Any positive value of RE indicates that the regression model has predictive skill and value. RE values for both models for both the early and late verification periods using the southern temperature record indicate that the models are reliable (Table 6.11). The coefficient of efficiency (CE) statistic (see Appendix F) is similar to the RE statistic but instead of comparing model estimates to the mean of the instrumental data of the calibration period, CE uses the mean of the verification period (Cook *et al*., 1999). As with the RE statistic, any positive CE value indicates that the regression model has some skill. CE results for both models in both the early and late verification periods using the southern temperature record suggest that the models are reliable at predicting southern regional temperatures (Table 6.11).

Since the SCRS and BULK models passed the verification statistics for each of the two sub-periods, FULL models were developed for the full calibration period 1939-2002. The FULL models explained 39.9% (SCRS) and 38.9% (BULK) of the May-August maximum temperature variance of the southern climate record (Figure 6.6c and 6.7c). Comparison of the two reconstructions against the independent northern regional temperature record over the 1898-2002 period yielded correlation values of r = 0.520 (SCRS) and r = 0.508 (BULK) suggesting that northern and southern temperature records shared some similarity (Table 6.11). To examine whether the southern MXD chronologies could reconstruct northern Yukon temperatures, a separate trial was conducted. This 'northern' model was developed based on the northern climate record and southern BULK chronology. Results showed that this trial model did not perform as well as the original reconstructions using the southern climate records.

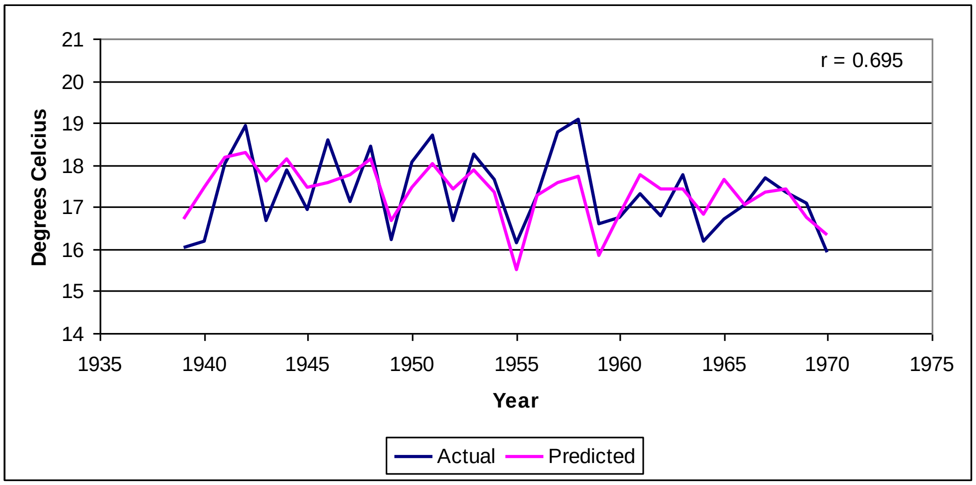
Table 6.11 Calibration and verification statistics for (a) the SCRS and (b) the BULK reconstructions of May-August maximum temperatures. r = correlation coefficient; r^2 = explained variance; aR^2 = square of the multiple correlation coefficient adjusted for loss of degrees of freedom; SE = standard error of the estimate; DW = Durbin-Watson statistic; RE = reduction of error statistic; CE = coefficient of efficiency statistic.

		Calibration					Verification			
a)	**Period**	**r**	**r^2**	**aR^2**	**SE**	**DW**	**Period**	**r**	**RE**	**CE**
SCRS	**1939-1970**	0.695	0.483	0.447	0.690	1.694	**1971-2002**	0.676	0.466	0.431
	1971-2002	0.656	0.431	0.392	0.786	1.251 [a]	**1939-1970**	0.642	0.520	0.483
	1939-2002	0.639	0.408	0.399	0.752	1.372 [a]	**1898-2002 ***	0.520		

		Calibration					Verification			
b)	**Period**	**r**	**r^2**	**aR^2**	**SE**	**DW**	**Period**	**r**	**RE**	**CE**
BULK	**1939-1970**	0.670	0.448	0.430	0.701	1.878	**1971-2002**	0.670	0.435	0.398
	1971-2002	0.630	0.398	0.377	0.795	1.060	**1939-1970**	0.630	0.488	0.448
	1939-2002	0.632	0.399	0.389	0.758	1.369 [a]	**1898-2002 ***	0.508		
	(North) 1898-2002	0.509	0.259	0.244	0.869	1.737	**1898-2002**	0.469	0.853	0.218

***** Verification for the 1898-2002 period is performed against the north regional temperature record
[a] These DW values were within the upper and lower bounds of the test statistic and thus were inconclusive. Erring on the side of conservatism, the null hypothesis of zero correlation in the residuals was not rejected.

a)



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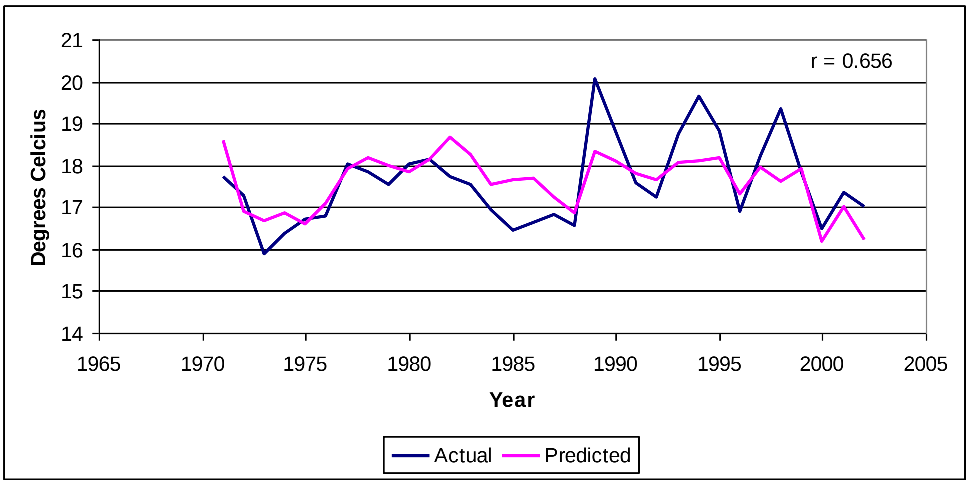

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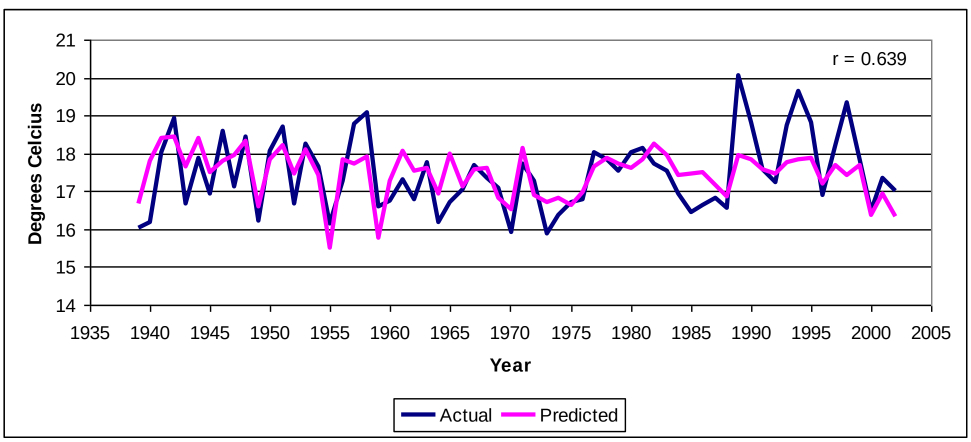
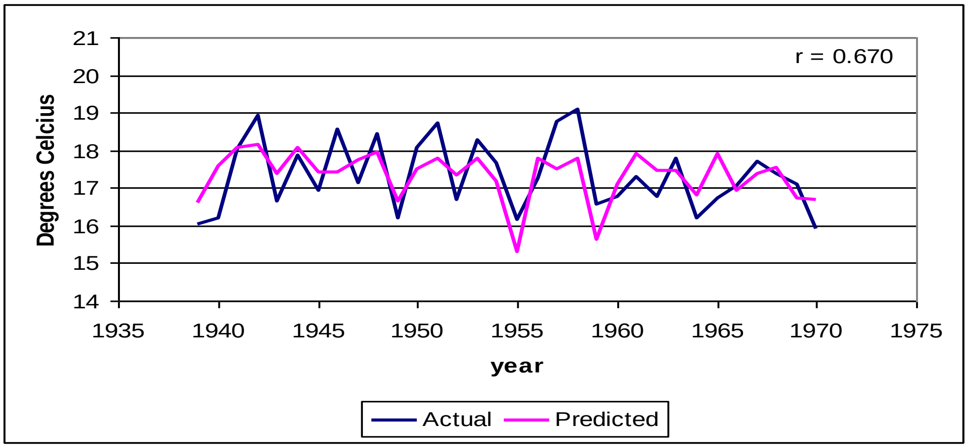


Figure 6.6 Comparison of actual vs. reconstructed May-August maximum temperatures (SCRS reconstruction) (a) EARLY (1939-1970) model, (b) LATE (1971-2002) model, and (c) FULL (1939-2002) reconstruction model.

a)



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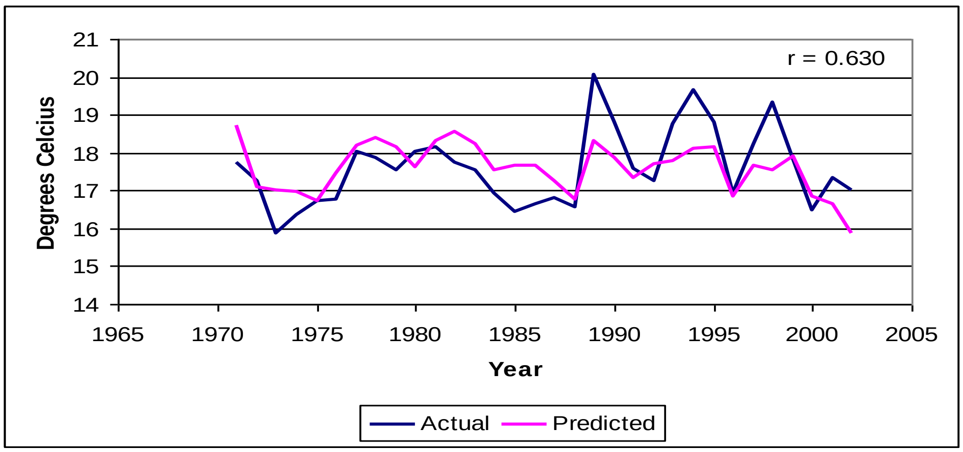

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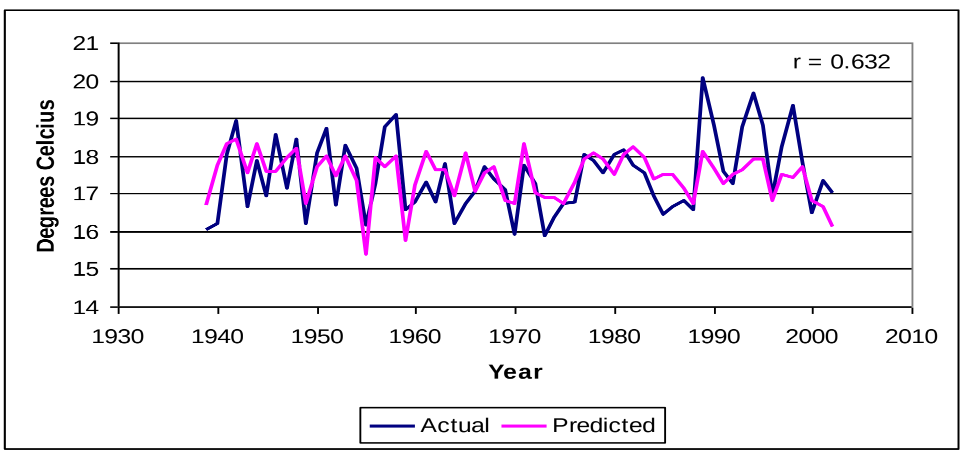
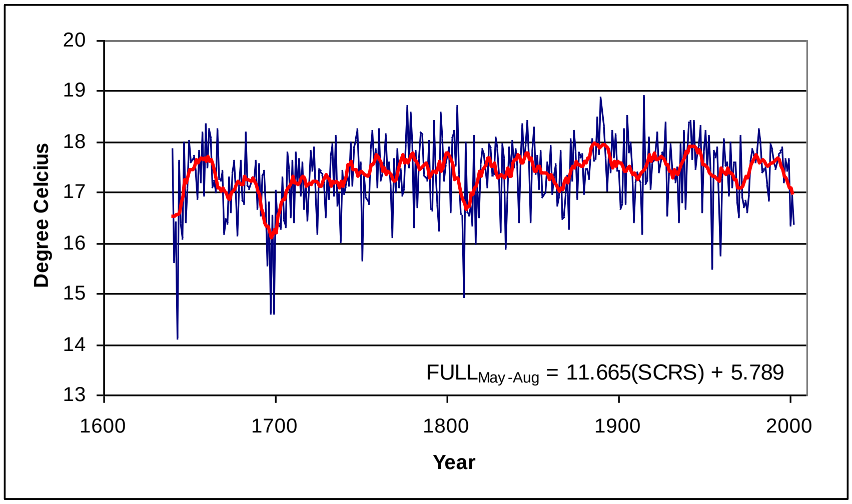


Figure 6.7 Comparison of actual vs. reconstructed May-August maximum temperatures (BULK reconstruction). (a) EARLY (1939-1970) model, (b) LATE (1971-2002) model, and (c) FULL (1939-2002) reconstruction model.

Figure 6.8 displays the May-August maximum temperature reconstructions based on the two full FULL models (Table 6.11). SCRS model equation was $FULL_{May\text{-}Aug}$ = 11.665(SCRS) + 5.789, while the BULK model equation was $FULL_{May\text{-}Aug}$ = 11.153(BULK) + 6.316. While both reconstructions extend back to 1522 (not shown), confidence in the reconstruction is limited to ca. 1640 for the SCRS record and 1623 for the BULK record based on EPS criteria (Figure 6.8). Mean temperature of the SCRS reconstruction is 17.35°C (1640-2002), while for the BULK record the average is 17.40°C (1623-2002; 17.38°C for common period 1640-2002). The reconstructions are strongly correlated (r = 0.962) over the common period 1640-2002. However, correlations between the chronologies using a 10-year moving window shows that the correlations between these two records vary between r = 0.795 to 0.999 (Figure 6.9). Periods exhibiting lower correlations included the early 1650s, 1720s, 1740s, early 1760s, late 1880s and post-1980. In many cases, these results correspond in part to the earliest records and start and end dates of chronologies in the SCRS record. For example, the poorer correlations found in the 1720s and late 1750s/early 1760s may reflect the early portions and inception of the Big Salmon (1723) and Dease Lake (1757) chronologies. Since individual site chronologies were weighted equally to create the SCRS record, the early part of these records have a disproportionate influence on the mean chronology (e.g. the 1730-1770 section of the chronology is based on 4 chronologies in SCRS but between 27-47 cores in the BULK chronology). Likewise, the poor correlations found post-1980 may be the result of chronology end dates (i.e. Dease Lake and Cassiar (1983); Monarch and Big Salmon (1999)). The drop in correlation occurring in the late 1880s/early 1890s is probably due to differences in growth between the six individual chronologies involved in the SCRS series. Between 1890-1894, MXD indices for Gray Mountain were much higher (mean difference +0.109) than the other five chronologies. This difference was likely minimized in the BULK chronology by the total number of individual samples covering this time interval from all six sites. Since the BULK reconstruction is not as susceptible to these issues and provided a conventional EPS-defined limiting date, preference is given to the BULK reconstruction in subsequent analyses.

SCRS Reconstruction



BULK Reconstruction

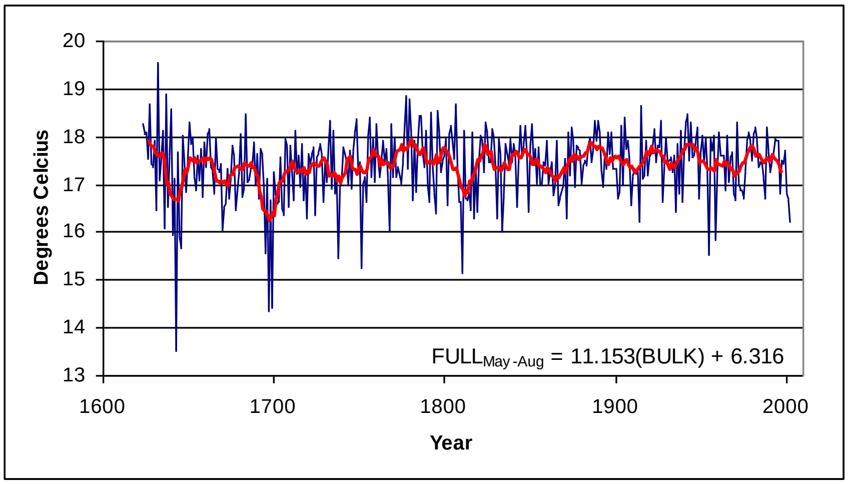


Figure 6.8 SCRS and BULK reconstructions of May-August maximum temperatures for the SW Yukon (with 10-yr moving average trendline in red). The full reconstructions extend from 1522-2002 but are truncated at 1640 (SCRS) and 1623 (BULK) based on EPS criteria (see text).

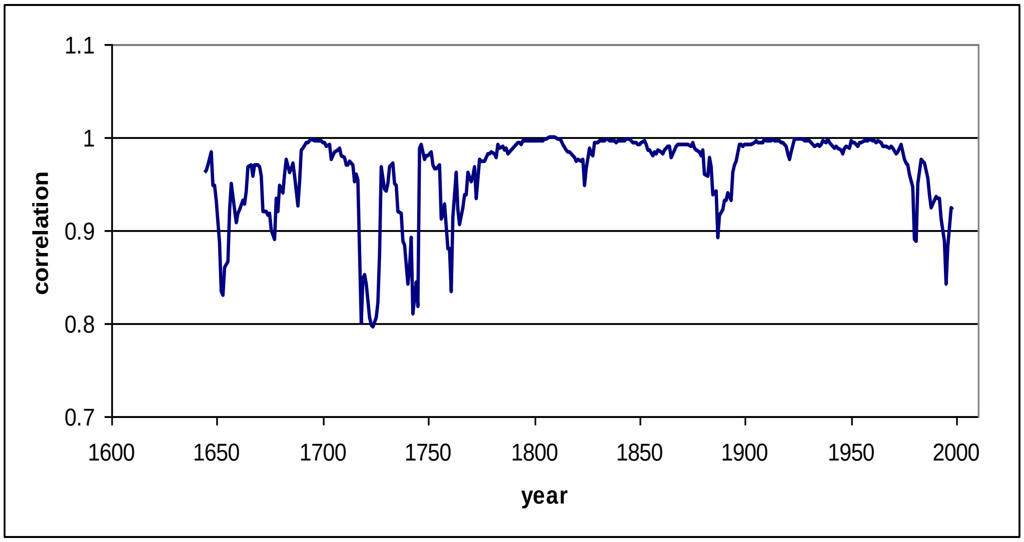


Figure 6.9 A 10-year moving window correlation between the SCRS and BULK May-August maximum temperature MXD reconstructions.

Throughout its length, the BULK reconstruction of May-August maximum temperature exhibits considerable interannual variability (Figure 6.8). The warmest reconstructed individual value occurs in 1632 (19.54°C), while the coldest value is in 1643 (13.52°C). Converting the series of reconstructed temperatures to z-scores and applying a 10-year moving average, longer decadal trends become more apparent (Figure 6.10). The reconstruction starts with a short period of warm conditions (1627-1636) followed by a prolonged period of colder temperatures (1637-1755). This span is interrupted periodically by brief (1-3) years of slightly warmer conditions resulting in a series of cool intervals. These cool intervals range in length between 10-23 years (mean 14.8 years). The 1688-1710 interval is the coldest recorded within the reconstruction (minimum temperature: 14.34°C (1697); mean temperature: 16.85°C). Warm conditions similar to those seen at the start of the reconstruction re-emerge from 1756-1804 before another major cold interval from 1805-1819. The reconstruction subsequently fluctuates between warm and moderately cool conditions throughout the 19th and 20th centuries, with cool intervals exhibiting progressively smaller amplitudes. The longest warm interval occurs from 1873-1908 (36 years) (maximum temperature: 18.34°C (1888); mean temperature: 17.63°C), followed by 1772-1804 (33 years) (maximum temperature: 18.84°C (1777); mean temperature: 17.64°C). While the early portion (1630s-1750s) of the reconstruction primarily displays a long-term cold period, most of the reconstruction is characterized by high frequency fluctuations between warm and cool conditions with intervals lasting no more than a decade or two. Conditions in the 20th century are primarily warm, particularly during the early half of the century.

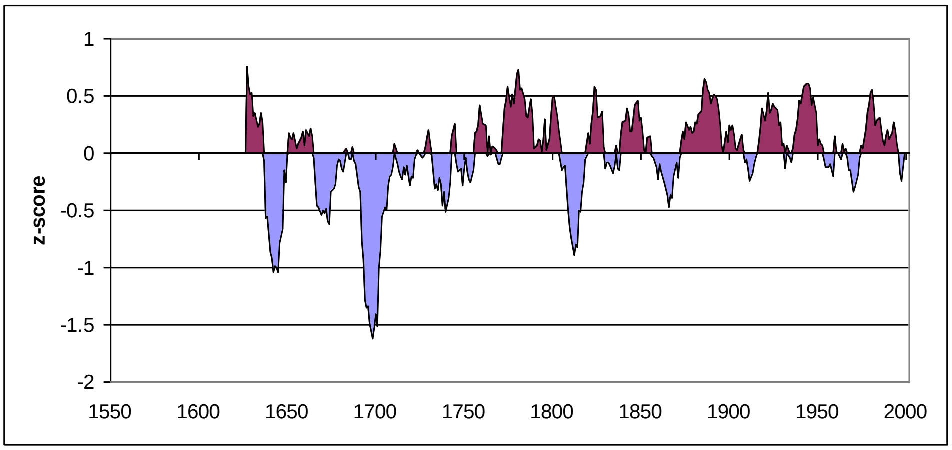
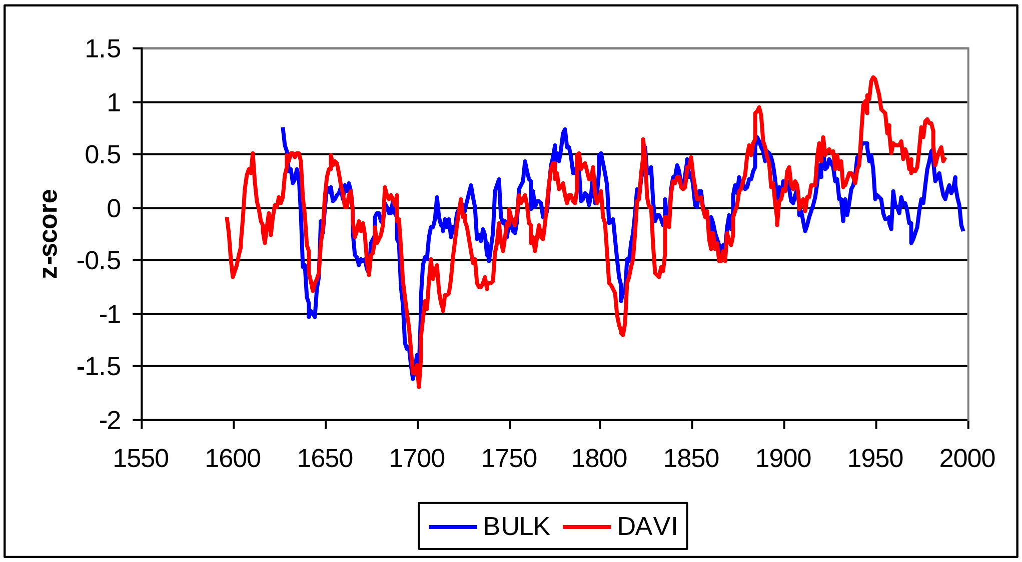


Figure 6.10 Warm and cool periods within the BULK reconstruction. The series was smoothed with a 10-yr. moving average window and converted to z-scores.

6.7.2 Comparison with Alaskan Reconstruction

The BULK reconstruction shows similarities with the warm season (July-September) mean temperature reconstruction developed by Davi *et al*. (2003) for the Wrangell Mountain region in southeast Alaska (Figure 6.11), an area immediately west of the Yukon/Alaska boundary and slightly further north than the chronologies used in the BULK reconstruction. Both reconstructions are based on maximum latewood density. Figure 6.11a illustrates the similarity between these two reconstructions. Over the 1623-1992 common period, the two reconstructions exhibit a mean correlation of r = 0.684. Both records capture the extreme cold periods during the early 1700s and early 1800s. Cool intervals during the 1640s, 1670s and 1860s, as well as warm intervals during the 1650s-60s, 1820s, 1840s and 1880s are also common in the two records. Using a 15-year moving window, running correlations between the two records do show variations over time ranging between r = -0.490 to 0.992 (Figure 6.11b). Differences between the two reconstructions are evident during the 18th century with the BULK record exhibiting moderately warmer temperatures than the Davi series as both recover from the extreme cold at the beginning of the century. Between 1777-1801, the two reconstructions appear

a)



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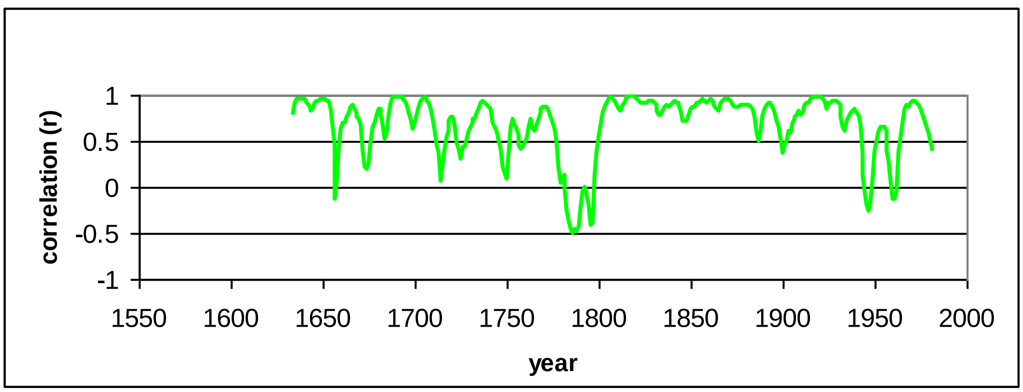
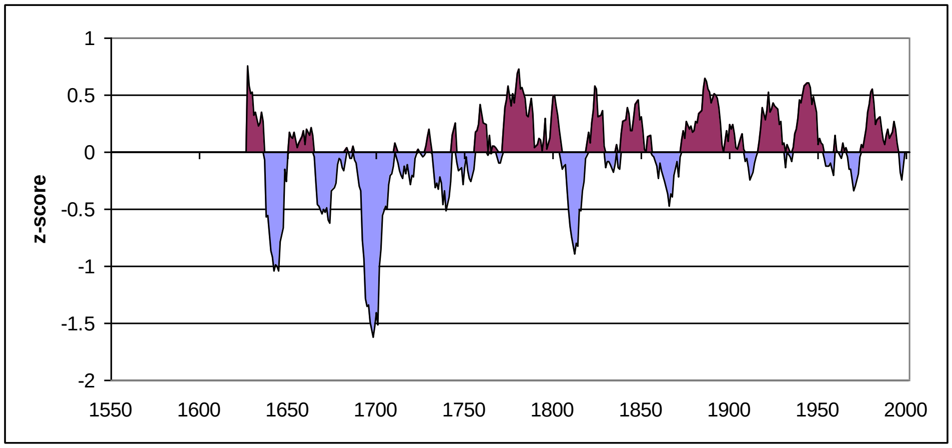


Figure 6.11 Time series plots of (a) the BULK and Davi *et al*. (2003) MXD reconstructions, and (b) 15-year running correlation between the two reconstructions. Each time series was converted to z-scores for comparative purposes and 10-year running average applied. Both reconstructions represent warm season temperatures (BULK: May-August max. temp.; DAVI: July-September mean temp.)

out of phase with each other. From 1777-1790 the BULK reconstruction shows warmer conditions whereas the Davi reconstruction displays a drop in temperature. From 1791-1801, this pattern alternates as the Davi series exhibits a recovery to warmer temperatures while the BULK series records a decrease. The two reconstructions display the most noticeable difference during the latter half of the 20th century. The Davi reconstruction shows a dramatic rise in temperature, peaking in 1949, while the BULK reconstruction exhibits temperatures similar to those experienced earlier in the century. Though temperature magnitudes between the two records differ during this period, the patterns of changes appear to be similar. Examination of the warm/cool periods of the two reconstructions (Figure 6.12a and 6.12b) indicates that although the decadal-multidecadal patterns are comparable between the two series, the Davi reconstruction shows a more pronounced long term, low frequency warming trend from the 1750s which is not evident in the BULK record. The BULK reconstruction exhibits more high frequency variability in its reconstructed temperatures. The absence of strong low frequency variability may reflect the short segment lengths encountered in the original data (see Section 6.3.2).

Examination of the ten warmest and coldest years of the two reconstructions (Table 6.12a and 6.12b) provides additional information regarding similarities and differences between the two records. As the reconstructed parameters differ (BULK is May-August maximum temperature; Davi is July-September mean temperature) comparisons are based on rank rather than absolute values. Five of the ten warmest years of the Davi reconstruction occur between 1946-1953, whereas the BULK record only reconstructs moderate temperatures during this period. The warmest reconstructed temperatures of the BULK record appear much earlier between 1627-1640 (4/10) and 1777-1796 (4/10). Only 1796 and 1915 are common between the two reconstructions. Comparisons of the coldest years in the reconstructions show greater similarity. Five of the ten coldest years are common to both records (1643, 1695, 1697, 1699, and 1810), though their individual rankings vary.

a)



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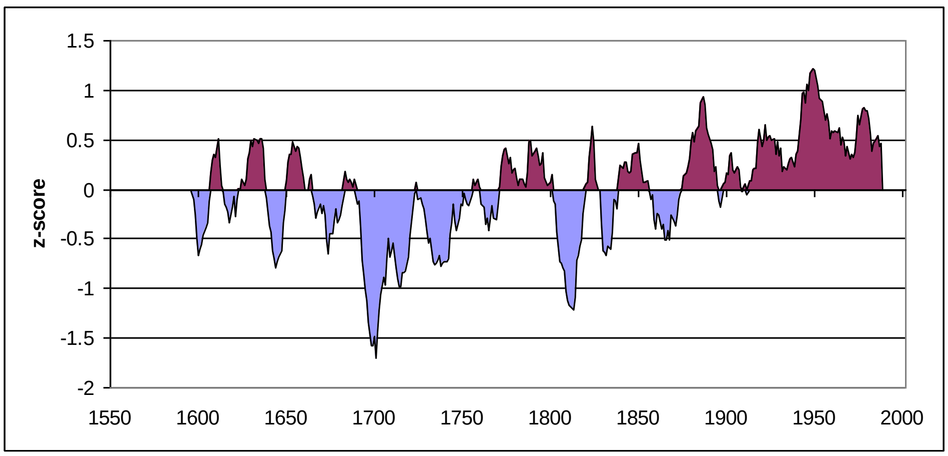


Figure 6.12 Warm and cool periods within (a) the BULK reconstruction, and (b) Davi *et al*. (2003) reconstruction. Each series was smoothed with a 10-yr. moving average window and converted to z-scores for comparison purposes.

Table 6.12 List of (a) ten warmest reconstructed years, and (b) ten coldest reconstructed years for the BULK May-August maximum temperature reconstruction and Davi *et al.* (2003) July-September mean temperature reconstruction. Years shown in bold indicate years common to both records.

a) Warmest Years

BULK

Rank	Year	Temp (°C)
1	1632	19.54
2	1637	18.87
3	1777	18.84
4	1779	18.79
5	1627	18.70
6	1806	18.67
7	**1915**	18.65
8	1640	18.57
9	1796	18.53
10	**1792**	18.50

DAVI

Rank	Year	Temp (°C)
1	1948	11.85
2	1989	11.81
3	1923	11.80
4	1951	11.77
5	**1792**	11.59
6	1890	11.50
7	1953	11.48
8	1947	11.40
9	**1915**	11.34
10	1946	11.34

b) Coldest Years

BULK

Rank	Year	Temp (°C)
1	**1643**	13.52
2	**1697**	14.34
3	**1699**	14.44
4	**1810**	15.14
5	1751	15.24
6	1738	15.47
7	1955	15.53
8	**1695**	15.57
9	1646	15.68
10	1959	15.84

DAVI

Rank	Year	Temp (°C)
1	**1810**	8.09
2	1831	8.21
3	**1695**	8.42
4	**1643**	8.45
5	1834	8.48
6	1809	8.53
7	**1697**	8.56
8	**1699**	8.56
9	1783	8.62
10	1817	8.67

Several studies (e.g. Jones *et al.*, 1995; Briffa *et al.*, 1998a; D'Arrigo and Jacoby, 1999; Davi *et al.*, 2003) have demonstrated the linkage between cold summers reconstructed by tree-rings (particularly MXD) and dates of volcanic eruptions. Sulfate aerosols emitted by volcanic eruptions can reflect incoming solar radiation leading to cooling within the troposphere (Bradley, 1988; Sigurdsson and Laj, 1992). Comparison of the BULK reconstruction with a listing of major explosive volcanic eruptions (Appendix G compiled from Jones *et al.*, 1995; Briffa *et al.*, 1998a; D'Arrigo and Jacoby, 1999; Deligne *et al.*, 2010) indicates several of these extreme cold years are synchronous with or immediately follow the dates of known volcanic events (Figure 6.13). The coldest year within the reconstruction, 1643, follows shortly after major

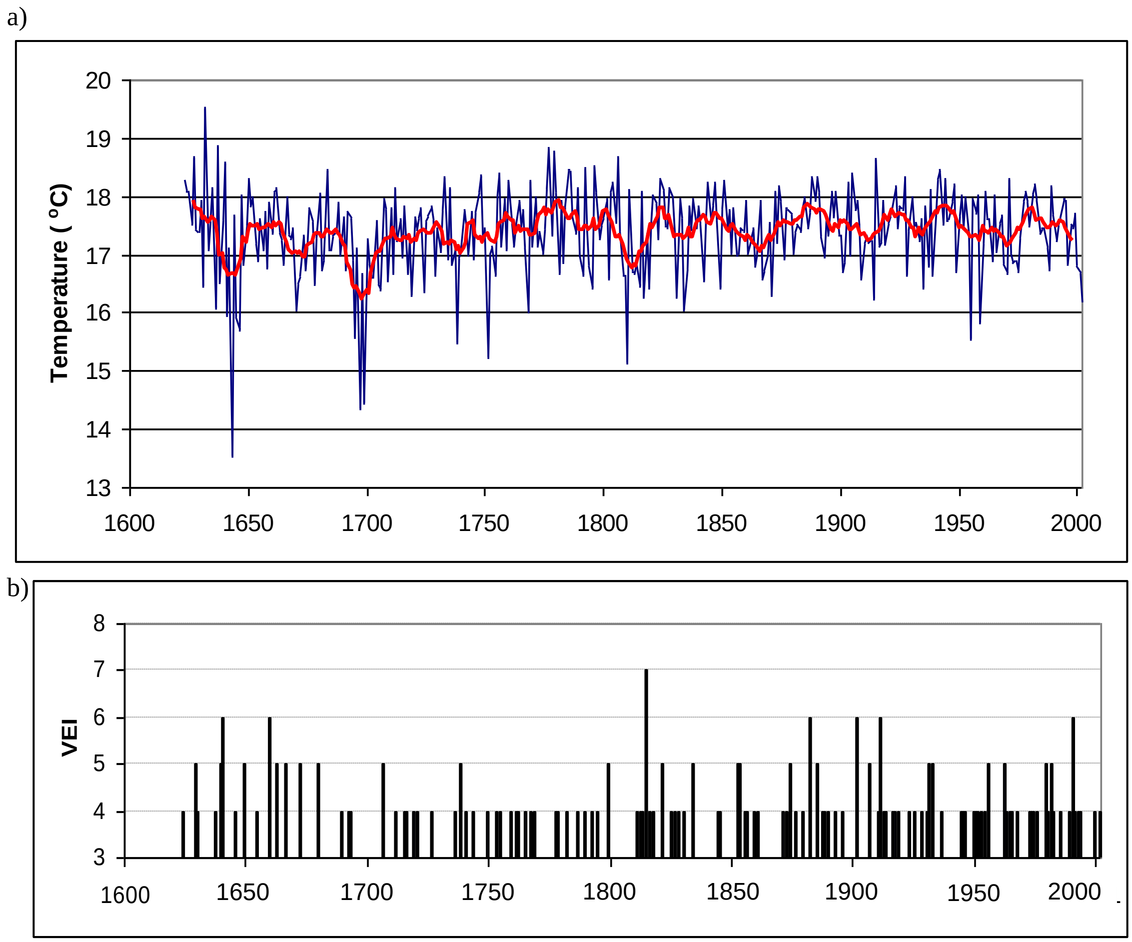


Figure 6.13 (a) BULK reconstruction of May-August maximum temperature (10-year moving average trendline in red), and (b) major volcanic events (Volcanic Explosive Index (VEI) ≥ 4) between 1623-2002 (eruptions listed in Appendix G).

major eruptions in Japan (*Komaga-Take*), Chile (*Llaima*) and the Philippines (*Mt. Parker*) in 1640. Reconstructed temperatures in 1641/42 were also low, possibly reflecting the influence of these volcanic events. D'Arrigo and Jacoby (1999) point out that the 'response' following an eruption may be seen in the year of the event or the subsequent year(s), depending on the season and latitude of the eruption. The next coldest years in the reconstruction occur in 1697 and 1699. Although the low temperature in 1697 may be associated with an eruption of *Komaga-Take* in 1694, it is quite unlikely that this event led to the low reading in 1699. The next documented major volcanic eruption is not until 1707 (*Fuji*, Japan). D'Arrigo and Jacoby (1999) report 1699 to be an uncommonly low density year in several of their chronologies from northwestern North America. Similarly, Jones *et al*. (1995) noted that 1699 was one of five extreme years common to both North America and Europe and they suggested that 1699 should be considered a candidate for a large, previously unknown volcanic eruption. Cold years in 1738 and 1751 may be associated with major eruptions in Japan (*Tarumai*) and Russia (*Ksudach*) respectively. The year 1810 also stands out in the BULK reconstruction as an extremely cold year. Examination of elevated sulfate concentrations in ice cores from Antarctica and Greenland have identified a previously unknown volcanic eruption which occurred in 1809 and could have accounted partially for the decline in temperatures preceding the major eruption of *Tambora* (Dai *et al*., 1991; Yalcin *et al*., 2006, Guevara-Murua *et al*., 2014). The eruption of *Tambora* in Indonesia (Volcanic Explosivity Index value of 7) in 1815 is significant in the record of known volcanic events. However, the effects of *Tambora* in North America were primarily concentrated in the east (D'Arrigo *et al*., 1996; D'Arrigo and Jacoby, 1999) with little evidence of cooling in the northwest (Luckman and Colenutt, 1988; Luckman, 1996; D'Arrigo and Jacoby, 1999). The years 1955 and 1959 also appear in the reconstruction as experiencing quite cold conditions. An eruption in Chile (*Carran-Los Venados*) in 1955 may be associated with the cool temperatures that year, but no volcanic event is documented for 1959. It is interesting to note that impacts from the six most explosive (VEI $\geq$ 6) eruptions documented (*Tambora* [1815], *Long Island* [1660], *Krakatau* [1883], *Santa Maria* [1902], *Katmai* [1912] and *Pinatubo* [1991]) are not seen as reconstructed extremely low temperatures of the BULK reconstruction. Similarly, there is no evidence for the eruption of *Laki (Grimsvotn)* in 1783 as noted by D'Arrigo and Jacoby (1999) in Alaska to the west. No large declines were recorded in the reconstruction associated with these event years (or 1-2 years subsequent). Jones *et al*. (1995) made similar observations regarding the absence of cool summers following the eruptions of *Krakatau* and *Santa Maria*. Though marked declines in MXD and temperature may coincide with major volcanic eruptions, caution must be taken in interpreting such occurrences. The effects of volcanic eruptions vary depending on location (of eruption and tree-ring site), the season and type of eruption and other factors (D'Arrigo and Jacoby, 1999). The associations observed here between reconstructed extreme cold years and known eruptions simply adds to documentation of the spatial signal of effects related to specific eruptions and evidence of local climate effects associated with these eruptions.

Solar variability is another forcing mechanism of global temperature changes. Satellite-based measurements have shown a correlation between solar irradiance and the 11-year sunspot cycle (Hoyt and Schatten, 1993; Lean *et al*., 1995; Beer *et al*., 2000). Comparison of the BULK and Davi reconstructions with an updated solar irradiance reconstruction based on sunspot activity (Lean, 2004), indicates that two of the main cold periods coincide with the Maunder (ca. 1645-1715) and the Dalton (ca. 1790-1830) Solar Minima (Figure 6.14). Similar to the discussion regarding volcanic forcing, this 'synchronicity' between low reconstructed temperatures and periods of reduced solar irradiance does not imply a direct connection between the two variables, but rather provides contextual information in interpreting the reconstructions.

Comparison of the BULK reconstruction with other tree-ring based proxy temperature records demonstrates how differing ring parameters and regional differences can affect reconstructions. The ring-width (RW) reconstruction of June-July maximum temperatures for the southwest Yukon developed by Youngblut and Luckman (2008) (Figure 6.15c) exhibits much lower interannual variability than either the BULK or Davi reconstructions examined earlier (Figure 6.15a and 6.15b). Though all three reconstructions capture the cool periods of the early 18th and early 19th centuries, the RW record indicates these periods lasted much longer (i.e. were multi-decadal) in comparison to the shorter intervals represented in the BULK and Davi reconstructions. Another difference in these records occurs during the recovery to warmer conditions in the late 19th century. While the BULK and Davi reconstructions show an increase in warm season temperatures beginning by the 1880s, the Youngblut and Luckman (2008) reconstruction suggests a much later recovery (ca. 1910). Such differences between the reconstructions may reflect differences between the tree-ring variables examined and their climatic responses. MXD is a good integrator of interannual summer variability while RW relationships may be more apparent on decadal and longer timescales (Jacoby and

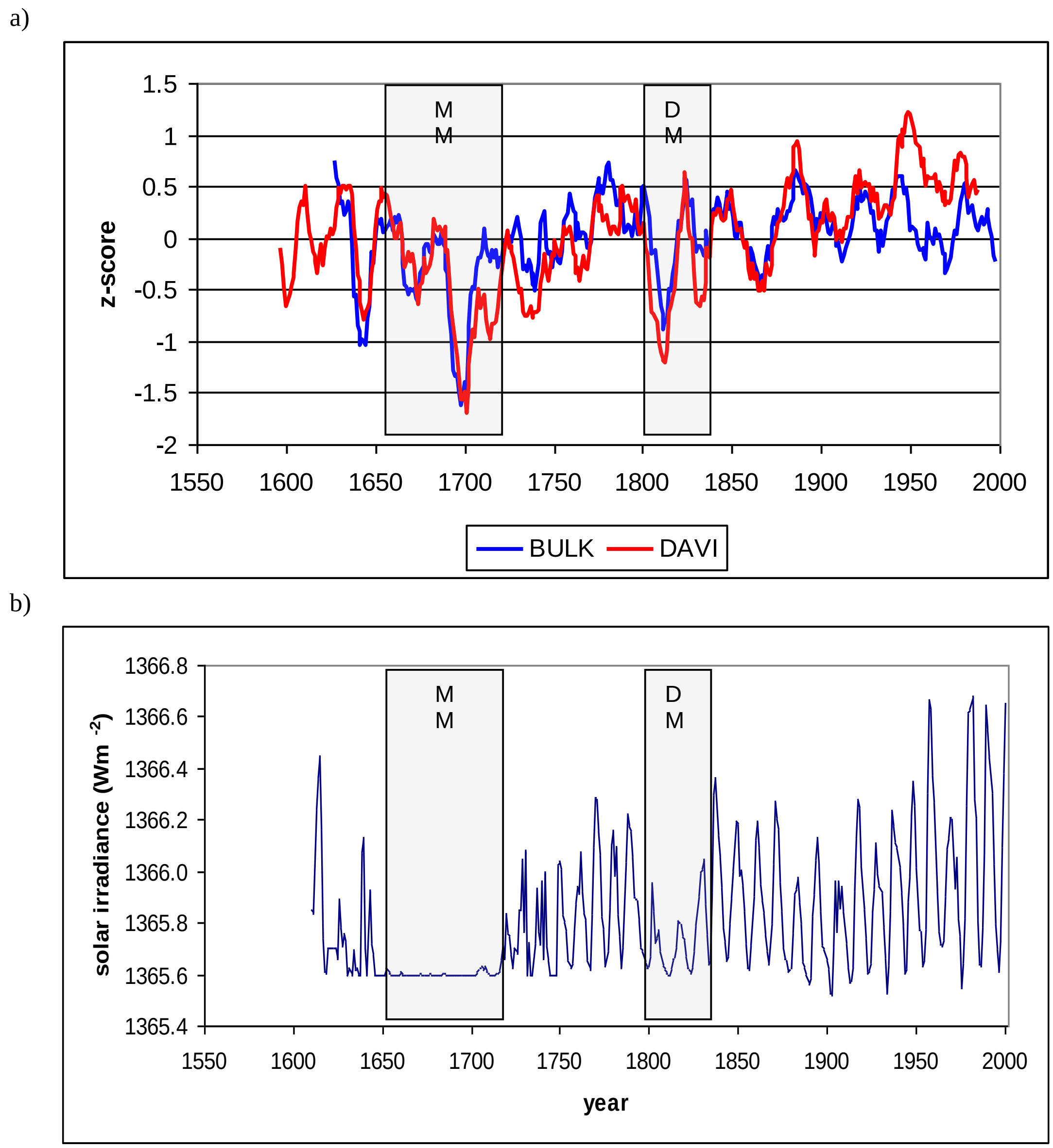
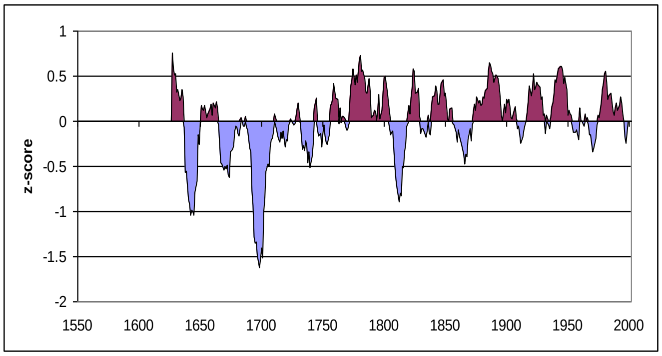
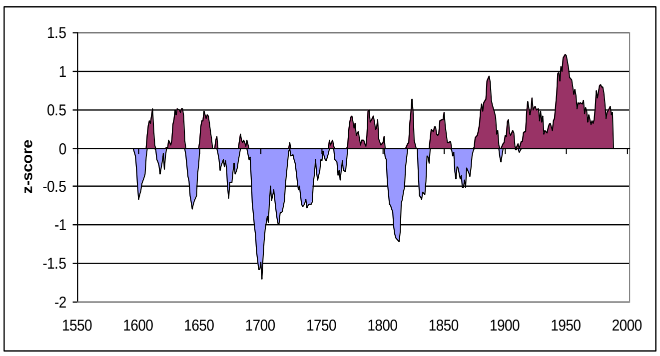


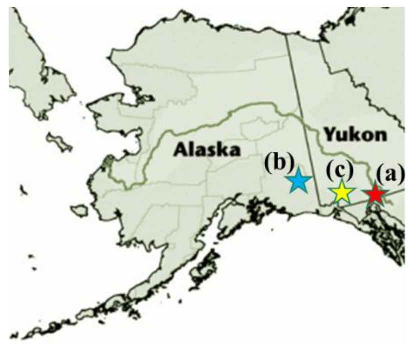
Figure 6.14 (a) Plot of BULK and Davi *et al.* (2003) reconstructions, with (b) solar irradiance reconstruction (data from Lean, 2004). Vertical shading denotes approximate timing and duration of solar activity minima [Maunder Minimum (MM) and Dalton Minimum (DM)].

a)

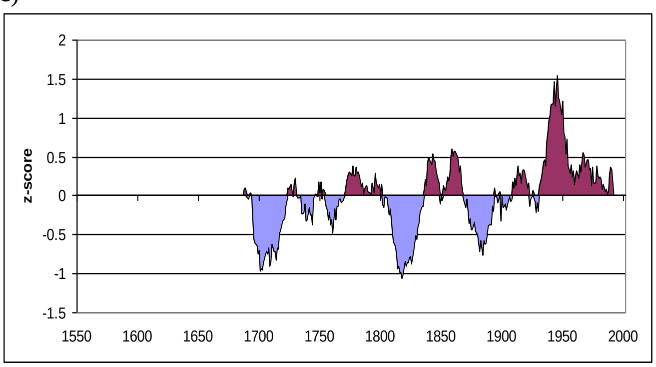


b)





c)



d)

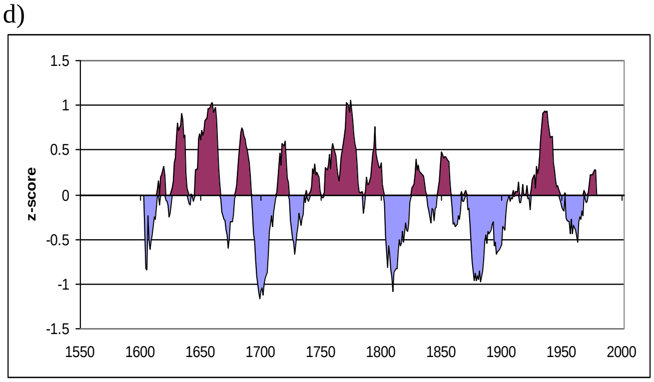


Figure 6.15 Warm and cool periods within (a) BULK, (b) Davi *et al*. (2003), (c) Youngblut & Luckman (2008) and (d) Briffa *et al*. (1992) (BCPNW) tree-ring reconstructions. Each series was smoothed with a 10-yr. moving average window and converted to z-scores for comparison purposes.

D'Arrigo, 1995; Schweingruber and Briffa, 1996).

Comparison of reconstructions with an April-September mean temperature MXD reconstruction for British Columbia-Pacific Northwest (BCPNW) developed by Briffa *et al*. (1992, see Figure 6.15d) provides a broader scale context for the previous records. Though primarily representing a region further south (44°-56°N, 119°-135°W), the BCPNW record exhibits some similarities with the previously discussed reconstructions. Like the BULK and Davi reconstructions, the BCPNW record exhibits warm and cool intervals generally lasting on decadal rather than multi-decadal scales as seen in the Youngblut and Luckman reconstruction. Again this likely represents the difference between reconstructions based on ring-density rather than ring-width. Similar to the Youngblut and Luckman record though, the BCPNW reconstruction shows a delayed recovery of warmer conditions following the cool period of the 19th century. Temperatures during the 20th century appear to peak earlier (ca. 1930s) in the BCPNW record, while maximum reconstructed temperatures of the Youngblut and Luckman series are not reached until ca. 1940s. Both the BULK and BCPNW reconstructions exhibit a cool period during the second half of the 20th century, which is not found in either the Davi or Youngblut and Luckman reconstructions. This cool period appears colder and of longer duration within the BCPNW record. Comparison between all these regional reconstructions indicate some common elements, such as the cold intervals at the start of the 18th century and the first quarter of the 19th century, but there remain differences likely due to differences in both the sites and regions covered, as well as the parameters reconstructed. While the other reconstructions exhibit evidence of multi-decadal patterns, the BULK reconstruction shows shorter, decadal patterns with smaller range.

6.7.3 Comparison with Other Proxy Climate Records

Many independent proxy climate records from northwestern North America often deal with very long timescales (e.g. Viau *et al*., 2008; Kurek *et al*., 2009) and lack the temporal resolution that tree-ring reconstructions provide. Certain studies though appear to provide results at scales enabling general comparisons with the tree-ring reconstruction of this study. Using paleolimnological analyses of chironomids and ostracodes from four lakes in the southwest Yukon, Bunbury and Gajewski (2012) developed estimates of mean

July air temperatures for the past 2000 years. This paleolimnological record showed generally cool temperatures between AD 1400 and 1900 with a warm interval occurring in the middle of this period documented by considerable change in chironomid and ostracode communities at ca. AD 1750. (Bunbury and Gajewski, 2012). This change appears to concur with the shift from cool to warm conditions during the mid-18th century recorded in the tree-ring reconstructions, particularly the BULK and Davi records (Figure 6.15a and 6.15b). Glacial history records from regions in Alaska and the southern Canadian Cordillera also appear generally to support findings of the tree-ring reconstructions. Evidence from the Wrangell Mountains of southern Alaska indicate glacial advances between ca. AD 1630 and 1720 suggesting cool conditions, followed by warming and glacial recession post-1800 (Wiles *et al*., 2002; Wiles *et al*., 2008). The period of advances generally correspond with cold intervals of the 17th and early-18th centuries in the tree-ring reconstructions, with warming trends appearing in the latter half of the 19th century. In a detailed history of glacier fluctuations in the Canadian Rockies during the Little Ice Age (LIA), Luckman (2000) noted two widespread periods of glacial advances and moraine building, ca. 1700-1725 and ca. 1825-1850. These two periods are also seen in the millennial summer temperature reconstruction from the southern Canadian Rockies (Luckman and Wilson, 2005) and also match up well with the extreme cold intervals found at the beginnings of the 18th and 19th centuries in the BULK reconstruction of the current study. While glacier advances often reflect periods of reduced temperatures, other factors such as increased precipitation can also play a significant role in the activity of glaciers (Luckman, 2000). Similarly, while paleolimnological proxy indicators can provide useful information regarding relationships with temperature, associations with other environmental variables (e.g. lake pH, salinity, conductivity, water chemistry) may also be important factors (Smol *et al*., 1994). Proxy records inherently contain complexities involving the relationships they convey which often makes direct comparisons challenging. The comparisons presented here are of a general nature providing independent supporting evidence for the climate trends witnessed in the tree-ring reconstructions.

Strong decadal-scale modes of variability have been identified in climatic studies involving the northern Pacific region. One of the key modes is the Pacific Decadal Oscillation (PDO), first identified by Mantua *et al*. (1997) but also referred to as the

Interdecadal Pacific Oscillation (IPO) (Power *et al*., 1999) or the North Pacific Oscillation (NPO) (Gershunov and Barnett, 1998). The PDO index is the leading component of an empirical orthogonal function (EOF) analysis of monthly North Pacific sea surface temperatures poleward of 20°N (Mantua *et al*., 1997; Mantua and Hare, 2002). Positive or 'warm' phases of the PDO, such as that experienced between 1977 and 1997, are typically associated with anomalously warm and wet conditions in northwestern North America while cooler and drier conditions are generally experienced during negative or 'cool' phases (Mantua and Hare, 2002; MacDonald and Case, 2005). Various studies have documented PDO phase shifts occurring during the 20th century in 1925, 1947 and 1977 (Hare and Francis, 1995; Zhang *et al*., 1997; Mantua *et al*., 1997). Comparison of the BULK tree-ring reconstruction with the PDO index of Mantua (http://jisao.washington.edu/pdo/PDO.latest) for the 20th century does not show a clear, strong relationship between the two series (Figure 6.16). Correlations between the two records were statistically non-significant ($p \leq 0.05$) whether calculated over the entire common period (1900-2002, r = 0.182) or each individual PDO phases (1900-1925, r = 0.201; 1925-1947, r = 0.161; 1947-1977, r = 0.167; 1977-2002, r = 0.067).

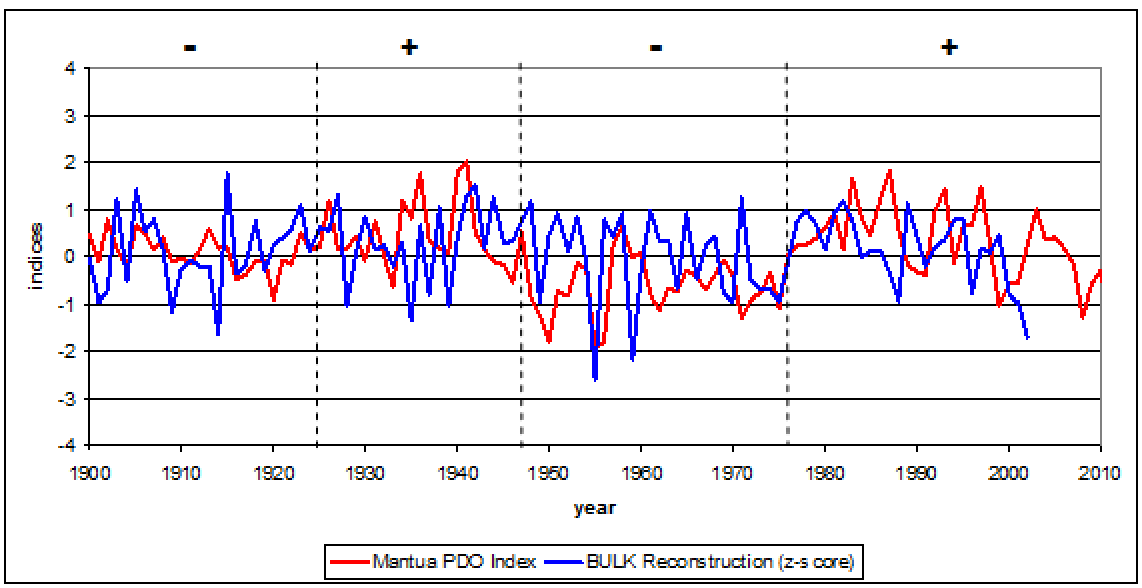


Figure 6.16 Time series plot of the Mantua PDO index and BULK May-August maximum temperature reconstruction (z-scores) over the 20th century. Dashed vertical lines indicate known PDO shifts between positive (+) and negative (-) PDO phases.

6.8 Conclusions

Fifteen MXD chronologies were developed for this study. Nine of these sites were sampled by UWO field parties, while data for six sites were obtained from the International Tree-Ring Databank (5 sampled by Fritz Schweingruber, 1 sampled by Julian Szeicz) to supplement and expand the spatial coverage of the MXD study network. Three of the chronologies exhibited low EPS and were subsequently removed from further study.

Analyses of the twelve remaining MXD chronologies indicated that strong regional growth patterns existed within the network. PCA and correlation analyses identified two main regional groupings: (a) a central/southern group, and (b) a northern group. Examination of correlations indicated that values were stronger for the 1900-1950 time period and showed weaker results over the 1950-2000 period. PCA also identified the central/south and northern groups, but also suggested an eastern group, particularly during the earlier 1900-1950 period. While slight variations in chronology PC loadings existed between time periods, a 'core' group of five sites (Big Salmon, Monarch, Dease Lake, Cassiar (UWO), and Cassiar) from the south/central region sharing a common growth signal consistently loaded together on the primary component for both halves of the 20th century.

Relationships between the twelve MXD chronologies and regional climate records for the Yukon indicated strong positive relationships between MXD and summer temperatures for both the northern and southern Yukon climate records. Analyses indicated that these significant relationships focused primarily on current year growth responses and did not extend to relations with previous year's growth. Strongest correlations were obtained with aggregated 'seasonal' (4-month) temperature data of the southern climate record rather than single or 3-month data. Unlike many of the RW chronologies that showed a dramatic shift in climate-growth responses from significantly positive to significantly negative between the first and second halves of the 20th century, the MXD chronologies displayed positive relationships with summer temperatures which were much more time stable. A core group of six chronologies, primarily located in the southwest Yukon and northern British Columbia, exhibited statistically significant positive correlations with May-August maximum temperatures throughout the 20th century. Based on this relationship, a regional MXD chronology (BULK) was created from the data for these six sites. Using this regional record, a dendroclimatic temperature reconstruction was developed to examine climate variability over several centuries.

The MXD reconstruction model ($FULL_{May\text{-}Aug} = 11.153(BULK) + 6.316$) explained 38.9% of the May-August maximum temperature variance of the southern Yukon climate record over the 1939-2002 calibration interval. The reconstruction spanned the period 1623-2002. This record exhibited a high frequency signal characterized by decadal variability. Between the mid-17th to mid-18th centuries, the reconstruction indicated a prolonged period of cool temperatures, followed by progressive warming to the end of the 18th century. Reconstructed temperatures in the 19th and 20th centuries fluctuated between warmer and cooler periods lasting no more than one or two decades. Comparison of the MXD reconstruction with other regional tree-ring reconstructions demonstrated general similarities in climatic trends, validating the results of the current record. The MXD reconstruction showed greatest similarity with decadal trends in the Alaskan Wrangell Mountains MXD record of July-September mean temperatures (Davi *et al*., 2003). Comparison with the Southwest Yukon RW reconstruction of June-July maximum temperatures (Youngblut and Luckman, 2008) showed some general common patterns but also highlighted differences between the records which may reflect the different tree-ring variables examined. Coherence between extreme cool periods of the reconstructions suggests the influence of larger-scale forcing mechanisms on climate (e.g volcanic activity, solar irradiance).

Unlike many ring-width records from the Yukon, maximum density chronologies primarily exhibited strong, temporally stable relationships with summer maximum temperatures and showed the greatest potential for development of a long temperature reconstruction. Representing the south-central Yukon, this reconstruction demonstrates good interannual and decadal signals but lacks a long-term, low frequency signal. This absence may be due to problems associated with samples cut into multiple, short segments for processing. Examination of responses in the northern Yukon was limited to two sites. Though one site (Rock River) did exhibit a strong positive relationship with summer temperatures during the first half of the 20th century, the responses were weaker during the second half. The other site (Campbell Dolomite) failed to show any statistically significant responses. Additional sample sites would be necessary to determine whether a truly regional response could be identified for sites in the northern Yukon. The MXD reconstruction developed in this study complements work in Alaska and the Northwest Territories, filling a geographical gap in the limited collection of density-based, temperature reconstructions developed for north-western North America.

CHAPTER SEVEN

Summary and Conclusions

7.1 Introduction

Previous studies have demonstrated a summer temperature signal in tree-ring series from the Yukon Territory (Jacoby and Cook, 1981; Pisaric, 2001; Youngblut and Luckman, 2008). However, there have also been suggestions of a loss in temperature sensitivity among some northern trees occurring during the latter half of the 20th century (Jacoby and D'Arrigo, 1995; Barber *et al*., 2000; Lloyd and Fastie, 2002). While these early studies focused primarily on forest stands in Alaska, research in the Yukon has also suggested evidence of change in the temperature signal (e.g. D'Arrigo *et al*., 2004a; Earles, 2008; Porter and Pisaric, 2011). These studies have been limited to areas in the northern Yukon Territory and tree-ring temperature relationships have not been examined over large parts of the Yukon. The primary goals of this thesis were to develop a tree-ring network that covered the Yukon; examine the climate signal(s) in ring-width and maximum latewood density series from this network; and, potentially, use these relationships to develop one or more long temperature reconstructions for this region. This chapter summarizes the key findings of this research and its implications for dendroclimatic studies of this northern region, and provide some recommendations for future work.

7.2 Key Research Findings

7.2.1 Ring-Width Records

The 111 white spruce site chronologies developed for this study represent the largest collection of tree-ring records for the Yukon Territory and adjacent areas of Alaska and northern British Columbia. A smaller network of 73 chronologies with adequate signal quality and a minimum length of 200 years was developed and used to examine variability in white spruce growth patterns and responses to climate over the region. Correlation and principal components analyses of the network identified 4 main regional groupings plus a distinctive group of chronologies located around the southwest shores of Kluane Lake in the southwest Yukon. Inter-site correlations of residual chronologies were generally stronger than those of standard chronologies indicating high frequency, interannual variability was an integral element of the growth patterns of the chronologies. Correlations between the standard chronologies were weaker but also identified these regional patterns. The mean inter-site correlations for the network were much stronger for the 1900-1950 period (r = 0.503 standard chronologies, r = 0.519 residual chronologies) compared with the 1800-2004, 1900-2004 and 1950-2004 time intervals examined (correlations ranged from 0.322 to 0.375 for standard chronologies, 0.393 to 0.455 for residual chronologies). Principal Components Analyses over the 1900-1950 period showed that 50 of the 73 chronologies loaded on the first principal component (PC) accounting for 45.6% of the growth variance in the network. Only 22 chronologies loaded on the first PC of the second half of the 20th century (only 27.1% of the variance). These analyses indicated that a strong common growth signal existed over much of the network for the first half of the 20th century but changes during the latter half led to much greater growth variability. There was also greater inter-site variability during the 19th century. Such widespread change during the twentieth century was probably due to a change in a large-scale forcing mechanism such as climate. Since climate records in the Yukon are relatively short, analyses into the climate-growth relationships of the ring-width chronologies were concentrated on 20th century data.

7.2.2 **Climate Records for the Yukon**

Two regional temperature and three regional precipitation records were developed to investigate the climate-tree growth relationships across the Yukon. Climate records for the Yukon are limited in number and in length. Based mainly on summer temperatures, two regional series were developed: a ‘northern’ group (Dawson, Mayo, Pelly Ranch) extended from 1898 to 2010 and a ‘southern’ group (Burwash, Haines Junction, Whitehorse, Teslin) covering the period 1939 to 2010. The two records are highly correlated (r = 0.82) over their common period. Both records exhibited similar high frequency patterns, although the ‘northern’ record generally exhibited 1-2°C warmer summer maximum temperatures. Summer minimum temperatures had relatively similar absolute values prior to ca. 1960, but the northern series warmed more and at a greater rate thereafter. Summer minimum temperatures for the southern series remained relatively stable whereas minimum temperatures of the northern series showed a progressive rise.

Examination of precipitation data from the Yukon also indicated regional variability. As seasonal distribution of precipitation showed marked summer maxima, summer variations were used to categorize the regions. Three regional series were developed: a 'northern' series (Dawson, Klondike and Tuchitua) spanned 1902-2003, a 'central' series (Pelly Ranch, Mayo, Carmacks and Burwash) from 1925-2010 and a 'southern' series (Teslin, Johnson Crossing, Watson Lake, Swift River, Whitehorse and Ross River) from 1939-2010.

7.2.3 **Ring-Width Climate-Growth Relationships**

Examination of climate-growth relationships involving the ring-width chronologies was carried out using various chronology-climate combinations over differing time periods. Initial analyses utilized the regional RW chronologies and monthly temperatures and showed statistically significant positive correlations with June maximum and mean temperatures of both the 'northern' and 'southern' climate records and negative correlations with previous July maximum and mean temperatures of the 'northern' climate series. Correlations involving the northern series were calculated over the period 1900-2003 while values with southern series covered 1939-2003 period. These significant correlations were only for single months, varied between regions and were not as strong as those seen in the published literature. Correlations with aggregated 'seasonal' climate data showed little improvement, further highlighting differences between the regions rather than shared responses across regions. More detailed examination of the responses of individual chronologies indicated considerable variability in the nature, strength and sign of response within each regional group. Therefore examination of 'regional' responses was abandoned in favour of individual, chronology-level climate-growth relationships.

Climate-growth responses for the 73 chronologies were calculated for and compared between the 1900-1950 and 1950-2000 time periods for the northern temperature record to determine whether the changes in the growth between the first and second halves of the 20th century were related to variations in climate. Analyses were also carried out using the 1950-2000 southern temperature record for comparison with relationships based on the northern record. However, significant correlations for the northern record after 1950 outnumbered those with the southern record, despite most sites being closer to the southern climate stations. During the 1900-1950 period tree-ring temperature relationships were dominated by strong positive correlations, particularly with current spring and summer minimum and mean temperatures. More than 70% of the chronologies in the network were significantly positively correlated ($p<0.05$) with June-August minimum temperatures and May-July mean temperatures (Table 7.1). The strongest of these significant correlations were from sites in the central and southern portions of the network, while the weaker correlations were for northern sites along the Dempster Highway. Positive correlations with summer minimum and mean temperatures were also present in the climate-growth relationships two years prior (i.e. ppMay-ppJuly). Correlations during the prior growth year (e.g. pMay-pJuly) showed fewer positive responses.

Responses to summer temperatures for the 1950-2000 period showed a dramatic shift from those of the first half of the century (Table 7.1). Many of the significant positive relationships with summer temperatures experienced during the first half were replaced by non-significant or negative correlations, particularly over the northern half of the network. Sites in the southern half of the Yukon showed mainly non-significant values that trended from slightly negative to slightly positive. The few sites which maintained significant positive correlations were found in the southwest Yukon and northern BC. The most prominent response during the 1950-2000 period was a negative relationship with spring temperatures. Significant negative correlations with current March-May temperatures were the most prominent with 47% or more of the network chronologies expressing this spring signal across the three temperature variables. Relationships with both the northern and southern climate records exhibited significant negative correlations with spring temperatures of the current growth year (Table 7.2). Correlations between chronologies and the northern climate record showed a greater number of significant values than with the southern record, especially in responses involving the previous growth year and two years prior.

Table 7.1 Summary of tree-ring relationships with summer (current May-July) mean temperatures of the northern and southern climate series.

	Statistically Significant Positive Values in 1900-1950			All Sample Sites		
Correlation summer mean temperature (May-July)	North		South	North		South
	1900-1950	1950-2000	1950-2000	1900-1950	1950-2000	1950-2000
Positive (99% significance level)	31	6	9	31	6	9
Positive (95% significance level)	26	1	5	26	1	5
Positive (not statistically significant)		14	24	16	14	29
Negative (not statistically significant)		17	19		24	27
Negative (95% significance level)		9			15	3
Negative (99% significance level)		11			13	
Total	57	57	57	73	73	73

Table 7.2 Summary of tree-ring relationships with spring (current March-May) mean temperatures of the northern and southern climate series.

Correlation spring mean temperatures (March-May)	North (1900-1950)	North (1950-2000)	South (1950-2000)
Positive (99% significance level)			
Positive (95% significance level)	3	1	1
Positive (not statistically significant)	55	8	11
Negative (not statistically significant)	15	21	22
Negative (95% significance level)		10	15
Negative (99% significance level)		33	24
Total	73	73	73

Relationships were also examined between the 73 chronologies and the three regional precipitation records. Results showed lower and less significant correlations than the temperature records. Significant ($p \leq 0.05$) relationships with the northern record during the 1900-1950 period were characterized by positive responses with previous summer (pJune-pAugust) precipitation (52 chronologies) and negative responses with previous early spring (pFebruary-pApril) precipitation (43 chronologies); relationships with the northern record during the 1950-2000 period were dominated by negative responses with current late autumn (September-November) precipitation (32 chronologies). Correlations involving the central and southern precipitation series over the 1950-2000 period also demonstrated negative responses with current spring precipitation (25 chronologies with April-June precipitation of the central series; 29 chronologies with May-July of southern series). Eight sites along the Dempster Highway were positively correlated with previous February-April precipitation of the southern climate series. This relationship provides limited support for the argument of moisture stress at these sites though it is surprising that it does not occur with the more proximal northern precipitation record.

The climate-growth relationships between the RW chronologies and both temperature and precipitation clearly show changes in their responses over the 20th century. This instability is a serious roadblock to the development of climate reconstruction(s) as it violates a central tenet of dendroclimatology, namely that the response is time stable affording consistent relationships during calibration/verification periods. Youngblut and Luckman (2008) were able to produce a reconstruction of June-July maximum temperatures based on seven select chronologies from the southwest Yukon which maintained stable positive responses over the 20th century. Six of these chronologies were in the 11 chronologies that maintained a strong summer signal (June-August maximum temperature) in the current study. Any reconstruction based on these 11 sites was likely to be very similar to the published reconstruction, therefore no new reconstruction was attempted using the RW chronology network.

7.2.4 **Maximum Latewood Density Network and Reconstruction**

Maximum latewood density (MXD) in conifer tree-rings has been demonstrated to correlate significantly with temperature at sites in northern latitudes, especially summer temperatures (Parker and Henoch, 1971; Briffa *et al.*, 1992; Jacoby and D'Arrigo, 1995). A network of 15 MXD chronologies was developed using six chronologies from the ITRDB and nine sites sampled by U.W.O. teams and processed at the facilities of Université Laval or Lamont (LDEO, New York). Twelve of these chronologies contained adequate signal strength for subsequent analyses. Correlation analyses and PCA were used to identify possible regional groupings of chronologies. The main group comprised six chronologies from sites in the central and southern Yukon. Chronologies in the northern and eastern Yukon formed smaller groups. Analyses showed that inter-site correlations were slightly stronger during the 1900-1950 period than the 1950-2000 period.

Climate-growth relationships of the MXD chronologies generally exhibited temporally stable temperature responses over the 20th century. Strong positive relationships between MXD and summer maximum temperatures were recorded across the 20th century, particularly for the core group of six sites in the south-central Yukon. The strongest correlations were between the south-central group and post-1950 May-August maximum temperatures of the southern temperature series. Analyses involving regional precipitation series indicated mixed results with only sporadic responses showing any significance; moreover, these responses did not appear to be time stable.

Based on the positive, consistent relationship between the MXD series for the core group of six chronologies in the south-central Yukon and post-1950 May-August (summer) maximum temperature, two MXD-based temperature reconstructions were developed. The SCRS regional chronology was derived by averaging the six 'core' individual chronologies. The BULK chronology was developed by combining all the MXD series from the six sites into a single file to develop a regional MXD chronology. The results using these two models were very similar. However, it is possible to define a normal EPS cutoff (1623) for the BULK chronology that also avoids issues with averaging the early poorly replicated portions of individual chronologies. Therefore subsequent analyses used the BULK chronology. Calibration and verification trials were conducted using a standard split period approach, with acceptable verification for 1939-1970 ($r = 0.630$) and 1971-2002 periods ($r = 0.670$), although the most extreme warm years are poorly estimated, a common occurrence with tree-ring-based reconstructions (Fritts, 1976; Fritts and Guiot, 1990). The model for the full calibration period 1939-2002 explained 38.9% of the May-August (summer) maximum temperature variance of the southern climate record. This model was used to develop a MXD-based summer maximum temperature reconstruction for the south-central Yukon from 1623-2002 – the first MXD-based reconstruction for the Yukon Territory. Throughout its length, this reconstruction exhibits considerable high-frequency, interannual variability although decadal patterns are also apparent. The overall mean of the reconstruction is 17.34ºC. The earliest period, from ca.1640-1750, is characterized by a series of cool periods of which 1688-1710 is the coldest (average 16.85ºC) and 1697 (14.34ºC) is the coldest year. After 1750, the reconstruction generally exhibits warmer conditions interspersed by short cool intervals (e.g. ca. 1805-1819, 1856-1872).

Comparison of the BULK summer maximum temperature MXD reconstruction with other regional climate reconstructions from northwestern North America shows general similarities suggesting widespread patterns of temperature variation. Low frequency, extended periods of cool temperatures of the 17th and early 18th centuries in the regional reconstructions probably reflect large-scale factors such as reduced solar irradiance (e.g. Maunder Minimum). Extreme cold intervals centred on the early 1700s and the early 1800s in the BULK reconstruction are also evident within the MXD-based reconstruction of July-September mean temperatures from the Wrangell-St. Elias Mountains (WR-ST) of southeast Alaska (Davi *et al*., 2003); the RW-based reconstruction of June-July maximum temperatures of the southwest Yukon (SWYK) (Youngblut and Luckman, 2008); and an April-September mean temperature MXD reconstruction for the British Columbia-Pacific Northwest region (BC-PNW) (Briffa *et al*., 1992) (Figure 6.15 in Chapter 6). A cool interval beginning ca. 1860 is also synchronous between these regional reconstructions, though this cool period appears much shorter and of much smaller magnitude in the BULK and WR-ST reconstructions than in the SW Yukon and BC-PNW reconstructions.

Though sharing certain elements with these other regional reconstructions, the BULK reconstruction has greater annual variability and lesser low frequency variability. Unlike the WR-ST and SWYK reconstructions, it lacks the low frequency trend culminating with sustained warmth during the second half of the 20th century and the BULK record is characterized by decadal rather than multi-decadal variability. This may, in part, be an artifact of the processing of the laths for MXD at Laval. While great care was taken to reassemble these small sections into complete cores for chronology development, the fragmentation of the core samples may have unintentionally suppressed the low frequency signal.

7.2.5 Conclusions

Analyses of the ring-width chronologies in this study clearly indicates that regional growth patterns exist within the network of northern boreal white spruce sites in the Yukon Territory. Correlation analyses and PCA of the chronologies identified several groupings representing regions in the east, southwest, north, and central Yukon, as well as a small distinct group located along the southwest shore of Kluane Lake. Mean chronologies of these groups exhibited regional growth variations distinguishing themselves from each other (Figure 3.19 in Chapter 3). Examination of climate-growth responses of the individual RW chronologies showed that relationships with temperatures were not temporally stable throughout the 20th century. During the first half of the century, the majority of the chronologies exhibited strong positive responses with summer minimum temperatures, whereas these same chronologies exhibit negative or non-significant responses to summer temperatures in the latter half, particularly within the northern half of the network. This 'divergence' phenomenon has been documented in other studies involving northern boreal stands (see review in D'Arrigo *et al*., 2008). The presence of divergence confounds one of the basic assumptions of dendroclimatology, i.e. that the relationship between the climate forcing and tree-growth is time stable, allowing the direct calibration of tree growth with instrumental temperature data over recent decades (D'Arrigo *et al*., 2008). When developing a reconstruction model, the assumption is that the process(es) affecting the tree's response to an environmental factor (such as temperature) have not changed from the calibration time period of the model to the period of reconstruction (Speer, 2010). Although evidence of divergence is documented, the actual cause or causes of this phenomenon are not clear. One of the leading hypotheses is that growth in northern high-latitude trees that was formerly temperature limited has become limited by moisture stress with increasing temperatures (Jacoby and D'Arrigo, 1995; Barber *et al*., 2000; Lloyd and Fastie, 2002). Other possible causes that have been proposed at a global scale include: an increasing trend in winter precipitation since the 1960s resulting in delayed snowpack melting and delayed growing season (Vaganov *et al*., 1999); falling stratospheric ozone concentration linked to increased ultraviolet (UV-B) radiation at ground level (Briffa *et al*., 2004); and even global dimming (Stanhill and Cohen, 2001).

Attempts have been made to circumvent this obstacle to climate reconstruction by eliminating recent decades from calibration models (e.g. Briffa *et al*., 2001; D'Arrigo *et al*., 2006). However, such an approach is problematic in the Yukon Territory given the short lengths of the instrumental records available in the region. It also removes the context for assessing recent temperature change. Wilson *et al*. (2007) developed an extratropical Northern Hemisphere temperature reconstruction by selecting and compiling tree-ring chronologies which showed no divergence against local temperatures, essentially forming a 'divergence-free' reconstruction. While showing some improvements over earlier reconstructions, this series still underestimated temperature values post-1988 (Wilson *et al.*, 2007). Studies by Wilmking *et al*. (2004, 2005), Driscoll *et al*. (2005), Pisaric *et al*. (2007) and Earles (2008) have documented a different approach by recognizing the co-existence of sub-populations within stands which exhibit opposing growth responses to climate variables. By separating 'positive' responders from 'negative' responders, it is possible to develop sub-site chronologies for each response group which could then be tested and selected for reconstruction development. The challenge with this approach is that each individual tree series has to be screened and separated based on their response prior to site chronology development. On a small scale (i.e. study involving a single site or limited number of sites with large sample size) this process may be manageable, but when large numbers of sites are involved this approach could become quite difficult.

While results from the RW network exhibited effects of divergence and prevented the development of a new regional temperature reconstruction, analyses involving the network of MXD chronologies demonstrated more stable, consistent temperature relationships. Strong, positive correlations between six MXD chronologies from the south-central Yukon and summer (May-August) temperatures of the southern regional temperature series formed the basis of the summer maximum temperature reconstruction from 1623-2002. Whereas studies such as Jacoby and D'Arrigo (1995), Briffa *et al*. (1998b) and D'Arrigo *et al*. (2004) documented divergence affecting their density data, the current study demonstrates this is not the case for the limited number of sites we sampled in the Yukon Territory. The climate-growth responses clearly showed a consistent relationship with summer temperatures. Similarly, Davi *et al*. (2003) also report the absence of divergence in their MXD records from the adjacent Wrangell Mountains in southeastern Alaska. As with ring-width, it is unclear why some MXD records show divergence while others do not. The addition of more sampled sites, representing a range of environmental conditions, and more detailed monitoring of tree growth processes (e.g. use of dendrometers) may provide greater insight into this phenomenon.

Detecting, understanding and developing approaches to recognize and remove divergence effects at local to regional scales is critical in developing chronologies that are the building blocks for reconstructions at local or larger, hemispherical studies.

7.3 Recommendations for Future Work

In the current study, examination of climate-growth relationships for the presence of divergence during 20th century focused on a split-period approach, dividing the century into two even periods (1900-1950, 1950-2000). As divergence has primarily been considered a phenomenon affecting trees during the latter half of the century, significant shifts in responses found between these two periods have provided some indication of possible divergence in the Yukon. This split-century approach has been used in other studies dealing with divergence (e.g. D'Arrigo *et al*., 2004b; Wilmking *et al*., 2004; Driscoll *et al*., 2005). Surprisingly, Porter *et al*. (2013) documented evidence of possible divergence occurring in white spruce in the Mackenzie Delta region of northwestern Canada as early as AD 1900. Future research into climate-growth relationships should include closer examination into the timing of divergent signals within tree stands. The application of 'moving window' correlations between tree-ring chronologies and instrumental climate records could be used as a tool to determine the onset of divergence with finer temporal resolution. Such research could address questions regarding whether divergence occurs synchronously in tree stands over large spatial scales or whether it exhibits a time-transgressive nature across northern landscapes, or is limited to certain species.

Another future research approach would be more extensive investigations of within-stand 'sub-populations' (i.e. positive and negative responders) of white spruce and other species. Wilmking *et al*. (2004), Pisaric *et al*. (2007), Earles (2008) and Porter and Pisaric (2011) have documented such sub-population responders within smaller regional studies in Alaska, the northern Yukon and Northwest Territories. Applying a similar approach to larger scale networks, e.g. the RW network of the current study, could provide broader insights into the occurrence of such within-stand sub-groups. This would likely require re-sampling of sites though to increase sample depth. The responder studies mentioned were limited to white spruce stands at higher northern latitudes (i.e. greater than 63.5ºN) and it is not known whether such sub-populations exist within stands at more southerly locations. Identifying and developing greater numbers of positive responder chronologies would provide additional data which could be used in future attempts at developing ‘divergence-free’ ring-width based reconstructions, similar to that of Wilson *et al*. (2007). Sample size is often a limiting factor in the ability to conduct responder analyses since large numbers are required to attain sufficient data for the creation of chronologies of each responder type.

The MXD chronologies examined in this study did not exhibit divergence and allowed the subsequent development of the BULK temperature reconstruction. However, the MXD site network was relatively limited spatially and individual sample depths were small. Future sampling to increase the number of sites in the MXD network and its spatial coverage would provide a more comprehensive view of the potential for MXD reconstructions in the Yukon. It also offers the possibility to develop longer chronologies and reconstructions by resampling at some of those sites where older trees have been identified in the present RW network.

Processing and developing MXD data is quite expensive, labour-intensive, and limited to a small number of tree-ring laboratories in North America equipped for such work. Recent, exploratory research has shown that minimum blue intensity (BI) of tree-ring samples can provide similar results to MXD for several species (McCarroll *et al*., 2002; Campbell *et al*., 2007; Wilson *et al*., 2014). This technique utilizes reflected blue light images produced on a standard flat-bed scanner and analyzed using commercially available tree-ring software (e.g. WinDENDRO™) and provides a simpler, more cost-effective paleoclimate proxy. Preliminary results from the analysis of BI on selected Yukon samples at the University of St. Andrews indicates that the technique can provide comparable results to MXD measures (Luckman *et al*., 2014).

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APPENDIX A

University of Western Ontario (UWO) *Picea glauca* Collection

Table A1

The following table presents a summary of the 111 white spruce (*Picea glauca*) sites contained within the UWO Tree-Ring Collection. Sample collectors' initials (Team) correspond as following: BHL (Brian H. Luckman), DL (David Luckman), RD (Richard Van Dorp), DM (David Morimoto), MK (Michael Kenigsberg), SE (Sean Earles), MM (Mariano Masiokas), CA (Carla Arunai), DY (Don Youngblut), EW (Emma Watson), MB (Myron Belej), MP (Michael Payne), JCA (Juan Carlos Aravena), JL (Jessica Lusted). Additional chronologies from JMS (Julian M. Szeicz), MFP (Michael Frederick Pisaric) and RDA (Rosanne D'Arrigo/Gordon Jacoby).

In column headings: 'Year' is year(s) site was sampled; 'N(s)' is number of series; 'N(t)' is number of trees; 'F.Yr.' is first year of chronology; 'L.Yr.' is last year of chronology.

#	Site Name	Code	Year	Lat. (N)	Long. (W)	Elev. (m)	N (s)	N (t)	F Yr.	L Yr.	T Yr.	Team
1	Campbell Upland	CAM	1989	68.27	133.33	120	28	13	1629	1988	360	BHL, DL
2	Midway Lake	MID	1989	67.20	134.57	500	22	10	1660	1988	329	BHL, DL
3	Richardson Mountain	RCH	2004	66.94	136.26	650	32	25	1855	2003	149	BHL, RD, DM, MK, SE, MB
4	Rock River	ROC	2004	66.91	136.35	500	131	68	1644	2003	360	BHL, RD, DM, MK, SE, MB
5	Interfluve	INF	2004	66.84	136.35	616	42	24	1800	2003	204	BHL, RD, DM, MK, SE, MB
6	Mt. Cronin	CRN	2004	66.81	136.34	579	46	24	1702	2003	302	BHL, RD, DM, MK, SE, MB
7	Vadzaih Kan Creek	VAD	2004	66.72	136.34	691	61	31	1632	2003	372	BHL, RD, DM, MK, SE, MB
8	Tsiivii Creek	TSV	2004	66.63	136.31	685	86	37	1527	2003	477	BHL, RD, DM, MK, SE, MB
9	Airstrip Eagle Plains	AIR	2004	66.42	136.58	705	60	30	1714	2003	290	BHL, RD, DM, MK, SE, MB
10	Corbett Hill	CRB	2004	66.33	136.73	720	45	24	1829	2003	175	BHL, RD, DM, MK, SE, MB
11	Scriver Creek	SCR	2004	65.84	137.67	848	111	66	1722	2003	282	BHL, RD, DM, MK, SE, MB
12	Ogilvie Ridge	OGL	2004	65.77	137.85	811	64	34	1696	2003	308	BHL, RD, DM, MK, SE, MB
13	Mt. Jeckell	JEK	2004	65.40	138.23	600	60	31	1664	2003	340	BHL, RD, DM, MK, SE, MB
14	Sappers Hill	SAP	2002	65.35	138.30	640	66	36	1773	2001	229	BHL, DY, RD, MM
15	TTHH	TTH	2001	65.33	138.33	915	69	48	1459	2000	542	RDA
16	Engineers Creek	ENG	2002	65.28	138.25	700	26	19	1616	2001	386	BHL, DY, RD, MM
17	Talus	TAL	2002	65.23	138.33	720	24	16	1590	2001	412	BHL, DY, RD, MM
18	Triangle	TRI	2002	65.13	138.37	915	18	12	1741	2001	261	BHL, DY, RD, MM
19	Distincta East	DSE	2004	65.07	138.22	965	75	25	1651	2003	353	BHL, RD, DM, MK, SE, MB
20	Distincta Peak	DSP	2002	65.07	138.23	886	63	37	1539	2001	463	BHL, DY, RD, MM
21	Distincta West	DSW	2004	65.07	138.31	985	61	26	1662	2003	342	BHL, RD, DM, MK, SE, MB
22	Blackstone River	BKS	2002	64.97	138.25	865	52	29	1671	2001	331	BHL, DY, RD, MM
23	Black City	BLK	2002	61.68	138.45	1004	20	13	1560	2001	442	BHL, DY, RD, MM
24	Carpenter Lake	CRP	2005	64.52	135.10	1100	49	26	1564	2004	441	BHL, RD, DM, SE, MP
25	Tombstone Mountain	TMB	1993/02	64.50	138.25	1006	100	84	1470	2001	532	JMS, BHL, DY, RD, MM
26	Worm Lake	WRM	2005	64.48	136.00	1125	48	27	1665	2004	340	BHL, RD, DM, SE, MP
27	North Klondike River	NKL	2002/04	64.44	138.26	975	80	44	1587	2003	417	BHL, DY, RD, MM, DM, MK, SE, MB
28	Bonnet Plume Lake	BNP	2005	64.30	132.03	1130	56	33	1609	2004	396	BHL, RD, DM, SE, MP
29	Clinton Creek	CLN	2005	64.26	140.39	1050	65	34	1679	2004	326	BHL, RD, DM, SE, MP
30	Misty Lake	MST	2005	64.18	131.30	1241	60	33	1629	2004	376	BHL, RD, DM, SE, MP
31	Jack Wade	JWD	2004	64.16	141.36	961	101	50	1641	2003	363	BHL, RD, DM, MK, SE, MB
32	Swede Dome	SED	2002	64.13	140.58	990	39	24	1692	2001	310	BHL, DY, RD, MM
33	Empire Creek	EMP	2002	64.12	139.68	1080	30	16	1704	2001	298	BHL, DY, RD, MM
34	Big Gold Creek	BGD	2004	64.11	140.75	1078	60	32	1694	2003	310	BHL, RD, DM, MK, SE, MB
35	Deadwood	DWD	2002	64.07	139.52	700	31	16	1928	2001	74	BHL, DY, RD, MM
36	Wernecke	WEN	2002/05	63.95	135.28	1254	86	48	1597	2005	409	BHL, DY, RD, MM, DM, SE, MP
37	Einarson Lake	EIN	2005	63.94	131.57	1124	40	23	1616	2004	389	BHL, RD, DM, SE, MP
38	Galena	GAL	2002/05	63.92	135.42	1204	55	30	1637	2004	368	BHL, DY, RD, MM, DM, SE, MP
39	Barlow Dome	BAR	2002	63.83	136.42	1160	77	37	1520	2001	482	BHL, DY, RD, MM
40	Pup 65	PUP	2002	63.82	137.25	975	26	13	1882	2001	120	BHL, DY, RD, MM
41	Highet Creek	HET	2002	63.77	136.25	1235	34	20	1660	2001	342	BHL, DY, RD, MM
42	Emerald Lake	EMR	2005	63.54	131.23	1130	73	33	1643	2004	362	RD, DM, SE, MP
43	Keele Lake	KEL	2005	63.52	130.45	1184	75	42	1572	2004	433	RD, DM, SE, MP
44	Hungry Mountain	HNG	2002	63.35	136.28	990	62	32	1857	2001	145	BHL, DY, RD, MM
45	MacMillan Pass	MPP	2002	63.18	130.17	1150	36	21	1644	2001	358	BHL, DY, RD, MM
46	MacMillian Pass East	MPE	2005	63.19	130.18	1195	24	14	1548	2004	457	BHL, RD, DM, SE, MP
47	MacMillian Pass West	MPW	2005	63.18	130.15	1200	17	8	1639	2004	366	BHL, RD, DM, SE, MP
48	Dewhurst Creek	DEW	2002/05	63.05	130.25	1120	28	17	1725	2004	280	BHL, DY, RD, MM, DM, SE, MP
49	Mt. Sheldon	SHL	2002	62.75	131.03	1150	16	8	1737	2001	265	BHL, DY, RD, MM
50	Lapie Pass	LPP	1996	62.42	131.17	1140	27	16	1654	1995	342	MFP
51	Anvil Mine	ANV	2002	62.30	133.33	1175	50	25	1505	2001	497	BHL, DY, RD, MM
52	Faro	FAR	2002/05	62.29	133.28	1205	83	44	1456	2005	550	BHL, DY, RD, MM, DM, SE, MP
53	Mt. Mye	MYE	2002	62.28	133.27	1205	41	20	1573	2001	429	BHL, DY, RD, MM
54	Little Salmon	LSM	2002	62.22	134.83	625	9	5	1909	2001	93	BHL, DY, RD, MM
55	Buttle Creek	BUT	2002	62.10	133.00	915	20	13	1799	2001	203	BHL, DY, RD, MM
56	Nahanni Spruce	NAH	2003	62.07	128.38	1150	63	33	1582	2002	421	BHL, RD, MM, MK, CA
57	Divide Spruce	DVD	2003	62.05	128.37	1156	56	25	1543	2002	460	BHL, RD, MM, MK, CA
58	Nansen Creek	NAN	2002	62.05	137.22	1115	49	27	1454	2001	548	BHL, DY, RD, MM
59	Webber Creek	WEB	2002	62.05	137.17	1340	78	46	1588	2001	414	BHL, DY, RD, MM
60	Mt. Berdoe	BRD	2002	62.03	136.23	1170	35	23	1618	2001	384	BHL, DY, RD, MM
61	Big Bend 2	BB2	2003	62.02	128.35	1342	42	23	1516	2002	487	BHL, RD, MM, MK, CA
62	Big Bend	BB1	2003	62.03	128.35	1277	52	28	1571	2002	432	BHL, RD, MM, MK, CA
63	Campsite	CMP	2003	62.02	128.49	1240	45	25	1507	2002	496	BHL, RD, MM, MK, CA
64	Victoria Creek	VIC	2002	62.02	137.03	1050	51	29	1756	2001	246	BHL, DY, RD, MM
65	NWT Pass	NWT	2003	62.02	128.36	1355	37	20	1658	2002	345	BHL, RD, MM, MK, CA
66	Tungsten	TNG	2003	61.98	128.25	1145	78	39	1562	2002	441	BHL, RD, MM, MK, CA
67	Koidern	KOI	1999	61.95	140.37	800	34	17	1796	1998	203	BHL, DY
68	Mt. Cook	COK	2002	61.90	132.87	1250	19	11	1621	2001	381	BHL, DY, RD, MM
69	Eagle	EG1	2003	61.86	128.34	1175	38	27	1641	2002	362	BHL, RD, MM, MK, CA
70	Eagle Twelve	ETW	2000	61.85	134.85	1130	78	40	1607	1999	393	BHL, EW, DY
71	Eagle 2	EG2	2003	61.83	128.30	1167	38	19	1657	2002	346	BHL, RD, MM, MK, CA
72	Aishihik	ASH	2000	61.72	137.28	975	59	31	1741	1999	259	BHL, EW, DY
73	Donjek	DNJ	1999	61.70	139.75	750	56	29	1614	1998	385	BHL, DY
74	Lapie Lakes	LPL	2002/05	61.69	133.07	1083	42	25	1660	2004	345	BHL, DY, RD, MM, DM, SE, MP
75	Little Hyland	LHY	2003	61.69	128.33	1207	41	24	1784	2002	219	BHL, RD, MM, MK, CA
76	Rose River	ROS	2002/05	61.62	133.06	1085	31	15	1539	2004	466	BHL, DY, RD, MM, DM, SE, MP
77	Duke Terrace	DUK	2004	61.48	139.08	785	30	28	1774	2003	230	BHL, RD, DM, MK, SE, MB
78	Rock Glacier Spruce	RGL	2003	61.37	128.35	1450	8	4	1731	2002	272	BHL, RD, MM, MK, CA
79	Sandpit	SND	2000	61.32	137.00	1000	65	33	1400	1999	600	BHL, EW, DY
80	Burwash	BUR	1999/00	61.28	138.88	840	79	37	1480	1999	520	BHL, DY
81	Cultus Bay	CUL	1999	61.15	138.43	805	41	21	1742	1998	257	BHL, DY
82	AINA	AIN	2002	61.12	138.40	825	40	22	1639	2001	363	BHL, DY, RD, MM
83	Canyon Lake	CNY	1999	61.12	136.98	900	43	22	1651	1998	348	BHL, DY
84	Extra Point	EXT	2004	61.13	138.45	788	8	8	1801	2003	203	BHL, RD, DM, MK, SE, MB
85	Fox Point	FOX	2004	61.12	138.42	785	8	8	1786	2003	218	BHL, RD, DM, MK, SE, MB
86	Rancheria Spruce	RHS	2000	61.10	130.67	1300	8	4	1762	1999	238	BHL, EW, DY
87	Jackson Point Good	JAC	1999	61.05	138.52	830	77	36	1685	1998	314	BHL, DY
88	Landslide Main	LND	1999/00/02	61.03	138.50	800	161	78	913	2001	1089	BHL, DY
89	Pipeline	PIP	2004	61.00	138.44	814	45	29	1724	2003	280	BHL, RD, DM, MK, SE, MB
90	Bullion Creek	BUL	2000	60.97	138.62	820	58	28	1754	1999	246	BHL, EW, DY
91	Telluride	TEL	1999	60.92	138.13	1400	89	50	1584	1999	416	BHL, DY
92	Gray Mountain	GRY	2001	60.80	134.57	1140	92	49	1512	2001	490	BHL, EW, DY
93	Spruce Beetle	SBE	1999	60.80	137.78	915	27	19	1902	1998	97	BHL, DY
94	Mt. McIntyre	MMC	2004	60.65	135.17	1232	51	25	1618	2003	386	BHL, RD, DM, MK, SE, MB
95	Coal Lake Road	COL	2004	60.59	135.07	1070	47	28	1729	2003	275	BHL, RD, DM, MK, SE, MB
96	Yukon Crossing Spruce	YKC	2000	60.57	134.68	670	7	4	1867	1999	133	BHL, EW, DY
97	Big Salmon	BSM	2000/03	60.56	133.13	1190	94	54	1655	2002	348	BHL, EW, DY, RD, MM, MK, CA
98	Kathleen Lake	KTH	1999	60.55	137.27	750	62	27	1625	1998	374	BHL, DY
99	Szeicz	SZC	2003	60.53	128.84	915	9	5	1792	2002	211	BHL, RD, MM, MK, CA
100	St. Elias Lake	ELI	1999	60.33	137.08	925	21	12	1806	1998	193	BHL, DY
101	Tagish	TAG	2003/05	60.27	134.18	1167	70	40	1566	2004	439	BHL, RD, MK, MM, CA, DM, SE, MP
102	Wheaton River	WHT	2005	60.20	135.29	1032	60	34	1666	2004	339	BHL, RD, DM, SE, MP
103	Rancheria Mountain Spruce	RHM	2003	60.16	129.99	1355	12	6	1884	2002	119	BHL, RD, MM, MK, CA
104	Tatshenshini	TAT	2004	60.02	136.87	883	56	25	1752	2003	252	BHL, RD, DM, MK, SE, MB
105	MacDonald Lake	MAC	2000	59.72	133.58	950	36	19	1580	1999	420	BHL, EW, DY
106	Monarch	MON	2000	59.50	133.68	1400	64	30	1579	1999	421	BHL, EW, DY
107	Cassiar	CAS	2003	59.27	129.83	1225	53	27	1570	2002	433	BHL, RD, MM, MK, CA
108	Troutline Creek	TRT	2003	59.28	129.83	1245	43	25	1676	2002	327	BHL, RD, MM, MK, CA
109	Jade City Spruce	JAD	2003	59.19	129.67	1316	16	10	1816	2002	187	BHL, RD, MM, MK, CA
110	Muncho Lake Slope	MCH	1995	58.94	125.76	850	27	14	1790	1994	205	BHL, JL
111	Summit Lake North	SUM	1995	58.77	124.67	1260	21	10	1677	1994	318	BHL, JL
112	Tanzilla Butte	TNZ	2003	58.38	129.86	1166	123	34	1710	2002	293	BHL, RD, MM, MK, CA
113	Smithers Ski 2	SKI	2003	54.77	127.25	1280	29	20	1671	2002	332	DY, EW, JCA, DM

APPENDIX B

Measures of Chronology Quality

Several statistical and standard dendrochronological measures are commonly used to examine tree-ring chronologies, in terms of ring-width variability and common signal. These chronology measures included: average mean sensitivity (MS), first-order autocorrelation (1AC), mean series intercorrelation (r), mean inter-tree correlation (RBAR), and expressed population signal (EPS).

Average mean sensitivity is a measure of the year-to-year variability of tree-ring widths. Mean sensitivity is calculated as follows (where *x* is the annual ring-width at year *t*):

$$\text{Mean Sensitivity} = \frac{1}{n-1}\sum_{t=1}^{t=n-1}\left|\frac{2(x_{t+1}-x_t)}{x_{t+1}+x_t}\right| \qquad \text{(B.1)}$$

(Fritts, 1976)

Values for sensitivity can range from 0, indicating that adjacent years exhibit identical measured widths, to 2 which would suggest an adjacent missing ring (Fritts, 1976). Higher mean sensitivity values generally indicate greater high-frequency variance within the tree-ring series. Mean sensitivity can be calculated for entire chronologies, or the individual component series. Generally, mean sensitivity values for chronologies are lower than the component series.

First-order autocorrelation is a measure of the correlation between the ring-width in year *t* and that of the subsequent year (*t*+1) in a given tree-ring series. Values for this statistic can range from -1 to 1, with higher values suggesting greater persistence in the growth patterns from year to year (Fritts, 1976). Generally, first-order autocorrelation and mean sensitivity display an inverse relationship, particularly when characterizing high-frequency variance in a tree-ring series (Fritts, 1976). As a result of needle retention from one year to the next and thus interannual contributions to growth processes, coniferous species are often characterized by higher autocorrelation values (Fritts, 1976).

By comparing replicate data series in the creation of a mean chronology, it is possible to examine the strength of common variability represented within a chronology.

This common variability, or ‘chronology signal’, represents the common growth forcing among the data comprising the chronology (Briffa, 1995). Mean series intercorrelation (r) values measure the correlation between core segments over all intervals involved in a site chronology. The intercorrelation (r) is measured as followed (where m_x, m_y, s_x and s_y are the means and standard deviations of the two sets of data at year t):

$$\text{Series intercorrelation} = \frac{\sum_{t=1}^{t=n}(x_t - m_x)(y_t - m_y)}{(n-1)s_x s_y} \qquad \text{(B.2)}$$

(Fritts, 1976)

A similar statistical measure also often used to gauge the common signal in a chronology is RBAR (or running $\bar{r}$). It is a running correlation between series, and thus is a good measure of the common signal strength through time (Cook *et al.*, 2000). While mean series intercorrelation involves all core segments over all intervals in a chronology (thus including within- and between-tree correlations), the moving correlation of RBAR focuses on between-tree correlations (Briffa, 1995). RBAR values can range from -1.0 to 1.0, though only positive values are considered meaningful (Briffa, 1995).

When evaluating a chronology, it is also important to consider the extent to which it retains its common signal with reduced sample depth. As a chronology extends further back in time, the record usually becomes comprised of fewer, older trees. The Expressed Population Signal (EPS) statistic is often used to assess the common signal in a chronology, and its change as a result of decreasing sample size (Briffa and Jones, 1990). EPS is calculated as follows (where t is the number of series and R_{bt} is the mean between-tree correlation coefficient):

$$\text{Expressed Population Signal (EPS)} = \frac{\mathrm{t}\,R_{bt}}{\mathrm{t}\,R_{bt} + (1 - R_{bt})} \qquad \text{(B.3)}$$

(Briffa and Jones, 1990)

EPS values can range from 0 to 1, where zero suggests no common growth signal in the chronology, while values reaching one suggest a “perfect” chronology comprised of an infinite number of samples exhibiting identical growth (Briffa, 1995; Wigley *et al.*, 1984). An EPS threshold value of 0.85 has commonly been used to define chronology lengths with acceptable high common signal strength (Wigley *et al.*, 1984). For this study, EPS values were determined using the program ARSTAN version 40c_win (2006), utilizing a 30-year moving window with a lag period of one year. A 30-year window length was selected to minimize the impact of high frequency variance on the calculations, but still provide sufficient information to determine when the common signal in the chronology deteriorated below acceptable levels (Briffa, 1995). Chronologies were deemed unacceptable where EPS values dropped below 0.85 for more than 10 consecutive years.

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APPENDIX C

Climate-Growth Responses of Regional Chronologies

Table C1

Correlations between 12-month (annual) averaged ‘northern’ temperature series and regional tree-ring records over the 1900-2003 period. Statistically significant correlations ($p=0.05$) are shown, positive relationships in red and negative relationships in blue. Values >0.250 or <-0.250 (bolded) are statistically significant at $p=0.01$.

Table C2

Correlations between 12-month (annual) averaged ‘southern’ temperature series and regional tree-ring records over the 1939-2003 period. Statistically significant correlations ($p=0.05$) are shown, positive relationships in red and negative relationships in blue. Values >0.315 or <-0.315 (bolded) are statistically significant at $p=0.01$.

Table C1

Maximum Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec		0.25				0.24
ppFeb-pJan		**0.27**				**0.26**
ppMar-pFeb		0.23				0.20
ppApr-pMar		**0.26**				0.24
ppMay-pApr		0.25				0.22
ppJun-pMay		0.25				0.22
ppJul-pJun		0.22				0.21
ppAug-pJul		0.21				
ppSep-pAug		0.21				
ppOct-pSep		0.21				
ppNov-pOct		0.20				
ppDec-pNov		0.19				0.20
pJan-pDec						
pFeb-Jan						
pMar-Feb						
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						0.22
pSep-Aug						0.24
pOct-Sep						0.25
pNov-Oct						**0.26**
pDec-Nov						**0.26**
Jan-Dec						0.25

Mean Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec		**0.27**				0.21
ppFeb-pJan		**0.30**				0.24
ppMar-pFeb		0.25				
ppApr-pMar		**0.29**				0.23
ppMay-pApr		**0.28**				0.21
ppJun-pMay		**0.27**				0.21
ppJul-pJun		0.25				0.20
ppAug-pJul		0.24				
ppSep-pAug		0.25				
ppOct-pSep		0.25				
ppNov-pOct		0.23				
ppDec-pNov		0.23				0.21
pJan-pDec		0.20				
pFeb-Jan						0.19
pMar-Feb						0.19
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						0.21
pSep-Aug						0.22
pOct-Sep						0.23
pNov-Oct						0.24
pDec-Nov						0.23
Jan-Dec						0.22

Minimum Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec		0.26				
ppFeb-pJan		**0.29**				0.20
ppMar-pFeb		0.26				
ppApr-pMar		**0.29**				0.21
ppMay-pApr		**0.29**				
ppJun-pMay		**0.28**				
ppJul-pJun		**0.26**				
ppAug-pJul		**0.26**				
ppSep-pAug		**0.26**				
ppOct-pSep		**0.26**				
ppNov-pOct		0.25				
ppDec-pNov		0.24				0.20
pJan-pDec		0.22				
pFeb-Jan						0.20
pMar-Feb						0.20
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						
pSep-Aug						
pOct-Sep						0.20
pNov-Oct						0.20
pDec-Nov						
Jan-Dec			-0.20			

Table C2

Maximum Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec						
ppFeb-pJan						
ppMar-pFeb						
ppApr-pMar		0.29				0.24
ppMay-pApr		0.27				
ppJun-pMay		0.26				
ppJul-pJun						
ppAug-pJul						
ppSep-pAug		0.24				
ppOct-pSep		0.24				
ppNov-pOct						
ppDec-pNov						
pJan-pDec						
pFeb-Jan						
pMar-Feb						
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						
pSep-Aug						
pOct-Sep						0.24
pNov-Oct						0.25
pDec-Nov						0.26
Jan-Dec				-0.25		

Mean Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec						
ppFeb-pJan						
ppMar-pFeb						
ppApr-pMar		0.29				0.26
ppMay-pApr		0.28				0.25
ppJun-pMay		0.27				0.25
ppJul-pJun		0.24				0.25
ppAug-pJul						
ppSep-pAug		0.25				
ppOct-pSep		0.26				
ppNov-pOct						
ppDec-pNov						
pJan-pDec		0.24				0.24
pFeb-Jan						0.24
pMar-Feb						
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						
pSep-Aug						
pOct-Sep						
pNov-Oct						
pDec-Nov						
Jan-Dec						

Minimum Temperature

	East YK (PC1)	SW YK (PC2)	Dempster (PC3)	Cent. North YK (PC4)	Cent. South YK (PC5)	Kluane (PC6)
ppJan-ppDec						
ppFeb-pJan						
ppMar-pFeb						
ppApr-pMar		0.28				0.25
ppMay-pApr		0.27				
ppJun-pMay		0.27				0.24
ppJul-pJun		0.25				0.24
ppAug-pJul						
ppSep-pAug		0.25				
ppOct-pSep		0.26				
ppNov-pOct						0.24
ppDec-pNov						0.27
pJan-pDec		0.25				0.27
pFeb-Jan						0.28
pMar-Feb						0.25
pApr-Mar						
pMay-Apr						
pJun-May						
pJul-Jun						
pAug-Jul						
pSep-Aug						
pOct-Sep						
pNov-Oct						
pDec-Nov						
Jan-Dec						

APPENDIX D

Climate-Growth Responses of Individual Chronologies

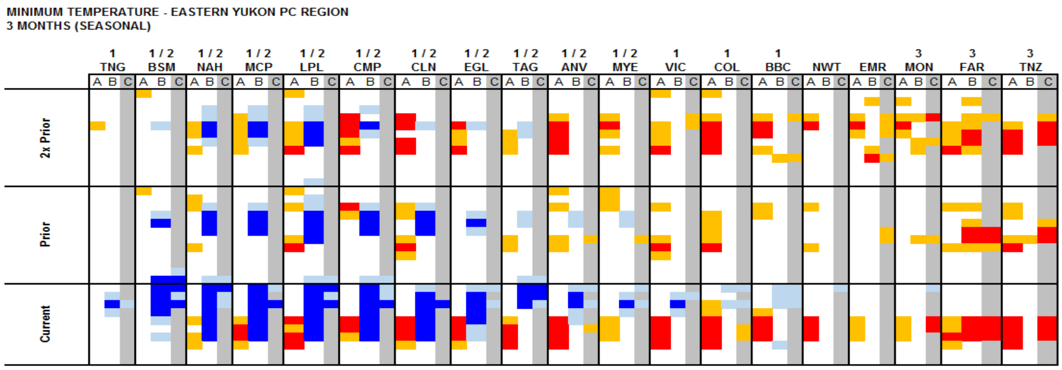
The following is a comprehensive examination of climate-growth responses of individual chronologies found within the six regional ring-width groupings previously defined in Chapter 3. Format of the tables follows the interpretative key shown in Table 5.7 of Chapter 5.

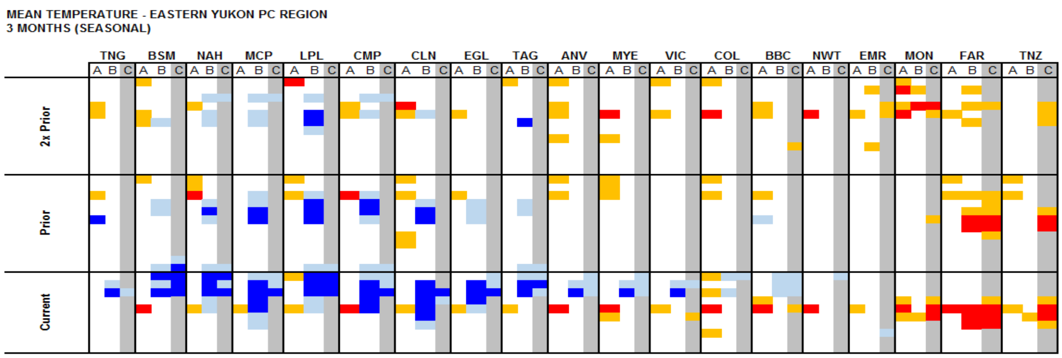
Eastern Yukon

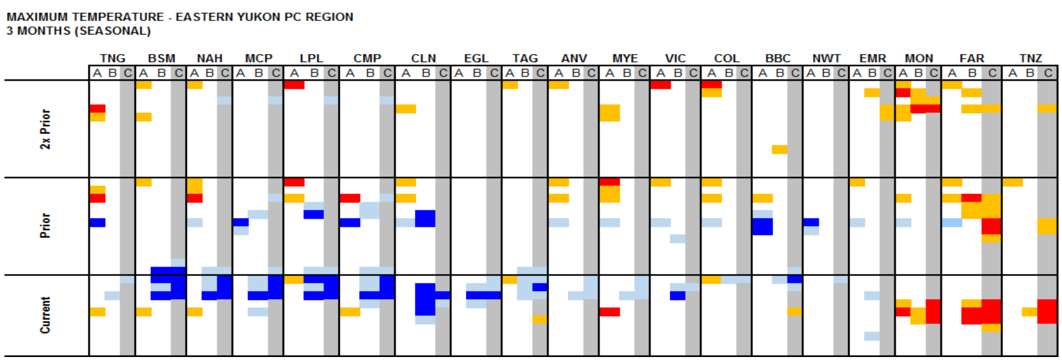
Analyses of the responses of individual chronologies within the regional groupings show diverse relationships with temperatures. The Eastern Yukon region is a good example of this diversity. At the regional level, climate-growth responses of the Eastern Yukon regional chronology were dominated by strong positive correlations with minimum and mean temperatures during summer months (especially current growth year and two-years prior) for the 1900-1950 period and significant negative correlations during current spring months for each of the temperature variables during the 1950-2000 period. However, the climate-growth responses of the individual chronologies within this group (Table D1) can deviate considerably from this pattern. The pre-1950 positive relationship with summer minimum temperatures appeared in the responses of 17 of the 19 individual chronologies of the region, and 18 chronologies with summer mean temperatures (Table D1). The only two chronologies which did not share in the minimum temperature response were Tungsten and Big Salmon, while only Tungsten lacked a significant positive response with mean temperature. Chronologies which displayed significant responses with summer minimum temperature showed a wider response window than those sites with mean or maximum summer temperatures. That is, significant responses with summer minimum temperatures tended to span May through October, whereas responses with mean or maximum temperature were restricted to May-July (Table D1). With regard to the strong negative signal with current spring temperatures reflected in the post-1950 results, 14 of the 19 chronologies in the region registered significant values at the p=0.05 level. This response was seen in all three of the temperature variables examined. The five chronologies which did not show this negative current spring signal were: NWT Pass, Emerald Lake, Monarch, Faro and Tanzilla Butte. The negative growth signal with prior year spring temperature, identified in the regional-level responses with minimum temperature, registered in only 10 of the 19 individual chronologies (p=0.05). The sites which failed to show this negative signal with prior year spring minimum temperature included Tungsten, Victoria Creek, Coal Lake Road and Big Bend, along with the five sites previously mentioned with the current spring signal. Interestingly, this prior spring negative signal was recorded in the responses of 8 chronologies when examined against mean temperatures (p=0.05), though the regional-scale results did not identify this response.

With regard to responses and the post-1950 northern and southern climate records, most of the chronologies registered the strong negative signal of the current growth year with both climate records. While the negative signal with the northern record often extended into the late summer months, the significant responses with the southern record were limited to spring months. Overall, the chronologies of the Eastern Yukon region can be classified into three groups based on their climate-growth responses (designated **1**, **2** and **3** along top of table in Table D1). The largest group (**1**) consists of those 14 chronologies which displayed a strong negative response with current spring temperatures (Tungsten, Big Salmon, Nahanni Spruce, MacMillan Pass Combined, Lapie Lakes, Campsite, Clinton Creek, Eagle Combined, Tagish, Anvil Mine, Mt. Mye, Victoria Creek, Coal Lake Road, Big Bend Combined). These sites are located in the southeast quadrant of the Yukon, concentrated either on the Yukon-NWT border or near Faro/Ross River (exceptions being Clinton Creek and Victoria Creek). The second group (**2**), a small sub-population of the first group, consists of the 10 chronologies which also registered a negative response with spring temperatures of the prior growth year (Big Salmon, Nahanni Spruce, MacMillan Pass Combined, Lapie Lakes, Campsite, Clinton Creek, Eagle Combined, Tagish, Anvil Mine, Mt. Mye). The third identifiable response group (**3**) consists of the three chronologies (Monarch, Faro and Tanzilla Butte) which displayed strong positive responses with summer growth in almost all growth years.

Table D1 Seasonal (3-month) climate-growth responses of chronologies from the Eastern Yukon group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (B) 1950-2000 period (northern climate record), and (C) 1950-2000 period (southern climate record). Numbers 1, 2 and 3 along top of table indicate chronologies in the three major groupings in the region.



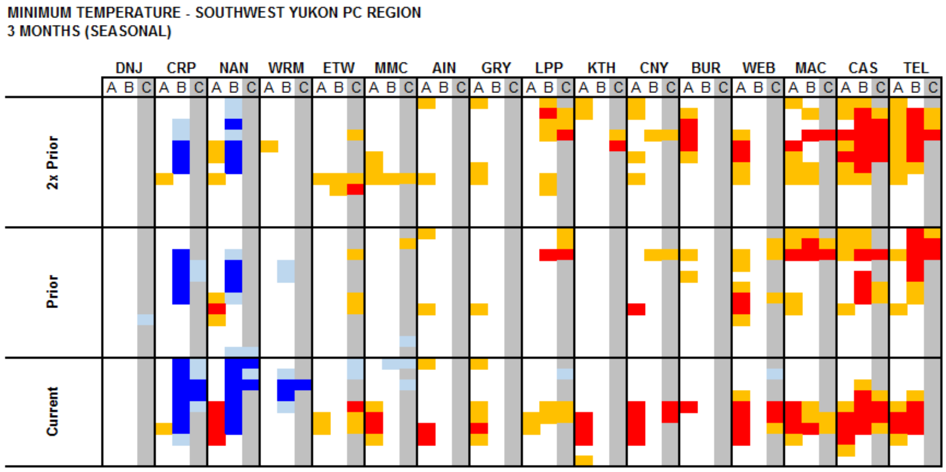


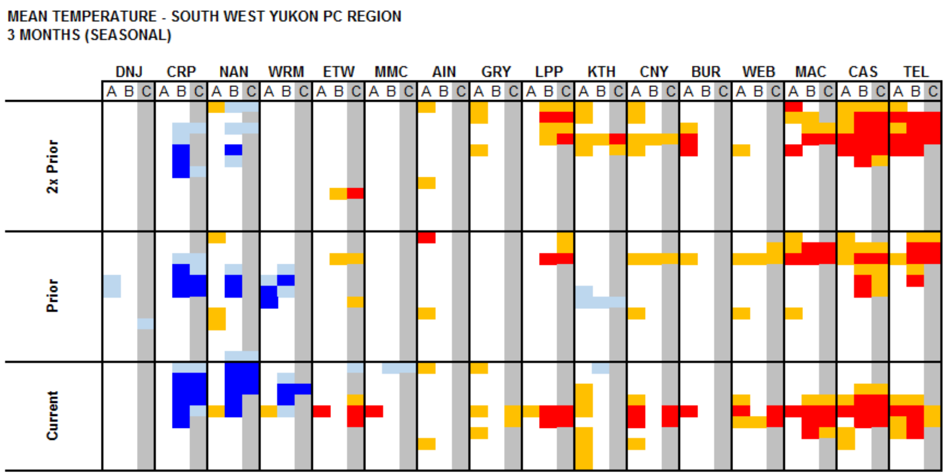


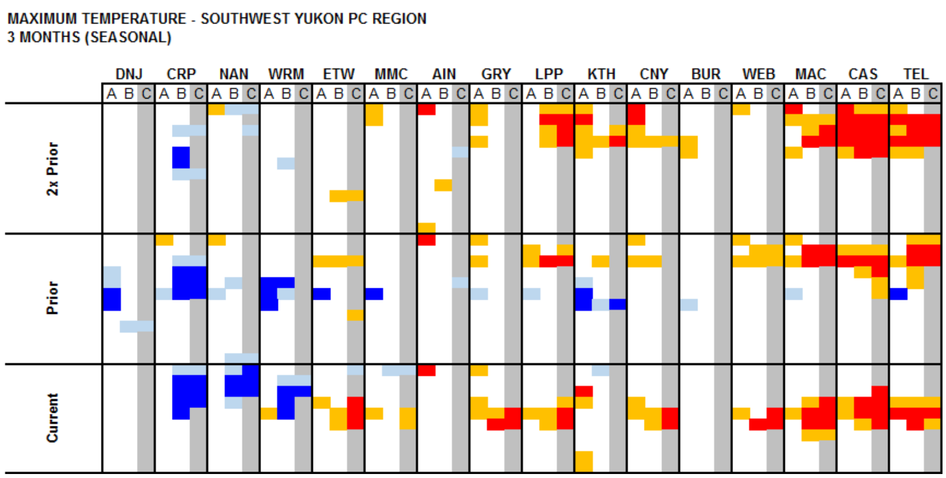
Southwest Yukon

Chronologies within the Southwest Yukon group also displayed strong variations in their climate-growth responses, leading to the identification of two distinct response groups (Table D2). Among the 16 chronologies of this region, 3 southern chronologies (MacDonald Lake, Cassiar, and Telluride) exhibited strong positive signals with spring/summer temperatures across the 36 month analysis window. This response was seen in all three temperature variables and was stable through time, appearing in all three time periods. A second group of chronologies situated further north (Carpenter Lake, Nansen Creek and Worm Lake) were identified by their strong negative responses to spring temperatures during the second half of the 20th century. While all three chronologies showed strong spring negative signals (p=0.05) during the current and previous growth years against the northern climate record, only Carpenter Lake demonstrated this response in all three spring seasons involved in the 36 month analysis window. Worm Lake did not show negative responses with spring temperatures (minimum and mean temperatures) during growth two-years prior, as was the case with Nansen Creek with respect to maximum temperature. In terms of negative responses with the southern climate record, all three chronologies displayed significant correlations with current spring months, but only the Carpenter Lake chronology showed similar responses with prior spring temperatures. The two distinct response groups, one positive and one negative, form the strongest signals in the region in terms of strength and presence across all three temperature variables. Thirteen chronologies (Donjek, Carpenter Lake, Nansen Creek, Worm Lake, Eagle Twelve, Mt. McIntyre, Gray Mountain, Lapie Pass, Kathleen Lake, Burwash, Webber Creek, MacDonald Lake and Telluride) did show a negative response to prior year summer temperature during the first half of the 20th century (Carpenter Lake, Worm Lake and Kathleen Lake displayed this response also during the latter half of the 20th century), though this was primarily limited to maximum temperature (exceptions being Donjek, Worm Lake and Kathleen Lake which showed pre-1950 negative responses with mean temperature). The Donjek site was distinctive in that while it did show significant negative responses to summer temperatures of the previous year (mean and maximum), it did not display similar negative results with summer temperatures of the current growth year or two years prior seen in other chronologies of this group. Unlike any other chronology in this region, Donjek did not show any marked significant correlations with minimum temperatures of the northern record. The remaining chronologies in this region were primarily characterized by varying positive correlations with temperatures, generally occurring during spring/summer months.

Table D2 Seasonal (3-month) climate-growth responses of chronologies from the Southwest Yukon group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (B) 1950-2000 period (northern climate record), and (C) 1950-2000 period (southern climate record).





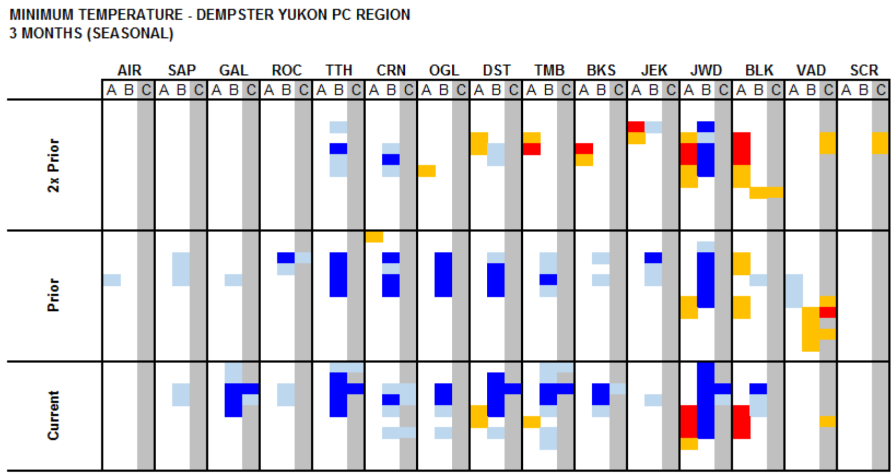


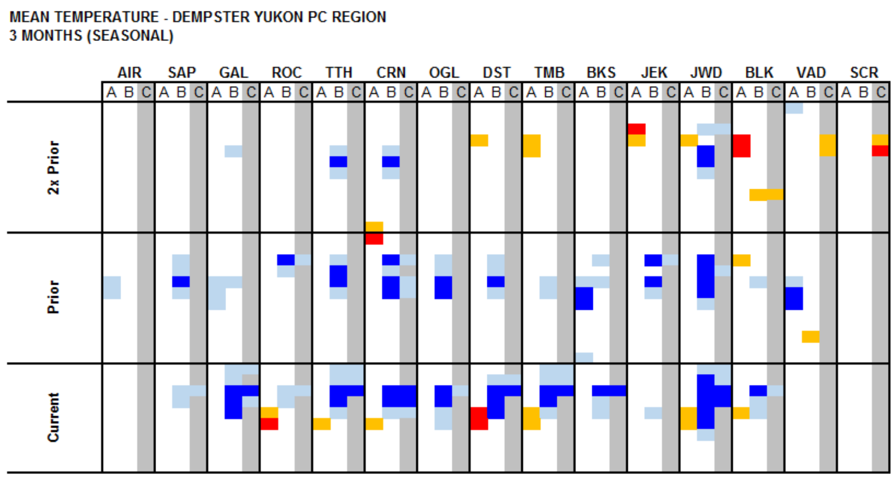
Dempster Group

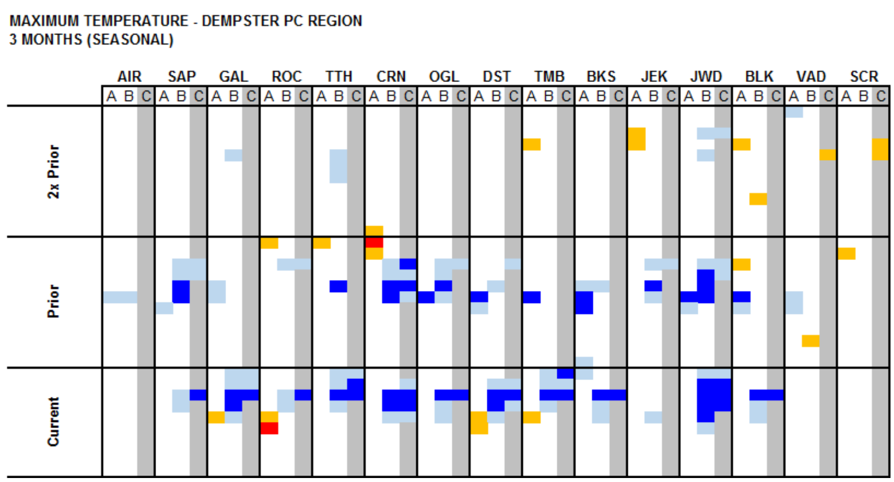
At the regional level, correlations indicated that climate-growth relationships for the Dempster grouping prior to 1950 showed mixed results over the 36 month analysis window, while results post-1950 were dominated by strong negative signals during spring months of the current and previous growth years. Results at chronology level supported these general findings. During the first half of the 20th century, a limited number of chronologies showed positive correlations between growth and summer temperatures. Distincta, Tombstone Mountain, Jack Wade and Black City all showed significant positive correlations with June-August temperatures of the northern climate record (both minimum and mean) during current growth year and two years prior (Table D3). Results for mean temperature indicated that, in addition to those four sites, Rock River, TTHH, and Mt. Cronin also showed significant positive correlations with current summer temperature during the pre-1950 period. However, during the prior growth year, negative correlations dominated the relationships between growth and summer maximum temperatures in the pre-1950 period (Table D3). Nine of the fifteen chronologies of the Dempster grouping (Airstrip Eagle Plains, Galena, Ogilvie Ridge, Distincta, Tombstone Mountain, Blackstone River, Jack Wade, Black City and Vadziah Kan Creek) showed significant negative correlations ($p=0.05$) with previous June-August maximum temperatures, while four of these sites (Airstrip Eagle Plains, Galena, Blackstone River and Vadziah Kan Creek) also showed negative results with previous June-August mean temperatures. Although the climate-growth relationships prior to 1950 were somewhat mixed in nature, significant correlations during the post-1950 period were essentially all negative. Reflected across all three temperature variables, these strong negative relationships focused on the late spring/summer months of the 36 month window (Table D3). Of the fifteen chronologies comprising this regional grouping, only two (Vadziah Kan Creek and Scriver Creek) failed to display any marked significant negative correlations during the post-1950 period (Airstrip Eagle Plains could also be included if the single significant correlation with previous June-August maximum temperature is excluded). In examining the northern climate correlation results against the southern climate results over the post-1950 period, a considerable number of the chronologies displayed negative correlations with both climate records. These chronologies included: Sappers Hill, Galena, Rock River, TTHH, Mt.

Cronin, Ogilvie Ridge, Distincta, Tombstone Mountain, Blackstone River, Mt. Jeckell, Jack Wade and Black City. There is only one significant positive relationship (Vadziah Kan Creek, 0.31 Jun-August minimum temperature) for any three month period of current year data from either temperature record. While the results between the Dempster chronologies and the northern climate record are understandable given the relative proximity of these sites to the climate stations comprising the northern record, the similar results with the southern record would suggest that the two climate records may not be all that different with regards to the conditions influencing tree growth. Investigating the shift in summer temperature responses, Earles (2008) revealed that some Dempster sites possessed sub-populations of trees which exhibited differing responses during the second half of the 20th century. Using 'responder analysis', it was shown that while many trees within a stand displayed the dominant negative response to summer temperatures for this period, some trees maintained a positive relationship. Such conflicting responses within a single stand further complicate the picture regarding climate-growth relationships in the Yukon.

Table D3 Seasonal (3-month) climate-growth responses of chronologies from the Dempster group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (B) 1950-2000 period (northern climate record), and (C) 1950-2000 period (southern climate record).





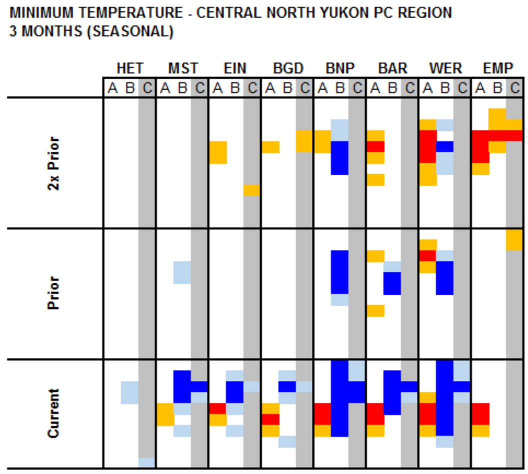


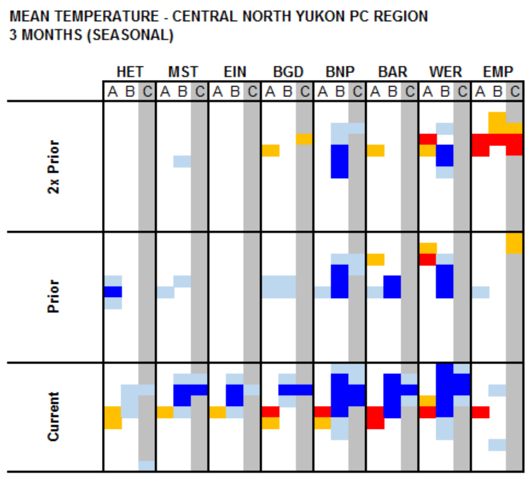
Central North Yukon

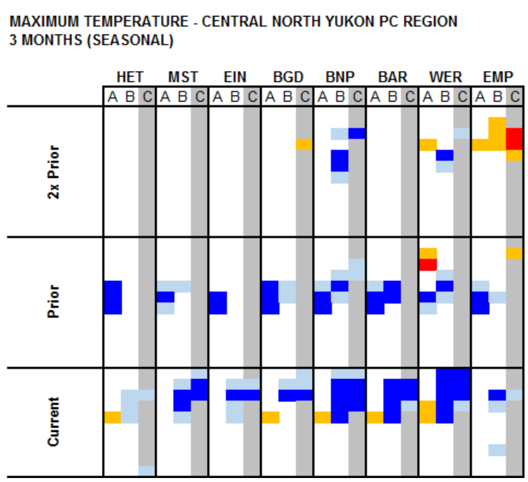
Regional level climate-growth results for the Central North Yukon region were rather similar to the Dempster region: the pre-1950 relationships were mixed, with positive results occurring with spring/summer temperatures during current growth year and two years prior and negative results with prior summer temperatures, while post-1950 relationships with spring/summer temperatures were strongly negative particularly over the current and previous year growth. Correlation results of the individual chronologies of this region highlighted the change in responses between the pre-1950 and post-1950 periods, especially those during the current growth year (Table D4). During the first half of the 20th century, significant positive correlations generally dominated the relationships between growth and current spring/summer temperatures over all three temperature variables (Table D4). Of the 8 chronologies of this region, 7 displayed positive correlations with current minimum temperatures May-August, all 8 showed positive results with current mean temperatures May-August, while 5 of the chronologies had positive correlations with current maximum temperatures May-July. During the second half of the 20th century though, all chronologies displayed significant negative or no correlation with current spring/summer temperatures (only the correlation between growth and current spring/summer minimum temperature for Empire Creek failed to show significant negative relationship). In most cases, these negative responses with current spring temperatures were seen with both the northern and southern climate records. This switch from positive to negative responses between the two time periods was evident in the majority of the chronologies for the current growth year; few chronologies displayed such changes in previous years. Bonnet Plume Lake did show a switch from positive to negative in the correlation between growth and minimum temperatures April-July two years prior, while Wernecke displayed response changes with spring/summer temperatures (minimum and mean) during growth of previous year and two years prior (Table D4). The other distinctive climate-growth pattern amongst the responses of the individual chronologies in this region is the negative correlations between growth and previous year spring/summer maximum temperatures which appears to be relatively time-stable over the entire 20th century. Correlation results indicated that 3 chronologies (Big Gold Creek, Bonnet Plume Lake and Barlow Dome) showed significant negative correlations ($p=0.05$) with previous June-

August mean temperatures for both the pre-1950 and post-1950 analysis periods. With regards to maximum temperature, 6 chronologies (Misty Lake, Big Gold Creek, Bonnet Plume Lake, Barlow Dome, Wernecke and Empire Creek) displayed similar time-stable negative results with summer temperature of the previous year. It would seem that whatever the mechanisms that drive the changes of the climate-growth responses between the pre-1950 and post-1950 periods are, they are primarily constrained to processes affecting current year growth and not carried over from previous years.

Table D4 Seasonal (3-month) climate-growth responses of chronologies from the Central North Yukon group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (B) 1950-2000 period (northern climate record), and (C) 1950-2000 period (southern climate record).



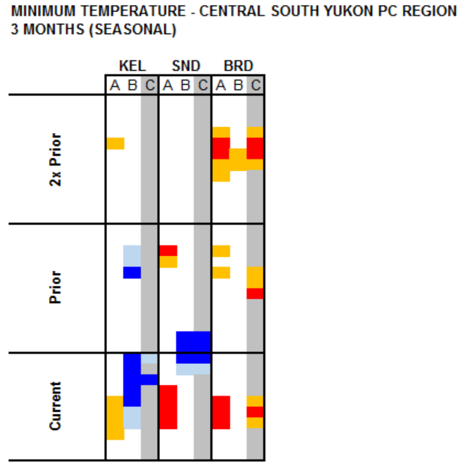


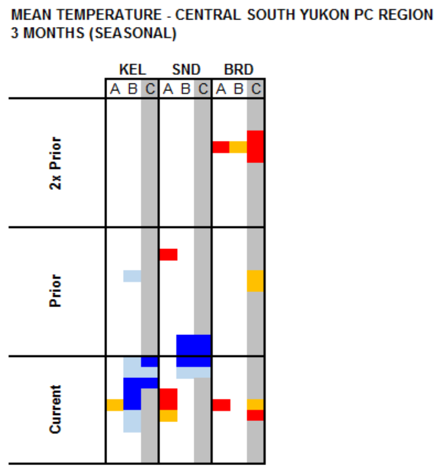


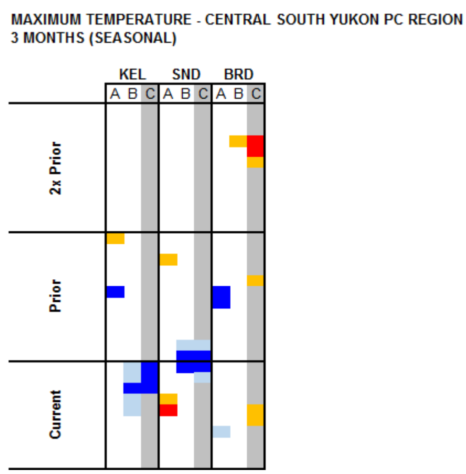
Central South Yukon

Regional level climate-growth results for the Central South Yukon region indicated positive relationships with late spring/early summer mean and minimum temperatures and negative relationships with previous summer maximum temperature during the 1900-1950 period. Negative relationships with current winter and early spring temperatures dominated the regional results for the 1950-2000 period. At the chronology-level, all three chronologies of the Central South Yukon did show strong positive correlations with current minimum and mean summer temperatures of the northern climate record prior to 1950 (Table D5). Positive relationships between growth and temperature involving previous years during the pre-1950 period were not as consistent. While Sandpit and Mt. Berdoe shared strong correlations with previous spring minimum temperatures, the Keele Lake chronology failed to show a similar result. Likewise, results two years prior indicated that Keele Lake and Mt. Berdoe had significant positive correlations with May-July minimum temperatures, but Sandpit did not. In terms of negative relationships during the pre-1950 period, only Keele Lake and Mt Berdoe showed significant negative correlations with previous June-August maximum temperature. Correlations during the second half of the 20th century were primarily negative in nature. Both Keele Lake and Sandpit showed strong negative correlations with previous winter and current early spring temperatures (over all three temperature variables). This pattern was evident in both the correlations with the northern climate record and the southern climate record. Mt. Berdoe was the only chronology which displayed positive correlations with the southern climate record, focusing primarily on the summer months of the 36 month analysis window. Overall, the results of the individual chronologies would suggest that the climate-growth relationships of these sites are different. While Keele Lake and Sandpit appear similar with their post-1950 negative responses to winter/early spring temperatures, Mt. Berdoe offers a different response pattern.

Table D5 Seasonal (3-month) climate-growth responses of chronologies from the Central South Yukon group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (B) 1950-2000 period (northern climate record), and (C) 1950-2000 period (southern climate record).



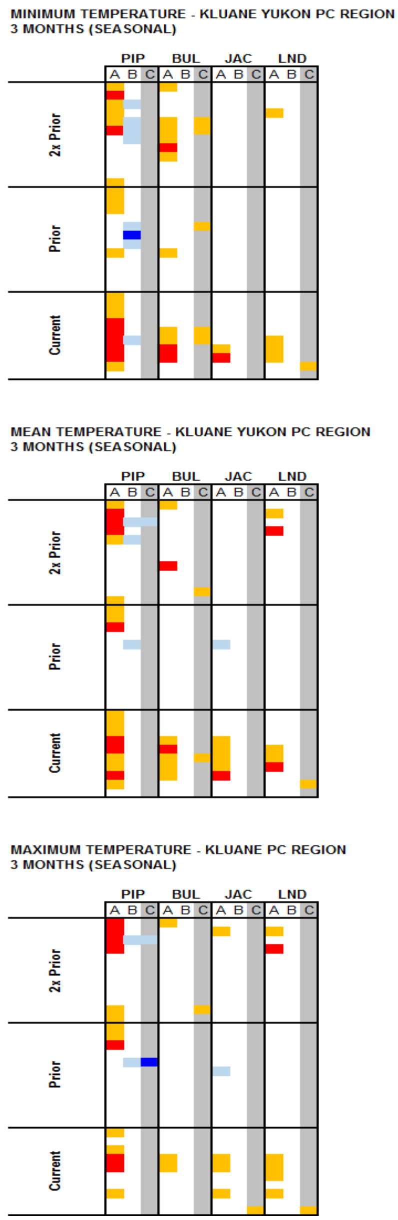




Kluane Group

Unlike the other regional groups examined, the correlation results of the Kluane chronologies (Table D6) showed few negative relationships, even during the second half of the 20^{th} century. Results for the pre-1950 period indicated that all four chronologies of this region correlated positively with current spring/summer temperatures of the northern climate record for all three temperature variables (Table D6). The Pipeline chronology also showed strong positive correlations with winter and spring temperatures of the two previous years, while Bullion Creek shared positive correlations with minimum temperatures between May-November two years prior. Jackson Point showed a negative response with previous May-July mean and maximum temperatures during the pre-1950 period, though none of the other chronologies recorded a similar result. Over the 1950-2000 period, Pipeline was the only chronology in the Kluane group which displayed significant negative climate-growth relationships, most significantly with minimum temperatures of the prior and two years prior summer periods (June-August).

Table D6 Seasonal (3-month) climate-growth responses of chronologies from the Kluane group. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom). Correlations are shown for (A) 1900-1950 period (northern climate record), (2) 1950-2000 period (northern climate record), and (3) 1950-2000 period (southern climate record).



Reference

Earles, S.P. 2008. Dendrochronological studies of white spruce in the northern Yukon, Canada. Unpublished M.Sc. thesis. University of Western Ontario. 148pp.

APPENDIX E

Climate-Growth Responses of Individual Chronologies for 1900-1950 period

Table E1

Correlation between seasonal (3-month) temperatures and ring-width for the 5 chronologies in PC2E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC2E with the highest values on the left.

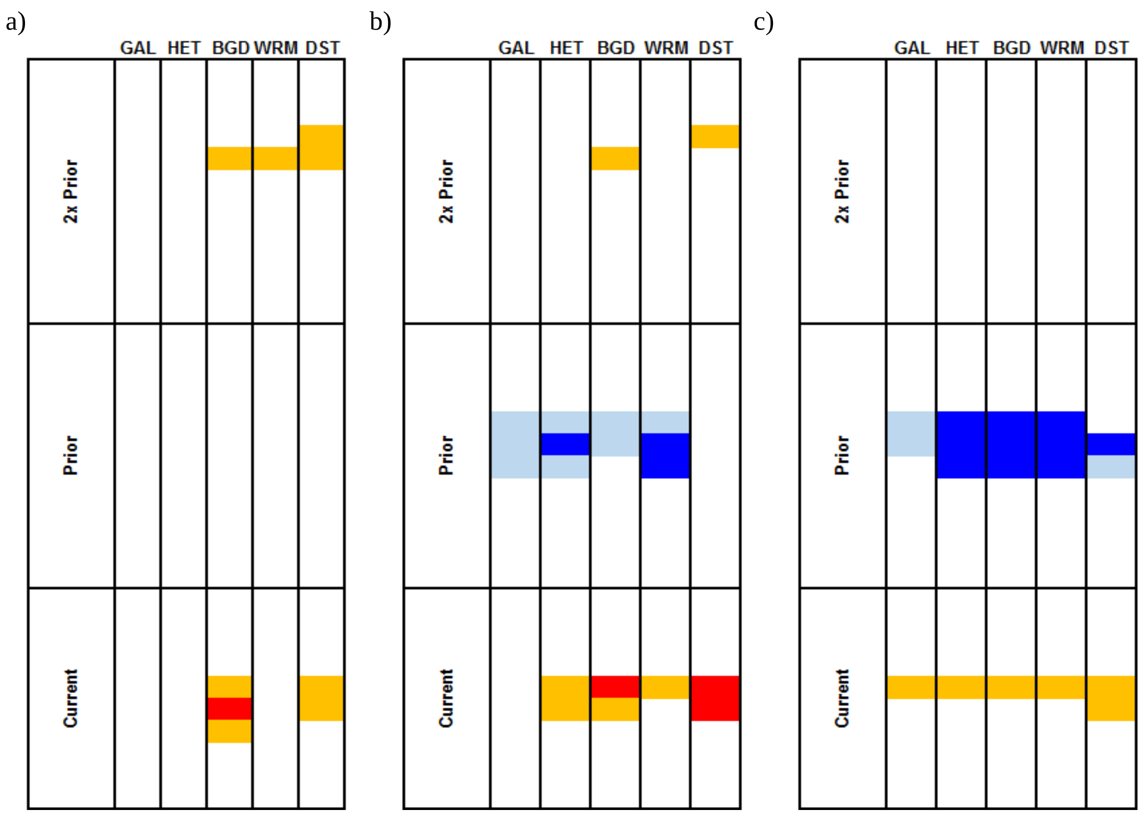


Table E2

Correlation between seasonal (3-month) temperatures and ring-width for the 6 chronologies in PC3E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC3E with the highest values on the left.

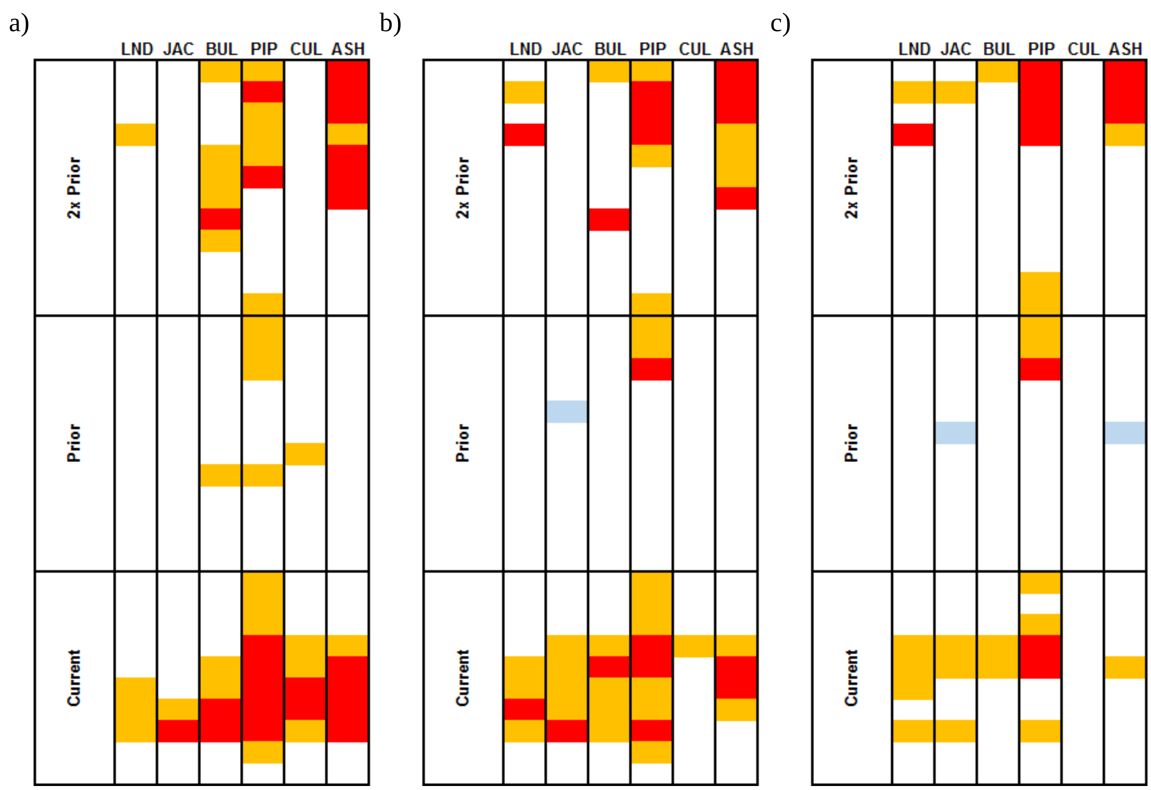


Table E3

Correlation between seasonal (3-month) temperatures and ring-width for the 3 chronologies in PC4E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC4E with the highest values on the left.

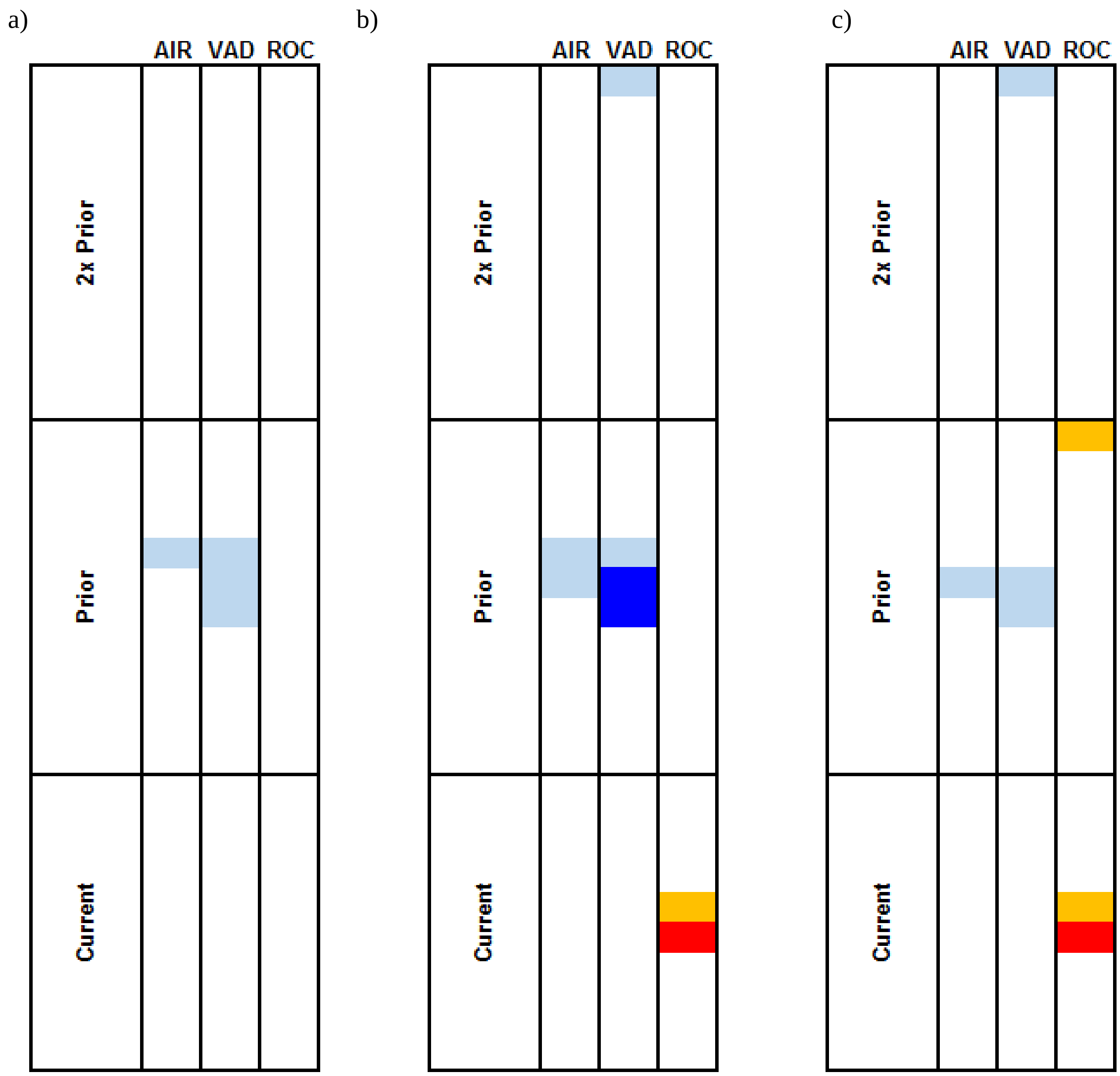


Table E4

Correlation between seasonal (3-month) temperatures and ring-width for the 3 chronologies in PC5E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC5E with the highest values on the left.

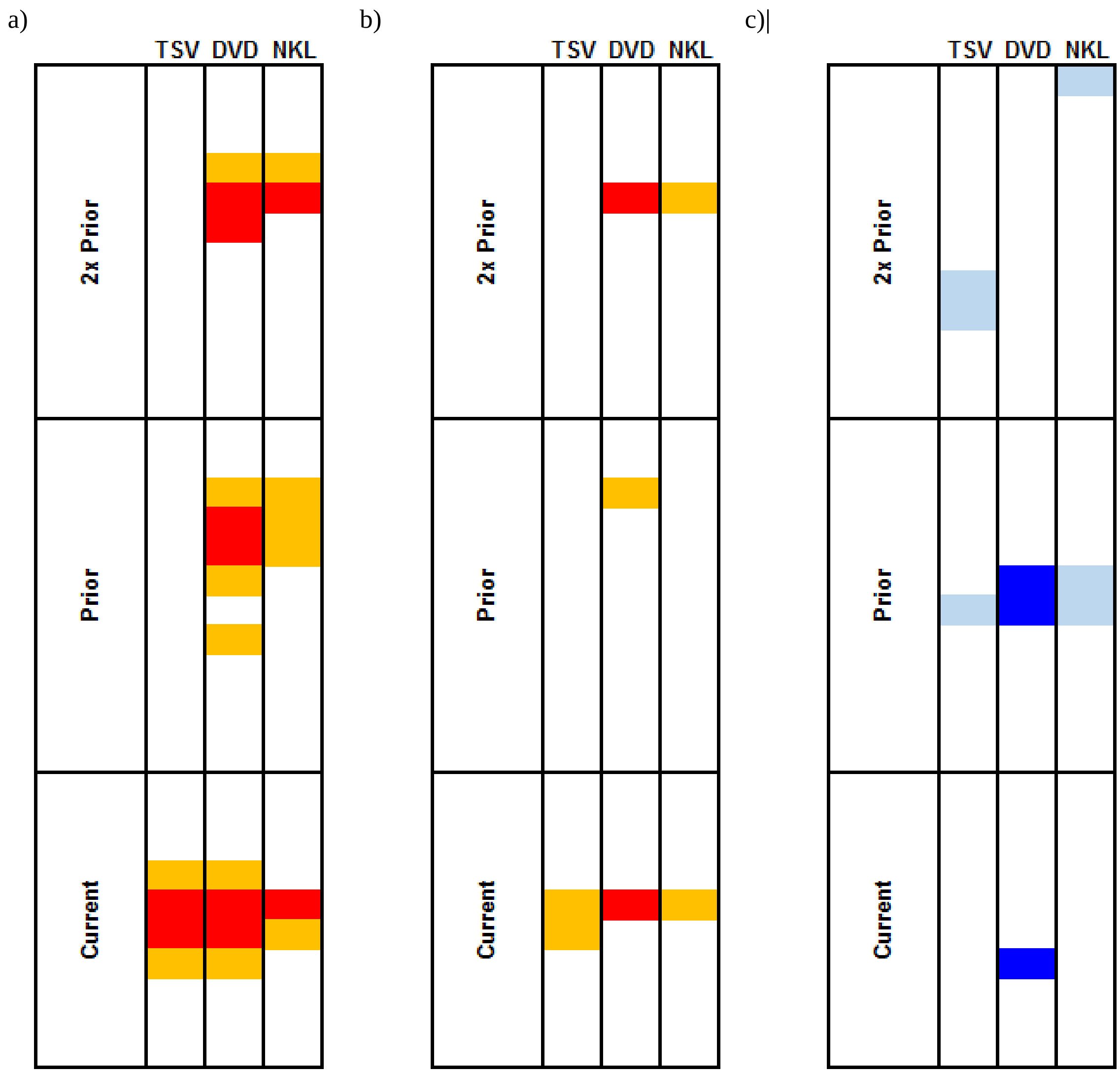


Table E5

Correlation between seasonal (3-month) temperatures and ring-width for the 2 chronologies in PC6E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC6E with the highest values on the left.

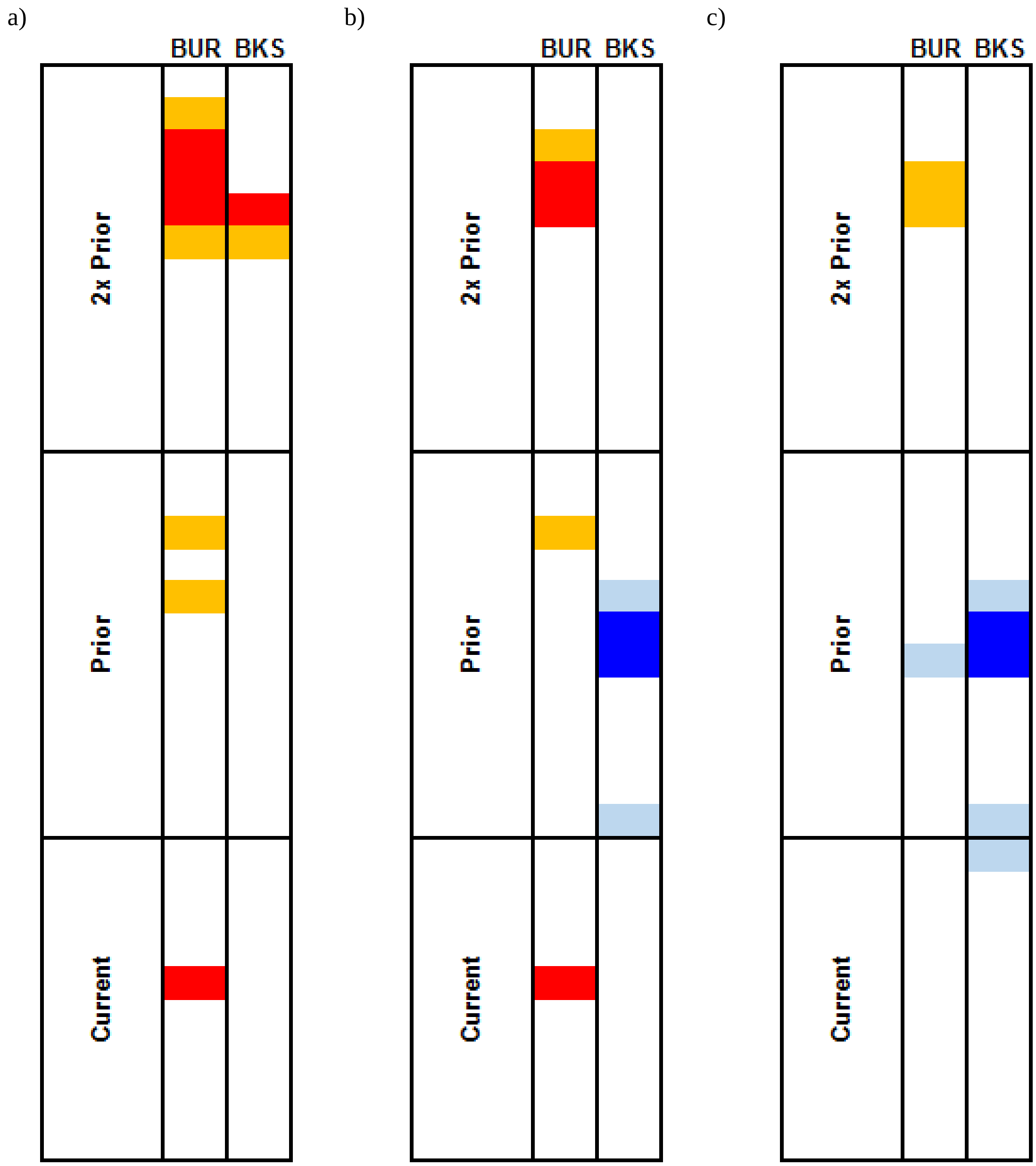


Table E6

Correlation between seasonal (3-month) temperatures and ring-width for the 2 chronologies in PC7E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature. The positioning of chronologies (columns) within the table is based on their loadings on PC7E with the highest values on the left.

a) b) c)

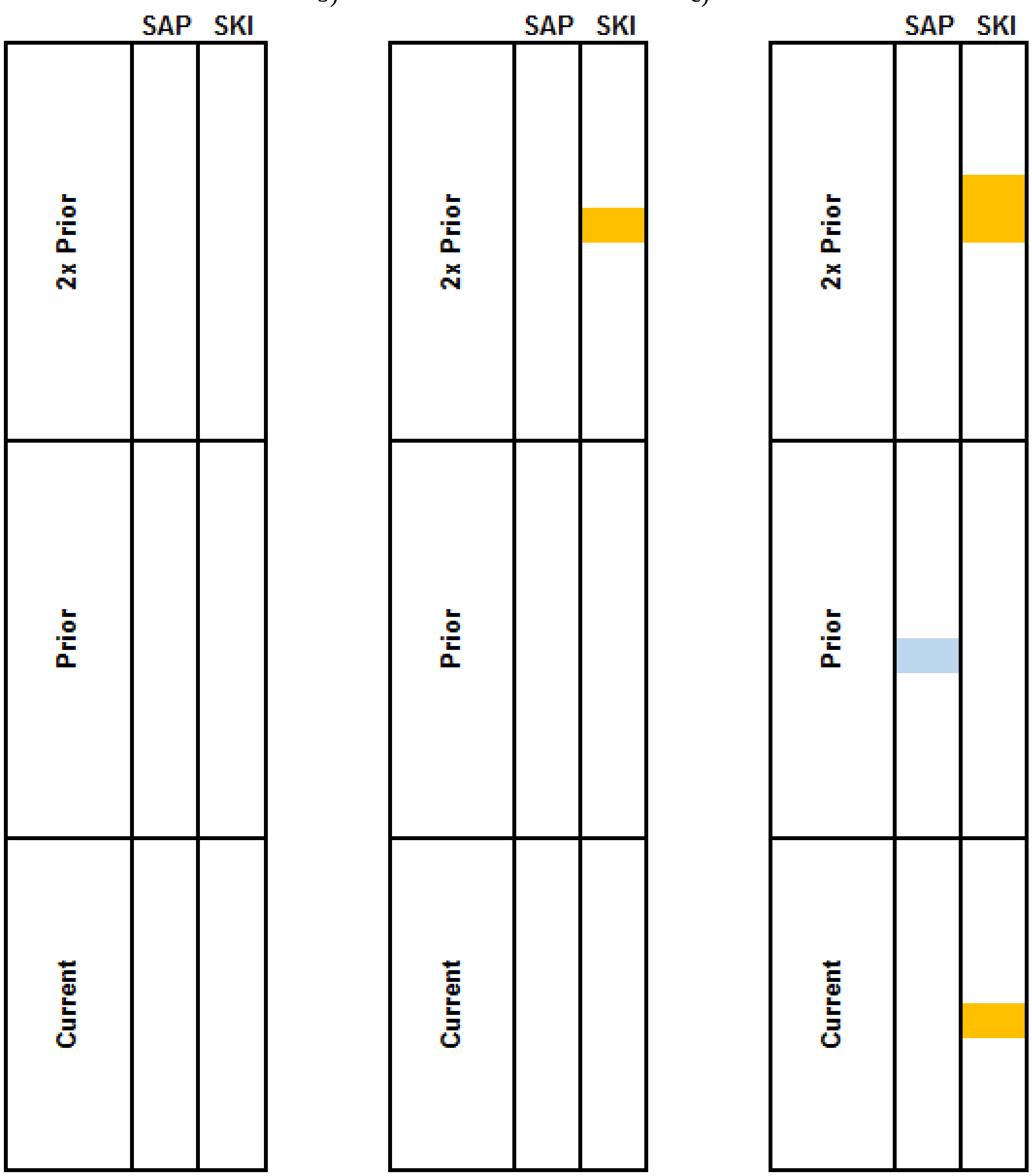
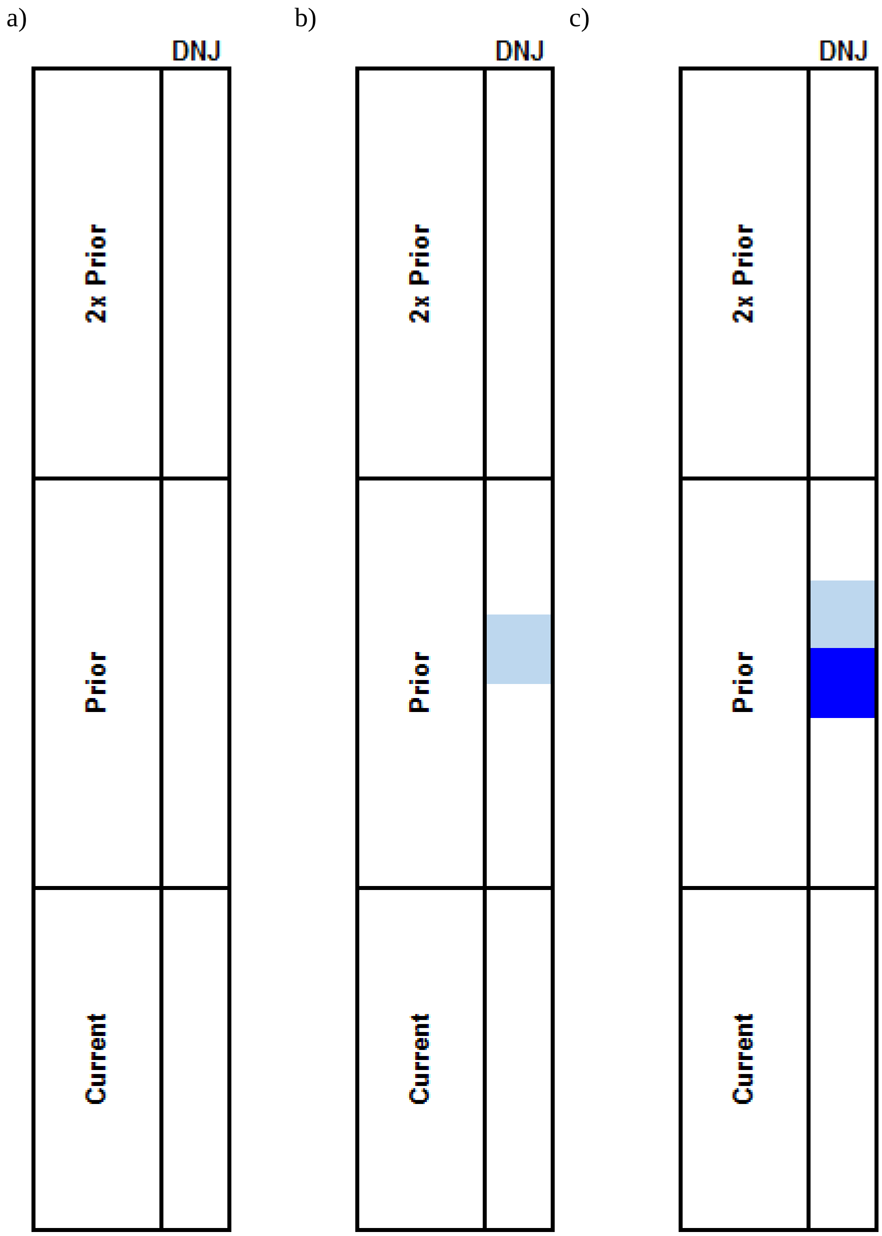


Table E7

Correlation between seasonal (3-month) temperatures and ring-width for the 1 chronology in PC8E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature.

Table E8

Correlation between seasonal (3-month) temperatures and ring-width for the 1 chronology in PC9E between 1900-1950. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for (a) minimum temperature, (b) mean temperature, and (c) maximum temperature.



APPENDIX F

Climate-Growth Responses of Individual Chronologies for 1951-2000 period

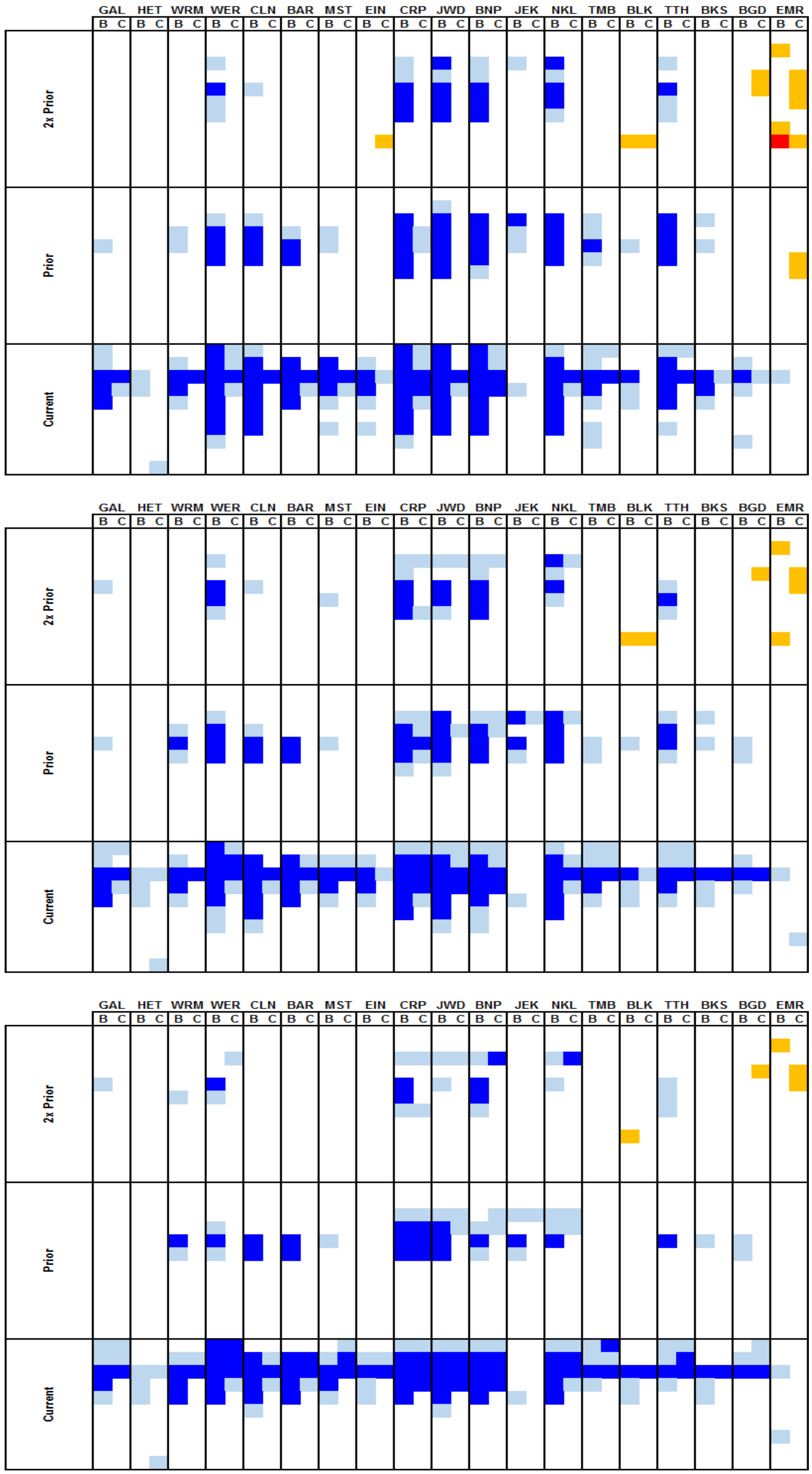
Table F1

Correlations between seasonal (3-month) temperatures and ring-width for the 19 PC2L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom).

Table F2

Correlations between seasonal (3-month) temperatures and ring-width for the 13 PC3L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (top), mean temperature (middle), and maximum temperature (bottom).

Table F1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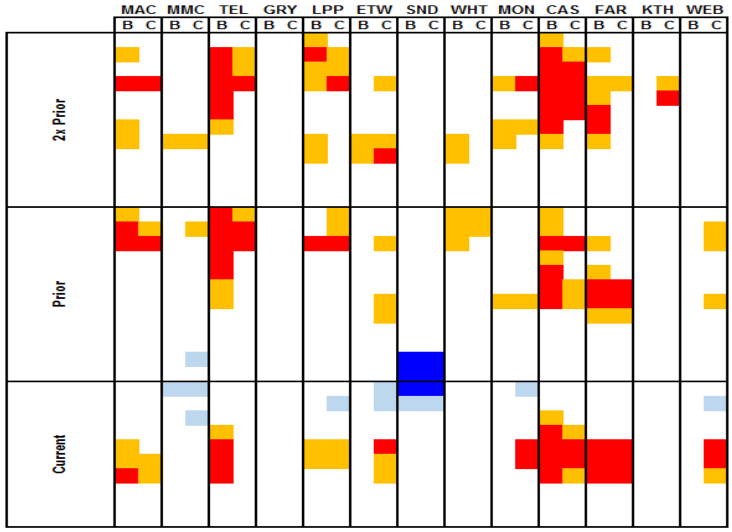
B C
2x Prior
Prior
Current

Table F2


MAC MMC TEL GRY LPP ETW SND WHT MON CAS FAR KTH WEB
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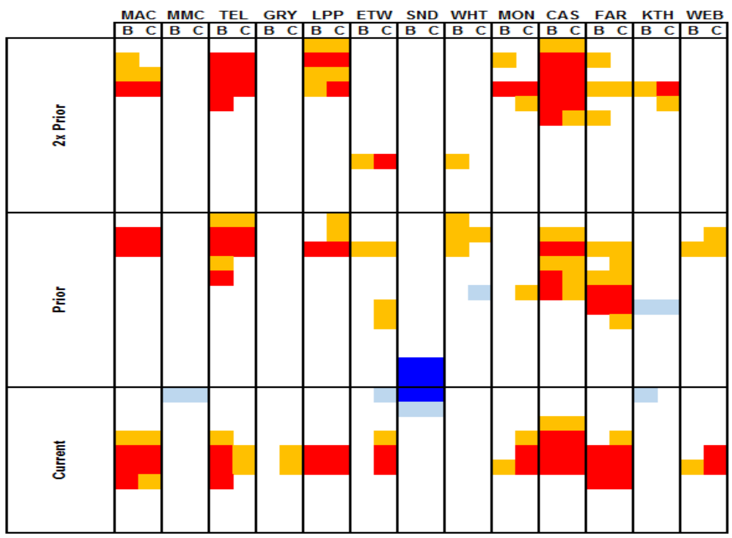
2x Prior
Prior
Current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B C B C B C B C B C B C B C B C B C B C B C B C B C
2x Prior
Prior
Current

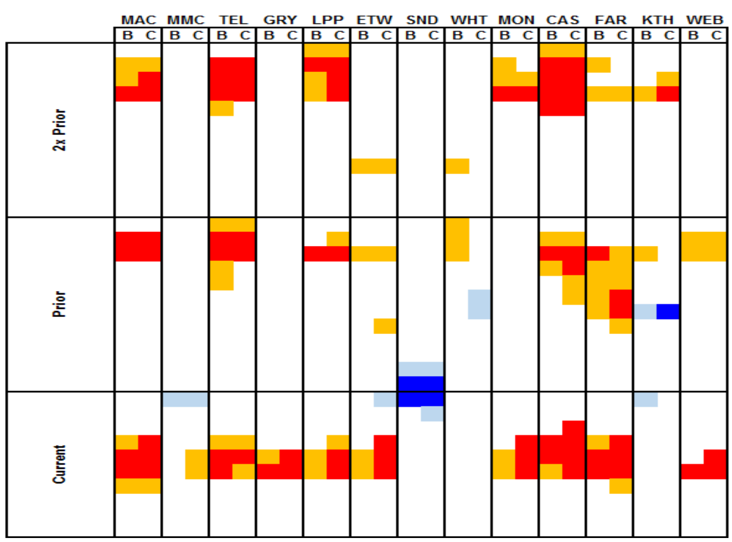

MAC MMC TEL GRY LPP ETW SND WHT MON CAS FAR KTH WEB
B C B C B C B C B C B C B C B C B C B C B C B C B C
2x Prior
Prior
Current

Table F3

Correlations between seasonal (3-month) temperatures and ring-width for the 8 PC4L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (left), mean temperature (middle), and maximum temperature (right).

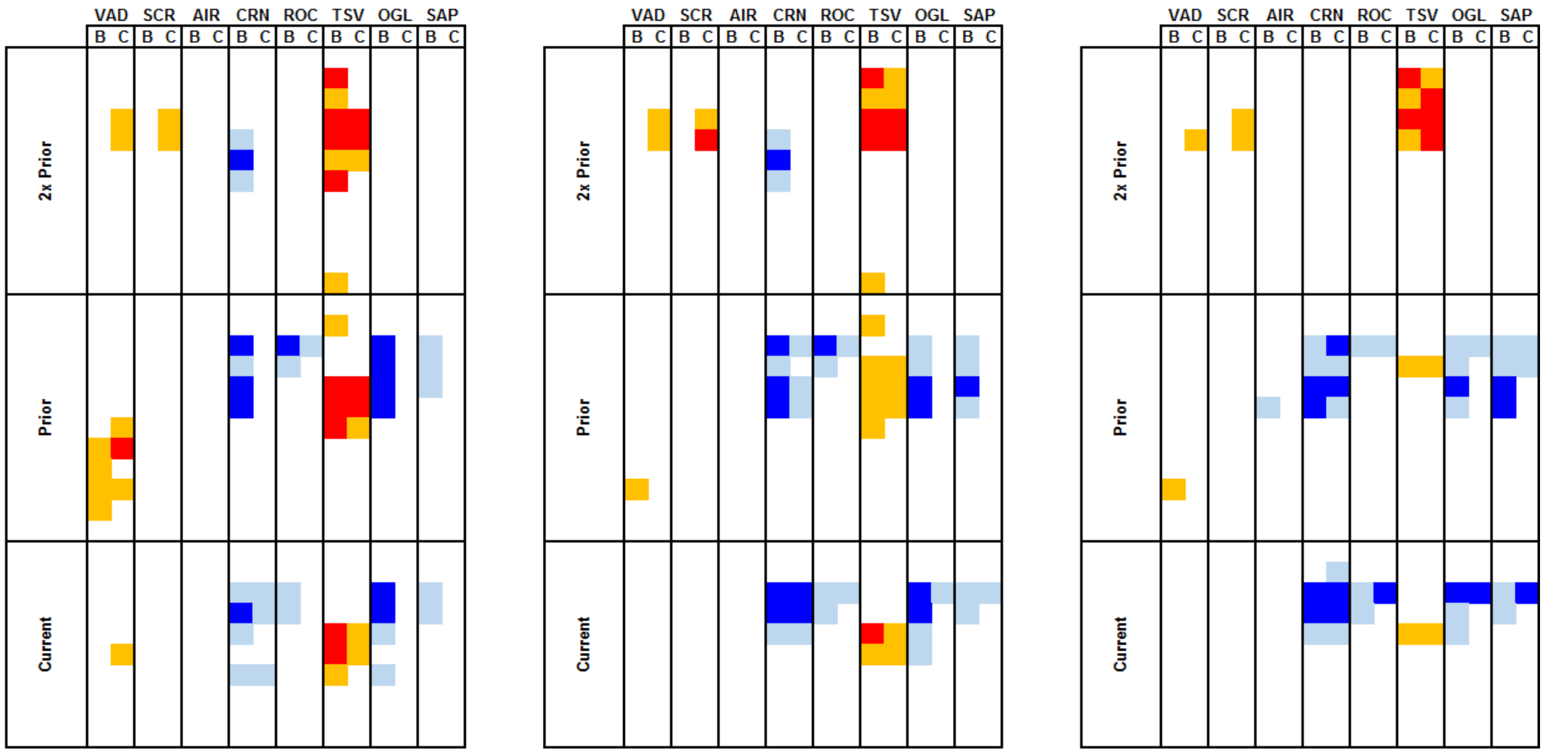


Table F4

Correlations between seasonal (3-month) temperatures and ring-width for the 6 PC5L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (left), mean temperature (middle), and maximum temperature (right).

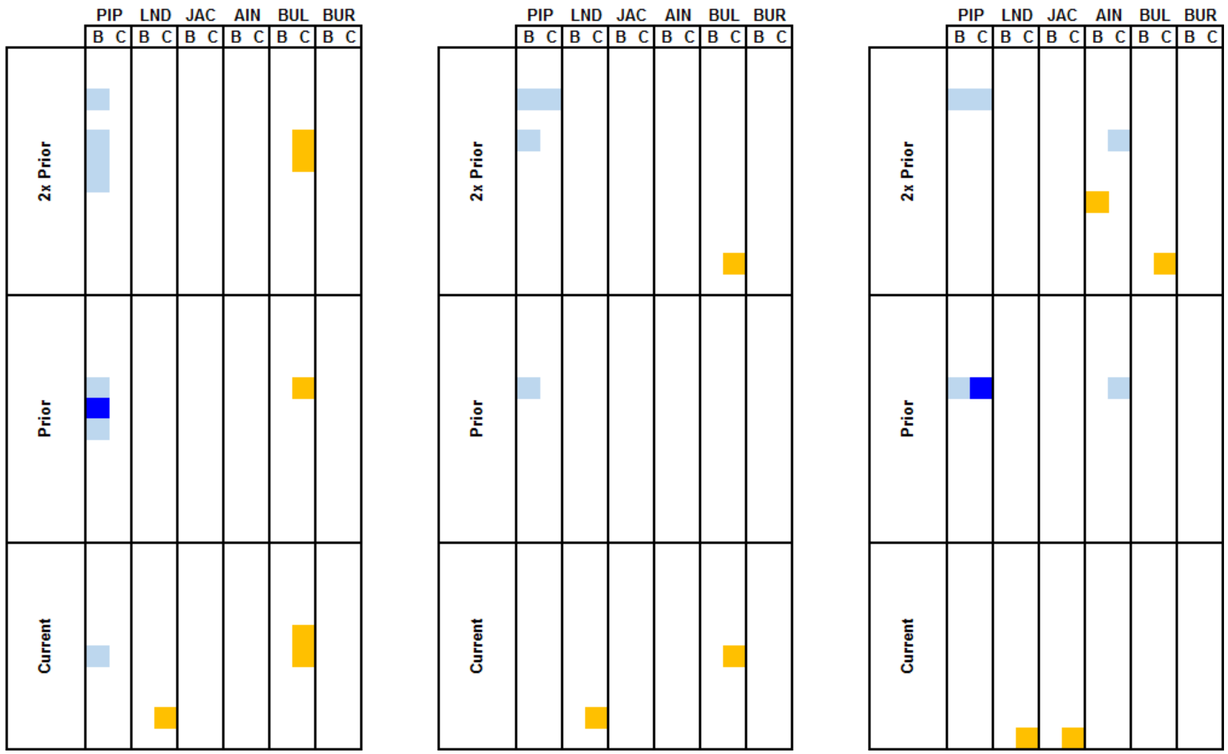


Table F5

Correlations between seasonal (3-month) temperatures and ring-width for the 2 PC6L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (left), mean temperature (middle), and maximum temperature (right).

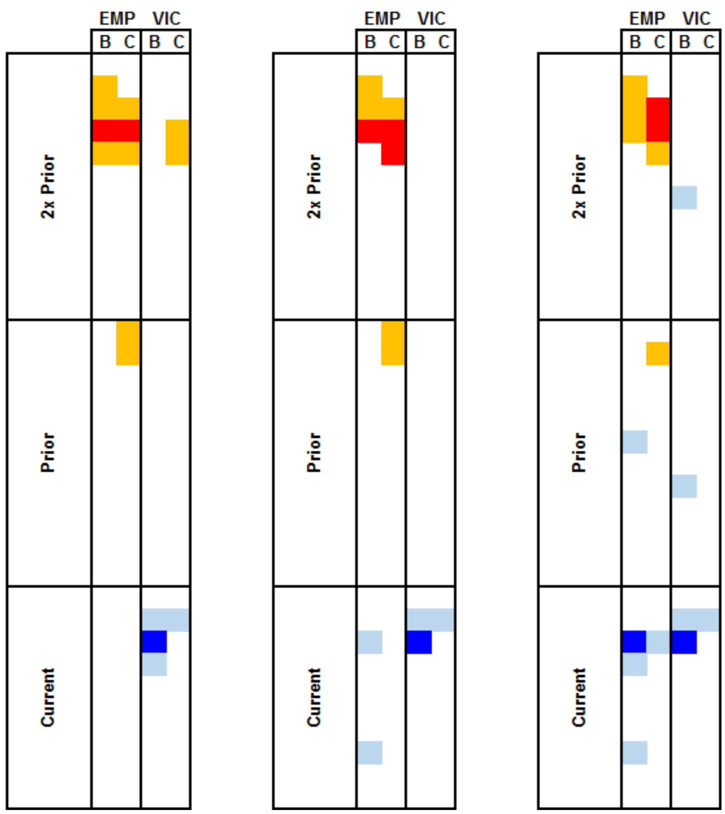


Table F6

Correlations between seasonal (3-month) temperatures and ring-width for the 2 PC7L chronologies for 1951-2000 time period. Each chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (left), mean temperature (middle), and maximum temperature (right).

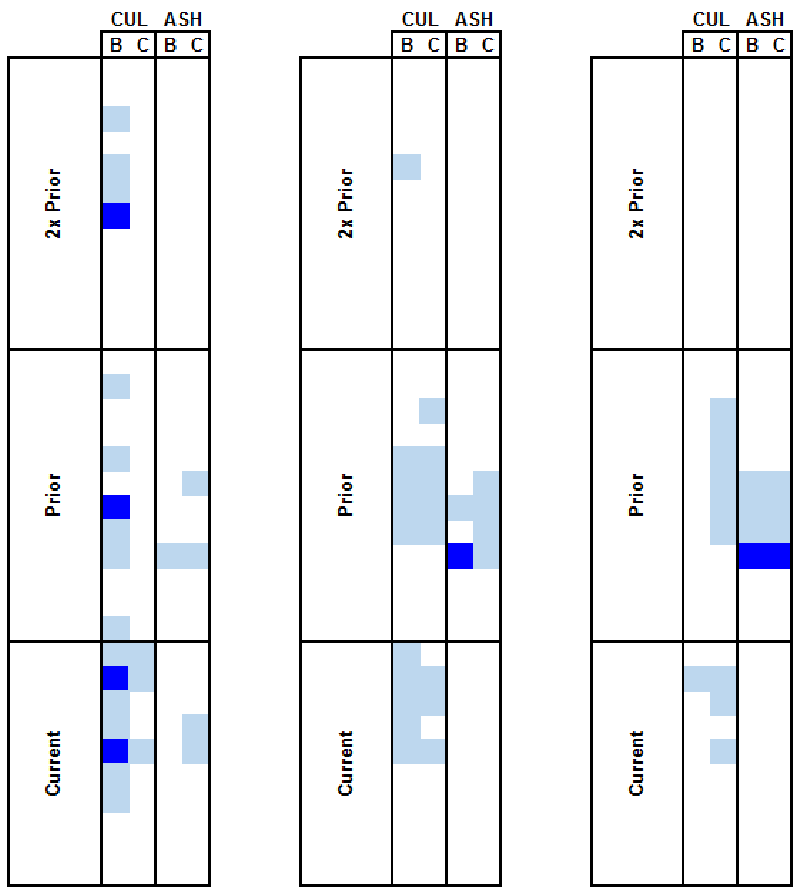
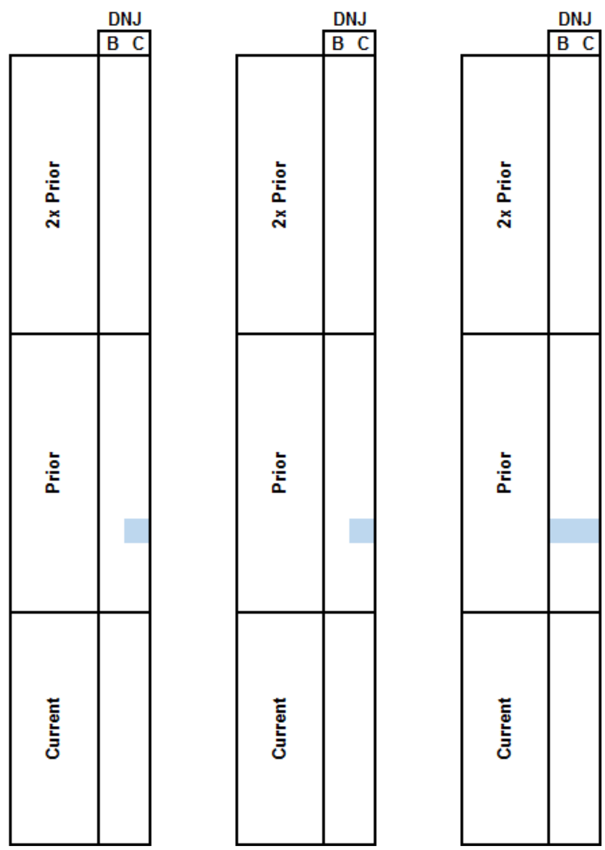


Table F7

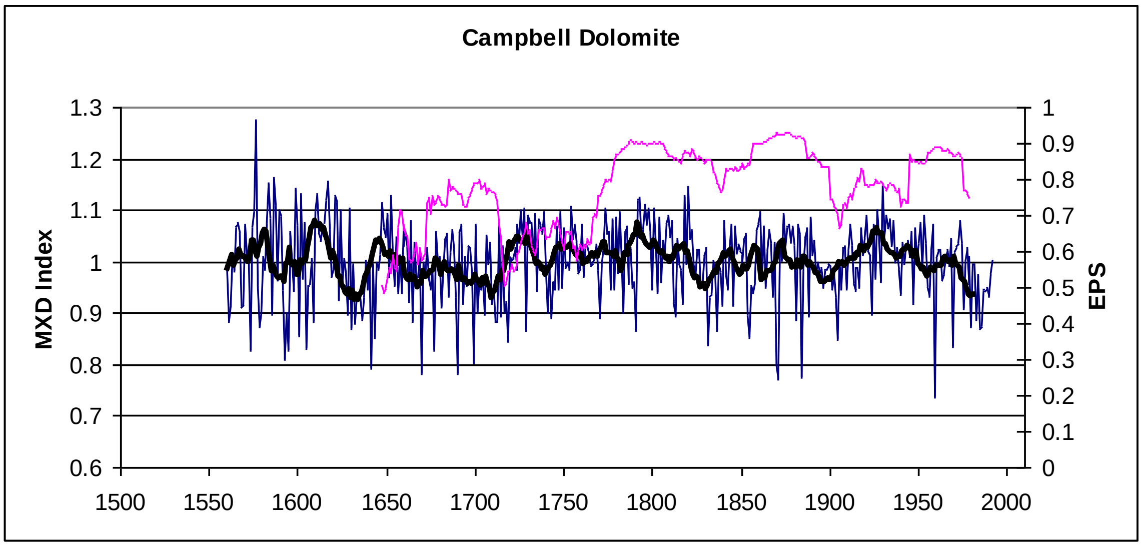
Correlations between seasonal (3-month) temperatures and ring-width for the 1 PC9L chronology for 1951-2000 time period (no chronologies loaded significantly on PC8L). This chronology shows two columns of correlation values; left column indicates correlations with northern climate record, while right column indicates correlations with southern climate record. Correlations significant at p=0.01 (positive=red, negative=dark blue) and p=0.05 (positive=orange, negative=light blue) are highlighted for minimum temperature (left), mean temperature (middle), and maximum temperature (right).

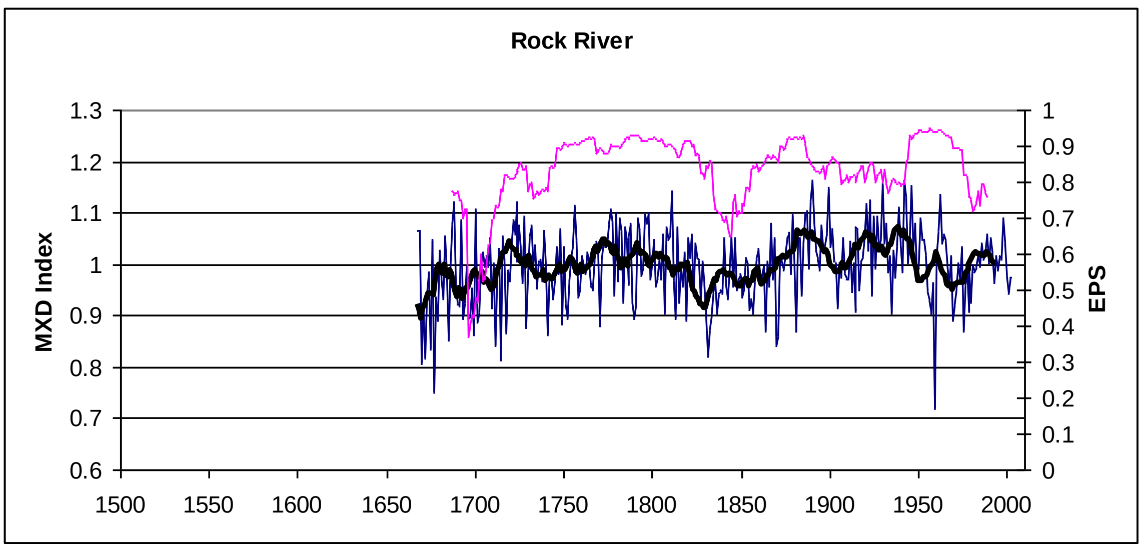


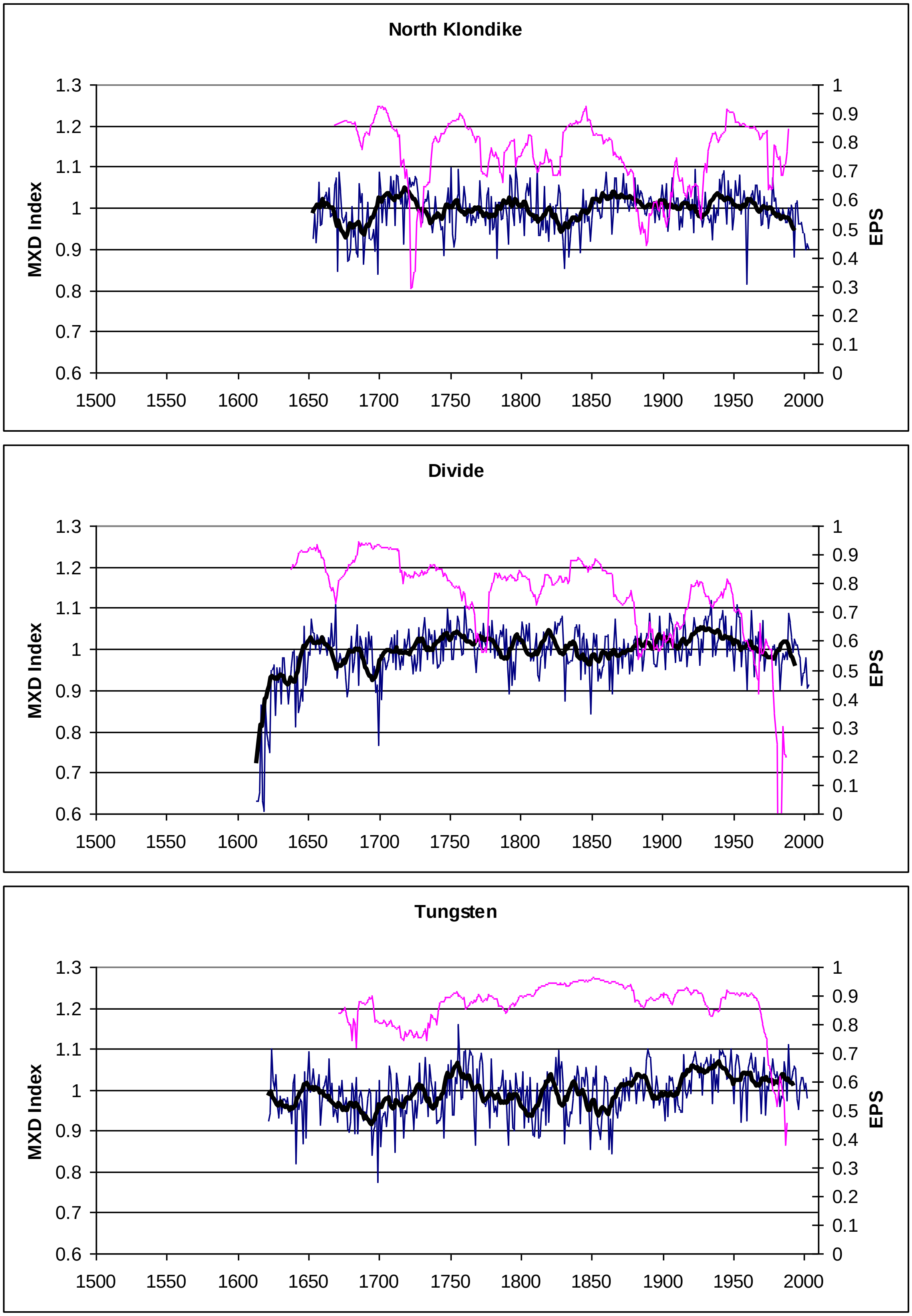
APPENDIX G

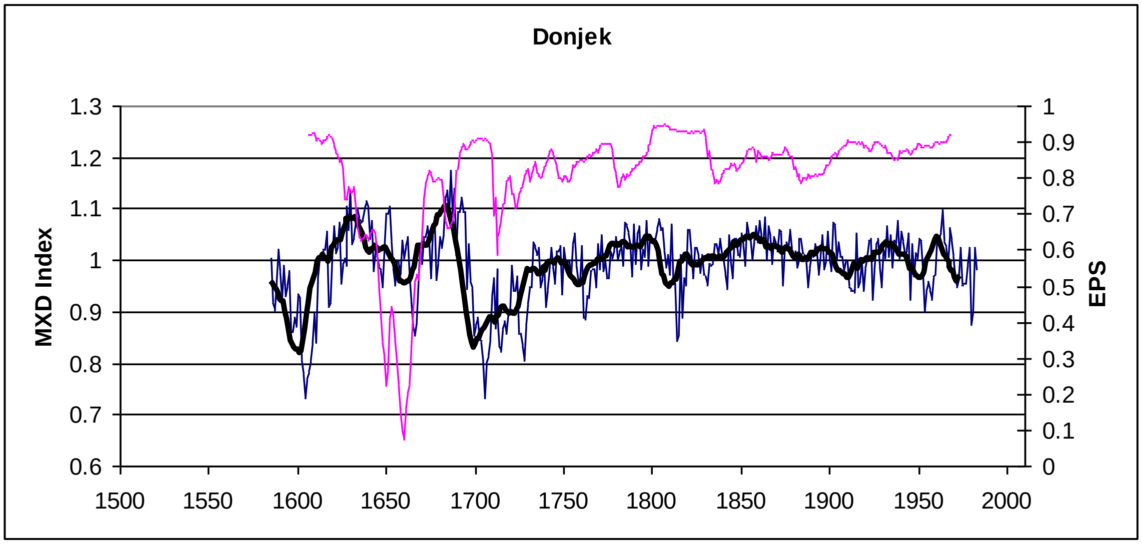
MXD Chronology Plots

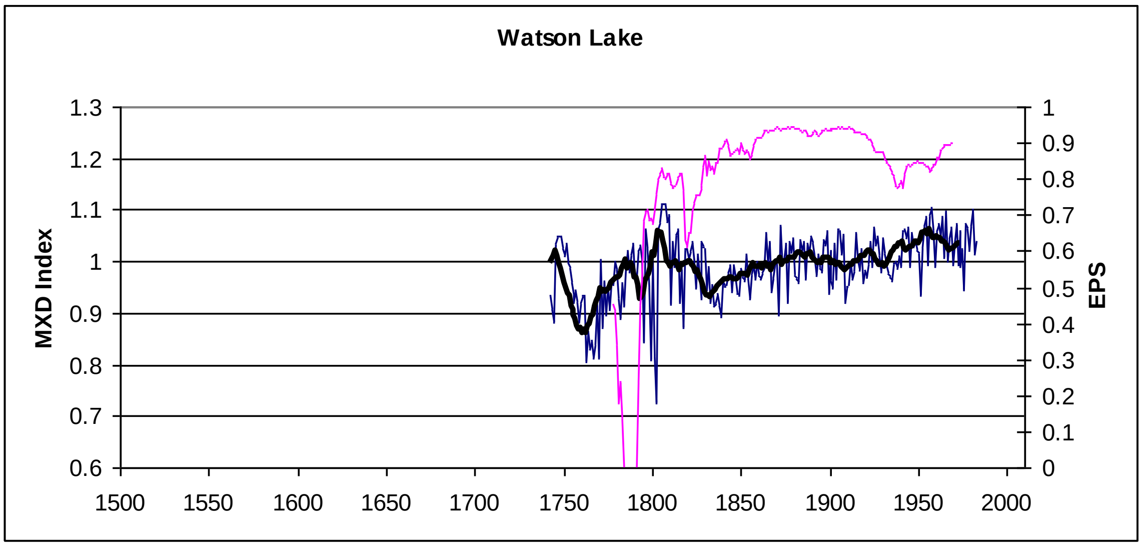
Time series plots of the fifteen MXD chronologies developed for current study. Full length chronology is shown (blue line) along with 10-year smoothing spline (thick black line). Expressed Population Signal (EPS) is shown (pink line) for each chronology. Plot scales are identical for comparison purposes (exception: MXD Index scale for Gray Mountain/Whitehorse chronology which was extended to due to its larger variability).






North Klondike
MXD Index
EPS
Divide
MXD Index
EPS
Tungsten
MXD Index
EPS


Donjek
MXD Index
EPS
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000


Watson Lake
MXD Index
EPS
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
1
0.9
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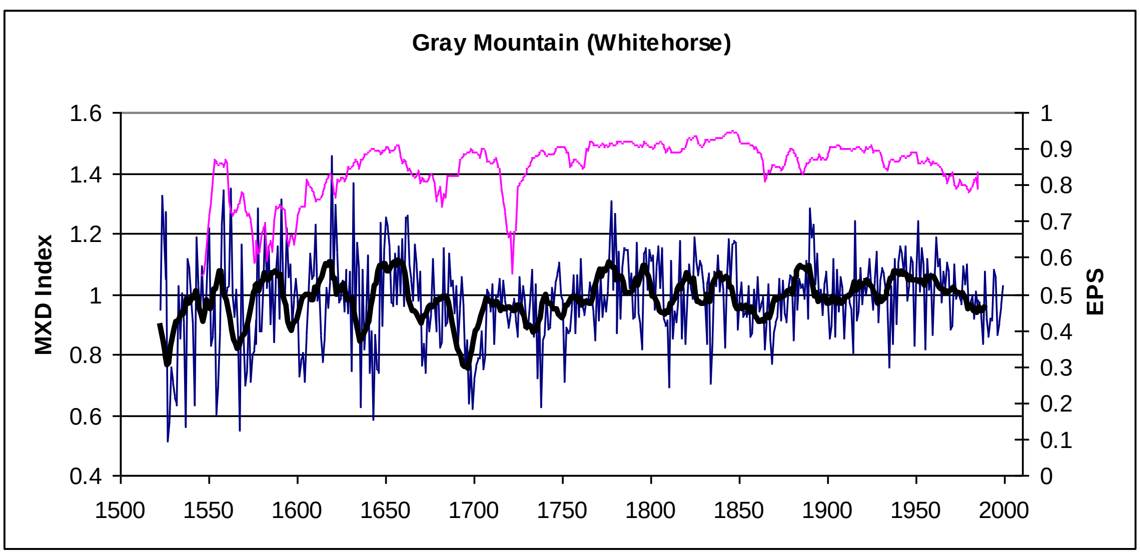
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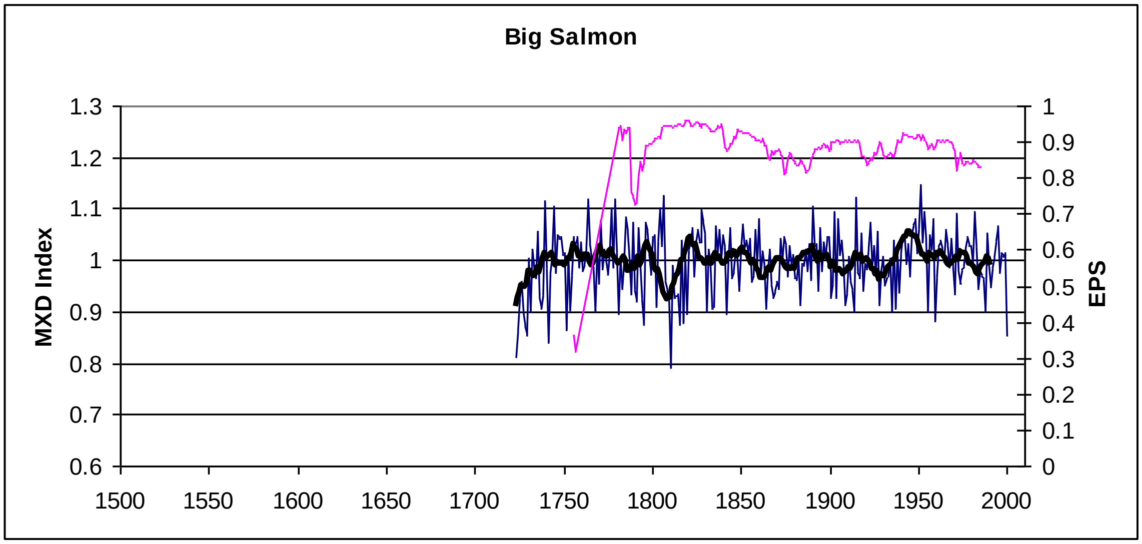
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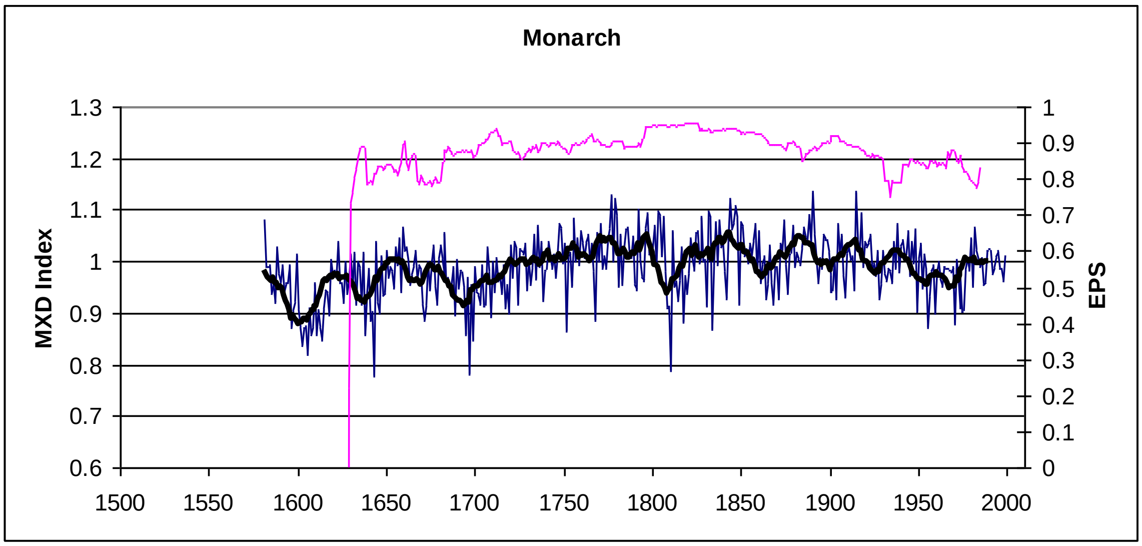
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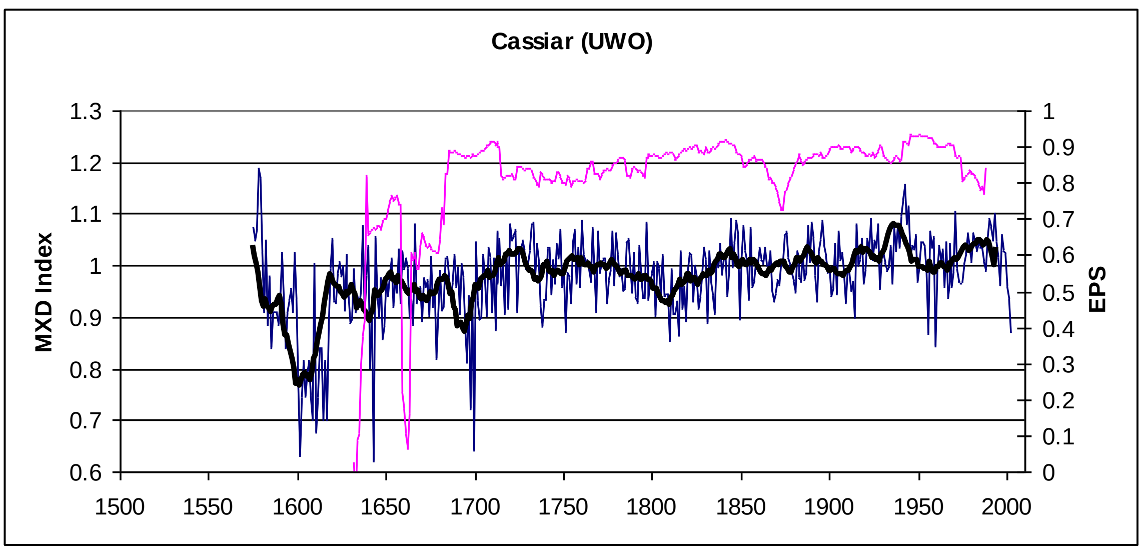
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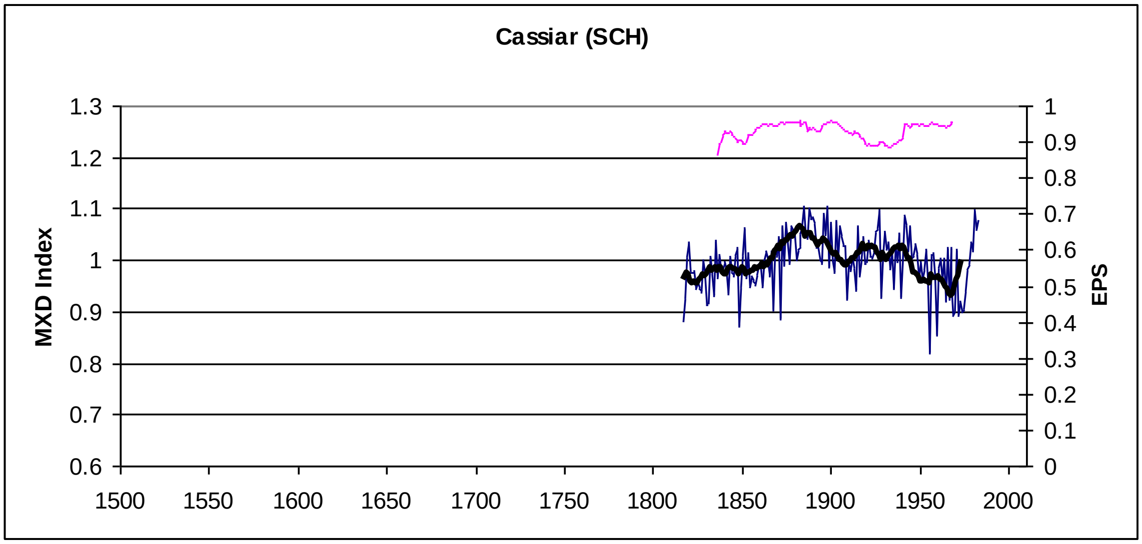
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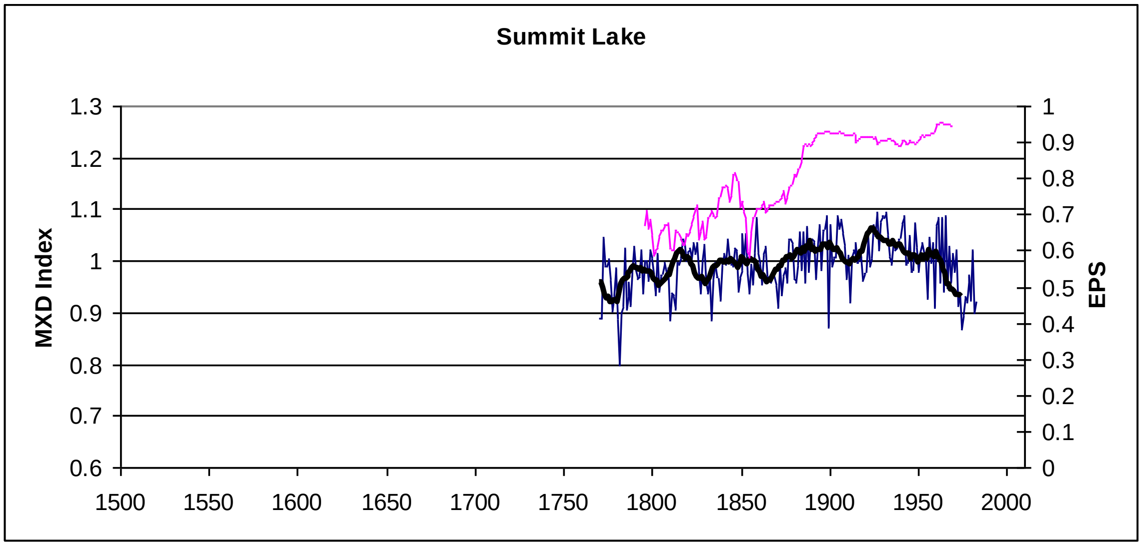
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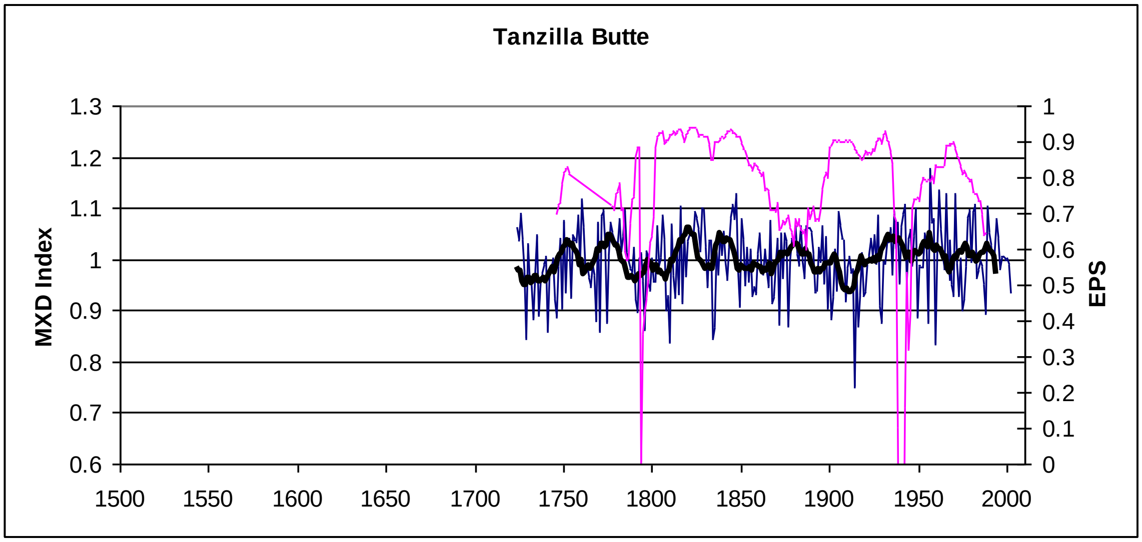
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MXD Index
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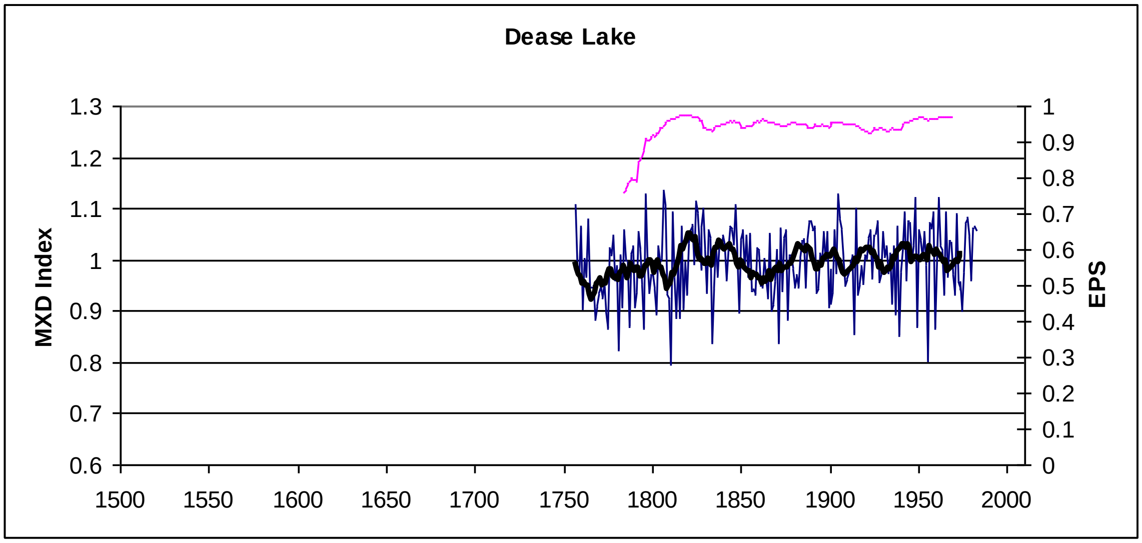

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APPENDIX H

Model Verification Statistics

Two statistical measures commonly used in reconstruction model verification are the Reduction of Error (RE) statistic and the Coefficient of Efficiency (CE) statistic.

The RE statistic calculates whether a climatological forecast provides a better estimate than using the mean of the actual meteorological data in the calibration period (Cook *et al*. 1994, 1999). It is calculated as:

$$RE = 1.0 - \left[\frac{\sum (x_i - \hat{x}_i)^2}{\sum (x_i - \bar{x}_c)^2} \right] \qquad \text{(H.1)}$$

(Cook *et al*. 1994, 1999)

where x_i and $\hat{x}_i$ are the actual and estimated data in year *i* of the verification period, and $\bar{x}_c$ is the mean of the actual data in the calibration period (Cook *et al*. 1994, 1999). The value of RE can range from 1.0 (i.e. perfect estimation) to negative infinity. RE values greater than zero indicate that the reconstruction is better than the calibration period mean (Cook *et al*. 1994, 1999).

The CE statistic is similar to RE though instead of measuring against the mean of actual data in the calibration period, it uses the mean of the verification period. The statistic is calculated as:

$$CE = 1.0 - \left[\frac{\sum (x_i - \hat{x}_i)^2}{\sum (x_i - \bar{x}_v)^2} \right] \qquad \text{(H.2)}$$

(Cook *et al*. 1994, 1999)

where x_i and $\hat{x}_i$ are the actual and estimated data in year *i* of the verification period, and $\bar{x}_v$ is the mean of the actual data in the verification period (Cook *et al*. 1994, 1999). Similar to RE, values for CE can range 1.0 to negative infinity. CE values greater than zero indicate that the reconstruction has predictive skill (Cook *et al*. 1994, 1999).

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APPENDIX I

List of Major Volcanic Eruptions

Table I1

The following is a list of major volcanic eruptions (Volcanic Explosive Index (VEI) ≥ 4) occurring between 1623-2002. The list is compiled from material from Jones *et al*, 1995; Briffa *et al*., 1998a; D'Arrigo and Jacoby, 1999; Deligne *et al*., 2010.

Year	Volcano Name	Country	VEI
1625	Katla	Iceland	4
1630	Furnas	Portugal	5
1630	Raoul	New Zealand	4
1631	Somma-Vesuvius	Italy	4
1638	Raung	Indonesia	4
1640	Parker [Falen]	Philippines	5
1640	Komaga-take	Japan	5
1640	Llaima	Chile	4
1641	Kelut	Indonesia	4
1646	Makian	Indonesia	4
1650	Santorini	Greece	4
1650	Merapi	Indonesia	4
1650	Shiveluch	Russia	5
1655	Taranaki	New Zealand	4
1660	Katla	Iceland	4
1660	Guagua Pichincha	Ecuador	4
1660	Teon [Serawema]	Indonesia	4
1660	Long Island	Papua New Guinea	6
1663	Usu	Japan	5
1667	Shikotsu [Tarumai]	Japan	5
1673	Gamkonora	Indonesia	5
1680	Tongkoko	Indonesia	5
1690	Chikurachki	Russia	4
1693	Serua	Indonesia	4
1693	Hekla	Iceland	4
1694	Komaga-take	Japan	4
1707	Fuji	Japan	5
1712	Chirpoi	Russia	4
1716	Taal	Philippines	4
1717	Fuego	Guatemala	4
1720	Bravo	Columbia	4

1720	Raoul	New Zealand	4
1721	Katla	Iceland	4
1727	Oraefajokull	Iceland	4
1737	Fuego	Guatemala	4
1739	Shikotsu [Tarumai]	Japan	5
1741	Oshima-Oshima	Japan	4
1744	Cotopaxi	Ecuador	4
1750	Ksudach	Russia	4
1754	Taal	Philippines	4
1755	Katla	Iceland	4
1760	Makian	Indonesia	4
1762	Planchon-Peteroa	Chile	4
1762	Pavlof Sister	United States	4
1763	Miyake-jima	Japan	4
1766	Hekla	Iceland	4
1768	Cotopaxi	Ecuador	4
1769	Usu	Japan	4
1778	Raikoke	Russia	4
1779	Sakura-jima	Japan	4
1783	Asama	Japan	4
1783	Grimsvotn [Laki]	Iceland	4
1787	Etna	Italy	4
1790	Kilauea	United States	4
1790	Alaid	Russia	4
1793	San Martin	Mexico	4
1795	Westdahl	United States	4
1800	St. Helens	United States	5
1812	Awu	Indonesia	4
1812	Soufriere St. Vincent	West Indies	4
1813	Suwanose-jima	Japan	4
1814	Mayon	Philippines	4
1815	Tambora	Indonesia	7
1817	Raung	Indonesia	4
1818	Colima	Mexico	4
1822	Galunggung	Indonesia	5
1822	Usu	Japan	4
1826	Kelut	Indonesia	4
1827	Avachinsky	Russia	4
1829	Kliuchevskoi	Russia	4
1831	Babuyan Claro	Philippines	4
1835	Cosiguina	Nicaragua	5
1845	Hekla	Iceland	4
1846	Fonualei	Tonga	4

1853	Chikurachki	Russia	5
1853	Usu	Japan	4
1854	Shiveluch	Russia	5
1856	Komaga-take	Japan	4
1857	Fuego	Guatemala	4
1860	Katla	Iceland	4
1861	Makian	Indonesia	4
1872	Merapi	Indonesia	4
1873	Grimsvotn	Iceland	4
1875	Askja	Iceland	5
1877	Cotopaxi	Ecuador	4
1877	Suwanose-jima	Japan	4
1880	Fuego	Guatemala	4
1883	Augustine	United States	4
1883	Krakatau	Indonesia	6
1886	Niuafo'ou	Tonga	4
1886	Okataina	New Zealand	5
1888	Bandaisan	Japan	4
1889	Suwanose-jima	Japan	4
1890	Colima	Mexico	4
1893	Calbuco	Chile	4
1896	Dona Juana	Columbia	4
1902	Santa Maria	Guatemala	6
1902	Soufriere St. Vincent	West Indies	4
1902	Pelee	West Indies	4
1907	Ksudach	Russia	5
1911	Taal	Philippines	4
1911	Lolobau	Papua New Guinea	4
1912	Novarupta [Katmai]	United States	6
1913	Colima	Mexico	4
1914	Sakura-jima	Japan	4
1917	Agrigan	United States	4
1918	Katla	Iceland	4
1919	Manam	Papua New Guinea	4
1919	Kelut	Indonesia	4
1924	Iriomote-jima	Japan	4
1924	Raikoke	Russia	4
1926	Avachinsky	Russia	4
1929	Komaga-take	Japan	4
1931	Aniakchak	United States	4
1931	Kliuchevskoi	Russia	4
1932	Azul	Chile	5
1932	Fuego	Guatemala	4

1933	Kuchinoerabu-jima	Japan	4
1933	Suoh	Indonesia	4
1933	Kharimkotan	Russia	5
1937	Rabaul	Papua New Guinea	4
1945	Avachinsky	Russia	4
1946	Sarychev Peak	Russia	4
1947	Hekla	Iceland	4
1950	Ambrym	Vanuatu	4
1951	Kelut	Indonesia	4
1952	Bagana	Papua New Guinea	4
1953	Spurr	United States	4
1955	Carran-Los Venados	Chile	4
1956	Bezymianny	Russia	5
1963	Agung	Indonesia	5
1964	Shiveluch	Russia	4
1965	Taal	Philippines	4
1966	Awu	Indonesia	4
1968	Fernandina	Ecuador	4
1973	Tiatia [Chachadake]	Russia	4
1974	Fuego	Guatemala	4
1975	Tolbachik	Russia	4
1976	Augustine	United States	4
1980	St. Helens	United States	5
1981	Pagan	United States	4
1981	Alaid	Russia	4
1982	Galunggung	Indonesia	4
1982	El Chichon	Mexico	5
1983	Colo [Una Una]	Indonesia	4
1986	Chikurachki	Russia	4
1990	Kelut	Indonesia	4
1990	Kliuchevskoi	Russia	4
1991	Hudson	Chile	5
1991	Pinatubo	Philippines	6
1992	Spurr	United States	4
1993	Lascar	Chile	4
1994	Rabaul	Papua New Guinea	4
2000	Ulawun	Papua New Guinea	4
2002	Reventador	Ecuador	4
2002	Ruang	Indonesia	4

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