Temporal instability of isotopes-climate statistical relationships - A study of black spruce trees in northeastern Canada

M. Naulier^{1,a}, M.M. Savard², C. Bégin², J. Marion², A. Nicault³, Y. Bégin¹

¹ Institut national de la recherche scientifique-ETE, 490 rue de la Couronne, QC, G1K9A9, Canada

² Geological Survey of Canada, Natural Resources Canada, 490 rue de la Couronne, QC, G1K9A9, Canada

³ Université Aix-Marseille, Méditerranéen de l'Arbois Avenue Louis PHILIBERT Bâtiment CEREGE BP 80, 13545 Aix-en-Provence, Cedex 4, France

Abstract

Climate reconstructions using stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values) in tree rings are based on relationships between present climatic conditions and isotopic series. This widely used approach relies on the assumption that correlations between stable isotopes and climatic conditions are steady over time. In this paper, we evaluate the strength of the correlations between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ series with several climatic parameters on fourteen black spruce trees coming from three different sites, in northeastern Canada. We applied a 21-year moving window on the r Pearson calculated between stable isotopes and March-May and June-August precipitation, June-August and April-June maximal temperatures. Our results indicate that despite the large distance and differences in stand conditions between the sites, the three sites responded in the same way over time. We show that because the climatic ambiance has changed during the 1980-1990 period due to a positive North Atlantic Oscillation index the $\delta^{13}\text{C}$ values are not controlled anymore by spring precipitation or summer maximal temperature in the following two decades. As opposed to $\delta^{13}\text{C}$ series, the relationship between summer maximal temperature and $\delta^{18}\text{O}$ values was stable over time, and decreased only in the last decade. All these results attest of a “divergence problem” in the last decades which is most pronounced for $\delta^{13}\text{C}$ series. We conclude that the spruce $\delta^{18}\text{O}$ series appears to be the most appropriate indicator for reconstructing June-August maximal temperature in the studied area despite the divergence issue, given that the calibration-validation tests and reconstruction can exclude the divergent last decade.

Keywords: divergence, carbon isotopes, oxygen isotopes, tree rings, *Picea mariana*.

^aE-mail of corresponding author (M. Naulier): maud.naulier@ete.inrs.ca

M. Naulier phone number: (+001) 418-261-0505

1. Introduction

Assessing the significance of modern global warming and predicting future climate requires characterizing the natural climatic variability along centuries. In order to evaluate this variability, it is necessary to use natural archives in which past climate information is contained. For example, it is possible to reconstruct the climate of the last millennium by using tree-ring isotopes of carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$). This kind of reconstruction is based on the close relationships between climatic parameters and isotopic series. Indeed, the $\delta^{13}\text{C}$ values depend on the ratio of leaf intercellular CO_2 (c_i) relative to the atmospheric CO_2 pressure (c_a), the $\delta^{13}\text{C}$ values of ambient air (Farquhar *et al.*, 1982) and soil moisture (i.e., Francey and Farquhar, 1982; Roden *et al.*, 2012). The c_i/c_a ratio is controlled by the photosynthetic capacity and the stomatal conductance, which is itself depending on the water vapor deficit of the air (correlated with air temperature). In addition, when trees are not in water-limited conditions, the photosynthetic capacity is the main control on carbon assimilation, implying that temperature and sunshine conditions influence $\delta^{13}\text{C}$ variations (Gagen *et al.*, 2012; Loader *et al.*, 2013; Young *et al.*, 2012). When under water-limited conditions, the isotopic ratios of trees depend on their stomatal conductance and are strongly linked to the precipitation and vapor pressure deficit. The change of $\delta^{18}\text{O}$ values in tree cellulose reflects the value of soil water and fractionation in the leaves due to stomatal aperture, evapotranspiration and Péclet effect (Anderson *et al.*, 2002; Barbour *et al.*, 2004; Roden *et al.*, 2000). The $\delta^{18}\text{O}$ values of soil water are largely inherited from precipitation and from its mixing with stationary soil water (Gasis and Feng, 2004), and sometimes possibly modified by evaporation effects.

When attempting to reconstruct climate, the response of isotopes to climatic parameters is usually determined by using statistical correlations (Pearson or Spearman coefficient). Once the best correlation is found, a response model is calibrated on the period during which climatic data are available. One limitation to this approach is the length of the measured climatic series which can cover more than one century in populated areas or only a few decades in remote areas. Generally, the strongest correlation leads to the choice of one climatic parameter acting as the main control on the isotopic ratios and the reconstruction of climate is then based on the isotope/climate relationship. For that part, the assumption is that only one climatic parameter controls isotopic variations, and that the correlation between tree-ring isotopes and the climatic parameter is stable over time, as dictated by the uniformitarian dendroclimatology principle. Another prerequisite to dendroclimatology is that the

present-day climatic controls on tree ring variability existed in the past. Otherwise, palaeoclimatic reconstructions would not be reliable (Fritts, 1976).

In order to evaluate the stability of the climate/tree-ring isotopic ratio over time, a few studies followed the evolution of the correlation between climatic parameters (temperature, relative humidity or precipitation) and isotopic series ($\delta^{13}\text{C}$ and/or $\delta^{18}\text{O}$) over the periods when reliable measured data are available. Attempts were made to assess the relationship between isotope ratios and climatic parameters with the centered moving average method (Aykroyd *et al.*, 2001; Etien *et al.*, 2008; Haupt *et al.*, 2011; Ogurtsov *et al.*, 2011; Reynolds-Henne *et al.*, 2007; Seftigen *et al.*, 2011). These studies have found losses of correlation through time, which vary depending on the isotopes used and the various climatic parameters selected.

Another issue in climatic reconstruction is referred to as the “divergence problem”, specifically denoting a departure between tree-ring indicators and temperature, and describing a loss of tree sensitivity with increasing temperature recorded by instrumental measurements since around the mid-20th century (D'Arrigo *et al.*, 2008). The phenomenon has been observed for ring width and density in several areas of the northern hemisphere (Büntgen *et al.*, 2008; D'Arrigo *et al.*, 2008; Driscoll *et al.*, 2005; Pisaric *et al.*, 2007; Zhang *et al.*, 2009). The ensuing inability of tree-ring reconstruction to reflect high-frequency regional climate signals has been attributed to several regional causes like a non-linear response from trees to recent climate warming or threshold responses (Vaganov *et al.*, 1999), increase of temperature inducing a drought stress (Barber *et al.*, 2000; Jacoby, 1995), delayed snow-melt and seasonality changes (Driscoll *et al.*, 2005; Vaganov *et al.*, 1999) and differential response to maximum and minimum temperatures (Wilson and Luckman, 2003). In addition, other studies have invoked the large-scale impacts of: global dimming due to air pollution, cloud cover changes, and diminishing stratospheric ozone which increases ultraviolet radiation (Briffa *et al.*, 2004). Although several causes have been proposed to independently explain the “divergence problem”, the issue is the source of animated debates in the literature because numerous causes might be interplaying in a given case, and the phenomenon is not always observed in dendrochronological studies (Esper *et al.*, 2009).

One can think that the divergence represents a consequential aspect in climatic reconstruction which should be cautiously considered. Currently, only a few studies have documented the divergence problem when using stable isotopes (Daux *et al.*, 2011; Hilasvuori *et al.*, 2009; Young *et al.*, 2010). Here, we want to evaluate if: (1) the isotopic tree-ring ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) series obtained for black spruce trees of northeastern Canada are devoid of a divergence effect in their relation with climate, i.e, if these

relations are stable over the instrumental period, and (2) determine which of the $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ proxies is the most appropriate to reconstruct the past summer temperatures. Our regional study uses the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series from three sites (well and moderately well-drained) first separately, and then combines them in order to create a regional curve for each isotopic series.

2. Materials and methods

In northeastern Canada, we have already studied the relationship between various climatic parameters and the isotopic ratios ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of living trees in several sites (Bégin *et al.*, 2015; Naulier *et al.*, 2014). We have determined that the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ variability was significantly linked to June to August (JJA) months and the better correlation was obtained with maximal temperature for both isotopic ratios. However, the $\delta^{18}\text{O}$ series correlate negatively with summer precipitation whereas the $\delta^{13}\text{C}$ series show strong positive correlations with spring precipitation (Bégin *et al.*, 2015; Naulier *et al.*, 2014; Table 3).

2.1. Ecology and climate of the study area

Three study sites have been selected (DA1, HM1 and L20), at the centre of the Québec-Labrador peninsula in northeastern Canada (Fig. 1, Table 1). The study area is on the Canadian Shield where the forest is mainly dominated by black spruce trees (*Picea mariana* [Mill] B.S.P), with balsam fir (*Abies balsamea* (L.) Mill.) and tamarack (*Larix laricina* (Du Roi) Koch) as secondary species. The sites are bordered by open spruce-moss with lichen woodlands growing on well-drained podzolic soils and regular slope

The regional forest has a natural fire rotation period estimated at 250 to 500 years (Boulanger *et al.*, 2012). The climate is continental and subarctic with short, mild summers and long, cold winters with a dominance of arctic winds under the influence of the Labrador stream. According to three meteorological stations of Environment Canada (Schefferville A., Wabush lake, Nitchequon), mean monthly temperatures from 1981 to 2010 varied from -22.9°C in January to 13.3°C in July. The climatic index (Naulier *et al.*, 2014) is the subtraction between the z-score of total precipitation minus

the z-score of the mean maximal temperature for the June to August period (Fig. 2A). Consequently, it represents the boreal climatic ambiances typically occurring during the growing season: hot and dry (low CI) or cold and wet (high CI). The use of such an index aimed at verifying if changes in summer ambiances occurred in the past. The results suggest that the climatic ambiance has passed from decades with several cold-wet episodes (1940-1992), to warmer and dryer conditions (post 1992) with practically no cold-wet phases or years with weather extremes (Fig. 2A). The summer and fall maximal temperatures have increased continuously since 1970, whereas winter and spring since 1990, with higher temperatures during the last decade (Fig. 2B).

In the studied area, the total annual precipitation averages 825 mm with up to 46% falling in summer (June to September). The lakes are generally frozen from mid-October to early June and the growing season is short (from middle/late June to early/middle September). The winter climate is strongly influenced by changes in atmospheric circulation patterns associated to the North Atlantic Oscillation (NAO; Hurrell *et al.*, 2003; Qian *et al.*, 2008). A high positive NAO index corresponds to a stronger than average westerlies over the middle latitudes. In northern Canada, such NAO index causes drier and colder winter than normal whereas a negative phase leads to warmer and wetter winter. Related changes in temperature and precipitation are known to affect the study area as they can extend from eastern North America to central Europe (Hurrell and Deser, 2010). The control of summer NAO on the boreal climate has only been documented once in eastern Canada (Folland *et al.*, 2009). This influence is much weaker in summer than in winter (Bonsal and Shabbar, 2011).

2.2.Samples and laboratory treatment

This study relies on unpublished $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ series obtained for five black spruce trees from site DA1, along with results for living black spruce trees sampled at the HM1 (5 trees) and L20 sites (4 trees) as described in Bégin *et al.* (2015) and Naulier *et al.* (2014) (Table 1; Fig. 1). The statistical analyses performed here using the unpublished and previously published data have never been presented in other publications.

Owing to the different purposes of the previously published studies, the trees sampled come from different types of sites. In fact, the trees were selected from well drained sites (HM1) and a moderately-well drained site (DA1 and L20; classes have been determined using the Canada National Soil

DataBase, NSDB 2013), and their tree ring width series extend between 1800 and 2003, 1800 and 2005, and 1880 and 2010, respectively. Each tree was sampled separately, and four radii per tree have been cut. Rings were sample with one-year resolution after 1940 and two-years before 1940. Corresponding tree rings from the different radii were combined into a single sample and α -cellulose was extracted according to a proven protocol (Green, 1963; Loader *et al.*, 1997; Rinne *et al.*, 2005) modified for small samples at Delta-lab laboratory of the Geological Survey of Canada. The final α -cellulose sub-samples were dried at 55°C for 12 hours. The expressed population signal (EPS; Wigley *et al.*, 1984) has been determined for the three sites, for the average of two sampling heights at L20 and for one height at HM1 and DA1 (Table 2). The results confirm that the group of trees sampled at every site is representative of the site population ($\text{EPS} \geq 0.85$). In this paper, we have averaged the ring isotopic series obtained for individual trees coming from the same site. This approach is allowing us to evaluate the stability of the isotope-climate relationships on regional and temporal dimensions, and to compare responses from different types of stand to climatic variability.

2.3. Climate data

Weather stations existing in the investigated region (Schefferville, Wabush lake and Nitschequon) are sparse and only covering a short period (1943-now; Fig. 1). In order to specifically extend the temperature data of the study sites, we used the Climatic Research Unit (CRU TS 3.1) data modelled by utilizing more distant meteorological stations (average of grid point with 0.50° step over the study area). Considering that data from CRU correlate with the temperature series resulting from the average data of the three regional stations at 89% for the 1943-2010 periods, we consider that CRU data are robust and can be used for correlation analyses. Nevertheless, some of the stations used by CRU include records dating back to prior to 1930 and are very distant. Such data are of poor quality and could lead to artefacts in the constructed temperature series. For example, the nearest station to our sites with temperature data extending to the pre-1943 period (Mistassini) correlates at 67% with the CRU data for the 1930-2010 period, but only at 46% when going back to 1901. Under 50% of correspondence with CRU data a series can be considered too poor to represent regional temperature. We have therefore limited our use of the CRU TS 3.1 data to the period 1930-2010. It is worth noting that the maximal temperature series is calculated as the daily maximal temperature averaged for every

month, confirming that a June to August maximal temperature series corresponds to the mean of the warmest summer temperatures for a given year.

We did not use CRU precipitation data because variations of precipitation are generally important at the regional scale (not the case for temperature series). We have therefore used records from the three meteorological stations closest to our sites (Schefferville, Wabush Lake and Nitchequon). The average precipitation during 1961 to 1985 period (overlap of the three stations) has been calculated for each station. Then, we have normalized each series relative to the overlapping period and finally calculated an average single regional series for the 1943-2010 period. Previous studies conducted in the study area have shown that $\delta^{18}\text{O}$ values strongly correlate with the JJA climatic series (maximal temperature and precipitation) and $\delta^{13}\text{C}$ values correlate with spring precipitation and summer maximal temperature (Bégin *et al.*, 2015; Naulier *et al.*, 2014).

2.4. Statistical treatments

All $\delta^{13}\text{C}$ values reported here have been corrected for industrial changes of $\delta^{13}\text{C}$ values in atmospheric CO_2 (Suess effect; Treydte *et al.*, 2001) and for the increase of atmospheric CO_2 concentrations (PIN correction; McCarroll *et al.*, 2009). The PIN correction permits to take account of the increase of CO_2 concentration and correct its impact on the relationship between isotopic ratios and the climate. The isotopic series of every site has been normalized by subtracting the mean isotopic values for its 1880-2003 period that corresponds to the common period between the series of the three sites. Then, we have average series from the three sites for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in order to construct one regional series by isotopic ratio.

We evaluated the stability of the relationship of the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series with the climatic parameters by applying a moving window technique on the Pearson correlation. This approach is commonly used in statistics to follow the relationship between two series over time, or in dendroclimatology to infer the temporal sensitivity of tree-ring parameters to climatic conditions and reveal possible modifications in such response over a given period of time. The window size is selected so to follow the correlation on low or high frequencies. A number of studies have checked the climate and isotope relationships and selected windows comprised between 15 and 40 years as based on the length of the climatic series available (Aykroyd *et al.*, 2001; Reynolds-Henne *et al.*, 2007; Seftigen *et al.*, 2011; Trindade *et al.*, 2011). In our study, we have chosen to use a 21-year moving centered

window so that our analysis can be statistically strong, keep climatic variations without creating artefact by smooth out the short-term amplitudes over a relatively long climatic period (Aykroyd *et al.*, 2001; Trindade *et al.*, 2011). For correlations between isotopic series and maximal temperature series, the 21-years moving window has been applied from 1930 to 2005 for the HM1 and DA1 series and, to 2010 for the L20 series, as dictated by the series length of the sites. For correlations between isotopic series and precipitation, the moving window has been applied from 1943.

We also tested if the JJA maximal temperature, spring and JJA precipitation series can be considered constant through time (i.e., no statistically significant shift in the mean of series). A homogeneity test permits to highlight if changes in correlation between climate and isotopic series are linked to break in climatic series. The Excel stat program has been used because it contains a macro with the Buishand bayesian test (Buishand, 1982). This test verifies if there is a shift in the mean of climatic series (with $p < 0.05$) at a known date. The p-value is given by using Monte Carlo method (1000 iterations). In this test, the H0 hypothesis supposes that the climatic series follows only one distribution and the H1 hypothesis suggests that there is a year from which the series mean is shifting. Afterward, we have assessed if the means are significantly different using a Student t-test ($p < 0.05$).

3. Results and interpretations

According to the Buishand test, the JJA maximal temperatures is showing a shift of mean after 1975, from an average of 15.7°C prior to 1995, to 16.6°C after (Fig. 3A). The JJA and MAM precipitation series do not show a shift in mean over the studied period 1940-2010 but several years are below normal between 1995 and 2005 (Fig. 3B). The significance of this difference between the two averages of the temperature series is confirmed by a Student t-test at $p < 0.05$. In addition, the mean shift in 1975 marks the beginning of a gradual increase in temperature ending in 2005, followed by a rapid increase between 2006 and 2010 (Fig. 3A). The $\delta^{13}\text{C}$ average of series shows an increase between 1940 and 1980 and is stable after 1980 (Fig. 4A).

We have compiled the correlations of the average isotopic series of the three sites with the climatic parameters from previous studies (Table 3). The DA1 and HM1 isotopic series only extended up to 2005. For that reason, we analyzed the correlations of isotopic series with temperature over the 1930-2005 period, and with precipitation over the 1943-2005 period. The best correlations were obtained for

the average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series from DA1 with JJA maximal temperature ($r=0.53$ and 0.49 , respectively). In addition, significant positive correlations of spring (March to May or MAM) precipitation were found with the average $\delta^{13}\text{C}$ series (except for site HM1), whereas negative correlations are found between JJA precipitation and the average $\delta^{18}\text{O}$ series from all sites (Table 3).

The temporal variability of the correlations between the isotopic values and JJA maximal temperature is different for the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series (Figs. 4B and 5B). Despite the distance between locations, the $\delta^{13}\text{C}$ and the $\delta^{18}\text{O}$ responses of the three sites are very similar for maximal temperature and precipitation at medium frequencies. The correlations of JJA maximal temperature with the $\delta^{13}\text{C}$ series are showing more variability than those with $\delta^{18}\text{O}$ values (Figs. 4 and 5). For the $\delta^{13}\text{C}$ values, the three sites show the same response to temperature and have a significant positive correlation between 1943 and 1975, except for L20 during the 1957-1963 period. However, 1975 marks a change in the $\delta^{13}\text{C}$ values-temperature relationships at every site because the correlations stay non-significant afterwards. Correlations between MAM precipitation and $\delta^{13}\text{C}$ values are non-significant at the beginning of the series (1955-1965), shifting towards positive correlation for L20 and the average series. However, an important decrease of the correlation occurs after 1992. Correlations with summer precipitations are poor and non-significant for the three sites (Table 3). Finally, the mean $\delta^{13}\text{C}$ series does not follow summer temperature or spring precipitation variations after 1990 (Fig. 4).

By opposition to the $\delta^{13}\text{C}$ series, $\delta^{18}\text{O}$ values show relatively steady correlations with precipitation and maximal temperature over time (Fig. 5). The $\delta^{18}\text{O}$ values of the three sites respond similarly through time. The correlations between $\delta^{18}\text{O}$ values and precipitation are significant and negative until 1973, and then are increasing to become non-significant, with an enhanced departure between sites. The correlations with temperature are positive and significant until 1995. Note that the dispersion between $\delta^{18}\text{O}$ values and T_{max} shows the greatest amplitude and a 5-year duration (2006-2010; not shown).

Overall, summer precipitation has decreased from above normal between 1961 and 1985, to reach near or below normal values after 1985, with more frequent hot and dry summer up until 2010. At the same time, maximal temperature of all seasons has importantly increased since 1975, and correlations of isotopic series with summer temperature are decreasing since 1995. Overall, the key observations here are that the statistical relationships between the isotopes and climatic conditions are changing over time, and the amplitudes of these changes vary with the isotopic ratios, climatic parameters and seasons considered.

273

274 **4. Discussion**

275

276 First of all, the $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ series respond similarly for the three studied sites despite the distance
277 between sites. Hence, we can stipulate that the mean $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ series for the three sites are
278 representative of the regional response of the forest to climatic conditions. Moreover, the losses of
279 correlations of the mean $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ series with climatic parameters appear to be also regional as they
280 are similar for the three sites. This observation suggests that the isotopic series are recording a change
281 of climatic ambiance over time in the studied region. According to the fact that $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series are
282 not well correlated, it is not surprising that they do not respond similarly to climatic parameters and do
283 not show similar correlation instabilities with climate over time.

284

285 **4.1. Influence of climatic parameters on the isotopic values**

286

287 The positive correlation between $\delta^{13}\text{C}$ values and spring precipitation prior to 1990 (Table 3 and Fig.
288 4C) only suggests that snow accumulation during the months preceding the beginning of the growing
289 season may have played a role in controlling carbon assimilation. A hypothesis is that a thick snow
290 cover during the March to May period might delay soil thawing, leading to low water availability in
291 soils when trees are initiating photosynthesis, at the beginning of the growing season (Lemieux, 2010).
292 These conditions reduce the stomatal conductance, and then, the discrimination against ^{13}C (i.e.,
293 increasing $\delta^{13}\text{C}$ values) during the spring conditions. The most important observation is that the studied
294 tree-ring $\delta^{13}\text{C}$ series are significantly correlated with summer temperature conditions for the period
295 prior to 1980. This observation is in agreement with the generally understood assimilation mechanisms
296 of carbon by trees (Farquhar *et al.*, 1982). The positive correlations between summer temperatures and
297 $\delta^{13}\text{C}$ values reflect the dependence of carbon isotopes to the photosynthetic rate and/or stomatal
298 conductance of trees during the growing season. The higher the temperature, the higher are the rates of
299 photosynthesis (or lower the stomatal conductance) and the lower is discrimination against the ^{13}C
300 (McCarroll and Loader, 2004). The control of summer temperatures on the tree-ring $\delta^{13}\text{C}$ variability
301 has also been demonstrated in other isotopic studies dealing with different tree species but under
302 similar climate conditions (i.e, Kirilyanov *et al.*, 2008 in Siberia; Holzäpfer *et al.*, 2012 in subarctic

Canada). In these areas like in northeastern Canada, it seems that precipitations are not the main control on carbon fractionation. Porter *et al.* (2009) and Saurer *et al.* (2004) also reported weak relationships between precipitation and $\delta^{13}\text{C}$ series. They suggested that trees in non-arid area, meaning not water-stressed, are not sensitive to variations of precipitations. Consequently, our results suggest that $\delta^{13}\text{C}$ values of tree-rings of black spruce trees in northeastern Canada, such as the ones for *Picea glauca* in western coast of Hudson Bay (Tardif *et al.*, 2008) are mostly dependant to climatic factors that control photosynthetic rate such as maximal temperature. However, the strong control of temperature on $\delta^{13}\text{C}$ values decrease after 1990, and this observation is discussed in more details in parts 4.2 and 4.3 of this article.

Statistical analyses also showed that $\delta^{18}\text{O}$ values of black spruce trees reflect summer temperature and precipitations conditions implying that these parameters are the main controls on oxygen isotopic fractionation. These observations are coherent with knowledge on $\delta^{18}\text{O}$ values in trees. Indeed, the major controls on $\delta^{18}\text{O}$ values are the isotopic signature of source water (itself linked to the isotopic ratio of rain water), the evaporative enrichment in the leaf due to transpiration, and exchange with xylem water during cellulose synthesis (Anderson *et al.*, 2002; Barbour *et al.*, 2004). The cellulose $\delta^{18}\text{O}$ values reflect the local precipitation $\delta^{18}\text{O}$ values and the ^{18}O enrichment in leaves due to evapotranspiration (Roden *et al.*, 2000). The $\delta^{18}\text{O}$ values of precipitation are directly correlated with the temperature prevailing during the formation of water droplets in clouds; and indirectly with the amount of precipitation (and relative humidity). Climatic factors that impact stomatal functioning (temperature and moisture) will consequently affect the oxygen isotopic values in tree-ring (Saurer *et al.*, 1997). It is consequently not surprising that both parameters influence $\delta^{18}\text{O}$ values of black spruce trees in northeastern Canada. These results are in agreement with other studies that have demonstrated similar correlations between temperature and $\delta^{18}\text{O}$ series in cold environments (i.e., Tardif *et al.*, 2008 in subarctic Manitoba, Porter *et al.*, 2009 in western Hudson Bay area; Holzäpfer *et al.*, 2012 in subarctic Canada; Bégin *et al.*, 2015 in northeastern Canada. However, it appears that the strong influence of JJA maximal temperature on $\delta^{18}\text{O}$ values decreased after 1995. This observation is discussed the following parts.

4.2. Highlighting a divergence between the isotopic series and climatic parameters

335 It has already been demonstrated that a change of the growing season, like an earlier start, due to
336 increased spring temperature could be responsible for the divergence observed between tree-ring
337 indicators and temperature series (i.e. Driscoll *et al.*, 2005; Vaganov *et al.*, 1999). In order to test this
338 assumption with our isotopic series and detect eventual changes in the growing season climate
339 conditions, we have tested if the isotopic values correlated with spring temperature or a combination of
340 spring-summer maximal temperature series in the last decades (Fig. 6). Surprisingly, we have
341 determined that the maximal temperature series of the April to June months became well correlated
342 with $\delta^{18}\text{O}$ values until 1995. For the relationship between the $\delta^{13}\text{C}$ series and spring conditions,
343 changes in the correlations are less pronounced, and do not show significant correlation.

344 Our study highlights that the $\delta^{13}\text{C}$ positive correlations with temperature decreased and even became
345 negative after 1980 at all sites, and that the inverse correlation with spring amount of snow became
346 non-significant after 1990, expressing a “divergence” with these two climatic parameters. We observe a
347 much lower amount of winter precipitation (67 cm snow depth or less) and a significantly decrease of
348 T_{max} (-0.75°C) between 1985 and 1995 relative to the preceding years. These observations coincide
349 with the period during which the winter NAO index (December to March) became strongly and
350 persistently positive (Hurrell and Deser, 2010). Changes in the wind direction and storminess
351 associated with positive phase of the NAO index are expected to modify the transport and convergence
352 of the atmospheric moisture, and thus, decrease in winter temperature and snow amount. It seems
353 therefore that the $\delta^{13}\text{C}$ series and their divergences with T_{max} and precipitation are affected by changes
354 in climatic ambiance under the strong influence of NAO.

355 One key feature of our results is the divergence due to a $\delta^{18}\text{O}$ decrease relative to temperature which
356 occurs in the last decade (1996-2010). Looking at the climatic conditions of the study area using the
357 climatic index or the Buishand test shows that, summers became warmer and/or drier (Figs. 2A and
358 3A) after 1975. A possible explanation for the divergence between temperature and $\delta^{18}\text{O}$ series is an
359 increase of summer temperature concomitant with a decrease in precipitation during a long period
360 possibly leading to water limitation (Daux *et al.*, 2011; Seftigen *et al.*, 2011). It has been explained
361 that, low precipitation concomitant with normal or above normal temperature can lead to low relative
362 humidity and thus, enhanced the isotope enrichment in the tree needles. The increased moisture stress
363 could also alter leaf conductance through decreased stomatal aperture (Seftigen *et al.*, 2011), resulting
364 in our case, to the decrease of $\delta^{18}\text{O}$ values. In our study, the three sites investigated are not under water-
365 limited conditions (weak correlation with precipitation). Thus, the cause of divergence is the result of
366 another phenomenon.

367 An important aspect relative to the relationship between $\delta^{18}\text{O}$ values and climate is that temperature
368 is the most important controlling factor in the investigated region, but spring conditions are playing an
369 increasing role during the last decade. Interestingly, there has been a shift in duration of the growing
370 season at our studied sites. Indeed, we observe that $\delta^{18}\text{O}$ values have changed proportionally with
371 April-August maximal temperatures after 1995, and concomitantly with an increase of spring and
372 autumn maximal temperature (Figs. 2 and 6). For the Québec boreal forest in general, it has been
373 reported that the growing season has started earlier following the increase of spring temperature, likely
374 making photosynthesis and water absorption by black spruce trees effective earlier (Logan *et al.*,
375 2011). In order to judge about the validity of such an assumption for black spruce trees of our studied
376 sites, we have calculated the mean degree-days for the 1943-2010 period following observations made
377 in Northeastern Canada by Logan *et al.* (2011), Mackey *et al.* (1996), Messaoud *et al.* (2007), and
378 others, and we counted the added days to the growing season (Fig. 7). Based on these studies, we have
379 considered that the growing season starts when the mean daily temperature is higher than 5°C for five
380 consecutive days after March 1st and ending when minimum temperature is lower than -2°C after
381 August 1st. Mean degree days have been calculated by averaging the minimal and maximal temperature
382 and then, subtracting 5°C to the result for every day (corresponding to the required temperature
383 necessary to initiate growth). Results indicate that the degree-days have increased, with a mean of
384 617°C/day prior to 1995, and 779°C/day after 1995, and that the length of the growing season has
385 increased by 26 days. Moreover, our calculations have highlighted that the growing season has
386 extended symmetrically, meaning at the beginning and at the end of the growing period, as it now
387 starting sooner (first days of May) and finishes later (first days of October; results not shown). This
388 observation is in agreement with other studies exploring the impacts of climate change in the Northern
389 Hemisphere and North American boreal forests on growing seasons (Barichivich *et al.*, 2012;
390 Barichivich *et al.*, 2013; Buermann *et al.*, 2013). If photosynthesis starts when water available to trees
391 is dominated by melting snow, a $\delta^{18}\text{O}$ decrease can occur because winter snow is greatly depleted in
392 ^{18}O relative to rain signal (Clark and Fritz, 1997). In addition, based on hydrograms we have compiled
393 for the last 50 years, there is generally no peak of autumnal recharge in the studied region. So the $\delta^{18}\text{O}$
394 values of source water in soils during the extended autumn growth period are either similar to summer
395 conditions or more negative since, without significant rain events, trees may use water from deeper soil
396 zones which are supposed to be more negative than upper zones. Hence relative to former years when
397 the growing season was shorter, the recent years (or last decade) are marked by lower $\delta^{18}\text{O}$ values from
398 the two ends of the extended growing seasons even if summer T_{max} has increased, providing a clear
399 mechanism to explain the divergence.

4.3. Possible explanations for the observed dendroisotopic divergence

We have described study cases of divergence between tree $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series and summer temperature documented in northeastern Canada for the first time, which result from a change in climatic ambience. As we have been using the available meteorological series that are only of short length, and are observing $\delta^{13}\text{C}$ trends modified early (1980) by a change in climatic ambience (divergence), it appears that $\delta^{13}\text{C}$ values are not the most suitable isotopic proxy for temperature reconstruction in this area. The $\delta^{18}\text{O}$ values are clearly controlled by temperature and the divergence effect on this indicator is limited to the last decade. Thus, a June-August maximal temperature reconstruction can be made with $\delta^{18}\text{O}$ series, but it requires removing the last decade for maintaining a strong correlation over the instrumental period. It is clear that, when considering the entire period, correlations of the $\delta^{18}\text{O}$ series with maximal temperature is significant ($r_{\text{pearson}} = 0.49$ and with a $p < 0.05$, the $r_{\text{critic}} = 0.325$); nevertheless, attention needs to be paid to the variability of this relationship at high frequencies. Calibration/verification test are needed to confirm the stability of this relationship over time, and allow producing climate reconstruction reliable for middle to low frequency changes.

Previous studies had shown that the $\delta^{13}\text{C}$ series became divergent with summer temperature in the recent decades in England, Europe and Fennoscandia (Hilasvuori *et al.*, 2009; Reynolds-Henne *et al.*, 2007; Seftigen *et al.*, 2011). These studies have invoked: (1) a non-linear response of tree due to increasing temperature inducing changes to the growing season (earlier start); (2) an increase of the moisture stress due to higher temperature and lower precipitation; and (3) an instability of the correlation between temperature and sunshine leading to a decrease of the temperature control on $\delta^{13}\text{C}$ values. Here we show for the first time that both $\delta^{13}\text{C}$ - T_{max} and $\delta^{13}\text{C}$ -precipitation correlations are lost in the recent years. The coincidence in these departures suggests that the same mechanism is responsible for the two divergences. Consequently, we propose another explanation of the divergence by invoking the influence of the NAO patterns on the regional climatic conditions, and consequently, on $\delta^{13}\text{C}$ variations (section 4.2). In the case of the tree-ring $\delta^{18}\text{O}$ - T_{max} divergence, only one study had previously discussed the potential causes of such departure (Daux *et al.*, 2011). In that particular case, the authors showed that larch isotopic series were diverging from temperature time-series after 1990, and they invoked an increase of summer temperature and moisture stress generating an uptake of deeper source water in soils during their summer growth. For the black spruce trees of Northern

Québec, we propose that the most appropriate explanation for the post-1995 divergence is an increased of water uptake from snow melt during the significantly longer growing seasons observed in the region of investigation for that period.

Our results strengthen the idea that the correlations between tree-ring isotopic ratios and climatic parameter can diverge in the recent decades, showing not only departures with temperature, but also with precipitation. We have also shown that the technique of the moving average window is suitable for detecting possible divergence effects. It might be possible to use a forward and inverse modeling approach such as the one proposed by Boucher et al. (2014) could also be used to address the question of non-stationary isotopic response to climate, and integrate this type of response in a millennial climate reconstruction. In any case, these types of approach are highly recommended before undertaking climatic reconstruction, to verify if strong and stable correlations exist between isotopic and climatic series and avoid faulty reconstructions of past climatic conditions.

5. Conclusion

Our study has demonstrated that $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ series of black spruce trees record summer maximal temperature and precipitation, but in an unstable way over time. The compilation of three distant sites with different drainages has shown that results from the mean series of the three sites can be taken into account for a regional synthesis. We have showed losses of correlation between JJA maximal temperature and $\delta^{13}\text{C}$ values in the last three decades, and with $\delta^{18}\text{O}$ values in the last decade. We attribute these losses of correlations to the “divergence problem” likely resulting from climate change. We further suggest that:

- a change of climatic ambiance have occurred in northeastern Canada after 1975, resulting in an earlier start and later end of the growing season, and in increased temperature for all seasons (Buishand test, climatic index and calculation of the growing season length);
- tree-ring $\delta^{13}\text{C}$ values are controlled by several climatic parameters (summer maximal temperature and spring precipitation), and are indirectly influenced in the last decades by a strong positive winter NAO index which results in divergent $\delta^{13}\text{C}$ and climatic series,
- the strong correlation between $\delta^{18}\text{O}$ values and temperature was generally steady through time;

460 - a $\delta^{18}\text{O}$ -temperature divergence occurred in the last decade and resulted from longer growing
461 seasons, specifically from early spring and autumn water uptake by trees, which has decreased the
462 $\delta^{18}\text{O}$ values even if summer Tmax has increased;

463

464 Finally, $\delta^{18}\text{O}$ are showing much less divergence than $\delta^{13}\text{C}$ series and are best suited as proxy for
465 climatic reconstruction in the studied region. The $\delta^{18}\text{O}$ series could therefore be used for June-August
466 maximal temperature reconstruction in northeastern Canada if the divergent years of the last decade are
467 discarded for the calibration-validation exercise.

468

469

470 **Acknowledgments**

471 The authors would like to thank Anna Smirnoff for her technical support during sample treatment and
472 analyses at the Delta-Lab of the Geological Survey of Canada. We are grateful to Fateh Chebana for his
473 stimulating discussions. We also would like to thank Dr. Etienne Boucher who made constructive
474 comments during a pre-submission review of this article. This research has been supported financially
475 by the NSERC-OURANOS Collaborative Research and Development grant (ARCHIVES project of
476 INRS-ETE), and the Environmental Geoscience Program of the Geological Survey of Canada.

477

References

- Anderson, W.T., Bernasconi, S.M., McKenzie, J.A., Saurer, M., Schweingruber, F., 2002. Model evaluation for reconstructing the oxygen isotopic composition in precipitation from tree ring cellulose over the last century. *Chemical Geology*, 182(2-4): 121-137.
- Aykroyd, R.G., Lucy, D., Pollard, A.M., Carter, A.H.C., Robertson, I., 2001. Temporal variability in the strength of proxy climate correlations. *Geophysical Research Letters*, 28(8): 1559-1562.
- Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *nature*, 405(6787): 668-673.
- Barbour, M., Roden, J., Farquhar, G., Ehleringer, J., 2004. Expressing leaf water and cellulose oxygen isotope ratios as enrichment above source water reveals evidence of a Péclet effect. *Oecologia*, 138(3): 426-435.
- Barichivich, J., Briffa, K., Osborn, T., Melvin, T., Caesar, J., 2012. Thermal growing season and timing of biospheric carbon uptake across the Northern Hemisphere. *Global Biogeochemical Cycles*, 26(4).
- Barichivich, J., Briffa, K.R., Myneni, R.B., Osborn, T.J., Melvin, T.M., Ciais, P., Piao, S., Tucker, C., 2013. Large-scale variations in the vegetation growing season and annual cycle of atmospheric CO₂ at high northern latitudes from 1950 to 2011. *Global Change Biology*, 19(10): 3167-3183.
- Bégin, C., Gingras, M., Savard, M. M., Marion, J., Nicault, A., & Bégin, Y. , 2015. Assessing tree-ring carbon and oxygen stable isotopes for climate reconstruction in the Canadian northeastern boreal forest. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 423, 91-101.
- Bonsal, B., Shabbar, A., 2011. Oscillations climatiques à grande échelle ayant une incidence sur le Canada, de 1900 à 2008. *Biodiversité canadienne : état et tendances des écosystèmes en 2010, Rapport technique thématique no 4* (Conseils canadiens des ministres des ressources. Ottawa, (Ont.). iii + 15 p.).
- Boucher, É., Guiot, J., Hatté, C., Daux, V., Danis, P.-A., Dussouillez, P., 2014. An inverse modeling approach for tree-ring-based climate reconstructions under changing atmospheric CO₂ concentrations. *Biogeosciences*, 11(12): 3245-3258.
- Boulanger, Y., Gauthier, S., Burton, P.J., Vaillancourt, M.-A., 2012. An alternative fire regime zonation for Canada. *International Journal of Wildland Fire*, 21(8): 1052-1064.
- Briffa, K.R., Osborn, T.J., Schweingruber, F.H., 2004. Large-scale temperature inferences from tree rings: a review. *Global and Planetary Change*, 40(1-2): 11-26.
- Buermann, W., Bikash, P.R., Jung, M., Burn, D.H., Reichstein, M., 2013. Earlier springs decrease peak summer productivity in North American boreal forests. *Environmental Research Letters*, 8(2): 024027.
- Buishand, T.A., 1982. Some methods for testing the homogeneity of rainfall data. *Journal of Hydrology*, 58: 11-27.
- Büntgen, U.L.F., Frank, D., Wilson, R.O.B., Carrer, M., Urbinati, C., and Esper, J.A.N., 2008. Testing for tree-ring divergence in the European Alps. *Global Change Biology*, 14(10), 2443-2453.
- Clark, I.D., Fritz, P., 1997. *Environmental isotopes in hydrogeology*, 328p. CRC press LLC, Boca Raton, Florida.
- D'Arrigo, R., Jacoby, G.C., Wilson, R., Liepert, B., Cherubini, P., 2008. On the 'Divergence Problem' in Northern Forests: A review of the tree-ring evidence and possible causes. *Global and Planetary Change*, 60(3-4): 289-305.
- Daux, V., Edouard, J.-L., Masson-Delmotte, V., Stievenard, M., Hoffmann, G., Pierre, M., Mestre, O., Danis, P., Guibal, F., 2011. Can climate variations be inferred from tree-ring parameters and stable isotopes from *Larix decidua*? Juvenile effects, budmoth outbreaks, and divergence issue. *Earth and Planetary Science Letters*, 309(3): 221-233.
- Driscoll, W.W., Wiles, G.C., D'Arrigo, R.D., Wilmking, M., 2005. Divergent tree growth response to recent climatic warming, Lake Clark National Park and Preserve, Alaska. *Geophysical Research Letters*, 32(20).
- Esper, J., Frank, D., 2009. Divergence pitfalls in tree-ring research. *Climatic Change*, 94(3), 261-266.

- Etien, N., Daux, V., Masson-Delmotte, V., Stievenard, M., Bernard, V., Durost, S., and Pierre, M., 2008. A bi-proxy reconstruction of Fontainebleau (France) growing season temperature from AD 1596 to 2000. *Climate of the Past*, 4(2), 91-106.
- Farquhar, G.D., O'Leary, M.G., Berry, J.A., 1982. On the Relationship Between Carbon Isotope Discrimination and the Intercellular Carbon Dioxide Concentration in Leaves. *Functional Plant Biology*, 9(2): 121-137.
- Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., Hurrell, J.W., 2009. The summer North Atlantic Oscillation: Past, present, and future. *Journal of Climate*, 22(5).
- Fritts, H.C., 1976. *Tree rings and climate*, London, New-York and San Francisco. Academic Press.
- Francey, R. J., and Farquhar, G. D., 1982. An explanation of $^{13}\text{C}/^{12}\text{C}$ variations in tree rings.
- Gagen, M., Zorita, E., McCarroll, D., Young, G. H., Grudd, H., Jalkanen, R., and Kirchhefer, A., 2011. Cloud response to summer temperatures in Fennoscandia over the last thousand years. *Geophysical Research Letters*, 38(5).
- Gazis, C., and Feng, X., 2004. A stable isotope study of soil water: evidence for mixing and preferential flow paths. *Geoderma*, 119(1), 97-111.
- Green, J.W., 1963. Wood cellulose. *Methods in Carbohydrate Chemistry* III: 9-21.
- Haupt, M., Weigl, M., Grabner, M., Boettger, T., 2011. A 400-year reconstruction of July relative air humidity for the Vienna region (eastern Austria) based on carbon and oxygen stable isotope ratios in tree-ring latewood cellulose of oaks (*Quercus petraea* Matt. Liebl.). *Climatic Change*, 105(1-2): 243-262.
- Hilasvuori, E., Berninger, F., Sonninen, E., Tuomenvirta, H., Jungner, H., 2009. Stability of climate signal in carbon and oxygen isotope records and ring width from Scots pine (*Pinus sylvestris* L.) in Finland. *Journal of Quaternary Science*, 24(5): 469-480.
- Holzkämper, S., Tillman, P. K., Kuhry, P., & Esper, J., 2012. Comparison of stable carbon and oxygen isotopes in *Picea glauca* tree rings and *Sphagnum fuscum* moss remains from subarctic Canada. *Quaternary Research*, 78(2), 295-302.
- Hurrell, J.W., Deser, C., 2010. North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems*, 79(3): 231-244.
- Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M., 2003. The North Atlantic Oscillation: climatic significance and environmental impact, 134. American Geophysical Union.
- Jacoby, G.C.e.D.a., R.D., 1995. Tree width and density evidence of climatic and potential forest change in Alaska. *Global Biogeochemical Cycles*, 9(2): 227-234.
- Kirdyanov, A. V., Treydte, K. S., Nikolaev, A., Helle, G., and Schleser, G. H., 2008. Climate signals in tree-ring width, density and $\delta^{13}\text{C}$ from larches in Eastern Siberia (Russia). *Chemical Geology*, 252(1), 31-41.
- Lemieux, J., 2010. *Phénologie de l'épinette noire dans le haut boréal: un patron de la croissance intra-annuelle primaire et secondaire en relation avec la température de l'aire journalière*. Mémoire présenté pour l'obtention du grade de Maître en Science de la Terre.
- Loader, N.J., Robertson, I., Barker, A.C., Switsur, V.R., Waterhouse, J.S., 1997. An improved technique for the batch processing of small wholewood samples to α -cellulose. *Chemical Geology*, 136(3-4): 313-317.
- Loader, N.J., Young, G.H.F., Grudd, H., and McCarroll, D., 2013. Stable carbon isotopes from Torneträsk, northern Sweden provide a millennial length reconstruction of summer sunshine and its relationship to Arctic circulation. *Quaternary Science Reviews*, 62, 97-113.
- Logan, T., Charron, I., Chaumont, D., Houle, D., 2011. *Atlas de scénarios climatiques pour la forêt québécoise*. Ouranos et MRNF, 55p + annexes.
- Mackey, B.G., McKenney, D.W., Yang, Y.-Q., McMahon, J.P., Hutchinson, M.F., 1996. Site regions revisited: a climatic analysis of Hills' site regions for the province of Ontario using a parametric method. *Canadian Journal of Forest Research*, 26(3): 333-354.
- McCarroll, D., Gagen, M.H., Loader, N.J., Robertson, I., Anchukaitis, K.J., Los, S.Y., G. H. F., Jalkanen, R., Kirchhefer, A., Waterhouse, J.S., 2009. Correction of tree ring stable carbon isotope chronologies for

573 changes in the carbon dioxide content of the atmosphere. *Geochimica et Cosmochimica Acta*, 73(6):
574 1539-1547.

575 McCarroll, D., Loader, N.J., 2004. Stable isotopes in tree rings. *Quaternary Science Reviews*, 23(7-8): 771-801.

576 Messaoud, Y., Bergeron, Y., Asselin, H., 2007. Reproductive potential of balsam fir (*Abies balsamea*), white
577 spruce (*Picea glauca*), and black spruce (*P. mariana*) at the ecotone between mixedwood and
578 coniferous forests in the boreal zone of western Quebec. *American journal of botany*, 94(5): 746-754.

579 Naulier, M., Savard, M.M., Bégin, C., Marion, J., Arseneault, D., Bégin, Y., 2014. Carbon and oxygen isotopes of
580 lakeshore black spruce trees in northeastern Canada as proxies for climatic reconstruction. *Chemical*
581 *Geology*, 374: 37-43.

582 National Soil DataBase, NSDB July 2013. <http://sis.agr.gc.ca/cansis/nsdb/index.html>.

583 Ogurtsov, M., Sonninen, E., Hiltavuori, E., Koudriavtsev, I., Dergachev, V., Jungner, H., 2011. Variations in tree
584 ring stable isotope records from northern Finland and their possible connection to solar activity.
585 *Journal of Atmospheric and Solar-Terrestrial Physics*, 73(2): 383-387.

586 Pisaric, M.F., Carey, S.K., Kokelj, S.V., Youngblut, D., 2007. Anomalous 20th century tree growth, Mackenzie
587 Delta, Northwest Territories, Canada. *Geophysical Research Letters*, 34(5).

588 Porter, T.J., Pisaric, M.F.J., Kokelj, S.V., Edwards, T.W.D., 2009. Climatic signals in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of tree-rings
589 from white spruce in the Mackenzie Delta region, northern Canada. *Arctic, antarctic and alpine*
590 *research*, 41, 497–505.

591 Qian, M., Jones, C., Laprise, R., Caya, D., 2008. The Influences of NAO and the Hudson Bay sea-ice on the
592 climate of eastern Canada. *Climate Dynamics*, 31(2-3): 169-182.

593 Reynolds-Henne, C., Siegwolf, R., Treydte, K., Esper, J., Henne, S., Saurer, M., 2007. Temporal stability of
594 climate-isotope relationships in tree rings of oak and pine (Ticino, Switzerland). *Global Biogeochemical*
595 *Cycles*, 21(4): GB4009.

596 Rinne, K.T., Boettger, T., Loader, N.J., Robertson, I., Switsur, V. R., and Waterhouse, J. S., 2005. On the
597 purification of α -cellulose from resinous wood for stable isotope (H, C and O) analysis. *Chemical*
598 *Geology*, 222(1), 75-82.

599 Roden, J.S., Lin, G., Ehleringer, J.R., 2000. A mechanistic model for interpretation of hydrogen and oxygen
600 isotope ratios in tree-ring cellulose. *Geochimica et Cosmochimica Acta*, 64(1): 21-35.

601 Roden, J.S., and Farquhar, G.D., 2012. A controlled test of the dual-isotope approach for the interpretation of
602 stable carbon and oxygen isotope ratio variation in tree rings. *Tree physiology*, 32(4), 490-503.

603 Saurer, M., Aellen, K. A. S. R., & Siegwolf, R., 1997. Correlating $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in cellulose of trees. *Plant, Cell &*
604 *Environment*, 20(12), 1543-1550.

605 Saurer, M., Siegwolf, R.T.W., Fritz, H.S., 2004. Carbon isotope discrimination indicates improving water-use
606 efficiency of trees in northern Eurasia over the last 100 years. *Global change biology*, 10, 2209-2120.

607 Seftigen, K., Linderholm, H.W., Loader, N.J., Liu, Y., Young, G.H., 2011. The influence of climate on
608 $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ ratios in tree ring cellulose
609 of *Pinus sylvestris* L. growing in the central Scandinavian Mountains. *Chemical Geology*, 286(3):
610 84-93.

611 Tardif, J.C., Conciatori, F., Leavitt, S.W., 2008. Tree rings, $\delta^{13}\text{C}$ and climate in *Picea glauca* growing near
612 Churchill, subarctic Manitoba, Canada. *Chemical geology*, 252, 88–101.

613 Treydte, K., Schleser, G.H., Schweingruber, F.H., Winiger, M., 2001. The climatic significance of $\delta^{13}\text{C}$ in
614 subalpine spruces (*L. otschental*, Swiss Alps). *Tellus* 53B, 593–611.

615 Trindade, M., Bell, T., Laroque, C., 2011. Changing climatic sensitivities of two spruce species across a moisture
616 gradient in Northeastern Canada. *Dendrologia*, 29: 25-30.

617 Vaganov, E., Hughes, M., Kirdyanov, A., Schweingruber, F., Silkin, P., 1999. Influence of snowfall and melt
618 timing on tree growth in subarctic Eurasia. *Nature*, 400(6740): 149-151.

619 Wigley, T., Briffa, K., Jones, P., 1984. On the average value of correlated time series, with applications in
620 dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology*, 23(2): 201-
621 213.

- 622 Wilson, R., Luckman, B., 2003. Dendroclimatic reconstruction of maximum summer temperatures from upper
623 treeline sites in Interior British Columbia, Canada. *The Holocene*, 13(6): 851-861.
- 624 Young, G.H.F., McCarroll, D., Loader, N.J., Kirchhefer, A.J., 2010. A 500-year record of summer near-ground
625 solar radiation from tree-ring stable carbon isotopes. *The Holocene*, 20(3): 315-324.
- 626 Young, G.H., McCarroll, D., Loader, N.J., Gagen, M.H., Kirchhefer, A.J., and Demmler, J.C., 2012. Changes in
627 atmospheric circulation and the Arctic Oscillation preserved within a millennial length reconstruction of
628 summer cloud cover from northern Fennoscandia. *Climate dynamics*, 39(1-2), 495-507.
- 629 Zhang, Y., Wilmking, M., Gou, X., 2009. Changing relationships between tree growth and climate in Northwest
630 China. *Plant Ecology*, 201(1): 39-50.

631

Figure 1: Location of sites (black circles) and meteorological stations (black stars).

Figure 2: A) June to August z-score Climatic index (1943-2010). B) Seasonal normalized maximal temperature (1961-1990) from CRU TS 3.1 smoothed with 11-year centred running mean: winter (grey line), spring (green line), summer (blue line) and fall (orange line).

7

8 Figure 3: Buishand statistical test ($p < 0.05$) for: A) JJA maximal temperature (black line); B)
 9 normalized JJA (black line) and MAM precipitation (dotted black line). The dotted horizontal lines
 10 represent the μ values calculated by the Buishand test.

11

12

13

14

15

16

17 Figure 4: A) Mean of the $\delta^{13}\text{C}$ series for all sites as a function of time. The grey bars represent the
 18 standard deviation between the three $\delta^{13}\text{C}$ series. Moving 21-year correlations between the $\delta^{13}\text{C}$ series
 19 and JJA maximal temperature (B) and MAM precipitation (C) for the three studied sites (HM1, blue
 20 line; DA1, red line; L20, green line; mean series, black line). The horizontal dotted black line
 21 represents the P value (<0.05 ; 0.43 for $n=21$) and the horizontal solid black line, the average correlation
 22 between the average isotope series of the three sites and climatic series for the entire period ($r=0.41$ for
 23 $\delta^{13}\text{C}$ with JJA maximal temperature, and $r=0.41$ with MAM precipitation).

24

Figure 5: A) Mean of $\delta^{18}\text{O}$ series for all sites as a function of time. The grey line represents the standard deviation between the three $\delta^{18}\text{O}$ series. Moving 21-year correlations between $\delta^{18}\text{O}$ series and JJA maximal temperature (B) and precipitation (C) for the three studied sites (HM1, blue line; DA1, red line; L20, green line; mean series, black line). The horizontal dotted black line represents the P value (<0.05 ; 0.43 for $n=21$) and the horizontal solid black line, the average correlation between the average isotope series of the three sites and climatic series for the entire period ($r=0.49$ for $\delta^{18}\text{O}$ with JJA maximal temperature, and $r=-0.44$ with JJA precipitation).

Figure 6: The 21-year running correlations of the $\delta^{18}\text{O}$ mean (blue line) and $\delta^{13}\text{C}$ series (red line) of the three studied sites with June-August (solid lines) and April-June (dotted lines) maximal temperatures. The horizontal black dotted lines indicate the P values (<0.05).

Figure 7. Mean degree days in black line and the number of days of the growing season (blue line).

Table 1: Location of sites, correlations (r Pearson) between their isotopic series, and distance between sites (km).

Sites	R pearson			Distance (km)
		$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	
HM1	L20	0.88	0.70	42
	DA1	0.84	0.76	114
DA1	L20	0.84	0.92	110

Table 2. EPS calculated for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for the three sites HM1, DA1 and L20.

Sites	EPS	
	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
HM1	0.87	0.83
L20	0.85	0.94
DA1	0.89	0.93

Table 3: Correlations between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ series from the studied sites and their average with climatic parameters.

Sites		Tmax (1930-2005)	Precipitation (1949-2005)
$\delta^{13}\text{C}$	L20	0.33	0.52* /0.12
	DA1	0.53	0.33* /-0.22
	HM1	0.41	0.19*/ -0.34
	Average 3 sites	0.41	0.41* /-0.12
$\delta^{18}\text{O}$	L20	0.41	-0.41
	DA1	0.45	-0.44
	HM1	0.49	-0.50
	Average 3 sites	0.49	-0.44

Significant correlations are in bold ($P<0.01$); correlations are all for June-August months, but March-May where * appears.