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Changing climatic sensitivities of two spruce species across a moisture gradient in Northeastern Canada

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ABSTRACT

This paper examines the variability in the relationship between climate and radial growth of black spruce (*Picea mariana* (Mill.) B.S.P.) and white spruce (*Picea glauca* (Moench) Voss) trees across central Labrador, Eastern Canada. Using climate-sensitive trees, an 11-year running Pearson correlation is applied to local records to examine the relationship between radial tree growth and climate over the last 50 years and the spatial pattern in this relationship with increasing distance inland from the Labrador Sea. Results indicate that there is a high degree of instability in the climate/tree-ring sensitivity despite an overall statistically significant relationship throughout the instrumental time period (1942 to present). Although some periods of reduced climate sensitivity are coincident with insect outbreaks, others cannot be explained by forest disturbance factors. Spatially, the two sites that are most representative of higher elevation areas have more time-stable climate-growth relationships than those inland or along the coast. The results also suggest that the stability of the relationship may be the result of moisture availability, rapid changes in precipitation and temperature, and site-specificity.

Introduction

This paper investigates the temporal stability of the relationship between radial growth in two spruce species and growing-season air temperature and precipitation across central Labrador, eastern Canada. Climate reconstructions from tree rings are a significant source of long-term high-resolution data on past climate variability, which can incorporate various spatial scales (i.e., hemispheric, Haugen, 1967; regional, Schweingruber et al., 1993; local, Trindade, 2009). A key component of the dendroclimatological approach is the stability of the relationship between tree rings and climate over time, as dictated by the *uniformitarian principle*. This principle, as it applies to dendroclimatology, requires that the present-day climatic controls on tree-ring variability must have been unchanged in the past in order for palaeoclimatic reconstructions to be reliable (Fritts, 1976). Increasingly, studies are reporting that the sensitivity of tree growth to climate in some species may not be as stable as once thought (Jacoby and D'Arrigo, 1995; Briffa et al., 1998). This raises concerns over the accuracy of dendroclimatic reconstructions, with the fear that if present environmental controls on tree growth are unstable, then the reconstruction of past climate and the prediction of growth under future climate scenarios may be unreliable.

Briffa et al. (1998) first reported on the reduced sensitivity of trees to temperature during the second half of the 20th century throughout the northern hemisphere. More recently, D'Arrigo et al. (2008) coined the term "divergence problem" to describe a weakening or change in the relationship between tree rings and temperature during the instrumental climate record. Their definition also described a unidirectional trend which may be closely linked to recent anthropogenic factors. The occurrence of this phenomenon has been identified in Alaska (Jacoby and D'Arrigo, 1995; Wilmking and Myers-Smith, 2008) and the Italian Alps (Carrer and Urbinati, 2006; Oberhuber et al., 2008).

Rather than a unidirectional trend, some studies report that the relationship between tree rings and climate may be irregular and possibly linked to natural environmental fluctuations such as moisture availability. For example, Wilmking and Myers-Smith (2008) interpreted changes in climate sensitivity between sites that differed in microtopography across peatland and open canopy forest as a product of moisture conditions, where drier sites exhibited a more stable relationship.

Central Labrador (latitude ~53°N) is on the easternmost edge of the North American boreal forest and is uniquely affected by both continental and marine influences. Inland, a more continental-like climate dominates throughout the year, whereas farther east

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Fig. 1. Location map of Labrador, illustrating the four study sites. Site 1 = Cartwright, Site 2 = Mealy Mountains, Site 3 = Red Wine Mountains, and Site 4 = Labrador City/Wabush. The triangles depict the location of the three Environment Canada climate stations from which data were used in this study.

the proximity of the Labrador Sea ensures a late spring and cool summers (Banfield and Jacobs, 1998). The occurrence of highlands across central Labrador, with a well-defined forest-tundra ecotone, permits sampling near treeline where the climate signal in tree rings should be amplified (Fritts, 1976). Four species are found at alpine treeline in Labrador: black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.) and eastern larch (*Larix laricina* (DuRoi) K. Koch). Of these, black spruce and white spruce radial growth are particularly climate-sensitive (Schweingruber et al., 1993; Trindade, 2009).

Dendroclimatic studies from central Labrador have shown that the radial growth of spruce trees is dependent on both temperature and precipitation (Schweingruber et al., 1993; Trindade, 2009) and further, like other parts of Labrador, the characteristics of the radial growth/climate relationship are heavily reliant on proximity to the Labrador Sea (Schweingruber et al., 1993; Payette, 2007; Trindade, 2009). In particular, the relationship between spruce radial tree growth and precipitation is opposite between coastal sites and those farther inland (Trindade, 2009).

Materials and methods

Tree-ring data

Samples were collected at four sites along the same latitude (~53–55°N) and at increasing distance from the Labrador Sea (Fig. 1 and Table 1). The proximity of the Labrador Sea influences the climate of Labrador and in turn, these climatic patterns shape the current tree distribution (Meades and Moores, 1989). Along the coast, strong ice-laden winds commonly prevent tree growth except in sheltered environments, whereas farther inland, regions of high-, mid- and low-subarctic forest dominate. At all sites, samples were collected at the highest elevation of the alpine treeline, where trees were still sufficiently wide to be cored (more than 10 cm in diameter). Only healthy trees were sampled; trees that looked damaged or in krummholtz-form were passed on. This ensured that the data set consisted of the most climatically sensitive trees possible (Fritts, 1976).

Eight tree-ring width chronologies were constructed from four sites across central Labrador using black and white spruce trees at each site (Fig. 1 and Table 1). Species were differentiated based on cone appearance ('stubby' for black spruce vs. elongated for white spruce) or crown shape (wider crown for black spruce vs. pyramid-shape for white spruce). Ambiguous tree forms were passed on. Each chronology was constructed based on 60 cores sampled at breast height from 30 trees using a 5.1 mm increment borer. Two cores were taken per tree at right angles to each other. Samples were processed using standard mounting and sanding procedures in order to expose the tree rings (Stokes and Smiley, 1968). Ring widths were measured with 0.001 mm accuracy using Windendro software (Guay et al., 1992).

Following visual analysis, crossdating of the measured radii was accomplished using COFECHA software (Holmes, 1983). Sample cores that did not crossdate into the master chronology were removed (more than 50% in some cases) to retain only the common signal within the chronology. Master chronologies were standardized in ARSTAN using a double detrending method to retain as much high-frequency signal as possible, while removing long term trends (Cook, 1985). The method used a negative exponential curve and a 32-year-cubic spline with 50% cut-off. This resulted in a unitless index of radial tree growth for each species at each site.

Climate data

Climate data were obtained directly from local Environment Canada stations (Fig. 1 and Table 1). Growing season (June–September) temperature and precipitation values are comparable across the transect; June–September average precipitation ranges from 88 to 98 mm and temperature from 10.4 to 12.8 °C (Environment Canada, 2008). The maritime influence on terrestrial climate, however, is most obvious during the spring and fall; the coast experiences on average 70 less hours of bright sunshine in the spring due to the higher incidence of fog and fall frost occurs approximately 2 weeks earlier at inland sites (Banfield and Jacobs, 1998).

The climate data used to establish the running correlations was from three Environment Canada climate stations located across central Labrador (Fig. 1 and Table 1). At the two eastern Sites (Sites 1 and 2), the climate data used was from the Cartwright station (Fig. 1 and Table 1). At this climate station, records illustrate that growing season precipitation values from the 1970s to the present increased relative to pre-1970s values and that the abrupt warming since the early 1990s is on par with global trends (Fig. 2, Sites 1(D) and 2(D)). In the Red Wine Mountains (Site 3), tree-ring width data were correlated against climate data from the Goose Bay station (Fig. 1 and Table 1). Similar to the Cartwright records, the Goose Bay data show that precipitation values were low at the beginning of the record (early 1950s) and peaked in the early 1980s and that the temperature values have been rising since the early 1990s, following cool decades in the 1970s and 1980s (Fig. 2, Site 3(D)). At the western most Site (Site 4), climate data was obtained from the Wabush climate station (Fig. 1 and Table 1). There is no discernable pattern in the precipitation data in this short climate record, but the temperature increase since the early 1990s is on par with the other climate stations in central Labrador (Fig. 2, Site 4(D)).

Table 1
Site characteristics for the four locations from which tree-ring chronologies were reconstructed. Climate stations used for each site are listed, along with the length of their instrumental record.

Site	Site name	Latitude (N)	Longitude (W)	Elevation (m asl)	Approximate distance from sea (km)	Climate data
1	Cartwright	53°43.0′	57°25.0′	550	40	Cartwright (1938 to present)
2	Mealy Mountains	53°36.5′	59°48.5′	570	140	Cartwright (1938 to present)
3	Red Wine Mountains	53°47.5′	62°5.0′	574	280	Goose Bay (1942 to present)
4	Wabush	52°55.8′	66°52.4′	730	660	Wabush (1961 to present)

Data analysis

Running correlations were used to track the relationship between radial growth and each climate variable over the time span of the eight master chronologies. Due to the limited length of instrumental climate records at some sites (1961 to present inland, Table 1), only 11-year running correlations were used. To do this, a correlation was established between the first eleven years of the climate record and the corresponding years for the tree-ring record. The same process was repeated, with a 1-year lag, to the end of the climate record. Previous studies have used longer correlations; for example, Carrer and Urbinati (2006), Wilmking and Myers-Smith (2008) and Jacoby and D'Arrigo (1995) calculated 100-year, 50-year and 31-year running correlations, respectively. Longer running correlation lengths enhance longer term shifts and smooth out short-term aberrations, whereas shorter correlation lengths high-

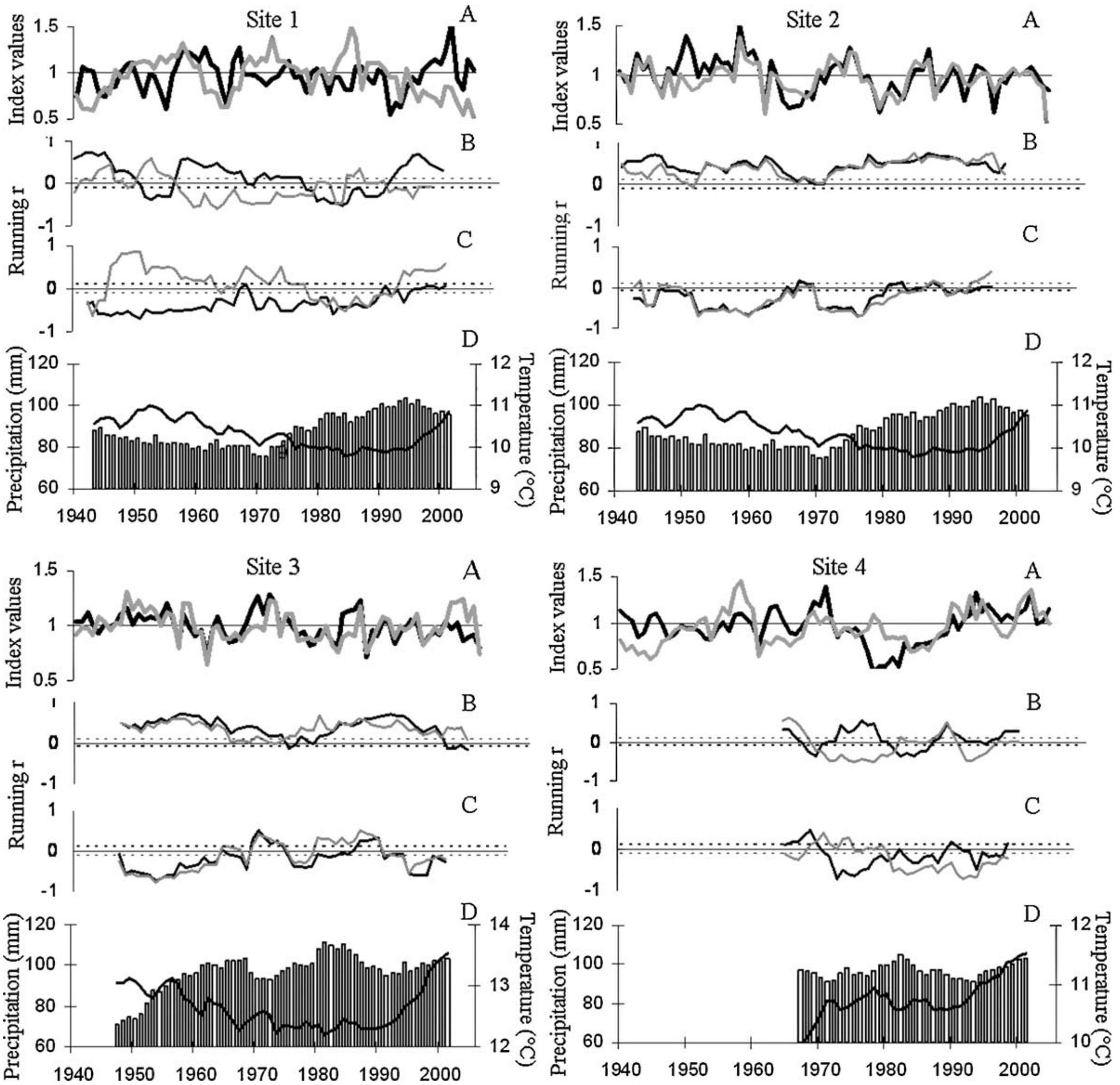

Fig. 2. The radial growth time series, correlations and climate results for black spruce and white spruce for four sites across central Labrador. In all cases, the black line represents the black spruce and the grey line represents the white spruce tree-ring width indices. The radial growth time series are shown in (A). The 11-year running correlation values between the tree-ring index and temperature and precipitation are shown in (B) and (C), respectively. The dashed lines about the zero line in (B) and (C) represent the cut-off values of 0.1 and −0.1, between which values are considered to exhibit neutral relationship between radial tree growth and the climate parameter on the graph. (D) Graphs of the 11-year running mean for averaged June–September climate data. The black line represents temperature and the bars represent precipitation.

light the fluctuations in sensitivity more than longer ones, thus amplifying the results in the immediate past. We argue that the use of short running correlations is appropriate here due to the limited instrumental data set.

Results

Site 1 – Cartwright

The radial growth patterns for the two spruce species at Site 1 are similar over the instrumental period, but display periodic deviations (e.g., 1950s, around 1970, 1980s and 1990s; Fig. 2, Site 1(A)). Temperature sensitivities are generally positive for black spruce and negative for white spruce with notable reversals in the 1950s and 1980s for both species and a gradual weakening from the 1950s to 1980 for black spruce (Fig. 2, Site 1(B)). Precipitation sensitivities are generally negative for black spruce and positive for white spruce with progressive weakening of this correlation for both species from the late 1940s to early 1960s, followed by several decades of marked fluctuations in strength and culminating in a reversal for black spruce in the 1980s (Fig. 2, Site 1(C)). Since the 1980s, the relationship between radial growth and precipitation for white spruce has strengthened and for black spruce has weakened, coincident with rising temperature (Fig. 2, Site 1(C and D)).

Site 2 – Mealy Mountains

The radial growth patterns for black and white spruce at Site 2 are very similar throughout the instrumental climate record with the exception of a departure of several years in the early 1950s (Fig. 2, Site 2(A)). Further, the climate sensitivities of both species to temperature and precipitation follow nearly identical patterns (Fig. 2, Site 2(B and C)). For the most part, the radial growth for both species is positively correlated to temperature, with a marked weakening for white spruce in the 1940s and both species during the 1960s and 1990s. The relationship between radial growth of spruce and precipitation appears less stable than that for temperature with prolonged periods of insensitivity (late 1940s, early 1950s, late 1960s, 1980 to mid-1990s) or relatively stable negative sensitivity (1950s, 1970s; Fig. 2, Site 2(C)).

Site 3 – Red Wine Mountains

The radial growth trends for black and white spruce trees at the Red Wine Mountains site are similar, although the patterns deviate slightly during the late 1960s and early 2000s (Fig. 2, Site 3(A)). The thermal sensitivity of both species is generally positive but fluctuates between weak (mid 1960s to 1980) and moderately strong (1950 to mid 1960s, 1980 to mid/late 1990s) on a regular basis over the 50-year record. The relationship between growing-season precipitation and radial growth of spruce is weakly negative to insensitive for most of the record with two periods of positive, though weak, sensitivity during the early 1970s and 1980s (Fig. 2, Site 3(C)).

Site 4 – Labrador City/Wabush

The radial growth patterns of the two species at Site 4 are similar from the early 1980s to the present, but during prior decades the patterns are either divergent (late 1970s) or vary in the magnitude of response between species (early 1940s, late 1950s, early 1960s and around 1970; Fig. 2, Site 4(A)). Over this short 30-year climate record the thermal sensitivity of the two spruce species is largely out of phase with markedly opposite sensitivities during the 1970s and early 1990s and the overall record for each species characterized by dynamic sensitivity. The relationship between radial growth of spruce and precipitation appears largely negative or neutral with one period of departure (1970s) between the species when white spruce was more or less insensitive and black spruce experienced a strengthening followed by a weakening negative sensitivity (Fig. 2, Site 4(C)).

Discussion

Fig. 3 summarizes the trends in 11-year running correlation values between radial growth of black and white spruce and growing-season temperature and precipitation across the four study sites. Its purpose is to facilitate analysis of spatial, temporal and inter-species trends in climate sensitivity and radial growth across the instrumental record (30–50 years or so). The magnitude and sign of the correlation values were arbitrarily classified to indicate when climate sensitivities abruptly reversed or when there were prolonged periods of insensitivity. An r-value between +0.1 and −0.1 was considered to represent a sufficiently weak correlation to indicate a lack of climatic sensitivity in radial growth records. In the following discussion, a *reversal* in climatic sensitivity is defined as an abrupt change from positive to negative (or vice versa). In contrast, a *shift* in climatic sensitivity is defined as a change from positive or negative to neutral (−0.1 to +0.1) correlation values.

Half of the reversals and shifts in Fig. 3 occur over the last 20 years of the record, a period characterized by increased precipitation at Sites 1 and 2, and fluctuating temperature (cooler 1980s and early 1990s, warmer late 1990s and 2000s) at all sites. The coincidence between the dynamic climate sensitivity of radial tree growth in spruce and recent climate changes across Labrador may hint at a causal link. However, the climate record is short and unlike other studies that have attributed a unidirectional shift in climate sensitivity to the divergence phenomenon, the multidirectional shifts or reversals reported here suggest an influence from other environmental factors on spruce radial growth.

Forest disturbances such as insect outbreaks may also play a role in fluctuating climate sensitivity in Labrador trees. Insect outbreaks cause narrow tree rings and can induce a loss in climatic sensitivity through defoliation, which causes the tree to allocate a portion of its resources to needle regeneration rather than radial growth (Kulman, 1971). Both black and white spruce are susceptible to spruce budworm (*Choristoneura fumiferana* (Clem.)) outbreaks and such events have been documented in Quebec (Boulanger and Arsenault, 2004) and shown to be synchronous across western (Nishimura, 2009) and central Labrador (Trindade, 2009) in the 1950s, 1970s and 1980s. Coincidentally, there are simultaneous shifts in climatic sensitivity of spruce across all sites in the 1950s, late-1960s and early 1970s, and from the 1980s to mid 1990s.

Although it is difficult to assess with absolute certainty whether these episodes of reduced climate sensitivity are solely the result of insect outbreaks, there is marked synchronicity between the Quebec and central Labrador budworm infestation histories and the variability in the relationship between radial growth and climate over the last half century. Shifts in climate sensitivity are not always synchronous with a reduction in radial tree growth, however, which would be expected if the two were exclusively linked through insect infestations. For example, at Site 2, significant reduction in radial growth is apparent in the 1960s and 1980s for both spruce species. During the former episode, both climate variables experience a shift in their sensitivity, but during the latter, only precipitation loses its sensitivity. In another example, the climate sensitivity of radial tree growth at Cartwright shifts during the late

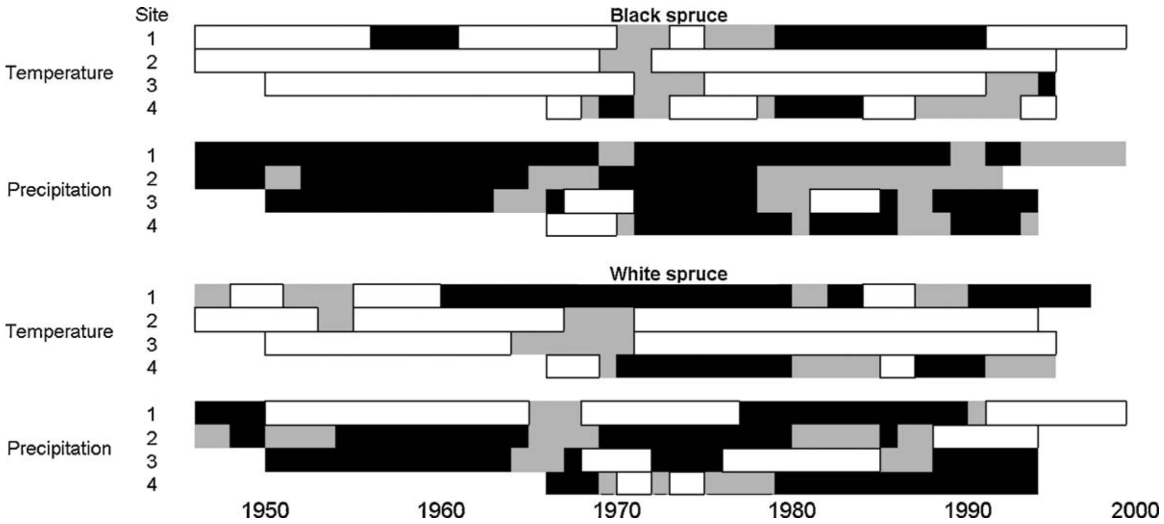

Fig. 3. Summary chart of all correlation values presented. White bars represent a positive correlation, black bars represent a negative correlation and grey bars represent neutral or no correlation.

Table 2

Characteristics of the tree-ring chronologies. Segments are the number of cores used to build each chronology. The inter-series correlation *r*-value is the measure of the overall fit between the segments used to build the chronology. The standard deviation determines the spread of that fit and the unfiltered autocorrelation is a measure of the influence of the radial growth of one year on the next year's growth. The mean sensitivity measures how much a ring width changes from one year to the next, irrespective of the previous-year's growth.

Site	Species	# cores	Period	Mean tree age (range)	Interseries correlation (r)	Standard deviation (SD)	Unfiltered autocorrelation (AC_f)	Mean sensitivity (MS)
1	Black Spruce	27	1851–2006	58 (22–111)	.435	.390	.535	.292
	White spruce	23	1823–2004	96 (54–152)	.478	.388	.640	.251
2	Black Spruce	32	1824–2005	88 (25–172)	.509	.335	.718	.267
	White spruce	45	1758–2006	97 (33–205)	.581	.376	.658	.251
3	Black Spruce	22	1813–2006	94 (43–160)	.456	.272	.682	.218
	White spruce	23	1840–2006	78 (41–160)	.520	.311	.618	.232
4	Black Spruce	24	1755–2006	105 (58–154)	.486	.289	.812	.184
	White spruce	24	1868–2006	88 (25–139)	.509	.452	.811	.202

1940s, late 1970s, and 1980s even though insect population levels are maintained below epidemic proportions at this coastal site. Another factor therefore must be triggering shifts and reversals in climate sensitivity of spruce trees in central Labrador.

There is a noticeable difference in the number of temperature-related ($n = 17$) and precipitation-related ($n = 30$) reversals in climate sensitivity to radial tree growth in the study area and furthermore, the fluctuations in sensitivity to precipitation appear to be related to moisture conditions. Tree-ring growth experiences a shift in sensitivity to precipitation (i.e., nears zero) during wetter periods whereas during drier decades, their sensitivity to precipitation is enhanced (Fig. 2). For example, at Sites 1 and 2 an increase in precipitation since the 1980s is mirrored by a decline in tree-ring sensitivity to precipitation (Fig. 2, Sites 1 and 2 (C and D)). Similar patterns were observed in a spatial context by Wilmking and Myers-Smith (2008) who reported that trees growing on sites with abundant moisture were less climatically sensitive than those growing under drier conditions. This latter effect may be paralleled in Labrador as a large proportion of the cores were removed to construct the final tree-ring chronologies (Table 2). It is possible that the high moisture levels, temporally and/or spatially in Labrador are causing a reduction in climate sensitivity.

Unexpectedly, there is no noticeable difference in the frequency of reversals between the four sites. In particular, at the coastal site the climate is strongly influenced by the Labrador Sea and hence it was expected that this site would yield unique results (Banfield and Jacobs, 1998). However, the main climatic differences between sites on the coastal and inland Labrador occur in the spring (amount of solar radiance) and fall (timing of the first frost) (Banfield and Jacobs, 1998). Since the climate data in this study encompasses the June–September period only, these climatic differences are likely not reflected in this analysis.

Conclusion

Until recently, it was generally assumed that the correlation value between a tree-ring index for a climatically sensitive species and the associated climate variable was somewhat constant over the instrumental period and therefore any reconstruction of past climate made on the basis of the correlation would generate a reliable palaeoclimatic record. The worldwide descriptions of 'divergence effects' have brought this somewhat into question.

In this study, we have illustrated that there is a high degree of instability in the climate/tree-ring sensitivities at various sites across central Labrador, despite statistically significant relationships over the instrumental record. Not all of these instabilities can be explained, even though some are probably coincident with past insect outbreaks in some form. The two sites that are from the high-elevation locations illustrate the most time-stable relationships, compared to the extreme coastal and extreme continental sites. There are also influences from moisture availability that seems to be affecting radial growth when associated with changes in temperature at each specific site.

The results presented here suggest that there needs to be additional control on future dendroclimatic reconstructions. The presentation of a running correlation graph of climate sensitivity, along with the standard calibration/verification graph would demonstrate the data quality on palaeoclimatic reconstructions. This paper has also shown that some sites are not suitable for dendroclimatic reconstructions, even if they appear to be so *a priori*. For instance, an alpine treeline may be climatically limited, and as such, deemed appropriate for a climatic reconstruction. But a deeper analysis may reveal periods of external influences on radial growth (e.g., insect outbreaks and fires), which probably effectively eliminate the consistent relationship between radial tree growth and climate, and ultimately would weaken any dendroclimatic reconstruction derived from the data.

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