A 211-year River Reconstruction of the Chic-Choc and McGerrigle Mountains of the Gaspésie from Tree-rings

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ABSTRACT

A 211-year River Reconstruction of the Chic-Choc and McGerrigle

Mountains of the Gaspésie from Tree-rings

By Alexandre V. Pace

Long instrumental records are needed to serve as baselines in order to fully understand naturally occurring streamflow and climate variability, especially in this era of rapid anthropogenic climate change. In most remote parts of Canada, both instrumental streamflow and climate data are of relatively short duration, spanning approximately 50 years in duration. Barring annually laminated varved sediments, tree-ring reconstructions with their absolute dates are the only feasible way to infer streamflow and climate data of the past at an annual or sub-annual resolution in such places. Such inferred paleo-hydrological and paleo-climate data has proved useful for better natural resource management, providing a much-needed long-term context. Here we present a 211-year high-frequency tree-ring-based reconstruction of the Sainte-Anne River, Gaspésie, Québec. This reconstruction shows that the short 49-year instrumental record does not capture the full range of the natural variability of the river, especially that of the periods of sustained low flows. This river arises in the interior of the Gaspé Peninsula, a region that contains some of the highest mountains in Québec. The instrumental streamflow and climate records are particularly short in this alpine region, which is the location of the *Parc national de la Gaspésie*. This alpine region is the home of the critically endangered southernmost herd of caribou in Canada and many rare, endemic plants. The Sainte-Anne River is also the site of an important Atlantic salmon fishery. Hence, a longer-term moisture record can serve as a useful tool for management of these threatened fauna, flora and ecosystems.

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1. INTRODUCTION

The long-term climate history of the Gaspé Peninsula is not well understood. Mountainous regions, especially those with periglacial environments such as the Gaspésie, are particularly vulnerable to rapid climate changes, but the regional, local and altitudinal effects vary significantly (Beniston, 2003; Capers et al., 2013; Fortin & Hétu, 2014; Gray et al., 2009; Lenoir et al., 2008; Pauli et al., 1996). The longest local climate stations that remain active in the interior Gaspésie begin in 1953, giving only a brief glimpse into the past. Studies of the region's climate records by Gagnon (1970) and Fortin et al. (2012, 2014, 2017) suggest that the peninsula's distinguishing geography drives changes in climate that may be substantial. Despite changes in the timing and type of precipitation across Canada, there have been variable and mostly insignificant changes in the regional precipitation trends of the Gaspésie and a slight, but insignificant, rise temperature since 1970 (Brown & Braaten, 1998; Fortin & Hétu, 2014; Gray et al., 2009). However, the weather station of highest elevation in the Gaspésie has anomalously recorded a decrease in winter precipitation from 1970-2012 (Fortin et al., 2017), suggesting that Gaspésie's higher elevations may be the first in the region to be significantly affected by climate change.

A detailed understanding of the region's climate variability and the impacts of climate change require a period of data longer than that provided by the short instrumental records available. The only method to infer long-term climate data at an annual and seasonal resolution is through the study of tree-rings. The Gaspé Peninsula's McGerrigle and Chic-Choc Mountains have strong potential for dendroclimatology, the study of climate using tree-rings. The high elevation of the area provides many mountain tops with clear tree lines and scree slopes, sites conducive to constructing tree-ring chronologies and potentially, reconstructions of past temperature, precipitation and streamflow. Along the Sainte-Anne River and its tributaries, there are many locations where trees grow on moisture-stressed rocky cliffs. In addition, the river runs along a rare old growth cedar grove, sampled previously in the 1980s by a leader in dendroclimatology (Cook, 1994; D'Arrigo and Jacoby, 1993).

Tree ring-based climate reconstructions can help local managers and planners such as the *Parc national de la Gaspésie* (PNG) and the wildlife reserves that surround the park, better understand the context of future regional warming and fluctuations in moisture conditions. As climate change intensifies over this century, the region is likely to experience more natural hazards such as fires, and significant impacts on hydrology, infrastructure and ecosystems (Fortin et al., 2017; Germain et al., 2009; Germain & Martin, 2012). Tree-ring based climate reconstructions can provide a greater understanding of the landscape, ecosystems and their threatened species. The PNG is home to the last population of caribou south of the Saint Lawrence River. The caribou here are designated a species at risk since 2001 (Gaspésie Woodland Caribou Recovery Plan 2002-2012, 2006) and are in continual decline due to habitat loss, predation and climate change (Ouellet et al., 1996; Dr. Martin-Hugues St-Laurent, Université de Québec à Rimouski, personal communication, May 2018). Furthermore, the spawning grounds of Atlantic salmon fisheries in the Sainte-Anne River of the PNG are a critical cultural and economic asset to preserve. Atlantic salmon have been extirpated from the northeastern USA and they are in decline along the east coast of Canada, and they show signs of decline in some rivers studied in the Gaspésie (Dionne & Cauchon, 2015; Government of Canada, 2012; Parrish et al., 1998). A moisture or river reconstruction using tree rings may inform management approaches related to Atlantic salmon in the region. Such a reconstruction may also be applied to flood management and related risk assessments (Ballesteros-Cànovas et al., 2015).

2. LITERATURE REVIEW

2.1 Understanding regional climate change

The effects of global warming vary and are difficult to predict at regional and sub-regional scales (Solomon et al., 2007; Watson et al, 1997). In many regions there is a lack of sufficient understanding of the past regional climate which is needed to evaluate local vulnerability to climate change, creating uncertainty in adaptation measures. Instrumental climate records provide only a brief glimpse of at the most 150 years into the past and which may be of a much shorter duration and more unreliable in less populated regions (Fortin et al., 2017; Le Houérou, 1996). These brief instrumental records can be supplemented with records from natural sedimentary archives or climate proxies. Climate proxies are a variety of biotic or abiotic deposits that are regularly formed and that have measurable characteristics significantly influenced by climate. Such proxy-based reconstructions are integral to key documents in the climate change literature including the Assessment Reports of the Intergovernmental Panel on Climate Change (D'Arrigo et al., 2008; Hughes, 2002; Mann et al., 1999; Masson-Delmotte et al., 2013; Solomon et al., 2007). Climate proxies of different temporal resolutions can be aggregated for robust intra-regional and inter-regional reconstructions of climate to reconstruct thousands of years of temperature and hydroclimate (Frank et al., 2010; Mann et al., 1999). A better understanding of the Earth's climate directly results from the increasing quantity and coverage of proxy data and reliable climate reconstructions (Jones et al., 2009). For many regions, dendroclimatology —the study of climate using tree-rings— is the sole method to create high resolution, annual and even sub-annual climate reconstructions of the past millennia.

2.2. Past climate and tree rings

Dendroclimatology is a subfield of dendrochronology. Both have their historical roots in the study of climate-related phenomena in the western United States but have been adapted to diverse environments across the globe. Tree-rings were first used for research at the turn of the 20^{th} century by the astronomer and geographer A. E. Douglas in Arizona to study sunspot cycles (Speer, 2010). These methods were expanded to other components of climate, first to study growing season climate variability and then to study less direct factors such as winter precipitation (St. George, 2014). In the southwestern United States, trees are particularly conducive to climate studies because the trees of open canopy forests have little to no competition for resources (Fritts, 1976). Sites here are often water-stressed and contain tree species with very long lifespans, with some individuals over 4000 years old (Ferguson, 1968). As a result, there is a very high concentration of long tree-ring records beginning before AD 1500 from the western USA, and from western Canada (Payette & Filion, 2010; Watson & Luckman, 2006).

A tree-ring based temperature or moisture reconstruction is the result of careful sampling of climate-sensitive trees, followed by the statistical manipulation of the series of their annual ring-widths to isolate and model their relationship with climate (Speer, 2010). Living trees are sampled manually and non-destructively with increment borers and dead trees are sampled with manual or electric saws. The samples are processed to increase visibility of the tree-rings and the ring widths are measured and digitized. A variety of computer tools are typically used to measure widths and develop chronologies (Bunn, 2008; Cook & Holmes, 1985; Grissino-Mayer, 2001; Holmes et al., 1983). Before averaging the individual tree-ring width series from the samples together to create a site chronology, each series is mathematically detrended to, in theory, remove patterns in the chronology from non-climatic effects such as growth or competition, which in dendroclimatology are not of interest (Cook & Peters, 1981). The correlations between a site chronology and the climate records are calculated to determine which, if any, climate variables the trees are sensitive to. Climate records of temperature (Buckley et al., 2010), precipitation (Lutz et al., 2012), streamflow (Nicault et al., 2014), drought (Meko et al., 1980) and atmospheric pressure systems (Pederson et al., 2004) have all been used to create tree-ring based reconstructions. The sample sites with a significant relationship to the same climate variable are then grouped together for a reconstruction of that climate variable prior to the beginning of instrumental records. Multiple linear regression is frequently used to model the relationship between the climate variable and the tree-ring chronologies for the timespan that they overlap, using the chronologies as the predictors and the climate variable as the predictand (Lutz et al., 2012; Meko & Graybill, 1995; Pederson et al., 2013). The modelled regression function is then applied to the portion of the tree-ring chronologies that extends before the period covered by the climate records, creating the reconstruction.

2.2.1 Site selection and sampling

The foundation of dendroclimatology rests on proper sampling and processing techniques, techniques elaborated by H.C. Fritts (1976). Temperature, moisture, snowpack, competition for light and soil nutrients are key environmental factors that may limit ring growth. The influence of climatic factors on the growth of tree rings can be emphasized during sampling by selectively sampling sensitive tree species at sites of extreme moisture- or temperature-stressed conditions (Speer, 2010). In practice, moisture-sensitive trees are selected based on the lack of water retention potential in the substrate (e.g. growing on a rocky surface, with little to no soil) and temperature-sensitive trees are typically sampled from alpine or arctic treeline, where colder conditions are closer to the threshold of photosynthesis during the growing season (Phipps, 1982). Sites not conforming to these extreme conditions may contain climate information as well, but the information is more likely to be less pronounced and a mix of different climatic factors (Cook & Kairiukstis, 1990; Pederson et al., 2004; Tardif et al., 2001).

In the traditional dendroclimatology of the semi-arid, open canopy forests of western North America, sampling 20 to 30 trees is sufficient to detect a growth signal that accurately represents the climate record of a site (Fritts, 1976). Dendroclimatology in the closed-canopy forests typical of eastern North America requires, in addition to more complex statistical processing, the collection of at least 50 to 100 tree samples to average out the changes in growth due to the competition for resources between trees (Cook & Peters, 1981; Speer, 2010). Conditions conducive to the preservation of dead wood are critical to extending chronologies past the lifespan of the sampled species, because dead trees can be dated using live trees and included in a chronology. Dry sites with slow rates of decomposition, as well as wood preserved in sediments at the cold, relatively anoxic bottom of lakes, are two types of sites conducive to well-preserved dead wood (Payette et al., 1985).

2.3 Hydrological phenomena and tree rings

Changes in regional hydrology directly due to global warming are extremely variable and uncertain, especially in mountain environments (Beniston, 2003; Huntington, 2006). As global temperature increases, the hydrological cycle is expected to intensify, but with variable regional effects that are expected to be more severe at mid- to high-latitudes (Fan & He, 2015). As a result of the high spatial variability of precipitation in mountainous landscapes, moisture conditions need to be studied at a relatively fine resolution. Accurately measuring changes in moisture through precipitation is inherently difficult because of the high spatial variability of precipitation and inaccuracies in rain gages due to evaporation, wind, blowing snow, rime load on instrumentation, condensation and other biases (Groisman & Ivanov, 2009; Yang et al., 1999). A stream gage measuring water flow rates in a river is often a more effective integrated measure of hydroclimate regionally and seasonally than the direct measurement of precipitation of individual locations (Trenberth et al., 2007). However, it is important to note that a stream gauge's accuracy can change over time due to streambed changes and may misrecord occurrences of extreme conditions (Meko & Woodhouse, 2011). In addition, river-ice and spring melt (high water level and flooding) are additional concerns for the maintenance of and guaranteed integrity of instrumentation on the long term.

An understanding of the past decadal-to-centennial-scale variations in hydroclimate is important to efficiently manage surface water resources both in the face of climate change (Ballesteros-Cànovas et al., 2015; Soloman et al., 2007), but also because the actual long-term natural variability of a region's hydroclimate is expected to be significantly higher than that captured by the short instrumental records (Cook et al., 2007). Short instrumental records of precipitation and streamflow can be supplemented by tree-ring based reconstructions. Streamflow reconstructions provide an understanding of the regional fluctuation of extremes —particularly floods and droughts— and can improve the reliability of empirical hydrological and process-based models (Meko & Woodhouse, 2011; Payette & Filion, 2010).

Streamflow and other hydrological reconstructions using tree rings are the domain of a dendrohydrology, a subfield of dendroclimatology. The impact of moisture availability on ring widths has long been known and studied (Zahner, 1968). Dendroclimatology proper uses tree-ring widths to model and reconstruct precipitation (e.g. Buckley et al., 2004). Dendrohydrology uses tree-ring widths to understand and reconstruct past conditions of streamflow, flood events, droughts, groundwater flows and snowpack (Loaigica et al., 1997; Pederson et al., 2013; Woodhouse, 2003). The relationship between trees and past hydrological phenomena goes beyond ring-width measurements alone. They also contain hydrological information in their wood density, stable oxygen isotopes and scarring (Au & Tardif, 2012; Boucher et al., 2011; Payette & Filion, 2010). In northeastern North America, only a handful of studies have taken advantage of the potential to create annual or sub-annual reconstructions of streamflow from tree-rings, but they have been very successful (Cook & Jacoby, 1977; Cook & Jacoby, 1983; Devineni et al., 2013; Nicault et al., 2014; Pederson et al., 2013).

2.4 Northeastern North America and tree-ring chronologies

Contrary early researchers' expectations, northeastern North America has been found to be suitable for dendroclimatological research. Early works suggested that the dense closed-canopy eastern forests would not be clearly controlled by climate to the same degree as in southwestern North America and that isolating the effects of climate might be infeasible (Fritts, 1976; Phipps, 1982). However, the viability of dendroclimatology in the closed canopy forests of eastern North America was proven by

Cook & Jacoby (1977; 1983) in their reconstructions of streamflow and droughts in New York State and Maryland. The statistical methods to extract a climate reconstruction from these trees are more challenging, but the techniques do exist and are reproducible (Cook, 1976; Cook & Peters, 1981). Graumlich (1993) found that climate was an important factor influencing the radial growth of 11 northeastern tree species growing at sites not traditionally perceived to be highly limited by climate. Pederson et al. (2013) demonstrated 13 species as useful in creating a well-replicated 500-year-long hydroclimatic reconstruction for New York State, including several rarely used species. Further north in Québec, Tardif et al. (2001) observed strong correlations between the growth of deciduous and coniferous species, and similar sensitivity to precipitation across species. In northeastern North America there are 13 tree-ring records longer than 500 years, the majority of which are either in the boreal forests or at the Arctic treelines of Québec (Payette & Filion, 2010). The longest tree-ring chronology in eastern North America is from black spruce (*Picea mariana)* at a northern tree-line site in Quebec, extending almost 2000 years in the past (Payette & Delwaide, 2004). Hence, with Cook and Jacoby's pioneering methods as foundation, many studies of climate and tree rings have successfully produced reconstructions in the closed canopy forests of the eastern continent.

Dendroclimatological studies in high latitudes, such as those in Québec, entail additional challenges for long sensitive tree-ring chronologies. In the boreal forests, there are few species with a long lifespan and conditions are more conducive to high-fire frequency and less conducive to the preservation of deadwood (Delwaide & Filion, 1999). Other threats to longevity in eastern boreal North America are eastern spruce budworm (*Choristoneura fumiferana*) epidemics, as well as extensive forestry (Bergeron et al., 1998). An important issue of climate reconstructions from northern forests is the 'divergence problem': a reduction of warm temperature signals of northern tree-ring chronologies since the 20th century (D'Arrigo et al., 2008). This complex issue further complicates the study of the Medieval Warm Period and causes a skewing of reconstruction results. Nevertheless, researchers have created long chronologies in the northeast region, particularly with black spruce (Payette & Filion, 2010). Methods such as using light rings as marker years have improved the feasibility of long black spruce chronologies in northern regions (Arseneault & Payette, 1997). A light ring is the result of a year with an abnormally short growing season, diminishing the amount of the dark, dense, late growing season growth (Filion et al., 1986). Climate signals from these black spruce chronologies in the north can be particularly site dependent (Payette et al., 1989), but have been found to generally be limited by winter and spring climate (Nicault et al., 2014). Deadwood preserved in peat bogs and in lakes have extended chronologies back to 184 BCE (Payette & Filion, 2010), showing that in northern regions, under the right conditions, tree ring chronologies can be comparable with the oldest chronologies in western North America.

Eastern white cedar (*Thuya occidentalis*) is a notable species for dendrochronology in northeastern North America because of its lifespan and climate sensitivity. The species has the longest lifespan of the North American boreal forest living well past 500 years at some locations and is second only to the bald cypress in lifespan in eastern North America (Payette & Filion, 2010; Kelly et al., 1994). Eastern white cedar chronologies are observed to have varying and complex climate sensitivities across their distribution (Archambault & Bergeron, 1992; Tardif & Stevenson, 1997; Buckley et al., 2004; Pearl et al., 2017). Some studies observe that the species tends to have a significant negative climate response to temperature and a positive response to early summer rainfall, even at sites 1000 km apart (Payette & Filion, 2010). Studies suggest that the species may have a consistent response to climate across the ecotone of the Québec's boreal forest (Payette & Filion, 2010; Tardif & Bergeron, 1997). The longest eastern white cedar chronology, in western Québec, spans from AD 1186 to AD 1987 and demonstrates a significant inverse relationship to a regional drought index, in addition to the response considered common of eastern white cedar stated above (Archambault & Bergeron, 1992). In southern Ontario, the rocky cliffs of the Niagara Escarpment protect the oldest known eastern white cedars, growing both in normal arborescent form as well as rare stunted, bonsai-like cedars (Kelly et al., 1994). The Niagara Escarpment tree-ring chronologies show a sensitivity to summer precipitation (Buckley et al., 2004). Eastern white cedar tree-ring chronologies have potential to extend even further back in time as its wood can be preserved in anaerobic conditions for at least 1000 years (Glaz et al., 2009)

There is potential for further development of eastern white cedar chronologies in southern Québec. A relatively long chronology dating back to AD 1404 was developed using an eastern white cedar stand at the base of Mont Albert (Cook, 1994a). However, Cook did not have a sufficient sample depth and the site was never successfully resampled, nor calibrated to instrumental climate records (Arseneault et al., 2013; Maxwell et al., 2011). Despite this, the chronology was used in a large northern hemispheric temperature reconstruction in support of a signal of increased temperature (D'Arrigo et al., 2006). Deadwood was not sampled at the site and its exact location was lost. If the site could be found again, a chronology could be properly developed and its relationship with temperature and hydroclimate records ascertained.

Besides black spruce and eastern white cedar species**,** there are a few useful notable species used for dendroclimatology in northeastern North America. Although not as common as black spruce in climate studies, white spruce *(Picea glauca)* is an abundant species in the boreal forest and has proven to be sensitive to spring and summer moisture levels and temperature (Juday et al., 2012). Moisture-sensitive white spruce chronologies over 900 years in length have been developed in northwestern Canada(Szeicz & MacDonald, 1996). From the Québec City region, white pine (*Pinus strobus*) and eastern hemlock (*Tsuga canadensis)* chronologies demonstrate significant interspecies correlation from sites over 100 km apart and the Rivière-du-Moulin chronologies reach back past over 500 years (Payette & Filion, 2010). Cook (1994b, 1994c) also developed chronologies from 300-year-old eastern hemlocks in the temperate forests of Pennsylvania. Most temperate forest types are likely to have several species that can be used in dendroclimatology.

In conclusion, there is great potential for continued tree-ring based climate reconstructions for southern Québec, particularly in the Gaspésie interior, an accessible location that is relatively undisturbed by extensive forest cutting and clearing. Cook's sampling in the region demonstrates an old growth forest and a hemispheric temperature reconstruction shows that the trees in the region are likely sensitive to the climate (D'Arrigo et al., 2006; St. George, 2014)

3. RESEARCH QUESTION

In the protected ecosystem of the *Parc national de la Gaspésie*, a potentially sensitive environment to early climate change, a knowledge of past moisture conditions is an important resource for understanding the regional environment. Instrumental records are relatively brief in the region and the baseline of past hydroclimatic conditions is unknown. Our aim is to investigate the following research question: is the hydroclimate of the Chic-Choc and McGerrigle Mountains of the Gaspésie more variable than suggested by the short instrumental records in the region?

The goals of this study are (1) to develop a tree-ring based reconstruction of past annual mean streamflow of the Sainte-Anne River, an important river passing through the *Parc national de la Gaspésie* and (2) to assess the context of the brief instrumental climate records using the streamflow reconstruction.

4. MANUSCRIPT

A 211-year River Reconstruction for the Chic-Choc and McGerrigle Mountains of the Gaspésie from Tree-rings

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4.1 INTRODUCTION

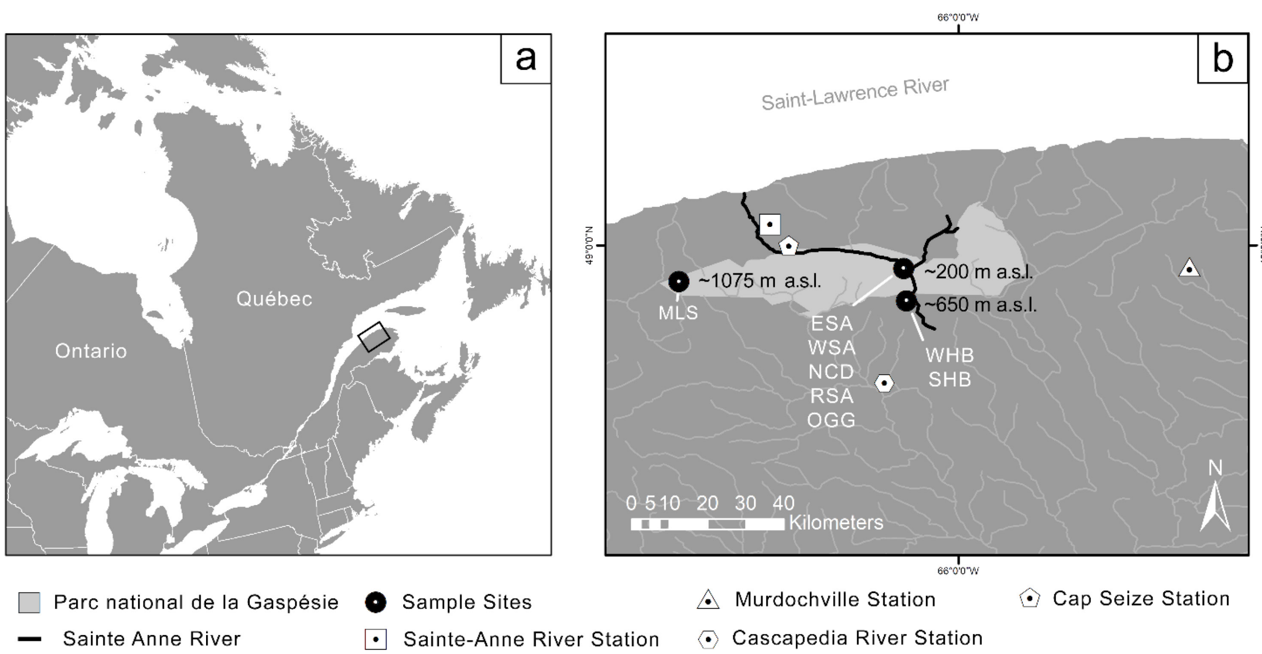
In most remote parts of Canada, both instrumental streamflow and climate data are of relatively short duration, spanning approximately 50 years in duration (Water Survey of Canada, 2020; Zhang et al., 2000). Barring annually laminated varved sediments, tree-ring reconstructions with their absolute dates are the only feasible way to infer streamflow and climate data of the past at an annual or sub-annual resolution in such places (Cook & Kairiukstis, 1990). Such inferred paleo-hydrological and paleo-climate data has proved useful for better natural resource management, providing a much-needed long-term context. Examples of such applications are the following: Woodhouse et al. (2006) reconstructed Upper Colorado River flows for the past five centuries. This reconstruction has been used by water managers to better manage scarce surface water supplies for the City of Denver and in the Colorado River Basin in the arid US Southwest (Meko & Woodhouse, 2011). Sauchyn et al. (2015) reconstructed Athabasca River flows at Fort MacMurray, Alberta, for the past nine centuries. This reconstruction gives a much-needed long-term context for the allocation of surface water for tar sands processing (Alberta Government, 2015). In remote northern Québec where instrumental data is of very short duration, Nicault et al. (2014) reconstructed two centuries of river flows at the Caniapiscau Reservoir, serving to inform water management at the La Grande hydroelectrical complex, the ninth largest in the world.

The objective of this manuscript is to produce streamflow and/or climate reconstructions based upon tree-rings for the mountainous interior of the Gaspé Peninsula, Québec, a region of southeastern Québec where the instrumental records are particularly short and sporadic. Although sparsely populated, the interior of the Gaspésie contains important wildlife refuges and forestry and fishery resources, hence having longer streamflow and/or climate records to serve as baseline references would be an important tool in the sustainable management of these refuges and resources. This is particularly true given that alpine regions such as the interior Gaspésie are expected to be affected soon and hard by anthropogenic climate change (Pauli et al., 2007; Malanson et al., 2011; Gottfried et al., 2012), hence any additional management tools are useful.

4.2 STUDY AREA

The study area is located 700 km northeast of Montréal in the Gaspésie region of Québec (48°56′00″N, 66°14′00″W). The Gaspé Peninsula juts into the Gulf of St. Lawrence and consists of high summits and deep valleys surrounded by steep coastline. It is formed by the northernmost part of the Notre-Dame Mountains, an extension of the Appalachian Mountains. Our sample sites are approximately 20 to 30 km inland from the northern coastline in the mountainous interior. At the intersection of the Chic-choc and the McGerrigle Mountains – two ranges within the Notre-Dame complex - lies the Sainte-Anne River Valley which runs north-south. The *Parc national de la Gaspésie* (PNG) covers an area of 802 km² in the interior of the Gaspé Peninsula (Figure 1), an area that triples in size when including the adjacent fauna reserves and controlled exploitation zones, which have lesser levels of protection. These wildlife reserves and the PNG protect a large part of the region characterized by white birch (*Betula papyrifera*) / balsam fir *(Abies balsamea*) boreal forest (82% of PNG area), white spruce (*Picea glauca)* / balsam fir forest at the sub-alpine level (13%) and sensitive upper alpine tundra environments (5%) (Gagnon, 1970; Grandtner, 1966; Ouellet et al., 1996). The peninsula's river valleys are important Atlantic salmon spawning grounds, and the mountains shelter rare endemic alpine plants and the last population of caribou south of the Saint Lawrence River. The summits within the park are among the highest in eastern Canada, including Mont Jacques-Cartier (1268 m) and the serpentine massif of Mont Albert (1151 m).

The climate regime of the Gaspésie is varied, as it is significantly affected by the mountainous landscape and the surrounding Gulf of Saint Lawrence and Atlantic Ocean (Figure 1) (Fortin & Hétu, 2014; Hétu & Gray, 2000). The annual climate averages in the Gaspésie are 0 to 3.2 °C at sea level along the peninsula's coast and range from -4 ºC in the highest interior alpine regions, to 3 to 5 °C warmer in the subalpine forests (Environment Canada, 2020a; Fortin & Hétu, 2009; Gagnon, 1970). The range in precipitation is also great, varying from about 825 mm on the coast to about 1660 mm in the mountains, of which approximately 30 – 40% falls as snow (Fortin et al., 2017; MacDonald, n.e.). Snow accumulation in the region is some of the highest in eastern Canada, but is considerably varied due to strong winds and the local topography; winds at summits can exceed 180 km/hr (Hétu & Vandelac, 1989). Winter accumulation of snow can reach up to 300 cm in alpine areas but can drop to 60 cm at lower elevations (Environment Canada, 2020b; Gagnon, 1970). At the highest elevations snowmelt ends only in June or July, while at lower elevations, the ground can be snow-free as early as April (Ouellet et al., 1996). The region's range in elevation, proximity to the coast and difficult terrain make for a high



spatial variability of temperature, precipitation and snow cover conditions, even within the mountains.

Figure 1. (a) The study site location and (b) the interior Gaspé Peninsula, showing sample sites and their average elevations, instrumental data sources and Parc national de la Gaspésie (PNG) boundaries.

4.3 METHODS

4.3.1 Tree-ring data

Three conifer species were sampled: eastern white cedar (*Thuja occidentalis* L.), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenburg), and white spruce (*Picea glauca* (Moench) Voss), from eight sites in and adjacent to the PNG during the Julys of 2017, 2018 and 2019 (Table 1 and Figure 2). Five sites, WSA, ESA, NCD, RSA, and OGG, are eastern white cedar sites in the PNG, with long-lived cedars, potentially allowing long reconstructions (Figure 1). Semi-open canopied WSA, ESA and NCD are located in mixed forests on steep cliffs along the Sainte-Anne River and its tributary, the Northeast Sainte-Anne River. Open-canopied RSA is a pure cedar stand located on a small island where the Northeast Sainte-Anne River joins the mainstem Sainte-Anne River. OGG is a closed-canopy old growth cedar grove at the base of Mont Albert which was possibly previously sampled by Cook (1994a) in 1981 (Figure 2a). OGG is a site with a high density of old cedars. Semi-open canopied SHB and WHB are moisture-stressed black spruce sites located on Mont Hog's Back, outside the south-eastern limit of the PNG in the *Réserve faunique des Chic-Chocs.* Here, stunted black spruce krumholtz dominates the upper south- and west-facing steep slopes in large patches growing over a substrate of scree (Figure 2b). Semi-open canopied MLS was a stunted mixed white spruce and balsam fir forest located at tree-line on the west-facing slope of Mont Logan in the eastern PNG, an accessible mountaintop known to have some of the highest snow levels in Quebec, hence potentially containing a good signal of the local snow-dominated hydrology.

Table 1. Characteristics of the eight sampling sites from the *Parc national de la Gaspésie* (PNG).

Site	Species	Location	Elevation
West Sainte-Anne (WSA)	*Thuja occidentalis*	48.946275 N 66.126176 W	200 m
East Sainte-Anne (ESA)	*Thuja occidentalis*	48.952816 N 66.128976 W	200 m
North of *Centre de Découverte* (NCD)	*Thuja occidentalis*	48.947806 N 66.119583 W	200 m
Island in Sainte-Anne River (RSA)	*Thuja occidentalis*	48.987361 N 66.948306 W	195 m
Old Growth Grove (OGG)	*Thuja occidentalis*	48.946371 N 66.126260 W	205 m
South Hog's Back (SHB)	*Picea mariana*	48.848624 N 66.106088 W	615 m
West Hog's Back (WHB)	*Picea mariana*	48.850056 N 66.108389 W	695 m
Mont Logan Summit (MLS)	*Picea glauca*	48.891460 N 66.644171 W	1075 m

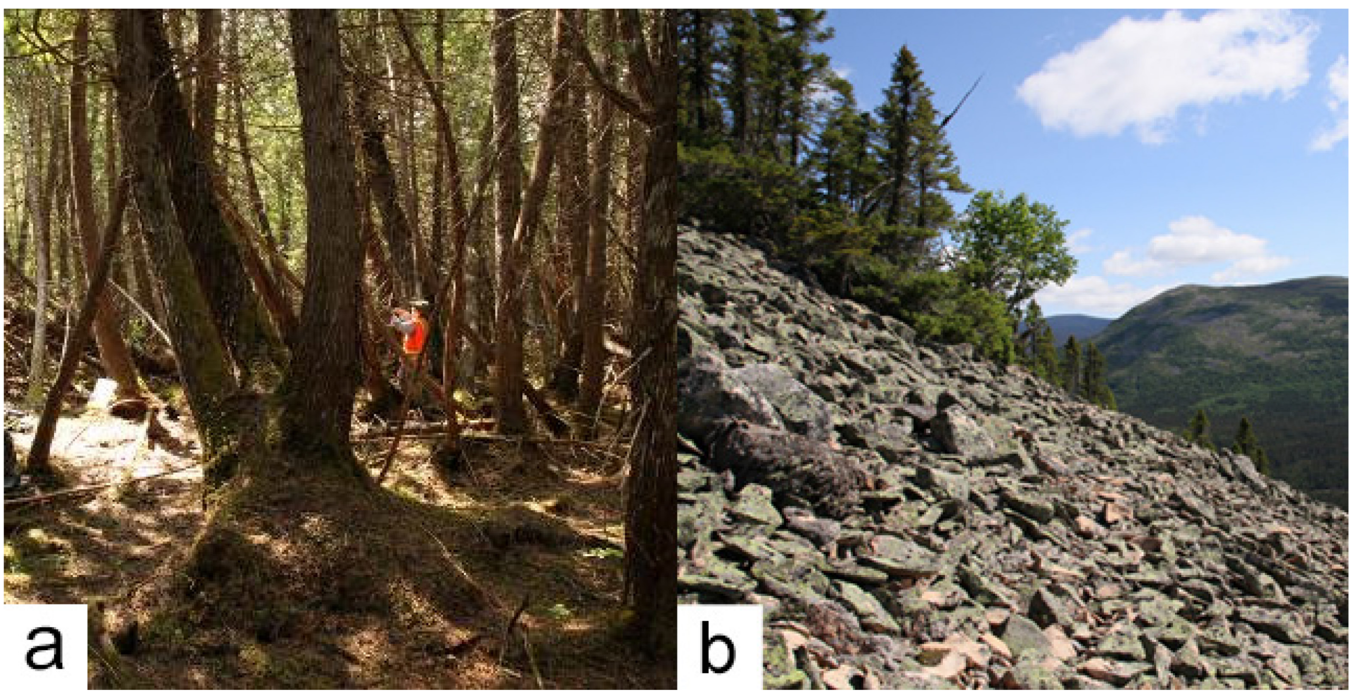


Figure 2. (a) The old growth cedar grove (OGG), and (b) the dry scree slopes of South Hog's Back (SHB).

At each of the eight sites, live trees were sampled according to standard dendroclimatological methods using Pressler increment borers to take two 0.5 cm diameter cores, at cross-slope position when needed (Speer, 2010). Dead wood lying on the ground at each site was sampled as 10 cm cross-sections with handsaws or electric reciprocating saws. Increment borer samples were mounted and all samples, including cross sections, were progressively sanded using 120, 220, 360, 480, 600 and 800 grit sandpaper. Samples were scanned at 2400 dpi resolution and annual ring-widths were measured using WinDendro®. On dead wood cross-sections, two transects were measured if possible. Samples were cross-dated with the aid of COFECHA (Holmes, 1983), which was also used to calculate series intercorrelation, mean sensitivity and first order autocorrelation for each site chronology.

After measurement and cross-dating, each tree-ring width series was standardized to remove the non-climatic effects of growth and forest dynamics using ARSTAN (Cook & Holmes, 1990). A conservative flexible cubic smoothing spline of 50 years with a 50% frequency cutoff was used on all series (Tardif and Bergeron, 1997; Tardif et al., 2001). For each site, standardized and residual chronologies were made by averaging all the standardized and residual ring-width series, respectively, from the location using the biweight robust mean (Appendix C) (Cook & Holmes, 1999). The variance in the mean chronologies was stabilized using methods described by Osborn et al. (1997), as well. An expressed population signal (EPS) of 0.85 was used to truncate the chronologies (Figure 5), ensuring that sample depth was sufficiently high so as to contain a stand-level signal (Wigley, 1984).

To better understand the relationship between tree-ring growth and local streamflow and climate, we calculated bootstrapped correlation coefficients between the residual chronologies from ARSTAN and the mean monthly streamflow and temperature and precipitation data using TreeClim (Zang & Biondi, 2015). These residual chronologies were used from all sites because the mean annual flows of the target river and other climate variables do not contain any autocorrelation. The instrumental record that was most consistently significantly correlated to the tree-ring chronologies was chosen for reconstruction.

Forward stepwise multiple linear regression (MLR) was used to model the relationship between the predictand (the instrumental data) and the chronologies (the predictors) using the GEOSA package in Matlab® (Dr. David Meko, Laboratory of Tree Ring Research, University of Arizona). As predictors , we explored prewhitening either the individual series and then averaging these series to form a residual chronology (the usual ARSTAN approach; Cook, 1985) or taking the averaged standardized chronologies from ARSTAN and then prewhitening them (Meko et al., 1993; Meko & Graybill, 1995). Predictors were lagged ± 2 years. Because of the short length of the available instrumental data, the validity of the MLR models was evaluated with leave-five-out cross-validation (Michaelsen, 1987). We used the F-statistic, R^2, R^2_{adj}, root-mean-square-errors of calibration ($RMSE_c$) and validation ($RMSE_v$), reduction of error (RE) and residual plots to evaluate the similarity between the models and the calibration period instrumental data. To guide the selection of skillful and parsimonious MLR models, we used the minimization of $RMSE_v$ (equivalent to the maximization of RE) as the stopping rule for the number of predictors. To guard against overfitting, we ensured that the distance between $RMSE_c$ and $RMSE_v$ was minimal for each model (Wilks, 2006). For each model, we guarded against multicollinearity by checking that the variance inflation factor (VIF) was less than 10.

To extend the length of the reconstruction, we then nested successive "best" fit models backward in time. This was done by successively dropping any chronologies from the predictor pool that did not extend further back in time than the predicted values of the current fitted model. This longer set of chronologies was then used to extend the next model further backward in time. This procedure of nesting successively longer reconstructions by fitting the best model and then removing any reconstruction length-limiting chronologies was repeated until $R^2_{adj} < 0.35$, which we used as our threshold of model skill.

Because a regression reconstruction inherently underestimates the variability of the past due to a certain amount of unexplained variance in each regression model, we adapted the standard approach

(Lutz et al., 2012; McCarroll et al., 2015; Martin et al., 2019) of restoring variance in a nested reconstruction by scaling the mean and variance of each progressively longer and less skillful model to match that of the best model over the period common to the two. We then similarly scaled the fully nested reconstruction to the target streamflow record over the calibration period of the best model. This approach maximized the length of record over which variance loss in progressively weaker models could be assessed and scaled the full nested reconstruction to the target record using the estimates of the best reconstruction model.

4.3.2 Instrumental streamflow and climate data

Instrumental streamflow and climate data from the study region are needed to determine which instrumental variables are suitable for reconstruction using the tree-ring chronologies. Data for the region is relatively limited because of the closure of several provincial streamflow gauges and several national weather stations since the 1960s, as well as significant portions of missing data in the records available (Fortin & Hétu, 2013). We retrieved instrumental records from two main sources: (1) mean monthly and annual streamflow (m^3/s) for the Sainte-Anne River, a major river in the PNG, and (2) temperature (ºC) and precipitation (mm) records from Murdochville, Québec (Figure 1) (Fortin et al., 2017).

The Sainte-Anne River gauges (# 021405 and # 021407) have a combined period from 1968 to present (*Centre d'expertise hydrique du Québec*, 2020). Gauge # 021407 is active and its record spans 1971 to 2018. Gauge # 021405 is closed, spans 1968-1975 and is located 1.3 km downstream of Gauge 021407. The flow of # 021405 for 1969-1970 was scaled by basin area and added to that of # 021407, extending that record. This gave a continuous water year record from 1969-2018, covering 49 years. Both gauges are located in a relatively undisturbed area outside of the PNG. Murdochville is a former copper mining town with an elevation of 574 m located 40 km east of the park limits and is one of the few interior communities and the only interior climate station. The meteorological records span from 1952 to 2017 (Environment Canada, 2020c; Fortin et al., 2017; Info-Climat, 2020).

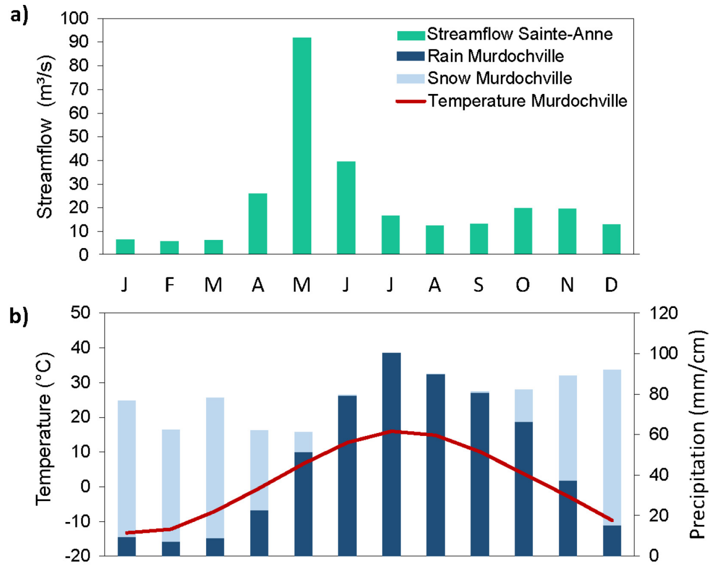


Figure 3. Mean monthly values of streamflow (m^3/s) for the Sainte-Anne River 1969-2018, and mean monthly temperature (°C) and precipitation, partitioned into total snow (cm) and total rain (mm) for the Murdochville station for 1953-2018.

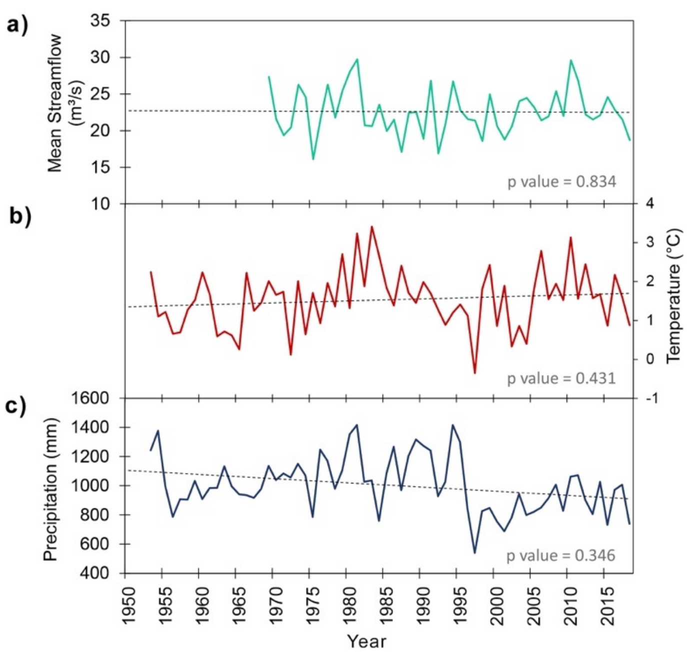


Figure 4. Plots of the (a) Sainte-Anne River mean annual water year flows (m^3/s), (b) Murdochville mean annual temperatures (°C), and (c) Murdochville precipitation (mm) records. The dotted lines show ordinary-least-squares trend lines together with their significance level.

4.4 RESULTS AND DISCUSSION

The majority of streamflow is the result of spring snowmelt between March and June, supplemented by important snowfall in March (Figure 3). The peak month of precipitation is in July. The monthly averaged temperature and precipitation records are consistent with the seasonal patterns of the climate normals available from coastal stations in the region, with a slightly colder range of temperatures, and higher precipitation (Environment Canada, 2020c). The streamflow and climate records available for the study region show non-significant annual trends. This may be a consequence of their short time span, in particular for the Sainte-Anne streamflow record (Figure 4); however Fortin and Hétu (2010; 2013) note a surprising lack of long-term trends in the region. The annual mean values of the climate data show no significant first order autocorrelation in one-tailed autocorrelation function tests.

The chronologies separate into two groups: the lowland eastern white cedar valley chronologies and the spruce alpine chronologies (Tables 1 and 2). All the five eastern cedar chronologies are in close proximity to the Sainte-Anne River, at an elevation of approximately 200 m (Table 1, Figure 1). The longest cedar chronologies are ESA and OGG, with a total length of 456 and 430 years, respectively. At OGG, the samples have the highest mean sample length, 215 years, of all the sites. As a result, all but the earliest 62 years demonstrated enough replication to be included in the reconstruction (Figure 5). The long timespan of ESA (1560-2017) is due to two cliff samples that were anomalies at the site. Here, the mean sample length of 149 is not substantially higher than the inter-site mean length of 122 years. Similarly, the three other river valley cedar sites have mean length values close to the inter-site mean (Table 2), with low replication before AD 1800-1850 (Figure 5). The mean series intercorrelation across all sites is 0.459. The series intercorrelation is reasonably consistent from site to site, with the exceptions of the highest value at OGG and the lower values at the two exposed Mont Hog's Back sites which contained difficult to cross-date krummholz (Table 2). The alpine sites are distinguished from the valley sites by their shorter mean sample lengths and higher mean sensitivities. White spruce at MLS have much more homogenous growing conditions than the black spruce at SHB and WHB, as shown by a lack of EPS cut-off (Figure 5) and higher series intercorrelation (Table 2). The descriptive statistics at these sites are similar to those of other studies involving boreal tree species in northeastern North America (Au & Tardif, 2011; Hofgaard et al., 1999; Tardif et al., 2001).

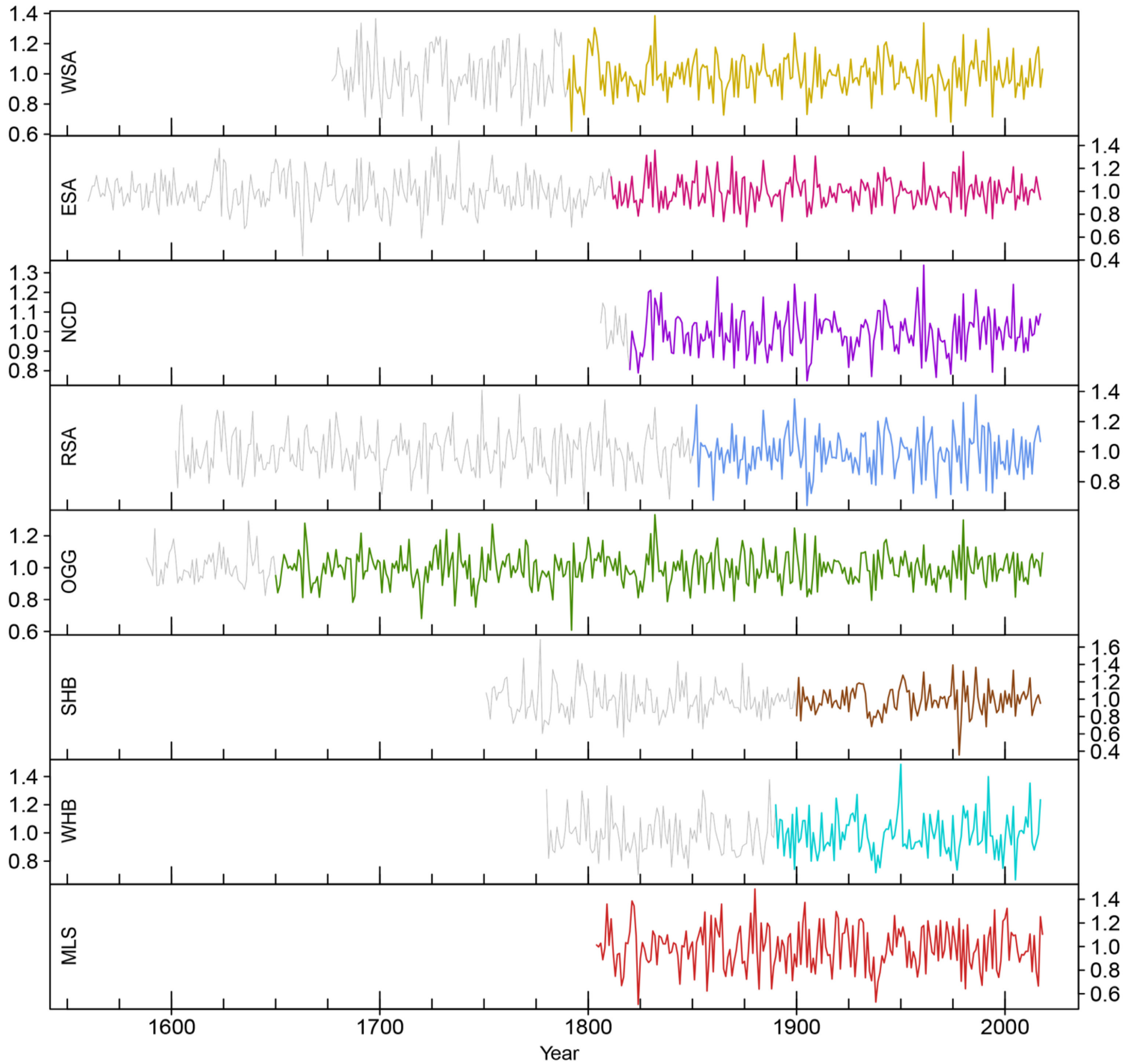


Figure 5. Residual tree-ring chronologies from ARSTAN from the eight sites from the *Parc national de la Gaspésie* (PNG) and its environs. Shown in color are the chronologies after the 85% EPS-cutoff. Shown in grey are the chronologies prior to the EPS-cutoff. Site codes following Table 1.

Table 2. Descriptive statistics from COFECHA's standardized chronology. Series intercorrelation statistics are based on overlapping 50-year segments. Mean length denotes mean sample length in the chronology.

Site	Number of cores	Span	Series intercorrelation	Mean sensitivity	1^{st}-order autocorrelation	Standard deviation	Mean length
WSA	99	1677-2018	0.453	0.176	0.57	0.378	155
ESA	46	1560-2017	0.435	0.179	0.35	0.403	149
NCD	85	1806-2017	0.473	0.194	0.48	0.474	109
RSA	70	1602-2018	0.514	0.189	0.23	1.678	133
OGG	368	1588-2017	0.533	0.171	0.33	0.226	215
SHB	73	1751-2017	0.409	0.282	0.67	0.258	96
WHB	79	1780-2017	0.375	0.284	0.57	0.246	78
MLS	79	1804-2018	0.477	0.297	0.57	0.249	95

The chronologies contain an effective moisture signal integrated over the watersheds of the PNG, as shown in Table 3. For six of the eight residual chronologies, TreeClim shows significant negative correlations between the residual tree-ring chronologies and June Sainte-Anne River flows (Table 3a). One of the two exceptions, SHB, shows instead a negative correlation between tree-ring widths and May Sainte-Anne River flows. The remaining exception, ESA, shows a high non-significant negative correlation between tree-ring width and June Sainte-Anne River flows (results not shown). There are scattered significant positive correlations between tree-ring width and August and September Sainte-Anne River flows for ESA, WSA, NCD, RSA and SHB.

Hence, when the Sainte-Anne River flow is high during the peak annual flow from snowmelt, annual tree-ring widths are narrower. When the Sainte-Anne River has relatively lower spring meltwater floods, the annual tree-ring widths are wider. The Cascapedia River, which drains the southern part of the Gaspé Peninsula, has a very similar pattern of correlations between its monthly flows and the residual tree-ring chronologies (Appendix A), particularly the significant negative correlations in June. The discontinued Cap Seize precipitation record (1935-1985) on the coast north of the PNG also has a related pattern of correlations between its monthly summed precipitation and the Sainte-Anne River Valley residual tree-ring chronologies: significative negative correlations with April precipitation (Appendix A). We interpret all of this as the trees capturing a snowpack volume signal: when snowpack is higher and remains on the ground longer, the Sainte-Anne June monthly flow coinciding with snowmelt will tend to be higher, as will the Cap Seize April snowfall (Figure 3). When snowpack is higher and remains on the landscape longer, it shortens the initial part of the growing season which determines tree-ring width (Brubaker, 1980; Deslauriers et al., 2010; Duchesne et al., 2012; Gedalof et al., 2004; Huang et al., 2010; Kirdyanov & Hughes, 2003; Lutz et al., 2012; Peterson & Peterson, 2001; Sanmiguel-Vallelado et al., 2019). Tree-ring growth can be negatively impacted by the delay of warm soil temperature since the soil warms only after snowpack is melted (Kirdyanov et al., 2003; Vaganov et al., 1999; Watson & Luckman, 2016). Several conifer species initiate growth of leaves and roots only after snow cover has melted (Hansen-Bristow, 1986; Worrall, 1983). Eastern white cedar can initiate growth as late as early June in mid-western Québec (Denneler et al., 2010). Depending on the season and moisture conditions, the snowpack-growth relationship varies. Snow accumulation too early in the autumn may negatively affect the next year's growth by inhibiting carbohydrate storage (Camarero et al., 2015; Carlson et al., 2017 Helama et al., 2013), explaining the negative relationship between tree-ring growth and streamflow in the previous year's October for RSA and WSA. It is true that in some cases a positive spring snowpack growth relationship can be observed such as in drought prone stands in western North America (Woodhouse, 2003; Pederson et al., 2011; St George, 2014). However, in the moist Gaspésie, the relationship appears negative.

The inconsistent late summer significant positive correlations between the Sainte-Anne River's (and Cascapedia River's) monthly flows and the chronologies suggest that even this relatively wet environment in the PNG can become water-stressed at the end of the summer (Table 3a and Appendix A). Here trees are showing increased tree-ring widths in response to late summer precipitation, which the monthly streamflows are reflecting with a short temporal lag. However, this response is much weaker and scattered and occurring at the time of year when streamflows are lower. Therefore, even though this relationship counteracts the strong negative relationship between tree-rings and May-June river flows, because flow in May-June forms such an important percentage (54%) of the total annual Sainte-Anne flow in this snow-melt dominated hydrological system, the chronologies adequately capture total annual flow with their negative relationship.

Table 3. (a) Summary of Sainte-Anne streamflow correlations with the residual chronologies. (b) Summary of Murdochville, Québec, temperature correlations with the residual chronologies. Correlations done in R with TreeClim and a 0.05 significance level. Note: (p) denotes previous year.

a)

	WSA	ESA	NCD	RSA	OGG	SHB	WHB	MLS
pAPR								
pMAY								
pJUN								
pJUL						+		
pAUG						+		
pSEPT								
pOCT	–			–				
pNOV								
pDEC						+		
JAN								
FEB			–					–
MAR								–
APR								
MAY						–		
JUN	–		–	–	–		–	–
JUL								
AUG		+	+				+	
SEPT	+			+				

b)

	WSA	ESA	NCD	RSA	OGG	SHB	WHB	MLS
pAPR								–
pMAY								
pJUN								
pJUL								
pAUG		–			–			–
pSEPT			+					
pOCT			+					
pNOV		+					+	
pDEC								
JAN								
FEB								–
MAR	–	–	–	–				
APR								
MAY					+			
JUN						–	–	
JUL								
AUG	+		+	+				
SEPT								

Unlike the correlations between May-June Sainte-Anne River flows and the chronologies which demonstrate a consistent common moisture signal across a broad geographic area, correlations between tree-ring widths and Murdochville mean monthly temperatures does not show such a common pattern for temperature response (Table 3b). There is a pattern of negative correlations between tree-ring widths and winter mean temperature in the valley of the Sainte-Anne River and Mont Logan, potentially due to the loss of protective snowpack since insufficient snowpack in the winter season may cause premature damage to conifers (Fritts, 1976; Frey, 1983; Wood & Smith, 2013). This also corresponds with the negative relationship between late winter streamflow and tree-ring width for MLS as higher flows at this time could be due to snowmelt from warmth, causing damaging exposure to the tree's roots. It also corresponds with the positive correlations between the Sainte-Anne River Valley chronologies and February and March Cap Seize precipitation, with more precipitation meaning more protective snowpack (Appendix A). There are positive correlations with August mean temperature at the low elevation sites in the Sainte-Anne River Valley (WSA, NCD, and RSA, which are all close together). But this pattern does not extend to the equally close by ESA and OGG sites, nor to the mid- or high-elevation sites (SHB, WHB and MLS). This leads us to conclude that our chronologies are primarily responding to late winter-early spring snowpack quantity, and not temperature. Of course, spring temperature will affect snowpack melt. However, if spring temperature was important in this system, we would expect to see positive correlations between tree-ring widths and April, May and June monthly temperatures. But we do not (with the exception of OGG), hence we conclude that the most important factor is snowpack quantity, which directly translates into river water in this cold, low-evaporation climate. Therefore, these chronologies are suitable for reconstructing the flow of the Sainte-Anne River (Figure 6).

We are assuming that temperatures at mid-elevation Murdochville can adequately represent temperature in the PNG 40 km away, but temperature is a broad climate field similar over a wide geographical area, so this is a reasonable assumption. Correlations between tree-rings widths and Murdochville monthly precipitation showed no consistent patterns and are not considered further (Appendix A). This could be since precipitation is a highly variable, local field, particularly in the mountains. However, the Sainte-Anne streamflow gauge produces a better-integrated and more local measure of precipitation and evapotranspiration for our sites.

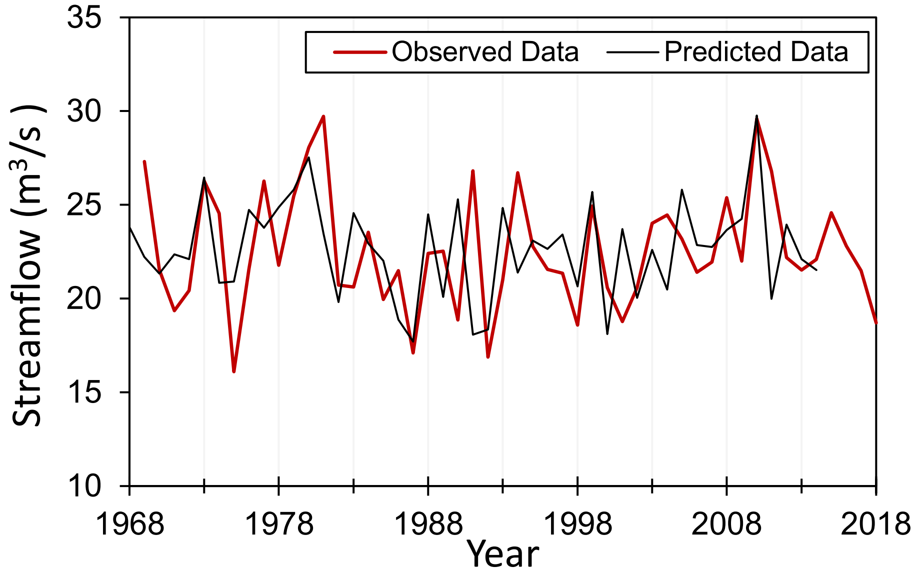


Figure 6. Calibration plot for the first nested reconstruction of the Sainte-Anne River mean annual water year flow. Shown are the 47 years of observed instrumental data from the *Centre d'expertise hydrique du Québec* gauges # 021405 and # 021407 and the tree-ring based reconstruction over their common interval 1969-2015. Variance scaling has not yet been applied to the reconstruction. See Table 4 for the reconstruction statistics.

Table 4. Statistics of the three nested reconstructions for the Sainte-Anne River water year mean annual streamflow spanning 1805-2015. *Subscript P# denotes a positive lag of length #, and subscript N# denotes a negative lag of length #.

Nested Recon #	**Predictors***	R^2	R^2_{adj}	$RMSE_c$	$RMSE_v$	***RE***	**Time span**	***F-stat. & (p-level)***
1	MLS, WSA, NCD_{N1}, ESA_{N2}, RSA_{N2}, WHB_{P1}, MLS_{P2}, OGG_{P2}, RSA_{P2}	0.61	0.52	2.296	2.612	0.36	1896-2015	6.43 (0.00002)
2	MLS, WSA, NCD_{N1}, ESA_{N2}, RSA_{N2}, MLS_{P2}, OGG_{P2}, WSA_{P2}	0.56	0.46	2.413	2.913	0.20	1855-2015	5.98 (0.00006)
3	MLS, WSA, WSA_{N1}, OGG_{N2}, WSA_{N2}, MLS_{P2}, OGG_{P2}, WSA_{P2}	0.48	0.37	2.615	3.060	0.12	1805-2015	4.38 (0.00081)

We explored various reconstruction methods, selecting among them by maximizing R^2_{adj} and *RE* and by minimizing $RMSE_c$ and $RMSE_v$ and their difference in order to optimize our models. Because the target mean annual stream flows contained no autocorrelation, we used prewhitened or residual chronologies as predictors. We explored as predictors prewhitening either the individual series and then averaging these series to form a residual chronology (the usual ARSTAN approach; Cook, 1985) or taking the averaged standardized chronologies from ARSTAN and prewhitening them (Meko et al., 1993; Meko & Graybill, 1995). We also explored using an untransformed versus a log_{10} transformed predictand. We found that prewhitened standardized predictors with an untransformed predictand worked best, producing the longest reconstructions with the highest R^2 and R^2_{adj}. Three progressively longer nested reconstructions with successively declining performance were fitted in this way (Table 4). The first nested reconstruction used nine predictors, spanned 1896-2015, and explained more than half of the observed variance in the instrumental data with $R^2 = 0.61$ (Figure 7). The second nested reconstruction used eight predictors, spanned 1855-2015, and explained more than half of the observed variance with $R^2 = 0.56$. The third nested reconstruction also used eight predictors, spanned 1805-2015, and explained a slightly less than half of the observed variance with $R^2 = 0.48$. All three models are skillful with $RE = 0.36, 0.20$ and 0.12, respectively. Although it is relatively distant to the Sainte

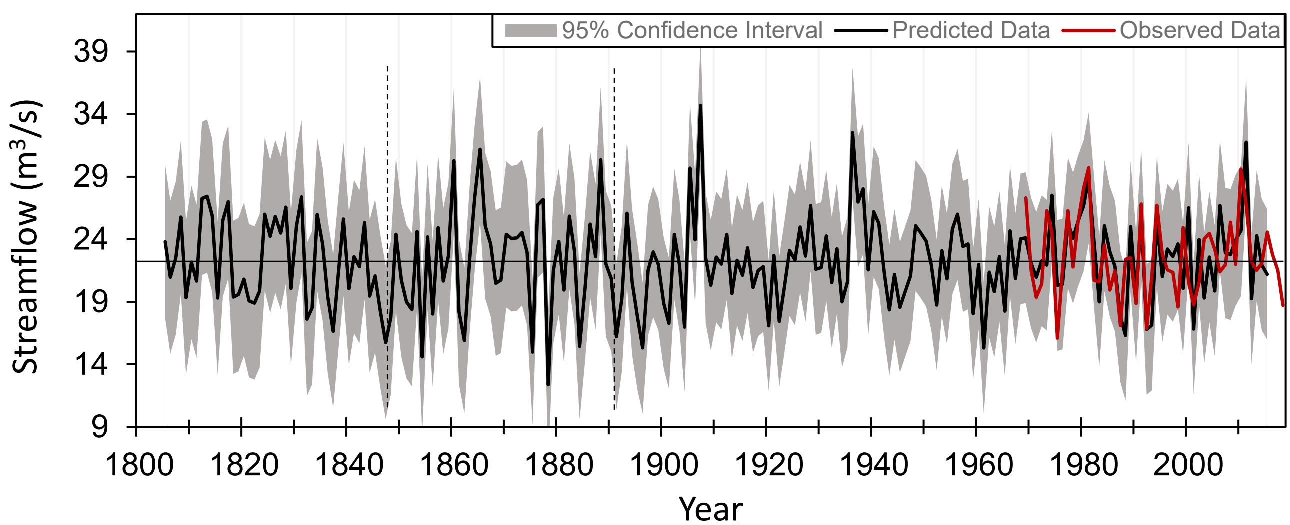


Figure 7. The nested high-frequency Sainte-Anne River, Gaspésie, water year mean annual streamflow reconstruction (m^3/s) (black) for 1805-2015, together with the instrumental flow record (red) and the 95% confidence intervals from the RMSEv (grey). Dashed vertical lines denote the changes from one nested reconstruction to the next. The thin black horizontal line shows the reconstruction mean.

Anne watershed, the Mont Logan site (MLS) is a prominent predictor in all nested reconstructions. It seems to be a sensitive site to snowpack quantity. Arid WHB is another highly sensitive site, but unfortunately, it is of short length. Although the number of predictors used is relatively high, it is not uncommon (Meko et al., 1980; Meko & Graybill, 1995; Martin et al., 2019) and we controlled for overfitting by ensuring that $RMSE_v$ is not much greater than $RMSE_c$ (Wilks, 2006). Lastly, as the final step in producing the full Sainte-Anne reconstruction, we scaled the nested reconstruction variance and mean to be the same as those from the instrumental data over the calibration interval 1969-2015, as the raw reconstruction does not produce the full range of observed data, as is typical of regression-based approaches (Figure 7) (Lutz et al., 2012; McCarroll et al., 2015; Martin et al., 2019).

The completed Sainte-Anne River reconstruction spans 1805-2015 (Figure 7). The reconstruction demonstrates that the short instrumental record for 1969-2018 does not capture the full range of natural variability of this river system. The minimum recorded mean annual water year low flow was 15.8 m^3/s in 1987. Our tree-ring reconstruction shows that streamflow has been lower on seven occasions: in 1847, 1854, 1875, 1878, 1884, 1896 and 1961. The maximum recorded mean annual water year high flow of 33.6 m^3/s in 2011 has been exceeded once in 1907, although it is known that tree-ring based river reconstructions have difficulty in capturing high flows (Fritts, 1978), but perhaps not in all cases (Pederson et al., 2013). The instrumental record of 49 years shows only one occasion when streamflow has remained below the instrumental mean of 22.6 m^3/s for four or more successive years: 1985-1988. This gives a false impression of how long the Sainte-Anne River can have below-mean flows for successive years. Our 211-year reconstruction shows six periods of below-instrumental-mean flows for four or more successive years (the longest below-instrumental-mean flow period in the instrumental record): 1818-1823 (6 years), 1844-1848 (5 years), 1889-1892 (4 years), 1894-1897 (4 years), 1917-1920 (4 years), 1942-1947 (5 years) and 1959-1963 (5 years). Hence, having the longer perspective of the tree-ring-based reconstruction shows that the Sainte-Anne River is more susceptible to prolonged periods of below-mean flows than previously appreciated, based upon the short instrumental gauge record. Although reconstructing pluvial periods is more challenging using tree-rings, our reconstruction shows six periods of above-instrumental-mean flows for four or more successive years: 1824-1828 (5 years), 1870-1873 (4 years), 1905-1908 (4 years), 1924-1928 (5 years), 1955-1958 (4 years) and 1977-1982 (6 years).

The reconstruction shows the high-frequency changes in the river flow only. Because we had to use such a conservative detrending method to remove stand dynamics, we were unable to reconstruct low-frequency variability (Tardif et al., 2001). Hence there may well be low-frequency variability present in the streamflow that we are unable to detect. A phase shift in interannual variability occurred at 1908. Prior to this time, 1805-1907, interannual variability was much higher, particularly for 1860-1907, relative to 1908-1973 (*F-statistic* $= 2.02$, $df = 102, 65$, $p = 0.001$; *F-statistic* $= 2.75$, $df = 47, 65$, $p = 8.8 \times 10^{-5}$), respectively. Post 1908, interannual variability tended to be lower, particularly for 1908-1935. Starting circa 1974, interannual variability increased again. This later variability change is barely insignificant relative to 1908-1973 (*F-statistic* $= 1.53$, $df = 41, 65$, $p = 0.06$).

Our 211-year reconstruction is of comparable length to the only other annual streamflow reconstruction from Québec (Nicault et al., 2014). However, the two reconstructions are not simple to compare since the Nicault et al. (2014) reconstruction was expressly constructed to contain as much low-frequency variability as possible, whereas our reconstruction was by necessity a high-frequency one. That said, although only ~600 km separates the two study regions, the two reconstructions do not have much in common. Their reconstruction has low flows during the 1820s, 1850s, 1920-1950 and early 1960s; and high flows during the 1810s, 1840s, 1870-1890 and 1910s. The only commonalities between the extreme periods of the two reconstructions are the Sainte-Anne River low flows in 1942-1947 and 1959-1965, and its high flows of 1870-1873. Nicault et al. (2014) found that streamflow in the Caniapiscau region is strongly affected by the Arctic Oscillation.

Despite the greater geographical distance, our reconstruction from the Gaspésie in southern Québec shows more common hydroclimatic conditions when compared to the moisture reconstructions from the northeastern United States along the Atlantic Seaboard. One event captured in reconstructions from both regions is the mega-drought of 1962-1966 (Cook & Jacoby, 1977, Hudson River; 1983, Potomac River; Devineni et al., 2013, Delaware River; Pederson et al., 2013, Hudson River) which appears in our record as a period of below-mean flows for 1959-1965 (with a brief hiatus of mean flow for 1964). This 1960s period of low flow is noted as highly abnormal in the northeastern United States, and was unprecedented in at least the last 180 years (Cook & Jacoby, 1983; Pederson et al., 2013). Our reconstruction contains five periods before the 1960s of multi-year low flows which are common periods of low moisture availability in the northeast United States: 1818-1823 (in the Potomac, Delaware and Hudson Rivers), 1844-1848 (Delaware and Hudson Rivers), 1889-1892 (Delaware River), 1894-1897 (Potomac and Hudson Rivers), 1917-1920 (Hudson River), 1942-1947 (Potomac, Delaware and Hudson Rivers). Hence, the long-term perspective of dendroclimatology shows that the mechanisms for prolonged drought in northeastern North America act on a broad geographical scale. Our reconstruction also shows five periods of multi-year high flows which are also common periods of high moisture availability in the northeast United States: 1824-1828 (in the Potomac, Delaware and Hudson Rivers), 1905-1908 (Potomac, Delaware and Hudson Rivers), 1924-1928 (Potomac River), 1955-1958 (Delaware and Hudson Rivers) and 1977-1982 (Potomac River). However, with pluvials the commonality over the wider geographic region is not as broad as with droughts, reflecting the importance of local factors in generating precipitation. There is an unfortunate lack of hydroclimate reconstructions from New England proper which makes these comparisons more challenging.

Previous researchers have hypothesised that the eastern white cedars of the Sainte-Anne River Valley that were sampled by E. Cook (1994a) contain a temperature signal, without calibrating against actual instrumental climate data which are unavailable for their chronology given its end date (D’Arrigo et al., 2006). If their site is the same as our OGG (likely given the high correlation $R = 0.9$ between the two chronologies for their common interval of 1696-1982), then our results suggest that this site contains more of a moisture than temperature signal.

In northeastern North American forests, the climate-tree-growth relationship is varied and multi-faceted (Tardif et al., 2001) which makes dendroclimatology in this region challenging (but rewarding). This is made evident by studies eastern white cedar that have shown a positive growth response to July and August streamflow of the previous year in western Québec at Lac Duparquet (Tardif & Bergeron, 1997), to summer precipitation in southern Ontario on the Niagara Escarpment (Buckley et al., 2004), to July temperature northern Manitoba (Tardif & Stevenson, 1997) and to the late-fall temperature of previous year (Au and Tardif, 2012). The response of the cedars in our study do not match those observed in the species elsewhere (Archambault & Bergeron, 1991; Pearl et al., 2017; Tardif & Stevenson, 1997). Other Québec studies using black spruce krumholtz (Arseneault & Payette, 1997; Payette et al., 1985) are located near the limit of the northern treeline and contain a temperature record spanning the past two millennia, rather than a hydroclimate signal like ours did.

Our two-century long Sainte-Anne River reconstruction can serve as a resource for the management of the PNG. The PNG is part of a provincial network of protected areas committed to conserve notable ecosystems and their cultural significance across Québec. Our Sainte-Anne streamflow reconstruction gives a history of past high-frequency changes in flows, to which winter snowpack is closely linked. This provides a longer-term context of water variability than the short instrumental record, giving a pre-industrial baseline of moisture conditions. The Sainte-Anne River is an important Atlantic salmon spawning ground, the recreational fishery of which provides a significant part of the PNG's services and revenue. The occurrence of high and low flows in spawning rivers detrimentally affects salmon habitat availability and breeding success, as well as modifying sediment budget, increasing water turbidity and disturbing river beds (Armstrong et al., 2002; Heggenes et al., 1996). The context given by the streamflow reconstruction may allow for better modeling of streamflow projections and better assessments of the impacts of global warming on the local salmon fisheries. The mountains of the interior Gaspésie are also the last refuge south of the Saint Lawrence River for the critically endangered caribou population. Our reconstruction gives insight on past snow pack conditions, which have important implications on caribou feeding habits and calf survival, especially in the face of global warming (Bergerud & Page, 1986; Festa-Bianchet et al., 2009; Mosnier et al., 2003). Predators are expected to be a greater threat for these Gaspésie caribou as snow pack is expected to decline by the end of the 21st century (Bates et al., 2008), thus permitting predators to reach breeding grounds earlier in the season (Martin Hughes-Saint-Laurent, personal communication, May 2020; Ouellet et al., 1996).

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5. CONCLUSIONS

The intensity and patterns of moisture change over the next century in northeastern North America are uncertain, especially in mountainous areas. Our 211-year reconstruction of the Sainte-Anne River gives a baseline to the region's hydroclimatic conditions, a potentially useful tool for assessments of future ecosystemic response, natural hazard risks and resource planning, in the context of climate change. Our reconstruction joins the short list of hydroclimatic reconstructions in northeastern North America. It is confirmation that the forests of the Gaspésie mountains, at all altitudes, can show a common growth response to moisture and are indeed viable for reconstructing past hydroclimate conditions. The reconstruction presented here reveals multiple periods of prolonged low flow and high flow in the Sainte-Anne River over the past two centuries, of which only a single period of low flow (1985-1988) and high flow (1977-1982) were captured in the instrumental records. These results show that the relatively stable hydroclimatic variability recorded over past 49 years by the Sainte-Anne River streamflow gauge is not representative of the long-term variability in the region.

There are many future considerations for the tree-ring chronologies and sample sites presented here, beyond the scope of this thesis. Although similarities between the Sainte-Anne River reconstruction and the more northern reconstruction of Nicault et al. (2014) are limited, their study found significant correlations between tree-ring growth and both the North Atlantic Oscillation and the Arctic Oscillation. Thus, the relationship between our tree-ring chronologies and atmospheric pressure systems is worth exploring, especially given the significance of large teleconnection patterns to snowpack in the region (Fortin and Hétu, 2014). Regional temperature or precipitation indexes such as those developed by Fortin et al. (2017), can be used to further study the growth-climate relationships of these chronologies. This may reveal the potential for our chronologies to infer conditions over a wider geographical area than reconstructed in this study. We have evaluated correlation analyses between our tree-rings and two other instrumental datasets available in the region, and they show patterns consistent with our results (Appendix A). The results suggest that a reconstruction of the Cascapedia River should be explored because the Cascapedia streamflow records show correlations to site chronologies very similar to those of the Sainte-Anne River. Exploring the principle component regression technique of reconstruction would be well-suited here. Another potential exploration is dendronivology research at the Mont Hog's Back sites according to the techniques of Payette et al. (1985; 1989). Site observations during fieldwork and tree-ring dating revealed a shift in black spruce growth from supranival, cushion-like krummholz growth forms to arboreal growth in the 1970s, which may suggest changes in snowpack at this altitude. Finally, there is also the potential that alpine sites (at least those drier than Mont Logan) have a more defined relationship between tree-ring width and growing season temperature (Appendix B).

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APPENDIX A

Tables showing TreeClim correlations between the ARSTAN residual tree-ring chronologies and (a) Cascapedia River streamflow gauge # 011001+ # 011003 (1967 to 2016), (b) Cap Seize mean monthly precipitation (1935-1985) Environment Canada station # 7051175 and (c) Murdochville, Québec, mean monthly precipitation (1953-2018). The Cascapedia River gauge captures a very large river network south of the park (1480 km²), a watershed larger than that of the Sainte-Anne station (720 km²), but the river system is less prominent in the PNG and drains the south of the peninsula rather than the north. Cap Seize is a station just outside the northern edge of the PNG, much closer to the sites than Murdochville (Figure 1). Only precipitation data is available from it.

a)

	WS	ESA	NCD	RSA	OGG	SHB	WHB	MLS
pAPR								
pMAY								
pJUN					+			
pJUL								
pAUG						+		
pSEPT								
pOCT				–				
pNOV								
pDEC						+		
JAN								
FEB								–
MAR								–
APR								
MAY								
JUN	–	–	–	–	–		–	
JUL							+	
AUG	+			+				
SEPT							+	

b)

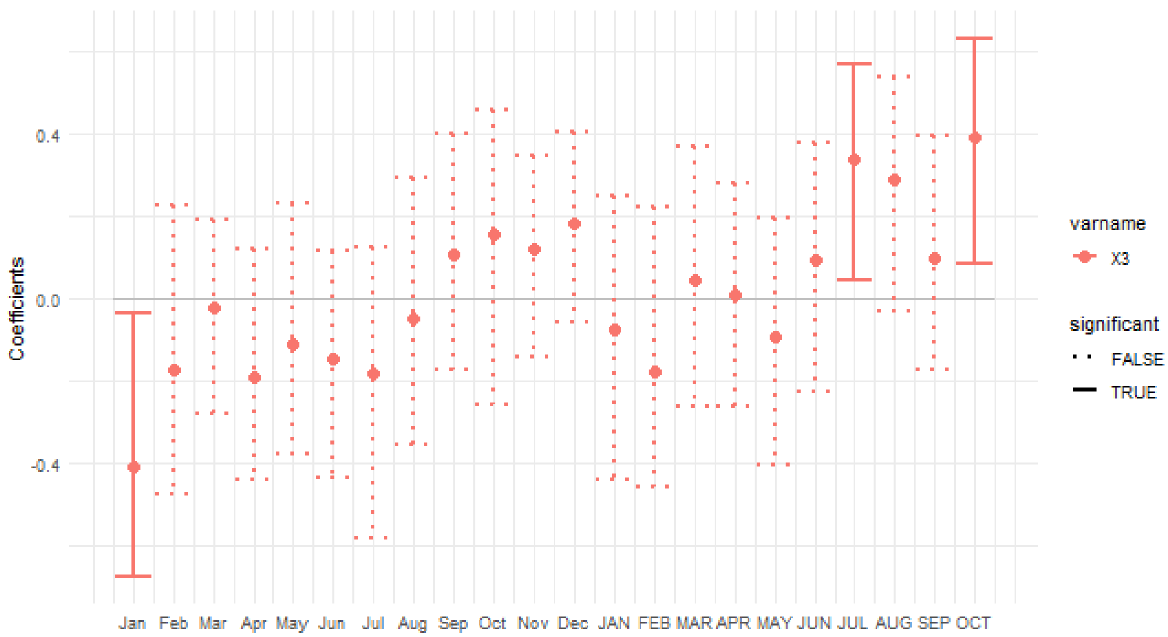
	WSA	ESA	NCD	RSA	OGG	SHB	WHB	MLS
pAPR					+			+
pMAY				–			+	
pJUN		+	+	+	+			
pJUL							+	
pAUG								
pSEPT							+	–
pOCT								
pNOV								
pDEC								
JAN								
FEB	+	+	+	+	+			
MAR		+		+	+			
APR	–	–	–	–				
MAY								
JUN								
JUL						+	+	+
AUG								
SEPT								

c)

	WSA	ESA	NCD	RSA	OGG	SHB	WHB	MLS
pAPR								
pMAY								
pJUN		+	+	+				
pJUL								
pAUG								
pSEPT								
pOCT								
pNOV								
pDEC								
JAN								
FEB								
MAR								
APR								
MAY								
JUN								
JUL								
AUG								
SEPT								

APPENDIX B

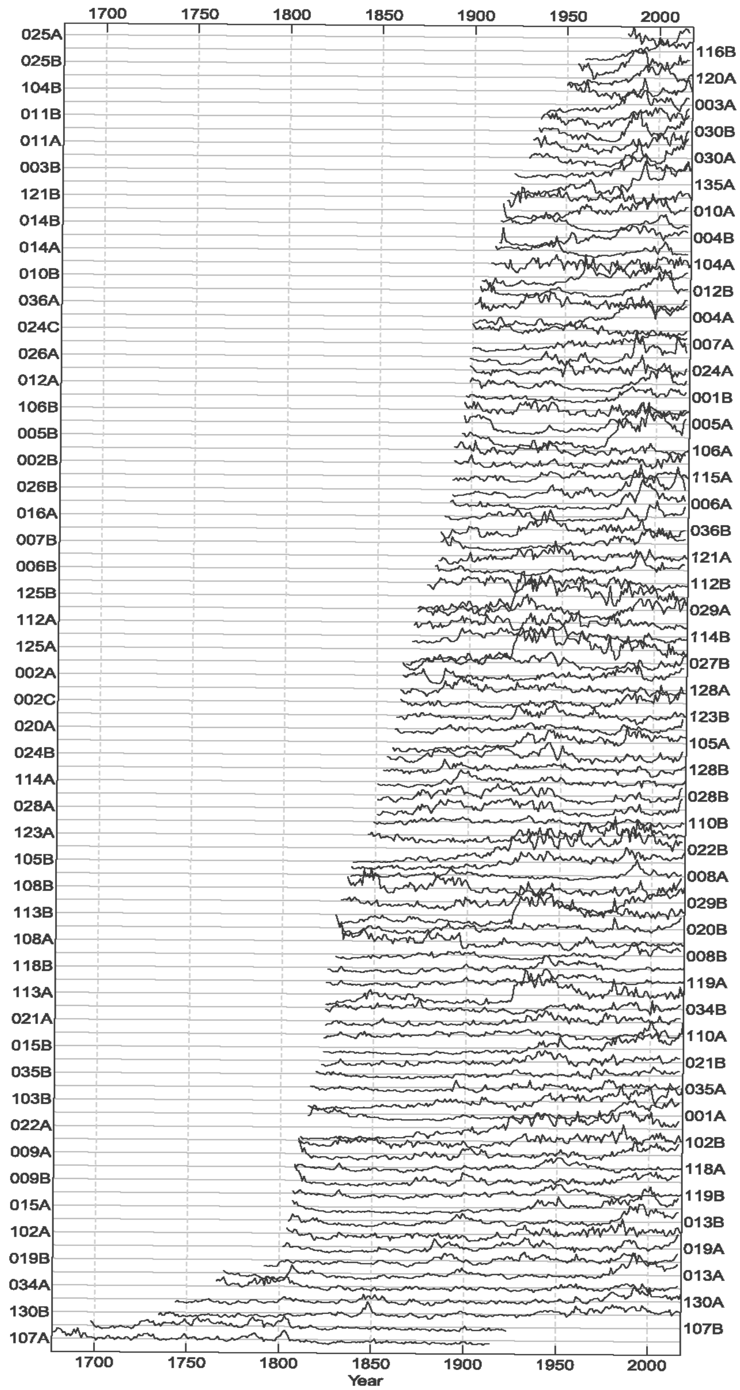
The TreeClim correlation coefficients of the relationship between the balsam fir (*Abies balsamea)* Mont Albert residual chronology and monthly mean Murdochville temperature over the period of 1953 to 2017. The relationship of tree-ring widths to the same year and prior of the growth year are compared to detect any lagged response. Unbroken and bolded lines are significant ($p < 0.05$) and 95% confidence interval is shown. A significant response to warm July and October temperatures is possibly a signal of the longer growing season at this high alpine site (1068 m).

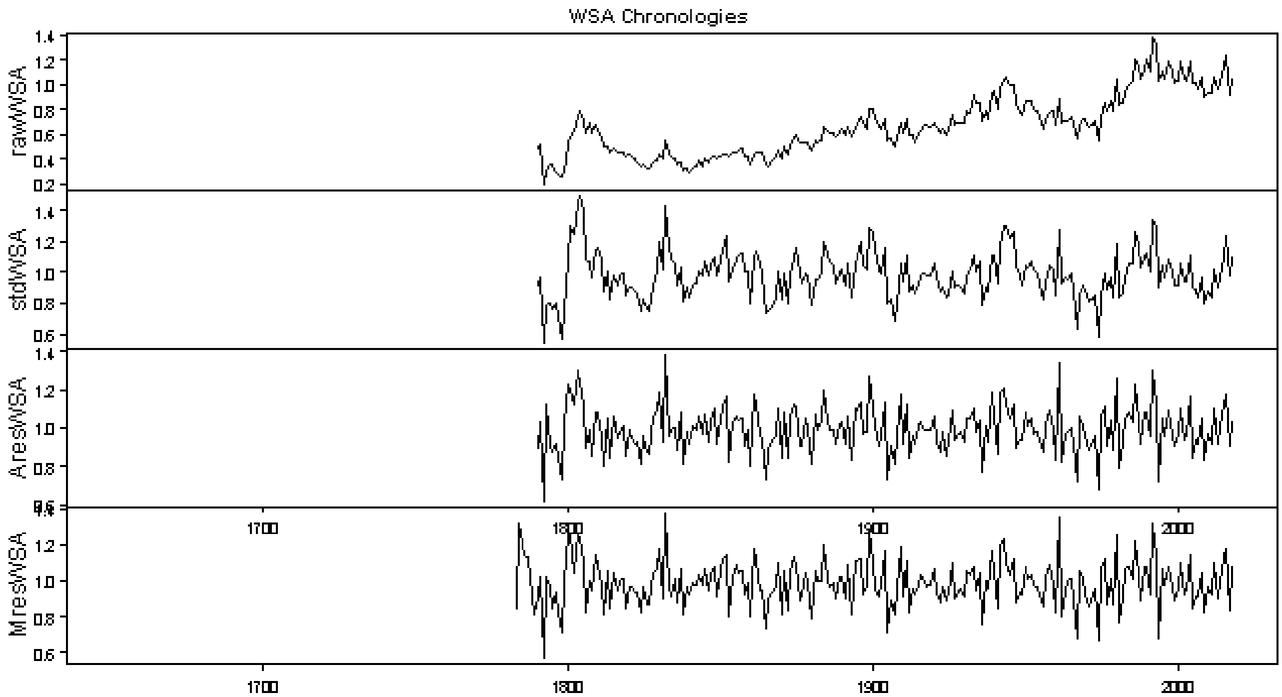


APPENDIX C

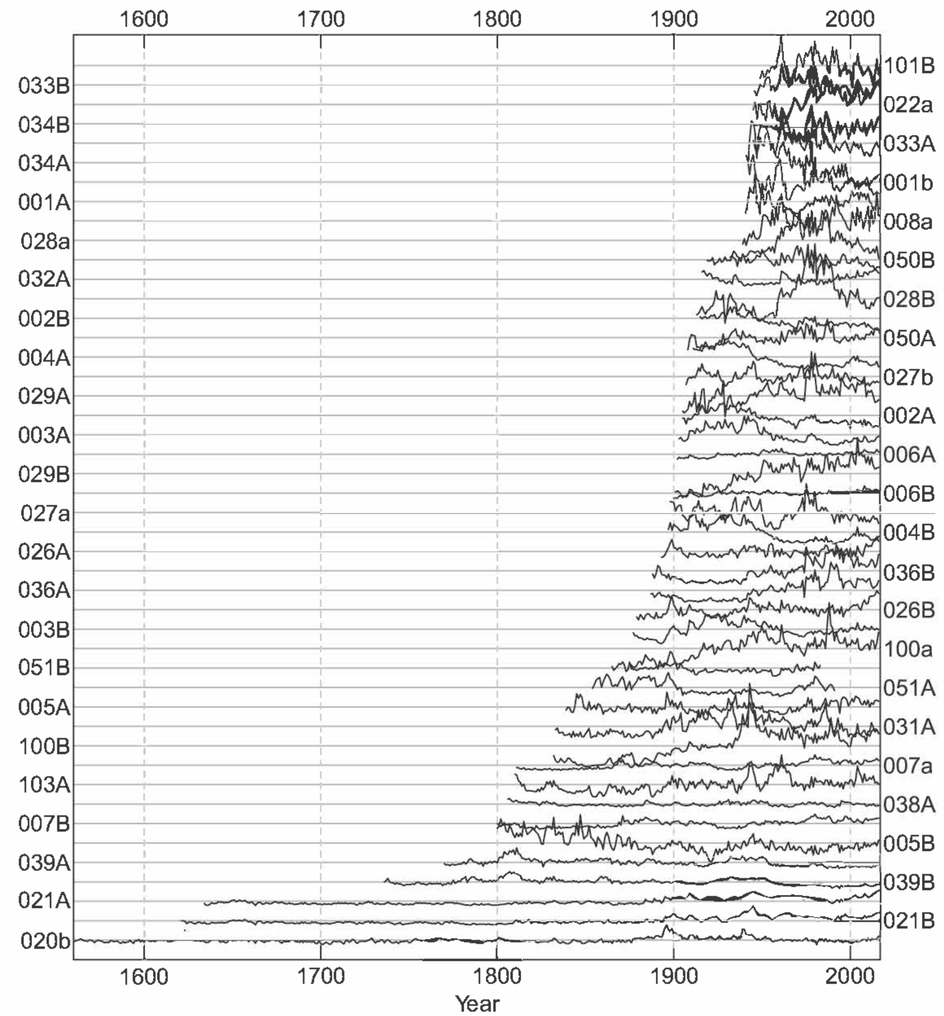
For each sample site, the individual ring-width series and the site chronologies are shown. First are raw measurements of individual samples as spaghetti plots, with the sample name on the vertical axis and the years on the horizontal axis. After the spaghetti plots, four versions of the site chronology are shown. The first is the raw chronology (raw) from ARSTAN, the result of a bi-weight robust mean of the samples from a site. The second is the standardized chronology from ARSTAN (std), the result of the bi-weight robust mean of all the sample ring widths from a site modified by a flexible cubic smoothing spline of 50 years with a 50% frequency cut-off to remove the effect of a tree's age on the ring-widths. The third is the residual chronology from ARSTAN (Ares), the result of the bi-weight robust mean of all the individual sample ring widths with the same modifications as the standardized chronology in addition to having autocorrelation removed. The fourth chronology is the residual chronology Dr. Meko's Matlab® code (Mres) (Dr. David Meko, Laboratory of Tree Ring Research, University of Arizona), a pre-whitened version of the standardized chronology (std) where autocorrelation is removed. The Mres chronologies are those used for the final reconstruction.

WSA Samples

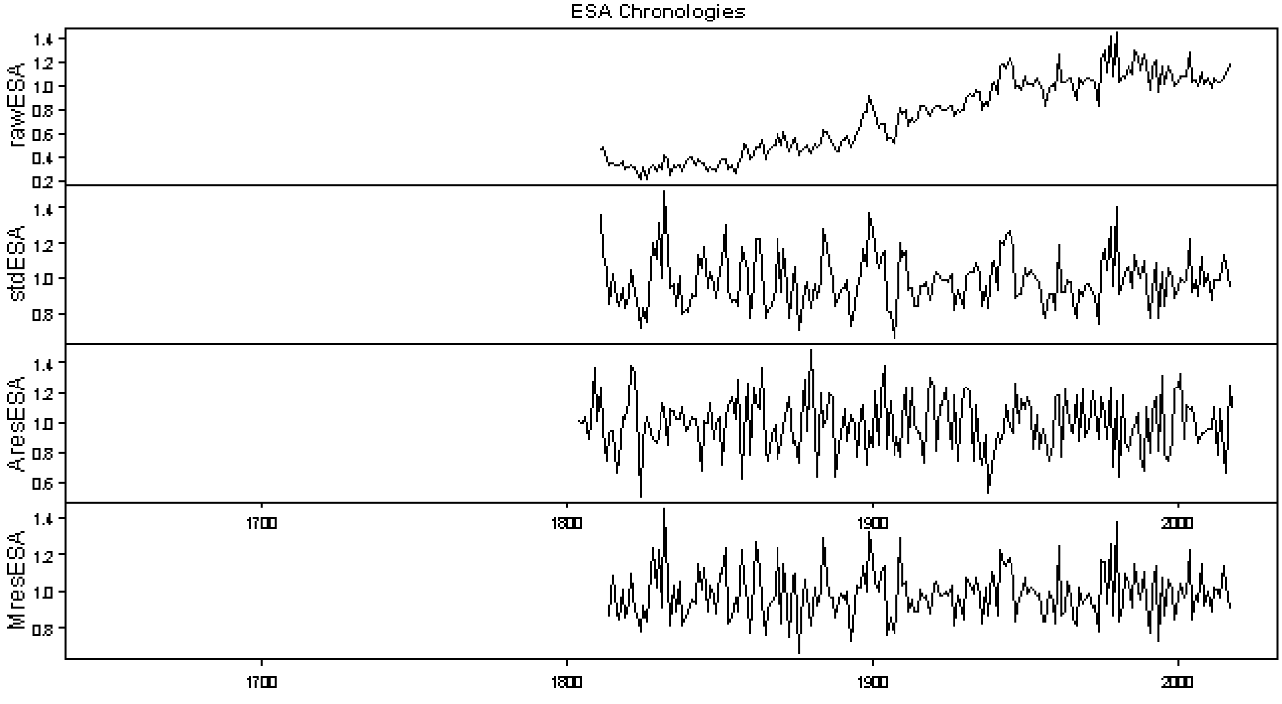



WSA Chronologies
rawWSA
stdWSA
AresWSA
MresWSA
1700
1800
1900
2000

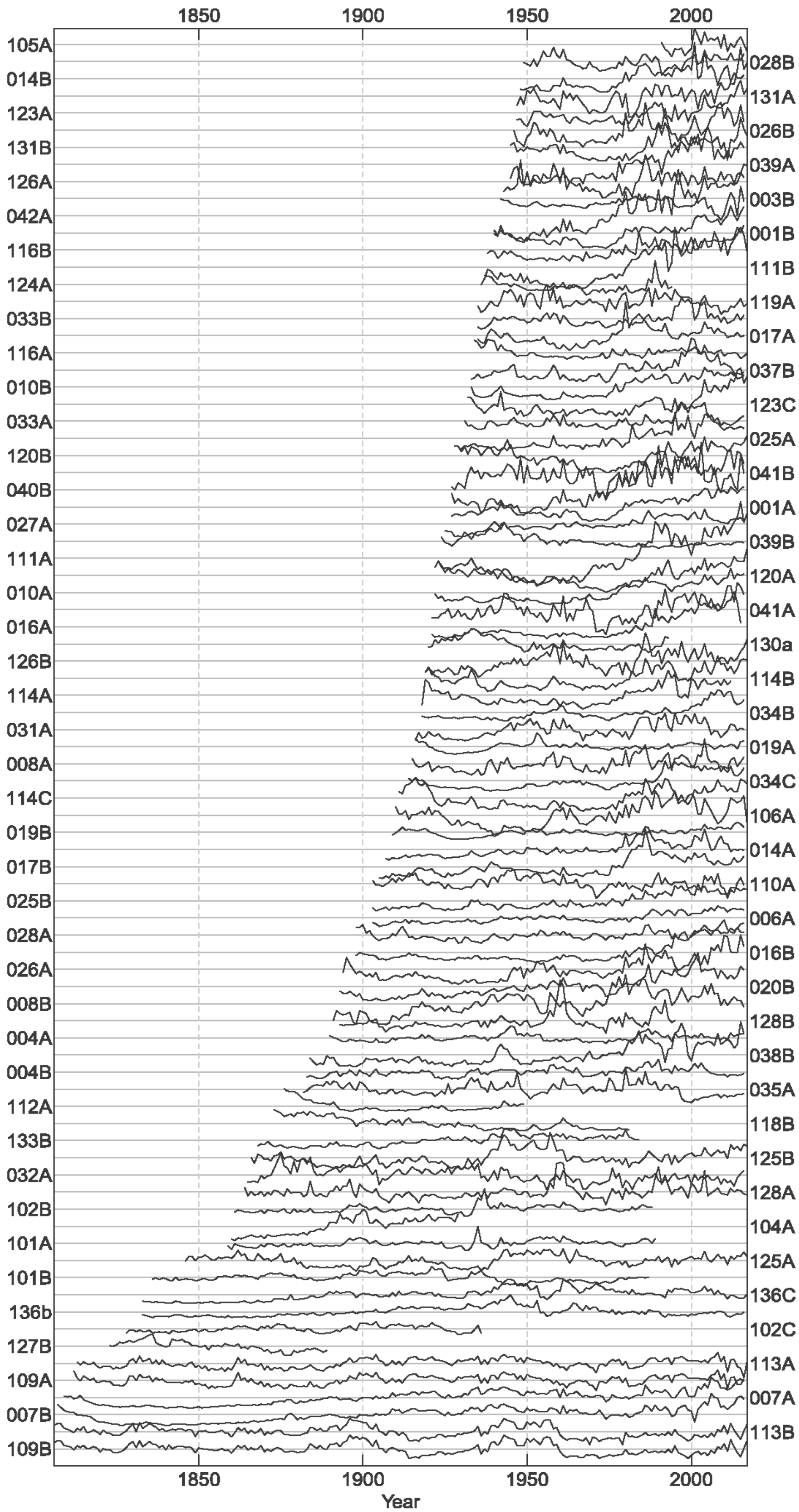
ESA Samples

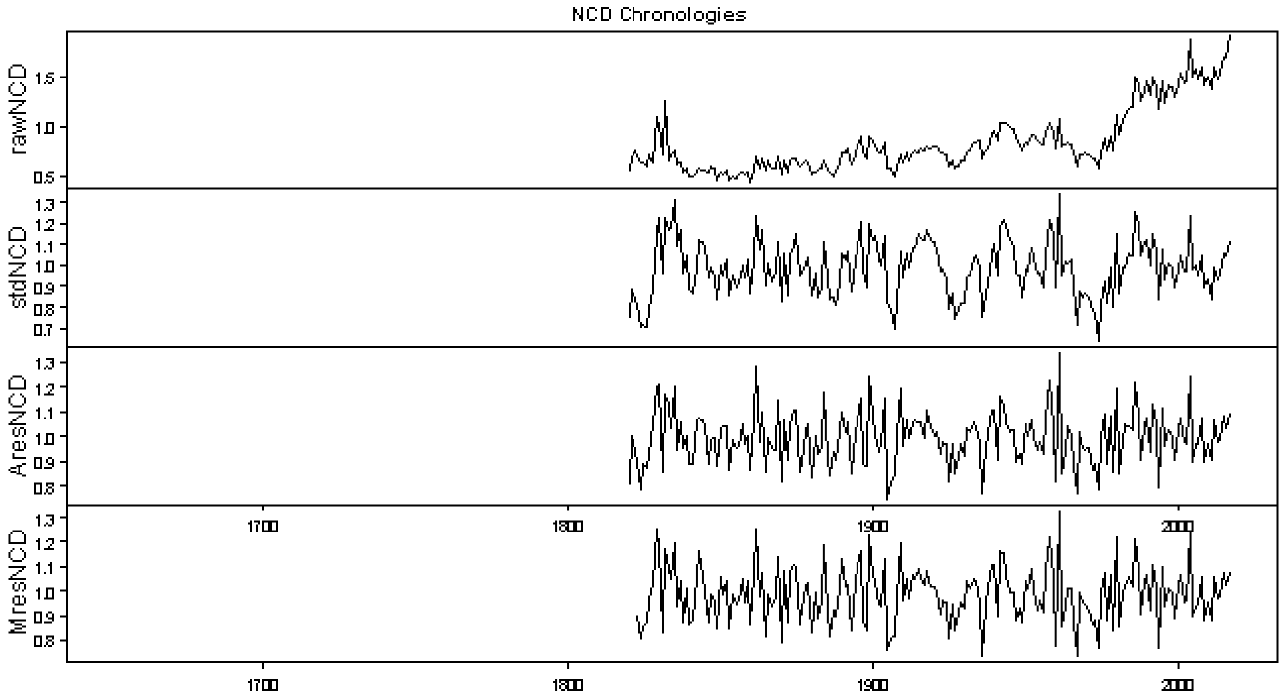


ESA Chronologies

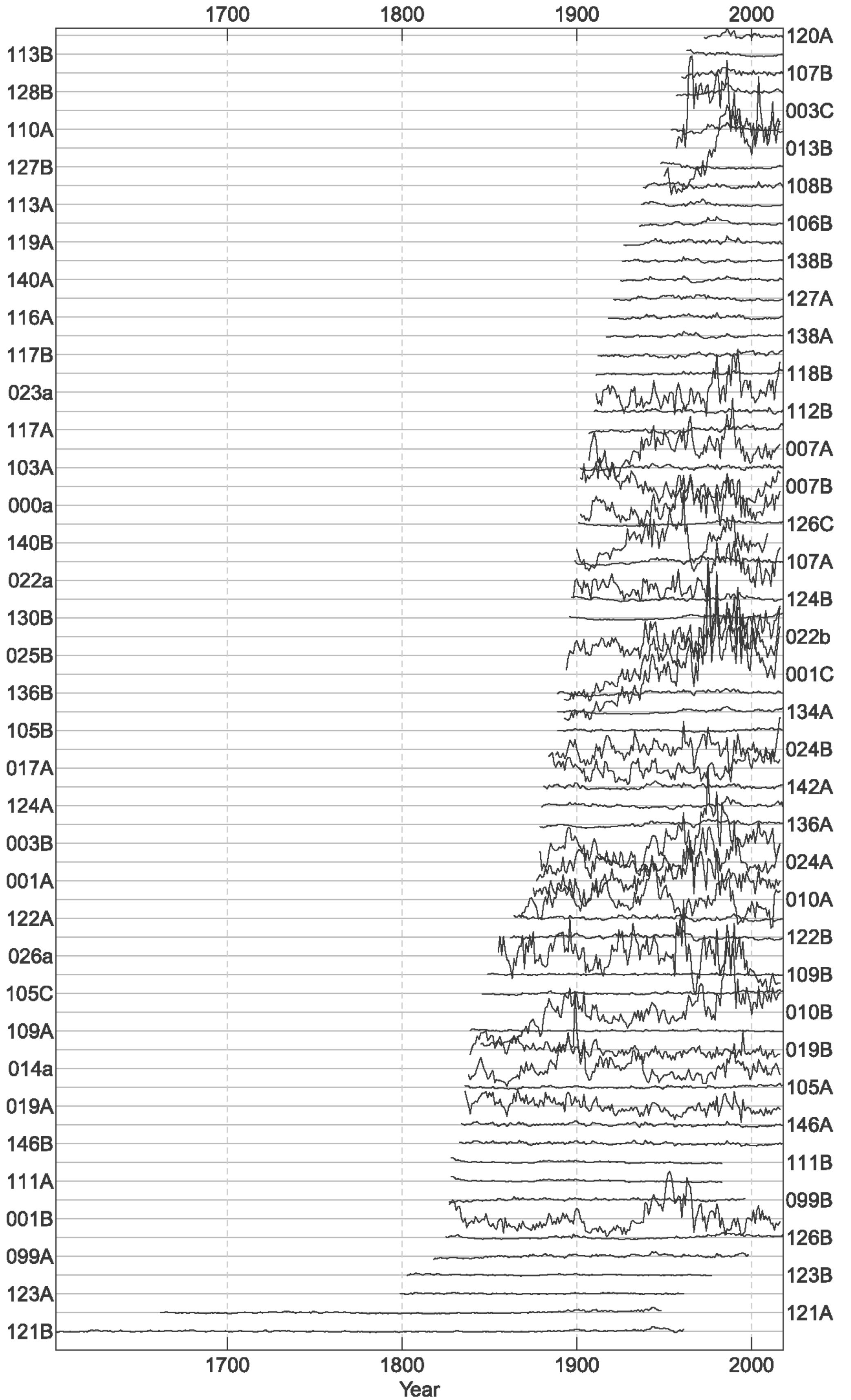


NCD Samples


1850
1900
1950
2000
105A
014B
123A
131B
126A
042A
116B
124A
033B
116A
010B
033A
120B
040B
027A
111A
010A
016A
126B
114A
031A
008A
114C
019B
017B
025B
028A
026A
008B
004A
004B
112A
133B
032A
102B
101A
101B
136b
127B
109A
007B
109B
028B
131A
026B
039A
003B
001B
111B
119A
017A
037B
123C
025A
041B
001A
039B
120A
041A
130a
114B
034B
019A
034C
106A
014A
110A
006A
016B
020B
128B
038B
035A
118B
125B
128A
104A
125A
136C
102C
113A
007A
113B
Year


NCD Chronologies
rawNCD
1.5
1.0
0.5
stdNCD
1.3
1.2
1.1
1.0
0.9
0.8
0.7
AresNCD
1.3
1.2
1.1
1.0
0.9
0.8
MresNCD
1.3
1.2
1.1
1.0
0.9
0.8
1700
1800
1900
2000
1700
1800
1900
2000

RSA Samples


1700
1800
1900
2000
Year
113B
128B
110A
127B
113A
119A
140A
116A
117B
023a
117A
103A
000a
140B
022a
130B
025B
136B
105B
017A
124A
003B
001A
122A
026a
105C
109A
014a
019A
146B
111A
001B
099A
123A
121B
120A
107B
003C
013B
108B
106B
138B
127A
138A
118B
112B
007A
007B
126C
107A
124B
022b
001C
134A
024B
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126B
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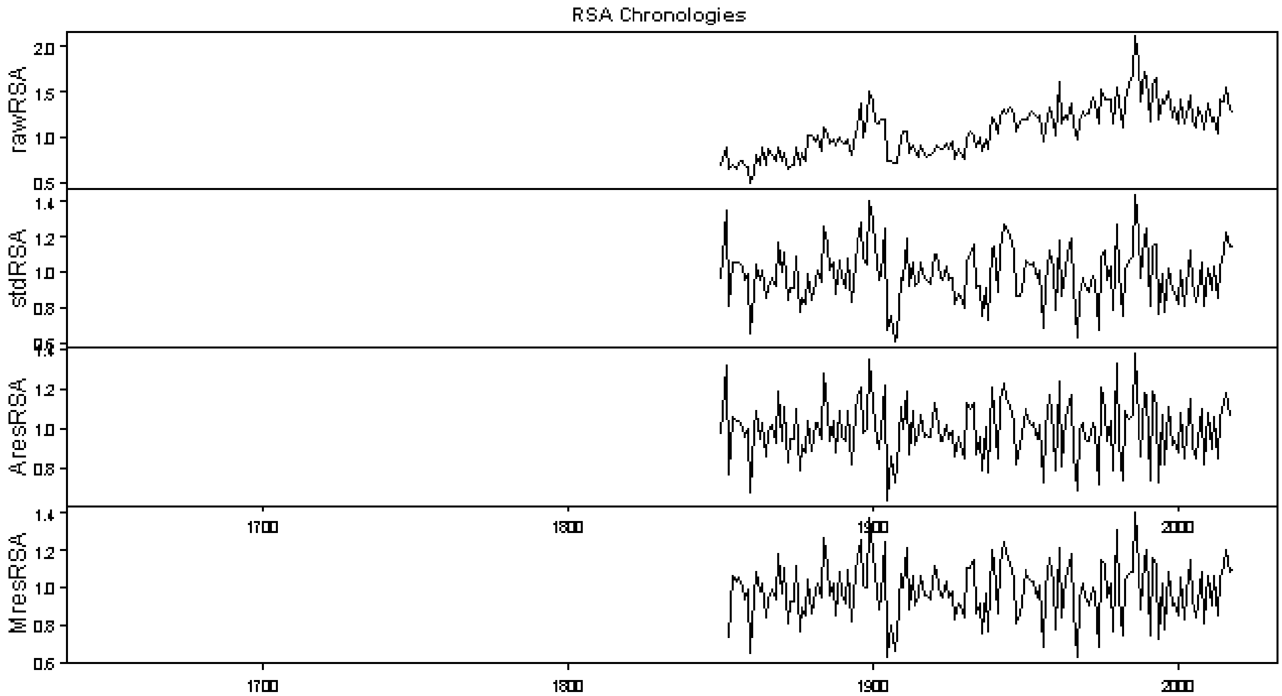
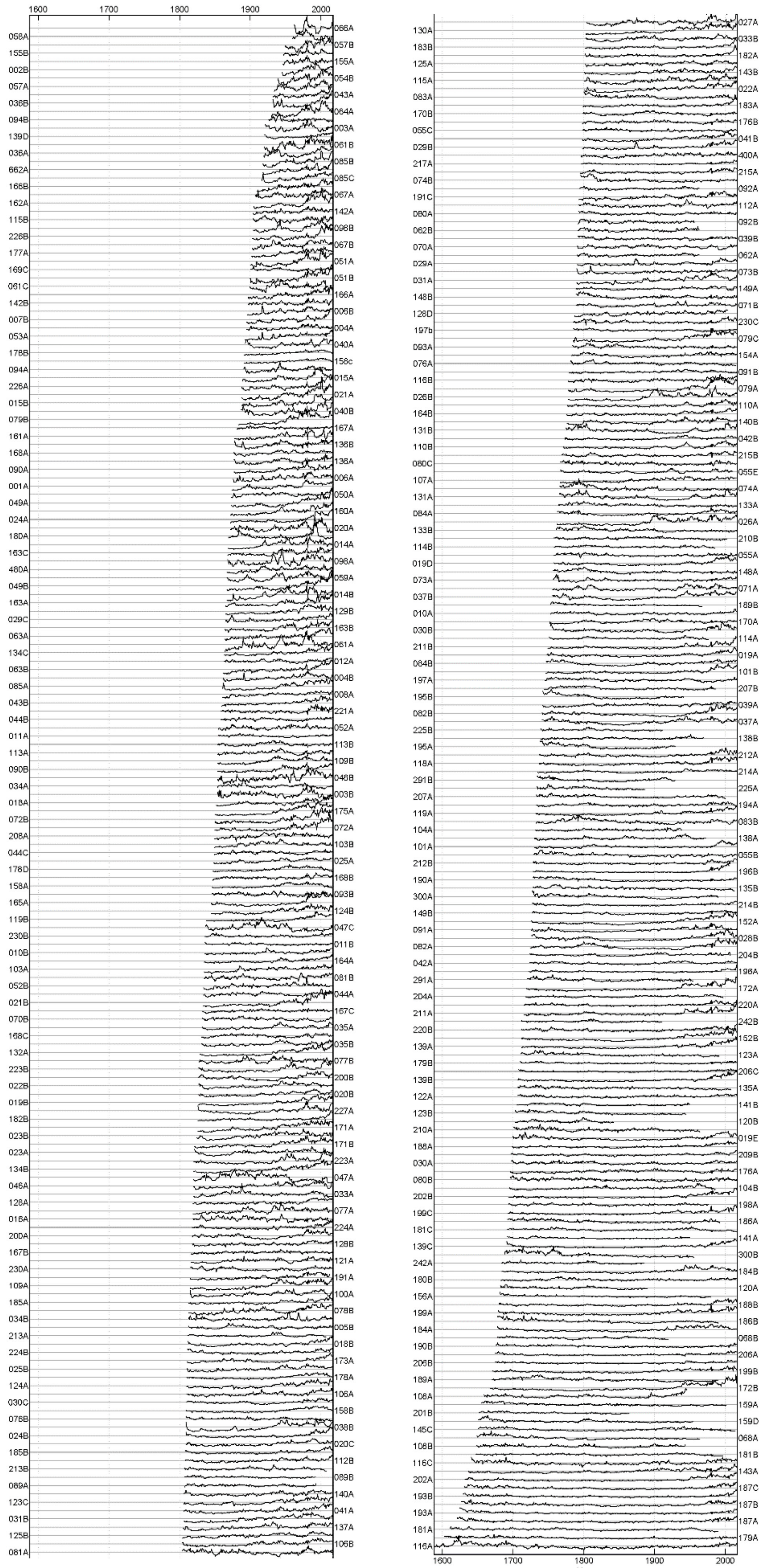
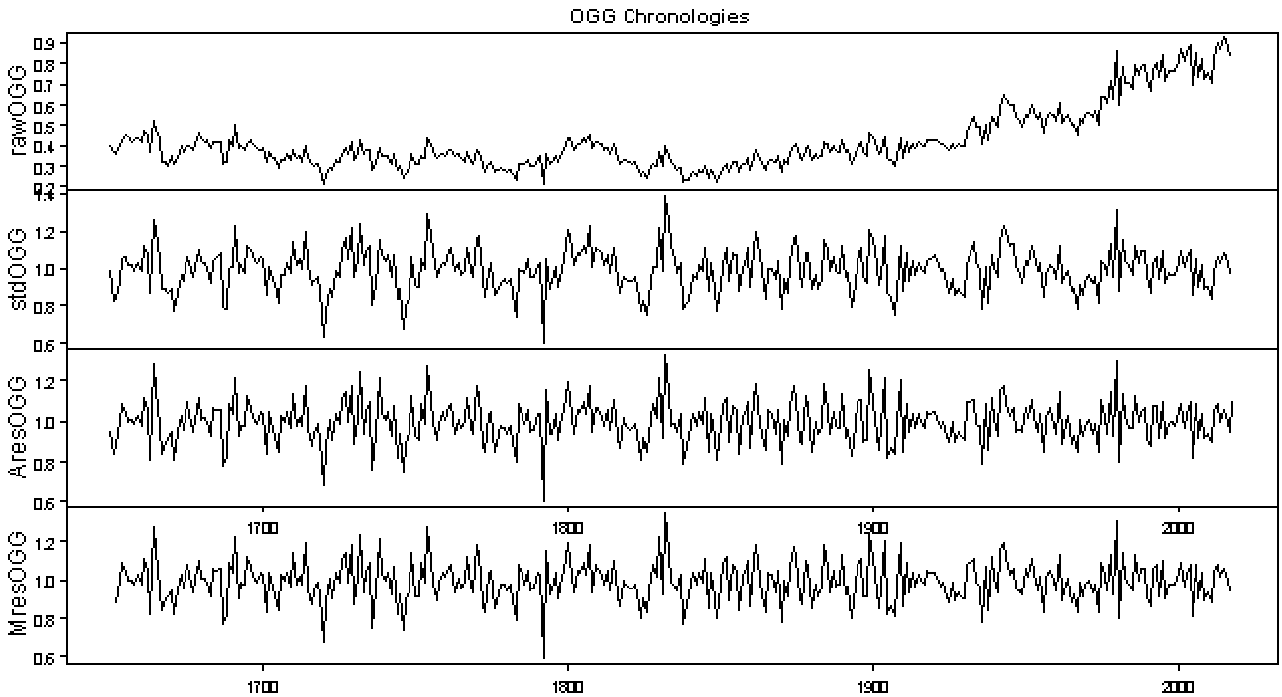
121A



RSA Chronologies
rawRSA
stdRSA
AresRSA
MresRSA
1700
1800
1900
2000

OGG Samples





OGG Chronologies
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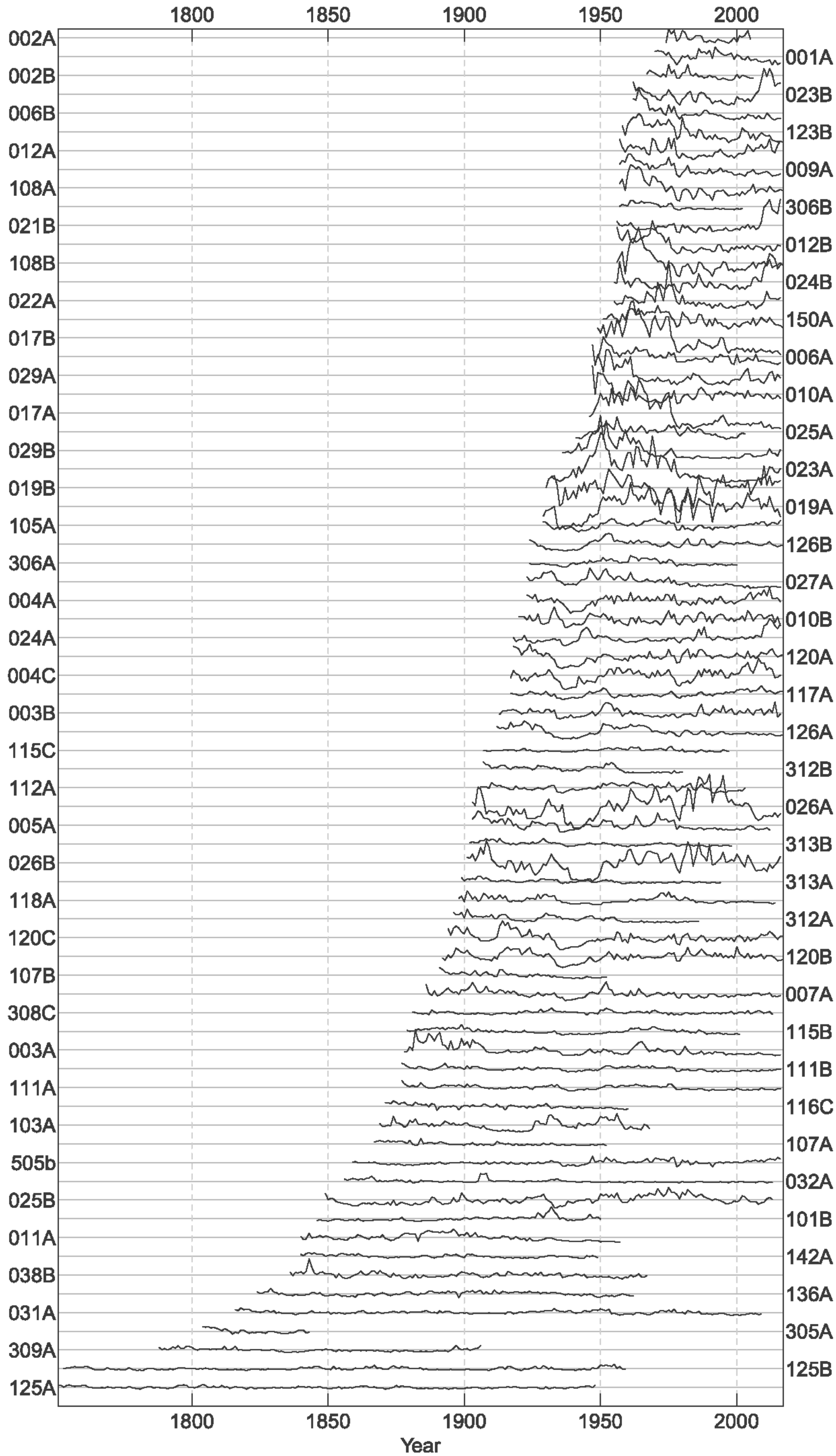
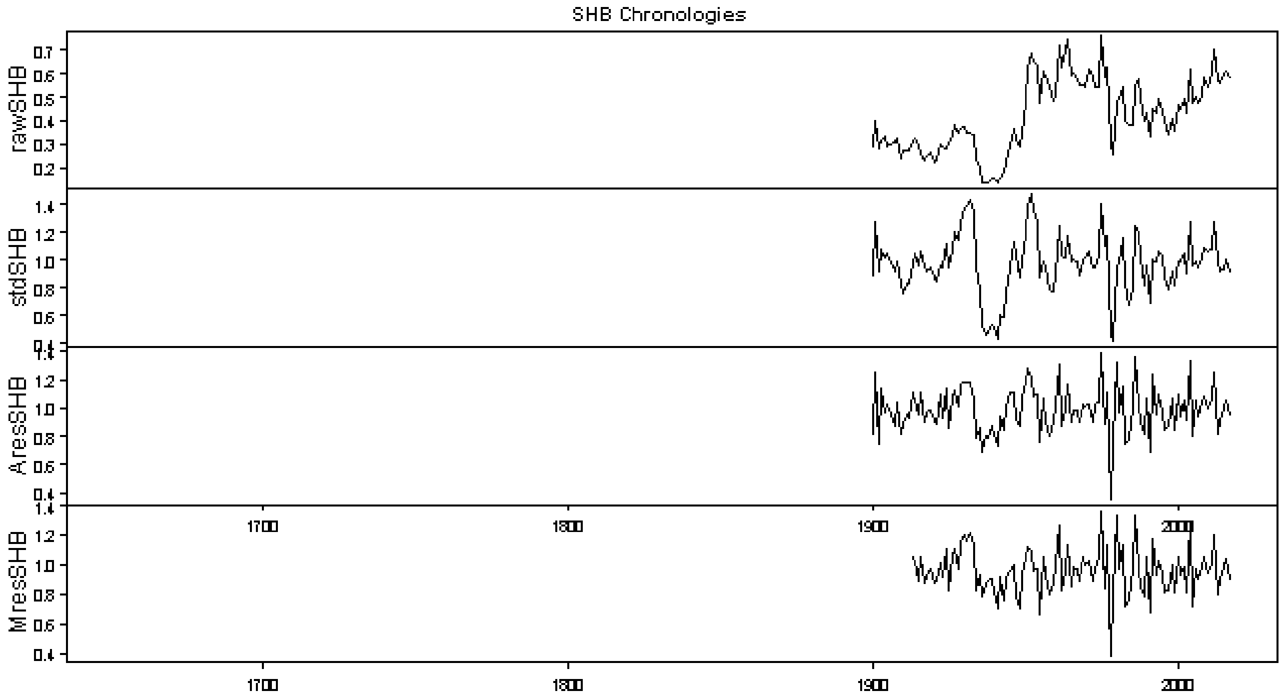
stdOGG
AresOGG
MresOGG
1700
1800
1900
2000

SHB Samples

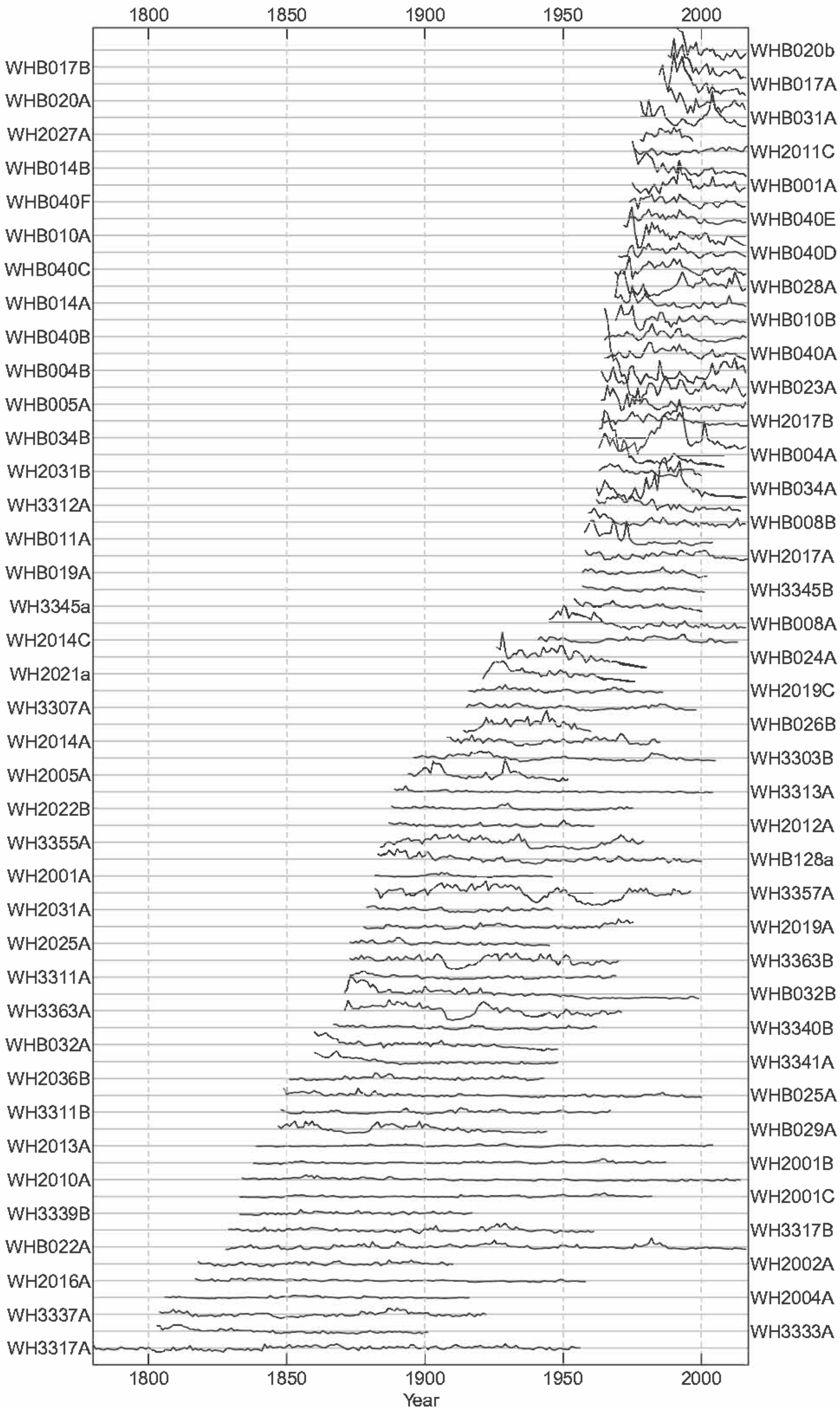


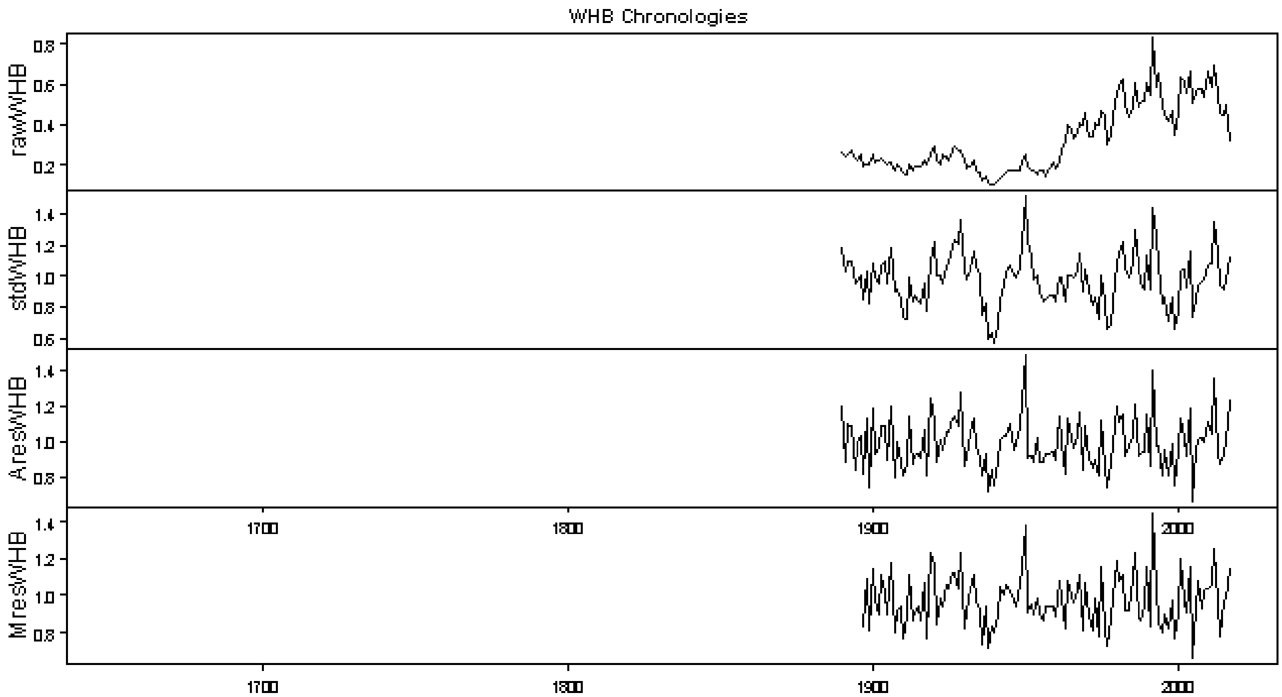
1800
1850
1900
1950
2000
002A
002B
006B
012A
108A
021B
108B
022A
017B
029A
017A
029B
019B
105A
306A
004A
024A
004C
003B
115C
112A
005A
026B
118A
120C
107B
308C
003A
111A
103A
505b
025B
011A
038B
031A
309A
125A
001A
023B
123B
009A
306B
012B
024B
150A
006A
010A
025A
023A
019A
126B
027A
010B
120A
117A
126A
312B
026A
313B
313A
312A
120B
007A
115B
111B
116C
107A
032A
101B
142A
136A
305A
125B
Year



SHB Chronologies
rawSHB
stdSHB
AresSHB
MresSHB
1700
1800
1900
2000

WHB Samples


1800
1850
1900
1950
2000
WHB017B
WHB020A
WH2027A
WHB014B
WHB040F
WHB010A
WHB040C
WHB014A
WHB040B
WHB004B
WHB005A
WHB034B
WH2031B
WH3312A
WHB011A
WHB019A
WH3345a
WH2014C
WH2021a
WH3307A
WH2014A
WH2005A
WH2022B
WH3355A
WH2001A
WH2031A
WH2025A
WH3311A
WH3363A
WHB032A
WH2036B
WH3311B
WH2013A
WH2010A
WH3339B
WHB022A
WH2016A
WH3337A
WH3317A
WHB020b
WHB017A
WHB031A
WH2011C
WHB001A
WHB040E
WHB040D
WHB028A
WHB010B
WHB040A
WHB023A
WH2017B
WHB004A
WHB034A
WHB008B
WH2017A
WH3345B
WHB008A
WHB024A
WH2019C
WHB026B
WH3303B
WH3313A
WH2012A
WHB128a
WH3357A
WH2019A
WH3363B
WHB032B
WH3340B
WH3341A
WHB025A
WHB029A
WH2001B
WH2001C
WH3317B
WH2002A
WH2004A
WH3333A
Year


WHB Chronologies
rawWHB
stdWHB
AresWHB
MresWHB
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0.4
0.6
0.8
0.6
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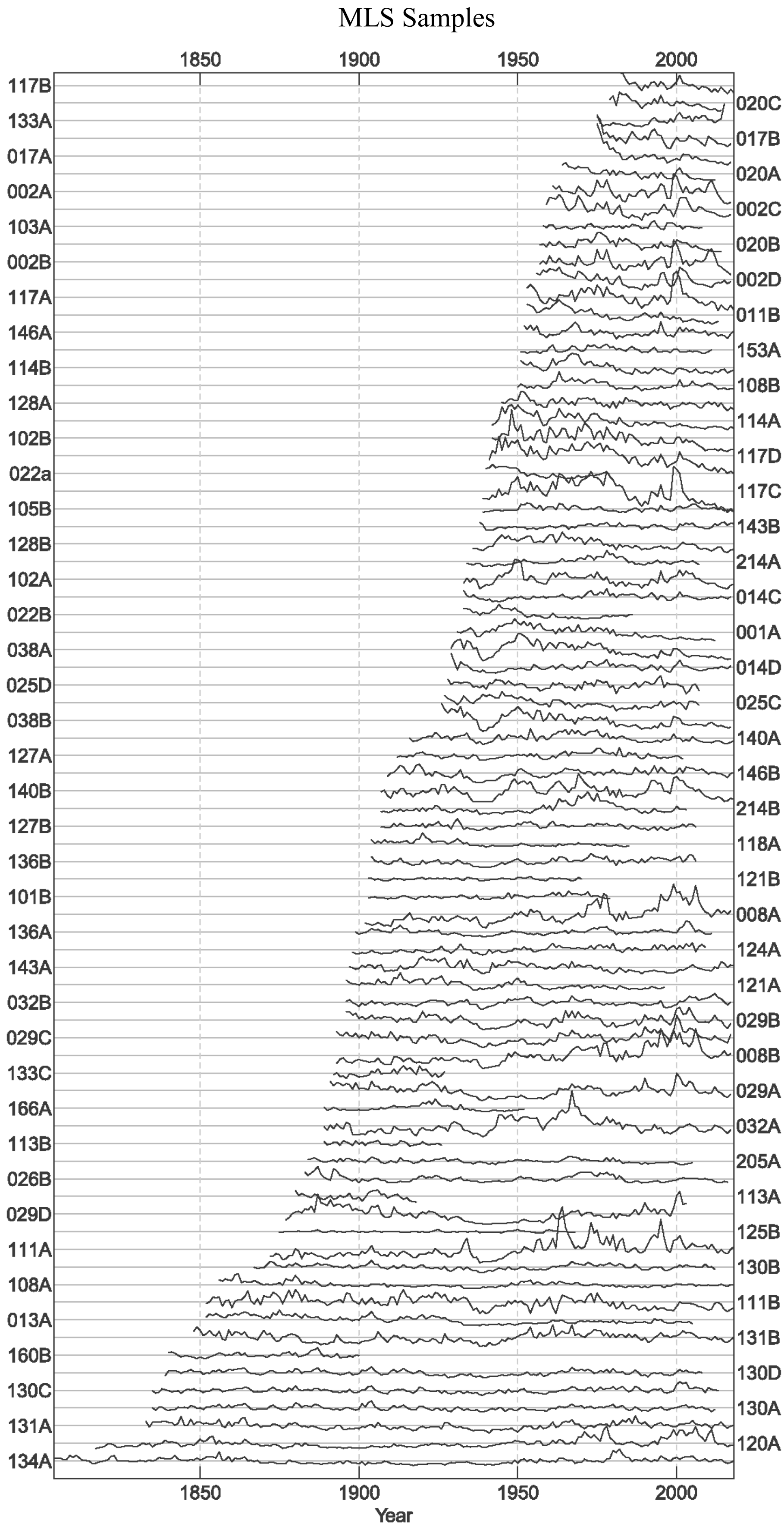
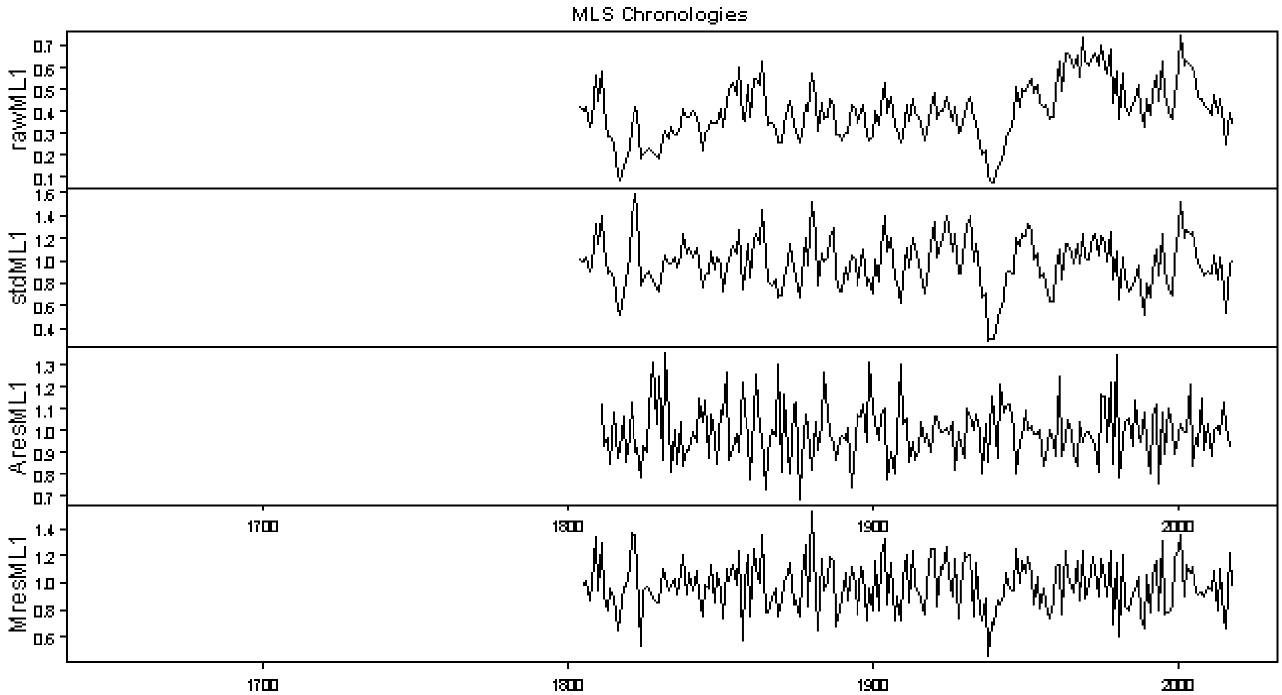
1.0
1.2
1.4
0.8
1.0
1.2
1.4
0.8
1.0
1.2
1.4
1700
1800
1900
2000
1700
1800
1900
2000



MLS Samples
1850
1900
1950
2000
117B
133A
017A
002A
103A
002B
117A
146A
114B
128A
102B
022a
105B
128B
102A
022B
038A
025D
038B
127A
140B
127B
136B
101B
136A
143A
032B
029C
133C
166A
113B
026B
029D
111A
108A
013A
160B
130C
131A
134A
020C
017B
020A
002C
020B
002D
011B
153A
108B
114A
117D
117C
143B
214A
014C
001A
014D
025C
140A
146B
214B
118A
121B
008A
124A
121A
029B
008B
029A
032A
205A
113A
125B
130B
111B
131B
130D
130A
120A
Year



MLS Chronologies
rawML1
stdML1
AresML1
MresML1
1700
1800
1900
2000