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Dendrochronological Studies of white spruce in the northern Yukon, Canada

Sean Patrick Earles
Western University

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Dendrochronological Studies of white spruce in the northern Yukon, Canada

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by

Sean Patrick Earles

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of the requirements for the degree of
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THE UNIVERSITY OF WESTERN ONTARIO
SCHOOL OF GRADUATE AND POSTDOCTORAL STUDIES

CERTIFICATE OF EXAMINATION

Supervisor	Examiners
Luckman, Brian	McBean, Gordon
	Pearce, Cheryl
	Pisaric, Michael Carleton University

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ABSTRACT

This thesis investigates the variation of ring widths from 23 white spruce (*Picea glauca*) treeline chronologies located along the Dempster Highway (61-68°N), bracketing the position of the classical TTHH site (65.33°N) in the Yukon. Relationships between the 18 strongest chronologies and mean monthly/seasonal temperatures from Dawson over the 1900-2000 period were examined using correlation analyses. Ring-width chronologies were commonly negatively correlated with prior summer temperatures over the entire 20th century but most strongly in the 1950-2000 period. However, several sites had positive relationships with summer temperatures in the 1900-1950 period and much weaker or negative relationships with summer temperatures over the 1951-2000 period indicating an apparent "divergent" response over the 20th century. "Responder analysis" of three highly replicated sites indicated two were dominated by strong negative relationships with summer temperatures in the late 20th century but the northernmost site contained trees that maintained a positive relationship with summer temperatures in the late 20th century.

Keywords: dendroclimatology, tree-rings, *Picea glauca*, white spruce, Yukon Territory, sensitivity, divergence

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CHAPTER ONE

Introduction

1.1 Introduction

Dendroclimatology is the 'science of using tree rings to study present climate and reconstruct past climate' (Grissino-Mayer, n.d.). Tree rings have been used as proxy climate indicators because the annual rings provide an absolute calendar date and the characteristics of individual tree rings may vary systematically in response to climate variables (Fritts, 1976; Bradley, 1985, Briffa *et al.*, 1996; Bradley, 1999). Climate reconstructions derived from tree-ring series are based on the relationships between tree ring parameters (e.g. annual ring width, latewood width/density, earlywood width/density, etc., Fritts, 1976) and derived instrumental climate data (e.g. temperature, precipitation, snowpack, etc.) from a nearby site. A primary assumption in dendroclimatological research is that the relationship between tree growth and climate remains stable over time (Fritts, 1976; Briffa *et al.*, 1992; Szeicz and MacDonald, 1995b). This assumption is based on the Principle of Uniformitarianism, namely that the biological processes controlling tree growth today must have been the same processes taking place in the past (Fritts, 1976). However, if the climate-tree growth relationship changes, these assumptions may no longer be valid.

Several temperature reconstructions have been developed from tree-ring studies at latitudinal and altitudinal treelines in the Canadian Rockies (Luckman, 1989; Luckman *et al.*, 1997; Luckman and Boninsegna, 2004; Luckman and Wilson, 2005), Northwest Territories (Szeicz and MacDonald, 1994; 1995a, b), Alaska (Jacoby *et al.*, 1985; Barber *et al.*, 2000; Davi *et al.*, 2003; Barber *et al.*, 2004; D'Arrigo *et al.*, 2004a) and the Yukon

Territory (Jacoby and Cook, 1981; Luckman and Youngblut, 2000; Watson *et al.*, 2000; Luckman *et al.*, 2001; Youngblut and Luckman, 2008). However, recent studies have documented a change in the climate-ring width relationship at several boreal forest treeline sites (e.g. Briffa *et al.*, 1998; D'Arrigo *et al.*, 2004b; Wilmking *et al.*, 2004; Wilmking *et al.*, 2005; Pisaric *et al.*, 2007), including the classic Twisted-Tree-Heartrot Hill (TTHH) site (Jacoby and Cook, 1981) first used to derive temperature reconstructions from boreal forest environments. If this situation is universal and correct, it has serious implications for the validity of proxy climate reconstructions from tree-ring series.

1.2 Research objectives and rationale

This thesis examines the spatial and temporal characteristics of tree growth of white spruce growing at treeline sites in the northern Yukon over the 20th century. Twisted-Tree-Heartrot Hill site (TTHH, 65.33° N; 138.33° W) is an early classic site from which the first temperature reconstruction was developed by Jacoby and Cook in 1981. Subsequently, a change in the limiting factor (temperature) that controls tree growth at this site was identified (Fritts and Lough, 1985; D'Arrigo *et al.*, 2004b) and succeeding work has identified similar effects that have been identified as the "Divergence Problem" (Wilmking *et al.*, 2004, 2005). Over the past 9 years researchers from the University of Western Ontario have developed a database of ca 150 tree-ring chronology sites across the Yukon and northern British Columbia (Luckman and Youngblut, 2000; Luckman *et al.*, 2001; Luckman, 2003). This thesis examines ring width patterns over the 20th century from some of the chronologies located near the TTHH site and explores the relationships between tree-ring width and temperatures from these sites. In addition, related studies by

Wilmking and others (Wilmking *et al.*, 2004; Driscoll *et al.*, 2005; Wilmking *et al.*, 2005; Pisaric *et al.*,2007) have suggested that some of the observed differences in signal between site chronologies may reflect different responses to the same climatic forcing from discrete sub-populations of "responder" trees within the same stand. This thesis will attempt to address both of these issues and evaluate the regional representativeness of the TTHH chronology based on comparison with sites within this new network.

Therefore the main objectives of this thesis are to:

1. develop a network of tree-ring width chronologies from sites located along the north-south Dempster highway that bracket the position of TTHH;
2. evaluate and establish the strength of the common signal within each chronology;
3. evaluate the spatial variability in the signal across this network and establish whether there are regional groupings based on high and low frequency chronology signals;
4. establish whether the TTHH chronology signal is regionally representative in this network;
5. evaluate the relationship between each chronology and climate data from the closest climate station at Dawson;
6. at sites with adequate sample depth, determine whether there are sub-populations of trees that show different responses to the same climate forcing.

The results may identify whether specific considerations need to be taken into account when developing chronologies from treeline white spruce sites for climate reconstruction work.

1.3 Thesis format

This thesis is presented in traditional format. Chapter 2 discusses the important ecological characteristics of white spruce and provides a detailed account of previous dendrochronological work conducted in northwestern North America. Chapter 3 describes the development of the white spruce chronology network and evaluates the dendrochronological characteristics of these chronologies. Spatial variations in the high and low frequency patterns of these chronologies and the representativeness of TTHH are discussed in Chapter 4. This chapter also investigates the relationship between the chronologies in this network and Dawson temperatures over the 20th century to evaluate potential changes in their response over this period. Differences in growth response for individual trees within the three most densely sampled sites are evaluated in Chapter 5 to establish whether different "responder chronologies" are present. Finally, Chapter 6 summarizes the overall findings and implications of this research and presents suggestions for future research.

CHAPTER TWO

Dendrochronological Studies of White Spruce in Northwestern North America

2.1 Introduction

Dendrochronological and dendroclimatological studies have targeted northern environments because trees growing at their ecological limits are most sensitive to variations in climate and are often slow growing, thus potentially providing long records of past environmental changes. Previous work has demonstrated that trees in these northern environments are sensitive to climatic fluctuations (Jacoby and Cook, 1981; Hansen and Lebedeff, 1987; Houghton *et al.*, 1990; D'Arrigo and Jacoby, 1992; Jacoby *et al.*, 1996; Luckman and Youngblut, 2000; Watson *et al.*, 2000; D'Arrigo *et al.*, 2004).

Instrumental climate records for these regions are generally short (<50 years); thus longer, annually resolved, proxy climate records are necessary to address long term climate variability and place current climatic trends into a broader perspective. Such records may be obtained from various natural archives (e.g. ice cores, lake sediments and tree rings), although tree rings provide the most widespread and generally available proxy data source for these areas (e.g. Luckman, 1997; Bradley, 2000; Briffa, 2000; Briffa and Matthews, 2002; Cook *et al.*, 2002).

Tree rings are considered the most readily available annually-resolved proxy data source that is ideal for climate change studies at treeline environments (Luckman, 2007). More specifically, white spruce (*Picea glauca* [Moench] Voss) has been extensively used in dendroclimatological studies in northwestern North America primarily because of its widespread distribution and longevity (e.g. Jacoby and Cook, 1981; Szeicz and MacDonald, 1995a, b; Luckman and Youngblut, 2000; Luckman *et al.*, 2001; D'Arrigo *et* *al.*, 2004; Wilmking *et al.*, 2004). This chapter is divided into three major parts: a brief discussion of elements of the basic ecology of *Picea glauca* relevant to this study; previous paleoclimatic and dendroclimatic studies at treeline in northern Canada and Alaska; and finally recent work regarding changes in climate – tree growth relationships observed in northwestern North America that form the fundamental target of this research.

2.2 The ecology of white spruce (*Picea glauca*)

The forests in the Yukon and Alaska are part of the Boreal Forest zone that stretches across North America (Larsen, 1980; Elliott-Fisk, 1988). In the Yukon white spruce (*Picea glauca*) is commonly the dominant tree species in the absence of fire and is also the most common treeline species (Larsen, 1980). Ritchie (1984) and Wahl *et al.* (1987) state that white spruce is usually intolerant of a high permafrost table and therefore is mainly found south of the limit of continuous permafrost. The typical boreal forest in this region is composed of both coniferous and deciduous trees. The dominant conifers are white spruce, black spruce (*Picea mariana* [Mill.] Britton, Sterns & Poggenb.), and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Occasionally larch (*Larix laricina* [Du Roi] K.Koch) occurs in northern areas, while pine, aspen, and birch are common fire sucessional species. The understory vegetation varies between sites but generally consists of shrub willow (*Salix spp*), birch (*Betula spp*), and alder (*Alnus spp*) plus mosses and grasses, Labrador tea (*Ledum spp*), crowberry (*Empetrum spp.*), reindeer moss (*Cladonia spp.*) and herbs such as dryas (*Dryas spp.*) (Larsen, 1980; Ritchie, 1984; Elliott-Fisk, 1988).

Forest fires are an important component in the establishment and development of white spruce dominant forests within the Yukon Territory. These fires regulate stand dynamics and can even aid in the seed germination process. Typically fires in this region do not completely remove the understory vegetation due to the moisture-rich moss layers that contain the white spruce seeds (Zasada, 1971). Since the seeds of white spruce trees are susceptible to fire damage, the trees must be effective seed dispersers to overcome the effects of local fire (Ritchie, 1984; Elliott-Fisk, 1988). The establishment of spruce dominant sites in northern environments is believed to be controlled partially by the absence of permafrost and the frequency of fire occurrences (Rowe, 1961; Nichols, 1976; Ritchie, 1984; Elliott-Fisk, 1988). Immediately following a fire, hardwood species such as aspen (*Populus spp.*) or birch (*Betula spp.*) plus pines (usually *Pinus contorta*) are the primary colonisers creating an environment suitable for the growth of white spruce seedlings. Subsequently, the stand becomes dominated by white spruce creating a shaded environment ideal for further white spruce colonization but unfavourable for shade-intolerant species such as pine and aspen (Oechel and Lawrence, 1985).

The amount of solar energy received at the surface at treeline in this region varies intra-annually due to the summer (high radiation) and winter (low radiation) seasons. The low levels of winter radiation are a function of both latitudinal effects (reduced day length and intensity of radiation) plus the high albedo of the winter snow cover (Oechel and Lawrence, 1985). The long wintering effect (wind damage, cold temperatures, aridity, etc.) can delay the start of photosynthetic activity in spruce until late June. Additionally, with the onset of the growing season, rapid growth of cells within the spruce trees occurs when the temperatures are warmed slowly; and all this growth could continue for a few months as long as the weather is appropriate (Oechel and Lawrence, 1985). However, wood produced during the later part of the growing season has been suggested to be mainly focused on cell enlargement and/or cell wall thickening (Jacoby and Cook, 1981).

Researchers have concluded that greater radial growth of spruce is correlated with current summer temperatures and previous autumn temperatures (Zasada and Gregory, 1969; Garfinkel and Brubaker, 1980). Specifically, summer temperatures, particularly above the July 10° C isotherm, are believed to be one of the primary controls on the growth of white spruce in the Yukon (Daubenmire, 1954). Therefore, it is anticipated that ring-width series from these regions are temperature-limited with narrow rings reflecting years with cooler summers and warmer summers resulting in wider rings.

The adaptation to and growth of white spruce in these treeline environments is partially due to its ability to initiate photosynthesis production immediately after snowmelt (Bliss, 1985). However, delays in snowmelt or periods of harsher climate reduce tree growth at northern treeline environments (Zasada and Gregory, 1969). Also, the temperature of the forest floor environment is important in dendrochronological studies because the temperature of the litter layer can be a critical determinant for tree growth. Goldstein *et al.* (1985) suggest that cooler soil temperatures around the roots of white spruce trees result in a resistance to water flow that can potentially limit tree growth in treeline environments. Jacoby and D'Arrigo (1995) emphasise that forest physiological parameters, e.g. moisture content and temperature of the active layer, can influence the sensitivity of the tree to climate. Therefore, it is anticipated that temperatures in the Yukon play a critical role in the growth of white spruce trees.

Overall the establishment and development of white spruce stands in the Yukon is very complex and sensitive to several climate parameters. In addition to climatic thresholds, the distribution of white spruce is partially controlled by fire frequency, succession and by the presence/absence of permafrost (Rowe, 1961; Nichols, 1976; Ritchie, 1984; Elliott-Fisk, 1988). Locally, treeline position along the Dempster Highway may be influenced by site factors (geology, soils, drainage, microclimates, etc.), but the general regional picture reflects broader, more common climatic patterns. Therefore, dendrochronologists target treeline environments to study past climate variability.

2.3 Tree ring studies in northwestern North America

Treeline white spruce sites in this region have been the target of many dendrochronological studies because of the longevity of this species and its ability to tolerate the harsh environmental conditions (e.g. Jacoby and Cook, 1981; Szeicz and MacDonald, 1994, 1995a, b; Barber *et al.*, 2000; Luckman and Youngblut, 2000; Watson *et al.*, 2000). These characteristics have led to the use of ring widths from white spruce as a primary proxy data source in climate change studies in northwestern North America. The classic dendroclimatic investigation from the Yukon was Jacoby and Cook (1981) who developed a 400 year-long white spruce ring-width chronology from the Twisted Tree – Heartrot Hill (TTHH, 65.33° N; 138.33° W) site at treeline north east of Dawson. The original chronology of 13 trees was shown to have a strong relationship with summer temperatures (degree days above 10° C), that was later used to reconstruct June/July degree day records for Dawson from 1550-1974 (Jacoby *et al.*, 1985). TTHH was the first temperature reconstruction from treeline in northwestern North America and also one of the first to utilize white spruce trees from the Boreal Forest. At about the same time, Garfinkel and Brubaker (1980) had also identified white spruce as a potential proxy climate indicator in Alaska. Their study used ring-width chronologies from 14 white spruce sites to reconstruct summer temperatures for Fairbanks, Alaska from 1829 to 1930.

The length of the reconstruction was limited by the young age of trees at the sample site in the Brooks Range. Fritts and Lough (1985), examining stand wide signals in a chronology network across North America, noted a deterioration in the relationship between their reconstructed average temperatures and northern hemisphere temperatures just before the 1950s.

The results from TTHH and Alaska led to a program of more extensive sampling by Jacoby *et al.* in Alaska and the NWT (Jacoby *et al.*, 1985; Jacoby and D'Arrigo, 1989; D'Arrigo *et al.*, 1992). The sites used in the previously studies were used to progressively develop a larger network of boreal tree-ring sites across northern treeline in Canada that resulted in some of the first reconstructions of Northern Hemisphere summer temperatures (Jacoby *et al.*, 1985; Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992; D'Arrigo *et al.*, 1992). These studies clearly demonstrated the potential for detailed proxy climate record development from white spruce in these northern environments. Based on their regional reconstructions, Jacoby and D'Arrigo (1995) suggested that growth of white spruce from treeline sites in Alaska was controlled primarily by temperature and moisture. Subsequent studies, updating the chronologies from some of these sites, have shown a loss of the temperature signal after the 1970s as the trees are considered to have become more moisture sensitive (Jacoby and D'Arrigo, 1995). This possible loss of temperature sensitivity or "divergence" has become a major topic for discussion over the last 10-15 years and are discussed more fully below.

Szeicz and MacDonald (1995) working in the Yukon and Northwest Territories (NWT) used valley floor and treeline white spruce stands to reconstruct summer temperatures back to A.D. 1638. Their analyses suggested that older (>100 years) treeline trees from their two Yukon sites (Richardson Mountain 66°43'N, 136°17'W;

Tombstone Mountain 64°31'N, 138°19'W) showed a different response to climate forcing than trees <100 years old. They also found differences between chronologies created by standard techniques (typically using trees of multiple ages but often >200 years old, e.g. Fritts 1976) and age dependent models for the sites in the Yukon. All of the chronologies created (based on both standard techniques and age dependent models) yielded results that were similar to others from North America (Jacoby *et al.*, 1985; D'Arrigo and Jacoby, 1992), but differences became apparent during the reconstruction stages. Basically the difference was that chronologies based on age dependant models had higher verification statistics for the reconstructions. Therefore, Szeicz and MacDonald (1995) built chronologies (excluding the Richardson Mountain site) that utilised only that portion of the tree-ring record from trees < 100 years old compared to more conventional chronology development techniques that mix trees of different ages.

In 1984 Schweingruber (1988) sampled a network of sites in western North America for tree-ring densitometry that included several sites in the Yukon. Later, in 1992, Schweingruber and Jacoby sampled a network of sites from west to east along the boreal treeline in Canada that ultimately became part of a circumpolar network of sites that has been used in many reconstructions of northern hemisphere temperatures (e.g. Briffa *et al.*, 1992; Schweingruber, 1992; Briffa *et al.*, 1994; etc.). Briffa *et al.* (1998) noted a weakening in the temperature sensitivity of maximum ring width density series from trees at elevational treeline in the northern hemisphere. Using the hemispheric-scale network of ring width and maximum density chronologies from across northern North America, Briffa *et al.* (1998) demonstrated a similar divergence in the N.W.T., Central Yukon and Alaska. These were the first studies to establish divergence on a hemispheric scale.

In 1999 Luckman and Youngblut carried out the first UWO sampling in the southwest Yukon (Watson *et al.*, 2000; Luckman *et al.*, 2001, 2002) that was subsequently expanded with sampling in 2000 and 2002-5 to develop the UWO database (Luckman 2006). Seven of these treeline spruce chronologies have been used to produce a June-July temperature reconstruction for Whitehorse from 1684-2000 (Luckman *et al.*, 2001, 2002; Youngblut and Luckman, 2008). These studies also developed a millennial-length spruce chronology from a site at the south end of Kluane Lake that has been used to date a number of glacier and lake level fluctuations (Luckman *et al.*, 2002, Van Dorp, 2004; Clague *et* al., 2006; Reyes *et* al., 2006). A network of 26 treeline *Abies lasiocarpa* (subalpine fir) sites has also been developed in this region (Kenigsberg, 2005). These chronologies are generally shorter than the white spruce chronologies but contain a similar climate signal that can be used with white spruce to analyze past climates. Some of the more southerly fir sites are also sensitive to snow/winter conditions (Kenigsberg, 2005). Payne (2006) developed chronologies from six *Picea sitchensis* (sitka spruce) sites in NW BC that also contained a similar climate signal to white spruce. The data used in the present study are from white spruce sites from the northern part of the extensive UWO network.

2.4 The divergence issue

Successful climate reconstructions are based on the validity of two basic principles of dendrochronology originally enunciated by Fritts (1976): the "Principle of Limiting Factors" states that, although many factors may be limiting to tree growth, biological growth can only proceed as fast as the most limiting environmental factor will permit. Should this factor no longer be limiting, some other factor will assume this role

(Fritts, 1976). The "Principle of Ecological Amplitude" states that trees growing outside their ideal range are most sensitive to environmental stresses. Therefore trees growing at their range limits are often targeted in dendroclimatic studies as tree growth in these areas are believed to be controlled by a single limiting factor. The influence of a single limiting environmental factor on growth is critical in developing synchronous variation in ring width patterns across a stand, thereby allowing crossdating of tree-ring series. Altitudinal and latitudinal treelines are clearly defined range limits, the position of which is primarily controlled by summer temperatures (Fritts, 1976). Therefore, it was assumed that, in the Central Yukon, summer temperatures have been (and continue to be) the primary limiting factor in the growth of white spruce at treeline. Consequently, treeline sites were targeted to develop tree-ring chronologies that were primarily sensitive to summer temperatures. However, in order to reconstruct past climates successfully from tree rings, uniformitarian principles must apply and the same limiting factor must operate over the period of record being investigated.

Recent work in the Yukon suggests that the limiting factor of tree growth in this region may be changing. Resampling of the TTHH site by Jacoby and others to update the ring-width chronology (Jacoby *et al.*, 1985; Jacoby and D'Arrigo, 1995; D'Arrigo *et al.*, 2004) indicated that the ring-width series were no longer temperature sensitive as they showed a growth decline during a period with increasing temperatures. D'Arrigo *et al.* (2004) demonstrated that if the temperature-ring width relationship derived from the 1900-1964 period was used to predict the tree ring widths for the 1900-2000 period (essentially inverting the relationship used in climate reconstructions), there would be a major divergence between the actual and predicted ring widths in the later part of the record (Figure 2.1: D'Arrigo *et al.*, 2004.). This divergence was attributed to a change in the limiting factor at the site. Whereas Jacoby and Cook (1981) had demonstrated a positive relationship between summer temperatures and ring widths over the period 1900-1975, the new results indicated an inverse relationship over the last ca. 40 years (Figure 2.1). D'Arrigo *et al.* (2004) considered that these elevational treeline white spruce sites were becoming moisture sensitive as had previously been observed for some sites in Alaska (Jacoby and D'Arrigo, 1995). Subsequently, they developed a theoretical model to show how the divergence at TTHH could be identified elsewhere across the region (D'Arrigo *et al.*, 2004).

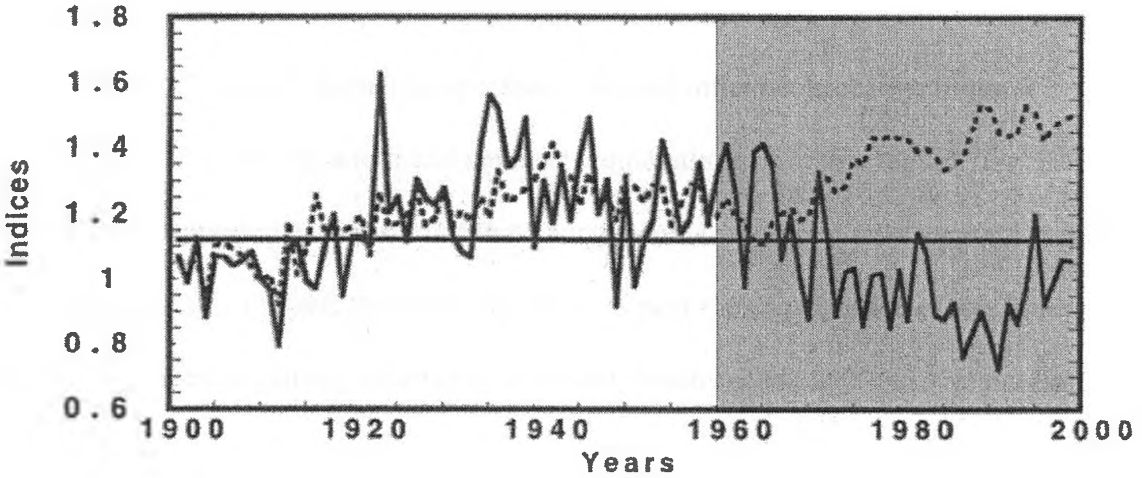

Figure 2.1 Divergence at the TTHH site (after D'Arrigo *et* al., 2004). The solid line is actual ring-width indices at TTHH from 1901-2000. The dotted line is ring width indices predicted from the relationship between ring – width and Dawson temperatures for 1900-1964 interval. The horizontal line is the mean ring width index over the 1901-1999 interval. The period of 'divergence' is shaded.

Studies at treeline sites in neighbouring Alaska have also shown that recent warming has caused a divergence in the climate-tree growth relationship that can be seen as a population-wide signal that is present at treeline sites (Fritts and Lough, 1985; Jacoby *et al.*, 1985; Briffa *et al.*, 1998; D'Arrigo *et al.*, 2004). These studies explored a greater range of treeline sites to identify whether the change witnessed at TTHH was local or widespread (D'Arrigo and Jacoby, 1993; Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998a; Lloyd and Fastie, 2002; Davi *et al.*, 2003). Barber *et al*, (2000) noted that closed canopy white spruce forests from Alaska also demonstrated a divergence between raw ring-width records and a combined temperature and precipitation index. Lloyd and Fastie (2002) investigated the response of white spruce growth to variations in locations and topography from sites at or just below treeline in the Seward Peninsula and Brooks Ranges, Alaska. They showed that drier sites in the Brooks Range exhibited divergence but wetter sites did not. Therefore, they suggested the drier sites were subject to a drought stress that, in addition to higher temperatures, helped influence a change in the relationship between ring width and summer temperatures from this region. Furthermore, their results supported earlier studies that showed cooler-marginal sites responded more positively to rising temperatures but warmer sites near the center of the of the Boreal Forest responded negatively (Barber *et al.*, 2000; Jacoby *et al.*, 2000; Lloyd and Fastie, 2002).

In the Wrangell Mountains in Alaska, immediately west of the Yukon, Davi *et al.* (2003) noted a deteriorating temperature signal after ca. 1970 in their treeline white spruce ring-width chronologies that coincided with a rise in temperatures in the region. They also suggested that drought stress had caused the change in sensitivity of these trees, and therefore they did not produce a temperature reconstruction from these ring-width data. However, they reported that maximum density tree-ring series from the same region maintained a strong, consistent temperature signal and created a successful temperature reconstruction from these data.

Several other studies from different species and environments have addressed the "divergence" issue, proposing a wide variety of mechanisms to explain the changing signal in ring-width series. These include: increased amounts of greenhouse gases (Briffa *et al.*, 1998), changes in winter precipitation and patterns which would affect the timing of the growing season (Jacoby and D'Arrigo, 1995; Vaganov *et al.*, 1999), an increase in insect populations during the growing season (Jacoby and D'Arrigo, 1995), and acid rain or increases in UVA, UVB and UVC radiation (Briffa *et al.*, 1998). Although each of these factors can influence tree or stand growth, it is probable that the divergence phenomenon does not have a single cause.

Wilmking *et al.* (2004) and Pisaric *et* al. (2007) have taken different approaches to this problem in a series of studies in Alaska and the Northwest Territories, Canada. Using treeline sites with a large sample depth, they identified sub-populations of "responder" trees that showed similar growth trends that were consistently positive, consistently negative or showed non-significant trends during recent 20th century warming. They suggest that the presence and proportions of these sub-populations may compromise the strength of the common stand-wide signal from these treeline sites, thereby accounting for some of these divergence effects (Wilmking *et al.*, 2004; Driscoll *et al.*, 2005; Wilmking *et al.*, 2005).

Driscoll *et al.* (2005) demonstrated that sub-populations of trees showed a consistent relationship with growth patterns prior to 1950 but that the relationship between each sub-population and climate weakened after ca. 1950. Although all the sites contained populations that were positively responding to April-July temperatures, two sites contained sub-populations that were negatively responding to post 1950 warming. Driscoll *et al.* (2005) suggested that these negative-responding sites were partially the result of a late growing season temperature-induced drought stress. Therefore, because two of the sites contained sub-populations with differing signals, it was possible that 'microsite' differences could be influencing tree growth for selected trees within the same stand (Driscoll *et al.*, 2005; D'Arrigo *et al.*, 2007). Driscoll *et al.* (2005) concluded that more detailed assessment of the climate-tree ring relationships are warranted in dendroclimatic studies of northern sites as various stresses (i.e. drought, anthropogenic, etc.) and microsite differences could be causing divergent growth responses between and within sites.

Subsequently, Wilmking *et al.* (2006) have demonstrated that positive and negative responding trees from sites in the Alaska and Brooks Ranges were responding to temperatures in different seasons. Positive responders to recent warming had their highest correlation with spring temperatures in prior years (March ($t - 1$) and April ($t - 2$) in the Alaska Range; April ($t - 1$, $t - 2$) in the Brooks Range), whereas negative responders were correlated with the previous years' July ($t - 1$) mean monthly temperature in both ranges. They also strongly recommended further research to understand the limiting factors upon growth with such forests (Wilmking *et al.*, 2004; Driscoll *et al.*, 2005; Wilmking *et al.*, 2005; Wilmking *et al.*, 2006). Other studies, e.g. Youngblut and Luckman (2008) working in southwestern Yukon, did not report "divergence" effects. In fact, they noted a stronger temperature-tree growth relationship in recent years (using monthly mean and max June and July temperatures), and suggested that possibly the southwest Yukon has not yet experienced the degree of summer season warming as other parts of the Yukon.

Based on these studies it appears that Boreal Forest trees located at elevational and latitudinal treeline from northwestern North America may have complex responses to recent temperature changes. In some (ideal) cases it appears that the entire stand may respond in a coherent manner to climate variations throughout its history resulting in a strong common signal over time (e.g. Jacoby and Cook, 1981; Szeicz and MacDonald, 1995). Alternatively, if the growth-limiting factor has exceeded a threshold, tree growth within an entire stand may now respond differently to an alternative stress (Briffa *et al.*, 1998; Barber *et al.*, 2000; Davi *et al.*, 2003; D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2006). Finally, different sub-populations of trees within the same stand may be responding differently to the same variations in climate during the last 40 years based on some local, probably site related, conditions (Barber *et al.*, 2004; Wilmking *et al.*, 2004; Driscoll *et al.*, 2005; Wilmking *et al.*, 2005; Wilmking *et al.*, 2006). This potential variability in response is a very significant issue for dendroclimatic research because it suggests that the climate-ring width relationship is not time-stable and challenges the uniformitarian principle that underlies all dendroclimatic reconstructions[1]. Therefore, a primary goal of this research was to explore these issues of differences in inter- and intra-chronology responses from a series of stands in the northern Yukon close to the classic TTHH site from which these phenomena were first described.

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[1] For a more detailed review of the divergence issue and the studies associated with this topic see D'Arrigo *et al.*, 2008.

CHAPTER THREE

The White Spruce Chronology Network

3.1 Introduction

This chapter describes the development and characteristics of a new set of white spruce chronologies sampled along the Dempster Highway between 64°N and 67°N that bracket the position of the TTHH site (65.33° N; 138.33° W, Jacoby and Cook, 1981). It will evaluate the dendrochronological and dendroclimatological quality of these chronologies and examine common regional or sub-regional patterns of ring-width variation between chronologies over the last 100 years. Later chapters will evaluate whether there have been significant changes in the relationships between climate parameters and ring width during the 20th century similar to those seen in some chronologies from adjacent areas (Barber *et al.*, 2000; D'Arrigo *et al.*, 2004; Driscoll *et al.*, 2005; Wilmking *et al.*, 2004, 2005; Pisaric *et al.*, 2007).

3.2 Site selection

Stands of white spruce were selected from sites close to the Dempster Highway that bracket the location of the classic TTHH site (65.33° N; 138.33° W) sampled by Jacoby and Cook in the 1970s. Treeline elevation varies from ca. 1000m in the south to 600m in the north (Figure 3.1) and the highway runs at or close to treeline throughout the sampled length of ca. 250 km. Typically, well established, mature white spruce dominated stands were targeted for sampling. More specifically, these stands were located at or close to elevational treeline and were generally healthy-looking, open-grown trees (i.e. free from signs of external disturbances and competition) (Figure 3.2). Older-looking trees were preferentially targeted. At some sites where field counting indicated that the stand being sampled consisted primarily of relatively young (ca. 100-150 years old) trees, sampling was curtailed and fewer trees were sampled. Between 10 and 84 trees were sampled at each site. This normally provided an adequate number of both young and mature trees for adequate signal strength in the chronology over the last century.

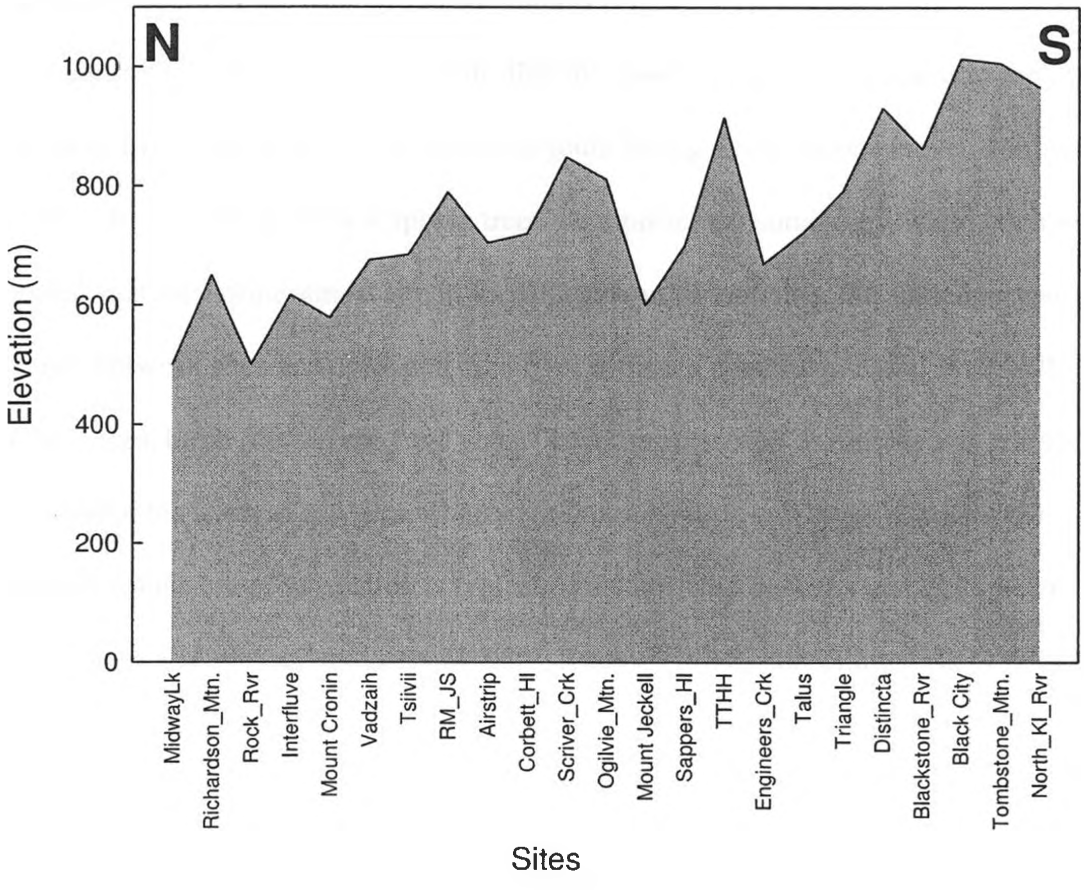

Figure 3.1 Site elevations for all 23 sites.

3.2.1 Site descriptions

Between the North Klondike River and the NWT border the Dempster Highway runs at, above, or just below treeline, crossing areas of northern Boreal Forest and Subarctic/Arctic Tundra (Bliss, 1988; Elliott-Fisk, 1988; Jacoby and Cook, 1981; Larsen, 1980). At the southern boundary of the study area treeline is at approximately 1000 metres and generally decreases in elevation northwards to about 600 metres along the western margin of the Richardson Mountains (Figure 3.1). However, there are local differences in treeline elevation controlled by aspect, drainage, and bedrock geology with an increasing contrast between north and south facing slopes as one moves northwards.

Both white and black spruce trees were present at some sites, while larch was also sampled at the northernmost site in the Richardson Mountains. The understory vegetation varies between sites and consisted mainly of different combinations of shrub willow (*Salix spp*), birch (*Betula spp*) and alder (*Alnus spp*); as well as mosses and grasses (Labrador tea (*Ledum spp.*), crowberry (*Empetrum spp.*), and dryas (*Dryas spp.*). The overall composite of vegetation is typical of the northern hemisphere circumpolar Boreal Forest belt as described by Larsen (1980), Ritchie (1984), and Elliott-Fisk (1988).

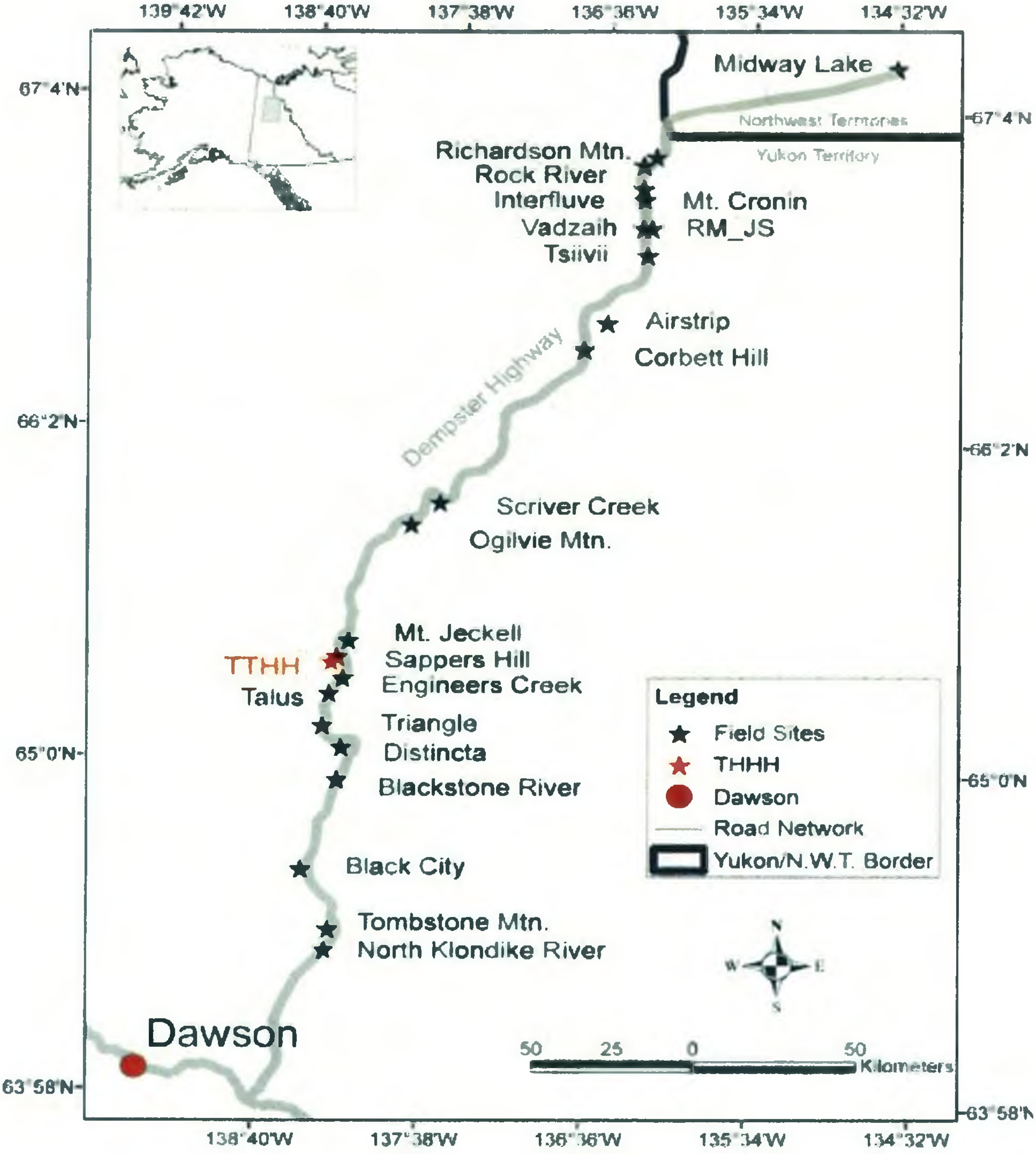

Figure 3.2 Map of the study area showing the location of sample sites with respect to Dawson and the Dempster Highway.

Twenty of the sites in the new network were sampled by UWO field parties in 2002 (southern sites) and 2004 (northern sites, Table 3.1). Several of the southern sites were resampled in 2004 to increase sample depth at these sites and/or for possible future densitometric studies. Data from an updated version of the TTHH chronology (sampled in 2001, D'Arrigo personal communication) and two sites sampled by Julian Szeicz in 1995 (Szeicz and MacDonald (1995b: available from International Tree Ring Data Bank ITRDB) are included in the analysis. In addition, data were used from trees sampled by Dr. B.H. Luckman on a reconnaissance visit to Midway Lake NWT in 1989. All sites except Midway Lake and TTHH were visited by the author during sampling in 2004. Site descriptions are based on personal observations, field notes or discussions with members of the appropriate field parties.

Table 3.1 Sample site characteristics.

Site Name	Code	Year Sampled	Collectors	Latitude (°N)	Longitude (°W)	Elevation (m)	Slope (°)	Aspect
Midway Lake	M89/N89	1989	UWO89	67.2	134.57	500	variable	variable
Richardson Mtns	Y4R	2004	UW004	66.94	136.26	650	5 - 10	SW
Rock River	Y4Z	2004	UWO04	66.91	136.35	476-523	variable	S
Interfluve	Y4Y	2004	UWO04	66.84	136.35	616	5 - 10	W
Mount Cronin	Y4C	2004	UWO04	66.81	136.34	567-590	variable	SW
Vadzaih	Y4V	2004	UWO04	66.72	136.34	661-690	25 - 30	S
Tsiivii	Y4W	2004	UWO04	66.63	136.31	685	5 - 10	W
RM_JS	RM	1994	JS	66.62	136.28	780-800	Variable	S
Airstrip	Y4A	2004	UWO04	66.42	136.58	705	10 - 15	variable
Corbett Hill	Y4G	2004	UWO04	66.33	136.73	720	variable	S
Scriver Creek	Y4H	2004	UWO04	65.84	137.67	848	15 - 20	S
Ogilvie	Y4O	2004	UWO04	65.77	137.85	811	0 - 5	S
Mount Jeckell	Y4M	2004	UWO04	65.40	138.23	600	25 - 30	SE
Sappers Hill	YU2	2002	UWO02	65.35	138.30	700	20 - 30	E
TTHH	N/A	2001	LDEO	65.33	138.33	N/A	N/A	NE.
Engineers Creek	YA2	2002	UWO02	65.28	138.25	660-680	20 - 40	E
Talus	YAA	2002	UWO02	65.23	138.33	722	variable	variable
Triangle	YBB	2002	UWO02	65.13	138.37	792	variable	S
Distincta	YD4/YDD/Y4W	2002/04	UW002/04	65.07	138.23	880-980	variable	variable
Blackstone River	YCC	2002	UWO02	64.97	138.25	862	25 - 30	E
Black City	YEE	2002	UWO02	64.68	138.45	1013	variable	Variable
Tombstone Mtns	YT2/TM	1993/02	JS/UWO02	64.50	138.25	1006	variable	Variable
North Klondike River	YKK/YK4	2002/04	2002/2004	64.44	138.26	965	Variable	E

Notes: Site names: TTHH = Twisted Tree-Heartrot Hill (Jacoby and Cook, 1981), RM_JS = Richardson Mountain (Szeicz and MacDonald, 1994b). Site collectors: UWO89 = B.H. and D.C. Luckman, UWO02 = B.H. Luckman, D.K. Youngblut, R.Van Dorp, M. Masiokas, C. Aruani, UWO04 = B.H. Luckman, R. Van Dorp, S.P. Earles, D. Morimoto, M. Kenigsberg, M. Belej. JS = Julian Sziecz *et al.* 1995, and LDEO = Lamont-Doherty Earth Observatory (various dates). All sites except Midway Lake are in the Yukon.

The two southernmost sites, **North Klondike River** and **Tombstone Mountain**, are in the North Klondike River valley on gently sloping lower valley sides or the valley floor where isolated, older spruce were present in a setting of younger trees. The **Tombstone Mountain** chronology is a composite based on tree-ring samples collected by Szeicz in 1993 (archived in the ITRDB) and UWO in 2002 and will be discussed in more detail below.

Between **Tombstone** and the **Blackstone River,** the highway crosses a broad open area of tundra known as the Blackstone Uplands. The **Black City** site is an isolated tree island in the center of this upland with a small number of large spruce trees growing out of the willow scrub. Although the site has been used by First Nations for many years, the chronology from this site showed little obvious evidence of anthropogenic disturbance and is the only one within this 30 km section of the transect.

The next group of sites **Blackstone River**, **Distincta, Triangle, Talus, Engineers Creek, Sappers Hill** and **Mount Jeckell** represent the lower slopes of the steep mountain ridges and valleys of the Ogilvie Mountains. We were unable, despite discussion with LDEO personnel, to identify the precise location of the original TTHH site (Jacoby and Cook, 1981) but our best estimate is that it lies between the Engineers Creek and Sappers Hill sites. Several of the study sites in this part of the transect (Blackstone River, Talus, and Engineers Creek) are on talus slopes from steep east-facing ridges flanking Engineers Creek.

North of Ogilvie River, the Dempster Highway climbs out of the Ogilvie valley and traverses a rolling upland area that is generally forested but with summit areas that occasionally reach or rise a short distance above treeline. The sample sites at **Ogilvie**

Mountain, Scriver Creek, Corbett Hill, and **Airstrip** are at these open summit locations, although the latter two are 70-80 km north of the southern pair.

The final series of sites are located along the flanks of the Richardson Mountains (**RM_JS, Tsiivii Creek, Vadzaih Kan Creek, Mount Cronin, Interfluve, Rock River, Richardson Mountain**). These are essentially low, fairly gentle-sloping interfluve sites lying between the shallow valleys of streams flowing westwards from the Richardson Mountains. The southern most sites are at similar elevations to the Corbett Hill and Airstrip sites. The **Rock River** site has four sub-sites which include larger trees growing in a more sheltered location within the White Fox Creek valley[2] that differ considerably from the more stunted trees on exposed sites on the adjacent upland. The chronologies from these sub-sites were combined as a single chronology. The data for the **RM_JS** chronology (Szeicz and MacDonald 1995c) is probably from this site as it contains the densest and most mature spruce forest north of Eagle Plains and is adjacent to the northernmost campsite along the Dempster Highway. The Richardson Mountain site is the last stand of trees along the highway and also contains a number of small larch from which a short chronology was developed. The **Midway Lake** site was sampled by Luckman in 1989 and is from the first stand of trees located where the Dempster Highway descends into the NWT. Sample depth at both the Richardson and Midway sites was limited due to the young age of most trees.

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[2] The site is close to the Rock River Campground but the creek is named White Fox Creek on the 1:250,000 maps.

3.3 Chronology development

3.3.1 Sampling, measuring, and chronology building

At each site two 5 mm cores were taken from between 10 and 84 healthy white spruce trees (free from external damage such as fire, insect, etc.). In many cases, given the small diameter of the trees, these were complete diameter cores; otherwise the cores were taken at orthogonal angles. Cores were prepared following standard dendrochronological procedures (Stokes and Smiley, 1968; Fritts, 1976, Cook and Kairiukstis, 1990) and measured to the nearest 0.001 mm using a Velmex Unslide traversing table and an AcuRite III digital counter. All of the measured ring-width series were visually crossdated and the dating was verified using the program COFECHA from the Dendrochronology Program Library (DPL) (Grissino-Mayer, n.d.) (Grissino-Mayer). Once crossdating was completed, tree-ring series were standardized using the computer program ARSTAN (version ARSO40_win, 2005) to compute ring-width indices and create the chronologies. This program allows interactive detrending as the user can view the raw measurements and trial curve fits for each series on the screen to ensure appropriate growth curves are applied to each series.

Each series was fitted with either a negative exponential, a Hugershoff curve, or straight line of zero or negative slope to remove the natural age-related (or biological) growth trend and indices were calculated by division[3]. This conservative standardization technique helps maintain most of the low frequency signal in these series and is used in most dendroclimatic studies (Cook, 1985). When all of the ring-width series were detrended, the indices from each series were averaged to form a chronology for each site

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[3] See Appendix One for a description on the components involved in a Tree-Ring series.

(Cook, 1985). The standard and residual chronologies (Cook *et al.*, 1990) were retained for subsequent analyses.

3.3.2 Measures of chronology quality

The evaluation of the quality of tree ring chronologies is based on a number of standard dendrochronological and statistical measures that describe ring width variability and the strength of the common signal within the chronology. The most important of these are average mean sensitivity (MS), series intercorrelation (r), first order autocorrelation (1AC), and expressed population signal (EPS). Average mean sensitivity is a measure of the year-to-year variability in a ring-width series. Mean sensitivity is calculated as,

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

(Fritts, 1976)

where x is the measured annual ring width in year t and n is the number of observations. This statistical measure is particularly sensitive to missing rings: individual values of 2 indicate one ring of the pair is missing/absent whereas values of 0 indicate identical ring-widths for adjacent rings (Fritts, 1976). First order autocorrelation (1AC) calculates the relationship between ring width in the growth year (t) and subsequent year ($t+1$) for the entire ring-width series. Higher values (closer to 1) indicate a strong persistence in growth patterns from year to year (Fritts, 1976). These two parameters (MS and 1AC) measure similar but different characteristics of the ring series that are related to year-to-year variability and tend to vary inversely.

Series intercorrelation (r) is a statistic that measures the degree of common signal between tree-ring series within a chronology. Typically, lower values indicate strong local (tree-to-tree) variability in the ring-width records within the stand, possibly related to disturbance, and/or microsite conditions. High intercorrelation indicates a strong stand`1wide control of growth that is usually external and mainly climate-related (Fritts, 1976). Higher intercorrelation aids crossdating as it indicates a similar limiting factor is influencing ring growth throughout the stand.

An important question in the evaluation of a chronology is the extent to which it retains a strong common signal with reducing sample depth in the earliest part of a chronology. This depends primarily on sample depth and the strength of the common signal (intercorrelation) between the tree-ring series (Briffa and Jones, 1990). The Expressed Population Signal (EPS) statistic is a measure of the strength of the common signal in the chronology and how well it might compare with an ideal chronology. The EPS is calculated as,

$$\text{Expressed Population Signal (EPS)} = \frac{\mathrm{n\,R}_{bn}}{\mathrm{n\,R}_{bn} + (1 - R_{bn})}$$

(Briffa, 1995)

where *n* is the number of tree cores (within the same series) and R_{bn} is the mean between tree (inter-tree) correlation coefficient. EPS values can range from 0-1; values closer to 0 indicate weak or no common growth signal within the chronology, and values approaching 1 indicating an ideal 'perfect' growth pattern that would be expected with an unlimited number of samples (Briffa, 1995; Wigley *et al.*, 1984).

In this study "shifting" EPS values were calculated for the entire length of the chronology using a 30-year moving window shifted using a one year lag to calculate EPS values for most of the chronology. The use of a one-year lag allows for the calculation of EPS values for each year and is short enough to identify where the sample depth or correlation is insufficient to ensure a high quality signal. Wigley *et al.*, (1984) suggest that a cut-off value of 0.85 should be used as a minimum threshold for acceptable chronology quality in dendrochronological studies. The chronologies in this study were truncated when the EPS value fell below 0.80 or were between 0.80 and 0.85 for more than 8 contiguous years. In the event that a chronology did not maintain an acceptable EPS value for the entire 20th century, interpretation of results including those chronologies were viewed cautiously.

3.4 Results

3.4.1 Chronology assessment

The raw chronology characteristics of the 23 sites in this study are presented in Table 3.2. The mean absolute raw chronology length was 350 years ranging from 149 years (Richardson Mtn.) to 542 years (TTHH). Sixteen of the chronologies have records that extend before 1700, and 6 (Tsiivii, RM_JS, Talus, Distincta, Black City and North Klondike River) predate 1600. The longest chronology, TTHH, begins in 1459. The three shortest chronologies are Richardson Mtn. (1855), Corbett Hill (1829), and Interfluve (1800).

The average tree and core sample depth for each site was 36 trees (65 cores) ranging from 10 trees at Midway Lake to 84 trees at Tombstone Mtn. (Table 3.2), and between 18 cores (Triangle) and 155 cores (Distincta). The mean length of the series was

184.6 years. However, the age distribution of the trees at many sites was quite skewed. Fifteen chronologies had over 90% of their cores >100 years old but only three had 90% >200 years. Five chronologies have > 50 trees but the percentage of old cores (>300 years) varies from 3.1% (Rock River) to 52% (Tombstone Mtn.). Overall, only 16.7% of the 1487 cores were >300 years and 14.5% were <100 years (Figure 3.3).

Table 3.2 Raw chronology characteristics.

Sample Site Name	Chronol Length	Total Years	# Trees	# Cores	Total Rings	Core Length								% >100 yrs	% >200 yrs	Mean M.L. cores	M.S. Cores	Mean RW
						< 50	50-99	100-149	150-199	200-299	300-399	400-499	>500					
Midway Lake	1660-1988	329	10	22	2629	0	10	3	4	3	2	0	0	54.5	22.7	119.5	0.233	0.580
Richardson Mtn.	1855-2003	149	25	32	3038	0	19	13	0	0	0	0	0	40.6	0.0	94.9	0.232	0.440
Rock River	1644-2003	360	68	131	19843	0	49	23	23	32	4	0	0	62.6	27.5	151.5	0.194	0.700
Interfluve	1800-2003	204	23	42	4638	1	16	16	7	2	0	0	0	59.5	4.8	110.4	0.218	0.330
Mount Cronin	1702-2003	302	24	46	8450	0	2	12	13	17	2	0	0	95.7	41.3	183.7	0.202	0.630
Vadzaih	1632-2003	372	31	61	11014	0	3	12	26	16	4	0	0	95.1	32.8	180.6	0.232	0.450
Tsiivii	1527-2003	477	37	86	17743	0	4	17	17	26	16	6	0	95.3	55.8	206.3	0.220	0.390
RM_JS	1547-1992	446	75	117	20693	6	26	26	11	30	16	2	0	72.6	41.0	176.9	0.244	0.387
Airstrip	1714-2003	290	30	60	10228	1	1	20	15	23	0	0	0	96.7	38.3	170.5	0.204	0.310
Corbett Hill	1829-2003	175	24	43	3974	0	28	10	5	0	0	0	0	34.9	0.0	92.4	0.226	0.610
Scriver Creek	1722-2003	282	66	111	16062	0	14	39	45	13	0	0	0	87.4	11.7	144.7	0.214	0.680
Ogilvie Mtn.	1696-2003	308	34	64	12801	0	0	12	11	40	1	0	0	100	64.1	200	0.199	0.380
Mount Jeckell	1664-2003	340	31	60	11149	0	0	25	7	24	4	0	0	100	46.7	185.8	0.216	0.370
Sappers Hill	1773-2001	229	36	66	10435	0	2	17	41	6	0	0	0	97.0	9.1	158.1	0.183	0.400
TTHH	1459-2000	542	64	69	18471	0	1	9	4	23	23	8	1	98.6	79.7	267.7	0.182	0.350
Engineers Creek	1616-2001	386	19	26	6354	0	0	4	2	5	15	0	0	100	76.9	244.4	0.177	0.260
Talus	1590-2001	412	16	24	6125	0	0	0	1	18	4	1	0	100	95.8	255.2	0.202	0.230
Triangle	1741-2001	261	12	18	2608	0	0	10	6	2	0	0	0	100	11.1	144.9	0.199	0.400
Distincta	1539-2003	465	73	155	40059	0	0	5	11	81	56	2	0	100	89.7	258.4	0.196	0.350
Blackstone River	1671-2001	331	29	52	11335	0	0	4	0	41	7	0	0	100	92.3	218.0	0.178	0.310
Black City	1560-2001	442	12	20	5493	0	0	1	0	11	6	2	0	100	95.0	274.7	0.195	0.400
Tombstone Mtn.	1470-2001	532	84	100	20795	3	22	2	0	21	36	12	4	75.0	73.0	208.0	0.212	0.248
N.Klondike River	1587-2003	417	44	80	15827	0	7	21	6	32	12	2	0	91.3	57.5	197.8	0.182	0.650
Average		350	38	65	12164	0.5	8.9	13.1	11.1	20.3	9.0	1.5	0.2	85.1	46.4	184.5	0.206	0.428

Notes: These data are for the total length of the raw chronologies (i.e. all measured and crossdated cores from the site); M.L. = Mean length of the cores; M.S. Cores = Mean Sensitivity of Cores; Mean RW = Mean ring width measurement (mm) for that chronology.

The distribution of tree ages (Figure 3.3) was skewed. Although old trees were found at many sites, they are relatively few in number and often insufficient for developing site chronologies longer than 200-250 years without more extensive sampling. This reflects the rapid reconnaissance style of sampling at these sites, but demonstrates that longer chronologies could be developed with more detailed and extensive sampling (or by combining sites). However, since the main focus of this research was on changes in response during the last century, this was not a concern at this stage for this study.

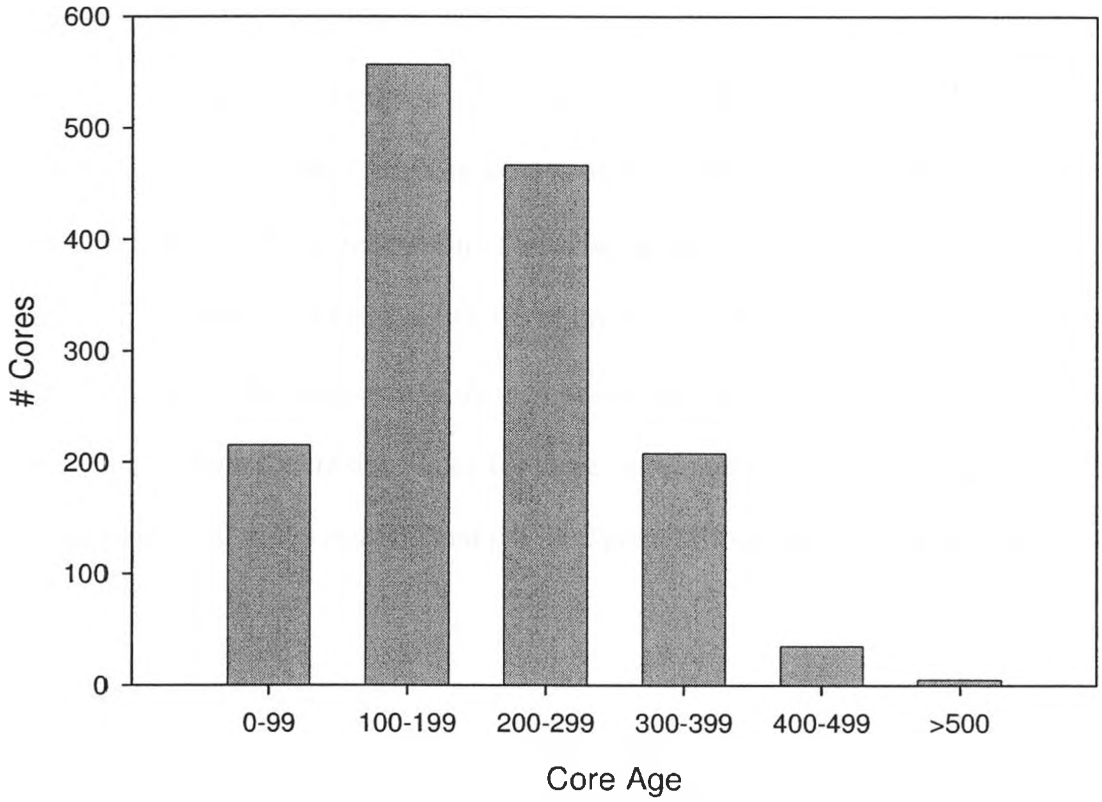


Figure 3.3 Tree core ages for all chronologies. (N = 1485 cores).

Szeicz and MacDonald (1994) used a network of sites from the N.W.T. and Yukon to investigate the differing climate response of trees with different ages and built chronologies using only trees of similar age for each time interval (e.g. building a 300 year-long chronology using only ring series from trees <100 years old). Their results indicated age dependence of response in some cases but not in others. This type of age stratification is not practiced in conventional dendroclimatology as it requires many more samples. However, some of the sites sampled for this study appeared to be composed of more than one generation of trees and ring-width series from these sites were examined carefully for any age related differences.

Two of the chronologies in this study area have unusually skewed age distributions. At the Corbett Hill site, 65.1% of the cores in this chronology are <100 years and it appears that regeneration of trees began around ca. 1930 (probably following a fire). For the Mount Jeckell site, 41.7% of the series contained between 100 and 150 years. To examine the influence of these younger trees on the overall chronology signal, separate chronologies were developed for these sub-populations at the two sites, namely pre- and post-1930 at Corbett Hill and pre- and post-1850 at Mount Jeckell (Table 3.3).

Table 3.3 Chronology statistics for each sub- and composite chronology.

Site	Sub-Site	# Cores	M.S.L. (yrs)	M.M. (mm)	M.S.		S.I.	1AC	Rbar
					Cores	Std. Chron.			
Corbett Hill	Pre – 1930	19	129.1	0.47	0.245	0.173	0.447	0.768	0.223
	Post – 1930	24	63.4	0.92	0.197	0.166	0.603	0.422	0.413
	Comp.	43	92.4	0.64	0.226	0.169	0.504	0.609	0.282
Mount Jeckell	Pre – 1850	34	231.1	0.31	0.218	0.147	0.545	0.727	0.328
	Post – 1850	27	126.3	0.52	0.210	0.150	0.669	0.611	0.469
	Comp.	60	185.8	0.37	0.216	0.143	0.581	0.696	0.380
Network Average		65	184.5	0.428	0.206	0.147	0.533	0.697	0.234

Notes: Comp. = Composite chronology. M.S.L. = Mean Segment Length in years. M.M. = Mean ring – width measurement in mm. M.S. = Mean Sensitivity of both the cores and Standard (Std.) Chronology. S.I. = Series Intercorrelation. 1AC = First order Autocorrelation. Rbar = Mean Rbar value of the standard chronology.

The statistics for the Corbett Hill site differ between the sub chronologies (Table 3.3) with the younger trees generally being lower in sensitivity, 1AC, and segment length but higher in SI, Rbar, and ring width. Both chronologies show a growth decline after ca. 1970 but trends for 1930-1970, are quite different (Figure 3.4). The older trees clearly show a growth release that coincides with the recruitment of the younger trees. This 'disturbance effect' is evidently a local stand wide occurrence. Therefore, the presence of this non-climatic signal in the chronology warrants its exclusion from analysis of any climate-related signal.

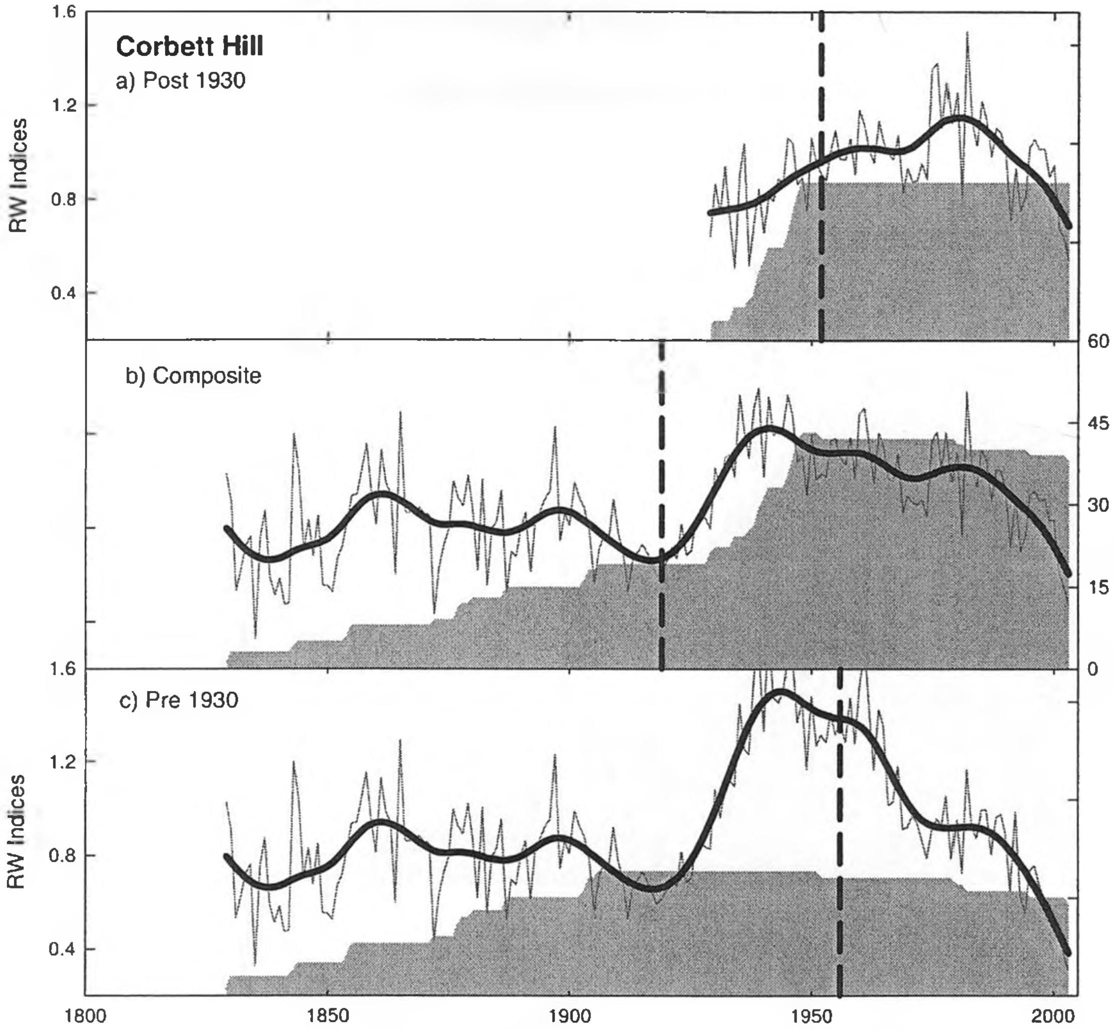


Figure 3.4 Standard chronologies for the Corbett Hill site. A. based on cores beginning around ca. 1930. B. composite chronology. C. based on cores beginning prior to ca.1930. Standard chronology plots are shown in dark grey (with a 25 year spline in bold). The number of series varies from 19 (pre-1930) to 43 (composite) and is represented by grey shading. The bold vertical dashed black lines represent the EPS cut-off for each chronology, "Pre-1930" – 1956; "Post-1930" – 1952; Composite 1919.

The sub-chronologies for the pre- and post-1850 sub-sites at Mount Jeckell (Figure 3.5), show similar high and low frequency trends during the 20th century. In general, the range of difference between the pre- and post-1850 statistics are less than the pre- and post-1930 Corbett Hill statistics. This could be attributed to the differences in the mean segment length between the two sites. Although a growth release occurred during the 1850-70s period, it does not appear to influence the 20th century signal, and therefore this chronology is acceptable for inclusion in the 20th century analysis.

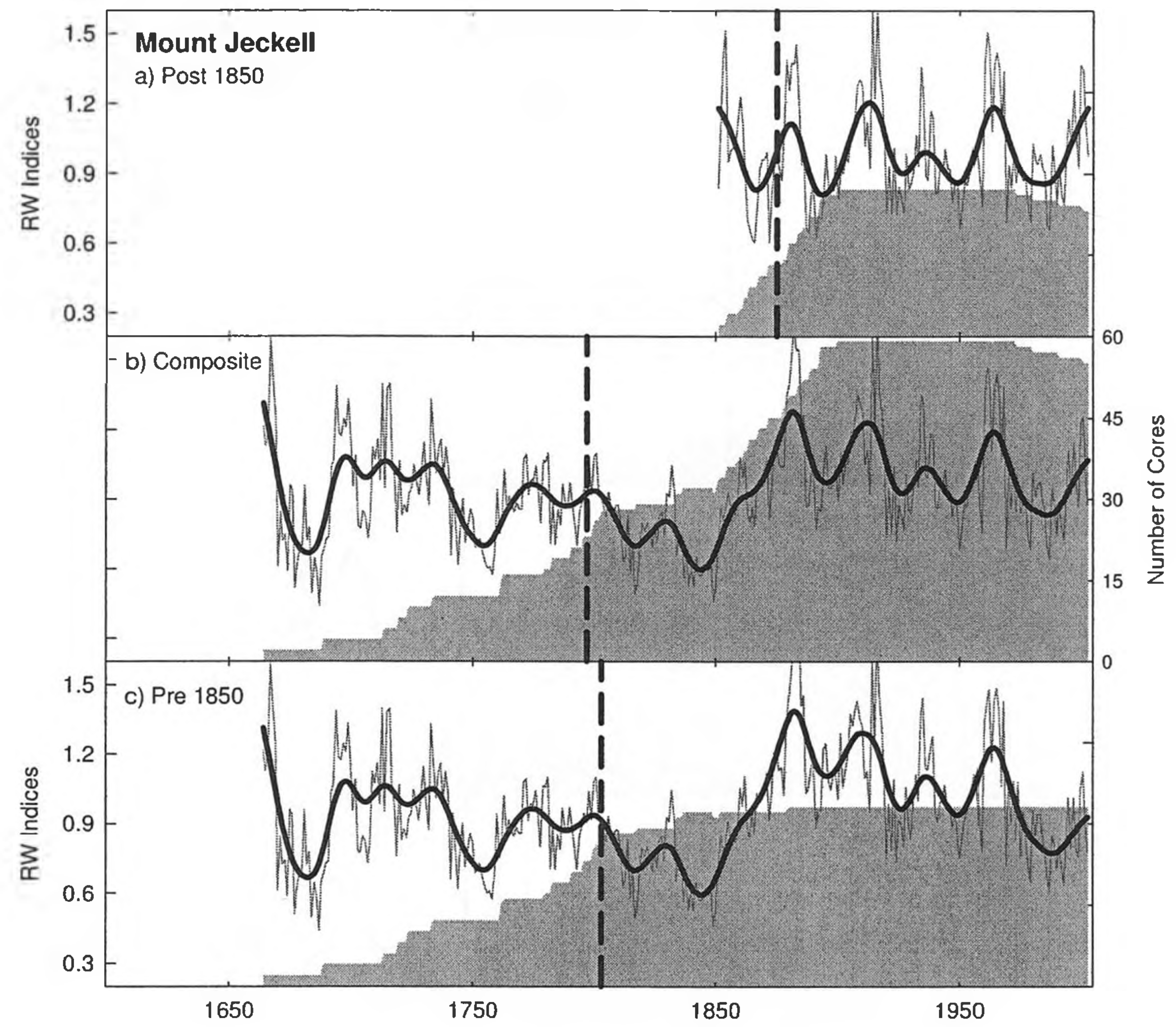


Figure 3.5 Standard chronologies for the Mount Jeckell site. A. based on cores beginning ca.1850. B. composite chronology. C. based on cores beginning prior to 1850. Standard chronology plots are shown in dark grey (with a 25 year spline in bold). The number of series varies from 27 (post-1850) to 60 (composite) and is represented by grey shading. The bold vertical dashed black lines represent the EPS cut-off for each chronology namely "Pre-1875"; "Post-1803"; Composite 1797.

Two chronologies (**Tombstone** and **Distincta**) within the network are composite chronologies. The **Tombstone** chronology is based on 9 trees from the UWO databank while the remaining 75 series are archived in the ITRDB (Szeicz and MacDonald, 1995c). Both sampling sites at Tombstone are located on the valley floor and only about 1 km apart. After detailed data quality assessment and comparison, they were combined to create a composite sample to improve sample depth (Figure 3.6).

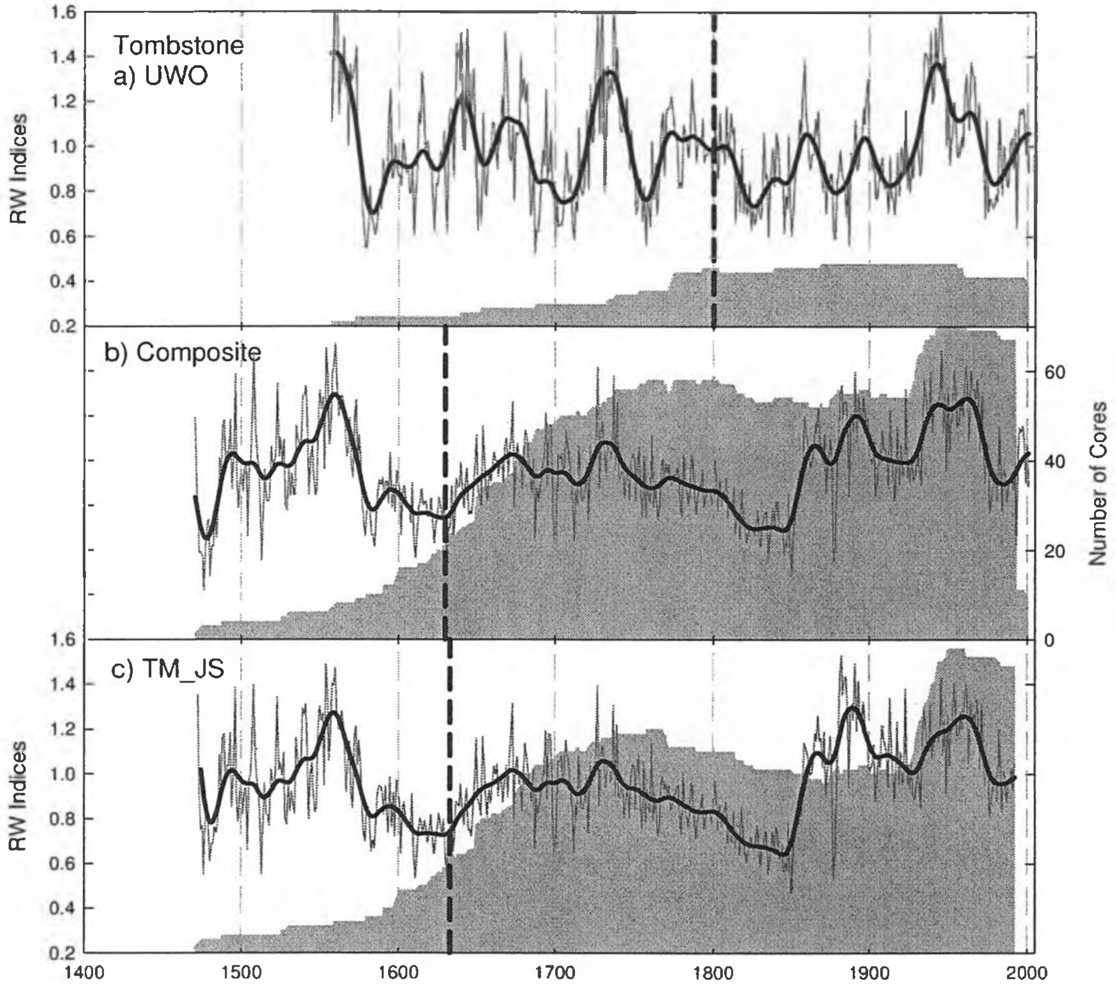


Figure 3.6 Standard chronologies for the Tombstone site. A. UWO Tombstone Chronology. B. composite chronology. C. Tombstone Mountain (Szeicz and MacDonald, 1995c). Standard chronology plots are shown in grey (with a 25 year spline in bold). The bold vertical dashed lines represent the EPS cut-off for each chronology; UWO = 1800; Composite = 1630; TM_JS = 1633.

The **Distincta** chronology is based on three sub-sites within ca. 3 km distance along the valley floor at the foot of a large east-west limestone ridge. The original site (YDD Distincta Peak, sampled in 2002) was sampled as a possible surrogate for TTHH. The site was revisited in 2004 to sample for densitometry and to increase sample depth. Based on extensive data comparison and the close proximity, the three sub-sites were combined into a composite chronology (Figure 3.7).

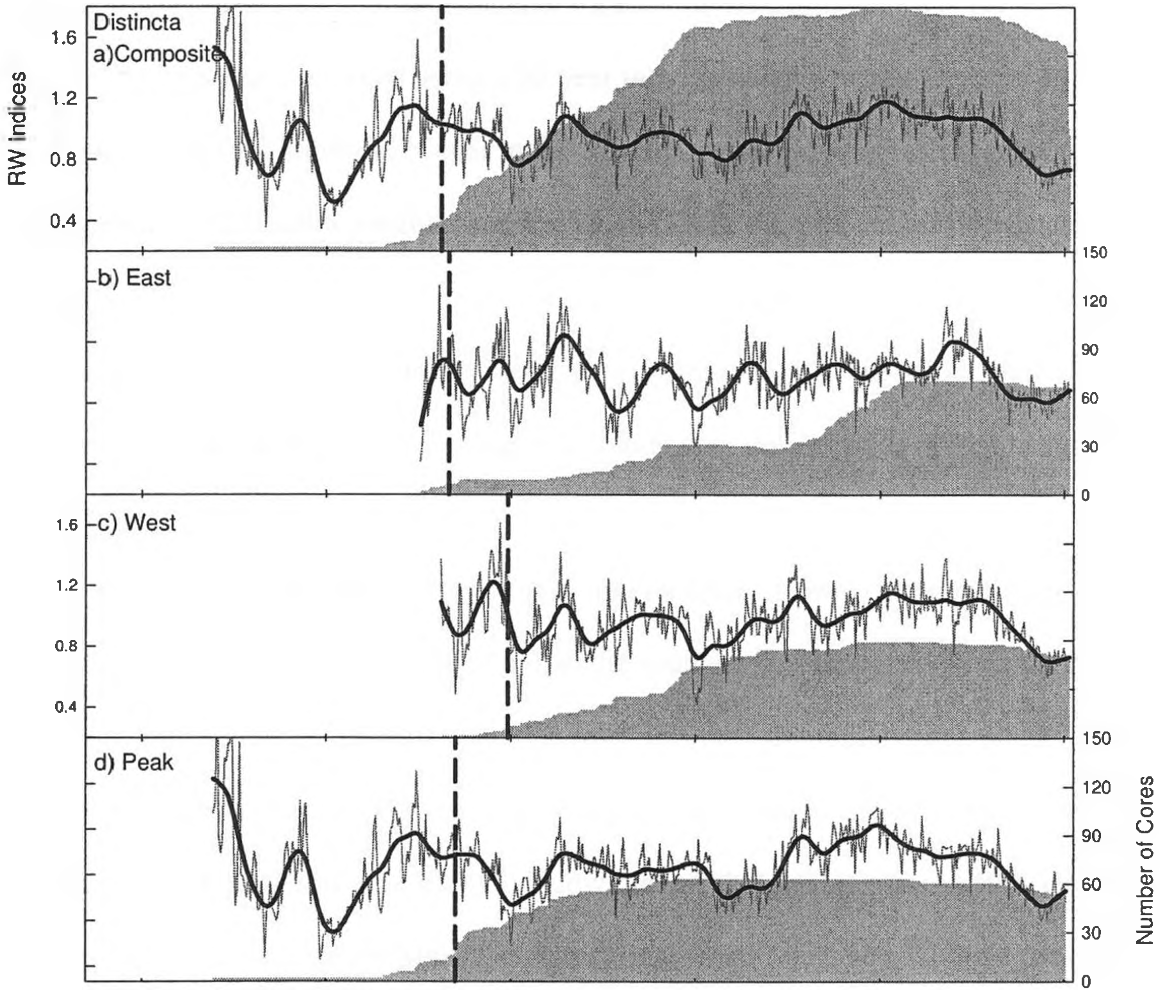


Figure 3.7 The three sub-sites of the Distincta Chronology. A. composite chronology. B. East. C. West. D. Peak. Standard chronologies are shown in dark grey (with a 25year spline in bold). The number of series varies from 70 (East) to 155 (Composite) and is represented in grey shading. The bold vertical dashed black lines represent the EPS cut-off for each chronology. The EPS cut-offs are the Composite 1662; East 1662; West 1698; and Peak 1670.

3.4.2 Assessing chronology signal strength

The EPS statistic was used to evaluate the signal strength within the standard and residual chronologies. The EPS statistic differs from the Rbar statistic in that sample depth is taken into consideration when calculating the EPS value. Sample depth at a site typically decreases in the earliest years of a chronology; therefore, the EPS statistic helps identify the portion of a chronology that maintains a strong common signal. The relationship between EPS and sample depth for each of the chronologies is presented in Figure 3.8. EPS was calculated using a 30-year moving window with a 1-year lag; this provides a value for almost every year in the chronology. Following the suggestions of Wigley *et al.* (1984) and Youngblut and Luckman (2008) the EPS cut off was located where the EPS value fell below 0.85 for more than 8 consecutive years or fell below 0.80. An 8-year window is short enough to identify when chronologies fall below the predetermined threshold but long enough to exclude very brief periods of loss in signal strength.

The EPS cut off varies by chronology and location. However, the northern chronologies tend to be shorter in length than the southern chronologies. The majority of the chronologies from the network maintain reliable signal strength throughout the 20th century, but 5 chronologies (Midway Lake, Richardson Mountain, Interfluve, Corbett Hill, Engineers Creek, and Triangle) fall below the threshold value prior to 1900 (Figure 3.8). However, as Richardson Mtn., Interfluve, Engineers Creek, and Triangle retained relatively high signals (in some cases > 0.85) back to 1900, these chronologies were retained for subsequent analysis for the 20th century period. The Midway Lake and RM_JS chronologies were excluded from further analyses because the chronologies ended in the1980s and did not span the entire 20th century.

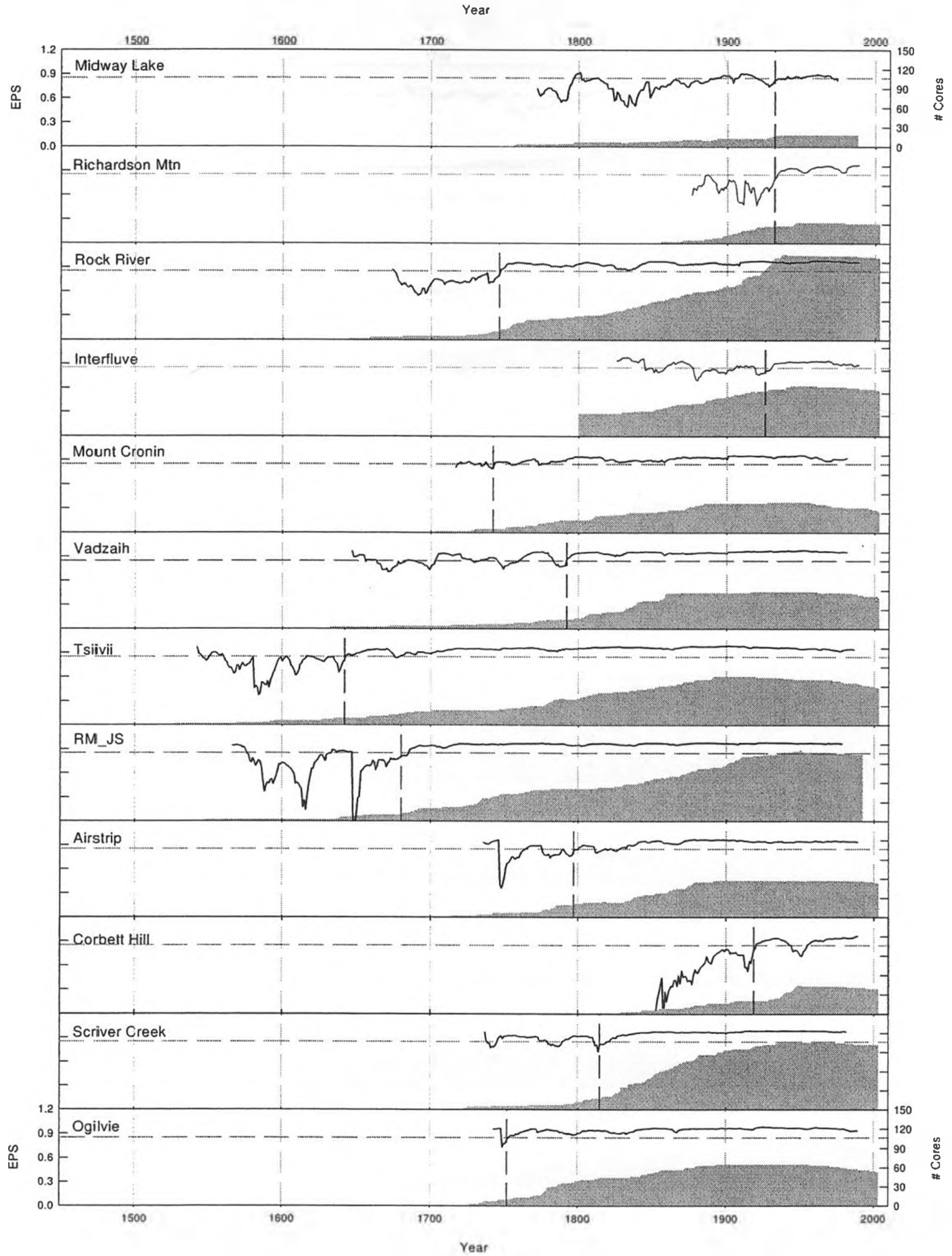


Figure 3.8 Running EPS values (black line) and sample depth (grey shaded area) for the Standard Chronologies. The dashed line represents the 0.85 threshold suggested by Wigley *et al.* (1984). To see Residual Running EPS Values see Appendix One Fig. A1.1.

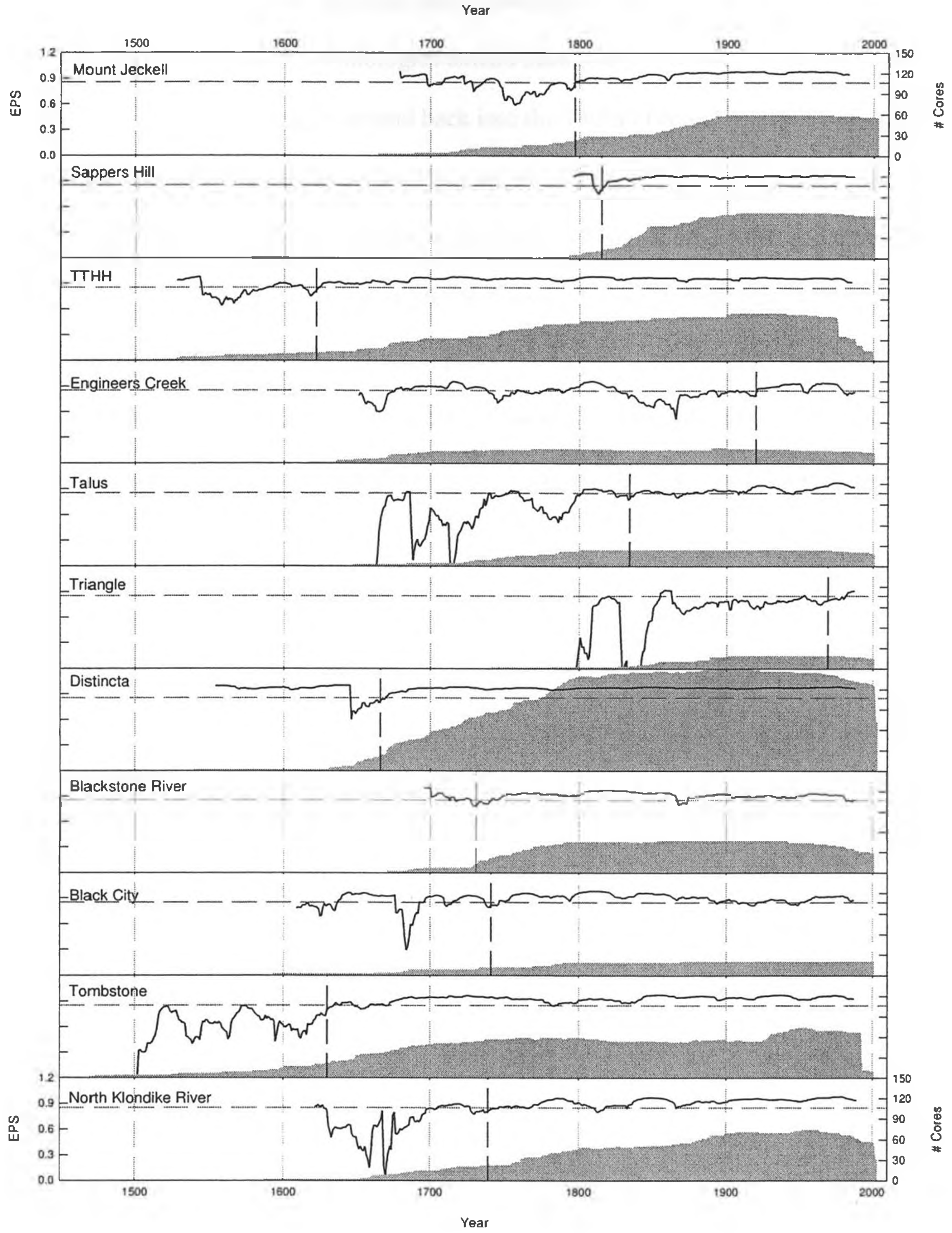


Figure 3.8 Continued.

Generally residual chronologies have a stronger common signal than standard chronologies. Five standard chronologies extend back into the 1600's (Figure 3.9), whereas 8 residual chronologies extend back into the 1500s (Table 3.4). Full standard chronologies are shown in Figure 3.9. The average percentage length of those standard and residual chronologies that maintain an adequate EPS signal are 55.6% and 69.6% respectively, with maximum values of 86.8% (Standard, Corbett Hill) and 96.8% (Residual, Distincta, Table 3.3). There appears to be a direct relationship between the number of samples and shorter EPS cut-offs. Four of the standard chronologies and 8 of the residual chronologies maintained adequate signal strength for over 80% of their absolute length.

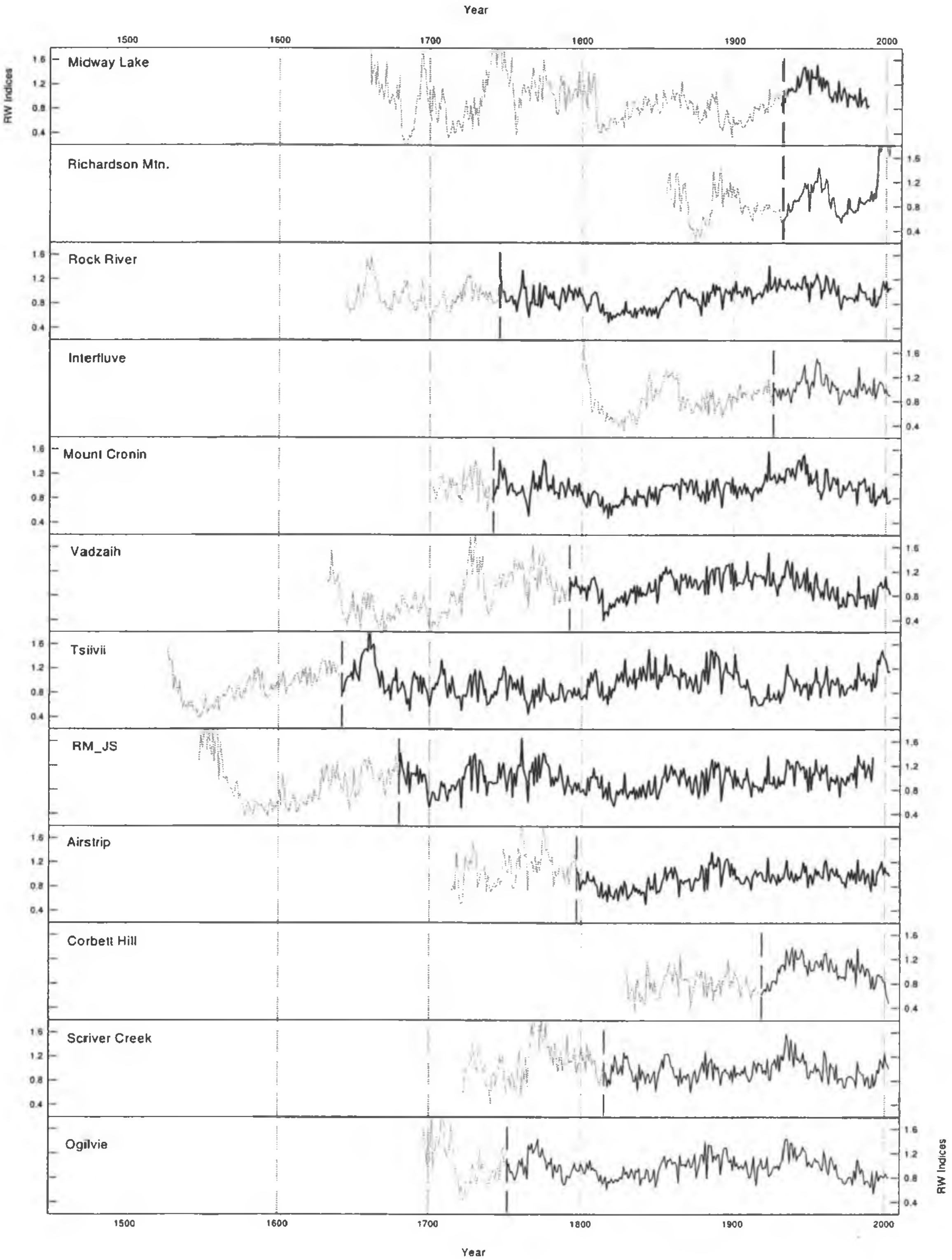


Figure 3.9 Standard Chronology plots. The grey lines represent those parts of the chronology that fall below the critical EPS threshold. The black line represents the reliable portions for this study. The vertical dashed black line represents the EPS cut-off for each chronology. To see Residual Chronology plots see Appendix One Fig. A1.2.

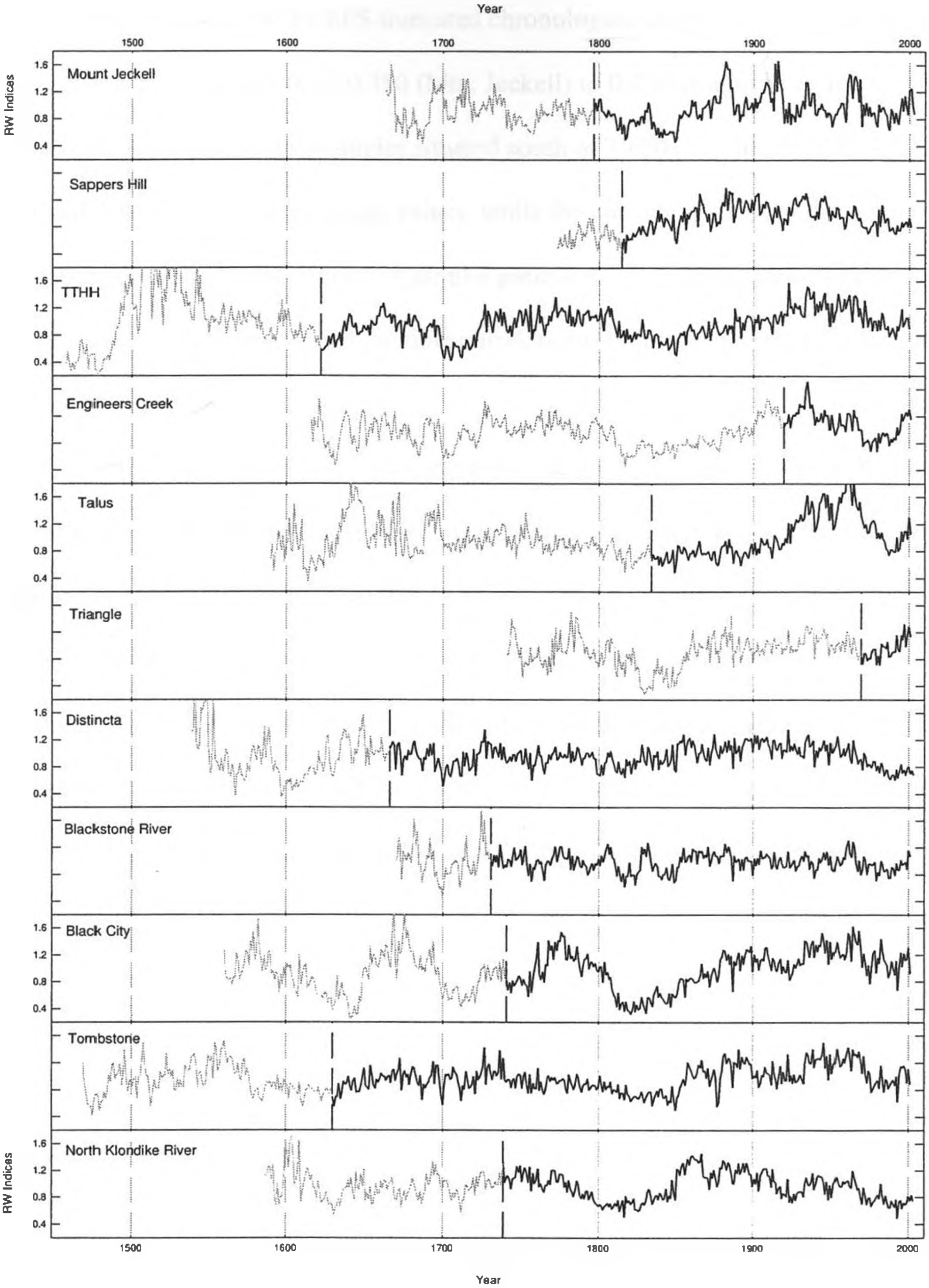


Figure 3.9 Cont.

The statistics for the EPS truncated chronologies are presented in Table 3.4. The Mean Rbar value ranges from 0.380 (Mtn. Jeckell) to 0.234 (Engineers Creek) with a mean of 0.304. Those chronologies situated south of TTHH and north of Mount Cronin typically show lower than average values, while the chronologies from the middle of the transect were found to be higher. A similar pattern exists with the series intercorrelation (S.I.) statistic: both measure all possible correlations within the raw (S.I.) and standard (Rbar) chronologies.

The mean index (M.I.) values ranged from 0.892 (Vadzaih) to 1.01 (Scriver Creek) (mean = 0.947) which suggests that the Vadzaih chronology contains extended periods of reduced growth. Two basic groupings can be identified based on these index values. North of Scriver Creek the majority of the sites had below average values whereas sites south of Corbett Hill contained higher than average values. It should be noted that the sites with the highest and lowest M.I. values although located adjacent to each other in the network are ca 50 km apart as the road is below treeline between these two sites.

Table 3.4: Summary statistics for the 23 chronologies.

Chronology	Trees	M.L. (years)	Oldest Living Tree	STD. EPS >0.85	% 0.85 or greater	RES. EPS >0.85	% 0.85 or greater	Mean Rbar	Mean Index	S.I.	M. S. (Std.)	1AC
Midway Lake	10	119.5	1757-1988	1932-1988	17.3	1909-1988	24.3	0.262	0.948	0.491	0.196	0.720
Richardson Mtn.	25	113.5	1855-2003	1932-2003	48.3	1932-2003	48.3	0.303	0.925	0.478	0.151	0.814
Rock River	68	151.5	1644-2003	1746-2003	71.7	1733-2003	75.3	0.259	0.920	0.533	0.122	0.705
Interfluve	20	117.9	1800-2003	1926-2003	38.2	1878-2003	61.8	0.241	0.912	0.473	0.143	0.714
Mount Cronin	24	183.7	1702-2003	1742-2003	86.8	1745-2003	85.8	0.307	0.965	0.548	0.144	0.562
Vadzaih	31	180.6	1632-2003	1792-2003	57.0	1709-2003	79.3	0.379	0.892	0.622	0.190	0.734
Tsiivii	37	206.3	1527-2003	1642-2003	75.9	1620-2003	80.5	0.352	0.944	0.615	0.151	0.710
RM_JS	75	176.9	1547-1992	1680-1978	67.0	1655-1978	75.8	0.306	0.942	0.601	0.176	0.654
Airstrip	30	170.5	1714-2003	1797-2003	71.4	1736-2003	92.4	0.324	0.973	0.591	0.150	0.578
Corbett Hill	24	94.8	1830-2003	1919-2003	48.6	1919-2003	48.6	0.282	0.895	0.504	0.169	0.609
Scriver Creek	66	144.7	1722-2003	1815-2003	67.0	1790-2003	75.9	0.372	1.010	0.614	0.170	0.571
Ogilvie Mtn.	34	200.0	1696-2003	1752-2003	81.8	1743-2003	84.7	0.327	0.986	0.584	0.135	0.649
Mount Jeckell	31	185.8	1664-2003	1797-2003	60.9	1768-2003	69.4	0.380	0.933	0.581	0.143	0.696
Sappers Hill	36	158.1	1793-2001	1815-2001	81.7	1796-2001	90.0	0.313	0.900	0.585	0.130	0.773
TTHH	64	267.7	1459-1975	1622-2000	69.9	1547-2000	83.8	0.367	0.983	0.620	0.139	0.835
Engineers Creek	19	244.4	1636-2001	1920-2001	21.2	1878-2001	32.1	0.234	0.974	0.484	0.108	0.811
Talus	16	255.2	1590-2001	1834-2001	40.8	1781-2001	53.6	0.258	0.974	0.483	0.142	0.801
Triangle	12	144.9	1741-2001	1969-2001	12.6	1858-2001	55.2	0.276	0.912	0.516	0.157	0.685
Distincta	73	258.4	1539-2001	1666-2003	72.7	1554-2003	96.8	0.306	0.954	0.574	0.140	0.644
Blackstone River	29	218.0	1671-2001	1731-2001	81.9	1700-2001	91.2	0.285	0.983	0.553	0.124	0.529
Black City	12	274.7	1560-2001	1741-2001	59.0	1693-2001	69.9	0.359	0.952	0.614	0.154	0.817
Tombstone Mtn	84	208.0	1560-1992	1630-2001	69.9	1621-2001	71.6	0.257	0.956	0.520	0.129	0.691
N.Klondike River	44	197.8	1587-2001	1739-2003	63.5	1695-2003	74.1	0.253	0.957	0.535	0.121	0.738
Average	**38**	**184.5**			**59.4**		70.5	**0.304**	**0.947**	**0.553**	**0.147**	**0.697**

Notes: M.L. = Mean length of the cores; STD. EPS >0.85 and RES. EPS >0.85 = Portions of these Chronologies that meet the signal strength criteria used. S.I. = Series Intercorrelation; M.S. = Mean Sensitivity; 1AC = First Order Autocorrelation; Std. Dev. = Standard Deviation (all for the Standard Chronologies).

The mean sensitivity (M.S.) statistics ranged from 0.196 (Midway Lake) to 0.108 (Engineers Creek) with an average of 0.147. In general, those chronologies (13/23) with mean sensitivities below the network mean are located in the southern portion of the network. The 10 chronologies with above average sensitivity are mainly in the northern portion of the network.

The first order autocorrelation (1AC) values ranged from 0.835 (TTHH) to 0.529 (Blackstone River) with a mean of 0.697. Low sensitivity values and high 1AC values are typical for spruce chronologies at treeline. The larger group of the chronologies that have high 1AC values are located in the Ogilvie Mountain foothills while a small group of four sites surrounding TTHH also have higher 1AC values. Examination of the relationships between Rbar, 1AC, M.S., and mean raw chronology length indicated significant relationships between chronology length and mean index ($r = 0.522$; $p = 0.011$), and inverse relationships with mean sensitivity ($r = -0.411$; $p = 0.051$) and mean ring width ($r = -0.487$; $p = 0.018$).

The average mean sensitivity for the entire network is 0.147, which is comparable to other white spruce chronologies and within range of other species used in dendroclimatic analyses from northwestern North America (Table 3.5). The 1AC for the network (0.697) is also within range of some species (subalpine fir, 0.651; larch, 0.707) while being higher than other species (sitka spruce, 0.558; mountain hemlock 0.520). Typically, white spruce from these environments have low mean sensitivities and high 1AC values. The mean length of the cores within the network was 184.5, which was slightly shorter than other white spruce sites from the Yukon, but longer than fir, hemlock, Sitka spruce, and larch in the Yukon. The network average is lower than other white spruce studies from the Yukon because tree stands tend to be younger as one approaches the latitudinal limit to growth.

Table 3.5 Treeline chronology statistics for other spruce chronologies in northwestern North America.

Species	N	M.L	M.S.I.	M.S.	1AC
White Spruce (*Picea glauca*) SW Yukon.[1]	17	236	N/A	0.200	0.720
**White Spruce (*Picea glauca*) Yukon. [2]	114	206	0.586	0.146	0.675
Subalpine Fir (*Abies lasiocarpa*) Central Yukon/Northern B.C.[3]	26	165	0.594	0.142	0.651
Sitka Spruce (*Picea sitchensis*) South Yukon[4]	6	142	0.646	0.149	0.558
Mountain Hemlock (*Tsuga mertensiana*) South Yukon[4]	1	105	0.590	0.150	0.520
Larch (*Larix laricina*) Central Yukon[5]	1	114	0.563	0.246	0.707

Notes: N = number of chronologies; M.L. = Mean Length of the cores; M.S.I. = Mean Series Intercorrelation; M.S. = Mean Sensitivity and 1AC = Mean First Order Autocorrelation from Standard Chronologies. Data from; [1](Luckman *et al.*, 2002); [2](Morimoto, personal communication); [3](Kenigsberg, 2005); [4](Payne, 2006); [5] Data archived in the UWOTRDB. ** This sample set of 114 chronologies contains some of the sites used in Luckman *et al.*, 2002 and the data used in this thesis.

3.5 Conclusion

The network of 23 treeline white spruce sites from the Central Yukon presented in this chapter are of comparable quality to other tree-ring data utilized for dendrochronological and dendroclimatic studies from the Yukon. Overall, tree age and chronologies are somewhat shorter in length than at other white spruce studies from the Yukon (Table 3.5), but are adequate for dendroclimatic investigations in this region.

Many chronologies show similar long term variation in ring width although the strength of the common signal varies among sites. Overall, the sites show common patterns of low growth during the early 1800s and increased growth from the 1850s until the early 1900s. There is a short period of low growth in the early 1900s and maximum growth in the mid 20th century. Growth patterns are somewhat more variable during the latter half of the 20th century, possibly reflecting site specific responses to recent warming in this region. These responses and the analysis of possible causes form the subject of the next chapters in this thesis.

CHAPTER FOUR

Analysis of the Common Signal within the Network

4.1 Introduction

Tree growth and the resulting ring-width series may be controlled by a wide variety of factors that operate at local to regional scales. The main purpose of chronology development and standardization is to identify and strengthen the common signal at a site that may reflect possible climate controls on growth (Cook, 1992). The first assessment of the new chronology network is to assess the similarity of the records between sites. The evaluation of the common signal between sites is important in dendroclimatic research as it can provide valuable information about the quality of reconstructions that can be developed from these data. More specifically, comparison of the individual chronologies is essential in the overall evaluation of the entire network because it can identify whether there are common growth patterns that may reflect common factors influencing tree growth across the region. The first part of this chapter will evaluate the correlations among chronologies across the network. Subsequent analyses will explore the relationships between these chronologies and climate over the 20th century.

4.2 Identifying the common signals within the network

The sampled transect extends ca 300km north – south and thus it is important to identify whether there are regional differences between these tree ring chronologies. More specifically, it is also important to determine whether the growth patterns present in the TTHH chronology (as demonstrated by D'Arrigo *et al.* (2004)) are present throughout the network. Some studies in this region have identified a "divergence" in late 20th century in the relationship between temperature and ring width (D'Arrigo *et al.*, 2004) but others have not (Youngblut and Luckman, 2008), and so it is important to identify whether these differences in the response are conditioned by regional or local differences between sites.

4.2.1 Marker ring analysis

Marker rings are distinctive rings in tree-ring series that are noticeably narrower or wider than adjacent rings and are key elements in the visual crossdating of tree-ring series (Fritts, 1976). Common patterns of marker rings across a network of chronologies usually indicate a regional climate forcing in specific years and can provide some early clues to the coherence in signal between tree-ring sites. In this study residual (high-frequency) chronologies (see Chapter 3) were used to identify marker rings that were defined as those rings greater than one standard deviation above or below the mean of each chronology. Those years with marker rings that occurred in 50 – 75% (moderate) or > 75% (extreme) of the chronologies are shown in Figure 4.1.

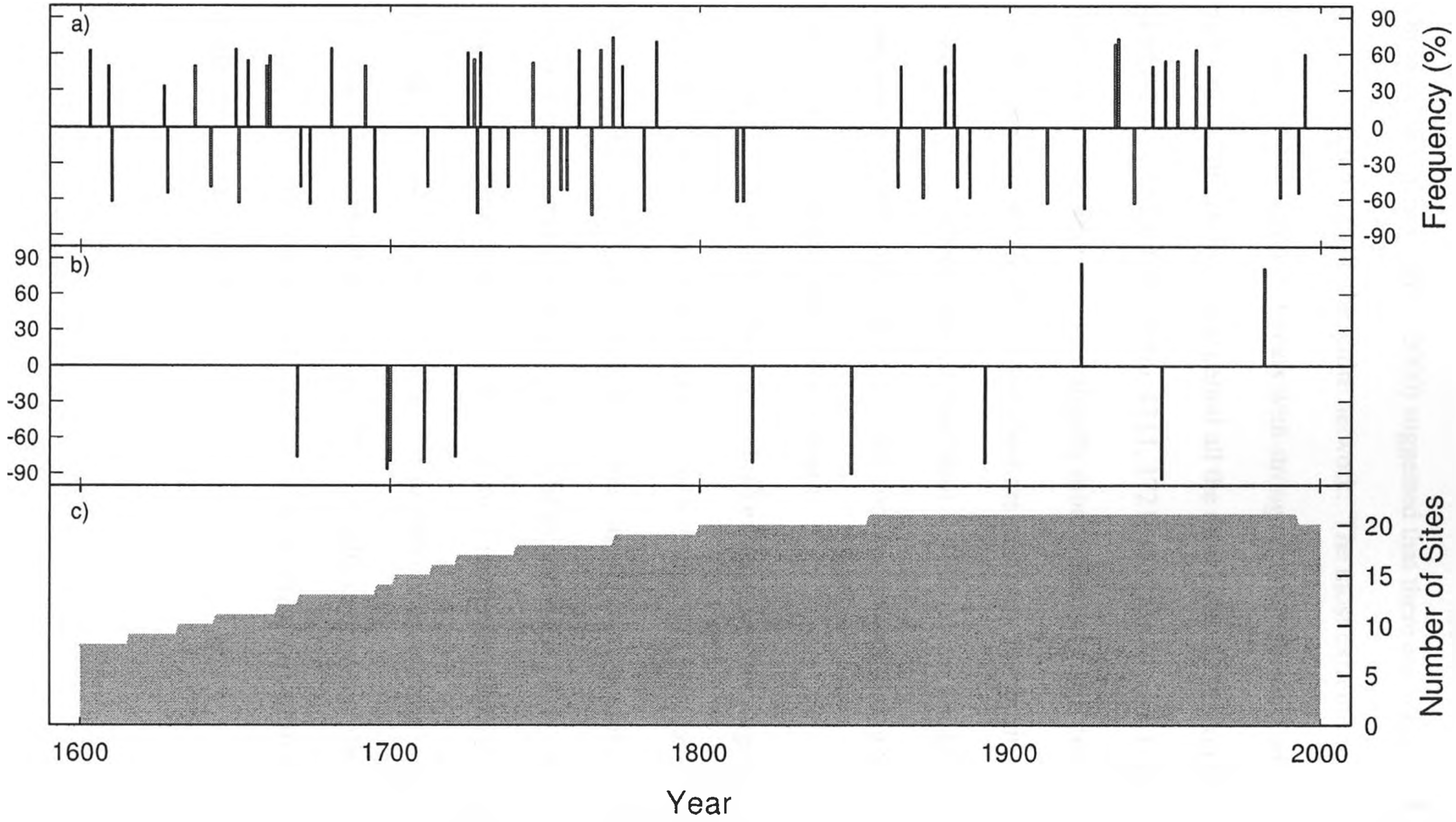


Figure 4.1 Summary of marker rings in the Residual Chronologies (1600-2000). A. Moderate years (marker rings occur in 50-75% of the chronologies). B. Extreme years (> 75% of chronologies). The height of the vertical bars represent the percentage of chronologies with ring widths > 1 standard deviation from the mean. Maximum sample depth of 22 chronologies between 1855 and 1988. There are only 2 chronologies that extend to 1500 and 8 before 1600. For complete Marker Ring details see Appendix Two.

The common occurrence of both negative and positive marker rings in the residual chronologies (years 1600 – 2000) suggested that there are regional forcings that influence tree growth throughout the entire network. The most extreme common marker rings (> 75%) indicate exceptional years with strong regional climate forcing throughout the network. In the 1600 – 1900 period all the most extreme marker rings identified were negative (i.e., 1670, 1699, 1700, 1711, 1721, 1817, 1849, and 1892). "Moderate" negative marker rings occurred slightly more frequently than positive "moderate" markers (24:21) over the whole record, but there are relatively few positive markers in the 19th century. These findings suggest that, prior to 1900, wider marker rings are less common than narrow marker rings and that conditions for growth during this period were not particularly favourable across the network.

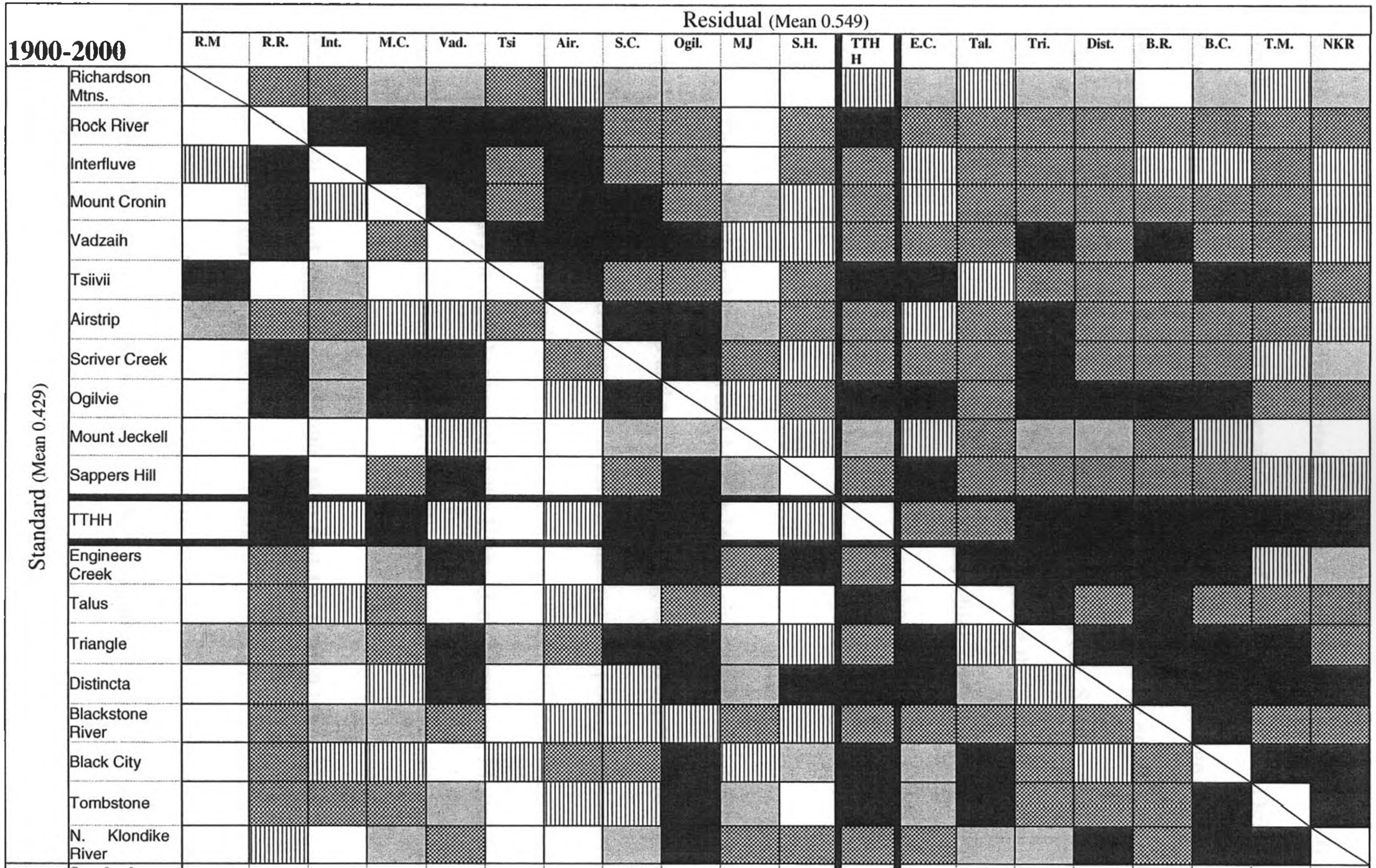
In the 20th century there were three extreme marker rings: positive markers in 1923 (86%) and 1982 (82%) and a negative marker in 1949 that occurred in all except one chronology (95%). Overall, there was slightly more positive moderate markers (10:8) in this time period (Figure 4.1). The period from 1935 – 1965 appears exceptionally variable with 7 of the 8 positive moderate markers in the 20th century, plus two negative ones, including 1949. The negative marker rings were more evenly distributed throughout the century. These results suggest that the climate in this region was quite variable over the 20th century with the most variability occurring within the middle of the 20th century.

4.2.2 Correlation analysis

Relationships among the chronologies were examined using Pearson Product-Moment correlation analyses on both standard and residual chronologies over three different time periods. The initial analysis examined the entire 20th century record to provide some indication of major groupings of sites. In this thesis, subsequent analyses will examine differences in the chronology groupings between the Early Period (1900-1950) and the Recent Period (1951- 2000).

4.2.2.1 Site relationships over the 20th century

The analysis was based on the 20 chronologies that span the 20th century, omitting the short Midway Lake and RM_JS sites and the disturbed Corbett Hill chronology. All records (chronologies) were truncated prior to 1900 although some do not maintain the 0.80 EPS threshold for the entire 20th century (see Chapter 3). The correlation matrix for the standard chronologies (Figure 4.2, lower section) revealed no strong geographical groupings. Three chronologies (Richardson Mountains 0.141, Tsiivii 0.215, and Mount Jeckell 0.293) were very poorly correlated within the network while the best correlated chronologies were distributed across the network (mean r > 0.494 for Rock River, Scriver Creek, Ogilvie, TTHH, Triangle, Black City and Tombstone). The residual chronology matrix (Figure 4.2, upper section) contained higher site correlations (mean = 0.549, Table 4.1), and only two sites, Richardson Mountain (0.384) and Mount Jeckell (0.361) had correlation values below 0.500.



Avg.	R.M	R.R.	Int.	M.C.	Vad.	Tsi	Air.	S.C.	Ogil.	MJ	S.H.	TTHH	E.C.	Tal.	Tri.	Dist.	B.R.	B.C.	T.M.	NKR
Standard	.141	.532	.346	.439	.462	.215	.425	.525	.545	.293	.416	.529	.450	.407	.505	.444	.474	.494	.500	.434
Residual	.384	.596	.539	.546	.588	.574	.573	.566	.587	.361	.506	.596	.543	.539	.595	.608	.592	.595	.574	.521

Figure 4.2 Correlation of Standard and Residual chronologies for the 1900 – 2000 interval.

> 0.6	0.59 – 0.50	0.49 – 0.4	0.39 – 0.30	< 0.29
■	▩	▥	░	□

Overall, the residual matrix identified two distinct regional groupings (north and south) that may be defined by most inter site paired correlations greater than 0.450. The northern group encompassed all of the sites north of Mount Jeckell (i.e. Ogilvie- Rock River, except for the Richardson Mtn. chronology) and had an average correlation within the group of 0.660 (Table 4.2) which was slightly higher than the entire network average. The southern group includes sites south of Mount Jeckell (i.e. Sappers Hill-North Klondike River) and incorporated 10 chronologies (unlike the 8 in the Northern grouping) with an average within-group correlation of 0.628[4]; which was slightly lower than the northern grouping (Table 4.2). TTHH was at the northern boundary of this group and had the second highest correlation within the network, only marginally less than Distincta (Figure 4.2).

The Richardson Mountain and Mount Jeckell sites were consistently the weakest correlated in both the standard and residual chronologies, and appeared to contain unique signals. The standard chronology at the Tsiivii site was also poorly correlated with other sites in the network, although the residual chronology was well correlated. Therefore, over the 20th century, it would appear that the Richardson Mountain, Mount Jeckell and possibly Tsiivii chronologies, are most strongly influenced by local (site) variation.

4.2.2.2 Split period analysis: the 1900-1950 and 1951-2000 intervals

Subsequent analyses divided the 20th century record into two equal parts to examine whether there were changes in the relationships between the chronologies in the first and second half of the century. The residual matrices (Figures 4.3 and 4.4; upper sections)

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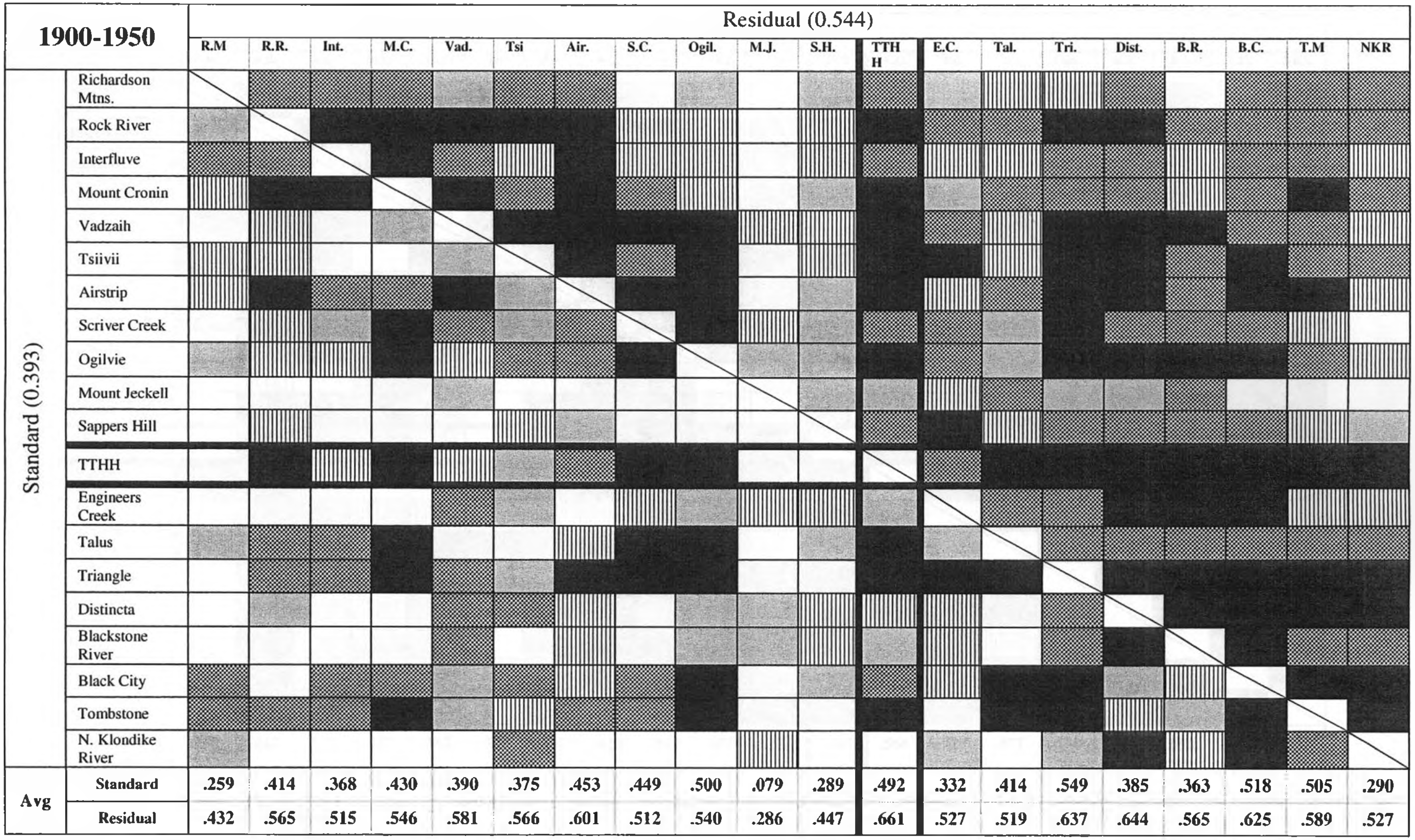
[4] Sappers Hill is the poorest correlated member of this group. If this chronology is excluded, the mean correlation increases slightly to 0.638.

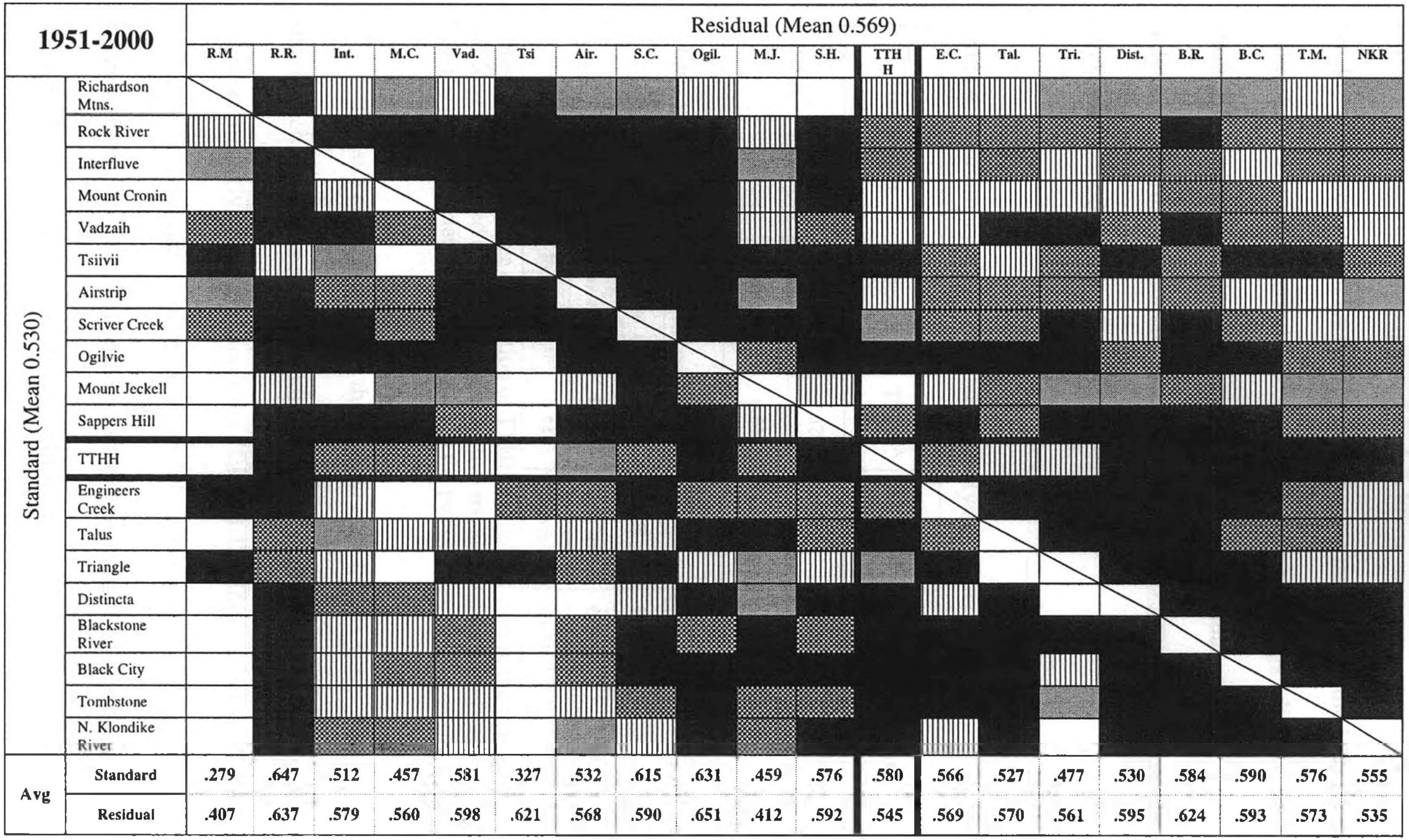
clearly identified similar regional groupings (Ogilvie to Rock River and Sappers Hill to North Klondike River) to those identified with the entire 20th century residual analysis. The average correlation among sites in the network for the 1900-1950 period was slightly less than that for the 1951-2000 interval (0.544 compared to 0.569) and the regional groupings were more clearly defined in the 1950-2000 interval. The average correlation over 1951-2000 was slightly greater than the results over the entire period (Table 4.1).



1900-1950		Residual (0.544)																			
		R.M	R.R.	Int.	M.C.	Vad.	Tsi	Air.	S.C.	Ogil.	M.J.	S.H.	TTHH	E.C.	Tal.	Tri.	Dist.	B.R.	B.C.	T.M	NKR
Standard (0.393)	Richardson Mtns.	╲	▩	▩	▩	▒	▩	▩		▒		▒	▩	▒	▥	▥	▩		▩	▩	▩
	Rock River	▒	╲	■	■	■	■	■	▥	▥		▥	■	▩	▩	■	■	▩	▩	▩	▩
	Interfluve	▩	▩	╲	■	▩	▥	■	▥	▥		▥	▩	▥	▥	▩	▩	▥	▩	▩	▥
	Mount Cronin	▥	■	■	╲	■	▩	■	▩	▥		▒	■	▒	▩	▩	▩	▥	▩	■	▩
	Vadzaih		▥		▒	╲	■	■	■	■	▥	▥	■	▩	▥	■	■	■	▩	▩	▥
	Tsiivii	▥	▥			▒	╲	■	▩	■		▥	■	■	▥	■	■	▩	■	▩	▩
	Airstrip	▥	■	▩	▩	■	▒	╲	■	■		▒	■	▥	▩	■	■	▩	■	■	▥
	Scriver Creek		▥	▒	■	▩	▒	▩	╲	■	▥	▒	▩	▩	▒	■	▩	▩	▩	▥	
	Ogilvie	▒	▥	▥	■	▥	▩	▩	■	╲	▒	▒	■	▩	▒	■	■	■	■	▩	▥
	Mount Jeckell					▒					╲	▒	▒	▥	▩	▒	▒	▩			
	Sappers Hill		▥				▥	▒				╲	▩	■	▥	▩	▩	▩	▩	▥	▒
	TTHH		■	▥	■	▥	▒	▩	■	■			╲	▩	■	■	■	■	■	■	■
	Engineers Creek					▩	▒		▥	▒	▥	▥	▒	╲	▩	▩	■	■	■	▥	▥
	Talus	▒	▩	▩	■			▥	■	■		▒	■	▒	╲	▩	▩	▩	▩	▩	▩
	Triangle		▩	▩	■	▩	▒	■	■	■			■	■	■	╲	■	■	■	■	■
	Distincta		▒			▩	▩	▥		▒	▒	▥	▥	▥		▩	╲	■	■	■	■
	Blackstone River					▩		▥		▒	▒	▥	▒	▥		▩	■	╲	■	▩	▩
	Black City	▩		▩	▩	▒	▩	▥	▩	■		▒	▩	▥	■	■	▒	▥	╲	■	■
	Tombstone	▩	▩	▩	■	▒	▥	▩	▩	■			■		■	■	▥	▒	■	╲	■
	N. Klondike River	▒					▩				▥			▒		▒	■	▥	■	▩	╲
Avg	Standard	.259	.414	.368	.430	.390	.375	.453	.449	.500	.079	.289	.492	.332	.414	.549	.385	.363	.518	.505	.290
	Residual	.432	.565	.515	.546	.581	.566	.601	.512	.540	.286	.447	.661	.527	.519	.637	.644	.565	.625	.589	.527

Figure 4.3 Correlation of Standard and Residual chronologies for the 1900-1950 period.

> 0.6	0.59 – 0.50	0.49 – 0.4	0.39 – 0.30	< 0.29
■	▩	▥	▒	



1951-2000		Residual (Mean 0.569)																			
		R.M	**R.R.**	**Int.**	**M.C.**	**Vad.**	**Tsi**	**Air.**	**S.C.**	**Ogil.**	**M.J.**	**S.H.**	**TTHH**	**E.C.**	**Tal.**	**Tri.**	**Dist.**	**B.R.**	**B.C.**	**T.M.**	**NKR**
Standard (Mean 0.530)	Richardson Mtns.	╲	■	▥	░	▥	■	░	░	▥			▥	▥	▥	░	░	░	░	▥	░
	Rock River	▥	╲	■	■	■	■	■	■	■	▥	■	▩	▩	▩	▩	▩	■	▩	▩	▩
	Interfluve	░	■	╲	■	■	■	■	■	■	░	■	▩	▥	▩	▥	▩	▩	▥	▩	▩
	Mount Cronin		■	▥	╲	■	■	■	■	■	▥	■	▥	▥	▥	▥	▥	▩	▩	▥	▥
	Vadzaih	▩	■	■	▩	╲	■	■	■	■	▥	▩	▥	▥	■	■	▩	■	▩	▩	▥
	Tsiivii	■	▥	░		■	╲	■	■	■	■	■	■	▩	▥	▩	■	▩	■	■	▩
	Airstrip	░	■	▩	▩	■	■	╲	■	■	░	■	▥	▩	▩	▩	▥	▩	▥	▥	░
	Scriver Creek	▩	■	■	▩	■	■	■	╲	■	■	■	░	▩	▩	■	▥	■	▩	▥	▥
	Ogilvie		■	■	■	■		■	■	╲	▩	■	■	■	■	■	▩	■	■	▩	▩
	Mount Jeckell		▥		░	░		▥	■	▩	╲	▥		▥	▩	░	░	▩	▥	░	░
	Sappers Hill		■	■	■	▩		■	■	■	▥	╲	▩	■	▩	■	■	■	■	▩	▩
	TTHH		■	▩	▩	▥		░	▩	■	▩	■	╲	▩	▥	▥	■	■	■	■	■
	Engineers Creek	■	■	▥			▩	▩	■	▩	▩	▩	▩	╲	■	■	■	■	■	▩	▥
	Talus		▩	░	▥	▥		▥	▥	■	■	▩	■	▩	╲	■	■	■	▩	▩	▥
	Triangle	■	▩	▥		■	■	▩	■	▥	░	▥	░	■		╲	■	■	■	▥	▥
	Distincta		■	▩	▩	▥			▥	■	░	■	■	▥	■		╲	■	■	■	■
	Blackstone River		■	▥	▥	▩		▩	■	▩	■	▩	■	■	■	■	■	╲	■	■	■
	Black City		■	▥	▩	▩		▩	■	■	■	■	■	■	■	▥	■	■	╲	■	■
	Tombstone		■	▥	▥	▥		▥	▩	■	▩	▩	■	■	■	░	■	■	■	╲	■
	N. Klondike River		■	▩	▩	▥		░	▥	■	▩	■	■	▥	■		■	■	■	■	╲
Avg	**Standard**	.279	.647	.512	.457	.581	.327	.532	.615	.631	.459	.576	.580	.566	.527	.477	.530	.584	.590	.576	.555
	Residual	.407	.637	.579	.560	.598	.621	.568	.590	.651	.412	.592	.545	.569	.570	.561	.595	.624	.593	.573	.535

Figure 4.4 Correlation of Standard and Residual chronologies for the 1951-2000 period

> 0.6	0.59 – 0.50	0.49 – 0.4	0.39 – 0.30	< 0.29
■	▩	▥	░	

However, there are clear differences between the two periods in the standard chronology relationships (Figures 4.3, 4.4, lower matrices). Sites were much more weakly correlated (mean r = 0.393) in the earlier period than the later period (r = 0.530, Table 4.1). The early period lacked any coherent groupings while the recent period showed a similar, though weaker, grouping to the residual matrices. In the recent period only the Richardson Mountain (mean correlation = 0.279) site was poorly correlated with other sites (all others are >0.477).

Table 4.1 Summary of the correlation analysis results.

Time Period		Chronology	TTHH[A]	Highest[B]	R	Lowest[B]	R	Network Average[C]
Entire	1900-2000	Standard	0.529	Ogilvie	0.545	Richardson Mtns.	0.141	0.429
		Residual	0.596	Distincta	0.608	Mount Jeckell	0.361	0.549
Early	1900-1950	Standard	0.492	Triangle	0.549	Mount Jeckell	0.079	0.393
		Residual	0.661	TTHH	0.661	Mount Jeckell	0.286	0.544
Recent	1951-2000	Standard	0.580	Rock River	0.647	Richardson Mtns.	0.279	0.530
		Residual	0.545	Ogilvie	0.651	Richardson Mtns.	0.407	0.569

Notes: A = The average correlation of TTHH against all sites in the network. B = The highest and lowest correlated sites and their respective mean correlation coefficients (r) for each analysis. C = The mean correlation of all the sites in the period of analysis.

The site chronology with the highest correlations varies between the residual and standard chronologies and within the period of analysis. With the exception of Triangle, the most strongly intercorrelated sites (Table 4.1, ‘Highest’ column) were all well replicated chronologies with mean correlations between 0.545 and 0.661. All except Rock River were located in the middle section of the transect. The TTHH site was well correlated over all periods analyzed and had the highest correlated residual chronology for the first half of the century. The most poorly correlated chronologies were from the Richardson Mountain and Mount Jeckell sites. At Mount Jeckell, the poor common signal could reflect the influence of a mixed population of older and younger trees that compromise the overall common climate signal. The Richardson Mountain chronology was retained from earlier analyses despite inadequate signal strength (low EPS) in the early 20th century. Based on these low correlation analyses, these two sites were removed from further analyses of the regional patterns of growth.

Overall, the residual chronologies had the highest correlation values within the network indicating a stronger interannual signal when low frequency trends are removed. More specifically, the residual matrices identified two regional groupings of sites (Ogilvie to Rock River and Sappers Hill to North Klondike River) and two sites (Richardson Mountain and Mount Jeckell) with more unique growth patterns. The strength of the relationship between sites within the two groups varied depending on the time period being investigated, but in general identified two regional groupings. The TTHH site was more strongly correlated with the southern group overall, but more strongly correlated with the northern group in the early period, although high correlations were found with several sites within the entire network depending on the time period investigated.

Examination of the correlations between the standard chronologies over the two time periods showed relatively weak grouping in the early period and over the entire 20th century, but standard chronologies grouped similarly to the residual chronologies in the late 20th century although less strongly. The average correlation for the standard chronologies in the network for the 1951-2000 period was slightly lower than the network average for the 20th century residual chronologies. The higher intercorrelation between the residual chronologies suggested that the interannual (high frequency) signal was stronger than the lower frequency, which may be more influenced by non-climatic variation between sites.

When comparing the northern and southern groups of sites over the 1900-2000 period (Table 4.2), the northern group had an average within-group correlation of 0.485 (residual 0.660; difference -0.175) while the southern grouping had a value of 0.536 (residual 0.628; difference -0.092). The average difference in correlation between the standard and residual chronologies across the entire network was 0.120. Correlations between the standard chronology for each site and all others in the network showed a greater range (0.141 to 0.545) compared with similar analyses for the residual chronologies (0.361 to 0.608). Part of the reason for the greater range of correlation values in the standard chronology matrix was due to the fact that some of the chronologies had inadequate signal strength during the earlier portion of their records.

Table 4.2 Average correlation between the entire network and selected groups.

		Network Average		Northern Group		Southern Group	
		Std	Res	Std	Res	Std	Res
Period	Entire	0.429	0.549	0.485	0.660	0.536	0.628
	Early	0.393	0.544	0.497	0.620	0.454	0.638
	Recent	0.530	0.569	0.623	0.723	0.629	0.627

Notes: The Network Average includes all chronologies. The Northern Group is Rock River, Interfluve, Mount Cronin, Vadzaih, Tsiivii, Airstrip, Scriver Creek and Ogilvie. The Southern Group is Sappers Hill, TTHH, Engineers Creek, Talus, Triangle, Distincta, Blackstone River, Black City Tombstone, and North Klondike River.

Correlations for standard chronologies in the first half of the record (Figure 4.3) range from 0.079 – 0.549 (residual chronologies ranged from 0.286 to 0.661), whereas mean correlations for standard chronologies were more closely grouped (0.270 to 0.647) in the latter interval (residual: 0.407 – 0.651; Figure 4.4). The highest correlations were between the residual chronologies over the last half of the 20th century (Table 4.2). These results generally show that there were stronger correlations between the residual chronologies than the standard chronologies, and that generally the relationships between chronologies were stronger in the later 20th century than in the earlier part.

4.2.3 Principal components analysis

Principal Components Analysis (PCA) was used to evaluate the homogeneity of the common signal within the tree ring network. This technique was used to identify covariance within a larger data set by creating factors (eigenvectors) that represent the colinearity within that dataset (Richman, 1986). In this analysis, PCA was used to analyze the correlations between the standard chronologies over a common period to produce a smaller number of eigenvectors that contain large portions of the common signal (Richman, 1986). By using the Varimax method within the PCA, each eigenvector extracted was created based on maximizing the variability within each factor while maximizing the variability between factors (Richman, 1986). Therefore, each factor created represents the common signal of that factor based on the chronologies grouped. Relationships between selected factors and climate will be explored in the next chapter.

4.2.3.1 Entire 20th century period

PCA was carried out on the 18 most strongly correlated standard chronologies over the 20th century and identified four different factors (Table 4.3). Eight sites loaded most strongly on PC1A (27.82% of the total variance, Table 4.3), mainly from the middle of the network, but there were some outliers (e.g. North Klondike River and Vadzaih). The North Klondike river site loaded almost equally on PC1A and PC2A whilst Ogilvie and Scriver Creek also loaded heavily on PC3A. The factor trend illustrated in Figure 4.5 showed higher growth from 1900-1940 and then a gradual decrease until a short period of increased growth in the 1990s. PC2A explains a similar amount of variance as PC1A (20.78%) and was more spatially coherent containing 5 sites from the "southern" group including TTHH. PC3A (17.52%) contained the three northernmost sites while PC4A (11.96%) consisted mainly of two adjacent northern sites.

Table 4.3 PCA output for the Standard Chronologies over the Entire period (1900-2000).

Rotated Component Matrix(a)				
	Component			
	1 (PC1A)	2 (PC2A)	3 (PC3A)	4 (PC4A)
Engineers Creek	**0.869**	0.128	0.078	0.176
Vadzaih	**0.834**	-0.018	0.337	0.187
Distincta	**0.800**	0.417	0.126	-0.201
Sappers Hill	**0.768**	0.167	0.241	-0.032
North Klondike River	**0.635**	**0.634**	-0.038	-0.089
Ogilvie	**0.600**	0.425	0.493	0.090
Scriver Creek	**0.596**	0.143	**0.575**	0.315
Triangle	**0.555**	0.210	0.338	**0.509**
Tombstone	0.196	**0.827**	0.311	0.210
Black City	0.237	**0.773**	0.191	0.361
Talus	0.017	**0.744**	0.455	0.080
TTHH	0.407	**0.626**	**0.510**	0.026
Blackstone River	**0.532**	**0.552**	0.041	0.264
Mount Cronin	0.334	0.247	**0.828**	-0.030
Rock River	0.453	0.286	**0.662**	0.235
Interfluve	-0.076	0.381	**0.567**	0.358
Tsiivii	-0.015	0.132	-0.013	**0.890**
Airstrip	0.181	0.200	0.471	**0.667**
Eigenvalue	**5.01**	**3.74**	**3.15**	**2.15**
% Explained Variance	**27.82**	**20.78**	**17.52**	**11.96**
Cumulative % Explained	**27.82**	**48.60**	**66.12**	**78.08**

Those values in **bold** represent loadings greater than 0.500 (the sites are ranked from high to low for each chronology).

The main difference between PC1A and PC2A (Figure 4.5) was that PC2A increased steadily from the 1940s to the 1960s and declined thereafter, levelling off somewhat in the late 1990s. PC3A showed low growth in the early 1900s, maximum growth from the 1920s through to the 1950s, and generally decreased growth to ca 2000. PC4A (not shown) has a similar trend to PC2A until the 1970s after which there was a rapid increase in growth. TTHH loaded quite heavily on PCs 1-3 through most heavily with the southern grouping, it was evident that, although several sites grouped with TTHH, this growth pattern was neither the dominant nor the only signal from within this network over the entire 20th century. Although most chronologies showed decreased growth in the latter part of the 20th century, the timing of maximum growth varied across the network.

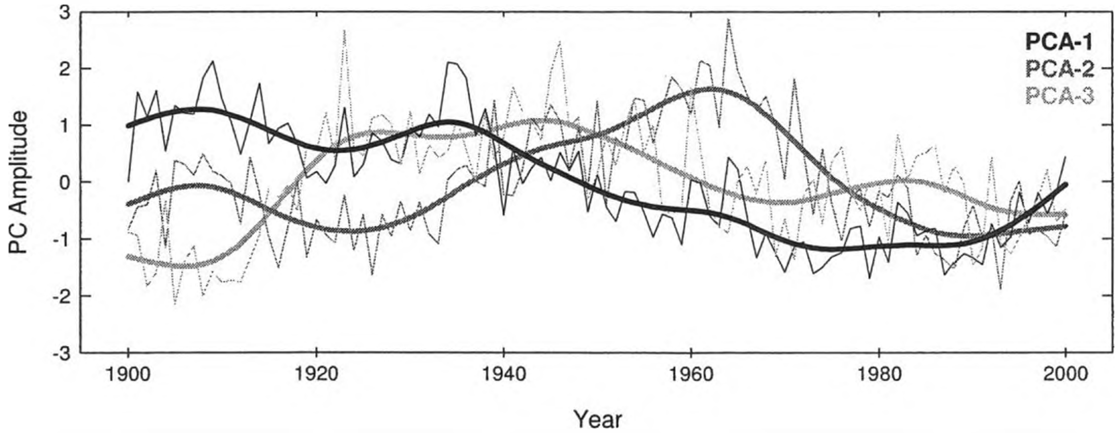


Figure 4.5 PCA loadings for the first three components of 1900 – 2000 period. 25-year splines superimposed (in bold). The TTHH site loads most strongly on PC2-1.

4.2.3.2 The early period (1900-1950)

As might be anticipated from the correlation results, PCA of the early period yielded different and more diverse results with 5 PCs created. PC1E (Table 4.4) included TTHH with most chronologies from the surrounding area and accounted for 26.68% of the total variance (Table 4.4). Mt. Cronin and Black City load higher than Tombstone on this PC but were more highly loaded on PCs 2 and 3 respectively. PC1E showed a steady increase from 1900s to 1940s when it began to decrease slightly (Figure 4.6). PC2E (15.91%) contained the three northernmost sites in the network (PC3A of the 1900-2000 analysis) that showed an overall increased growth trend with the highest values in the 1920s and 1940s. PC3E (15.41%) almost equally weighed, contains two southern sites plus Tsiivii with the lowest growth between 1910s – 1940s. PC4E (14.88%) and PC5E (9.58%) both contained sites from the southern and middle regions of the network and showed different trends. Few of these groups were geographically coherent and this period had the poorest correlation between chronologies.

Table 4.4 PCA output for the Standard Chronologies over the Early period (1900-1950).

Rotated Component Matrix(a)	Component				
	1 (PC1E)	2 (PC2E)	3 (PC3E)	4 (PC4E)	5 (PC5E)
Scriver Creek	**0.842**	0.128	-0.010	0.337	0.081
Talus	**0.799**	0.419	0.009	-0.101	0.235
Ogilvie	**0.798**	0.195	0.329	0.185	0.068
Triangle	**0.719**	0.232	0.315	0.418	0.109
TTHH	**0.716**	0.440	0.080	0.300	0.131
Tombstone	**0.607**	0.462	**0.553**	0.107	-0.087
Interfluve	0.241	**0.805**	0.212	0.084	-0.005
Mount Cronin	**0.625**	**0.725**	-0.028	0.096	0.048
Rock River	0.319	**0.717**	-0.045	0.311	0.351
North Klondike River	0.023	-0.036	**0.933**	0.150	0.048
Black City	**0.626**	0.256	**0.660**	0.021	0.142
Tsiivii	0.274	0.060	**0.556**	0.193	0.366
Vadzaih	0.282	0.092	0.140	**0.878**	-0.008
Airstrip	0.293	0.492	0.072	**0.672**	0.097
Distincta	-0.024	0.118	**0.582**	**0.627**	0.289
Blackstone River	0.097	0.092	0.412	**0.509**	0.398
Sappers Hill	0.096	0.173	0.164	0.066	**0.917**
Engineers Creek	0.467	-0.334	0.173	0.437	**0.499**
Eigenvalue	**4.80**	**2.86**	**2.78**	**2.68**	**1.73**
% Explained Variance	**26.68**	**15.91**	**15.42**	**14.88**	**9.59**
Cumulative % Explained	**26.68**	**42.59**	**58.01**	**72.89**	**82.47**

Those values in **bold** represent the loading greater than 0.500 (the sites are ranked from high to low for each chronology).

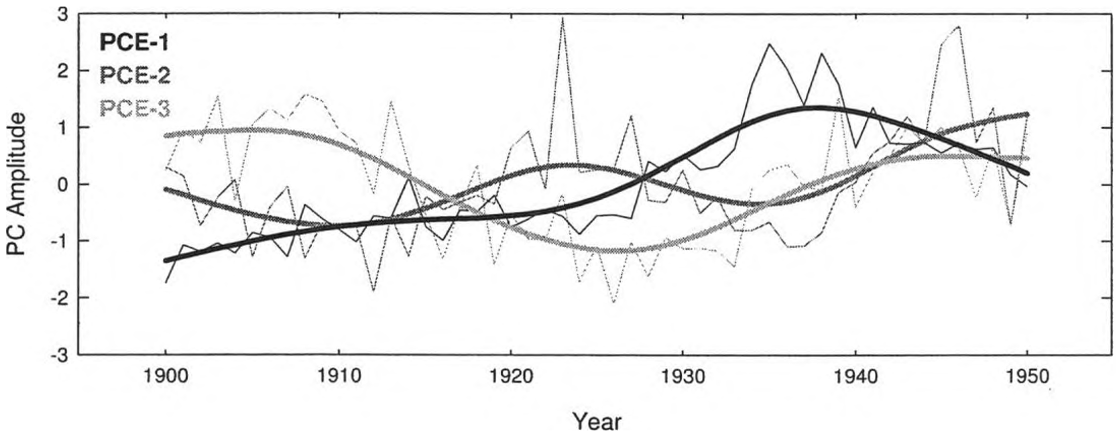


Figure 4.6 PCA loadings for the first three components of 1900-1950 period. 25-year splines superimposed (in bold). The TTHH site and signal are contained within PC1-2.

4.2.3.3 The recent period (1951-2000)

PCA of the last 50 years produced the strongest regional grouping with PC1L including 7 of the 9 sites south of Sappers Hill (including TTHH, Table 4.5) and 34.64% of the total variance (Table 4.5). This group showed the highest growth through the 1960s and decreased thereafter with a slight recovery in the 1990s (Figure 4.7). PC2L (24.55%) showed a similar but subdued pattern through to the 1980s but then accelerated growth through to 2000. The patterns of PC1L and PC2L in this analysis were very similar to PC2L and PC4L respectively in the PCA of the entire record. PC3L (22.35%) showed a steady decline in growth from the 1950s through to 2000 with a small increase around 1980. This grouping was most similar to the correlation results with most "northern" sites loading at > 0.488 on PC3L and most southern sites on PC1L. PC2L has a mixed group geographically, but most chronologies except Tsiivii and Triangle had a high subsidiary loading on the appropriate PC for their region.

Table 4.5 PCA output for the Standard Chronologies over the Recent period (1951-2000).

Rotated Component Matrix(a)			
		Component	
	1 (PC1L)	2 (PC2L)	3 (PC3L)
Talus	**0.888**	0.118	0.189
TTHH	**0.878**	0.163	0.286
Distincta	**0.856**	-0.001	0.389
North Klondike River	**0.849**	0.002	0.445
Tombstone	**0.841**	0.233	0.241
Blackstone River	**0.730**	0.469	0.148
Black City	**0.719**	0.330	0.339
Tsiivii	-0.156	**0.876**	0.166
Triangle	0.213	**0.871**	0.103
Engineers Creek	**0.506**	**0.761**	0.052
Scriver Creek	0.292	**0.725**	0.488
Vadzaih	0.223	**0.675**	**0.556**
Airstrip	0.178	**0.668**	**0.508**
Mount Cronin	0.301	0.086	**0.804**
Interfluve	0.258	0.349	**0.699**
Rock River	0.435	0.457	**0.687**
Sappers Hill	0.482	0.266	**0.678**
Ogilvie	**0.627**	0.229	**0.671**
Eigenvalue	**6.23**	**4.42**	**4.02**
% Explained Variance	**34.64**	**24.55**	**22.35**
Cumulative % Explained	**34.64**	**59.19**	**81.54**

Those values in **bold** represent the loading value greater than 0.500 (the sites are ranked from high to low for each chronology).

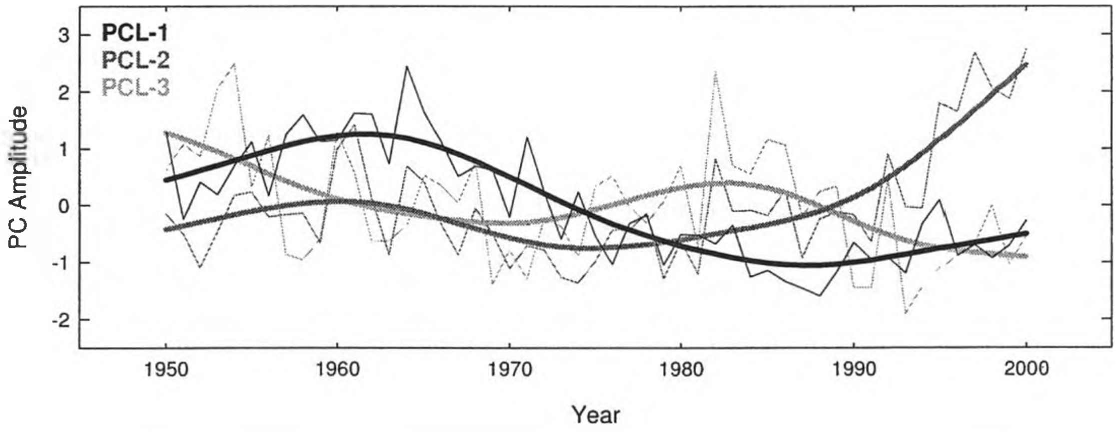


Figure 4.7 PCA loadings for the first three components of 1951-2000 period. 25-year splines for each loading superimposed (in bold). The TTHH signal is contained within PC1-3 (1st loading).

The results from PCA indicated that the low frequency trends over the entire network were quite variable, especially during the first half the 20th century. The results for the entire 20th century identified 4 components accounting for 78.08% of the total variance. The TTHH chronology was grouped into PC2A that showed decreased growth after ca 1970. However TTHH also showed relatively high loadings on PCs 1A and 3A indicating some overlap in signal with the other groups. The dominant PC over the whole century (PC1A) showed an overall decreasing trend in growth from ca 1940 to the 1980s with a minor recovery in the 1990s. In the split period analysis, TTHH loads with the first PC in both analyses. Results for the earlier period showed more variable patterns with 5 components identified that accounted for 82.47% of the total variance. TTHH was included with PC1E that showed an increasing trend of growth from 1900 until about the1940s where the growth began to decrease. Growth patterns in the later 20th century were more coherent among the sites with only 3 main components being identified, containing 81.54% of the total variance. All components showed periods of increased and decreased growth but differ in the timing of these periods with maximum growth in the 1960s (PC1L), 1990s (PC2L), and the 1950s and 1980s (PC3L). This analysis identified regional groupings of common trends with those sites north of TTHH having either a significant increase or a slight decrease in growth during the last ca 20 years (Figure 4.7) Those sites south of Sappers Hill (including TTHH) display the dominant and most regionally coherent signal of decreased growth in the late 20th century.

When looking at the results from the PCA it was evident that some of the sites consistently load together and in the same PC. Rock River, Interfluve, and Mount Cronin (the 3 northernmost sites in this analysis) consistently load within the same group, but never within the first PC. Similarly TTHH, Talus, and Tombstone all load with the same PC group, loading on the PC2A for the 20th century analysis but in the first PC for the split period analyses. Two other sites, Scriver Creek and Triangle, both loaded in the first PC for the entire and early periods and in PC2L for the recent period. The remaining sites lack any consistent patterns in the PCA loading results. Generally, those sites north of Scriver Creek load together and the southern sites load together and typically in the first PC.

4.2.4 Summary

Marker ring, correlation, and principal component analyses were used to identify common patterns of variability in the tree ring chronologies in this network. Marker ring analysis showed strong, synchronous, high frequency variability among sites in extreme years giving prominent marker rings throughout the network. Over the last 100 years (Figure 4.2) it was apparent that positive markers were more common than negative markers, and most of the positive markers occurred during the middle part of the last century that also contains the strongest negative marker ring (1949). During the last 30 years, marker rings are less common suggesting that some trees were responding more to local variability than they did previously or that there had been fewer extreme years.

Correlation analyses were used to examine relationships between the chronologies over the 20th century and to provide an indication of the strength of the common signal across the network. These analyses showed that the Richardson Mountain and Mount Jeckell sites had weak correlations with other sites in the network and they were removed from further analyses. In general, correlation among the residual chronologies was significantly greater than among the standard chronologies suggesting that the interannual variation in ring width was more strongly related to climate than the low frequency trends in these records.

The correlation analyses revealed two main groupings of sites, particularly in the residual chronologies (Figures 4.2, 4.3 and 4.4). The southern sites between Sappers Hill and North Klondike River formed the most coherent group in all analytical periods (Table 4.2). The other common group contained northern sites between Ogilvie and Rock River. This northern group was not as strongly correlated as the southern group, but there were good correlations between adjacent sites (Table 4.2).

The standard chronologies contained greater low frequency variability and correlation analyses revealed a less coherent picture. Over the 20th century the standard chronologies showed a weak grouping of southern chronologies (Sappers Hill to North Klondike River) but no easily identified group in the north of the transect. No geographically coherent groupings were identifiable in the analysis for the early 20th century period, but southern and northern groups of chronologies were more apparent over the 1951-2000 period. These results indicate that the strength of common signal between standard chronologies was quite variable over the 20th century.

Separate PCA analyses were carried out on 18 standard chronologies for the entire 20th century and on each half of that record separately. The PCA groupings for the whole period and early 20th century lacked strong regional association, but groupings from the post-1950 period were quite similar to those from the correlation analysis. TTHH was grouped into the first PC in both split period analyses but PC2A for the 20th century analysis. The low frequency signal in the early period was quite variable but the major differences between the groups defined by PCA are the timing and amplitude of higher growth periods during the later 20th century.

Two sets of chronologies group consistently together over all periods, the three northernmost chronologies and a grouping of TTHH, Talus, and Tombstone in the middle of the transect. The TTHH group (PC1A, PC2E, PC1L) showed peak growth in the 1920s to 1940s and a decline thereafter, whereas the northern group (PC3E, PC3L), although decreasing during the1950s-1970s, showed a slight increase in the 1980s and decreased thereafter. The other dominant PC (PC1A, PC2L) consists of several sites with peak growth in the 1940s and growth decline throughout the late 20th century until a marked recovery after the 1980s. Essentially, the post-1980 period showed some sites with significantly increased growth, some with a slight increase, and others with decreased growth. TTHH was grouped with the dominant PC (PC1L) over this interval (growth decline 1960s-1980s with little change thereafter), however this PC only accounted for 34.64% of the variance in the 1951-2000 analysis. Therefore, although the pattern of growth at TTHH was seen at other sites, this pattern was neither universal nor dominant indicating a variety of responses to recent climate variability occurred in the chronologies within this network.

4.3 Climate-tree growth relationships

4.3.1 Introduction

All tree-ring chronologies contain variations in growth that may be related to individual trees, to particular site or disturbance characteristics, or to some common external factor such as climate. Common patterns of white spruce tree growth from this area of the Yukon are believed to be controlled primarily by summer temperatures (D'Arrigo *et al.*, 2004). The degree to which tree-ring chronologies capture the common climate signal depends on the strength of the relationship between climate and tree growth at a site. This relationship is complex as many localized factors can influence growth. As stated earlier (Chapter 2), dendroclimatic studies assume that the relationship between climate and tree rings is constant over time. However, a number of studies have shown that the common 'stand-wide' signal in several regions in the Yukon or Alaska has deteriorated or weakened after ca 1950 (e.g. Jacoby and D'Arrigo, 1995; Briffa *et al.*, 1998; D'Arrigo *et al.*, 2004). Therefore, careful examination of the stability of this relationship is necessary to identify and understand the common signal and its relationship with climate. The remainder of this chapter examines the relationship between the instrumental record from the closest climate station and 18 standard and residual chronologies over the 20th century in an attempt to isolate the potential common climate signal throughout the network or from specific groups of chronologies within that network.

4.3.2 Methods

Establishing the climate- tree growth relationships over the 20th century is important because it can identify the dominant climate signal(s) influencing tree growth over the entire period of analyses. Pearson Correlation Analysis was extensively used to examine the climate-tree growth relationships. Standard chronologies (including TTHH) were correlated against mean monthly and seasonal temperature values from Dawson, Yukon. As previous dendroclimatic studies (Fritts,1976; Jacoby and Cook, 1981; Jacoby and D'Arrigo, 1989; D'Arrigo *et al.*, 1992) that climate from years(s) prior to the growth year may influence tree growth, climate data from earlier years was included in these analyses. These climate-tree growth relationships were analyzed using a 20-month climate window extending from the previous January (pJan) until August of the current year (see e.g. Luckman *et al.*, 2002). The initial analyses investigated the temperature-tree growth relationships over the entire 20th century. Subsequent analyses in this thesis determined whether these relationships were consistent over split period analyses using two 50-year periods.

Correlation analyses were carried out between the tree-ring data (18 standard tree-ring chronologies plus 5 principle components) and climate data. The climate data used were individual mean monthly temperatures for each month from January of the previous year to August of the growth year for Dawson, Yukon. Subsequent analyses were carried out for annual (Jan-Dec) and seasonal (Winter (DJF), Spring (MAM), Summer (JJA), and Fall (SON) data. Significant ($p \leq 0.05$) relationships were identified and considered for further analyses in this thesis.

4.3.2.1 Climate data

Ideally, the climate record needed to calibrate tree-ring climate relationships should be located in close proximity to the tree ring sites (if possible within the network), and be complete, homogenous and as long as possible. Fortunately, the longest homogeneous climate record in the Yukon is for Dawson which is also the closest site to the tree-ring chronologies. Unfortunately, it is the only site in the Yukon with data prior to 1924, is a valley floor site and is between approximately 100 km from the nearest tree-ring site. However, the next closest site is at Mayo (record 1924-2006, 504 m elevation and ca. 150 km from the closest site. Therefore, the Dawson record was used as the data for this analysis.

The Dawson meteorological station (64.05° N; 139.13° W; 370 m) is located approximately ca. 100 km southwest of the network and has a temperature record from 1897 to 2004. The temperature record from Dawson had been used for all analyses of climate-tree growth relationship at TTHH (D'Arrigo *et al.*, 2004). In the present study these data were accessed from the Adjusted Historical Canadian Climate Data (AHCCD) website (http://www.cccma.ec.gc.ca/hccd/) maintained by Environment Canada. This data set had been corrected for errors and inhomogeneities (Vincent, 1998; Vincent and Gullett, 1999). The Dawson record consisted of mean monthly maximum, minimum and mean temperatures, rainfall, snowfall and precipitation. Each record varied in length and completeness. There were no missing values for the 20th century temperature series. Mean summer temperature is 13.2° C over this period.

4.3.2.2 Tree ring data

The tree ring data used in the following analyses were the 18 standard chronologies considered suitable for further analyses (see sections 3.3 and 3.4). Analyses were also carried out using selected results from the PCA of these chronologies. Combinations of chronologies used in the PCA of the 20th century (highest loadings) are shown in Table 4.6 and time series plots of the individual chronologies shown in Figures 4.8, 4.9, 4.10 and 4.11.

Table 4.6 Chronology association for the 20th century analyses.

Chronology	PC1A	PC2A	PC3A	PC4A	PC1E	PC2E	PC3E	PC4E	PC5E	PC1L	PC2L	PC3L
Rock River			X			X						X
Interfluve			X			X						X
Mount Cronin			X			X						X
Vadzaih	X							X			X	
Tsiivii				X			X				X	
Airstrip				X				X			X	
Scriver Creek	X				X						X	
Ogilvie	X				X							X
Sappers Hill	X								X			X
TTHH		X			X					X		
Engineers Creek	X								X		X	
Talus		X			X					X		
Triangle	X				X						X	
Distincta	X							X		X		
Blackstone River		X						X		X		
Black City		X					X			X		
Tombstone		X			X					X		
North Klondike Rr	X						X			X		

The groups listed represent the combinations of chronologies loading the highest within each factor.

Those standard chronologies grouped into PC1A showed an overall decreasing trend over the 20th century with some of the chronologies displaying an increase in recent years. In most of the chronologies, there was increased growth just prior to the1940s followed by a steady decline (Figure 4.8). The majority of chronologies grouped in PC2A showed an increase until just before 1940 after which ca 30 years of steady growth were followed by decreasing growth. All of the chronologies from this group showed a sharp increase over the last ca 20 years (Figure 4.9). The chronologies grouped in PC3A showed a relatively uniform growth pattern over the entire 20th while the two chronologies (Tsiivii and Airstrip; Figure 4.10) in PC4A had an early period of reduced growth followed by an increase through the remaining part of the century (Figure 4.11).

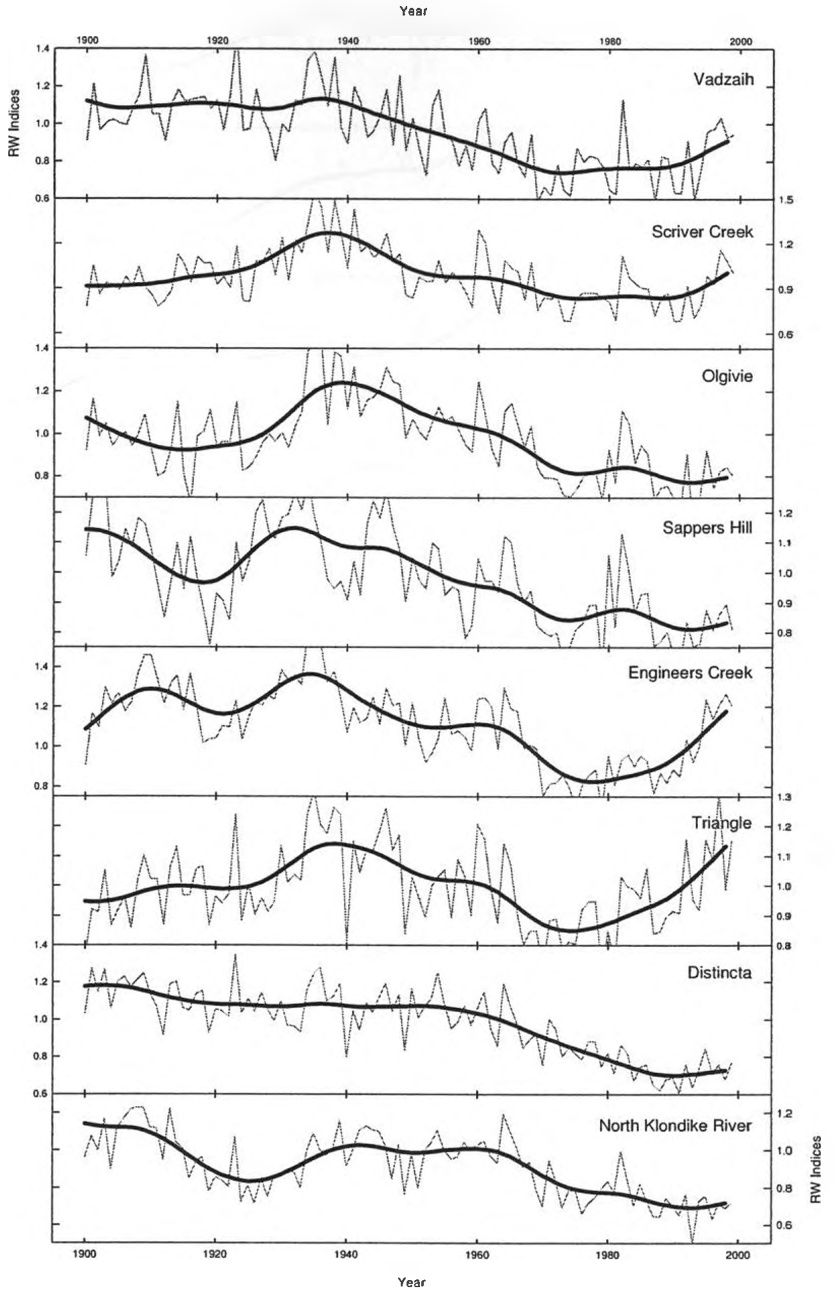


Figure 4.8 Standard chronologies that group in PC1A. The low frequency trend has been highlighted by using a 25-year spline. The vertical scales are variable to emphasize the common low frequency trends between chronologies in the group.

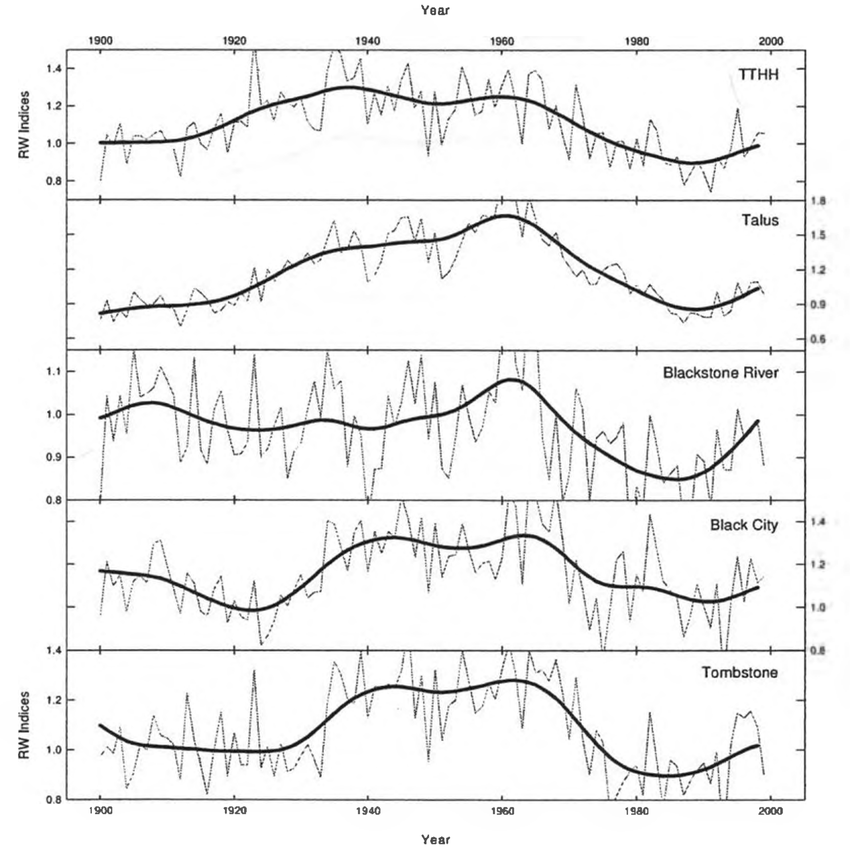


Figure 4.9 Standard chronologies that group in PC2A. The low frequency trend has been highlighted by using a 25-year spline. The vertical scales are variable to emphasize the common low frequency trends between chronologies in the group.

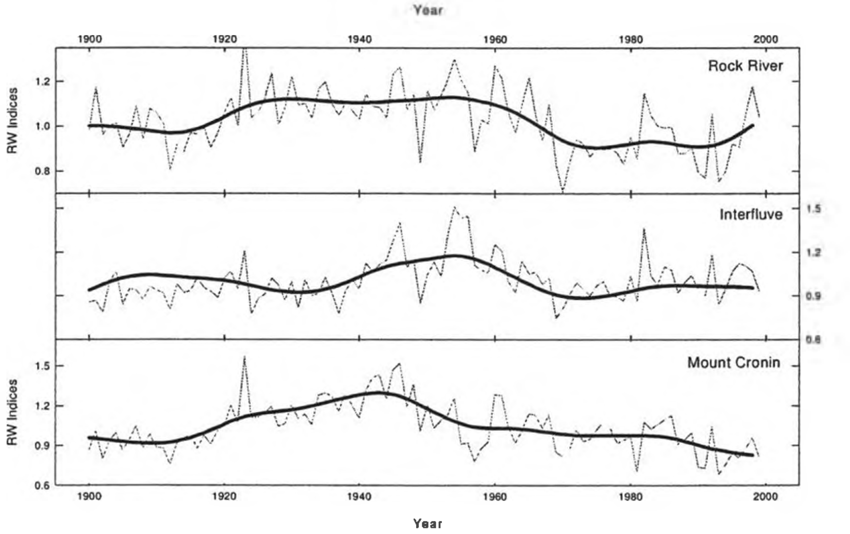


Figure 4.10 Standard chronologies that group in PC3A. The low frequency trend has been highlighted by using a 25-year spline. The vertical scales are variable to emphasize the common low frequency trends between chronologies in the group.

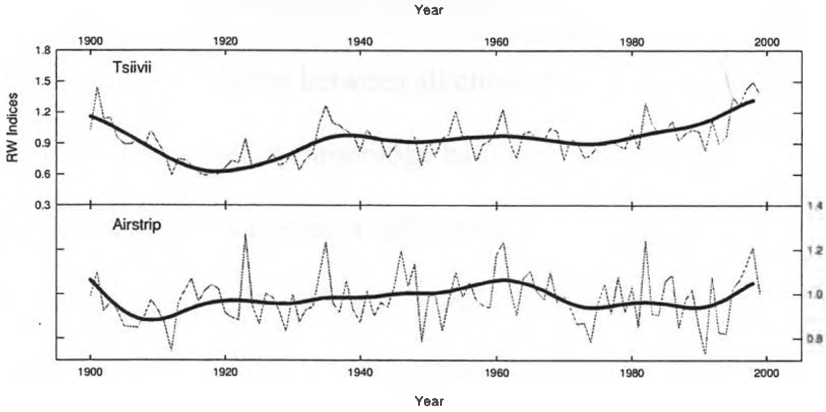


Figure 4.11 Standard chronologies that group in PC4A. The low frequency trend has been highlighted by using a 25-year spline. The vertical scales are variable to emphasize the common low frequency trends between chronologies in the group.

4.3.3 Results

4.3.3.1 The 20th century

The results from the correlation analyses between the standard chronologies and mean Dawson temperatures are summarized in Tables 4.7 and 4.8. Minimum and maximum temperatures were also used, but not discussed here since the results were similar to the results from the mean temperatures discussed below. Most of significant correlations were negative (63 monthly analyses, 39 seasonal ones). The monthly correlations were mainly previous summer (usually previous June and July) and current spring (mainly March) and all are negative. Results for the temperatures in summer of the growth year were weaker but, interestingly, three northern sites showed positive relationships with June; however, four southerly sites were negatively correlated with June and July. The seasonalized data showed strongest relationships with previous summer (16/18 negative) and growth-year spring (13/18 negative). Only Tsiivii was positively correlated with summer, but six other sites were negatively correlated with this season. Tsiivii, Interfluve, and Tombstone were the only sites not correlated negatively with pJuly, the average correlation between all chronologies and pJuly was -0.359 and -0.339 for pSummer. The standard chronology having the strongest relationship with these two temperature variables was Distincta (pSummer = -0.531; pJuly = -0.466; $p \leq 0.05$). Monthly and seasonalized results for the PCs showed a similar pattern but were weaker. Generally, TTHH showed similar correlation patterns to the majority of the sites.

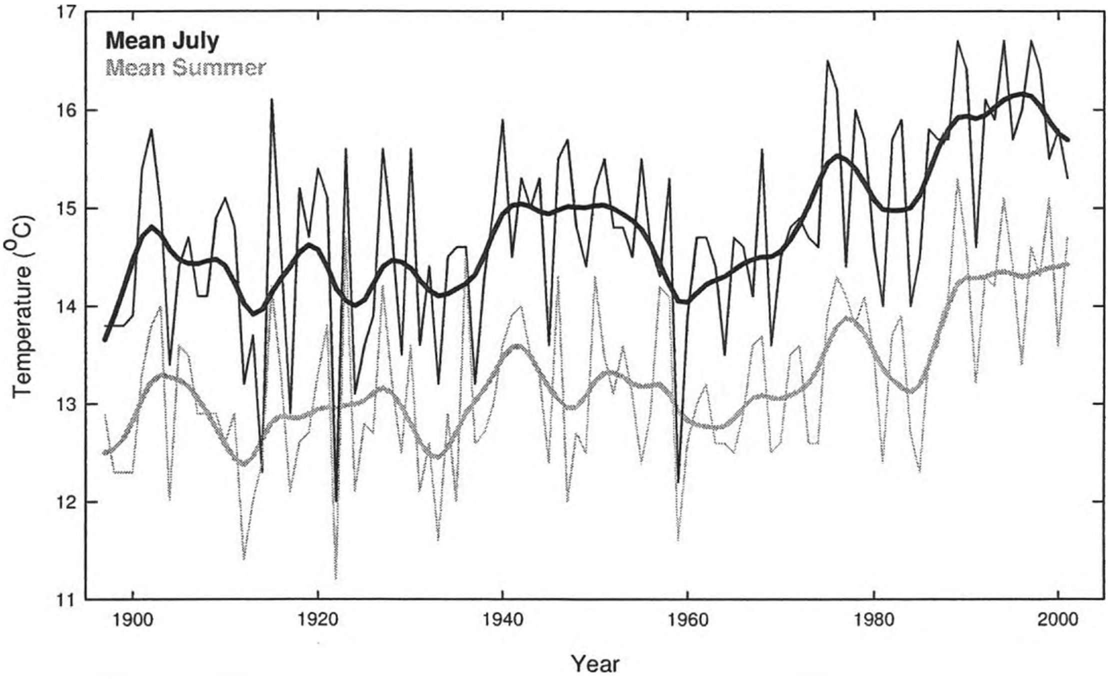


Figure 4.12 Mean Dawson temperature 1900-2000. Previous July (black) and previous Summer (June, July and August mean monthly temperatures) with 10 year splines for each plot superimposed (in bold).

Table 4.7 Significant correlations ($p \leq 0.05$) between mean monthly Dawson temperatures and standard chronologies over the 1900-2000 period.

1900-2000	pJan	pFeb	pApr	pJune	pJuly	pAug	Feb	Mar	Apr	May	June	July
Rock River			-0.22	-0.22	-0.35			-0.30				
Interfluve	0.22	0.22									0.21	
Mount Cronin					-0.34	-0.22		-0.26				
Vadzaih				-0.23	-0.45	-0.27	-0.20					
Tsiivii			0.21							0.37	0.39	
Airstrip		0.24		-0.24	-0.31						0.22	
Scriver Creek					-0.34	-0.22						
Ogilvie				-0.28	-0.40	-0.29		-0.23				
Sappers Hill			-0.25		-0.36	-0.23		-0.34			-0.20	-0.20
TTHH				-0.30	-0.40		-0.23	-0.30	-0.23			
Engineers Creek					-0.30						-0.24	-0.24
Talus					-0.26			-0.20				
Triangle					-0.23							
Distincta			-0.24	-0.29	-0.53	-0.23	-0.30	-0.43	-0.26		-0.34	-0.24
Blackstone River				-0.31	-0.44		-0.22	-0.32	-0.20			
Black City				-0.24	-0.21				-0.20			
Tombstone				-0.30				-0.25	-0.24			
NKR				-0.29	-0.48	-0.24	-0.23	-0.34			-0.26	-0.25
# Positive	**1**	**2**	**1**							**1**	**3**	
# Negative			**2**	**10**	**15**	**7**	**5**	**10**	**5**		**4**	**4**
PC1-1				-0.20	-0.43	-0.27		-0.20	-0.23			-0.28
PC2-1				-0.26	-0.25				-0.28	-0.27		
PC3-1	0.23											
PC4-1		0.22	0.28						0.20		0.25	0.43

Table 4.8 Significant correlations ($p \leq 0.05$) between seasonal and annual mean Dawson temperatures and standard chronologies over the 1900-2000 period.

1900-2000	pAnnual	pWinter	pSpring	pSummer	pAutumn	Annual	Winter	Spring	Summer
Rock River			-0.26	-0.33				-0.29	
Interfluve	0.23	0.23							
Mount Cronin				-0.32				-0.21	
Vadzaih				-0.43		-0.20		-0.22	
Tsiivii			0.22						0.38
Airstrip				-0.29					
Scriver Creek				-0.33					
Ogilvie			-0.21	-0.44				-0.26	
Sappers Hill			-0.20	-0.36				-0.27	
TTHH				-0.33	0.21			-0.35	
Engineers Creek				-0.30					-0.21
Talus				-0.21				-0.21	
Triangle				-0.22					
Distincta			-0.27	-0.47		-0.34		-0.46	-0.24
Blackstone River			-0.22	-0.42		-0.28		-0.34	
Black City				-0.21					
Tombstone				-0.32				-0.30	
NKR				-0.45		-0.25		-0.35	-0.22
# Positive	**1**	**1**	**1**		**1**				**1**
# Negative			**5**	**16**		**4**		**11**	**3**
PC1-1			-0.20	-0.40		-0.21		-0.26	-0.23
PC2-1				-0.23				-0.29	
PC3-1									
PC4-1	0.23		0.27						0.38

4.3.3.2 Split period analyses

Split period analyses were undertaken to examine whether the tree-ring/climate relationships differed between the first and second halves of the 20th century (Tables 4.9-4.12). For the monthly analyses most results for the first half of the 20th century (Table 4.9) showed positive relationships, particularly for June and July of the growth year and the northernmost sites. About 25% of the sites showed negative correlations with prior June and July plus January of the growth year. Seasonal correlations (Table 4.10) showed positive relationships (7 of 18) with the summer of the growth year and four sites were negatively correlated with prior summer. For the latter part of the 20th century almost all significant correlations with monthly data were negative (Table 4.11) and most strongly with prior June (9/18) and July (14/18) plus April (11/18), May (9/18) and July (7 chronologies) of the growth year. Seasonal correlations (Table 4.12) were negative with spring and summer in the prior (10/18; 14/18) and current year (13/18, 6/18) respectively.

Significant correlations were generally more numerous and stronger in the latter half of the century. Many chronologies changed the sign of correlations with summer temperatures of the growth year going from positive to negative relationships. Chronologies at both ends of the network and TTHH responded positively with June temperatures. The distribution of sites indicating a positive relationship with summer was similar to that of chronologies correlated with the individual summer months. The chronologies in the central part of the network (including TTHH) lacked any significant relationships with July temperature. Four chronologies (Tsiivii, Airstrip, Distincta and Blackstone River) were negatively correlated with pJuly and pSummer temperatures.

The results over the 1951-2000 period were similar to the entire 20th century differ from those for the 1900-1950 period with substantially more negative (74) than positive (6) significant correlations between the chronologies and mean monthly temperatures. The strongest relationships over this period were between 14 chronologies (including TTHH) and pJuly and pSummer. Vadzaih, Tsiivii, Engineers Creek, and Triangle were the only chronologies not in this group. Summer and spring seasons of the prior year plus April and spring of the current year had the highest numbers of negatively correlated chronologies (14, 10, 11 and 13 respectively, Tables 4.11 and 4.12).

Table 4.9 Significant correlations ($p \leq 0.05$) between mean monthly Dawson temperatures and standard chronologies over the 1900-1950 period.

1900-1950	pJan	pFeb	pApr	pMay	pJune	pJuly	pAug	Jan	Apr	June	July
Rock River	0.28									0.34	0.34
Interfluve	0.42	0.39								0.30	0.35
Mount Cronin	0.39									0.29	
Vadzaih			0.29		-0.33	-0.42					
Tsiivii										0.33	0.29
Airstrip					-0.32	-0.34					0.30
Scriver Creek											
Ogilvie											
Sappers Hill											
TTHH										0.36	
Engineers Creek								-0.30			
Talus	0.33										
Triangle											
Distincta						-0.35		-0.37	-0.28	0.45	
Blackstone River					-0.34	-0.28	-0.29	-0.28			
Black City				0.29							0.30
Tombstone					-0.28					0.40	0.31
NKR				0.31						0.33	
# Positive	**4**	**1**	**1**	**2**						**8**	**6**
# Negative					**4**	**4**	**1**	**3**	**1**		
PC1-1											
PC2-1	-0.33					-0.35		-0.34			
PC3-1										0.37	0.34
PC4-1						-0.31					
PC5-1									-0.35		

Table 4.10 Significant correlations ($p \leq 0.05$) between seasonal and annual mean Dawson temperatures and standard chronologies over the 1900-1950 period.

1900-1950	pAnnual	pWinter	pSpring	pSummer	pAutumn	Winter	Summer
Rock River							0.41
Interfluve	0.43	0.45					0.35
Mount Cronin	0.36	0.32					0.34
Vadzaih				-0.42			
Tsiivii							0.29
Airstrip				-0.35			
Scriver Creek							
Ogilvie							
Sappers Hill							
TTHH							0.34
Engineers Creek							
Talus	0.33				0.30		
Triangle							
Distincta				-0.31		-0.28	0.35
Blackstone River				-0.42			
Black City			0.33				
Tombstone							0.34
NKR			0.30				
# Positive	**3**	**2**	**2**		**1**		**7**
# Negative				**4**		**1**	
PC1-1							
PC2-1	-0.29			-0.34			
PC3-1			0.32				0.29
PC4-1							0.33
PC5-1							

Table 4.11 Significant correlations ($p \leq 0.05$) between mean monthly Dawson temperatures and standard chronologies over the 1951-2000 period.

1951-2000	pFeb	pMar	pApr	pMay	pJune	pJuly	Mar	Apr	May	June	July
Rock River		-0.32	-0.31		-0.26	-0.39		-0.31			
Interfluve						-0.29	-0.30	-0.31			
Mount Cronin			-0.31			-0.49		-0.45			
Vadzaih	0.36										
Tsiivii	0.34			0.30						0.42	0.34
Airstrip	0.32					-0.37					
Scriver Creek						-0.35					
Ogilvie			-0.30		-0.32	-0.57		-0.36	-0.36		-0.35
Sappers Hill					-0.37	-0.45			-0.29		
TTHH			-0.30	-0.32	-0.38	-0.52	-0.37	-0.39	-0.44		-0.35
Engineers Creek											
Talus		-0.39	-0.36	-0.35	-0.32	-0.58	-0.33	-0.38	-0.41	-0.30	-0.52
Triangle											
Distincta			-0.32	-0.29	-0.34	-0.53	-0.43	-0.48	-0.47		-0.44
Blackstone River		-0.29				-0.52	-0.34	-0.33	-0.35		
Black City					-0.33	-0.42		-0.32	-0.45		-0.32
Tombstone					-0.32	-0.53	-0.40	-0.41	-0.47		-0.33
NKR			-0.32	-0.28	-0.47	-0.61	-0.39	-0.51	-0.52		-0.49
# Positive	**3**			**1**						**1**	**1**
# Negative		**3**	**7**	**4**	**9**	**14**	**7**	**11**	**9**	**1**	**7**
PC1-1				-0.35	-0.36	-0.54		-0.35	-0.48		-0.50
PC2-1	0.32										0.37
PC3-1						-0.39		-0.38			

Table 4.12 Significant correlations ($p \leq 0.05$) between seasonal and annual mean Dawson temperatures and standard chronologies over the 1951-2000 period

1951-2000	pAnnual	pWinter	pSpring	pSummer	Annual	Spring	Summer
Rock River			-0.38	-0.36		-0.36	
Interfluve				-0.32	-0.30	-0.36	
Mount Cronin			-0.36	-0.50		-0.42	
Vadzaih							
Tsiivii	0.38	0.35					0.33
Airstrip				-0.34			
Scriver Creek				-0.36		-0.28	
Ogilvie			-0.33	-0.51	-0.28	-0.42	-0.34
Sappers Hill			-0.28	-0.44		-0.33	
TTHH			-0.33	-0.41	-0.45	-0.51	-0.28
Engineers Creek							
Talus	-0.31		-0.49	-0.47	-0.32	-0.48	-0.43
Triangle							
Distincta			-0.36	-0.41	-0.45	-0.59	-0.39
Blackstone River			-0.31	-0.38	-0.32	-0.45	
Black City				-0.32		-0.42	
Tombstone			-0.29	-0.45	-0.48	-0.55	-0.33
NKR			-0.35	-0.53	-0.45	-0.60	-0.43
# Positive	**1**	**1**					**1**
# Negative	**1**		**10**	**14**	**8**	**13**	**6**
PC1-1	-0.30		-0.37	-0.40	-0.39	-0.48	-0.38
PC2-1	0.28	0.32					
PC3-1				-0.43		-0.29	

4.3.3.3 Discussion

The examination of the standard chronologies identified different relationships with temperatures depending on the time period being investigated. Summarizing the results from all three time periods (Tables 4.7 – 4.12), it was apparent that the chronologies from the 1900-2000 and 1951-2000 intervals were generally negatively correlated with temperatures. These results were mirrored by the regional PCs defined in the earlier analysis. The 1951-2000 period contained the largest number of significant correlations for monthly temperatures with 74/80 of these being negative. Similar results were seen in the analysis of the 20th century record where 63 of 72 significant correlations were negative. Results for the early 20th century were weaker and more variable with 23 of 36 significant correlations being positive. All three periods of analyses showed negative relationships between ring widths and temperatures in the previous summer.

However, relationships between temperatures and growth in the current year changed from positive to negative for a number of sites over the 20th century based on the split period analysis: only some of the most northern sites retained a significant positive correlation with temperatures in the summer months throughout the 20th century.

The two dominant relationships seen over the 20th century were the negative relationships between growth and pJuly and pSummer mean temperatures. However, the strength of these relationships varies through the 20th century. Figures 4.13 and 4.14 show shifting correlation analyses between each standard chronology and pJuly and pSummer temperatures using a 20 year moving window, advanced by one year. Stronger negative relationships are observed between ca. 1914-1932; 1955-1970, and in the 1980s with weaker, dominantly negative, relationships for the intervening periods. When looking at a "spaghetti plot" of the moving correlations between each of the 18 standard chronologies and pJuly and pSummer, it was apparent that each followed a similar pattern. Figures 4.15, 4.16 and 4.17 show moving correlation patterns between the 18 standard chronologies and current July and Summer temperatures (respectively) that have more positive correlations than Figures 4.13 and 4.14. The correlation patterns present in the current years growth figures (4.15, 4.16 and 4.17) show a significant change in correlation sign between 1965-1975, a pattern that was absent with the moving correlation with the previous year's growth. Mean June temperatures contained the highest number of positive correlations over the 1900-1950 period with the standard chronologies (Table 4.9), but displayed a similar pattern to the current July temperatures (Figures 4.15 and 4.16). Figure 4.17 best shows the change in relationship between the standard chronologies and current summer temperatures as positive correlations are present from 1910-1950; where the correlations become negative until 1975 where they began to become a positive again, a trend that is similar to TTHH (dark grey).

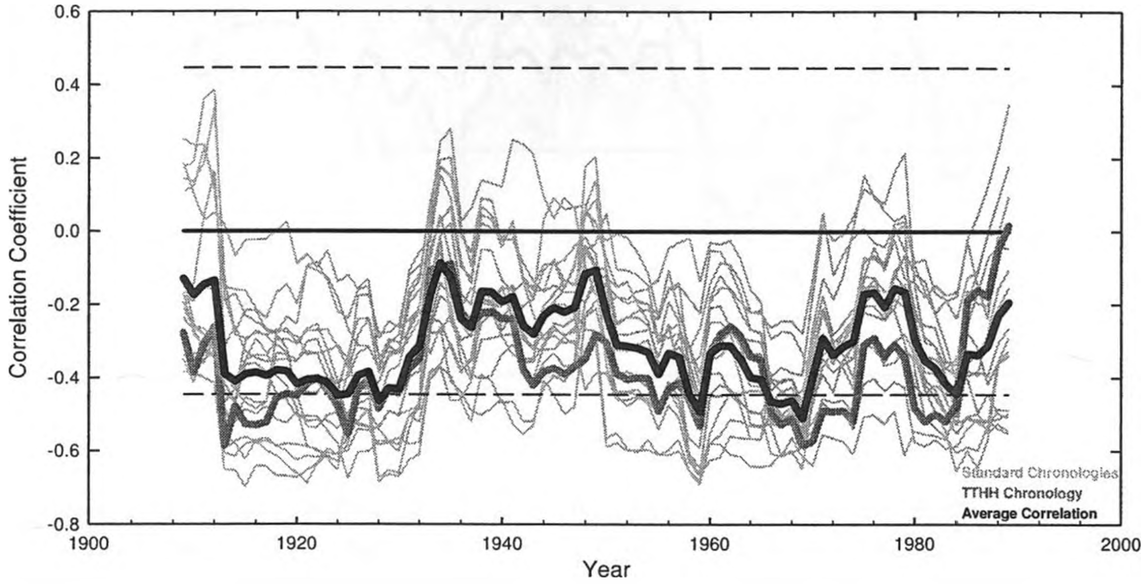


Figure 4.13 Moving correlations (20-year - moved ahead one year) over the entire 20th century between each standard chronology (TTHH in dark grey) and previous July mean monthly temperatures (grey) with the average of these correlations in bold. The dashed lines represent the statistical threshold ($p \leq 0.05$).

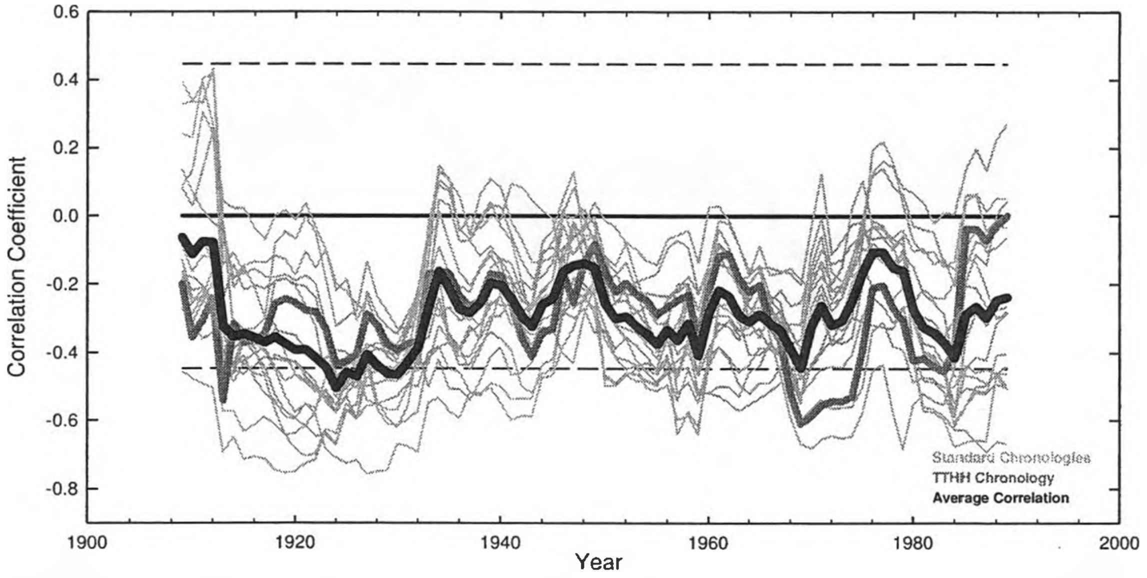


Figure 4.14 Moving correlations (20-year - moved ahead one year) over the entire 20th century between each standard chronology (TTHH in dark grey) and previous Summer (average June, July and August) mean temperatures (grey) with the average of these correlations in bold. The dashed lines represent the statistical threshold ($p \leq 0.05$).

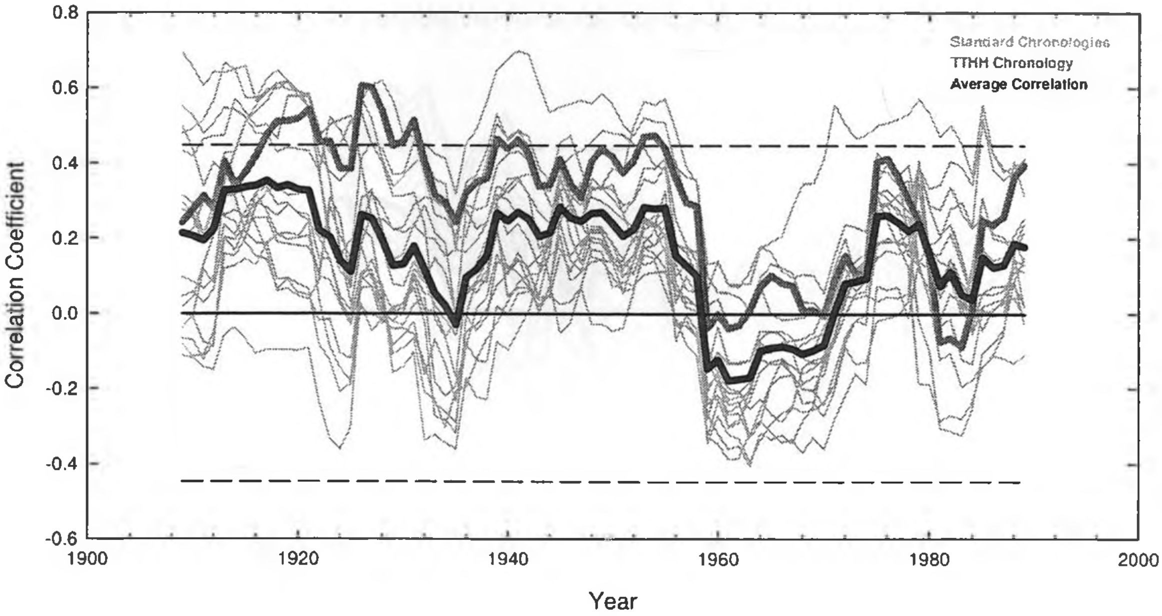


Figure 4.15 Moving correlations (20-year - moved ahead one year) over the entire 20th century between each standard chronology (TTHH in dark grey) and June mean monthly temperatures (grey) with the average of these correlations in bold. The dashed lines represent the statistical threshold ($p \leq 0.05$).

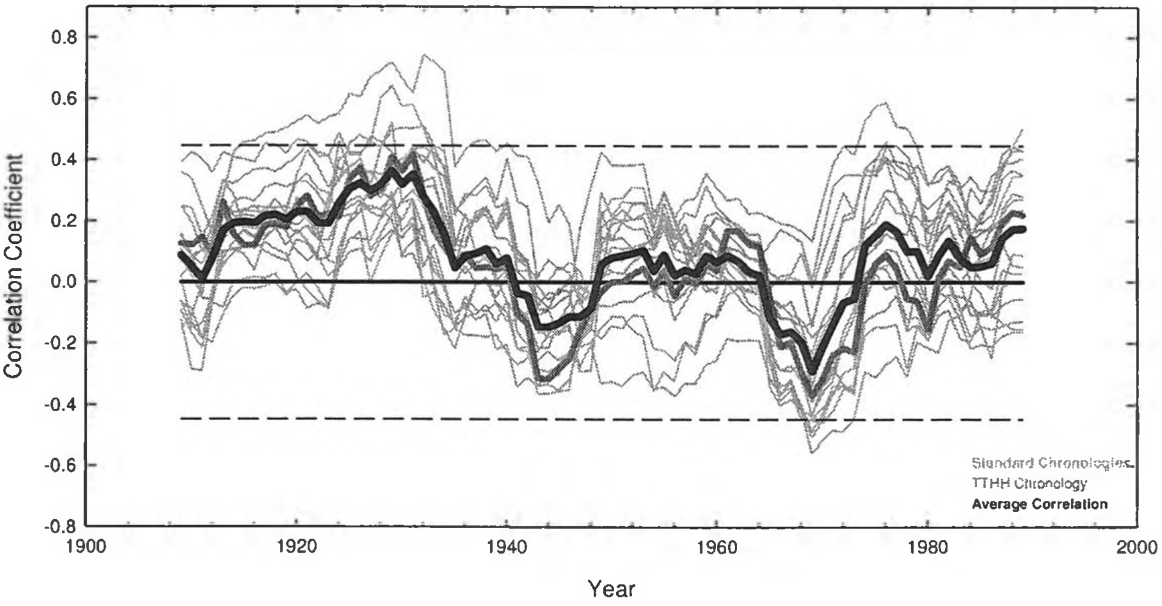


Figure 4.16 Moving correlations (20-year - moved ahead one year) over the entire 20th century between each standard chronology (TTHH in dark grey) and July mean monthly temperatures (grey) with the average of these correlations in bold. The dashed lines represent the statistical threshold ($p \leq 0.05$).

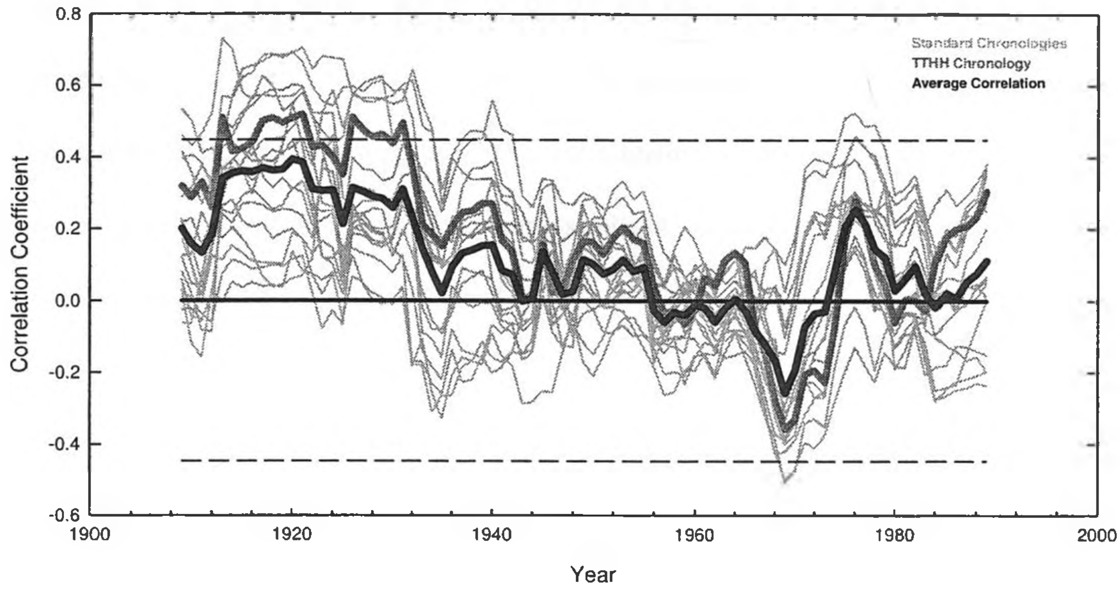


Figure 4.17 Moving correlations (20-year - moved ahead one year) over the entire 20th century between each standard chronology (TTHH in dark grey) and Summer (average June, July and August) mean temperatures (grey) with the average of these correlations in bold. The dashed lines represent the statistical threshold ($p \leq 0.05$).

The results over the 1951-2000 period were similar to those of the entire 20th century with the most common significant correlations having negative relationships with pJuly (14), pummer (14), p(13), and April (10) of the current year. The negative correlations with pJuly were slightly stronger during this period with an average correlation of -0.47 (compared to -0.36 during the full 20th century period and -0.35 during the 1900-1950 period). The 1900-1950 period does show positive relationships for some sites for June (8), July (6) and summer temperatures of the growth year, but only a very few sites had positive relationships in the late 20th century.

These climate-tree growth analyses indicated that generally the strongest relationships between the standard chronologies and climate over the entire period were negative correlations with temperatures in the preceding summer and particularly July (Tables 4.11 through 4.16). Shifting period analysis showed distinct intervals of stronger and weaker expressions of this relationship over the 20th century. Some sites showed positive relationships that became negative in the second half of the century. It was also noted that TTHH correlated with the dominant climate variable identified within each time period of investigation indicating some similarity between this network of sites and the TTHH chronology.

CHAPTER FIVE

Intra-Site Variability in Tree Ring Responses

5.1 Introduction

Dendroclimatic research, specifically climate reconstruction, is based on the "Principle of Limiting Factors" and the "Principle of Ecological Amplitude" (Chapter 2). In general, both principles assume that the relationship between climate and tree growth stays constant over time ('the Uniformitarian Principle', see Fritts, 1976). A weakening of the common signal from treeline sites in the Northern Hemisphere, specifically northwestern North America, has been documented in recent years (e.g. D'Arrigo *et al.*, 2004), and one proposed explanation has been the presence of mixed climatic responses from within the same stand of trees (D'Arrigo *et al.*, 2004; Pisaric *et al.*, 2007). In some cases the temperatures are thought to have exceeded a specific threshold inducing increased moisture stress in the trees, and thus causing a loss of the temperature signal (e.g. Barber *et al.*, 2000; Lloyd and Fastie, 2002). This "divergence" in response compromises some of the basic assumptions of dendroclimatology and has extremely important implications for future dendroclimatological research.

In studies of this problem in Alaska, Wilmking *et al.* (2004, 2005) identified distinctive sub-population signals within sites that compromised the strong common stand-wide signal previously assumed to occur at such sites. Wilmking *et al.* (2004) used an extensive Alaskan database of tree-ring series and identified groups of trees within a site that differed in their response to climate and developed separate "responder" chronologies for these distinctive groupings. Using the correlation values between individual tree chronologies (developed by averaging the detrended indices for all cores in each tree) and a temperature index, they used cluster analysis to identify the two most dominant variables that separated the trees on the basis of common signals. One group contained trees having a negative correlation (< -0.25) with temperatures of the prior July, while the other group contained those trees with a positive (> 0.25) correlation score with spring temperatures, both over the 1951-2000 period. These groups of trees were used to develop individual ‘responder’ chronologies. Once the responder chronologies were created, analyses of the relationships with climate variables pre- and post-1950 was completed and discussed. Based on these responder chronologies, Wilmking *et al* (2004, 2005) concluded that the presence of multiple climate signals from the same stand of trees could have been overlooked in some studies because dendroclimatologists generally only focus on the strongest or aggregate common signal. However, they also found that the exposure to recent warming has strengthened the negative growth response of trees in this region and that drought stress may also be influencing tree growth at treeline sites. Both of these conclusions challenge the basic principles of dendroclimatology, more specifically studies that assume the relationship between tree growth and climate remains constant over time.

This chapter examines whether similar “responder chronologies” occur in the three sites along the Dempster Highway that had the greatest sample replication. In this analysis the “responder” chronologies were compared with standard chronologies from the same sites, the relationships between the “responder chronologies” and climate variables are analyzed and conclusions drawn about the importance of these effects.

5.2 Methods

Chapter 4 examined climate-tree growth relationships for the 20th century for 18 site chronologies along the Dempster Highway, Yukon using standard dendroclimatic procedures. This chapter evaluates the possibility that some of these study sites contain sub-populations of trees that differ in their response to the same climate, thereby diluting any strong stand wide common climate signal. The analysis of sub-populations within a site requires a large sample depth (e.g. Wilmking *et al.*, 2004) to ensure adequate signal strength in the resulting chronologies. Therefore, only the three most replicated sites (Rock River, Distincta and North Klondike River) were used in this analysis. The ring-width series developed for these sites in Chapter 3 were used to create individual "tree" chronologies by averaging the indices for both radii (see Wilmking *et al.*, 2004). Only trees where both series spanned the entire 1900-2000 period were used in this analysis to maintain sufficient sample depth over the entire period and to reduce any potential age-related effect on the common signal from the inclusion of younger trees (Fritts, 1976).

At each site, examination of the relationships between the individual tree chronologies and monthly/seasonal temperatures at Dawson was carried out using the same climate variables and the same techniques as those used in Chapter 4. Significant ($p > 0.05$) relationships over the entire 20th century were identified to provide an indication of the overall relationship between individual trees and Dawson climate variables. Subsequent analyses examined these relationships for the two halves of the 20th century separately. These analyses identified the most strongly correlated climate variables based on the highest number of significant correlations for trees at each site. These variables were then examined to identify whether the tree populations at each site contained a single dominant climate signal or whether different responses were present.

Where multiple signals existed, groups of tree chronologies with significant correlations with specific climate variables were used to develop one or more new "responder chronologies" for the site. Individual tree chronologies were only used in a single responder chronology.

5.2.1 Climate data

The Dawson mean, minimum, and maximum monthly and seasonal climate data were used for this analysis. Maximum summer temperatures show a slight linear trend while minimum summer temperatures have a strong positive trend. Generally, tree growth is more strongly correlated with mean and minimum temperatures (see below). For a more detailed description of the climate data used, see Chapter 4.

5.2.2 Tree-ring data

Three sites, Rock River (46 trees), Distincta (64 trees), and North Klondike River (30 trees) had adequate sample depth for these analyses. North Klondike River (NKR) and Distincta were from the southern half of the network while Rock River was the most northerly site with adequate signal strength (see Chapter 3). Distincta was sampled as three adjacent sub-sites in two different years and contains the highest number of trees sampled at any site. There were no major variations in site characteristics among the sub-sites. Sampling at Rock River identified 4 sub-sites, 2 in a sheltered valley and floodplain and two on the adjacent interfluve[5]. The Rock River site also contained higher numbers of older trees compared to adjacent sites. At North Klondike River the same stand was

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[5] Unfortunately the original field notebook for this site was mislaid and the exact location of these sub-sites within the valley and on the interfluve cannot be verified.

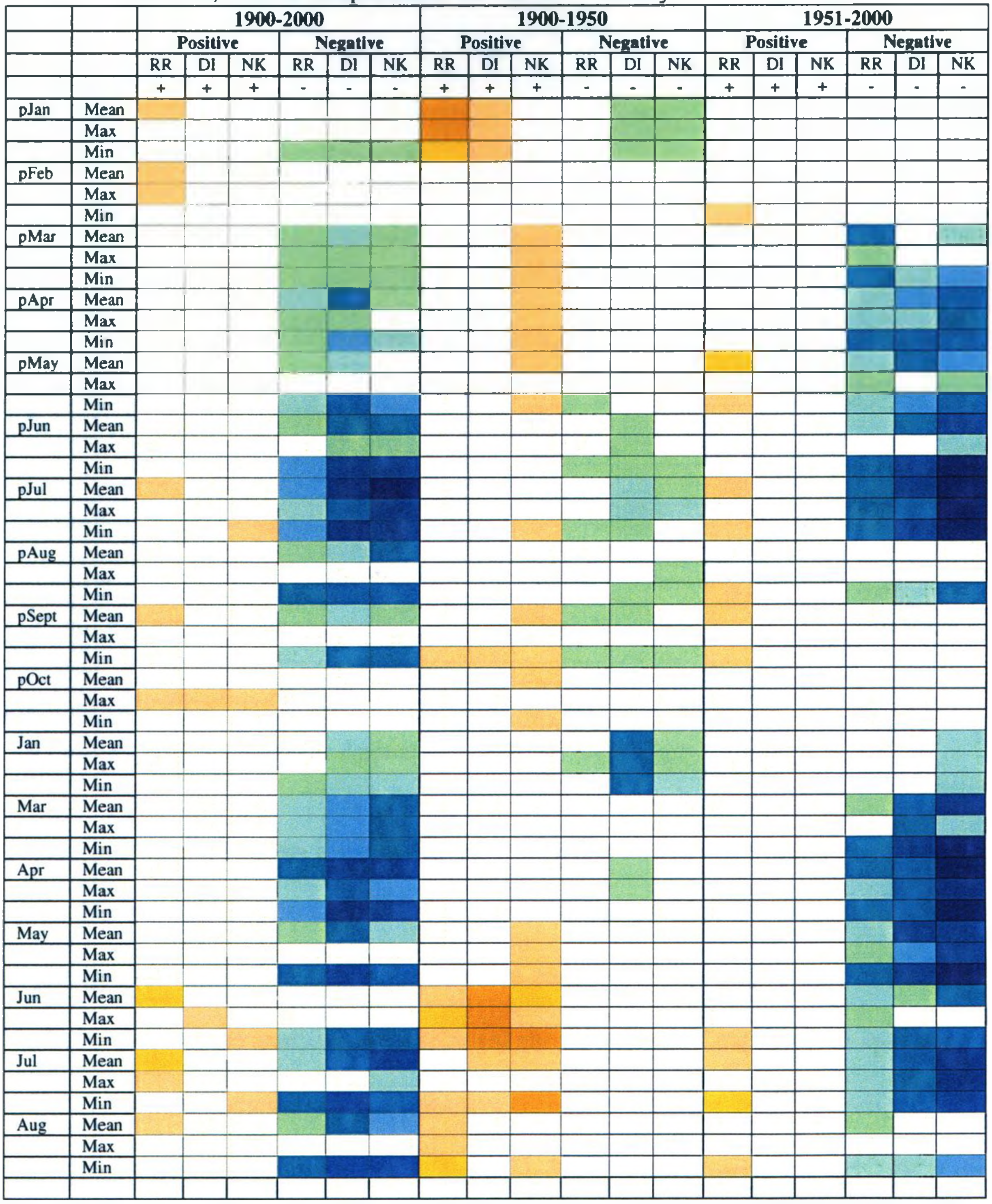
sampled in two different years. For each site, new "responder chronologies" were created based on the relationship between tree chronologies and Dawson temperatures.

5.3 The relationship between "tree chronologies" and Dawson climate

5.3.1 The 20th century (1900-2000)

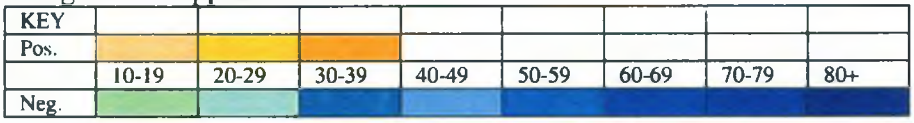
Most of the trees from each site over the entire 20th century were negatively correlated with monthly and seasonal temperatures (Tables 5.1 and 5.2). Higher percentages of trees from Distincta and NKR were negatively correlated with Dawson temperatures when compared to the Rock River site. At least 75% of the trees from Distincta and NKR were negatively correlated with mean July temperatures of the previous year (Table 5.1). Each of these sites also had higher percentages of negative correlations with seasonally-averaged temperatures (Table 5.2) with 77% of the trees from Distincta being negatively correlated with mean spring temperatures and 80% of the NKR trees being negatively correlated with mean summer temperatures of the previous year. Only 48% of the trees from Rock River were negatively correlated with mean July temperatures from the prior year and also with minimum temperatures of spring of the current year. Fewer than 20% of the trees from either Distincta or NKR had positive correlations with any of the Dawson climate variables tested. However 20 – 28% of the trees from Rock River were positively correlated with mean summer, June and July temperatures of the current year and winter temperatures of the previous year.

Table 5.1 Percentage of significant correlations between tree indices and monthly Dawson, Yukon temperatures for the 20th century.



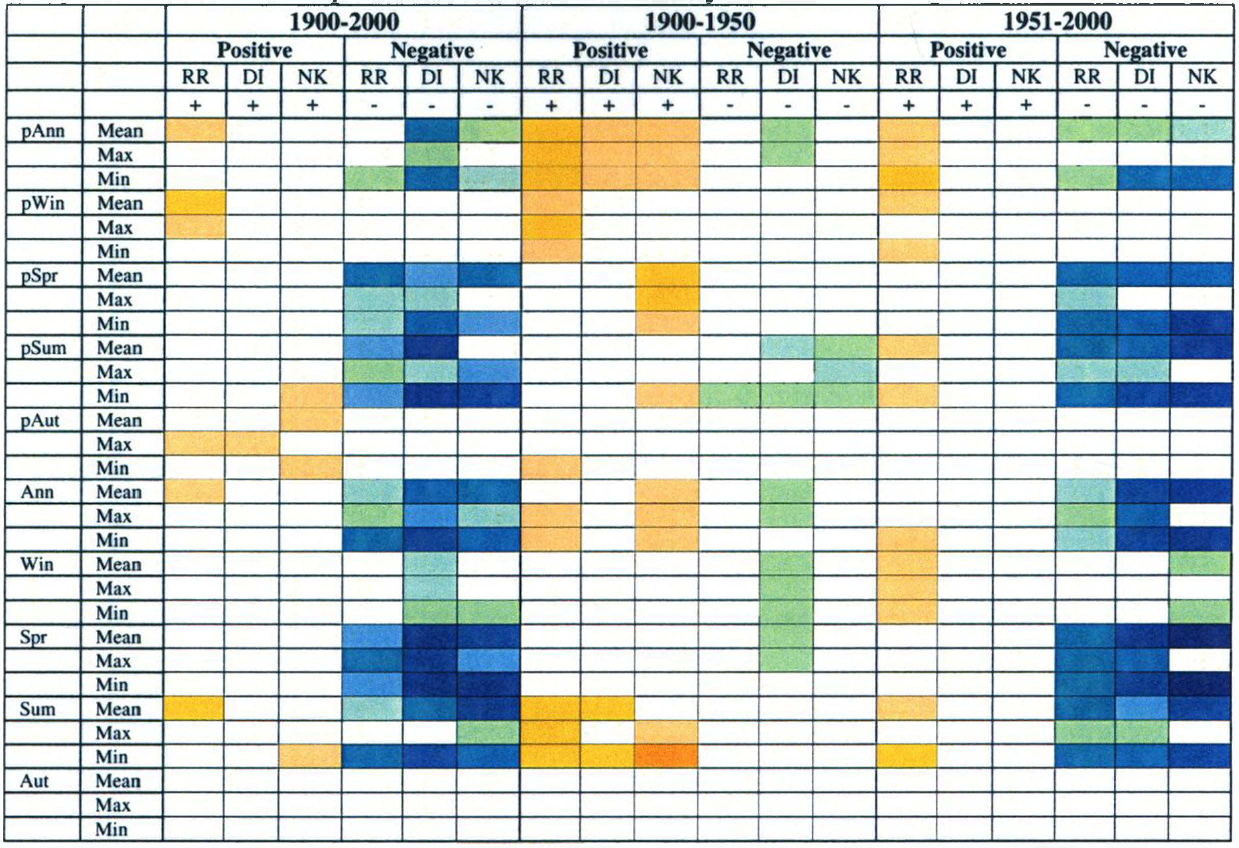
		1900-2000						1900-1950						1951-2000					
		Positive			**Negative**			**Positive**			**Negative**			**Positive**			**Negative**		
		RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK
		+	+	+	-	-	-	+	+	+	-	-	-	+	+	+	-	-	-
pJan	Mean	🟧						🟥	🟧			🟩	🟩						
	Max							🟥	🟧			🟩	🟩						
	Min				🟩	🟩	🟩	🟨	🟧			🟩	🟩						
pFeb	Mean	🟧																	
	Max	🟧																	
	Min													🟧					
pMar	Mean				🟩	▨	🟩			🟧							🟦		▨
	Max				🟩	🟩	🟩			🟧							🟩		
	Min				🟩	🟩	🟩			🟧							◼	▨	▦
pApr	Mean				▨	🟦	🟩			🟧							▨	▦	◼
	Max				🟩	🟩				🟧							▨	▨	🟦
	Min				🟩	▦	▨			🟧							◼	◼	◼
pMay	Mean				🟩	▨				🟧				🟨			▨	🟦	▦
	Max																🟩		🟩
	Min				▨	◼	▦			🟧	🟩			🟧			▨	▦	🟦
pJun	Mean				🟩	◼	◼					🟩					▨	🟦	◼
	Max					🟩	🟩					🟩							▨
	Min				▦	■	■				🟩	🟩	🟩				🟦	◼	▩
pJul	Mean	🟧			▦	▩	█					▨	🟩	🟧			🟦	◼	█
	Max				▨	◼	■					▨	▨				🟦	🟦	█
	Min			🟧	▦	▩	■			🟧	🟩	🟩		🟧			🟦	◼	█
pAug	Mean				🟩	▨	◼												
	Max												🟩						
	Min				🟦	🟦	🟦					🟩	🟩	🟧			🟩	▨	🟦
pSept	Mean	🟧			🟩	▨	🟩			🟧	🟩	🟩		🟧					
	Max																		
	Min				▨	🟦	🟦	🟧	🟧	🟧	🟩	🟩	🟩	🟧					
pOct	Mean									🟧									
	Max	🟧	🟧	🟧															
	Min									🟧									
Jan	Mean					▨	🟩					🟦	🟩						▨
	Max					🟩	🟩				🟩	🟦	🟩						▨
	Min				🟩	▨	▨					🟦	▨						▨
Mar	Mean				▨	▦	◼										🟩	🟦	◼
	Max				▨	▦	◼											🟦	▨
	Min				▨	▦	◼										🟦	◼	▩
Apr	Mean				🟦	■	◼					🟩					🟦	🟦	▩
	Max				▨	◼	▦					🟩					▨	🟦	▩
	Min				▦	▩	■										🟦	🟦	█
May	Mean				🟩	🟦	▨			🟧							▨	◼	◼
	Max									🟧							🟩	▦	◼
	Min				🟦	◼	🟦			🟧							🟦	◼	▩
Jun	Mean	🟨						🟧	🟥	🟨							▨	🟩	🟦
	Max		🟧					🟨	🟥	🟧							🟩		
	Min			🟧	▨	◼	◼	🟧	🟥	🟥				🟧			▨	🟦	🟦
Jul	Mean	🟨			▨	🟦	■		🟧	🟧				🟧			▨	◼	◼
	Max	🟧					▨										▨	🟦	◼
	Min			🟧	🟦	◼	🟦	🟧	🟧	🟥				🟨			▨	◼	◼
Aug	Mean	🟧			🟩	🟦	▦	🟧									🟩		
	Max							🟧											
	Min				🟦	◼	◼	🟨		🟧				🟧			▨	▨	▦

Note: Total number of trees: Rock River (RR: 46), Distincta (DI: 64) and NKR (NK: 30). Full numeric data are given in Appendix Three.



KEY								
Pos.	🟧	🟨	🟥					
	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
Neg.	🟩	▨	🟦	▦	◼	■	▩	█

Table 5.2 Percentage of significant correlations between tree indices and seasonal Dawson temperatures for the 20th century.



		1900-2000						1900-1950						1951-2000					
		Positive			Negative			Positive			Negative			Positive			Negative		
		RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK	RR	DI	NK
		+	+	+	-	-	-	+	+	+	-	-	-	+	+	+	-	-	-
pAnn	Mean	🟧				🟦	🟩	🟧	🟧	🟧		🟩		🟧			🟩	🟩	🟦
	Max					🟩		🟧	🟧	🟧		🟩		🟧					
	Min				🟩	🟦	🟦	🟧	🟧	🟧				🟧			🟩	🟦	🟦
pWin	Mean	🟧						🟧						🟧					
	Max	🟧						🟧											
	Min							🟧						🟧					
pSpr	Mean				🟦	🟦	🟦			🟧							🟦	🟦	🟦
	Max				🟦	🟦				🟧							🟦		
	Min				🟦	🟦	🟦			🟧							🟦	🟦	🟦
pSum	Mean				🟦	🟦						🟦	🟩	🟧			🟦	🟦	🟦
	Max				🟩	🟦	🟦						🟦				🟦	🟦	
	Min			🟧	🟦	🟦	🟦			🟧	🟩	🟩	🟩	🟧			🟦	🟦	🟦
pAut	Mean			🟧															
	Max	🟧	🟧																
	Min			🟧				🟧											
Ann	Mean	🟧			🟦	🟦	🟦			🟧		🟩					🟦	🟦	🟦
	Max				🟩	🟦	🟦	🟧		🟧		🟩					🟩	🟦	
	Min				🟦	🟦	🟦	🟧		🟧				🟧			🟦	🟦	🟦
Win	Mean					🟦						🟩		🟧					🟩
	Max					🟦						🟩		🟧					
	Min					🟩	🟩					🟩		🟧					🟩
Spr	Mean				🟦	🟦	🟦					🟩					🟦	🟦	🟦
	Max				🟦	🟦	🟦					🟩					🟦	🟦	
	Min				🟦	🟦	🟦										🟦	🟦	🟦
Sum	Mean	🟧			🟦	🟦	🟦	🟧	🟧					🟧			🟦	🟦	🟦
	Max						🟩	🟧		🟧							🟩	🟩	
	Min			🟧	🟦	🟦	🟦	🟧	🟧	🟧				🟧			🟦	🟦	🟦
Aut	Mean																		
	Max																		
	Min																		

Note: Total number of trees: Rock River (RR: 46), Distincta (DI: 64) and NKR (NK: 30). Full numeric data are given in Appendix Three.

5.3.2 Split period analyses 1900-1950 and 1951-2000

Over the 1900-1950 interval few trees showed negative correlations with any temperature parameter with maximum negative numbers being ca 30 % for pJuly at Distincta. As with the analysis of the regional chronologies in Chapter 4, the split period analysis identified higher numbers of positive correlations during the 1900-1950 period and strong negative correlations during the 1951-2000 period. During the first half of the 20th century, 33% of trees from Distincta showed positive correlations with mean June temperatures and a similar number (34%) had negative correlations with maximum and minimum January temperatures. In the second half of the century most trees at Distincta and NKR were negatively correlated with mean spring (70%), minimum May, Annual

(67%) and mean May (66%) temperatures, while few trees showed positive correlations. Similar to the results presented in Chapter 4, higher numbers of negative correlations with June and July temperatures of the previous year were also present (similar to NKR).

The trees from the NKR site showed a similar pattern to Distincta with higher numbers of positive correlations during the 1900 – 1950 period and higher numbers of negative correlations during the latter half of the century. During the first half of the century, 30% of the trees were positively correlated with minimum June, July, and summer temperatures. The latter half of the century contained higher numbers of negative correlations with 87% of the trees being negatively correlated with mean and minimum May and spring temperature (Table 5.1). Most trees from the NKR site responded in a similar pattern to the site chronology presented in chapter 4, and no alternate signal was identified here.

At Rock River, at least 30% of the trees during the 1900 – 1950 period were positively correlated with maximum and mean January temperatures of the previous year and 28% had positive correlations with minimum summer and maximum annual temperatures of the prior year. Relatively few trees showed negative relationships with any monthly or seasonal temperatures over this interval. In the latter half of the 20th century, only 10 – 20% of trees at Rock River were positively responding and only moderate numbers (20 – 30%) were negatively responding trees. This contrasts sharply with the Distincta and NKR sites that were dominated by negatively responding trees in this period. At Rock River the maximum number of responders was 39% for trees negatively correlated with mean, maximum, and minimum spring, minimum April, and prior spring temperatures. However, at least 28% of the trees were negatively correlated with present mean and minimum summer, June and July temperatures. Therefore, both negative and positive (minimum summer) responder trees were found at this site and two responder chronologies were developed (Figure 5.2).

The aggregate relationships between individual tree chronologies and Dawson climate data were similar to the results for the standard chronologies presented in Chapter 4 with the strongest and most common significant correlations being negative during the entire 20th century. Over this period more than 75% of the trees at both Distincta and NKR had negative correlations with temperature variables but only a few (<20%) were positively correlated. By comparison Rock River contained only 48% of significant negative correlations but somewhat higher percentages (28%) of positive relationships. Nevertheless, despite the different relative proportions of negative correlations at each site, the highest negative correlations were dominantly with previous July, psummer, and spring of the current growth year. These negatively responding relationships are similar to those for the standard chronologies from the northern sites (including Rock River) that were positively correlated with June temperatures and the southern sites (including Distincta and NKR) that had negative correlations with June and July temperatures. These results help demonstrate the variability in tree and site responses to similar climate variables through out the network. Although the results from Rock River show a mixed response, it would appear the majority of trees at these three sites have a similar negative response to several climate variables.

5.4 The development and evaluation of responder chronologies

The results from the correlation analyses for the 20th century reported above were relatively variable, but identified common patterns of significant correlations with mean current spring and previous summer temperatures over the entire century. The relationships were found to be similar for the entire 20th century and the 1951-2000 period, while the 1900-1950 period contained a greater diversity of relationships. In these analyses the strongest relationships over all were for the late 20th century, and, therefore, this period was used to determine the groupings of trees for responder chronologies. The results from Distincta and NKR indicate a single dominant signal similar to that identified in Chapter 4. However, the Rock River site contains groups of trees with both positive and negative correlations with Dawson summer temperatures, and therefore different responses (multiple signals) exist within that site. Negative responder chronologies were developed for each of the three sites by selecting those trees that were significantly (and negatively) correlated with mean spring and summer temperatures over the 1951-2000 interval. These negative responder chronologies included 62%, 59% and 25% of the trees at Distincta, NKR and Rock River respectively. A positive responder chronology was developed for the Rock River site based on 19% of the trees (Table 5.3). The relationships for the trees at Rock River that were excluded from the two responder chronologies lacked any common patterns and contained varying numbers and combinations of non significant correlations.

Table 5.3 Chronology statistics for Standard and Responder Chronologies.

Chronology	Trees	M.L. (years)	STD. EPS >0.85	% 0.85 or greater	Mean Rbar	Mean Index	M. S. (Std.)	1AC
Rock River	68	151.5	1746-2003	71.7	0.259	0.920	0.122	0.705
Pos Rock	13	182.0	1889-2003	44.4	0.371	0.983	0.136	0.625
Neg Rock	17	203.7	1909-2003	27.5	0.343	0.930	0.136	0.776
Distincta	73	258.4	1666-2003	72.7	0.306	0.954	0.140	0.644
Neg Dist	45	271.1	1669-2003	90.1	0.379	0.971	0.137	0.558
NKR	44	197.8	1739-2003	63.5	0.253	0.957	0.121	0.738
Neg NKR	26	227.4	1898-2003	25.4	0.299	0.954	0.122	0.772

Notes: Trees = Total number of trees used in the creation of the chronology; M.L. = Mean length of the cores; STD. EPS >0.85 = Portions of these Chronologies that meet the signal strength criteria used; M.S. (Std.) = Mean Sensitivity for the Standard chronologies; 1AC = First Order Autocorrelation (all for the Standard Chronologies).

5.4.1 Evaluating the responder chronologies

Table 5.3 compares the basic chronology statistics for the standard site chronologies developed in Chapter 3 and the responder chronologies for each site. The mean length of the tree ring series in the responder chronologies was greater than those in the original chronologies because shorter series (those which did not span the entire 20th century) were excluded from the responder analyses. However, except for Distincta, the EPS-defined length of the responder chronologies was much shorter than the original standard chronologies because of the lower number of trees. However, all chronologies had adequate signal strength over most of the 20th century. The responder chronologies had higher Rbar statistics (Table 5.3) because they shared a stronger common signal than the original standard chronologies.

The low frequency patterns of the Distincta and NKR negative responder chronologies (Figures 5.1 and 5.2, respectively) were broadly similar with lower growth in the early 1800s, increased growth to the 1840s and 1850s followed by relatively high growth until ca 1950 after which growth rapidly declined with a slight increase in the

1990s. Moreover the low frequency trends in the standard and negative responder chronologies for these two sites were also very similar as might be expected given they both contain about 60% of the trees at these two sites. The two Distincta plots (Figure 5.1) follow very similar trends back until ca 1670 when the responder chronology deteriorates and loses signal strength. The low-frequency trends for the two chronologies at NKR were also very similar back to ca 1700, even though the responder chronology lacks adequate signal strength prior to 1900. A greater degree of variability between the two plots appears during the mid 1900s, with both entering the 21st century with rising trend.

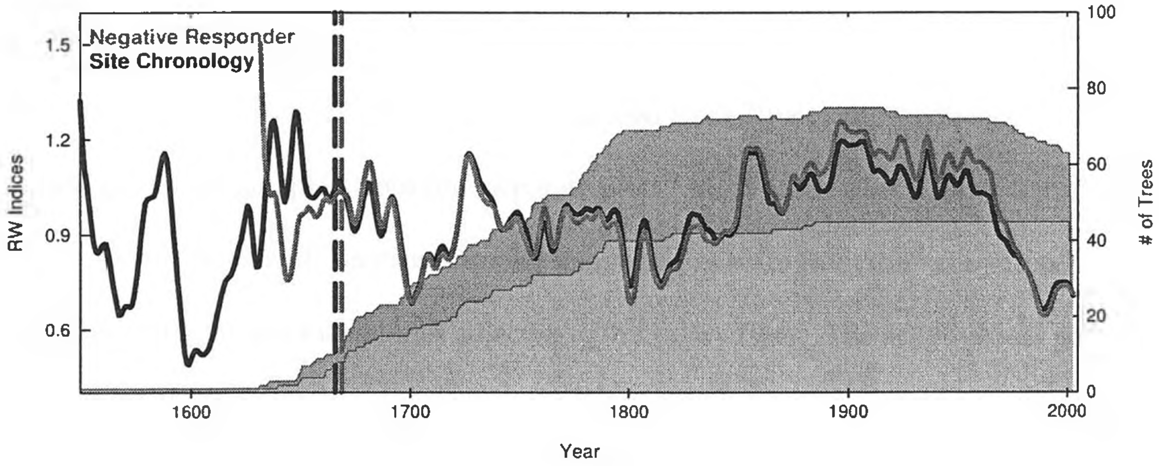


Figure 5.1 Standard and Responder chronologies for Distincta (10-year splines). The vertical black and dark grey dashed lines represent the EPS cut-off for each chronology (dark grey (negative responder): 1669; black (site chronology): 1666). The grey shaded area represents sample depth of the site chronology (dark grey) and negative responder chronologies (light grey).

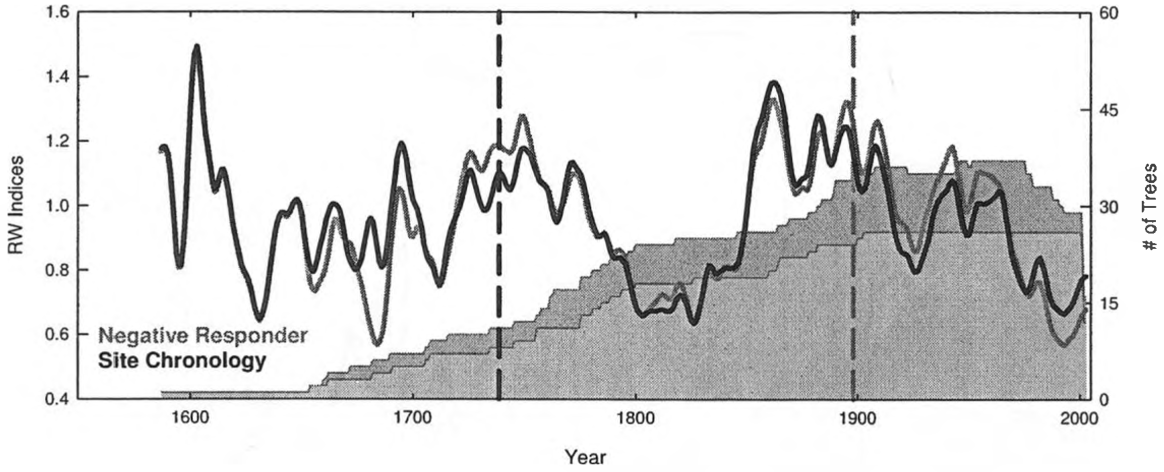


Figure 5.2 Standard and Responder chronologies for NKR (10-year splines). The vertical black and dark grey dashed lines represent the EPS cut-off for each chronology (dark grey (negative responder): 1898; black (site chronology): 1739). The grey shaded area represents sample depth of the site chronology (dark grey) and negative responder chronology (light grey).

The tree chronologies used to create the two Rock River site responder chronologies were sampled from four separate plots. Most of the trees having significant positive correlations with Dawson summer temperatures were from the valley floor with only 8 (of 30) trees from the slopes adjacent to the valley floor. The negative and positive responder chronologies were quite different. The negative responder chronology (Figure 5.3) was similar to Distincta and NKR though the increase in the 19th century is less pronounced. The trees used to create the negative responder chronology included almost equal numbers of trees from the interfluve and more sheltered valley sites. The positive responder chronology showed a slightly increased trend from 1900-1975 where the trend began a steady climb and levels out just after 2000. The original standard chronology contains elements of both responder chronologies, although it more closely follows the pattern of the better-replicated negative responder throughout the 1800s, but it was less variable than (and intermediate between) either in the 20th century. The trends of both responder chronologies from Rock River diverge after ca. 1970 with the negative responder chronology behaving similarly to the standard chronology.

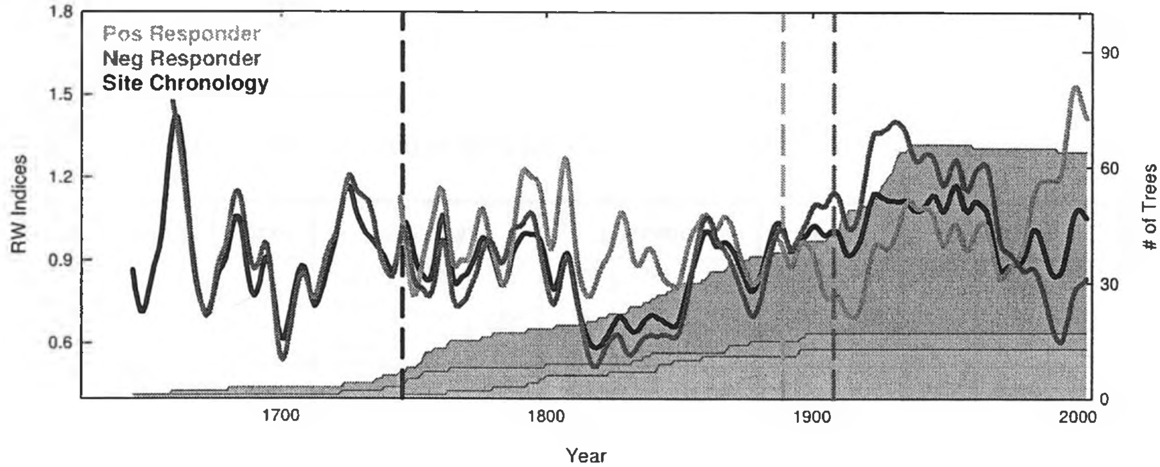


Figure 5.3 Rock River standard and responder chronologies (10-year splines). The vertical black, dark and light grey dashed lines represent the EPS cut-off for each chronology (light grey (positive responder): 1889; dark grey (negative responder): 1909, and black (site chronology): 1746). The grey shaded area represents sample depth of the chronologies (in order from highest to lowest (site chronology, negative responder, and positive responder).

Table 5.4 shows correlations between the standard and responder chronologies with spring and summer temperatures for the previous and current growth years. Given the strong similarities between the standard and negative responder chronologies at Distincta and NKR, the results were predictably very similar except that the responder chronologies usually had a slightly stronger common signal. This was anticipated given that the cores entering this chronology were selected on the basis of their common signal. At Rock River the standard and negative responder chronologies showed similar negative relationships with present and prior spring and summer, although the relationships with the responder chronologies were much stronger. The positive responder chronology did correlate significantly with present and prior spring and summer temperatures for both the late 20th century and the entire century. In this case the weaker correlations of the standard chronology clearly reflect a mixture and degradation of signals from these two groups.

Table 5.4 Corrleations between responder and standard chronologies and temperatures.

Chronology	Trees	pSpring			pSummer			Spring		Summer		
		1900 - 2000	1900 - 1950	1951 - 2000	1900 - 2000	1900 - 1950	1951 - 2000	1900 - 2000	1951 - 2000	1900 - 2000	1900 - 1950	1951 - 2000
Rock River	68	-0.26		-0.38	-0.33		-0.36	-0.29	-0.36		0.38	
Pos Rock	13	0.26		0.30	0.21		0.30	0.23	0.28	0.43	0.30	0.46
Neg Rock	17	-0.35		-0.53	-0.40		-0.50	-0.40	-0.55	-0.23	0.36	-0.47
Distincta	73	-0.27		-0.36	-0.47	-0.31	-0.41	-0.46	-0.59	-0.24	0.35	-0.39
Neg Dist	45	-0.32		-0.41	-0.48	-0.31	-0.44	-0.48	-0.61	-0.28	0.35	-0.43
NKR	44		0.30	-0.35	-0.45		-0.53	-0.35	-0.60	-0.22		-0.43
Neg NKR	26	-0.24		-0.42	-0.47		-0.52	-0.40	-0.61	-0.30		-0.48

Note: Only those correlation values significant at the P=0.05 level are shown.

5.5. Summary

Three sites within the Yukon study area had adequate sample depth for a "responder" chronology type of analysis. The Distincta and NKR sites contain single "responder" chronologies that were very similar to the standard chronologies developed for those sites: they contain the majority of the cores at each site and had strong common relationships with mean monthly/seasonal Dawson temperatures (including summer and spring) over the 1951-2000 period. The responder and standard site chronologies at both Distincta and NKR had similar relationships with mean Dawson summer and spring temperatures (Table 5.4) namely being negatively correlated with spring and summer temperatures over the entire 20th century and within the 1951-2000 period. Although some trees at NKR showed positive relationships with June and July (and summer) temperatures of the current year in the early 20th century, stronger (negative) relationships were observed during the latter half of the twentieth century in almost all cases (Table 5.4). Spring temperatures were found to generally have stronger negative overall correlation values than summer temperatures during the 1951-2000 period, but both follow a similar pattern. During the 1900-1950 period the Distincta standard and negative responder chronologies were both positively correlated with summer temperatures of the current year and negatively correlated with summer temperatures during the recent period (1951-2000), a trend that was not as obvious in the NKR trees.

Unlike the Distincta and NKR sites, Rock River contained positive and negative responding trees (Tables 5.3 and 5.4). The correlation patterns of the standard and negative responder chronologies were similar (to Distincta and NKR above), although the negative responder chronology did have stronger negative correlations with both spring and summer temperatures of the current and previous year. The correlations of the positive responder chronology were opposite and showed lower correlations (all positive) throughout the 20th century with both spring and summer temperatures of the previous and current year (Table 5.4). Table 5.5 shows the individual trees that were included in positive and negative responder chronologies at Rock River. The trees used to create the positive responder were sampled mainly from the smaller trees on the interfluve site, while the negative responder trees were almost equally sampled from both valley and interfluve sites. Therefore, the Rock River results indicated that different climate/growth responses occurred at this site. The specific cause of these differences was not apparent from the available data, but may most likely be related to site conditions.

Table 5.5 Composition of positive and negative responder groups at Rock River, Yukon.

Number of Trees	Positive Responder		Negative Responder	
		Sub - Site		Neg
1	Y4Z1X	AF	AF	Y4Z2X
2	Y4Z50	B	AF	Y4Z06
3	Y4Z51	B	AF	Y4Z14
4	Y4Z52	B	AF	Y4Z22
5	Y4Z59	B	AS	Y4Z30
6	Y4Z61	B	AS	Y4Z33
7	Y4Z62	B	AF	Y4Z34
8	Y4Z66	B	AF	Y4Z46
9	Y4Z70	B	B	Y4Z53
10	Y4Z82	B	B	Y4Z54
11	Y4Z89	B	B	Y4Z56
12	Y4Z97	B	B	Y4Z63
13	Y4Z98	B	B	Y4Z64
14			B	Y4Z71
15			B	Y4Z72
16			B	Y4Z75
17			B	Y4Z79

Notes: A = sampled in the valley; B = sampled on the interfluve. F = sampled from the flat area within the valley, and S = sampled from the slope in the valley.

The analyses from these three sites complement the results from Chapter 4. They indicate that the dominant negative relationship over the 20th century between tree growth and spring and summer temperatures of the prior and present year is real and occurred throughout the network of sites along the Dempster Highway. Most of the trees from two of the three sites examined maintained a negative correlation between tree chronologies and spring and summer seasonal Dawson temperatures of the prior and present year. The strength of this relationship was strongest during the latter half of 20th century with slightly weaker, yet still significant, correlations over the entire century. Although this negative relationship was common within these sites and others within the region, some sites showed a weaker relationship due to the presence of mixed signals (i.e. some trees retained a positive or weaker relationship with summer temperatures). Trees from the most northerly site, Rock River, had a mixed response to spring and summer seasonal temperatures at Dawson of the prior and present year, results that coincided with the trees reported by Wilmking *et al.* (2004, 2005) in Alaska. The varying tree response to similar temperatures was only identified in one of the three sites in this analysis. However, increasing sample depth from other sites within the network could reveal similar results for sites that did not show a dominant negative response in Chapter 4.

CHAPTER SIX

Summary of Significant Findings and Recommendations for Further Research

6.1 Introduction

Dendrochronological and dendroclimatological studies have targeted sites at northern treelines because tree growth in these environments has been documented to be sensitive to temperature change (e.g. Jacoby and Cook, 1981). However, this research fundamentally assumes that the relationship between tree growth and climate remains stable over time (Fritts, 1976; Briffa *et al.*, 1992; Szeicz and MacDonald, 1995). Recently, several studies from northern North America have noted a change in the climate signal from some treeline sites, suggesting this assumption may no longer be valid as the temperature sensitivity of these trees could be changing (Briffa *et al.*, 1998; D'Arrigo *et al.*, 2004b). Several of these studies have focused on the classic Twisted Tree-Heartrot Hill (TTHH) site in the Yukon and adjacent sites within Alaska (e.g. Lloyd and Fastie, 2002; D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2004; Wilmking *et al.*, 2005 and others). Changes in climate-tree growth relationships at a site have significant implications for the reconstruction of past climate variability from tree rings as they challenge some of the fundamental assumptions of dendroclimatology. This thesis developed a network of white spruce (*Picea glauca*) ring-width chronologies from sites along the Dempster Highway, Yukon, bracketing the position of the TTHH site and examined the relationships between these chronologies, the TTHH site, and the nearby climate record at Dawson, Yukon. This chapter summarizes the major findings of this research and presents some recommendations for further research.

6.2 Summary of significant findings

6.2.1 The chronology data base

A network of 23 white spruce tree-ring chronologies was developed from sites located along the Dempster Highway, Yukon based mainly on sites sampled by UWO field parties in 2002 and 2004. This network of sites brackets the position of the classic TTHH site (65.33° N; 138.33° W) sampled by Jacoby and Cook in the 1970s. The mean raw chronology length in this network is 350 years with a maximum length of 477 years at Tsiivii. The TTHH chronology has a total length of 542 years. Sample depth at each site varied between 10 and 73 trees. However, as many sites had low sample depth in the earliest years, the mean usable (EPS defined) length is 210 years with maxima of 362 years at Tsiivii and 379 years at TTHH. In general, these chronologies were shorter than other Yukon chronologies: 14 were of acceptable quality back to 1800 and 17 had good records for the 20th century. Chronologies have an average mean sensitivity of 0.15 and moderate series intercorrelation (mean Rbar = 0.30) comparable with TTHH (0.14 and 0.37 respectively). Generally, the chronologies show lower growth during the early 1800s and increased growth between the 1850s and early 1900s. There is, however, considerable variability in growth patterns during the latter half of the 20th century. Analysis of the chronology-climate relationships during the 20th century was subsequently based on 18 of these chronologies.

6.2.2 The common signal within the network

Marker ring, correlation, and Principal Component Analyses were used to examine the common signal throughout the network over the 1900-2000 period. The marker ring analysis showed strong, common, high frequency variability among the sites throughout the network based on residual chronologies. During the 20th century significant positive marker rings occurred in 1923 and 1982 (86% and 82% of the 23 chronologies respectively), and the most extreme negative marker ring (1949) occurred in all but one chronology. More positive than negative marker rings occurred during the twentieth century with the majority of these marker rings present in the middle of the century. Network-wide marker rings became less apparent after 1970 suggesting that trees have responded more to local variability (or responding differently) during the past few decades.

Correlation analyses between the chronologies over the 20th century consistently identified two main groups of chronologies, basically those north and south of the Ogilvie River (latitude 65.77°N). Stronger, more coherent, patterns (higher correlations) were observed between the southern group of sites, and TTHH (65.33°N) grouped most strongly with these southern chronologies. The most geographically coherent groups occurred during the latter half of the century, with weaker groupings during the first half of the century and over the entire century. Residual chronologies were more strongly correlated across the network than standard chronologies suggesting that interannual variability in the ring-width series was more strongly related to climate. The standard chronologies showed greater variability between sites over the 20th century.

An important goal of this research was to examine the regional representativeness of the TTHH signal within this network of sites. PCA was carried out over the entire 20th century record and for the 1900-1950 and 1951-2000 periods separately. Results from both split period analyses grouped TTHH into the dominant (first) PC loading (see Chapter 4), but results from the entire 20th century grouped TTHH into the second PC loading. These results mirrored the correlation analyses, revealing that the low frequency signal in these chronologies was more variable during the latter half of the 20th century. The proportion of variance explained by the dominant PCs varied between 35% for the 1951-2000 period (PC1L) and 27% for the earlier period (PC1E) with TTHH loading on PC1 in both analyses. PC1 for the entire period (PC1A) represents 28% of the variance in these chronologies and consists mainly of several southern sites with TTHH loading most strongly on PC2. Therefore, although the low frequency pattern of growth at TTHH is seen at other sites, this pattern was neither universal nor dominant indicating that a variety of responses to recent climate variability occurs in the chronologies within this network.

6.2.3 Relationship between the chronologies and climate

The relationship between the standard and residual chronologies for 18 sites and mean, maximum, and minimum temperatures from Dawson, Yukon were examined using correlation analyses over the 1900-2000, 1900-1950 and1951-2000 periods. Separate PCA was carried out on 18 standard chronologies for the entire 20th century to evaluate the homogeneity of the common signal within the tree ring network. The strongest relationships were for the 1951-2000 period that identified the highest number of significant correlations (80) between ring widths and climate variables, the majority of these relationships being negative (74) with present summer and previous July mean temperatures.

Over the entire 20th century period 63 of the 72 significant correlations between the standard chronologies and temperatures showed similar patterns. The negative correlations with July (summer) of the previous year were slightly stronger during the

1951 – 2000 period with an average correlation value of -0.47 (-0.41) compared to -0.36 (-0.34) during the full 20th century period. A 20 year moving window (move ahead one year) correlation analysis between ring widths and previous July and summer temperatures over the 20th century showed stronger negative relationships between 1914-1932; 1952-1970, and during the 1980s, with weaker, still dominantly negative, relationships for the intervening time periods. The results for the 1900-1950 period were weaker and more variable with 23 of the 36 significant correlations between ring widths and temperature variables being positive. Most of these positive correlations were with June, July, and summer temperatures of the current year.

Based on these climate-tree growth analyses, the strongest relationships between the standard chronologies and climate over the entire 20th century period were negative relationships with July and summer temperatures of the preceding year. The split period analysis identified distinct intervals of stronger and weaker correlations, with some sites having a positive relationship during the early part of the century and a negative relationship during the latter half. TTHH correlated with the dominant climate variables for each time period investigated, indicating that similarity exists between many of the study sites along the Dempster Highway and the TTHH chronology. However, even though sites have a summer temperature signal in the early part of the century, most sites had lost this signal in the latter half of the century indicating that the sensitivity of these chronologies changed over the 20th century.

6.2.4 Within site variability

Distincta, Rock River, and North Klondike River (NKR) are highly replicated sampled sites along the Dempster Highway and were used to investigate whether sub–populations of trees occurred at these sites that showed different responses to climate (i.e. differing responder types as per Wilmking *et al.*, 2004). Replicating the analyses of Wilmking *et al.* (2004, 2005), individual tree chronologies were created for each site and the relationship of these individual tree chronologies and mean, maximum and minimum temperatures at Dawson were examined using correlation analyses. After determining the dominant climate parameter(s) influencing tree growth in these tree chronologies, separate "responder" type chronologies were created using only those tree chronologies with statistically significant correlations to selected and dominant climate variable(s).

The Distincta and NKR sites contained single dominant negative "responder" chronologies that were similar to the standard chronologies for these sites, although they also contained a few positive responder trees. These responder and standard site chronologies had similar relationships with mean Dawson summer and spring temperatures, i.e. strong negative correlations with spring and summer temperatures over the entire 20th century and within the 1951-2000 periods. NKR contained a few trees with positive relationships with June and July (and summer) temperatures of the current year in the early 20th century, but contained stronger negative relationships during the latter half of the 20th century in almost all cases. During the 1900-1950 period the Distincta standard and negative "responder" chronologies were both positively correlated with summer temperatures of the current year but negatively correlated during the recent period (1951-2000), a trend that was not as obvious in the NKR trees. The negative responder chronology for Distincta was created based on 62% of the total trees from this site and maintained an EPS value > 0.85 until 1669 (1666 in the original). The NKR negative responder chronology contained 59% of the total trees sampled but only maintained an EPS value until 1898; which is a much shorter period when compared to the standard chronology EPS date of 1739. Overall, however, higher correlation values were observed between the negative responder chronologies from Distincta and NKR and July and summer temperatures of the previous year and current growth year.

The Rock River site contained more balanced numbers of trees showing positive and negative responses to Dawson temperatures. The positive correlations with summer temperatures between the 1900-1950 period were maintained for some trees during the latter half of the century, and a positive responder chronology was created based on 13 tree chronologies. A negative responder chronology was also developed based on 17 trees that were negatively correlated with July and summer temperatures of the previous year. Both the positive and negative responder chronologies had shorter EPS-limited chronologies of 1889 and 1909 respectively than the standard chronology for the site (1746). The negative responder chronology from Rock River contained more strongly negative correlations with July and summer temperatures than the standard chronology. Correlations of the positive responder chronology were not as strong as the negative correlations but did attain the 95% confidence level. The positive responding trees were mainly smaller trees on the interfluve sub-site whilst the negative responders were almost equally divided between valley and interfluve sub-sites. However, these two "responder chronologies" are based on less than half of the trees at this site.

The results from these three sites indicate that the dominant relationships with temperatures at these sites in the last half of the 20th century are negative but that there are divergent responders at some sites.

6.3 Concluding remarks

The complex relationship between tree growth and climate variables has been explored using a network of sites from the Dempster Highway in the Yukon Territory. The sites bracket the position of TTHH and allow evaluation of the regional importance of the TTHH signal. D'Arrigo *et al.* (2004) indicated that the ring-width series of this classic site are no longer temperature sensitive. TTHH showed a generally increasing growth trend from 1900 until about 1940 where the trend levels out until the late 1960s and begins to decline until the 1990s. The original TTHH chronology demonstrated a positive relationship between summer temperatures and ring widths over the 1900-1975 period whereas the updated results indicate an inverse relationship over the last ca 40 years. The results from the network of sites studied in this thesis indicates that, although this pattern of growth was seen at 5 or 6 other sites, it is neither universal nor dominant, indicating that a variety of responses to recent climate variability occur in the tree-ring chronologies from this part of the Yukon.

Most of the sites sampled along the Dempster Highway showed negative relationships with summer temperatures of the present and previous year over the entire 20th century, although several sites had a positive response during the 1900-2000 period followed by stronger negative response over the 1951-2000 period, i.e., there has been a change in the dominant relationships between tree-ring width and temperatures over the 20th century. The strongest relationships are with specific months. Examination of sup-populations of trees at three sites indicate that only one site (the most northern) showed mixed responses to temperatures, and, therefore, the presence of sub-populations of trees at these sites is not a sufficient explanation for the loss of a temperature sensitive signal. However, there is a need to examine the possible effect of microsite differences to account for these effects. In evaluating the pre-20th century records, most of the sites exhibited lower growth during the early 1800s followed by increased growth until the early 1900s. The 20th century contains lower growth during the early years followed by increased growth until the 1950s. Growth during the latter half of the 20th century was more variable but generally showed a negative trend throughout the network.

6.4 Recommendations for future research

Based on the results from this research, future dendroclimatic research dealing with the sensitivity issue in northern treeline environments is imperative. More studies are necessary to understand the complex and changing relationships between tree growth and climate in these northern environments. Some recommendations include,

1. **Greater attention to variability within sample site conditions**. Understanding the complex relationship between tree growth and site conditions is extremely important in dendroclimatic studies. Greater attention to details of microsite conditions during sampling may help isolate local influences upon tree growth that could explain differences in growth responses from trees within the same site. Sampling for this project was mainly on a reconnaissance basis; observing additional site information for each tree sampled would be time consuming but could provide additional insight into growth variability among trees in the same stand.

2. **Utilizing different tree species.** White spruce has been used extensively in dendroclimatic studies because of its longevity and its ability to tolerate harsh environmental conditions (e.g. Jacoby and Cook, 1981; Szeicz and MacDonald, 1994, 1995a, b). Although white spruce dominates the boreal-tundra ecotone in northwestern North America, other species are present (e.g. black spruce (*Picea mariana*) subalpine fir (*Abies lasiocarpa*) and larch (*Larix laricina*)). Using different tree species from these environments could provide alternate information on the tree growth-climate relationship, especially over the recent time period.

3. **Increase sample depth at these sites.** Larger sample numbers would ensure stronger common signals or allow the identification of sub-population signals within individual sites. Currently, few sites from these environments attain the sample depth required to identify whether different responder trees are present. Studies from Alaska have utilized an extensive sample database to create responder chronologies acceptable in the dendroclimatic community (e.g. Wilmking *et al.*, 2004; 2005).

4. **Utilize alternate methods of chronology development to analyze the low frequency patterns and isolate sites with mixed signals.** Several studies have suggested that "divergence" may partially reflect standardization issues (Briffa and Osborn, 2004). Some recent studies in northwestern North America have utilized multiple methods for chronology development to help understand various influences from different age classes (e.g. Szeicz and MacDonald; 1995), and mixed or sub-populations (e.g. Wilmking *et al.*, 2004). Further exploration and

application of these techniques may lead to a better understanding of the results presented in this thesis.

5. **Direct monitoring of climate-growth relationships**. Ultimately the climate-tree growth relationship is best addressed by detailed measurements of tree response to local climate using dendrometers or similar instruments that measure growth directly. These dendrometers should be used at sites with existing (or new) climate stations to help provide a better understanding of the relationships between growth and climate variables at a variety of timescales.

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APPENDIX ONE

Additional Material for Chapter Three – The white spruce chronology network

The Linear Aggregate Model for Tree – Ring Series

The linear aggregate model for tree-ring series describes the annual ring – width growth within a tree – ring series, expressed as an aggregate of factors as follows:

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

(Cook, 1985)

Where R_t is the measured annual ring – width,
A_t is the age – related growth trend,
C_t is the climate – related signal,
D1t is the endogenous disturbances affecting each specific tree,
$\delta D2_t$ is the exogenous disturbances affecting the entire stand with δ indicating either the presence ($\delta = 1$) or absence ($\delta = 0$) of the disturbance,
E_t is the error accumulated from measurement error or random variations.

For the purposes of dendroclimatic analyses, isolating the climate signal factor is important. Isolating the climate signal from within a tree-ring series requires multiple steps in the processing, but is critical when developing chronologies. The samples from the study area were free of both endogenous and exogenous disturbances, and removing the age related growth rate (detrending, standardizing, etc.) emphasizes the common climate signal in these chronologies.

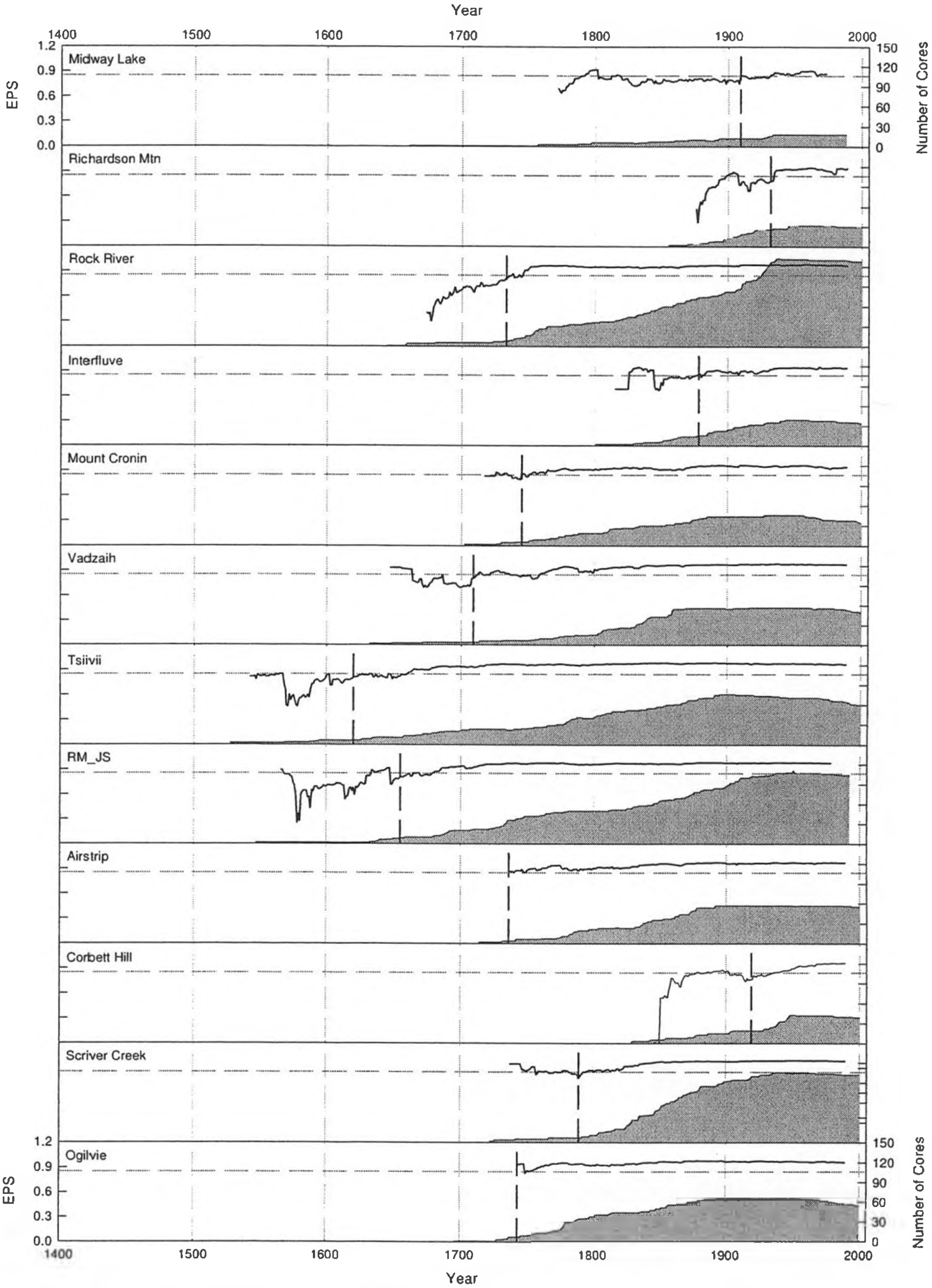

Figure A1.1 Running EPS values (black line) and sample depth (grey shaded area) for the Residual Chronologies. The dashed line represents the 0.85 threshold suggested by Wigley *et al.* (1984).

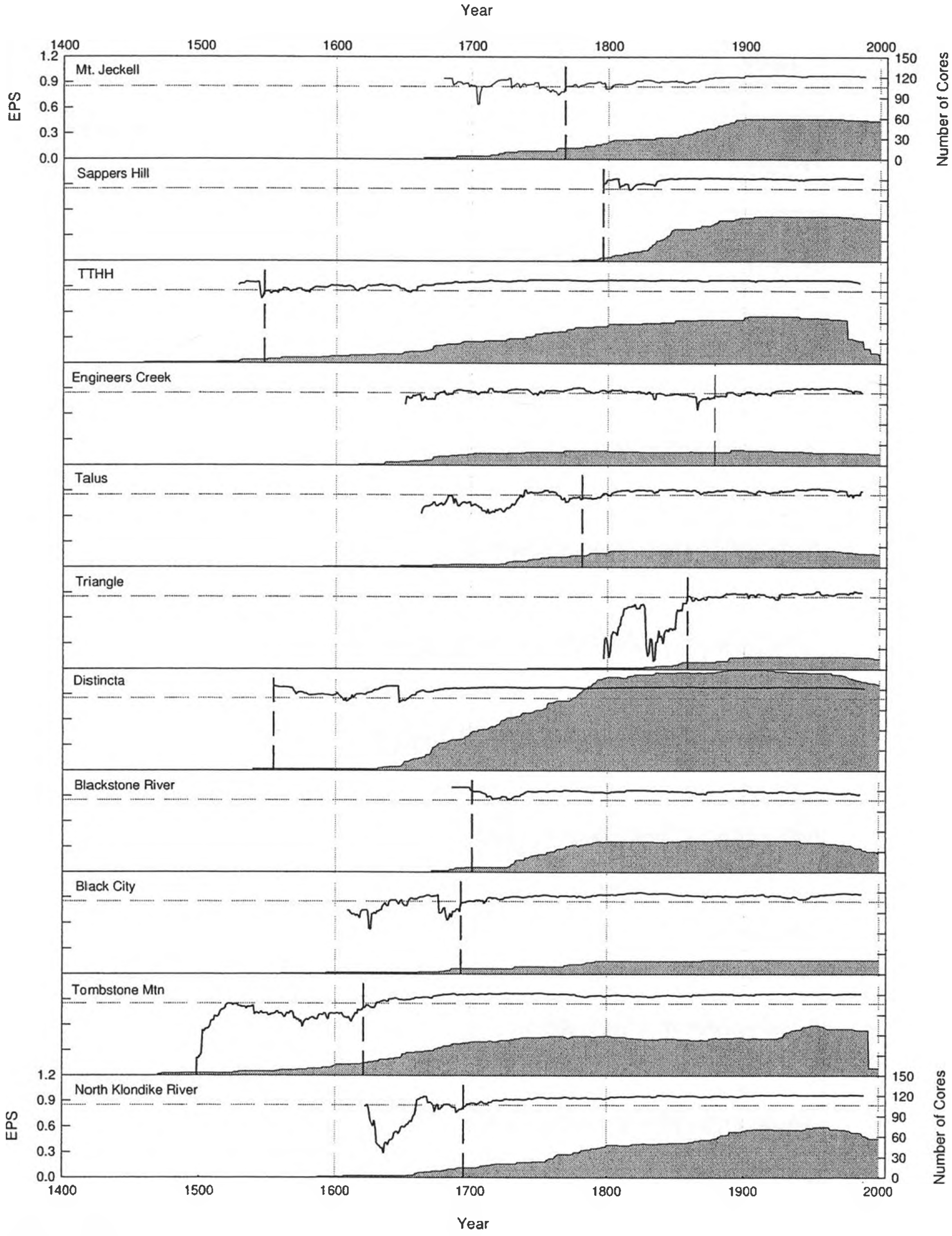

Figure A1.1 Continued.

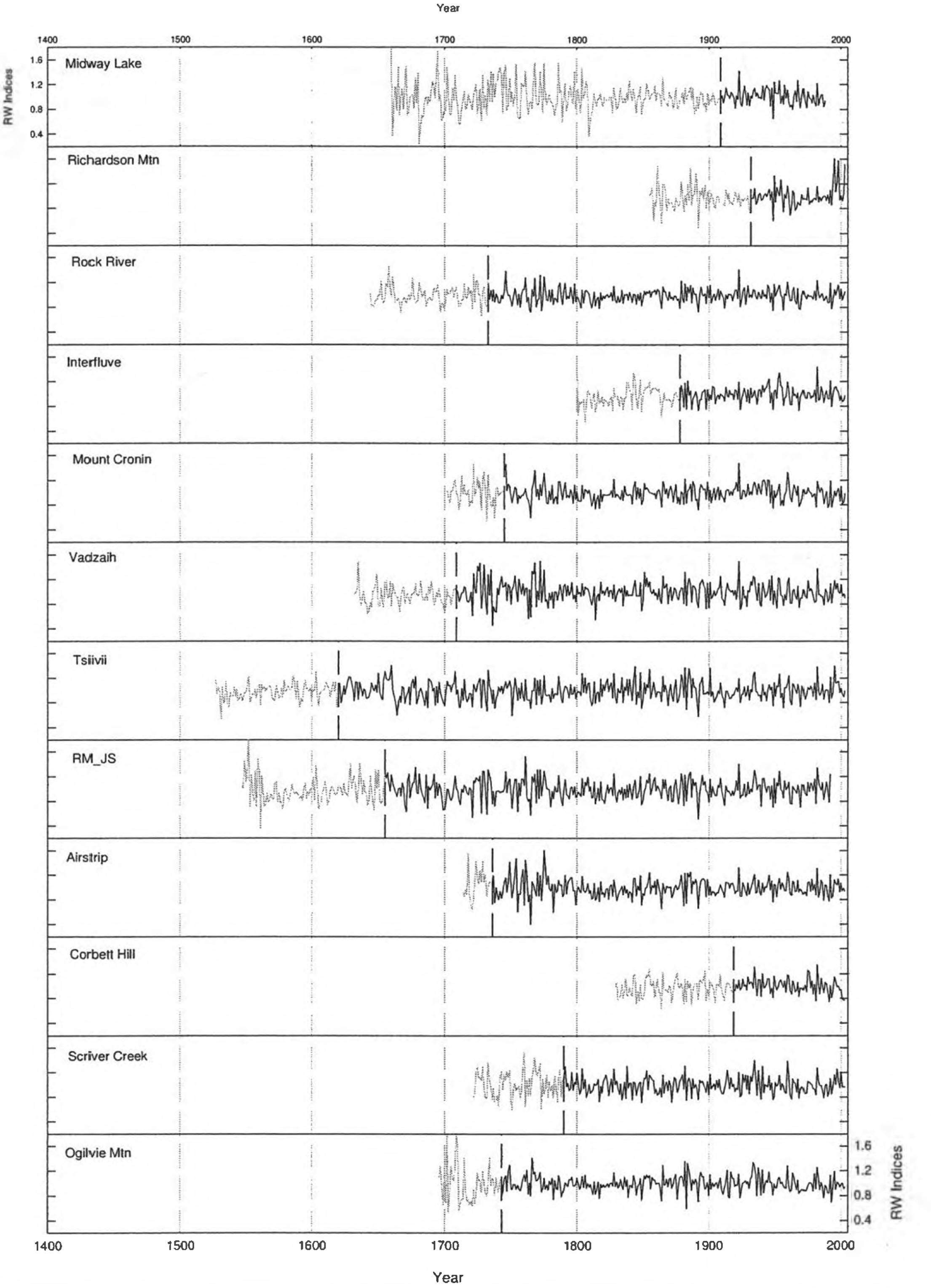

Figure A1.2 Residual Chronology plots. The grey lines represent those parts of the chronology that fall below the critical EPS threshold. The black line represents the reliable portions of these chronologies for this study. The vertical dashed black line represents the EPS cut-off for each chronology.

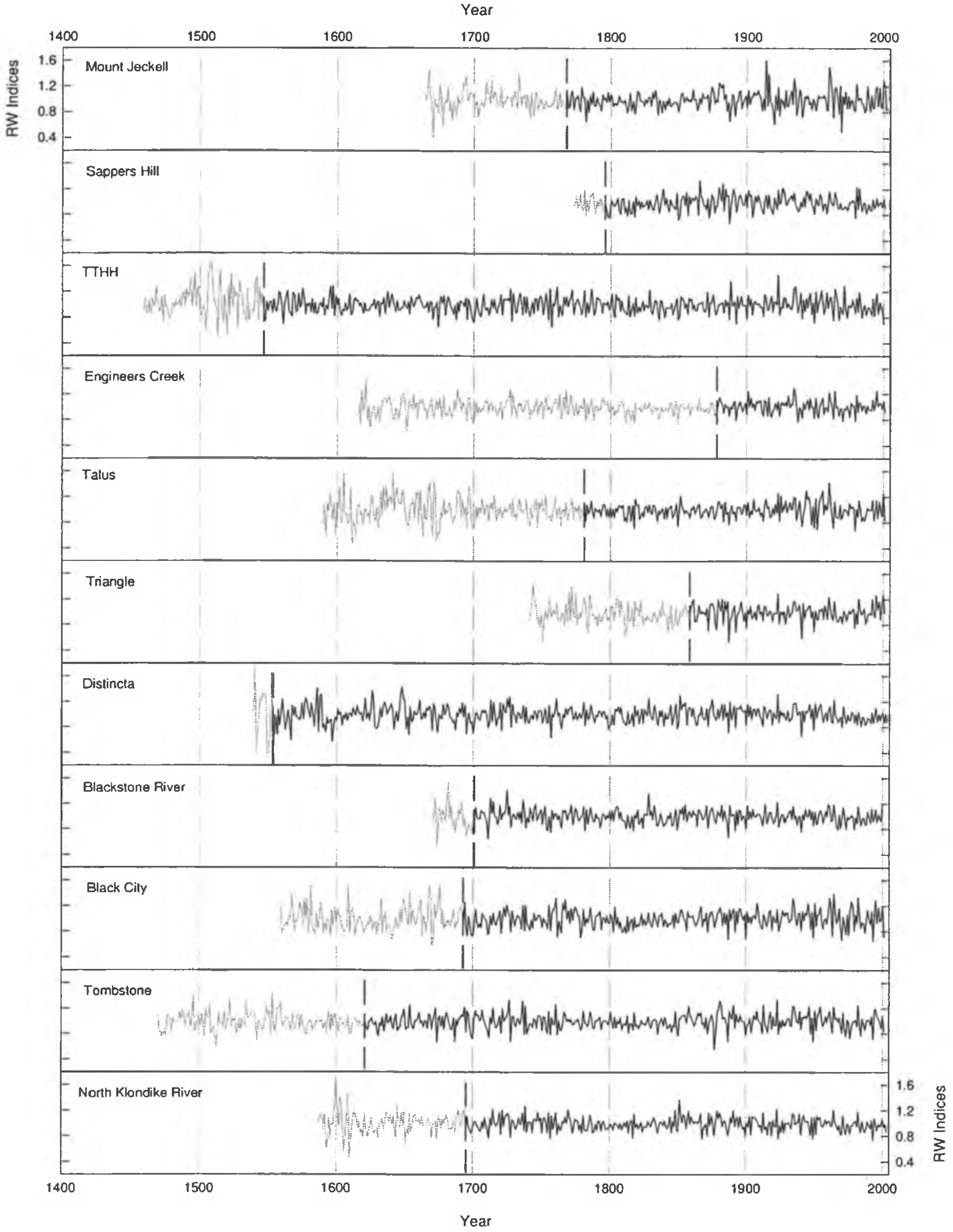

Figure A1.2 Continued.

APPENDIX TWO

Additional Material for Chapter Four – Analysis of the Common Signal within the Network

Marker ring analysis

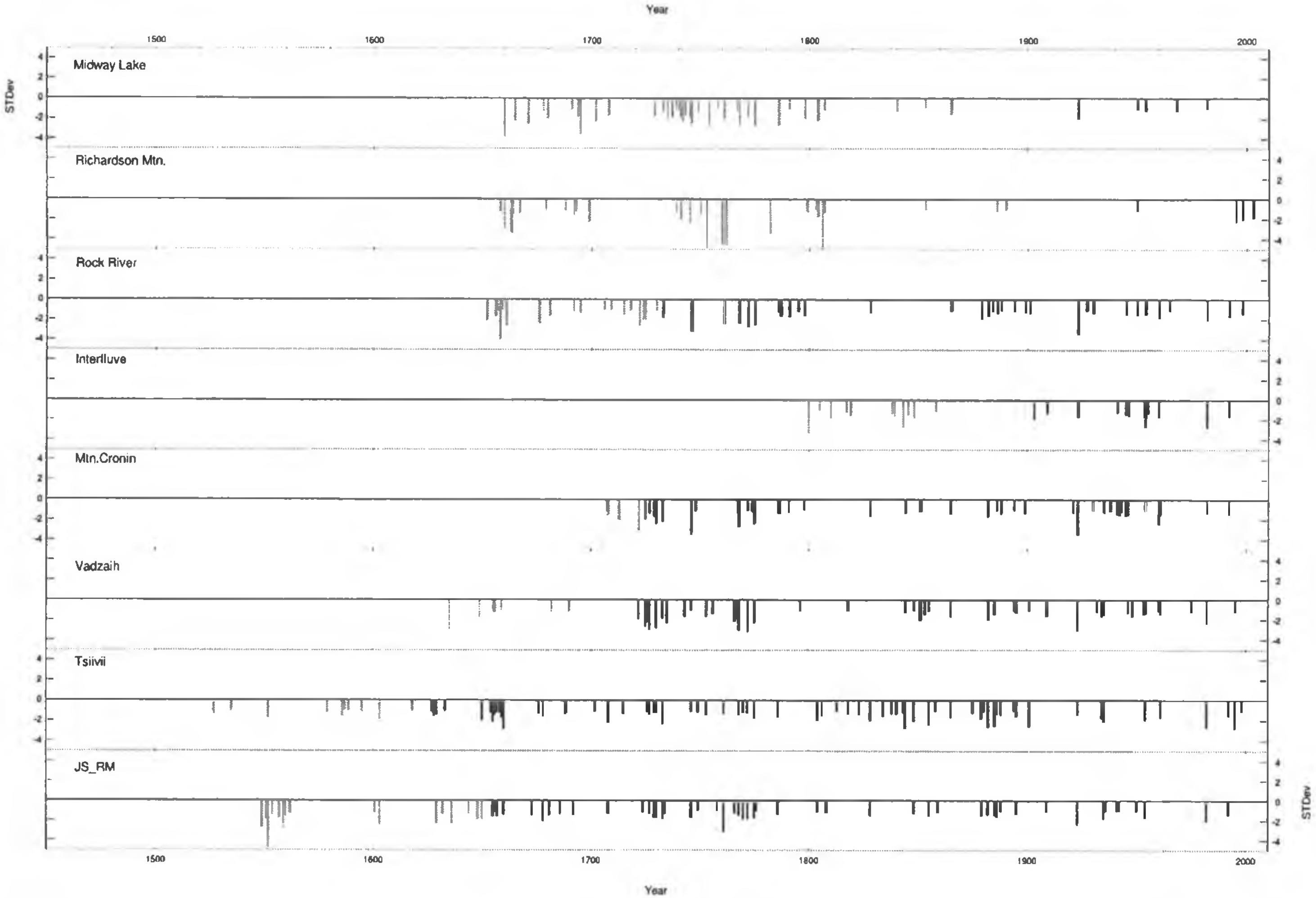

Figure A.2.1 Negative maker rings in the residual chronologies – 1450-2000. Only rings >-1 standard deviation are shown. Years shown in grey are outside the period with EPS>0.85.

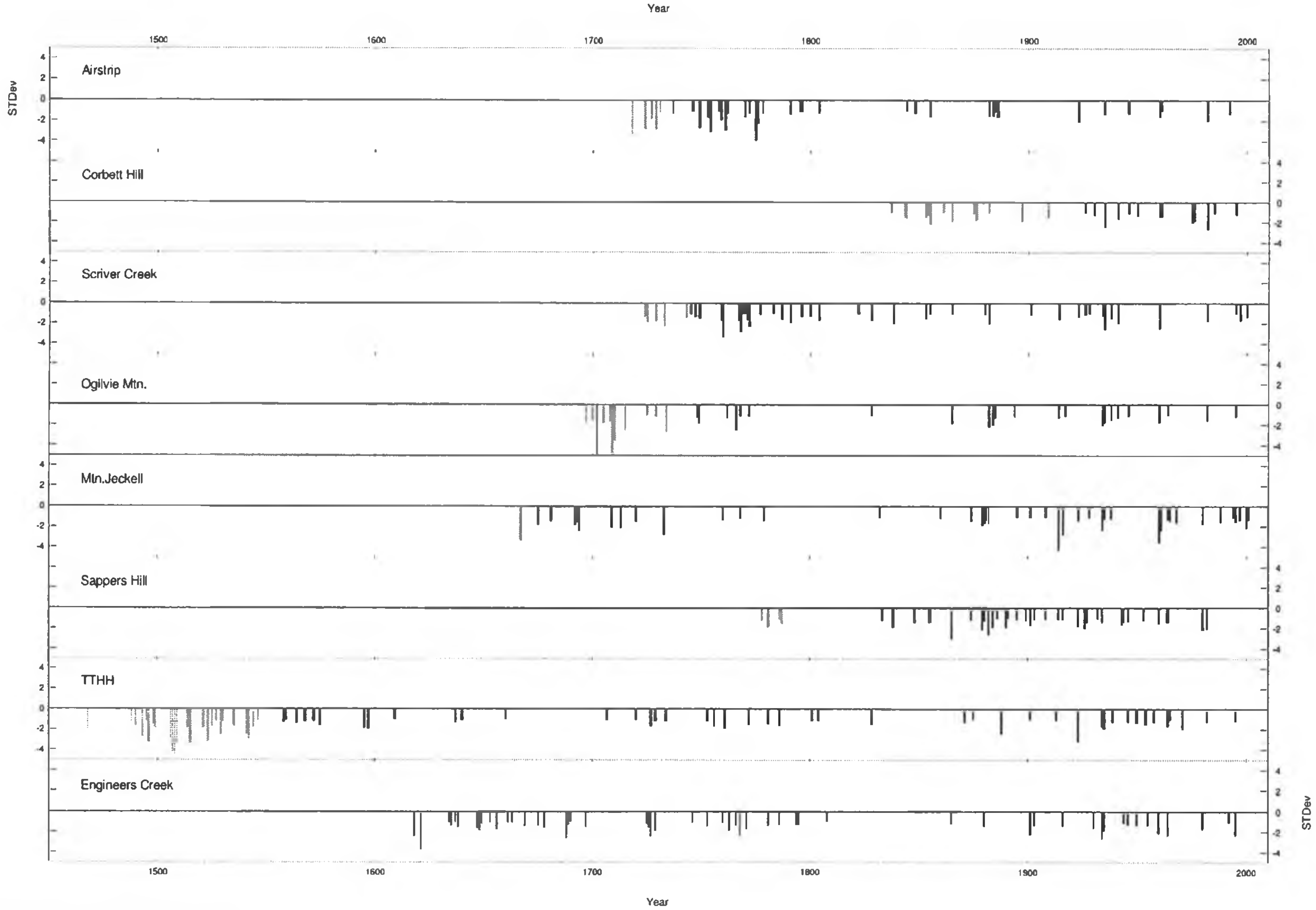

Figure A.2.1 Continued

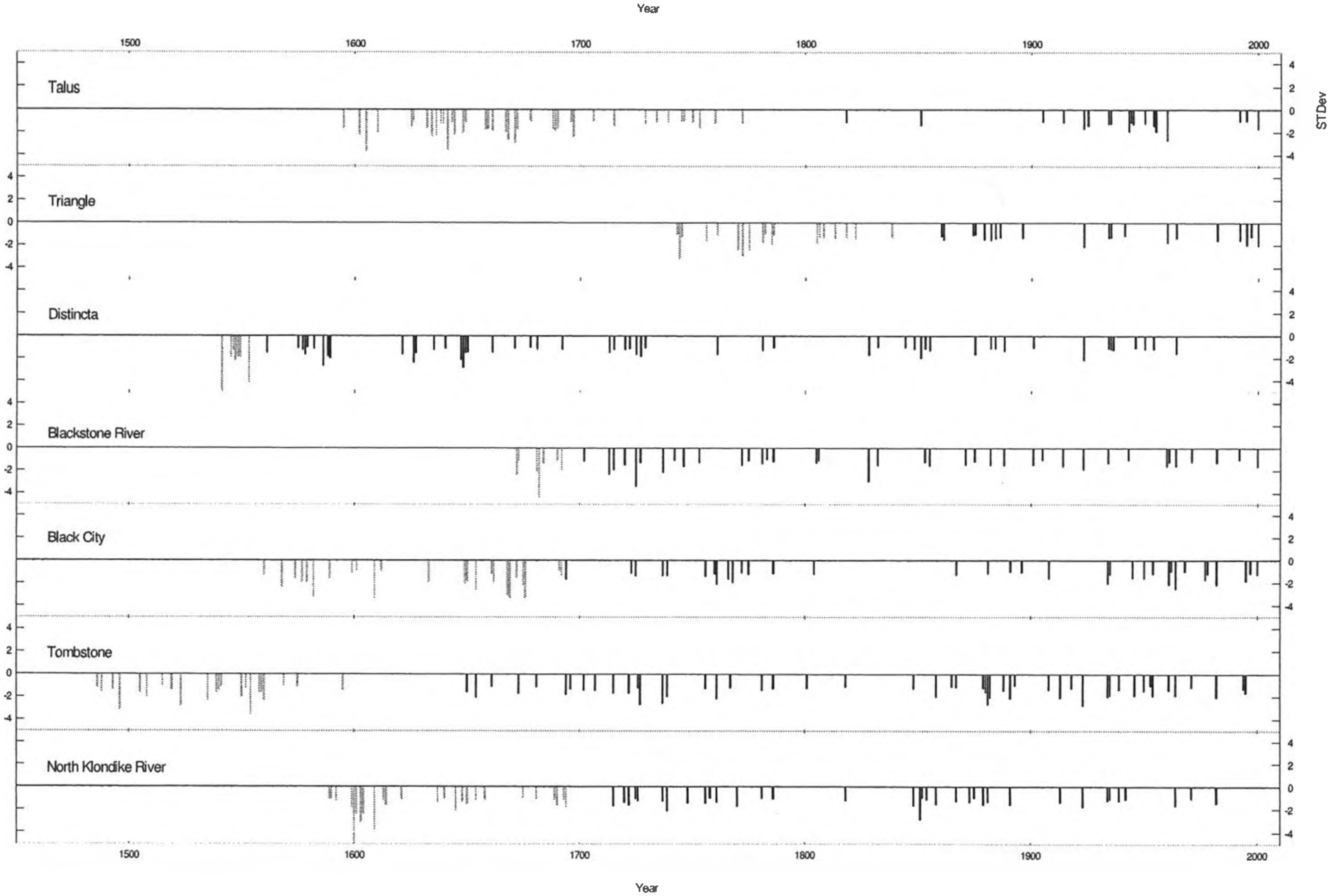

Figure A.2.1 Continued

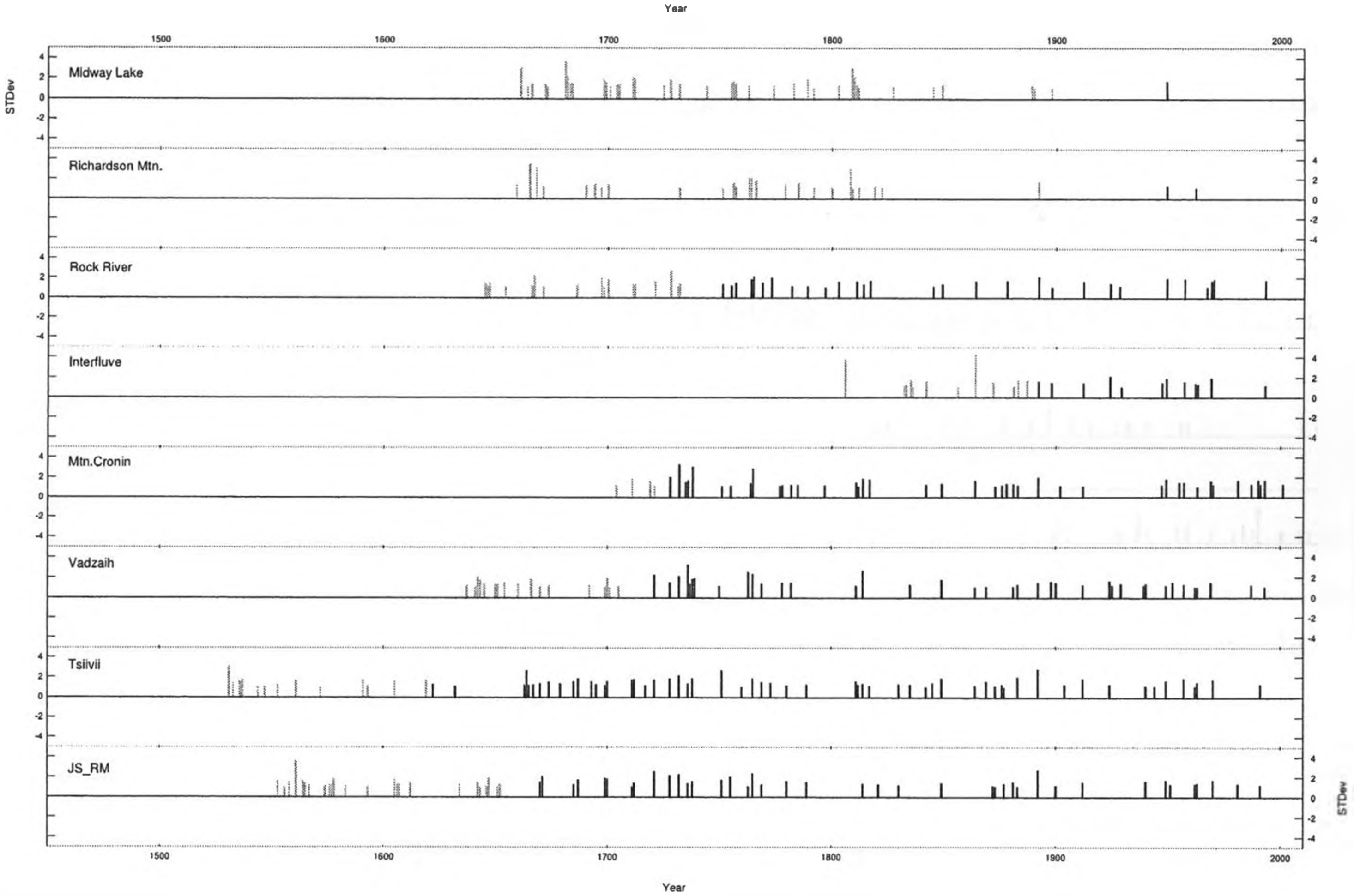

Figure A.2.2 Positive maker rings in the residual chronologies from 1450 – 2000. Only rings >+1 standard deviation are shown. Years in grey are outside the period with EPS>0.85.

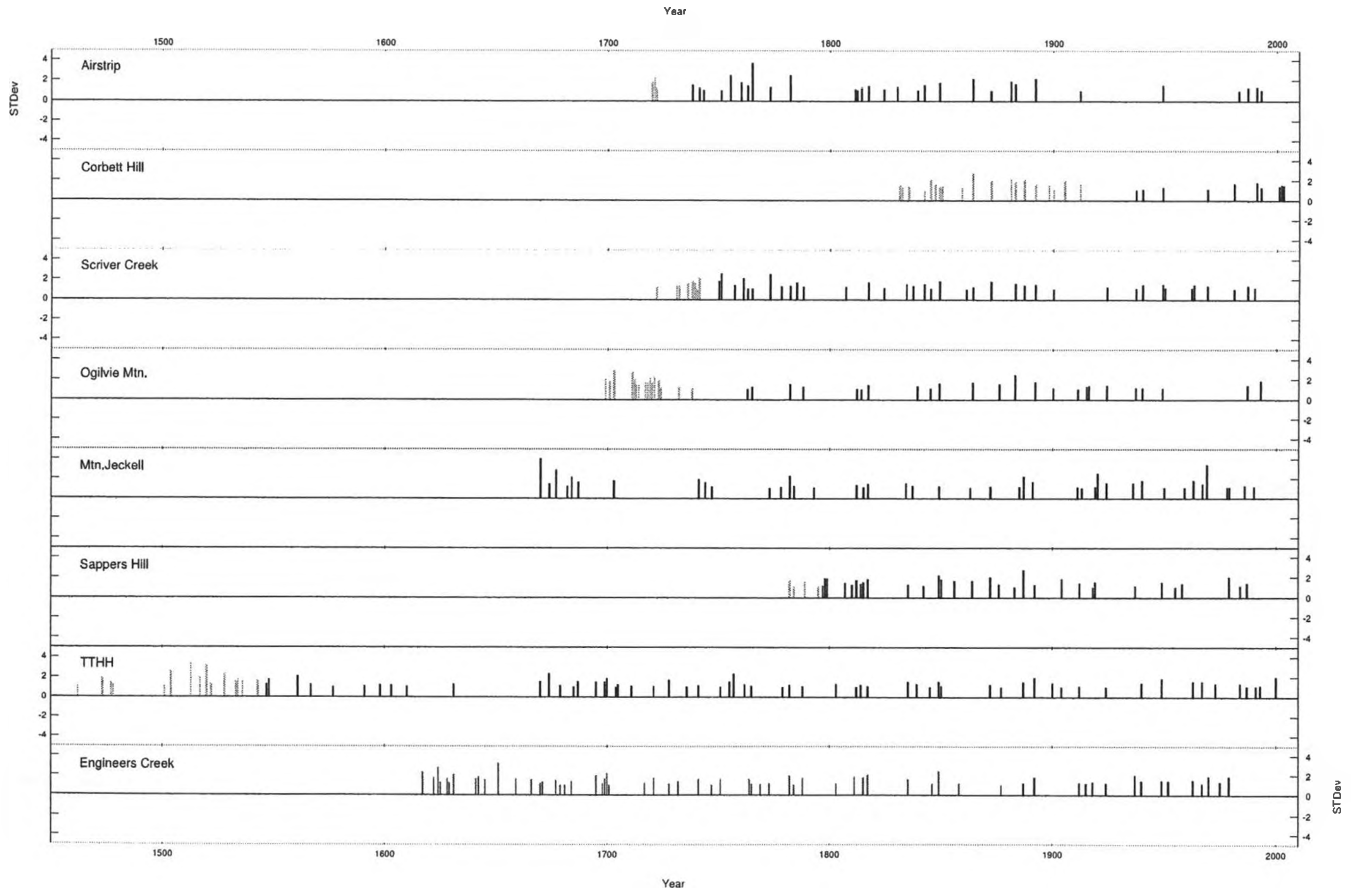

Figure A.2.2 Continued.

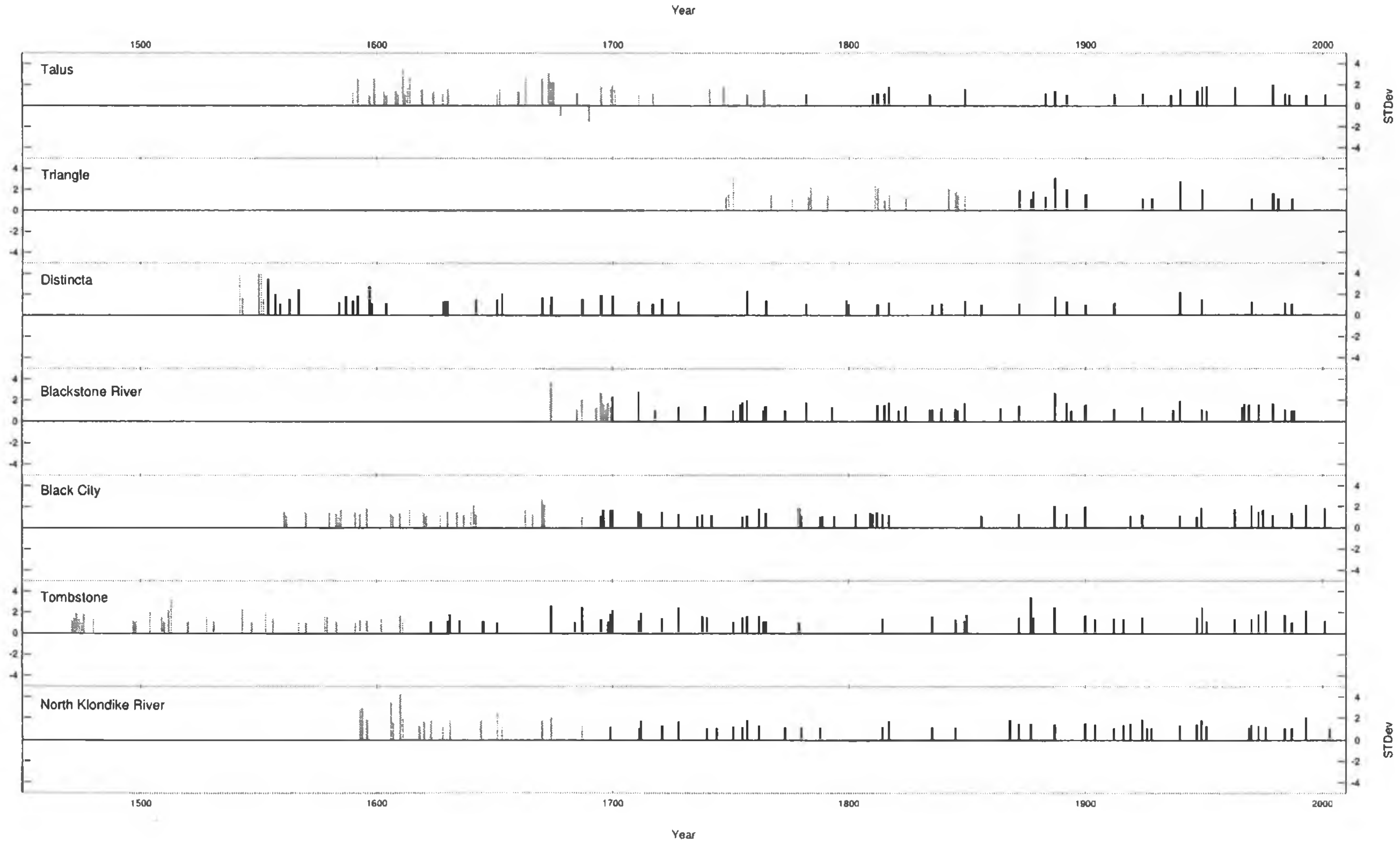

Figure A.2.2 Continued.

APPENDIX THREE

Additional Material for Chapter 5

Table A.3.1 Number of significant positive (P>0.05) and negative (P<0.05) correlations between tree indices and mean, maximum and minimum monthly temperatures at Dawson during the 20th century. Total number of trees: Rock River (46), Distincta (64) and NKR (30).

Months		Entire 20th century 1900-2000						Early Period 1900-1950						Late Period 1951-2000					
		Rock River		Distincta		NKR		Rock River		Distincta		NKR		Rock River		Distincta		NKR	
		+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
pJan	Mean	11		2	8		7	30	2	13	13	3	13	2	4	2	5		
	Max	7		2	6		0	35	2	11	13	7	10		4		3		
	Min		11	2	11		17	28	2	11	19		13	7	4	2	5		3
pFeb	Mean	11		2		3				6	2	3		9	2				
	Max	11		2		3				6		3		9					
	Min	2				3				6	2	3		13					
pMar	Mean	2	17	2	20	3	13	2		3		10			30		6		20
	Max	4	17	2	16	3	17	2		3		10			11				
	Min	2	11	2	19	3	17	2		3	2	10		2	37		28		40
pApr	Mean	9	24	2	33	7	17	7		6		13		9	28	3	44	3	50
	Max	9	11	3	14	3	3	7		3		17		9	26	3	20	3	37
	Min	4	17	2	47	7	27			8		10		9	35	3	52	3	57
pMay	Mean	9	15	3	20	3		2	2	2		13		20	24	3	31	3	40
	Max	2	2	2	2	3		2	4	2	2	7		9	15	3	8	7	10
	Min	7	26	2	50	7	40	4	11			17		15	28	3	48		53
pJun	Mean		11		39		37		4		14		3		26		34		60
	Max		2		17		13				14		3		7				20
	Min	4	41	2	63	7	63		13	2	16	7	13	9	35	2	64		80
pJul	Mean	11	48	2	75	3	80		4		25		17	11	37	5	61	3	83
	Max		22	2	53		67		7		22		23	7	35	3	55		80
	Min	7	41	5	72	10	63	4	11	3	17	13	7	15	30	3	61	3	80
pAug	Mean	4	17	5	25		37		2		2			4	2	8			
	Max							2	4	2	6	3	10			6			
	Min	2	37	6	56	3	57	9	4	6	13	7	10	11	11	5	22	3	30
pSept	Mean	15	11	3	22	3	17	7	15	8	16	10	3	11	2			7	
	Max	4	2		2			2	4	2	9	3	3	2					
	Min	2	22	8	34	3	33	11	17	11	16	13	10	17		2		7	
pOct	Mean	4		8		7		7	9	9		17				2			
	Max	15	2	16		13		2	7	8		7		2					

	Min	4		5		7		9	7	5		17				2			
pNov	Mean			3						6	2								
	Max	2		5						5									
	Min			5						6	2					2			
pDec	Mean	2			2						6					2			
	Max	2			2						6			2		2			
	Min				2						5			2					
Jan	Mean	4	4		22		17	7	9	2	33		17	4	4		6		23
	Max	2	2		17		10	4	11	2	34		10	2	4		5		23
	Min		13		23		20	4	9	2	34		20	7	4		5		23
Feb	Mean	7		2	2			2		2				4					
	Max	4		3	2					2				4					
	Min			2	2			2		2					7	2		3	
Mar	Mean	4	24		44		33	2	9		2	3	3		17		55		77
	Max	2	28		47		33	2	7		3	3	3		7		36		27
	Min		22		47		33	2	7		2	3	3		33		63		80
Apr	Mean	4	35	2	66		63		2		14			9	37	2	56		80
	Max	4	24	2	58		43		7		17			7	24	2	53		70
	Min		43	2	70		67		2		9		3	7	39	2	59		80
May	Mean	4	11		36		20	4	4			13		7	28		66		87
	Max		9		6		7	4	7		2	10			15		48		60
	Min	4	33	2	61	7	50		2	2		13	3	7	37	2	69		87
Jun	Mean	22	2	3	2	3	3	17		33		27		9	28	3	19	3	30
	Max	4		11	2			20		30		13			11				
	Min	7	22	5	30	10	33	17	4	30		30	3	15	28	5	34	3	50
Jul	Mean	28	26	3	55	7	60	9		11		10		15	28	3	56	3	77
	Max	13		2	6		20	7		2				4	26	2	39		70
	Min	7	37	6	64	10	57	11	7	14	8	30	7	20	28	2	55	3	60
Aug	Mean	11	17	2	30		43	11							11	2	6		7
	Max	2	2					15		3		3	7						
	Min	2	39	6	61	3	60	28		8		10		11	20	2	28		43

Table A3.2 Number of significant positive (P>0.05) and negative (P<0.05) correlations between tree indices and mean, maximum and minimum seasonal and annual temperatures at Dawson during the 20th century.

Seasons		Entire 20th century 1900-2000						Early Period 1900-1950						Late Period 1951-2000					
		Rock River		Distincta		NKR		Rock River		Distincta		NKR		Rock River		Distincta		NKR	
		+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
pAnnual	Mean	15	7		36	3	17	26	2	14	13	13	7	15	15	3	16	3	23
	Max	7			13	3	3	28	2	11	13	13	3	11	7	2	3		
	Min	4	17	6	39	7	27	26	4	14	9	13	7	20	15	3	33	3	33
pWinter	Mean	20			5			13	2	3		3		13		3	2	3	
	Max	17		2	3			20	2	5		7		9		3	2		
	Min			2	3			13	2	3	2	3		17		3	2	3	
pSpring	Mean	9	35		42	3	30	4	4	8		20		7	35	3	50	3	53
	Max	4	20	3	25	7	7	9	2	8		23		2	28	2			
	Min	4	28	2	50	7	43	4	4	5		17		7	39	3	56	3	70
pSummer	Mean	9	43		72		80		4		22		10	11	35	3	50	3	77
	Max		11		25		40		2				20		26	3	23		
	Min	7	43	5	72	10	67	2	13	5	17	13	13	13	33	3	61	3	73
pAutumn	Mean	4			8	10		7	2	6	2	3		2		2			
	Max	11		11		7			4	8	2	3		7		2			
	Min	9		8		13		15	2	8	3	7	3			5			
Annual	Mean	17	24		58		37	7	4	3	11	10	7	9	28		63		70
	Max	9	15		41		23	13	4	2	14	13		7	17		53		
	Min	2	33	2	64	3	50	11	7	5	9	10	7	11	28		67		73
Winter	Mean	9			22		7	2			14			13	2		6	3	13
	Max	7			23		7	2			16		3	13	2		6		
	Min		7		16		10	2		2	13			15			6	3	13
Spring	Mean	2	46		77		67	4	4		13	7	7	4	39	2	70		87
	Max	4	33	2	69		43	7	7		13	3	3	2	39	2	52		
	Min	4	48	2	75	3	73	2	7		8	7	7	9	39	2	64		87
Summer	Mean	28	24		38	7	60	22		22		7		15	33	3	45	3	67
	Max	7	2				10	24		9		10		2	17	2	16		
	Min	7	39	5	63	17	53	28	2	23	3	30	7	24	30	5	58	3	60
Autumn	Mean								2		3		7						
	Max	2	7				3		2		3		3						
	Min								2		3		7						