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Tree-ring evidence of recent climate changes in the Mackenzie Basin, Northwest Territories

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Abstract: Three long-term climate reconstructions based on tree-ring analysis for the boreal and forest tundra biozones in the Mackenzie valley are presented. The northernmost site (Eskimo Lakes site) provides the longest tree ring chronology, covering the period of 1172–1991, while the boreal sites (Mountain River) span the last five hundred years. Even though sampled sites correspond to different environments and are separated by hundreds of kilometres, they show similarities in long-term climatic trends. The period known as the “Medieval Warm Period” was follow by a long period of cold, dry conditions between 1330 and the early 1900s. This suppressed growth period, corresponding to the “Little Ice Age”, was briefly interrupted by milder conditions during the first half of the sixteenth century. Finally, all tree-ring chronologies show a increasing growth at the beginning of the twentieth century.

Résumé : Trois reconstitutions climatiques à long terme fondées sur l’analyse des cernes de croissance des arbres dans les biozones de la forêt boréale et de la toundra dans la vallée du Mackenzie sont présentées. Le site le plus au nord (lacs Eskimo) livre la dendrochronologie la plus longue, qui s’étire sur la période de 1172 à 1991, tandis que les sites de la forêt boréale (rivière Mountain) renseignent sur les cinq derniers siècles. Même si les sites échantillonnés correspondent à des environnements différents et qu’ils sont séparés par des centaines de kilomètres, les tendances climatiques à long terme qu’ils indiquent affichent des ressemblances. La période chaude médiévale a été suivie par une longue période de conditions froides et sèches entre 1330 et le début du 20e siècle. Cette période de croissance ralentie, correspondant au «Petit âge glaciaire», a été interrompue brièvement par des intervalles à conditions plus douces durant la première moitié du 16e siècle. Enfin, toutes les données chronologiques basées sur les cernes de croissance des arbres révèlent une croissance accrue au début du 20e siècle.

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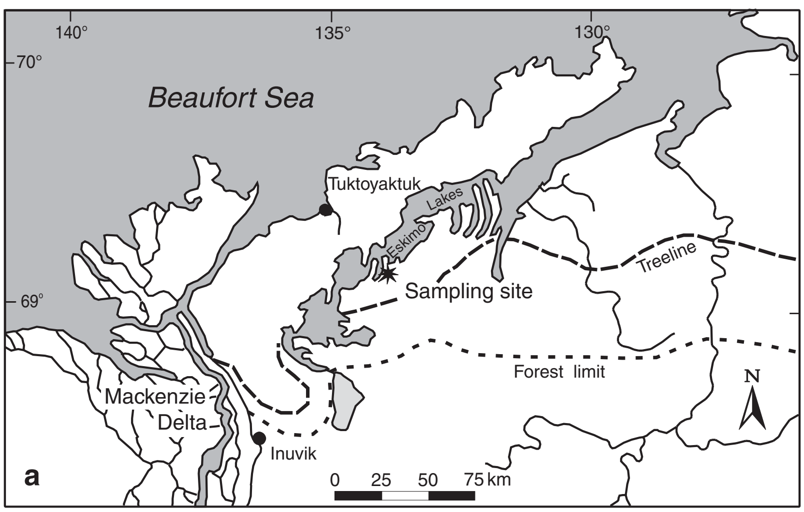
INTRODUCTION

The Mackenzie valley encompasses different vegetation zones, ranging from boreal forest to shrub tundra. During the Holocene, the distribution of vegetation in the Mackenzie valley has undergone important modifications in response to major climatic changes. Such modifications occurred because the species present and tree growth in high latitudes are strongly influenced by temperature regime. In treeline environments, moisture is normally adequate and tree growth is highly dependent on summer temperatures (growing season). Tree rings offer the greatest potential for reconstruction of climate because of the large geographical distribution of suitable sites, the annual resolution, and the relatively long time span of records. Moreover, several studies have demonstrated that boreal species in marginal environments, especially at the northern treeline, retain a strong temperature signal in their ring-width records (Jacoby and Cook, 1981; Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1992).

This paper presents climatic interpretations from tree-ring chronologies obtained within the two most important vegetation zones in the Mackenzie valley: the boreal forest and the forest tundra. The first chronology is from Eskimo Lakes area near the Tuktoyaktuk Peninsula (Fig. 1a) and reveals climatic changes over the past 800 years near the treeline in the high subarctic area. Two other chronologies come from the Mountain River area (Fig. 1b) located in the upper section of the boreal forest. One of these is representative of sheltered conditions (forest chronology) while the other represents exposed conditions (krummholz chronology). In all cases, the presence of subfossil material (dead stems lying on the surface or still in living position) allows chronologies to be extended substantially beyond those given by living trees.

DENDROCHRONOLOGY AND DENDROCLIMATIC TECHNIQUES

Climate interpretations from tree rings can be extended into the past, well beyond the age of living trees, by crossdating. Individual trees are sliced or bored, and the width of the rings measured, usually with the aid of a binocular microscope. A graph of ring width versus age in years gives a tree-ring series. Crossdating requires a search for distinctive patterns of wide or narrow rings and matching these, first between living and dead trees, then between progressively older dead trees. This procedure gives a ring-width chronology with an exact year of formation for each ring. It is beneficial to have



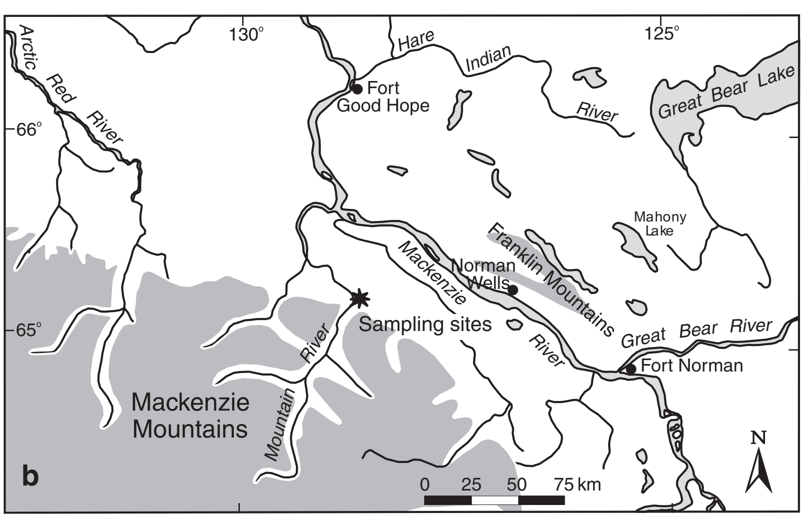


Figure 1.

Location of sampling sites: ***a)*** *Eskimo Lakes site and* ***b)*** *Mountain River sites.*

several trees of overlapping age to assist with the recognition of false rings, missing rings, or frost rings formed in response to extreme conditions.

The raw ring-width sequences developed in this study are composed of several series, each of which may show influences not directly linked to climate. These influences include a tree's biological growth trend, whereby ring widths generally tend to decrease with age, or the effects of natural disturbances such as landslides. At the Mountain River site, long-term growth of trees was influenced by slow eolian sedimentation. These trends are removed from each individual series by a standardization process.

The standardization process is done by fitting a smooth curve to each tree-ring series and dividing each ring width by the corresponding value given by the curve. The overlapping parts of these transformed series are averaged and used to produce a 'standard chronology'. The standard chronology emphasizes short-term variation over the life of individual trees used to construct the chronology, but eliminates information on longer term climatic variation. To obtain longer term trends present in tree-ring series, each ring's width was divided by the mean ring width for that series to produce a normalized series. These series show trends spanning the full average life of trees and are used to construct an 'absolute chronology' (Archambault and Bergeron, 1992).

Under some conditions, ring width characteristics of a given year are strongly influenced by the growth of previous years (biological persistence effect). Therefore, when an attempt is made to calibrate a tree-ring series with an instrumented climate record (e.g. measured temperatures at a meteorological station), the influence of climate factors may be obscured by the influence of biological factors. To determine if this is the case, each ring of a series can be compared with the previous year's ring. This is referred to as autocorrelation. If the autocorrelation is high, then biological effects are strong. Once recognized, they can be removed to produce a 'residual chronology'. This type of chronology is most valuable for determining the correlation of ring width with measured climatic variables.

The relationship between tree-ring chronologies and monthly climate variables was examined by correlating ring-width indices with monthly mean temperature and total precipitation for each month from April of the year before ring formation through August of the year of ring formation for the closest meteorological station (Inuvik station for Eskimo Lakes chronology and Norman Wells station for Mountain River chronologies). This range of climatic variables was chosen because it includes two complete growing seasons and allows the importance of factors acting during the year preceding ring formation to be assessed (i.e. bud formation, foliage protection, moisture storage). Reduced vegetative structure caused by severe conditions during the previous fall and winter (bud and needle desiccation and/or abrasion) will have a negative effect on photosynthetic activity and, consequently, on tree growth. Finally, because ring width rarely depends on a single climatic variable (Earle et al., 1994), various combinations of seasonal climatic variables were also investigated to better explain growth variation.

When the relationship between tree growth and monthly climate variables is sufficiently strong (r>0.5–0.6) to suggest a statistical link between a specific variable and ring width (Fritts, 1976; Garfinkel and Brubaker, 1980), this regression can be used as a basis for reconstructing climate variations before the period of climate records. This is true for the Eskimo Lakes chronology where tree growth was strongly correlated with mean July temperature. Since the data set in this case consists of a single chronology derived from one measured variable (total ring width) the model consisted of a simple linear regression. Even when there is no clear statistical connection between a specific climate variable and ring width, past environmental conditions, including climate factors, can be estimated directly from longer term tree-growth patterns.

Trees at the Eskimo Lake and Mountain River sites were sampled between 1990 and 1992. Because most of the sampled trees come from exposed sites where radial growth series may contain several growth anomalies (missing rings, frost rings, etc.) reflecting extreme growing conditions, complete cross-sections were taken as close to ground level as possible.

TREELINE SITE — ESKIMO LAKES CHRONOLOGY

Study site

This site is located on the south shore of Eskimo Lakes (69°08′N, 132°13′W) about 105 km northeast of Inuvik and 48 km southeast of Tuktoyaktuk (Fig. 1a). It is representative of the arctic treeline in the lower Mackenzie valley and lies within a continental subarctic climate. Meteorological data recorded since 1957 at the Inuvik weather station show a mean annual air temperature of -96°C (Fig. 2), and a mean monthly air temperature for July of 14°C. On average, the degree-days of growth (>5.5°C) equal 654. Total annual precipitation is 256 mm, while total annual snowfall is 175 cm (55% of total precipitation). Summers are characterized by frequent incursions of Pacific air masses (30–40% of days) in the form of rain-producing cyclones (Ritchie, 1984). The site is underlain by continuous permafrost.

Tree-ring samples were collected from white spruce trees (*Picea glauca* (*Moench*) *Voss*) that lie in the northernmost part of the forest tundra, between the forest limit and the tree-growth limit. Small forest stands (up to 7 m tall) surrounded by low shrubs characterize the vegetal landscape (Fig. 3). No evidence of fire (charcoal, snags, etc.) was found on the site, suggesting that these small stands evolved naturally without fire disturbance for several centuries or even millennia. This old-growth treeline vegetation is composed of living and dead white spruce stems of all ages and of different shrubby or normal growth forms. Tree-ring dating of the dead population, still in growth position or lying on the surface, indicates that subfossil stems can remain undecomposed for up to 500 years depending on site conditions. For these reasons, this site offers a high potential for a reconstruction of climatic history at the treeline.

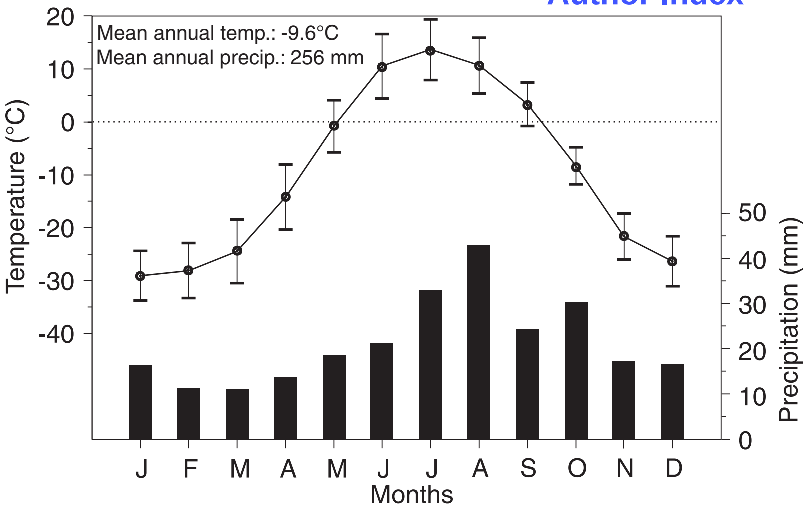


Figure 2.

Mean monthly temperature and total precipitation, Inuvik weather station (1957–1989). Error bars indicate standard deviation for temperature (from Environment Canada, 1993).

Figure 3. *Old-growth white spruce stand at the treeline on the south shore of Eskimo Lakes (Eskimo Lakes sampling site) which is characterized by the presence of living and subfossil individuals. Photograph by C. Bégin. GSC 2000-028A*

Dendrochronology

Fifty-four radii from 28 trees (26 radii from living trees and 28 radii from dead trees) were crossdated and averaged to produce the Eskimo Lakes chronology, covering the 820 years from AD 1172 to 1991 (Fig. 4). The main difficulty encountered was the extreme narrowness of the annual rings, the mean ring width being only 0.18 mm. Nevertheless, of the 12 909 annual rings crossdated, only seven locally absent rings were identified (0.05%). The mean correlation between the 54 series and the master chronology was 0.524, a figure indicating strong common variance and excellent crossdating between all samples.

Variations in absolute ring widths, especially in the smoothed form (Fig. 4b), show two general periods of increasing growth, separated by a period of slow growth. The first accelerated period of growth occurred between AD 1172 and 1335, when growth remained far above the mean for each year except for 1248 to 1275, when tree growth experienced a severe depression; however, the portion of the chronology between 1172 and 1265 must be interpreted cautiously since it is represented by only two series. This period of strong tree growth was then followed by a lengthy period (1336–1903) when growth was mostly below the mean. During these 567 years of slow growth, the fifteenth and sixteenth centuries showed slight improvement in growth within the interval 1507 to 1512. The following three centuries (seventeenth to nineteenth) represent the most difficult period for tree growth; the lowest ring-width values were recorded in 1652, 1685, 1707, 1721, and 1827. Since 1904, tree growth has begun to increase rapidly, reaching a maximum in 1948. Since then, tree growth has decreased slightly, yet remained above the mean value.

Climate reconstruction

Of the 23 variables analyzed in the correlation function procedure, only July mean temperature ($r = 0.559$) and previous November precipitation ($r = 0.417$) were significantly correlated with annual growth expressed as the residual chronology (Fig. 5). Combinations of monthly temperatures gave lower correlation values than for July mean temperature alone. The standardized chronology was also subjected to the correlation analysis to check if it was influenced by the same variables. The response was quite similar for both chronologies, although correlations with the standardized chronology were not as strong as with the residual chronology. The positive correlation between growth and July temperatures has been observed in different subarctic areas (e.g. Garfinkel and Brubaker, 1980; Jacoby and Cook, 1981). It suggests that high temperatures during the growing season enhance tree growth by increasing soil temperature, irradiance, and net photosynthesis. The positive response of growth to previous November precipitation probably reflects the protective role of snow cover against winter desiccation and foliage abrasion by wind.

The mean July temperature reconstruction is simply a rescaling of the original residual chronology (Fig. 6a). A smoothed version of the reconstruction expressed as deviation from the 1957–1989 Inuvik mean (Fig. 6b), shows the twentieth-century average July temperature to be 0.05°C warmer than present temperature and at least 0.6°C warmer than previous centuries. This is probably an underestimation of the actual temperature increase since it is obtained from the residual chronology. The standard chronology is also

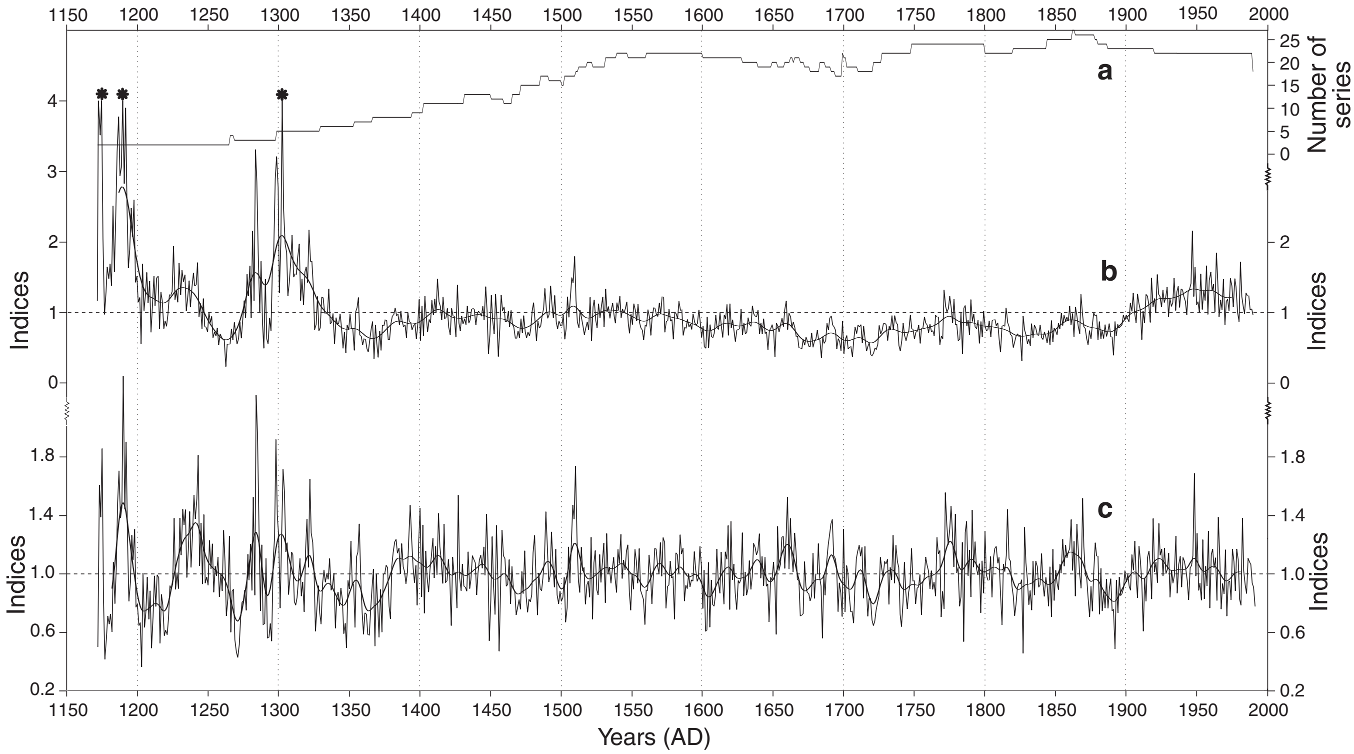


*Figure 4. Tree-ring chronologies; **a)** the number of series included in each portion of the chronology; **b)** absolute ring width; and **c)** standardized chronologies from Eskimo Lakes (treeline) site. Smoothed lines are 15 year running means. Indices above 4.0 (*) are truncated.*

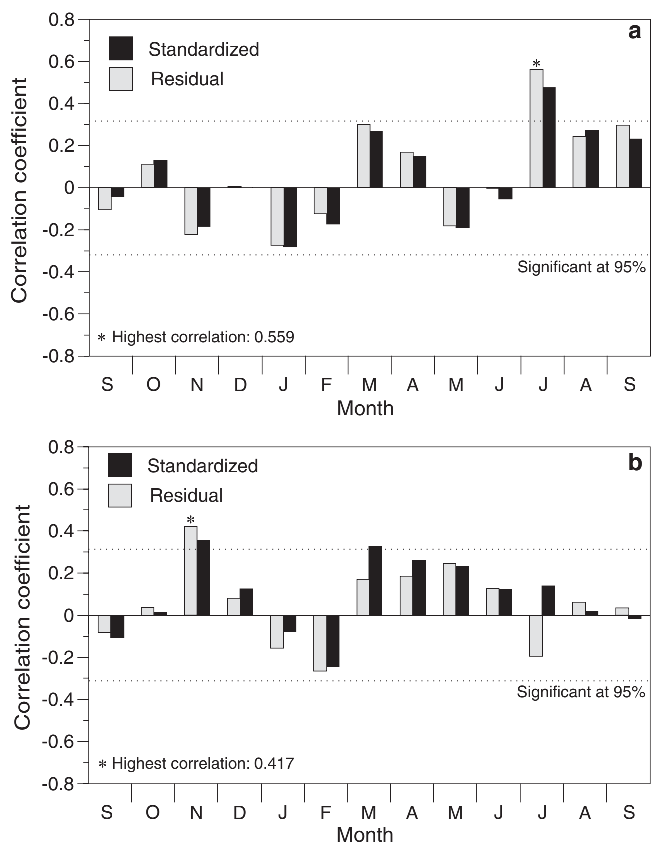


Figure 5.

*Correlation of tree growth with **a)** monthly mean temperature and **b)** total monthly precipitation at Inuvik (1957–1989) for the standardized and residual Eskimo Lakes treeline chronology.*

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positively related to July mean temperature, although at a lower level of confidence. A regression with the standard chronology suggests a 1.5°C increase in mean July temperature relative to the seventeenth to nineteenth centuries. This correlates very well ($r = 0.519$, $p < 0.0001$) with a 374-year reconstruction of northern hemisphere annual temperatures (D'Arrigo and Jacoby, 1992) developed using boreal treeline sites. The colder July temperatures prior to the twentieth century correspond to the period known as the Little Ice Age (Grove, 1988). Our tree-ring data indicate that this period would have extended from 1336 to 1903 at the treeline in the north Mackenzie valley. Except for some short intervals when July temperatures have been above the present value (particularly 1507 to 1512), the Little Ice Age July temperature was about 0.3°C colder than the present normal.

BOREAL SITES (FOREST AND KRUMMHOLZ) — MOUNTAIN RIVER CHRONOLOGIES

Study sites

A forest and a krummholz (stunted, gnarled growth often found at the treeline) site in the vicinity of Mountain River (65°14′N, 128°33′W) about 80 km west of Norman Wells (Fig. 1b) have also been studied. Climate characteristics have been provided by the Norman Wells weather station where complete records are available since 1943. Mean annual air temperature is -6.1°C (Fig. 7) with a large range in extreme daily temperatures varying from -43°C in January to 24°C in July. The average annual precipitation totals 321 mm. The study area is located in the upper Mackenzie section of the boreal forest where conifers locally occupy well drained terrains. Terraces and valleys have been colonized by forest in which white spruce (*Picea glauca* (*Moench*) *Voss*) is the dominant tree species, often found in association with gray alder

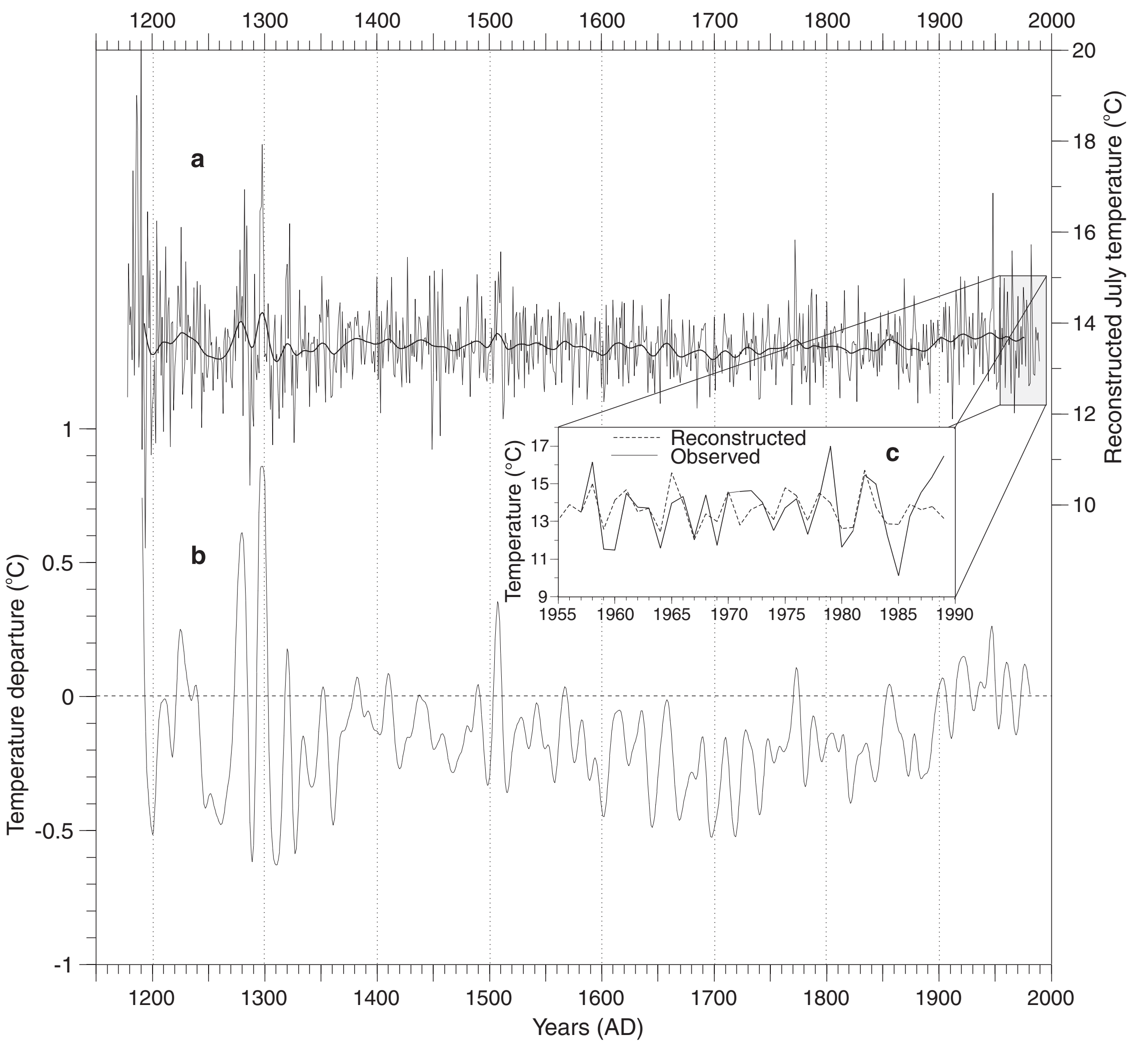

Figure 6. *Reconstructed July temperature at Inuvik for* ***a)*** *the period 1172–1991 and* ***b)*** *temperature departure from the 1957–1989 normal period. Comparison between the reconstructed (dashed) and actual (solid line) July temperature for the period 1955–1989 is shown in* ***c)****.*

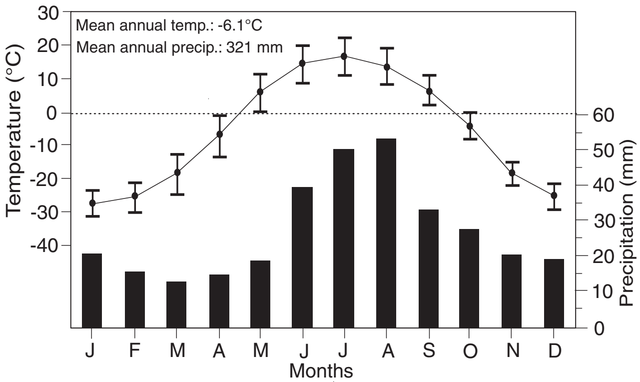

Figure 7. *Mean monthly temperature and total precipitation, Norman Wells weather station (1944–1989). Error bars show standard deviation of temperature (*from *Environment Canada, 1993).*

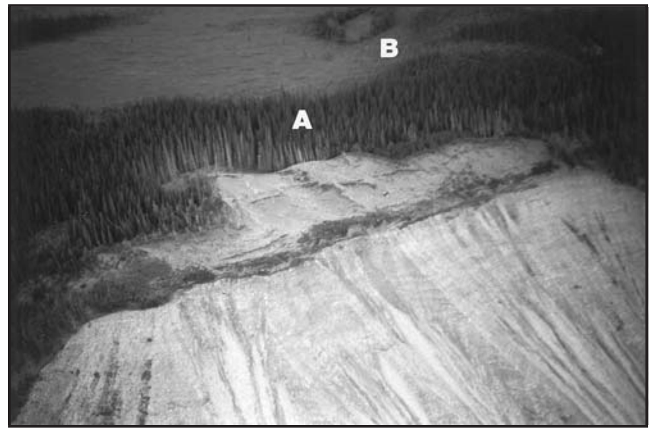

Figure 8. *Oblique aerial photograph showing the white spruce forest '**A**' and krummholz '**B**' sampled stands at the edge of a glaciofluvial terrace along Mountain River. Photograph by C. Bégin. GSC 2000-028B*

(*Alnus incana* (*L.*) *Moench*). In closed forest, various species of feather mosses cover the ground surface. Clonal populations of balsam poplar (*Populus balsamifera L.*) and various shrub species (e.g. *Eleagnus commutata Bernh.*) have colonized zones experiencing active alluvial or eolian deposition.

Both sites are located at the top of an 85 m high glaciofluvial terrace overlooking Mountain River (Fig. 8). The terrace surface is mostly occupied by peatland where stunted white spruce and larch (*Larix laricina* (*Du Roi*) *Koch*.) are growing. The terrace edge is affected by eolian deposition that generates, in some places, small cliff-top dunes (Bégin et al., 1995). Forest tree-ring samples were collected from this forest margin, while the krummholz tree-ring samples were collected from a stunted tree stand growing on a rocky ridge located behind the forest margin on a site experiencing a harsher growing environment.

Dendrochronology

Forest site

Several generations of trees that evolved in the cliff-top eolian environment (Fig. 8) were used to produce the Mountain River forest chronology. A total of 161 samples were taken from 1) fossil trees exposed in the deflation zone (n = 66), 2) both dead and living trees found on the dune slipface (n = 38), and 3) living trees in the periphery of the dune area (n = 57). Of all the samples collected, only 42 radii from 27 trees were crossdated and averaged to produce the forest chronology. Most samples were rejected to avoid the influence of sand deposition on growth patterns. Nevertheless, the resulting chronology covers a period of 471 years, from AD 1521 to 1991. Within the 11 130 annual rings crossdated, seven locally absent rings were identified (0.06%). The crossdating procedure was facilitated by the presence of reliable light rings, especially those from 1871, 1884, and 1959. The mean correlation between the 42 individual series and the master was 0.409.

Long-term environmental changes are clearly shown in the absolute ring-width chronology (Fig. 9b). Excluding the portion of the chronology prior to 1595, which is represented by less than three series, three distinct periods appear in the remaining 400 years. The interval between 1595 and 1777 is characterized by a slow growth where values oscillate around or slightly below the mean. After 1777, tree growth decreased substantially to reach its minimum value in 1809. It remained systematically below the mean until 1852. Within this period of suppressed growth, the interval from 1809 to 1813 represents the most difficult growing conditions. Since 1852, radial growth increased gradually until the end of the nineteenth century and reached maximum growth between 1899 and 1901. Radial growth decreased slightly between 1908 and 1948, but then decreased dramatically to the mean value of the present day.

Krummholz site

The sampled krummholz stand has similarities to the Eskimo Lakes site. It is an old-growth white spruce stand that has escaped natural fire for a long time and it is composed of living and dead trees rarely exceeding 3 m in height; however, this exposed vegetation is primarily characterized by the complex growth forms of trees. Multistem structures and localized foliage give the trees a bonsai-like appearance (Fig. 10).

A total of 65 stems (27 living and 38 subfossils) were sampled, but most of them were rejected after analysis because of the narrowness of their annual rings. In some cases, decades of rings were totally missing in the series. Twenty-seven radii from 17 trees were selected for the construction of the Mountain River krummholz chronology that covers 507 years, from AD 1485 to 1991. Out of the 8038 annual rings crossdated, only three locally absent rings were identified (0.036%). The mean ring width was 0.16 mm and the mean correlation between the 27 individual series and the master was relatively low, with r = 0.441.

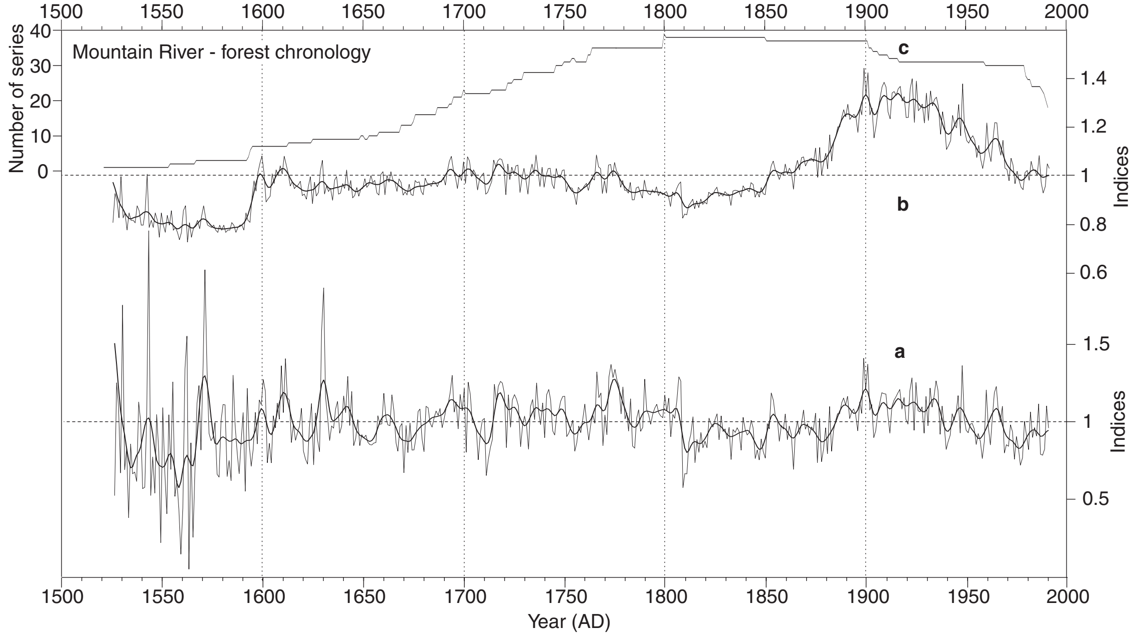

Figure 9. ***a****) Standardized and* ***b)*** *absolute ring width chronologies from Mountain River (forest) site. Smoothed lines are 11 year running means. The number of series included in each portion of the chronology is shown in* ***c)****.*

Environmental changes within the krummholz site are expressed in the absolute ring-width chronology (growth indices). Two periods of increased growth, separated by a long period of slow growth, appear in the long-term tree-ring pattern (Fig. 11b). The three periods are fortunately represented by enough series to be interpreted adequately (four tree-ring series occur before 1503 and six before 1533). The period between AD 1485 and 1573 is characterized by accelerated tree growth which remained far above the mean except for the intervals of 1500–1504 and 1534–1538, when growth decreased sharply. After 1573, tree growth decreased abruptly and remained mostly below the mean for the next three centuries, between 1574 and 1918. Within this lengthy period of slow growth, the intervals of 1602–1607, 1670–1675, 1832–1835, 1878–1884, and 1895–1898 were particularly critical for tree survival and the strongest negative deviations occurred in 1606, 1834, and 1895; however, this period was also characterized by a few intervals when growth exceeded the mean in response to better climatic conditions. Such intervals occurred between 1628 and 1637, 1772 and 1783, and 1801 and 1808. Finally, a period of improved growth conditions occurred during the twentieth century, between 1919 and today. Tree growth has increased progressively and reached a maximum value in 1955. Since that year, the growth has decreased.

CLIMATE INTERPRETATIONS

The two tree-growth curves show how growth conditions have fluctuated during the last centuries in the Mountain River area (Fig. 9, 11). The climatic significance of these variations can be estimated by examining the potential relationships between climatic factors and tree-ring values. The

Figure 10. *General view of the old-growth, white spruce, krummholz stand at the Mountain River site (Mountain River krummholz sampling site) characterized by stunted subfossil and living trees. The growth form of the approximately 400-year-old living tree in the centre shows the erosional snow/air interface (1.05 m). Person at the left side gives the scale. Photograph by C. Bégin. GSC 2000-028C*

correlation of monthly mean temperature and monthly precipitation with forest and krummholz chronologies is presented in Figures 12 and 13, respectively. Both chronologies show a different response to climate.

In general, tree growth at the forest site shows a consistent negative response to summer temperature and a positive (although not statistically significant) response to precipitation in several months. In more detail, the mean temperature of the preceding June appears to be the most important climatic variable in terms of tree growth (r = -0.44); however,

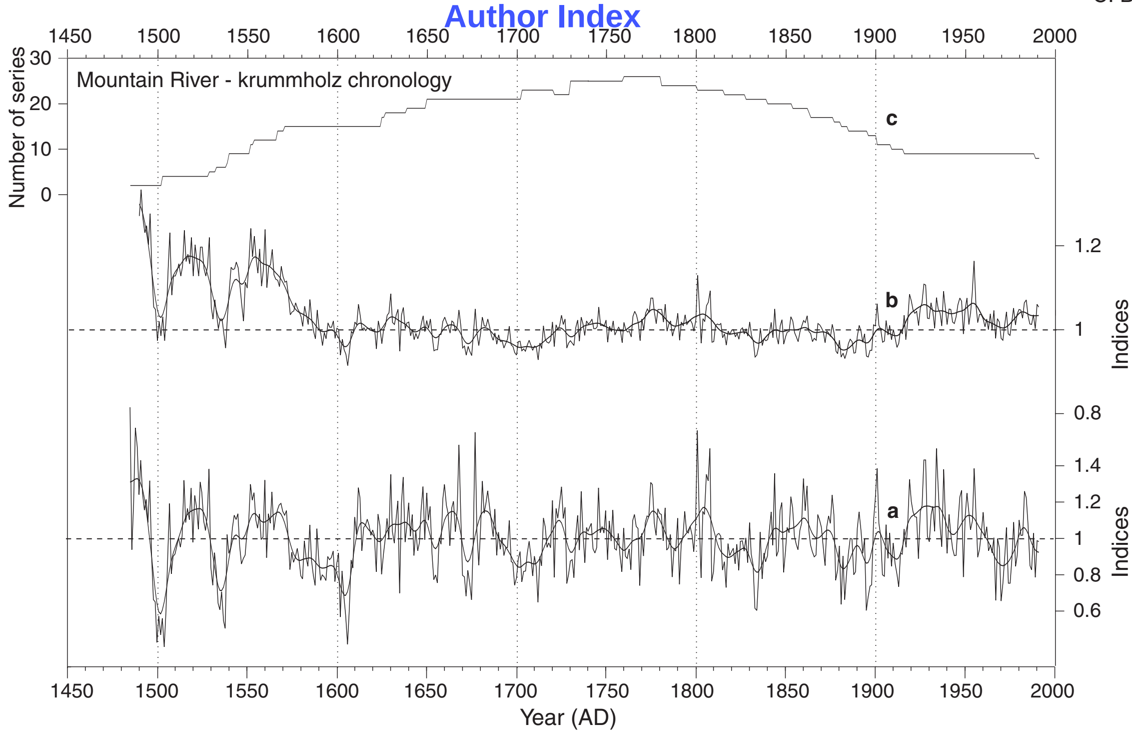

Figure 11. ***a****) Standardized and* ***b)*** *absolute ring width chronologies from Mountain River (krummholz) site. Smoothed curves are 15 year running means. The number of series included in each portion of the chronology is shown in* ***c****).*

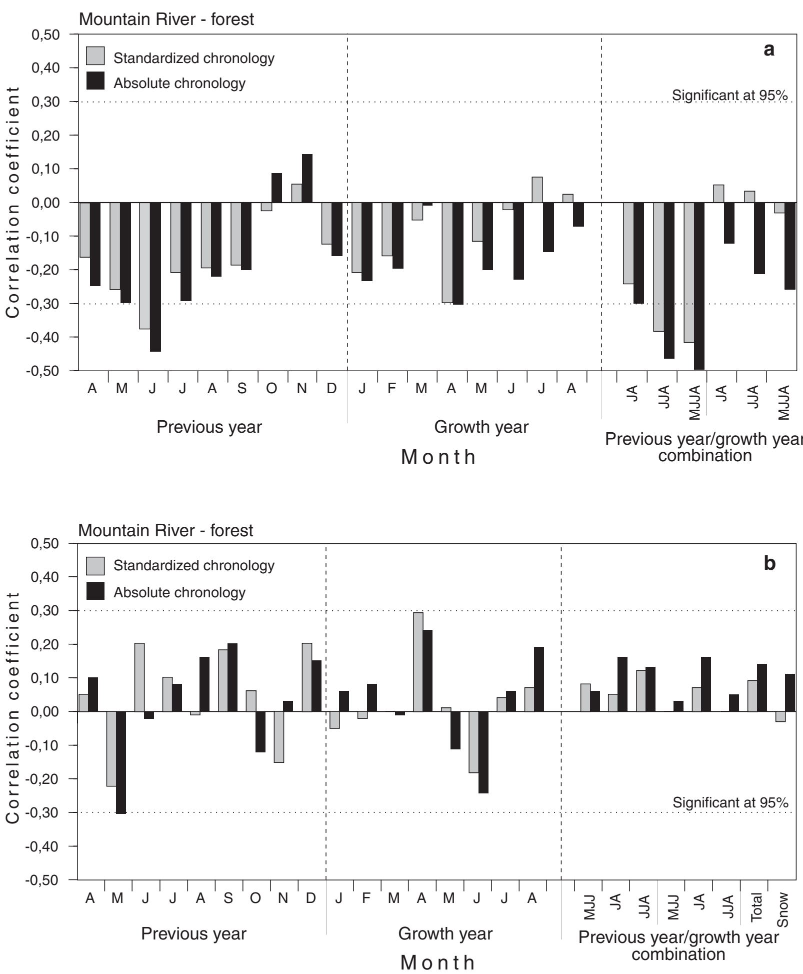

Figure 12.

Correlation of tree growth with ***a)*** *monthly mean temperature and* ***b)*** *total monthly precipitation at Norman Wells (1944–1989) for the standardized and absolute Mountain River forest chronology.*

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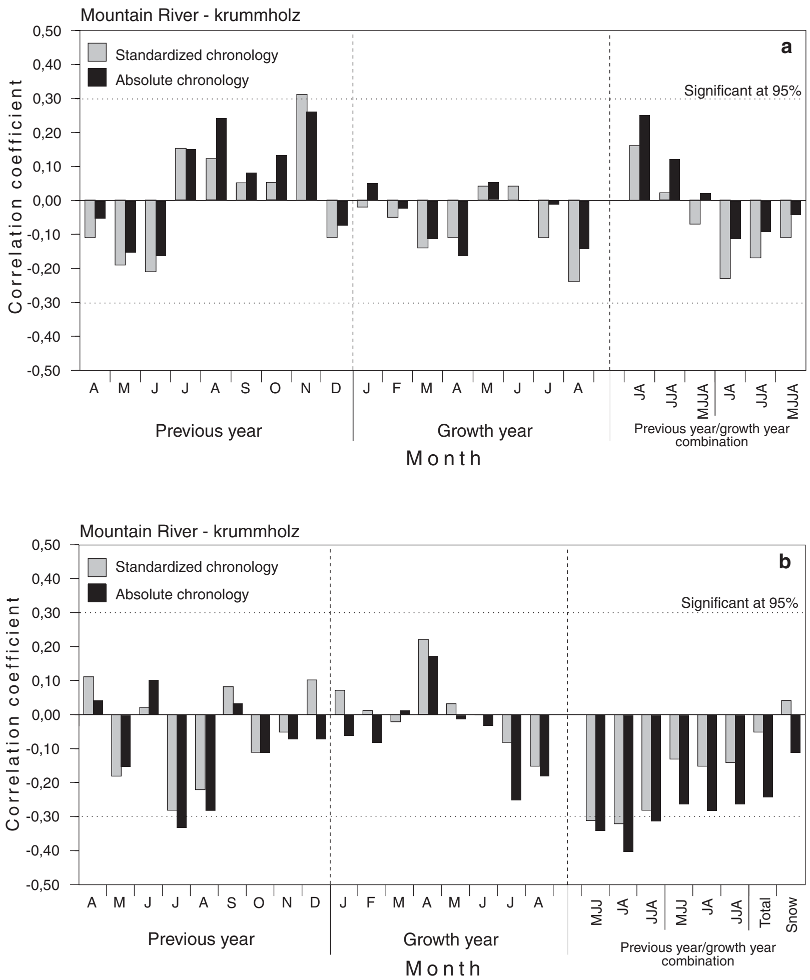

Figure 13.

*Correlation of tree growth with **a)** monthly mean temperature and **b)** total monthly precipitation at Norman Wells (1944–1989) for the standardized and absolute Mountain River krummholz chronology.*

averaging monthly temperatures from groups of months provides a stronger negative correlation between summer temperatures preceding ring formation (May to August) and ring width (r = -0.49). This relationship is apparent in Figure 14a, in which average summer temperatures prior to growth and the inverse of the tree-ring indices are plotted on same scale ordinates. Using the inverse indices when the correlation is negative makes the correspondence more visible. On the other hand, correlations between forest-site tree growth and precipitation show no clear trends. The only determinant variable is precipitation in the preceding May, which has a negative effect on growth. Precipitation during the previous summer (June to September) and during the current spring (April), although not significant, is positively correlated with ring width. The opposite response of growth to temperature and precipitation seems typical for dry sites in subarctic environments (Villalba and Veblen, 1994). In fact, as noted by other workers (Bongaonkar et al., 1994), excessive solar radiation associated with higher temperatures during summer has a direct effect on evaporation and the depletion of soil moisture. Since higher temperatures are physiologically more conducive to better growth in boreal environments, the negative response here is probably due to the dominant role of temperature in determining available moisture for the trees. Finally, the analysis of the climate-growth relationship also suggests that warm and dry springs (especially in April) could be critical for tree growth, probably by increasing desiccation damage (D'Arrigo et al., 1992). For those reasons, fluctuations in the Mountain River forest chronology should be interpreted more in terms of water stress than strictly in terms of summer temperatures. The increasing radial growth at the end of the nineteenth century reflects increasing precipitation and soil moisture associated with the twentieth-century warming (Jones et al., 1986). The suppressed growth conditions which characterize the Little Ice Age (Grove, 1988), and particularly the period of 1780–1850, indicate a strong water stress in trees.

The situation is quite different at the krummholz site where tree growth exhibits a negative correlation with previous and current summer precipitations and positive correlation with previous summer (July to August) and fall (November) temperatures (Fig. 13). The significant negative correlation between summer precipitation and radial growth is also obvious in Figure 14b where total July–August precipitation of the previous year is plotted against the inverse of the tree-ring indices. Climatic conditions during the year prior to growth seem significant at this exposed site. The negative response of radial growth to summer precipitation indicates that such stunted trees, characterized by a reduced leaf surface, are not sensitive to water stress during the summer. The krummholz response to climatic factors is thus similar to the

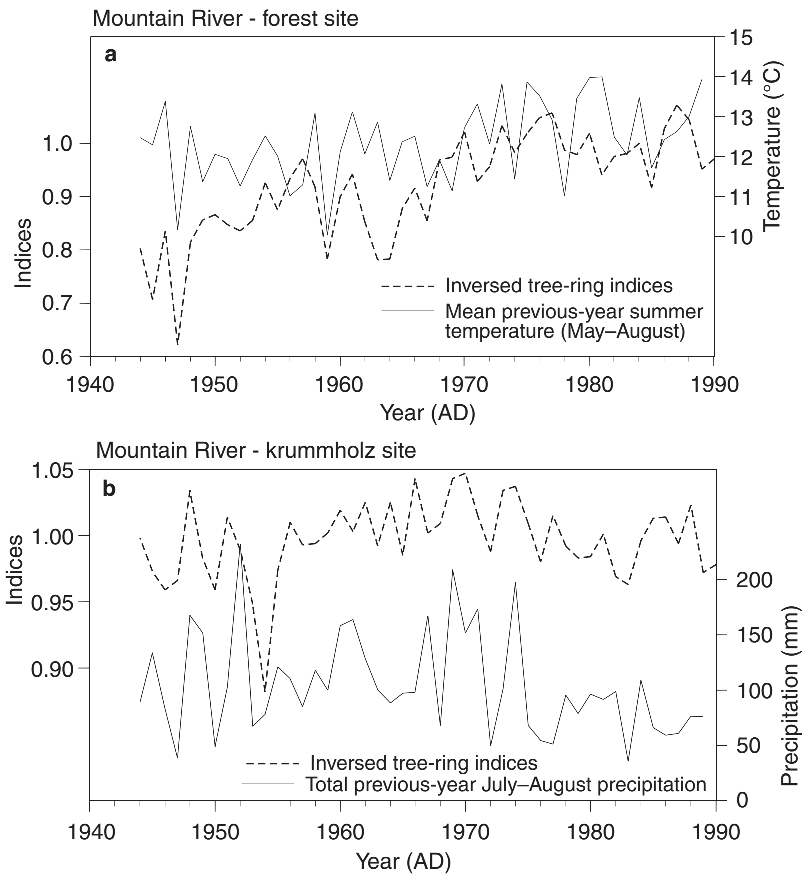

Figure 14.

***a**) Comparison between absolute tree-ring indices (inversed) of forest chronology and mean summer temperature (May–August) of the previous year. **b**) Comparison between absolute tree-ring indices (inversed) of krummholz chronology and total July–August precipitations of the previous year.*

one observed at several treeline sites where tree growth is favoured by warm conditions during the previous summer. Note that moisture stress during the spring can represent a problem for further tree growth. The correlations of April temperature (negative) and precipitation (positive) with tree growth indicate that the initiation of photosynthesis when the soil is still frozen can increase desiccation processes and foliage damage. The physiological interpretation of the climate-growth relationship shows that variations in the tree-ring pattern at the krummholz site provides information about summer temperature since AD 1500. The krummholz chronology (Fig. 11) suggests that warm, and probably wet, conditions prevailed during the sixteenth century, before onset of the cooler period of the Little Ice Age (approximately 1600 to 1900). Most trees in the krummholz germinated during this mild period and developed a normal shape (single erect stem). The absence of erosion marks on subfossil trees suggests that the protective snow level was probably higher at this time. Conversely, the following lengthy depressed period on the tree-ring curve shows the 'Little Ice Age' cooling effect on tree growth. Summers were cooler and probably drier, while the protective snow cover had decreased substantially. In the same area, low snow level and the ensuing low water level prior to the twentieth century has allowed the stabilization of glaciofluvial slopes and, consequently, the cliff-top dune surface (Bégin et al., 1995). The increasing desiccation and winter abrasion seriously deteriorated the leaf structure of trees and would have been responsible for the krummholz development during these three centuries. Fortunately, trees were able to recover partially during short milder episodes centring around the mid-1600s and the early 1800s.

Since the early 1900s, warmer summers and increasing snow associated with the 'Twentieth Century Warming' and deduced from slope activity and dune dynamics (Bégin et al., 1995) allowed trees to increase their radial growth. As mentioned before, snow level in such an exposed environment is a key factor for tree growth. It determines the proportion of trees exposed to winter sand and ice abrasion and hence the overall shape of trees. When snow level increases, the number of terminal buds protected by snow also increases, allowing the development of new leaders. Because of the physiological relationship between the overall photosynthetic structure and radial growth, ring width significantly increases; however, this increase in growth indices was not as spectacular as in the 1500s, probably because most of trees were more than 400 years old and had a substantially reduced vegetative structure when the climate changed. Nevertheless, the positive reaction of such dying trees clearly indicates that environmental conditions, and particularly summer temperature, have changed substantially since 1920.

SYNTHESIS AND CONCLUSION

The results presented in this paper clearly show the potential of tree-ring series to provide high resolution (annual) proxy climate data that span the last few centuries or the last millennium in the Mackenzie valley. Treeline environments in the Eskimo Lakes area are particularly promising for long-term reconstructions because of the presence of old-growth conifer stands and their sensitivity to environmental changes. Even if chronologies cover different time intervals and represent past conditions in contrasting environments separated by hundreds of kilometres, they show similarities in long-term climatic trends. Climatic trends over the last millennia in North America and Europe from several proxy climate indicators seem to have been recorded in tree-ring sequences in the Mackenzie valley. Suppressed growth between the mid-1500s and early 1900s and the following increasing growth is a feature of all three locations presented here (Fig. 15). The depressed growth period that is apparent since ca. AD 1330 in the Eskimo Lakes chronology, corresponds to the 'Little Ice Age' (Grove, 1988). This well known cold period has been responsible for significant glacier advances in the Canadian Rockies (Luckman, 1986, 1994) and for altitudinal tree-line regression (Kearney and Luckman, 1987). In marginal forest environments (e.g. Eskimo Lakes and Mountain River krummholz) the cooling effect seemed severe enough to transform forest sites into krummholz, mostly by decreasing snow level. In the Mountain River area, the tree growth-climate relationship indicates that, during the Little Ice Age, ring width has decreased in response to a moisture stress.

Depending on the site, some milder intervals occurred during the Little Ice Age. The period from approximately AD 1500–1550 has been the most important one and is recorded in both exposed sites (Eskimo Lakes and Mountain River krummholz). Warmer conditions centred in the sixteenth century have been recorded in other sensitive tree-ring sequences in the Rockies (Luckman, 1994) and in northern Quebec (Payette et al., 1989). The Mountain River chronologies do not reveal what has happened in the boreal forest before about 1500; however, the tree-line chronology suggests that the first half of the sixteenth century has to be viewed only as a brief warm interval within the cold Little Ice Age that seems to have prevailed since 1330. The Eskimo Lakes chronology also shows that the period from 1172 to 1330 was particularly favourable for tree growth. Overall, the highest tree growth values were recorded during this period, suggesting that summers were probably warmer than today. Moreover, the normal shape of subfossil trees associated with this period indicates that winters probably were also milder with a greater snowfall. Such environmental conditions probably correspond to the end of the period known as the 'Medieval Warm Period', which spans from about the ninth to the fourteenth centuries (Hughes and Diaz, 1994). The tree-ring signal from Eskimo Lakes seems consistent with historical records from western Europe which indicate the predominance of warm springs and dry summers throughout most of the thirteenth century (from AD 1220–1310). Finally, all tree-ring chronologies show a relatively abrupt increasing

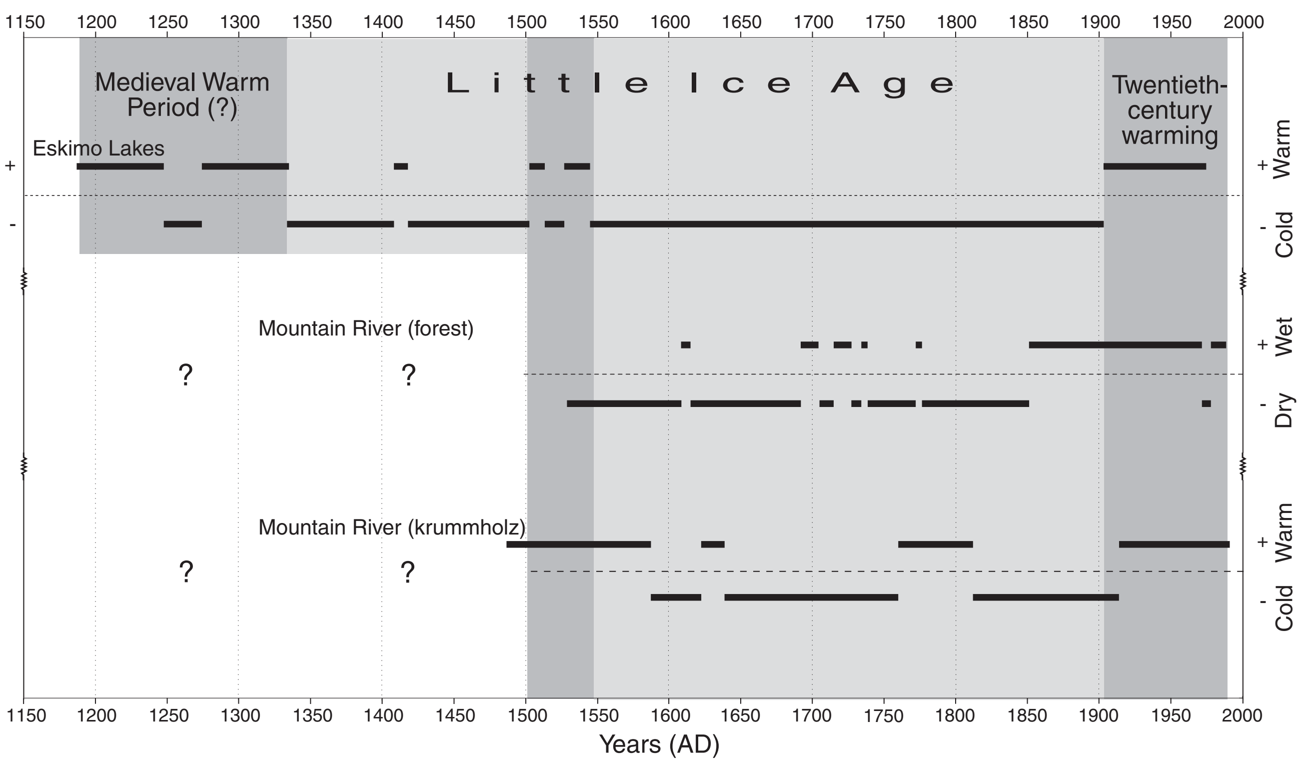

Figure 15. Synthesis of the reconstructed climate changes based on tree growth–climate relationship for Eskimo Lakes and Mountain River sites. Tree-growth excursions above and below the mean are indicated by straight lines, while shades of grey emphasize broad-scale climate changes. Boundaries of broad climatic periods are based on tree-ring patterns presented in this paper.

growth at the beginning of the twentieth century. In the forest site at Mountain River, the increasing growth started in mid-1800s while it started in early 1900s at the other two sites which are more exposed. The long-term warming trend since approximately 1880 is one of the most ubiquitous features in northern North American tree-ring records (Jacoby and Cook, 1981; Jacoby et al., 1985; Payette et al., 1985; D'Arrigo and Jacoby, 1992; Szeicz and MacDonald, 1994). It has also been recorded in cores from the southern Greenland ice cap based on predominance of melt layers (Bradley and Jones, 1993), and in recession rates of alpine glaciers in Alaska (Heusser and Marcus, 1964).

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