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Tree-ring stable isotopes for regional discharge reconstruction in eastern Labrador and teleconnection with the Arctic Oscillation

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Abstract

In northeastern Canada (Labrador), instrumental climatic data cover less than 70 years and long reconstructions from natural archives are non-existent. This study specifically aims at helping filling this gap of knowledge by testing the possibility of reconstructing the regional 1800–2009 discharge of the lower Churchill River from black spruce tree-ring $\delta^{13}C$ and $\delta^{18}O$ series. The results illustrate direct relationships of summer climatic variables/derived parameters (maximum temperature, total precipitation and vapor pressure deficit) with tree-ring isotope values. Importantly, they show an inverse correlation between tree-ring isotope values and regional river discharge due to common climate forcing. To a lesser extent, transpiration also affects the river discharge and tree-ring isotopic compositions. The reconstructed river discharge series agrees with an independent reconstruction based on the ANATEM method (1880–2009 period). The agreement between the two reconstructions validates the two approaches for reconstructing regional hydroclimatic conditions at high latitudes. Moreover, the reconstructions suggest that summer discharge has decreased over the past 200 years in eastern Labrador and more broadly at the Québec-Labrador peninsula scale. This trend correlates with the long-term summer Arctic Oscillation (AO) that influences summer regional climatic conditions. This research contributes with other studies to build up observations linking summer AO and eastern Canada climatic conditions, and calls for research on mechanisms explaining these relationships during summer.

Keywords Past discharge reconstruction · Carbon isotopes · Oxygen isotopes · Tree rings · Arctic Oscillation · Labrador

1 Introduction

Impacts of climate change on global hydrological regimes exert great pressure on water resources, and in several areas of the world, adaptation represents one of the biggest socio-economic challenges of the twenty-first century. This is the case in Canada, the second largest generator of hydroelectricity in the world, with 60% of its power coming from river dams. Consequently, the hydropower industry in this country needs understanding the natural variations in surficial water resources (Natural Resources and Canada 2018). Zhang et al. (2001) have shown that modification of precipitation, temperature, snowpack and potential evapotranspiration have significantly influenced annual river discharge with a general decrease across Canada during the last century. However, predictions of streamflow through modelling differ from a region to another, with an annual decrease in the Prairies, an increase in New Brunswick, Labrador and northern Canada, and a mixed trend in Yukon, Ontario and Quebec (Cohen et al. 2015; Déry et al. 2009; Mortsch et al. 2015; Roberts et al. 2012; Rood et al. 2005, St. George 2007). It seems that large-scale atmospheric and oceanic variability modes influence seasonal climate, which in turn modifies annual river discharge in various Canadian regions (Bonsal and Shabbar 2008). For example, teleconnection between winter atmospheric large-scale circulation such as the North Atlantic Oscillation (NAO) and the

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Journal : Large 382	Article No : 4731	Pages : 16	MS Code : CLDY-D-18-00681	Dispatch : 20-3-2019

Arctic Oscillation (AO) indices with yearly river discharge and groundwater have been observed in northeastern Canada (Anctil and Coulibaly 2004; Bonsal and Shabbar 2008; Coulibaly et al. 2000; Coulibaly and Burn 2005; Déry et al. 2009; Nicault et al. 2014; Tremblay et al. 2011). During a positive phase of NAO and AO, winter precipitation are lower than normal, hence reducing annual streamflow (Bonsal and Shabbar 2008).

Hydrological models are developed from instrumental hydroclimatic data series, which are generally discontinued, scarce or short (40–50 years). This short coverage limits (1) examining past natural river variations, (2) optimizing model calibration, and (3) predicting recurrence of extreme events. In other words, simulating hydroclimatic variabilities and estimating future drought risks are tasks destined to very limited success if longer series are not available. Paleoclimate proxies such as ice cores, peat deposits, marine and lake sediments, speleothems and tree ring have the potential to compensate for the lack of direct measurements by extending climatic series back in time. During their formation, paleoclimate proxies are modulated by climatic conditions, so that they provide an indirect record of climatic variables at various time scales. Trees under temperate conditions offer the advantage of an absolute dating at annual or sub-annual resolution, are widely distributed and can provide several-century long series of climate proxies. Among the different existing tree-ring indicators, ring width have been extensively used to reconstruct streamflow in arid, semi-arid and temperate regions (e.g., Axelson et al. 2009; Case and MacDonald 2003; Coulthard and Smith 2016; Elshorbagy et al. 2016; Hart et al. 2010; Sauchyn et al. 2015; Stockton and Fritts 1973; Woodhouse and Lukas 2006). However, ring width series have to be corrected for tree age-dependent biological growth trends using statistical detrending methods prior to infer any climatic signal. Depending on the detrending model, low-frequency information related to climate variability can be potentially lost (Sullivan et al. 2016). Tree-ring carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope series require analytical efforts differing from traditional tree-ring investigations, and they provide complementary information as biogeochemical processes influenced by ambient conditions and responsible for modifying variations in both proxies slightly differ (Naulier et al. 2015a). In general, they also present the advantage of not needing to be corrected for developmental effects. Nonetheless, some studies have reported that, in some cases, physiological processes such as tree age, size and height could influence tree-ring isotope composition (Brienen et al. 2017; Marshall and Monserud 2006; Treydte et al. 2006). During carbon assimilation by trees, gaseous diffusion and carboxylation are the first processes that modulate tree-ring $\delta^{13}C$ values. Those mechanisms discriminate against the heavy carbon isotope (^{13}C) modifying the CO_2 $\delta^{13}C$ values from − 8‰ in the atmosphere to − 27‰ in leaves (Farquhar et al. 1989). Thus, carbon isotopic fractionation is defined by the following equation (Farquhar et al. 1982):

$$\delta^{13}C_{plant} = \delta^{13}C_{atm} - a - (b - a)(c_i/c_a) \tag{1}$$

where a represents the discrimination against ^{13}C during diffusion, b the discrimination against ^{13}C associated with carboxylation, and where c_i and c_a are the intercellular and ambient CO_2 concentrations, respectively. As to tree-ring $\delta^{18}O$ values, they mainly reflect three processes: (1) assimilation of source water imprinted by precipitation signals possibly mixed with stationary soil water; (2) transpiration enriching and Péclet effect depleting needle water; and (3) biochemical fractionation during the synthesis of organic matter (Anderson et al. 2002; Barbour 2007; Ferrio and Voltas 2005; Gazis and Feng 2004; Roden et al. 2000). The latter process should stay constant through time (Leuenberger 1998) whereas water uptake by roots should not cause any fractionation (Wershaw et al. 1966). Therefore, several studies have used the climatic signal contained in tree-ring $\delta^{13}C$ and $\delta^{18}O$ values of α-cellulose to reconstruct temperature and precipitation over centuries or millennia (Bégin et al. 2015; Csank et al. 2013; Hook et al. 2015; Naulier et al. 2015a; Porter et al. 2014).

To our knowledge, up to now only two studies have used tree-ring isotopes to reconstruct streamflow variations (Waterhouse et al. 2000; Wils et al. 2010). Waterhouse et al. (2000) observed a highly significant inverse correlation between river flow and scots pine $\delta^{13}C$ values during growing season in western Siberia. They invoked a moisture transferred from river to trees through air which influences stomatal aperture and hence tree-ring $\delta^{13}C$ values. They also show that the strength of the relationship is distance-dependant, as trees at the river edge had higher correlations than trees 60 m away. Wils et al. (2010) found a significant negative correlation between the isotopic series from African pencil cedar trees and river flow of the previous dry season in Ethiopia. They argued that river flow reflects plant water availability. During the previous dry season, increase in water stress reduced the amount of needles for the next growing season. The available resources (water and nutrients) are thus diverted to the remaining needles, increasing needle-level photosynthetic rate and consequently the $\delta^{13}C$ values.

The province of Newfoundland and Labrador is the fourth most important producer of hydroelectricity in Canada, with the Churchill Falls hydroelectricity generating station in Labrador producing about 5400 of 7400 MW for the province (Government of Newfoundland Labrador 2018a). The longest instrumental river-flow series goes back to 1954 for the Churchill River (Government of Canada 2018a). Analyses of trends and variability in regional streamflow in the

Journal : Large 382	Article No : 4731	Pages : 16	MS Code : CLDY-D-18-00681	Dispatch : 20-3-2019

Northern Québec Labrador region show increase from 1970 to 1979, decrease from 1980 to 1989, and increase from 1990 to 2007 of annual and summer streamflow (Déry et al. 2009; Jandhyala et al. 2009; Sveinsson Oli et al. 2008). In this region, the May to June discharge is principally influenced by snow/ice melting, and spring precipitation leading to spring flood peak, while precipitation mainly influences the July–September discharge (Robichaud and Mullock 2001). During summer, temperature and humidity also play an important role for regional discharge as they influence water evaporation. Until now, only one study attempted to extend instrumental hydrological series in the Québec-Labrador peninsula. This study combined tree-ring indicators (widths, densities and stable isotope ratios), to understand past long-term water supply variability for the La Grande hydro-power generation system (15,240 MW) located at about 700 km west from Churchill River (Nicault et al. 2014). Therefore, the main objective of this research is to produce long dendroisotopic series to: (1) evaluate their potential as proxies for reconstructing regional hydroclimatic conditions over the last two centuries in the lower Churchill River region, and (2) understand past natural variations in this area.

2 Materials and methods

2.1 Study area and sample collection

The study area is located in the east-central part of Labrador, Canada (Fig. 1). The area sits on the eastern part of Precambrian Canadian shield formed during the Greenville orogeny. The bedrock is largely composed of quartzo-felspathic gneisses intruded by large body of anorthosite-adamellite plutons emplaced during the Middle Proterozoic (Greene 1974). The retreat of the Laurentide ice sheet during the last glaciation shaped the regional topography by leaving drumlins and rocky hills covered by a thin layer of ablation till. The valleys have been filled with Quaternary materials such as fluvio-glacial, fluvio-marine, fluvial or lacustrine sandy deposits (Dyke et al. 2002; Payette et al. 1989). The study area is located in the High Boreal Forest ecoregion including Lake Melville and Churchill River valley. The relief is characterized by low altitude plateaus (≈ 500 m.a.s.l.) and river terraces remodelled by eolian activity. This ecoregion is part of the boreal forest biome with spruce-lichen forests on river terraces and on upland, and mixed forests on valley slopes (Government of Newfoundland Labrador 2018b).

The study area is part of the Interior Labrador climate zone defined as a continental regime with prevailing westerly and southwesterly winds carriyng relatively cool and dry air during long severe winters with deep snow cover, and warmer summer. However, the High Boreal Forest ecoregion experiences relatively shorter winters and cooler summers than surrounding ecoregions because of a bioclimatic gradient due to the converging effects of both maritime and continental climatic influences (Nishimura and Laroque 2011; Roberts et al. 2006). The maritime climatic conditions are influenced by the cold Labrador Current bringing Arctic water along the Labrador coast (Sicre et al. 2014; Trindade et al. 2011a). The Happy Valley-Goose Bay meteorological station registered from 1942 to 2009 an average annual temperature of approximately 0.2 °C and an average precipitation amounts of approximately 1070 mm, 47% of which fall as snow (Government of Canada 2018b). The growth season lasted 130 days on average since 1942 with the average starting and ending

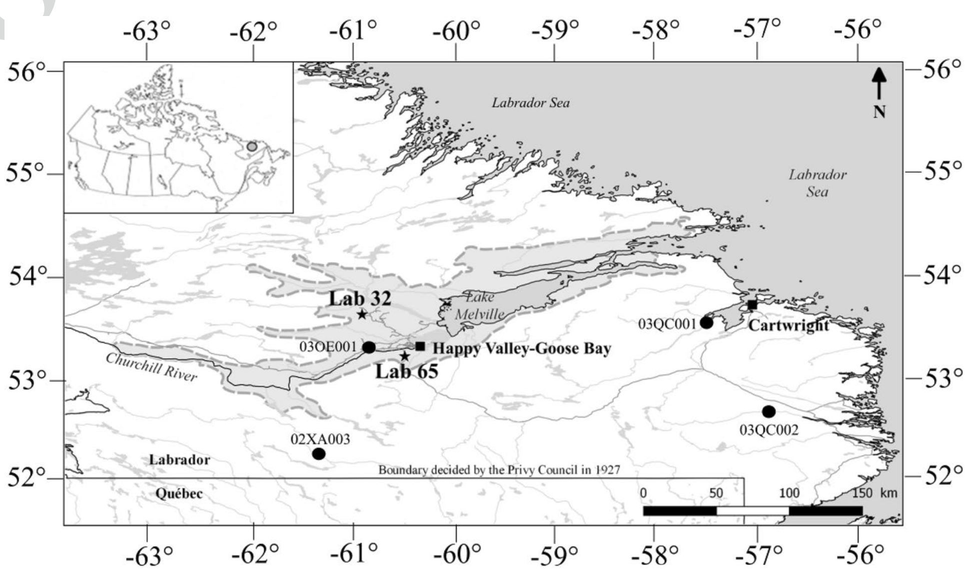

Fig. 1 Location of Lab 32 and Lab 65 sites (black stars) and hydrological stations (black circles) used for reconstruction and validation in the lower Churchill River region, Labrador. Weather station (Goose A) is located at Happy Valley-Goose Bay. The light grey zone represents the High Boreal Forest ecoregion

Journal : Large 382 | Article No : 4731 | Pages : 16 | MS Code : CLDY-D-18-00681 | Dispatch : 20-3-2019

dates around the third week of May and second of October, respectively (Government of Canada 2018c).

For the purpose of this research, two sites were selected near the mouth of the Churchill River and Melville lake. Site Lab 32 is located 50 km northwest of Happy Valley-Goose Bay and 47 km north of the Churchill River (53°36′35.64″N, 60°53′07.08″W; Fig. 1). This site is at an altitude of 215 m.a.s.l., on a gentle slope of well-drained podzol, and is covered by an old closed black spruce stand with lichens and feather mosses. The till cover is discontinued by the presence of outcrops causing relatively heterogeneous edaphic conditions. A total of 32 healthy (i.e., no visual health issues, no wound or anomaly, straight growth), dominant or co-dominant (i.e., representing well the group, growing under low competition) black spruce [*Picea mariana* (Mill.) BSP] specimens, aged from 50 to 290 years, were selected during summer 2009 and fall 2010 for dendrochronological analysis. Site Lab 65 is located 8 km south of the Churchill River (53°11′50″N, 60°27′47″W; Fig. 1) at an altitude of 90 m.a.s.l.. The study site is an even-aged black spruce forest growing on a well-drained brunisol. Twenty healthy black spruce trees from this site were selected for dendrochronological analysis during fall 2010.

For each tree, four cores were extracted with a 90° interval at the standard height of 1.4 m with an increment borer to establish the tree-ring chronologies (mean age of 185 and 193 years for sites Lab 32 and Lab 65, respectively). Each core was subsequently sanded until wood cells were visible. Tree rings were dated and measured with standard dendrochronological methods A special care has been taken during growth depression associated to outbreak events caused by the presence of eastern spruce budworm [*Choristoneura fumiferana* (Clem.); Boulanger and Arseneault 2004; Dobesberger et al. 1983; Nishimura 2009; Raske et al. 1986]. During the twentieth century, the most severe growth depressions have been identified for the 1910–1920s, 1940–1950s, 1970–1980s periods over the Québec-Labrador peninsula. A statistical analysis was then performed to confirm dating with the COFECHA program (Holmes 1983). For dendroisotopic analysis, cross-section were sampled at breast height on 5 and 4 specimens (minimum age of 100 years and healthy appearance) among trees sampled at sites Lab 32 and Lab 65, respectively.

2.2 Sample preparation, treatment and isotopic analysis

2.2.1 Inter-tree variabilities of isotope series

Prior to reconstructing dendroclimate, it is essential to establish the level of replication required and use an adapted protocol to yield a representative site signal with a satisfactory signal-to-noise ratio. Although some researchers propose averaging the isotope series from individual trees to produce a single isotope series and characterize uncertainties related to dendroclimatic reconstruction (Dorado Liñán et al. 2011; McCarroll and Loader 2004), a realistic and more practical approach would use pooling strategy on individual trees prior to isolation of α-cellulose. This method yields similar results to those obtained from averaging individual isotope series whilst leading to a large reduction of sample numbers that have to be prepared (Borella et al. 1998; Daux et al. 2018; Liu et al. 2015; Szymczak et al. 2012; Treydte et al. 2001; Woodley et al. 2012). Moreover, whereas four to five trees were considered to be satisfactory to provide a representative site scale signal, recent studies have demonstrated that higher levels of replication (≥ 10 trees) based on confidence intervals should be considered to obtain a more reliable low-frequency signal (Daux et al. 2018; Loader et al. 2013b). In addition, former studies have shown that variations within a ring are between 0.5–1.5‰, and 0.5–2.0‰ for $\delta^{13}C$ and $\delta^{18}O$ values, respectively (Leavitt 2010). Therefore, in the present study, several cores per tree were selected to overcome the intra-tree variability which can parasitize the isotopic signal. In order to validate this approach and to evaluate the inter-tree isotopic ranges, a test was performed. Nine individual specimens were selected at both sites and four radii were sub-sampled with a 90° interval from the cross-section. In addition, previous research work at site Lab 32 showed that it is relevant to use whole ring isotopic signals instead of latewood values as there is no significant difference between $\delta^{13}C$ and $\delta^{18}O$ values of latewood and whole ring (Alvarez et al. 2018). Therefore, total wood from annual tree rings were manually separated for 1960–1984 period using thin stainless-steel blades. After test validation, the pooling method was applied to the rest of the chronological series. Same-year rings were combined by ensuring that each tree has the same mass contribution with 1-year resolution at site Lab 65, and with 2-year and 1-year resolution for 1800–1939 and 1940–2009 periods, respectively, at site Lab 32.

2.2.2 Extraction of α-cellulose and isotopic analysis

Samples were homogenized in a Wiley grinding 40 mesh mill and then placed in tightly sealed fiber filter bags (Ankom F57) for subsequent chemical treatments. The α-cellulose from all samples was extracted as it contains the strongest environmental signal compared with bulk wood for boreal black spruce trees (Bégin et al. 2015). Briefly, the protocol consisted in removing organic soluble compounds using consecutive mixture of benzene/methanol (1:1), acetone and demineralized water. Afterward, lignin was removed using a solution of demineralized water, sodium chlorite and pure glacial acetic acid. Holocellulose was separated using a 17% sodium hydroxide solution. The remaining α-cellulose in fiber filter bags was then soaked in a 10% acetic acid solution, carefully rinsed with demineralized water and dried overnight.

The $\delta^{13}C$ and $\delta^{18}O$ values were measured on a total of 1790 samples at the Delta-Lab of the Geological Survey of Canada, in Québec City. All cellulose samples were analyzed using an elemental analyzer (Costech) for $\delta^{13}C$ and a thermal conversion elemental analyzer (TC/EA; Finnigan Mat) for $\delta^{18}O$ measurements, coupled to an isotope ratio mass spectrometry (Delta Plus XL; Finnigan Mat). The isotopic ratios are reported with the conventional δ notation relative to VPDB for carbon isotopes and VSMOW for oxygen isotopes in permil (‰). The analytical accuracies of these instruments were 0.1‰ for $\delta^{13}C$ and 0.2‰ for $\delta^{18}O$, and established using international and in-house standards (NBS-19, LSVEC, IAEA-CH-6 and vanillin for $\delta^{13}C$ and IAEA-602, IAEA-C3, vanillin and sucrose for $\delta^{18}O$). The external analytical precision obtained from 180 replicates were 0.1 and 0.2‰ for $\delta^{13}C$ and $\delta^{18}O$ values, respectively. Complete $\delta^{13}C$ series were corrected to account for anthropogenic changes in the atmospheric CO_2 $\delta^{13}C$ values (data used from McCarroll and Loader 2004 and the Scripps CO_2 program) and increase of atmospheric concentration (pCO_2). To correct for the latter on plant response, we converted the Matlab code from McCarroll et al. (2009) to the R code that follows a 6-steps procedure (see Supplementary material). This correction mainly attempts to obtain $\delta^{13}C$ values close to what they could have been under pre-industrial conditions by assuming a passive response to rising pCO_2 and applying a loess regression to extract $\delta^{13}C$ low-frequency changes.

2.3 Hydroclimatic data and statistical approach

In order to reconstruct regional discharge in the lower Churchill River region, we evaluated (1) the influence of climatic conditions on tree-ring isotope series and regional discharge, and (2) the relationship between tree-ring isotope series and regional discharge. To this aim all statistical analyses and reconstruction were performed using the R software (Core Team 2018).

2.3.1 Climatic and hydrologic series

The Adjusted and Homogenized Canadian Climate Data (AHCCD) from the Goose Bay weather station, located at the Canadian Forces Base of Goose Bay, were used (Goose A station data available at http://ec.gc.ca/dccha-ahccd). Complete and continuous total precipitation and temperature series have been recorded at the station since 1942. The investigated climatic series included total monthly precipitations (Ptotal), monthly maximum, minimum and average temperatures (Tmax, Tmin and Tmean, respectively), and vapor pressure deficit (VPD) integrating temperature and relative humidity (Allen et al. 1990) for a 15-month period (from July of the previous growing season until September of the current year).

The Churchill River gauge station (Fig. 1; 03OE001) record was disrupted after impoundment of the river for the production of hydroelectric power in 1971 by Hydro-Québec and Churchill Falls (Labrador) Corporation (Grimard and Jones 1982). Natural discharge data are therefore only available for the 1954–1971 period, which is insufficient to calibrate the model and produce a robust reconstruction. In order to extend instrumental data series and produce a regional discharge index, the discharge series of three rivers close to the Churchill river were normalized by dividing each year-value by the average of the series for the common 1979–2009 period, which corresponds to the period covered by the shortest series ($River_{index}$; Fig. 1; 03QC001, Eagle River, 1969–2009; 03QC002, Alexis River, 1978–2009; 02XA003, Little Mecatina River, 1979–2009; Government of Canada 2018a). The resulting normalized river series were then averaged for each year on a 15-month period (same as climatic series).

2.3.2 Relationships between tree-ring isotope series and regional discharge

To obtain the same temporal resolution between the two sites, the Lab 32 series were annualized using a cubic spline interpolation for 1800–1939 period. The $\delta^{13}C$ and $\delta^{18}O$ series were averaged between sites to obtain a unique carbon and oxygen series ($\delta^{13}C_{mean}$ and $\delta^{18}O_{mean}$) for understanding tree processes and their relationship with climatic conditions. Under boreal environments, climatic variables, which are linked to one another, concur in influencing $\delta^{13}C$ and $\delta^{18}O$ values. For that reason, the $\delta^{13}C$ and $\delta^{18}O$ series covary and they can be combined to obtain a unique isotopic series integrating a multi-variable regional signal. In other words, the combination of both isotopes provides complementary climatic information (Ferrio and Voltas 2005). As the variable aimed to be reconstruct (discharge) integrates the influence of different climatic variables, which also influence tree-ring isotope series, the isotopic series have to be combine to integrate maximum of information. This approach also minimizes the non-climatic portion of the isotopic signals which increases statistical relationship with hydroclimatic variables (Bégin et al. 2015; Loader et al. 2008; McCarroll et al. 2003). The $\delta^{13}C$ and $\delta^{18}O$ series from the two sites were thus combined with a z-score ($\delta^{13}C\_\delta^{18}O_{combined}$) in order to give a similar weight at each isotopic ratio for reconstruction purpose. This method was supported by the weighted approach proposed by McCarroll et al. (2003) which is based on the percentage of total variation explained by each isotope. Using this weighted approach,

Journal : Large 382 | Article No : 4731 | Pages : 16 | MS Code : CLDY-D-18-00681 | Dispatch : 20-3-2019

the $\delta^{13}C$ and $\delta^{18}O$ accounted for 51 and 49% of the river discharge variations, respectively. Pearson correlation coefficients were then calculated to examine the statistical relationships between tree-ring isotope series, climatic variables/derived parameter and regional discharge series. A linear simple regression model was used to fit the relationship between the combined tree-ring isotopic series ($\delta^{13}C\_\delta^{18}O_{combined}$) and regional discharge series (average June, July and August River$_{index}$), and summer River$_{index}$ was then reconstructed back to 1800. Therefore, the discharge reconstruction was based on nine trees from two sites located at ca. 50 km from each other. In order to assess the robustness of the calibration model, a twofold cross-validation technique was used on instrumental data (covered period: 1969–2009). Root mean squared error (RMSE) and coefficient of determination (R^2) were calculated for calibration period, while Reduction of Error (RE) and Coefficient of Efficiency (CE) were calculated to evaluate reconstruction skills (Briffa et al. 1988).

2.3.3 Reconstruction validation

In the perspective of reconstruction validation, independent reconstructions are essentials. However, neither long instrumental streamflow records, nor reconstruction based on independent proxies or methods to compare with tree-ring isotope reconstruction did exist prior to this study in the investigated region. Streamflow variability reconstruction from tree-ring series and ANATEM model have been tested and compared over the 1881–2011 period in northern Québec. The results obtained suggested that different reconstruction methods have to be applied within the same catchment for the purpose of comparison and validation (Brigode et al. 2016). Hence, the ANATEM reconstruction model was applied. ANATEM offers the advantage of combining local observations and large-scale climatic information such as geopotential heights field to reconstruct a past climatic ensemble (temperature and precipitation) based on synoptic situation similarities between days from recent and past periods. Then, a rainfall–runoff model—previously calibrated on the observed period using available discharge series—is used to transform this climatic series into streamflow series (for more details see Brigode et al. 2016; Kuentz et al. 2015). Therefore, the model was applied for the 1880–2009 period using the following hydroclimatic: geopotential heights from NOAA 20CR reanalysis (Compo et al. 2011), air temperature from the Berkeley Earth Surface Temperature (Rohde et al. 2014), air temperature and precipitation from the NRCan gridded dataset (Hutchinson et al. 2009) and discharge data from the three individual rivers (Eagle River, Alexis River and Little Mecatina River).

3 Results

3.1 Inter-tree variabilities of isotope series

At the studied sites, the $\delta^{13}C$ values of the nine individual trees varied from − 24.4 to − 20.6‰ (Fig. 2a) after correction for the Suess effect and increase of pCO_2, and de-trending of the series with a high-pass filter. Eight of the trees, within the same range of absolute values, show an average of − 23.0‰, whereas one tree has a higher average at − 21.1‰. For the $\delta^{18}O$ values (Fig. 2b), all trees are within the same range with values from 21.4 to 26.1‰ and an average of 23.7‰, excepted one which has an average of 25.5‰. Moreover, ring width series decrease from 1910 to 1920, 1950 to 1957 and 1974 to 1981, with minimal growth associated with outbreak episodes in 1915, 1952 and 1977, respectively (Fig. S2). During the 1910–1920 and 1950–1957 episode, $\delta^{13}C$ and $\delta^{18}O$ values are relatively constant (Fig. 3a, b, respectively) suggesting no specific influence from budworm defoliation on isotopic signals. During the 1974–1981 episode, $\delta^{13}C$ mean values decrease from 1975 to 1978 and increase from 1979 to 1984 (Fig. 2a). Those observations are opposite to those of previously studied black spruce trees (Simard et al. 2008, 2012). The $\delta^{18}O$ mean values show two decreases in 1977 and 1980 for almost each trees

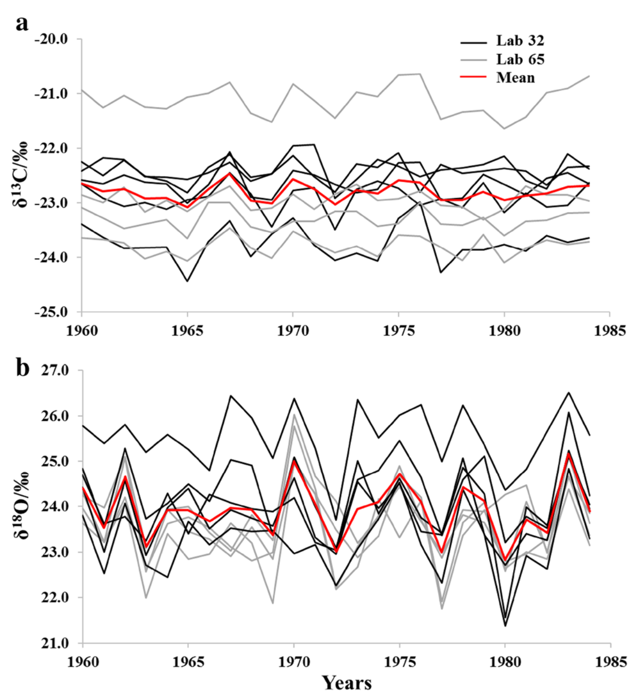

Fig. 2 Tree-ring $\delta^{13}C$ corrected and de-trended (**a**) and $\delta^{18}O$ de-trended values (**b**) for the nine individual trees from site Lab 32 (black line) and Lab 65 (grey line). Red line is the mean of the nine trees

Journal : Large 382 | Article No : 4731 | Pages : 16 | MS Code : CLDY-D-18-00681 | Dispatch : 20-3-2019

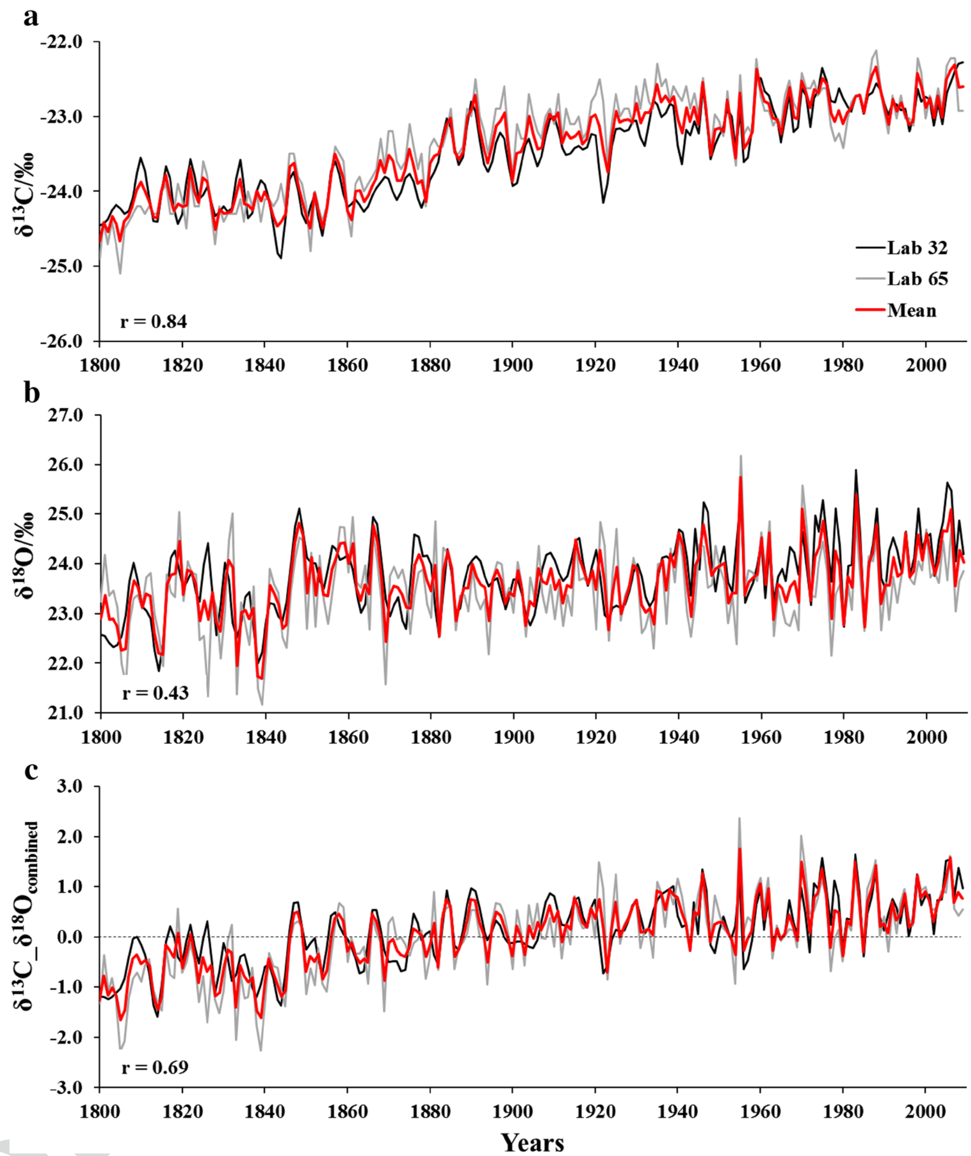

Fig. 3 Tree-ring $\delta^{13}C$ series at sites Lab 32 (black line) and Lab 65 (grey line), and regional $\delta^{13}C_{mean}$ (red line) (**a**); tree-ring $\delta^{18}O$ series (**b**); and the resulting final isotopic series combined using z-score (**c**), see 2.3 for details

(Fig. 2b). Such decreases are also observed during other years not related to budworm outbreak episodes. One explanation could be that black spruce is a tertiary food source for budworm after balsam fir and white spruce likely yielding less severe tree defoliation during the outbreak episodes in Labrador (Nishimura 2009). This is particularly due to the speed of shoot development during spring. Balsam fir and white spruce shoots develop faster, which makes them more susceptible to defoliation (Blais 1962; Nealis and Régnière 2004). In all likelihood, tree-ring $\delta^{13}C$ and $\delta^{18}O$ series at Lab 32 and Lab 65 are not significantly influenced by budworm defoliation during outbreak episode. Even through two trees show higher values for $\delta^{13}C$ and $\delta^{18}O$ series likely related to metabolic differences or edaphic conditions, inter-tree $\delta^{13}C$ and $\delta^{18}O$ values from the nine selected trees show significant statistical correlation ($r=0.40$ and 0.59, respectively), resulting in a high expressed population signal (EPS; 0.86 and 0.93 for $\delta^{13}C$ and $\delta^{18}O$, respectively). The EPS values for $\delta^{13}C$ is slightly higher than the acceptable threshold of 0.85, while it is higher for the $\delta^{18}O$ (Buras 2017; Wigley et al. 1984) meaning that for this study, nine trees are sufficient to represent the site signal, which allows pooling tree ring from same years and obtaining $\delta^{13}C$ and $\delta^{18}O$ series for sites Lab 32 and Lab 65. Those results are in accordance with the number of trees suggested by Daux et al. (2018; 8 and 10 trees for $\delta^{13}C$ and $\delta^{18}O$, respectively) to generate an isotopic mean series representative of the population for conifer species.

3.2 Tree-ring $\delta^{13}C$ and $\delta^{18}O$ series at the two studied sites

In the studied area, tree-ring corrected $\delta^{13}C$ values of the two selected sites (not de-trend) are significantly correlated

($r=0.84$; $p<0.05$; $n=210$; Fig. 3a). The long-term trend of the $\delta^{13}C_{mean}$ (mean for Lab 32 and Lab 65 sites) fluctuates around −24.1‰ from 1800 to 1859 followed by an increase between 1860 and 1959 and fluctuates around −22.8‰ between 1960 and 2009. The $\delta^{13}C_{mean}$ inter-annual variations fluctuate between −24.8 and −22.3‰ with an average of -23.4‰. There is also a statistically significant correlation between $\delta^{18}O$ isotopic series of Lab 32 and Lab 65 ($r=0.43$; $p<0.05$; $n=210$; Fig. 3b). The $\delta^{18}O_{mean}$ of the two sites shows a steady increase from 1800 (22.9‰) to 2009 (24.0‰), short-term variations between 21.6 and 25.7‰, and an average value of 23.6‰.

The individual $\delta^{13}C_{mean}$ and $\delta^{18}O_{mean}$ series show significant complementarity ($r=0.45$; $p<0.05$; $n=210$) as they are highly, but differently, correlated with the same climatic variable/derived parameter (T_{max} and VPD; Table 1). The $\delta^{13}C\_\delta^{18}O_{combined}$ series of Lab 32 and Lab 65 are thus highly correlated ($r=0.69$; $p<0.05$; $n=210$; Fig. 3c), allowing their combination to obtain a single isotopic series representative of the lower Churchill River region hydroclimatic conditions. The $\delta^{13}C\_\delta^{18}O_{combined}$ mean series for the two sites shows a flat trend from 1800 to 1849 followed by an increase between 1850 and 1959 and a flat trend between 1960 and 2009.

3.3 Relationships between isotopic series and hydroclimatic variables

The $\delta^{13}C_{mean}$ and $\delta^{18}O_{mean}$ series display significant correlations with some climatic variables (Table 1). The regional $\delta^{13}C_{mean}$ shows the highest correlation with T_{max} and VPD from May–August. Oxygen isotopic ratios have an inverse correlation with P_{total} and a positive correlation with VPD and T_{max} for the same period. Therefore, the final $\delta^{13}C\_\delta^{18}O_{combined}$ series correlates well with the three climatic variables. There are also inverse statistically significant correlations between the $\delta^{13}C$ and $\delta^{18}O_{mean}$ and $River_{index}$ from June–August and the highest correlations are found for the final $\delta^{13}C\_\delta^{18}O_{combined}$ series ($r=-0.56$, −0.55, −0.31, −0.66 for June, July, August and average June–August $River_{index}$, respectively; $p<0.05$; $n=41$). The relationships between $River_{index}$ and climatic factors suggest that spring end and summer conditions are important drivers on regional discharge.

Table 1 Significant statistical correlations between the tree-ring isotopic series and hydroclimatic variables (all correlations are significant at $p<0.05$, $n=41$)

	T_{max}	P_{total}	VPD	$River_{index}$
$\delta^{13}C_{mean}$	0.64[a]	−0.36[a]	0.65[a]	−0.60[d]
$\delta^{18}O_{mean}$	0.53[a]	−0.42[a]	0.56[a]	−0.58[d]
$\delta^{13}C\_\delta^{18}O_{combined}$	0.63[a]	−0.45[a]	0.66[a]	−0.66[d]
$River_{index}$	−0.49[b]	0.63[c]	−0.60[e]	–

Selected bold periods are for both variables

[a]May–August

[b]June to Sept

[c]May to Sept

[d]June–August

[e]May–August VPD correlated with June–August $River_{index}$

3.4 Regional discharge reconstruction from the tree-ring $\delta^{13}C$ and $\delta^{18}O$ combination

The summer regional discharge (June–August) in the lower Churchill River region was reconstructed for the 1800–2009 period (Fig. 4). The quality of reconstruction is assessed based on a cross-validation method (Table 2). The R^2 of the two calibrated periods are highly significant ($p<0.01$) and both RE and CE of the verification periods are >0 which indicates that the model skills are adequate (Cook et al. 1999). The R^2 of the total period ($R^2=0.44$; used for the final reconstruction) shows excellent coherence between observations and simulations of the $River_{index}$. The significant statistical correlation between discharge index reconstruction and natural discharge data from the lower Churchill River ($R^2=0.31$; $p<0.05$; $n=18$) validates the predictive ability of the model. Moreover, reconstructed June–August discharge series show varying climatic conditions over the last 200 years with a long-term decrease from 1800 to 2009 and short-term decreases that are associated to drought periods (e.g., 1935–1954, 1982–1990) when compared with the drought index of Standardized Precipitation-Evapotranspiration Index (SPEI03; Begueria et al. 2018).

3.5 Isotopic reconstruction compared with the ANATEM reconstruction

Overall, the ANATEM method results show a good fit with the tree-ring isotope series reconstruction, with a statistically significant correlation ($r=0.41$; $p<0.05$; $n=130$; Fig. 5). The two reconstructions show a long-term decrease of summer discharge, all along the studied period. Moreover, the reconstructed interannual variabilities are quite similar for the 1941–2009 period, while they are different between 1880 and 1940. One explanation could be that trees from the study region are barely sensitive to precipitation variability as water availability is not a limiting factor due to the annual high supply in precipitation (around 1070 m/year from 1942 to 2009). Thus, short term variations of discharge reconstructed from tree-ring isotopic series might not respond readily to the precipitation varibility, whereas the ANATEM discharge reconstruction uses precipitation variability as an input variable. Another explanation could be related to the climatic reanalysis used by the ANATEM model. Scarce geopential height data before 1950 (Cram et al. 2015) might increase error on

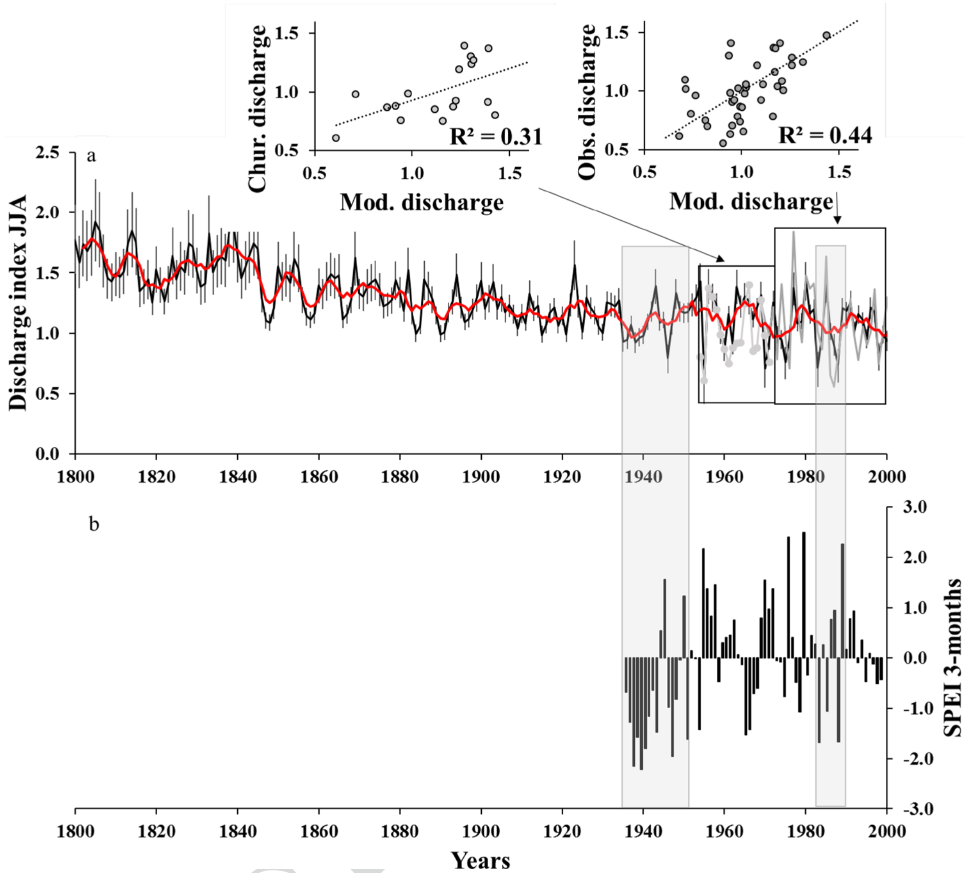

Fig. 4 Summer regional discharge (June–August; **a**) reconstructed from the combined tree-ring isotopic series ($\delta^{13}C\_\delta^{18}O_{combined}$) for the 1800–2009 period (black line), with 5-year moving average (red line). Error bars represent the 95% confidence interval. The modeled reconstruction is also compared with the observed $River_{index}$ for the 1969–2009 period (solid grey line; upper right scatterplot), the observed Churchill River discharge for the 1954–1971 period (03OE001 station; open grey line; upper central scatterplot) and the summer SPEI 3-month (**b**)

Table 2 Statistics of model calibrations using a simple linear regression method

	Calib 1969–1988	Verif 1989–2009	Calib 1989–2009	Verif 1969–1988	Total period 1969–2009
R^2	0.45		0.43		0.44
RMSE	0.24	0.20	0.16	0.27	0.22
RE		0.42		0.44	
CE		0.13		0.32	

Coefficient of determination (R^2) and root mean square error (RMSE) are given for calibration steps while reduction of error (RE) and coefficient of efficiency (CE) are given for the verification steps

precipitation reconstruction used for the rainfall-runoff model and thus on discharge reconstruction in the region.

4 Discussion

4.1 Relationships between climatic conditions, tree-ring stable isotopes and regional discharge

Streamflow reconstruction from tree-ring $\delta^{13}C$ and $\delta^{18}O$ values entails understanding the existing relationships between climatic conditions, tree-ring isotopes and water resource. Although the effect of climatic variables is relatively direct on processes controlling isotopic fractionation and water variability, the relationships between river flow and tree-ring isotopes are indirect. Two isotope-based river-flow reconstructions from tree rings invoked key mechanisms to explain the cause and effects links between $\delta^{13}C$ series and river flows (Waterhouse et al. 2000; Wils et al. 2010). In the present study, Lab 32 and Lab 65 are located at 47 and 8 km, respectively, from the Churchill River, which discards the direct influence of river moisture to trees invoked by Waterhouse et al. (2000). Moreover, under the known climatic conditions of the region, water availability is not a limiting factor for tree growth and could rather be a reducing factor for climate sensitivity of tree-ring width chronologies (Nishimura and Laroque 2011; Trindade et al. 2011b). At Lab 32 and 65, tree-ring width series show inconsistent or non-significant correlations with climatic variables (data not show), while tree-ring isotope series significantly correlate with summer conditions. Those climatic conditions directly influence stomatal aperture of tree needles, photosynthesis and the distillation of cloud masses that regulate tree-ring $\delta^{13}C$ and $\delta^{18}O$ variations. Using tree-ring stable isotopes rather than width is thus recommended for reconstructing river discharge in the climatic context of this study.

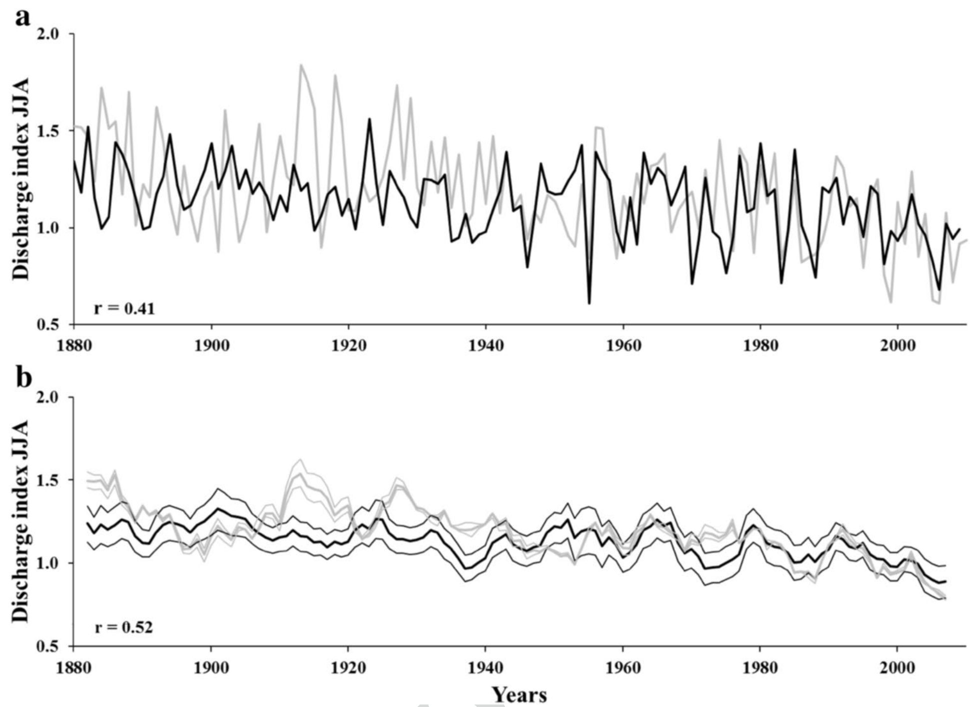

Fig. 5 Summer discharge reconstruction using tree-ring isotopes (black line) and the ANATEM method (grey line) for **a** raw yearly data, and **b** 5-year moving average data with 95% confidence interval

The weak correlation between tree-ring $\delta^{13}C$ values and precipitation suggests that precipitation is not the main control on carbon fractionation in trees of the area. This interpretation makes sense as the abundance of precipitation provides unlimited water supplies to the trees (Bégin et al. 2015; Naulier et al. 2015b; Porter et al. 2009; Saurer et al. 2004). In addition, in this non water-limited context, the photosynthetic capacity is mainly influenced by temperature and sunshine conditions, and exerts the principal control on carbon assimilation (Gagen et al. 2011; Loader et al. 2013a). The significant correlation between $\delta^{13}C_{mean}$ and T_{max} from May to August supports this interpretation. To a lesser extent, there is a potential control of relative humidity on ^{13}C fractionation via stomatal conductance as $\delta^{13}C_{mean}$ values correlate with May–August VPD (Scheidegger et al. 2000).

Relationships found between tree-ring $\delta^{18}O_{mean}$ and May–August T_{max}, P_{total} and VPD indicate that these climatic variables and derived parameters are the main controls on the oxygen isotopic fractionation, which is consistent with the following well-known mechanisms. Temperature controls the precipitation amount, type (rain, snow, etc.,) and isotopic fractionation during droplet formation from clouds (Clark and Fritz 1997; Dansgaard 1964), while a combination of temperature, precipitation and humidity affects stomatal functioning (Saurer et al. 1997). The VPD positive correlation with the $\delta^{18}O_{mean}$ values confirms the influence of those climatic variables on plant transpiration, and thus, on the ^{18}O discrimination occurring at the leaf level (Ferrio and Voltas 2005).

At a broader scale, a site located 660 km west in Quebec from Lab 32 and Lab 65, shows tree-ring $\delta^{18}O$ average around 3‰ lighter (Naulier et al. 2014) than the signal at the presently studied sites. In this area, climate is continental and subarctic with short, mild summers and long, cold winters with a dominance of arctic winds under the influence of Labrador Current. These results suggest a continental effect of the water $\delta^{18}O$ fractionation when clouds move inland from the open Labrador Sea. Moreover, in the study region, a bioclimatic gradient has been observed through the relationship between tree-ring width and summer temperature (Nishimura and Laroque 2011): the most eastern sites show a significant relationship between tree growth and July temperatures, whereas the western sites tended to correlate with May, June and August temperatures. The authors interpreted these results as demonstrating a bioclimatic gradient from coastally proximal, maritime-influenced sites, and inland, continentally influenced sites, with transition occurring approximately 330 km inland from the coast. The $\delta^{13}C_{mean}$ and $\delta^{18}O_{mean}$ values of the lower Churchill River region at about 230 km from the coast are thus most likely influenced by maritime climate impacted by the cold Labrador Current. Finally, other studies have demonstrated similar correlations between temperature, precipitation, VPD, and black spruce isotope series in cold environment (Bégin et al. 2015; Naulier et al. 2014). These studies along with the present one thus show that black spruce trees are sensitive to the same climatic variables within the Québec-Labrador peninsula.

Results also show significant correlations between June to September $River_{index}$ and T_{max}, May to September $River_{index}$

Journal : Large 382 | Article No : 4731 | Pages : 16 | MS Code : CLDY-D-18-00681 | Dispatch : 20-3-2019

and P_{total}, and June–August $River_{index}$ and May–August VPD. They strongly suggest that the climatic variables controlling tree-ring stable isotopes are also the main drivers influencing regional discharge during summer. This observation agrees with few others studies showing that both water supply and tree-ring indicators are controlled by similar combinations of climatic variables in the Canadian northeastern boreal forest (Bégin et al. 2015; Nicault et al. 2014). These mechanisms explain the significant inverse correlation found between $\delta^{13}C_{mean}$ and $\delta^{18}O_{mean}$ with $River_{index}$ from June to August. The combination of T_{max}, VPD and P_{total} triggers this indirect relationship, each at various degrees. In practical terms, during wet and cold summer conditions, low T_{max}, VPD and high P_{total} decrease tree-ring $\delta^{13}C$ and $\delta^{18}O$ values and increase water discharge, and dry and hot summer conditions generate the opposite. Moreover, terrestrial biosphere models have demonstrated that plant transpiration directly influences land surface water regimes during summer. Soil moisture and continental runoff decrease when stomatal opening releases water from trees, and they increase when stomatal closure retains water (Betts et al. 2007; Cao et al. 2010; Gedney et al. 2006; Knauer et al. 2017). Throughout a study across Canada, Wang et al. (2013) have shown that evapotranspiration is mainly controlled by surface heat fluxes in regions where water is abundant. For the studied region, this means that temperature, sunshine and VPD partly influenced stomatal conductance, and then evapotranspiration, which directly influences summer regional discharge. All of these interpretations strengthen the postulate that the tree-ring $\delta^{13}C$ and $\delta^{18}O$ combination can serve to reconstruct summer regional discharge. Reconstruction from the ANATEM method supports this point as it significantly correlates with the tree-ring isotopic reconstruction (Fig. 5). The two discharge reconstructions show a significant long-term decrease suggesting that this part of Canada has experienced an overall decrease in summer discharge over the past 200 years. This observation is in accordance with studies showing evidences of high water level during the first half of the nineteenth century that has been recognized as one of the coldest intervals of the Little Ice Age with the persistence of cold and humid conditions in northern Québec (Bégin and Filion 1988; Bhiry et al. 2011). In addition, when comparing the tree-ring isotopic reconstruction with discharge instrumental series located as far as 900 km north west and 1300 km south west (Grand Baleine and Harricana River, respectively), a similar decrease is observed since 1915 (Fig. S3). Those results suggest that likely all the Québec-Labrador peninsula experienced a general decrease in the summer river discharge. Interestingly, tree-ring stable isotopes series and consequently summer discharge reconstruction series show significant correlation with the AO that potentially influences the observed long-term discharge decrease (Thompson and Wallace 2000), and this relationship is dealt with in the next section.

4.2 Teleconnections between large-scale atmospheric variability and reconstructed discharge

Over various Canadian regions, large-scale atmospheric and oceanic variability modes influence seasonal climate and the stronger links are generally reported to occur during the cold season, while less robust relationships are described for summer (Bonsal and Shabbar 2008). Some studies also find a significant lagged relationship between winter El Niño/Southern Oscillation, Atlantic Multidecadal Oscillation, Pacific North American, NAO and AO, and spring to summer climate (Asong et al. 2018; Ogi et al. 2003, 2004; Shabbar and Skinner 2004). Ogi et al. (2004) suggested that there is a persistence from one mode of the NAO/AO in winter to a similar mode in summer. In northern/northeastern Canada, winter climatic conditions are mainly driven by winter NAO and AO, which are strongly linked (both showing positive phases driving anomalously cold temperatures during winter; D'Arrigo et al. 2003; Rogers and McHugh 2002; Thompson and Wallace 2001). The AO represents the atmospheric mass exchange between middle and high latitudes and it is frequently discussed along with the NAO as they resemble in many aspects (Thompson and Wallace 1998). Changes in atmospheric circulation associated with these oscillations can thus lead to changes in seasonal climatic conditions. Other studies have emphasized the important influence of NAO/AO on tree growth and biomass production during summer in the northeastern part of Canada (Boucher et al. 2017; Buermann et al. 2003; Cho et al. 2014; Ols et al. 2018). Some of these studies discuss the impact of winter atmospheric conditions associated with NAO/AO on spring and summer tree activities. For example, a positive phase of winter NAO/AO enhanced cooler and drier conditions and decreases the normalized difference vegetation index during the following spring. However, growth of black spruce trees from Quebec responds to summer, rather than winter, NAO and AO with a significant negative relationship since 1980 (Ols et al. 2018). Interestingly, in the present study, the final $\delta^{13}C\_\delta^{18}O_{combined}$ series do not show statistical links with the NAO, but is positively correlated with the summer AO index ($r = 0.37$; $p < 0.05$; $n = 101$).

As tree-ring isotopic series and river discharge are inversely correlated and respond to similar climatic conditions, the summer discharge reconstruction necessarily shows an inverse correlation with summer AO (Fig. 6). Similar results have been observed by Nicault et al. (2014) between reconstructed summer discharge and summer AO index ($r = -0.42$; $p < 0.05$) at a site located 700 km west from the Churchill River. These authors found low, but significant correlations between the summer AO/NAO and temperature, without being able to link the AO influence to known mechanisms. In the present study area, the AO summer index

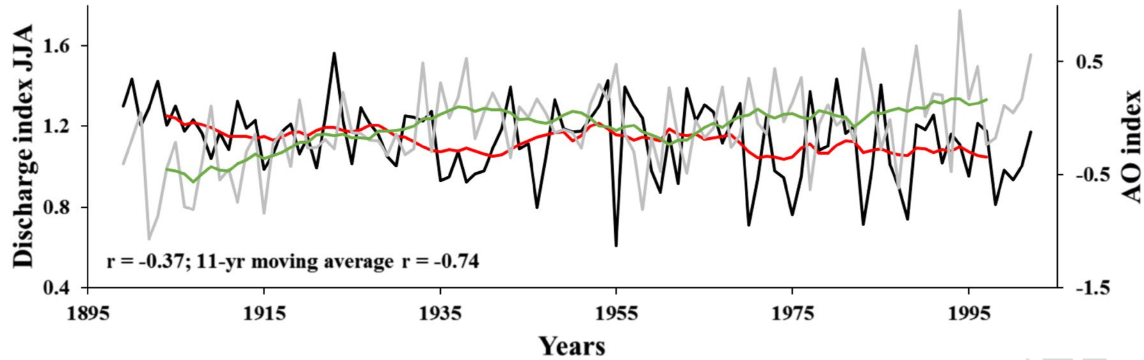

Fig. 6 Summer discharge reconstruction from tree-ring isotopes (black line) inversely correlating with the summer AO index (grey line). Red and green lines represent 11-year moving average for discharge reconstruction and AO index, respectively

correlates directly with summer T_{max} ($r = 0.41$; $p < 0.05$; $n = 61$), but the AO annual index inversely correlates with the annual T_{max} ($r = -0.49$; $p < 0.05$; $n = 61$). The latter correlation likely reflects the relationship between winter AO index and winter temperature ($r = -0.63$; $p < 0.05$; $n = 61$). The winter AO index also shows low correlation with spring and summer temperature ($r = -0.14$ and 0.16, respectively; $p < 0.05$; $n = 61$), suggesting a very moderate influence of AO index on the following seasons. Those observations suggest that various mechanisms play within the year to modulate the relationship between AO and temperature. As shown previously, the winter AO index relationship with winter conditions is well understood in northeastern Canada, whereas the summer AO index influence on summer conditions is barely documented. The present study underlines this influence of summer AO on low and mid-frequency variations of the reconstructed summer regional discharge, likely operating through AO's effects on summer regional climatic conditions. Indeed, further investigations are required to determine the mechanisms at play for AO to regulate summer river discharge in eastern Labrador.

5 Conclusion

This study confirms that the approach used in this research is one of the most relevant tools to document the variability of past hydroclimatic conditions in the northeastern boreal forest where water availability is not constraining the growth of trees. The statistical examination suggests that summer T_{max}, P_{total} and VPD are the main drivers of the $\delta^{13}C$ and $\delta^{18}O$, and regional discharge variations, and expresses an indirect link between the isotopic series and the discharge in the studied region. In addition, evapotranspiration partly contributes directly to linking tree-ring isotopic attributes to water discharge. Hence, tree-ring stable isotopes can serve for reconstructing summer regional discharge. Moreover, the significant correlation between reconstructions from tree-ring isotopes and the independent ANATEM method validates the two approaches. The reconstructions suggest that this part of Canada has experienced an overall decrease in summer discharge over the past 200 years. The summer AO is inferred to affect low and mid-frequency variations of summer regional climatic conditions in this region. Future research should examine potential mechanisms by which summer AO index operates to regulate summer climatic conditions and regional discharge.

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