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Toward understanding nonstationarity in climate and hydrology through tree ring proxy records

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Key Points:

- Significant nonstationarities exist in the mean and autocorrelation structure
- Unlike the mean, autocorrelation changes consistently across space
- A 30 year period is not representative of long-term hydrologic properties

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Abstract Natural proxy records of hydroclimatic behavior, such as tree ring chronologies, are a rich source of information of past climate-driven nonstationarities in hydrologic variables. In this study, we investigate tree ring chronologies that demonstrate significant correlations with streamflows, with the objective of identifying the spatiotemporal patterns and extents of nonstationarities in climate and hydrology, which are essentially representations of past "climate changes." First and second-order nonstationarities are of particular interest in this study. As a prerequisite, we develop a methodology to assess the consistency and credibility of a regional network of tree ring chronologies as proxies for hydrologic regime. This methodology involves a cluster analysis of available tree ring data to understand and evaluate their dependence structure, and a regional temporal-consistency plot to assess the consistency of different chronologies over time. The major headwater tributaries of the Saskatchewan River basin (SaskRB), the main source of surface water in the Canadian Prairie Provinces, are used as the case study. Results indicate that stationarity might never have existed in the hydrology of the region, as the statistical properties of annual paleo-hydrologic proxy records across the basin, i.e., the mean and autocorrelation structure, have consistently undergone significant changes (nonstationarities) at different points in the history of the region. The spatial pattern of the changes in the mean statistic has been variable with time, indicating a time-varying cross-correlation structure across the tributaries of the SaskRB. Conversely, the changes in the autocorrelation structure across the basin have been in harmony over time. The results demonstrate that the 89 year period of observational record in this region is a poor representation of the long-term properties of the hydrologic regime, and shorter periods, e.g., 30 year periods, are by no means representative. This paper highlights the need to broaden the understanding of hydrologic characteristics in any basin beyond the limited observational records, as an improved understanding is essential for more reliable assessment and management of available water resources.

1. Introduction

The design and management of water resource infrastructure have been generally based on the information available in the observational record, with the central, default assumption of stationarity [*Brown*, 2010; *Lins and Cohn*, 2011; *Milly et al*., 2008]. In practice, observational records of hydrologic variables have been commonly assumed to be a realization of a stationary stochastic process whose statistical characteristics are contained in the records. *Milly et al*. [2008] called for the abandonment of the use of the stationarity assumption in the design and management of water resource systems and asserted that "stationarity is dead," because of the substantial anthropogenic changes to the Earth's climate. The stationarity assumption "implies an assumption of a physical constancy of the mechanisms participating in the formation of the streamflow, from the regimes of precipitation and evaporation in the river basin, to geomorphological, pedological, and other physical conditions; it is of course well known that this assumption is not true in general and that it diverges from reality with the length of the period considered" [from *Klemeš*, 1989]. Such nonstationarities have also introduced new challenges to the science of hydrology and have significant implications for hydrologic and land surface modeling [*Wagener*, 2007; *Wagener et al*., 2010].

Natural proxy records of hydroclimatic behavior over the past several centuries or millennia have introduced opportunities to go beyond the limited periods of observational records, as a vehicle for better understanding and addressing the nonstationarity in climatic and hydrologic variables. Tree rings are superior proxy records of paleo-hydrology in comparison with the majority of other natural proxy records, because of their wide availability in various regions and their capability of archiving hydroclimatic behavior at a fine temporal resolution (i.e., yearly and subyearly). The typically significant correlation between annual hydrologic variables such as streamflow and annual growth rate (i.e., tree ring index chronologies) in a region is the basis of the reconstruction of paleo-hydrology.

Tree ring data have been used to reconstruct the paleo-time series of various variables such as precipitation [e.g., *Blasing et al*., 1988; *Cleaveland and Duvick*, 1992; *Till and Guiot*, 1990], temperature [e.g., *Briffa et al*., 1990; *Fritts and Lough*, 1985], streamflows [e.g., *Cleaveland and Stahle*, 1989; *Gou et al*., 2007; *Sauchyn et al*., 2011; *Woodhouse et al*., 2006], and Palmer drought indices [e.g., *Cleaveland and Duvick*, 1992; *Stockton and Meko*, 1975]. Tree ring data have also been utilized for an improved assessment of future climate change [e.g., see *Lutz et al*., 2012]. *Wettstein et al*. [2011] discussed the coherence in statistical properties of tree ring time series, including autocorrelation, across the Northern Hemisphere as local climate signals.

On the basis of the science of dendrohydrology, this study follows two main objectives:

1. The development of a methodological framework to evaluate the consistency and credibility of tree ring time series as proxies for time series of hydrologic variables. The credibility is assessed with respect to regional, spatiotemporal consistency of tree ring time series obtained from different chronology sites across the basin, and the correlation strength between the tree ring data and annual streamflows during the period of observational record.
2. The identification of the timing and extent of nonstationarity in statistical properties of paleo-hydrologic proxy time series, mainly the mean and autocorrelation. One key question is if the period of observational record adequately represents the long-term statistical properties of hydroclimatic behavior of the basin.

The nonstationarity in statistical properties of hydroclimatic variables is a representation of climate change. According to the glossary of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), climate change refers to "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer," and "the classical period" for averaging climate variables is 30 years, as defined by the World Meteorological Organization [*IPCC*, 2014].

The headwater tributaries of the Saskatchewan River Basin (SaskRB), originating from the Rocky Mountains in Alberta, Canada, are used as the case study. These tributaries are the main source of surface water in the Canadian Prairie Provinces [*Wheater and Gober*, 2013]. Water demands are growing in these provinces with the growth in population and agricultural/industrial activities. Therefore, the effective management of water resources is of high priority in the region to minimize vulnerability to climate change and drought. There have been efforts to reconstruct the annual streamflows for different tributaries of the SaskRB [*Axelson et al*., 2009; *Case and MacDonald*, 2003; *Sauchyn et al*., 2011]. Further, *Fleming and Sauchyn* [2013] analyzed the previously reconstructed streamflow time series of two major tributaries of the SaskRB to study the shifts and variance in water availability.

In the present study, we take a novel approach and directly analyze all individual tree ring paleo-hydrologic proxy time series (i.e., chronologies), instead of the common practice of first reconstructing paleo-hydrologic time series (e.g., through multiple linear regression) and then, if desired, analyzing the reconstructed time series. This way, the artifacts of imperfect mapping of proxy time series onto hydrologic time series can be avoided. Note that natural proxy records (including tree rings) are not fully capable of explaining change and variability in climate and hydrology. An important assumption, in common with conventional dendrohydrological practice, is that unexplained effects in the relationship between hydrology and growth are unlikely to be sufficiently systematic, over the long time scales of interest, to confound the interpretation of the paleo-reconstructions presented here.

This paper is organized as follows. Section 2 presents the definition of stationarity/nonstationarity followed by a brief historical overview of relevant opinions and research in the field of hydrology. Section 3 gives an overview of the study area and the utilized tree species and chronology sites across the basin. Section 4 presents the methodology and reports the analyses and results. The paper ends with conclusions, in section 5.

2. Nonstationarity in Hydrology: Definitions and Understandings

In mathematics, a stochastic process is deemed “strictly stationary” if its joint probability distribution, which includes all statistical properties of any order, does not change with shifts in time. “Second-order stationarity” (also called weak or wide-sense stationarity), which is of particular interest in the analysis of hydrologic time series, is defined as the quality of a stochastic process in which only the first and second-order statistical properties do not vary with time [*Salas et al*., 1980]. Changes to any of these statistical properties (i.e., the mean, variance, and autocorrelation structure) can imply environmental/climate changes. Nonstationarities in hydrology exist across a range of time scales, e.g., from hourly to decadal or longer, and can be attributed to different environmental and/or climatic sources. Nonstationarities that are due to seasonality or well-understood deterministic processes, such as land use changes or regulation, can in principle be modeled and removed from time series [*Lins and Cohn*, 2011]. However, there are nonstationarities in hydrology that are fundamentally uncertain and chaotic in nature, particularly over longer time scales, and their identification may not be possible from the relatively short periods of observational records.

Hydrologists have been aware of the existence of nonstationarities in natural processes for many years. *Klemeš* [1974] stated that “Traditionally, it has been assumed that, in general, the geophysical, biological, economical, and other natural processes are nonstationary but within relatively short time spans can be well approximated by stationary models.” He later [*Klemeš*, 1989] argued that “despite the preaching about the importance of long records, hydrologists are in fact more comfortable with short ones; the stationary hypothesis is much more easily defensible for, say, a 30 year record than it would be for a 300 year record.” This awareness has of course extended well beyond the hydrologic community, as, for example, *Mitchell* [1976] who discussed the drivers of climate variability on time scales from hours to aeons. *Salas and Boes* [1980] pointed out that “certain hydrologic data appear to indicate the presence of abrupt or gradual shifts in the mean and possibly in other statistical characteristics.” *Koutsoyiannis* [2003] stated that intensive research efforts resulted in the strong conclusion that the climate has always changed irregularly on all time scales, as observed in long, proxy hydroclimatic time series. *Blöschl and Montanari* [2010] also noted that climate changes have occurred over a multitude of scales with diverse impacts on different hydrological characteristics such as glacier and river flow regimes.

Portions of nonstationarities in climatic and hydrologic variables that are evident in periods of observational record have been typically detected in the form of monotonic upward or downward trends and/or shifts in the mean. Different statistical tests have been used in the literature to detect trends in observed hydrologic time series [e.g., see *Abdul Aziz and Burn*, 2006; *Bárdossy and Caspary*, 1990; *Burn and Hag Elnur*, 2002; *Dahamsheh and Aksoy*, 2007; *Hamed*, 2008]. Different segmentation procedures have also been developed to identify the points in time when, supposedly, the mean shifts. These procedures divide nonstationary time series that are piecewise stationary into multiple stationary segments [e.g., see *Appel and Brandt*, 1983; *Gedikli et al*., 2008; *Hubert*, 2000]. *Koutsoyiannis* [2003] demonstrated that the trends observed for short time periods (i.e., periods of observational record) may be cycles of almost all frequencies in the timeframe of the whole time series, superimposed in random sequence. Such local trends were deemed by many as deterministic components of the time series, however, *Koutsoyiannis* [2003] pointed out that these climate changes were irregular and there might not exist any accurate deterministic model that could describe and predict them. From the perspective of climate change impact analysis, *Blöschl and Montanari* [2010] emphasized the importance of putting limits to the interpretation of trends in the data, as possibly misinterpreted trends, which are actually long cycles, should not be extrapolated into the future.

Research efforts for the detection of trends and nonstationarities of hydrologic time series have been mainly focused on the mean (first-order stationarity). There have also been studies on changes in variance of annual time series [e.g., *Coulibaly and Burn*, 2004; *Perreault et al*., 2000; *Whitcher et al*., 2002]. However, the autocorrelation structure, which represents the persistence in time series, has been arguably assumed constant over time in the hydrologic literature, with limited exceptions. The work of *Dakos et al*. [2008] and *Lenton* [2011], in which paleo-climate data have been analyzed, shows that the autocorrelation in hydroclimatic time series can significantly change with time, and some increased autocorrelation (“slowing down” characteristics) may be a sign of reaching a critical tipping point which can result in abrupt climate change.

Short-term persistence (also known as short-range dependence or short-term memory) is typically demonstrated through exponentially decaying autocorrelation functions, and can be attributed to the physical processes involved in hydrologic systems such as watershed storage [*Salas et al*., 1980]. Hydrologic time series may also possess long-term persistence (also known as long-range dependence or long-term memory), which can be represented by power-like (very slowly) decaying autocorrelation functions and can be in effect for decades, centuries, or millennia. The possible existence of long-term persistence in hydrologic time series was found by *Hurst* [1951]; thus, the "Hurst exponent," which is a measure of long-term persistence, and the controversial "Hurst phenomenon" on the presence of long-term persistence. A detailed description of the Hurst phenomenon can be found in *Koutsoyiannis* [2002]. *Montanari* [2003] reviewed studies characterizing long-term persistence in hydrology and pointed out that long-term persistence may be present in hydrologic records. However, many researchers are reluctant to accept this observation, which has resulted in a controversial debate, due to the lack of a convincing physical explanation for such extraordinary persistence.

Klemeš [1974] demonstrated that long-term persistence might be attributed to nonstationarities in the mean of the hydrologic time series. He illustrated through a simple example how shifts in the mean could result in the inferred presence of extremely high, long-term persistence. *Diebold and Inoue* [2001] argued that stochastic regime switching is intimately related to long memory and easily confused with it. *Fortin et al*. [2004] addressed the autocorrelations induced by sudden shifts in the mean of time series and emphasized the importance of adequately representing the observed persistence in shifting mean models. *Hubert* [2000] also demonstrated that time series with abrupt changes in the mean exhibit strong temporal persistence, but with poor possibilities to fit any autoregressive model.

One open question when investigating the stationarity/nonstationarity in hydroclimatic time series is the "proper length" of the window on which the statistical properties should be calculated, in order that the change in those properties by shifting the window can be representative of the stationarity/nonstationarity. The mathematical definition of stationarity (presented above) does not address this question, as theoretically, a stochastic process can generate a number of realizations, and therefore, the target statistical properties can be calculated at each time step, independent of other time steps. However, in case of observed hydroclimatic time series, where the existence of an underlying stochastic process is hypothesized for sake of mathematical convenience, only a single realization is available. Therefore, the statistical properties of a window of the time series act as surrogates for the statistical properties of the underlying, but unknown, stochastic process. The caveat is that different lengths of this window may lead to different conclusions about stationarity/nonstationarity, and generally, shorter window lengths are expected to demonstrate larger nonstationarity. This question is somewhat addressed in this study, as two different lengths of window (30 years and 89 years = the length of the period of observational record) are used in the analysis.

The general shortness of the periods of observational record in hydrology limits our ability to appropriately explore the quality and extent of long-term trends and cycles, which are first-order nonstationarities (i.e., in the mean). This shortness also seriously limits the investigation of possible nonstationarities in the second-order statistical properties of hydrologic time series, such as the autocorrelation structure. Such a limitation is one main motivation for seeking long, natural records that are correlated with hydrologic variables and may act as proxies for hydroclimatic behavior over an extended period of time. The present study is an attempt to overcome this limitation by using tree ring proxy records to explore and understand first and second-order nonstationarities in climate and hydrology, recognizing that the science of paleoecology has substantially benefited from a variety of natural proxy records to characterize the changes and nonstationarity in climate [e.g., *Wirtz et al*., 2010], floodplains and river networks [e.g., *Brown*, 2002], lakes [e.g., *Gore*, 1988], tree lines [e.g., *Pellatt and Mathewes*, 1994], etc., over the Holocene and beyond.

3. Case Study and Data

The Saskatchewan River basin (SaskRB) is a Regional Hydroclimate Project of the World Climate Research Programme's Global Energy and Water Exchanges (GEWEX) project. This basin has an area of some 406,000 km^2, which covers parts of the Canadian provinces of Alberta, Saskatchewan, and Manitoba, and the American state of Montana. A map of the SaskRB, with detail of its major tributaries in Alberta, is shown in Figure 1. The majority of water in this basin (80–90%) originates from the Rocky Mountains in Alberta, while a large portion of the basin on the prairies never contributes runoff to the main streams [*Martz et al*., 2007; *Pomeroy et al*., 2005]. Reliable evaluation and management of water resources are critically important

Figure 1. Map of the tributariris of the Saskatchewan River basin and the locations of the chronology sites (circles) and streamflow gauges.

in this large basin, which is a pivotal agricultural region in Canada. The share of surface water consumptive use by irrigated agriculture in the South Saskatchewan River basin is high at 86% [*Martz et al*., 2007]. In addition, there are other significant competing water demands across the basin including municipal, hydropower, and industrial uses. The SaskRB experiences one of the most extreme and changing climates in the world and embodies a set of critical challenges for water security, which are of particular importance to Canada and globally [*Wheater and Gober*, 2013]. While scenarios of future climate point to a wetter but warmer future [*Khaliq et al*., 2014], *Martz et al*. [2007] projected that streamflows will decrease across the basin due to climate change, with the Red Deer River suffering the most with an average decrease of 13%, followed by the Bow River at 10% and the Oldman River at 4%.

The analysis of proxy records collected from the chronology sites across the major tributaries of the SaskRB, the North Saskatchewan, Red Deer, Bow, and Oldman Rivers, is of interest in this study, as these tributaries are the main source of surface water in the SaskRB. A set of naturalized flow time series for the historical period 1913–2001 at the four gauging stations shown in Figure 1 is used in this study to demonstrate the correlations between the tree ring data and streamflows. The naturalized flows at each gauge have been generated by Alberta Environment and hypothetically represent the flow regime in the basin as if there were no human interventions. There is a relatively rich source of tree ring data available across the SaskRB headwater areas, grouped in 33 tree ring chronologies shown in Figure 1. The chronology site numbers in this figure refer to the site numbers given in Table 1, where the tree species and available data periods are also reported. The North Saskatchewan and Oldman Rivers contain the majority of the chronology sites, whereas, in the Red Deer subbasin, appropriate long-living, moisture sensitive trees have not yet been identified and sampled. Note that the chronology sites located in the southern tributaries of the Oldman River are considered a distinct group in parts of the analyses in this study. The length of tree ring records varies significantly at different chronology sites. The longest records available in the North Saskatchewan and Oldman subbasins date back to the 1000s and 1300 s, respectively, while the shortest record used begins at 1800 A.D.

Most of the tree ring chronologies are from low elevations and dry sites, south and west-facing slopes with thin soils. The sites were chosen for the lack of availability of soil moisture except during snowmelt or after a rain. Thus, they record intervals when precipitation is lacking. The moisture sensitivity of these chronologies has been previously verified in terms of the consistently positive and significant correlations between

Table 1. List of Chronology Sites and Their Tree Species, Associated River Basins, and Data Availability[a]

River Basin	Number	Chronology Site (Code)	Tree Species	Latitude	Longitude	Elevation (m)	Data Available From
North Saskatchewan	1	BSG	PG	52.6	−116.6	1810	1730
	2	DEA	PM	52.19	−116.44	1320	1520
	3	WIP	PF	52.15	−116.4	1315	1750
	4	WRC	PM	52.072	−116.388	1420	1620
	5	TWO	PM	52.06	−116.43	1560	1540
	6	SFR	PF	52.048	−116.398	1390	1038
	7	WPP	PF	52	−116.45	1356	1110
	8	SKC	PF	51.97	−116.72	1423	1680
	9	OCPc	PC	49.7	−114.1	1280	1790
Bow	10	JOLA	PM	51.96	−115.491	1405	1446
	11	WCH	PM	51.3	−114.7	1351	1390
	12	SIP	PM	51.1	−115	1250	1740
	13	UPLA	PE	50.609	−115.119	1730	1660
Oldman	14	WCK	PM	50.088	−114.141	1536	1750
	15	CAL	PM	50	−114.2	1677	1640
	16	BMN	PF	49.93	−114.03	1297	1580
	17	LBC	PM	49.9	−114.2	1602	1610
	18	OMR	PM	49.9	−114.2	1331	1370
	19	BDC	PM	49.9	−114.2	1661	1550
	20	OMRw	PF	49.8	−114.2	1427	1640
	21	WSC	PM	49.9	−114.1	1575	1570
	22	DCK	PM	49.9	−114.4	1648	1660
	23	BCK	PM	49.81	−113.94	1592	1660
	24	CAB	PM	49.7	−114	1395	1440
	25	HEM	PF	49.66	−113.78	1308	1510
	26	ELK	PF	49.6	−114.6	1384	1540
	27	BVL	PM + PF	49.4	−114.1	1427, 1567	1730
	28	TAB	LL	49.31	−114.43	1838	1616
Southern Tributaries	29	LEE	PF	49.14	−113.45	1258	1579
	30	LEC	PM	49.14	−113.45	1258	1758
	31	BZR	PF	49.1	−113.46	1468	1570
	32	CMT	PM	49.07	−113.9	1284	1500
	33	BND	PM	49.007	−113.895	1297	1800

[a] The processed record for each chronology site starts at the given year above and ends at 2001 with no gaps. PG for *Picea glauca*, PM for *Pseudotsuga menziesii*, PF for *Pinus flexilis*, PC for *Pinus contorta*, PE for *Picea engelmannii*, and LL for *Larix laricina*.

annual and summer precipitation and standardized ring width [e.g., *Axelson et al*., 2009; *Sauchyn et al*., 2011]. For the same network of sites, positive correlations between temperature and ring width are rare.

In the University of Regina Tree-Ring Lab, increments of annual growth were measured to within 0.001 mm from high-resolution (1200+ dpi) images of polished wood samples using WinDendro Density, a semiautomated image analysis system designed for tree rings. The measured tree ring series were standardized using the program ARSTAN [*Cook*, 1985], applying conservative detrending by a negative exponential curve, used to remove the juvenile biological growth trends in the tree ring series. Appropriate detrending of tree ring width records is important, as low-frequency trends in tree ring width time series due to long-term climate variations may not be easily distinguishable from age-dependent biological growth trends. The description of different detrending methods in dendrohydrology can be found in *Fritts* [1976] and in *Cook and Briffa* [1990]. The standardized ring-width series were averaged for each site, using a mean value function that minimizes the effects of outliers. The resulting time series of the "standard index chronology" possesses a mean value of about unity (for sufficiently long time series), which corresponds to the normal growth rate. In this paper, the terms "standard index chronology," "standard chronologies," "growth rate," and "growth index" are used interchangeably. A full description of the methods used for building the chronologies is available in *Axelson et al*. [2009] and *Sauchyn et al*. [2011].

In this study, we directly analyzed the standard chronologies rather than the further processed products such as "residual index chronologies," which are obtained by fitting an autoregressive moving average (ARMA) model to the entire standard index chronology time series and calculating the residuals [*Cook*, 1985]. Although residual index chronologies do not possess any noticeable autocorrelation when the autocorrelation is calculated over their full-length period, in their subperiods, there may still exist some significant, positive or negative, autocorrelation structure. More importantly, ARMA models are capable of

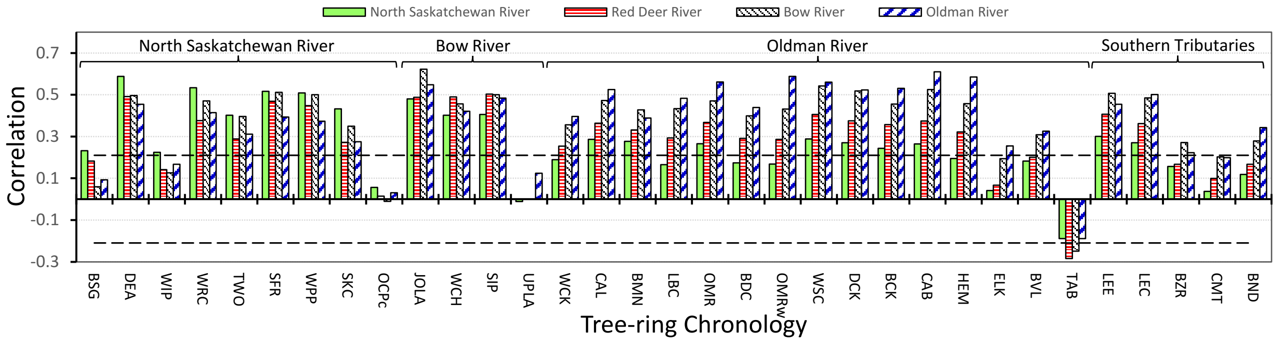

Figure 2. Linear correlation coefficients between the standard chronologies and the average water year flows in North Saskatchewan, Red Deer, Bow, and Oldman Rivers—the dashed lines represent 5% two-tailed significance levels.

modeling not only short-term persistence in time series but also their long-term variabilities. Therefore, there is a significant risk that residual index chronologies may be emptied of long-term-variability information available in the associated standard chronologies.

4. Methods and Results

4.1. Analysis of Regional Spatiotemporal Consistency of Chronologies

In this section, the standard chronologies and observed streamflows are analyzed to evaluate their dependence structure, consistencies, and spatial variabilities over time, and autocorrelation structure. First, the correlation coefficients between the average water year (September to August) naturalized streamflows and the standard chronologies at the 33 tree ring chronology sites over the historical period are evaluated (see Figure 2). There is a range of correlation coefficients from negligible to significant between the streamflows and index chronologies at different sites—the highest correlation coefficient is 0.62, which is calculated between flows in the Bow River and the JOLA chronology site. Flows in the North Saskatchewan River are significantly correlated with the chronologies located in its own basin, while the correlation with farther chronologies located in the Oldman basin is substantially reduced. In contrast, flows in the Oldman River demonstrate large correlations not only with its neighboring chronologies, but also with the chronologies located in the North Saskatchewan basin. The three chronology sites that show insignificant correlations with the flows, UPLA, OCPc, and TAB, are discarded in the rest of the analysis. In common with established dendrohydrological practice, the subsequent analyses assume that unexplained effects do not confound the interpretation of results.

4.1.1. Clustering Analysis of Chronologies

Agglomerative hierarchical clustering analysis [*Johnson*, 1967] is used to assess the correlation structure (similarities/dissimilarities) of the annual series of different chronology sites across the basin over the common period 1800–2001. The "similarity" of two individual chronology sites in this study (the clustering "distance metric") is assessed in terms of the correlation coefficient. To assess the similarity between two clusters of chronology sites, the "furthest distance" is used, which is the furthest distance among all the pairs of individuals in the two clusters. This cluster analysis provides useful information on how and to what extent different groups of chronology sites behave similarly over time. Possible dissimilarities between groups of chronologies imply that they respond to different climate signals and may carry different sources of information, potentially useful for reconstruction of paleo-hydrology.

Figure 3 shows the resulting dendrogram, which represents a hierarchy of clusters of chronology sites. The numbers shown on the different clusters represent the minimum correlation coefficients between all the pairs of sites in the corresponding clusters. In other words, the correlation coefficient of any pair of sites in a cluster is equal to or greater than the given number. The maximum and minimum correlation coefficients between all pairs of sites are 0.90 and -0.15, respectively. Three meaningful clusters (i.e., groups of sites) can be identified, corresponding to the three basins of the Oldman, Bow, and North Saskatchewan Rivers. These three clusters are referred to as the "main clusters" of the three basins in the rest of this paper. The

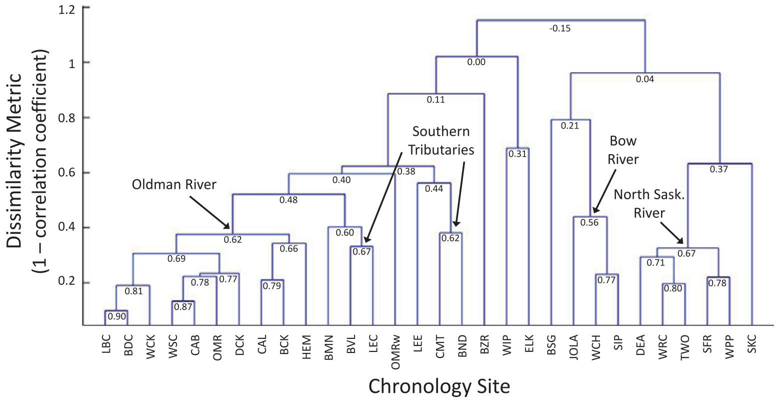

Figure 3. Dendrogram of the chronology sites located across the tributaries of SaskRB based on the agglomerative hierarchical clustering analysis—the correlation coefficient used as the clustering distance metric and the number shown on each of the clusters represents the minimum correlation coefficient between all the pairs of sites in the cluster.

correlations among the chronology sites located in the basin of Southern Tributaries are not sufficiently significant to form a unified cluster, despite their geographical proximities. The chronology sites not belonging to any of these clusters behave relatively independently.

4.1.2. Regional Consistency of Chronologies

Figure 4 is designed to evaluate the consistency of the growth rate time series over time at different chronology sites across the basin. This plot, which is inspired by the widely used double mass curve for checking consistency in hydrologic variables [*Duggal and Soni*, 1996], compares the cumulative growths over time (i.e., the cumulative index chronology) at different chronology sites. A cumulative time series is assumed to be consistent in this context if it generally follows a straight line with the slope of unity (the average annual growth rate is one) and only deviates from the line within a range that is visually consistent with other chronology sites. By this means, the cumulative time series that significantly deviate from the general low-frequency trend (i.e., cyclic trends with long periods) existing in other time series (possibly due to poor detrending) can be identified. According to Figure 4, the chronology sites CMT and LEE, which are in close proximity, demonstrate some significant low-frequency trends that are not consistent with the rest of the chronology sites, and therefore, are discarded in the rest of the analysis. In terms of higher-frequency

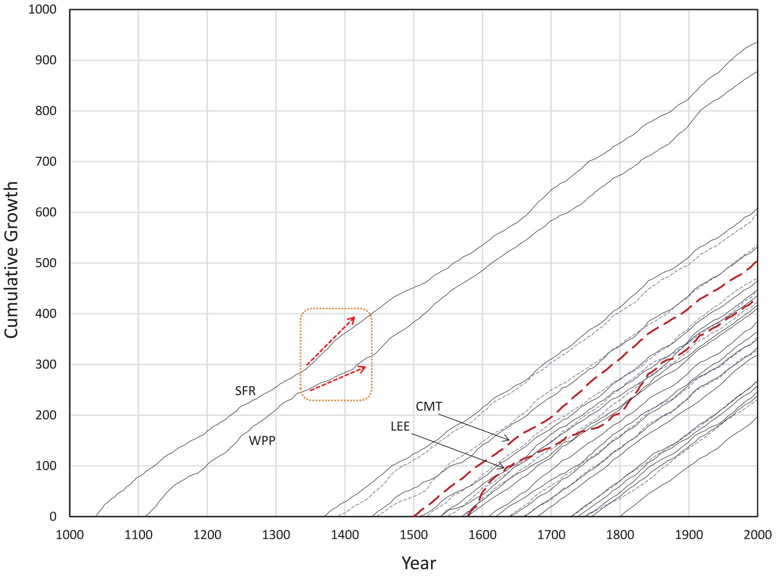

Figure 4. Cumulative standard chronologies (i.e., cumulative growth over time) at different chronology sites across the SaskRB—a cumulative time series is assumed to be consistent if it generally follows a straight line with the slope of unity, relatively consistently with other sites in the basin.

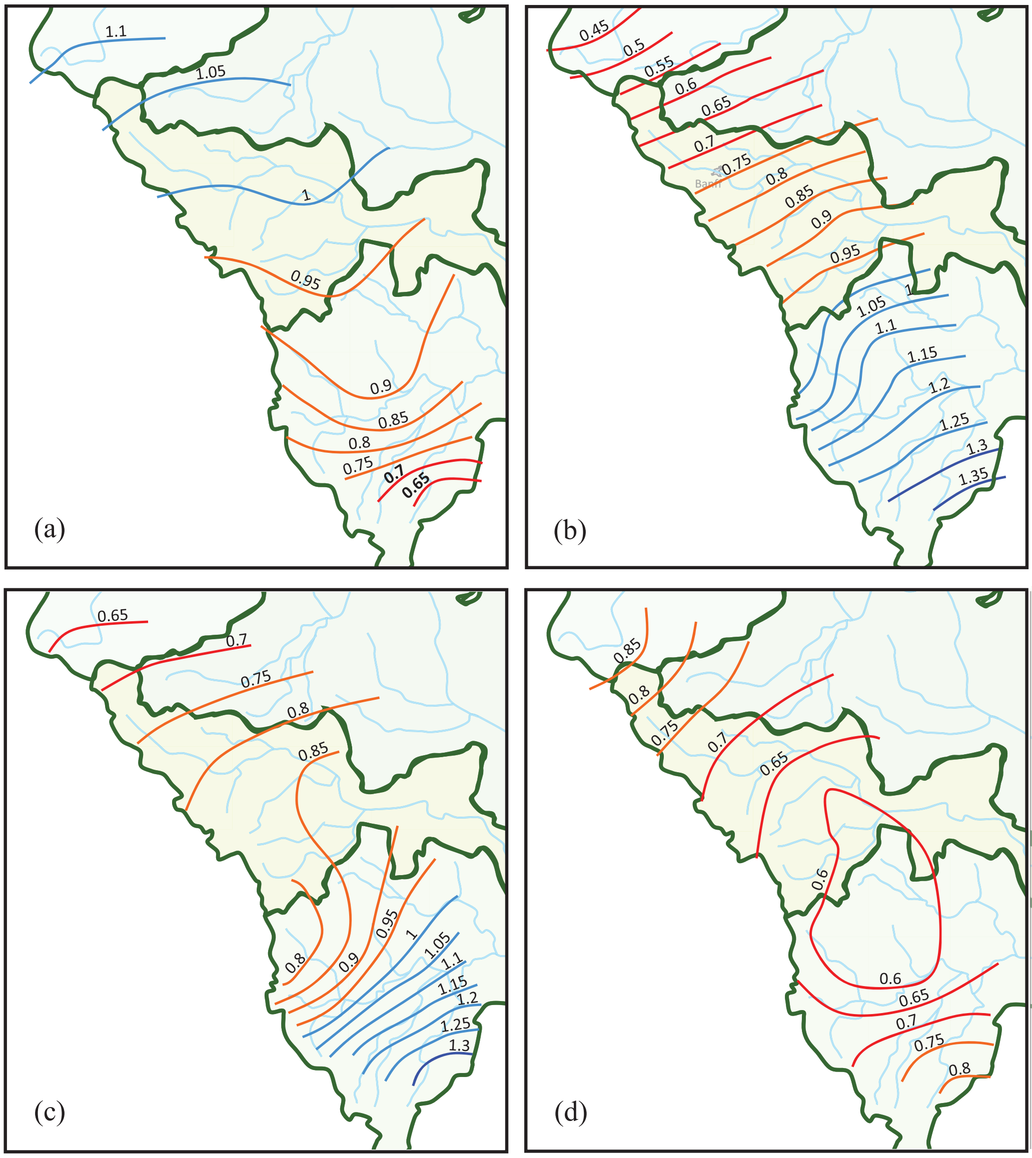

Figure 5. Contour maps of 5 year average growth rates (average index chronologies) across the tributaries of SaskRB at different periods: (a) 1687–1691, (b) 1714–1718, (c) 1841–1845, and (d) 1934–1938—contour values equal or greater than one represent the normal or higher growth (wet) conditions and the values smaller than one represents poor growing (dry) conditions.

trends, differences between some of the chronology sites at certain periods of time can be discerned, indicating that in the same periods, they might have experienced different hydroclimatic conditions. Such differences may seem significant in some cases. For example, see the divergence of SFR and WPP in the period 1330–1400 as marked on Figure 4.

4.1.3. Contour Maps of Paleo-Periods

Figure 5 shows the contour maps of the average growth rate over four 5 year periods (i.e., 5 year average standard chronologies) across the headwaters of SaskRB, interpolated using kriging. Only the growth rate data at the chronology sites that demonstrate significant correlation with annual streamflows during the historical period in their corresponding basins have been used to generate these maps. Given that the growth rate is a proxy for the hydrologic condition (wetness and dryness), such contour maps allow investigation of the spatial variability of available water over time. In this figure, the growth rate of unity corresponds to the normal growing condition (i.e., normal hydrologic years) and the rates greater/smaller than one suggest wet/dry hydrologic years—the standard deviation of growth rate over time in our data set is about 0.3. The four contour maps shown in Figure 5 are samples of a variety of situations that have occurred in the basin and been reflected in our paleo-records. For example, according to this figure, in the period 1714–1718, the growth rate was very low in the northern part of SaskRB, indicating an extremely dry condition, whereas the southern part of the basin experienced wet conditions. This trend is reversed in the period 1687–1691, such that the southern areas were dry, while the North was above normal wetness. The contour map of 1841–1845 is relatively similar to that of 1714–1718 in pattern, with a larger gradient in the south and milder gradient in the north. The contour map of 1935–1939 represents a situation of below normal everywhere across the basin, when the Bow and Oldman Rivers were the driest and the North Saskatchewan River was the least dry basin of all. Notably, the spatial pattern of growth in this last period is fully consistent with the measured streamflows for the same period in the North Saskatchewan, Red Deer, Bow, and Oldman Rivers.

4.2. Identification of Nonstationarities

Under the validated assumption that the growth rates of trees, represented by standard chronologies, are reliable proxies for hydrology, we directly investigate the existence and significance of nonstationarities in the statistical properties of the time series of index chronologies. We attempt to evaluate how well the available data in the period of observational record (i.e., 1913–2001) are representative of the longer-term behavior of the system. To this end, for each chronology site, the statistical properties of the segment of the time series that overlaps with the period of observational record are compared with the statistical properties of the full-length time series.

4.2.1. Changes in the Mean and Autocorrelation

Figure 6 shows the scatterplots of the mean, standard deviation, and lag-1 autocorrelation of chronologies in the historical period versus the same properties calculated over the full available records at each site. The ideal lines in the plots represent stationarity in the associated statistical properties. Figure 6a indicates that the mean growth in the North Saskatchewan River basin over the historical period is an *overestimation* of the long-term mean growth in this basin. In contrast, in the Oldman River basin, the mean growth over the historical period is an *underestimation* of the long-term mean growth in the basin. In terms of the standard deviation, however, the chronology sites at different basins are better scattered around the ideal line, with marginal tendency toward underestimation (see Figure 6b). According to Figure 6c, the autocorrelation is slightly to significantly underestimated for the majority of the chronology sites.

Further, a window with the length of the period of observational record (89 years) is shifted along the full length of each time series of growth rates, and the changes in the statistical properties over time (calculated on the portion of the time series within the window) are evaluated. Figure 7 shows the time series of the 89 year moving mean at the chronology sites of the main clusters (identified in section 4.1.1) for the North Saskatchewan, Bow, and Oldman Rivers. The values of the 89 year moving mean vary significantly over time at all the chronology sites. The majority of the chronology sites within each basin behave relatively consistently over time relative to each other, but are different from the chronology sites of the other basins. The consistencies for each basin, however, diminish for the time periods around and prior to 1600, particularly for the North Saskatchewan River, where the values of the mean growth at the chronology sites with the longest records diverge significantly (also already represented in Figure 4). These inconsistencies challenge the reliability of the reconstruction of paleo-hydrology for any time period prior to 1600, based on the currently available tree ring data. The time series of the 89 year moving mean for different chronologies of the Oldman River basin seem to behave more consistently than those of the North Saskatchewan River basin.

Figure 8 shows the time series of the lag-1 autocorrelation calculated over the 89 year moving window along the full records of chronologies in North Saskatchewan and Oldman Rivers. The average autocorrelation time series at each basin represents the autocorrelation of a time series obtained by averaging the time series of all the chronology sites located in the main cluster of that basin. As can be seen, the autocorrelations at all chronology sites vary significantly and relatively coherently with time. Unlike the mean, the variations in the autocorrelations are quite similar for the North Saskatchewan and Oldman Rivers. However, the two chronology sites in the North Saskatchewan River with the longest records demonstrate inconsistent autocorrelations in the period around 1400–1750, when the autocorrelations decline significantly (even below zero) at times.

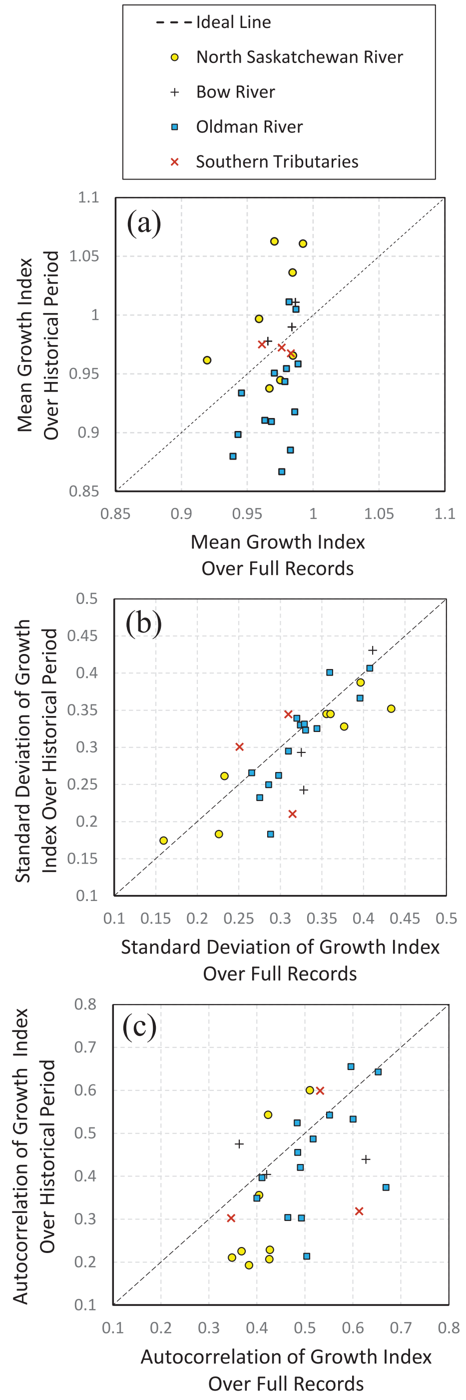

Figure 6. Scatterplots of statistical properties of growth rates (index chronologies) over the historical period (1913–2001) versus the same properties over the full records at all chronology sites.

4.2.2. Significance of Changes in Statistical Properties

To approximate the distribution of the statistical properties (the mean and autocorrelation of growth rates) of the underlying population of the data in the period of observational record, the bootstrapping technique [*Efron and Tibshirani*, 1994] is used. Bootstrapping involves random sampling with replacement from the dataset (resampling the sample data) and allows estimation of the sampling distribution of different statistics. This technique provides confidence limits on the statistical properties of the information available in the period of observational record, thereby providing benchmarks for demonstrating the magnitudes of changes in statistical properties (nonstationarities) when going beyond the period of observational record. The block bootstrap method of *Politis and Romano* [1994], which uses random block lengths with a geometrical distribution, is used in this study to replicate the dependence in the time series. For each of the mean and autocorrelation at a basin, 10,000 sets are generated, each with 89 members randomly sampled with replacement out of the 89 year historical period. The statistical properties of each set are calculated, resulting in 10,000 samples of the mean and 10,000 samples of autocorrelation. The generated samples of the mean and autocorrelation statistics are used to empirically approximate their distributions for each basin.

In addition, two statistical tests, *t* test (parametric) and Wilcoxon rank sum test (nonparametric), are used to evaluate if changes in the mean and median properties of the time series over time are statistically significant. Their null hypotheses are that the two samples are from (1) normal distributions with equal means and unknown variances (for *t* test), or (2) distributions with equal medians (for Wilcoxon rank sum test). In this study, different segments of the time series are tested against other segments, particularly the historical period (1913–2001) for which observed flows are available, and the significance levels at which the null hypotheses are rejected by the two tests are calculated.

Figure 9 shows the cumulative distribution functions of the mean statistic of annual growth inferred from the data in the historical period. In this figure, 5% and 95% percentiles can be interpreted as 90% bootstrapping confidence limits on the estimation of the mean based on the historical sample. Figures 10a and 11a show the time series of annual growths averaged across the main clusters of chronologies of the North Saskatchewan and Oldman basins, respectively, and Figures 10b and 11b show their 89 year moving means along with the 90% and 95% confidence intervals estimated through bootstrapping of data in the historical period (from Figure 9). Both of the time series of Figures 10b and 11b go well beyond their associated confidence

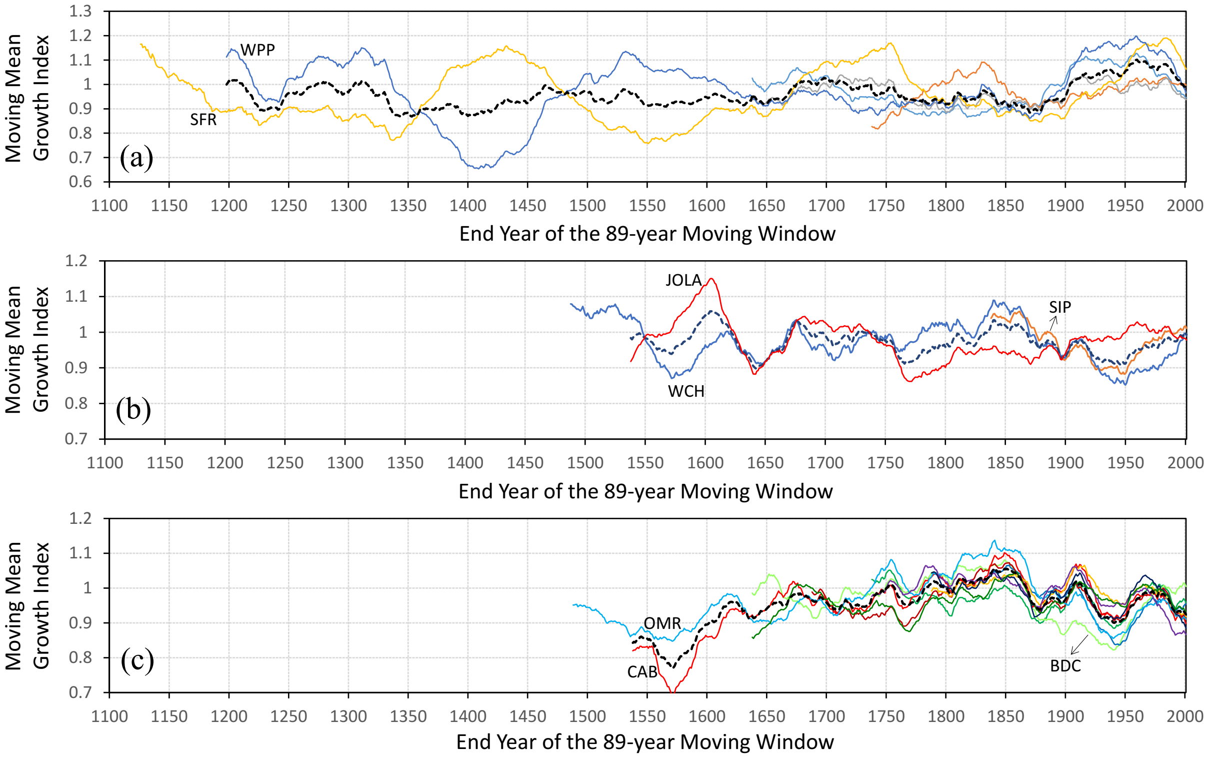

Figure 7. Time series of moving mean index chronologies with a moving window of 89 years, for the chronology sites of the main clusters of (a) North Saskatchewan River, (b) Bow River, and (c) Oldman River—the dark dashed lines represent the mean time series averaged over all the chronology sites in the main clusters of the basins.

limits at some periods in time, indicating significant nonstationarities in the 89 year mean. For example, for the North Saskatchewan River basin, the mean of the 89 year periods ending between 1920 and 1980 is significantly larger than the mean over the historical period. Notably, in the period 1770–1880, when the values of the 89 year mean in Oldman River are significantly higher than the associated upper confidence limit, the corresponding values in North Saskatchewan River are fluctuating around the associated lower confidence limit. This observation implies that when the Oldman River basin was experiencing very wet conditions, the North Saskatchewan River basin was under dry conditions.

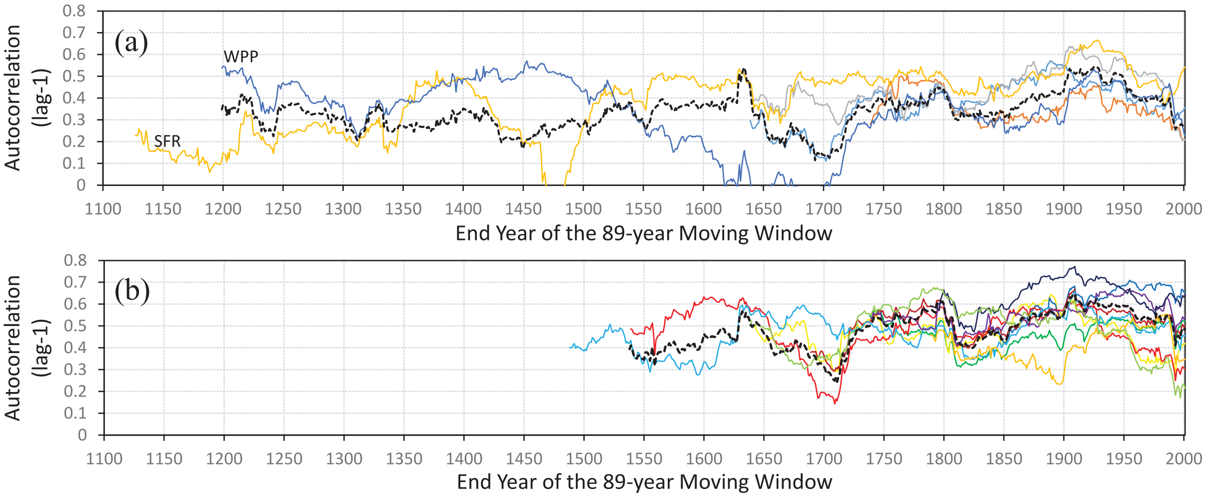

Figure 8. Time series of lag-1 autocorrelation in index chronologies based on a moving window of 89 years, for the chronology sites of the main clusters of (a) North Saskatchewan River and (b) Oldman River—the dark dashed lines represent the autocorrelations of time series averaged over all the chronology sites in the main clusters of the basins.

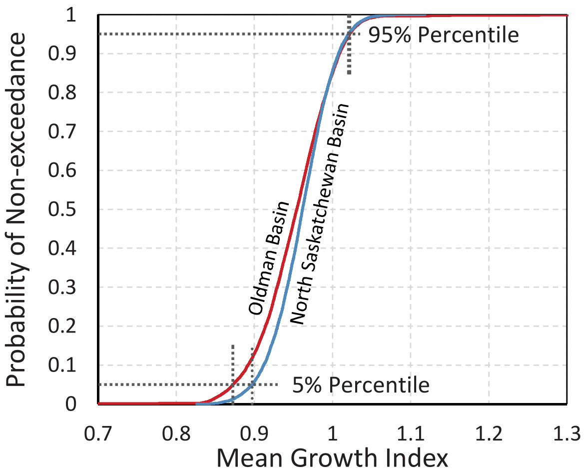

Figure 9. Cumulative probability functions of the mean statistic of annual growth rates over the historical period (1913–2001), obtained by bootstrapping.

Figures 10c and 11c show the significance levels at which the null hypothesis is rejected by the *t* test and Wilcoxon rank sum test for different 89 year periods compared with the historical period. For example, in the North Saskatchewan basin, with a significance level of 0.01 according to *t* test, the 89 year period ending at 1400 (the period 1312–1400) is from a different population distribution than that of the historical period. As an example in the Oldman basin, the 89 year period ending at 1850 (the period 1762–1850), with a significance level of 0.003 according to *t* test, is from a different population distribution than that of its historical period. With higher significance levels (say 0.1), there are multiple periods in the history of the hydrologic behavior of the two basins for which the mean and median properties are significantly different from those of the historical period.

Figure 12 shows the time series of the lag-1 autocorrelation of annual growth rates calculated on the 89 year moving window for the North Saskatchewan and Oldman basins, along with the inferred 90% confidence intervals on the estimation of the lag-1 autocorrelation. In both basins, the lag-1 autocorrelation statistic varies significantly with time and goes beyond the 90% confidence limits at some time periods.

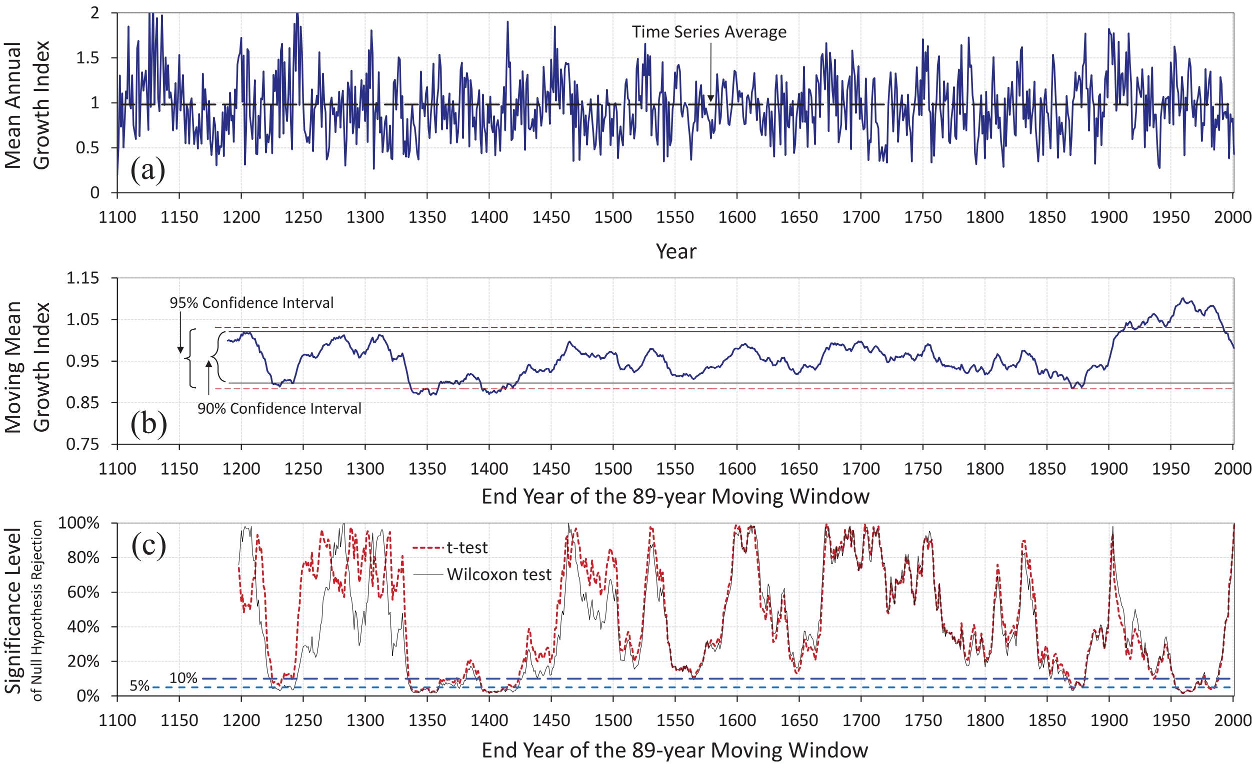

Figure 10. (a) Time series of annual growth averaged across the main clusters of chronologies of the North Saskatchewan basin, (b) 89 year moving mean of the time series shown in Figure 10a along with 90 and 95% confidence intervals of the mean statistic estimated through bootstrapping of data in the historical period, and (c) significance levels of *t* test and Wilcoxon rank sum test at which the null hypothesis is rejected—for any given time window of 89 years, the null hypothesis is that the 89 year sample and the historical period sample are from the same population.

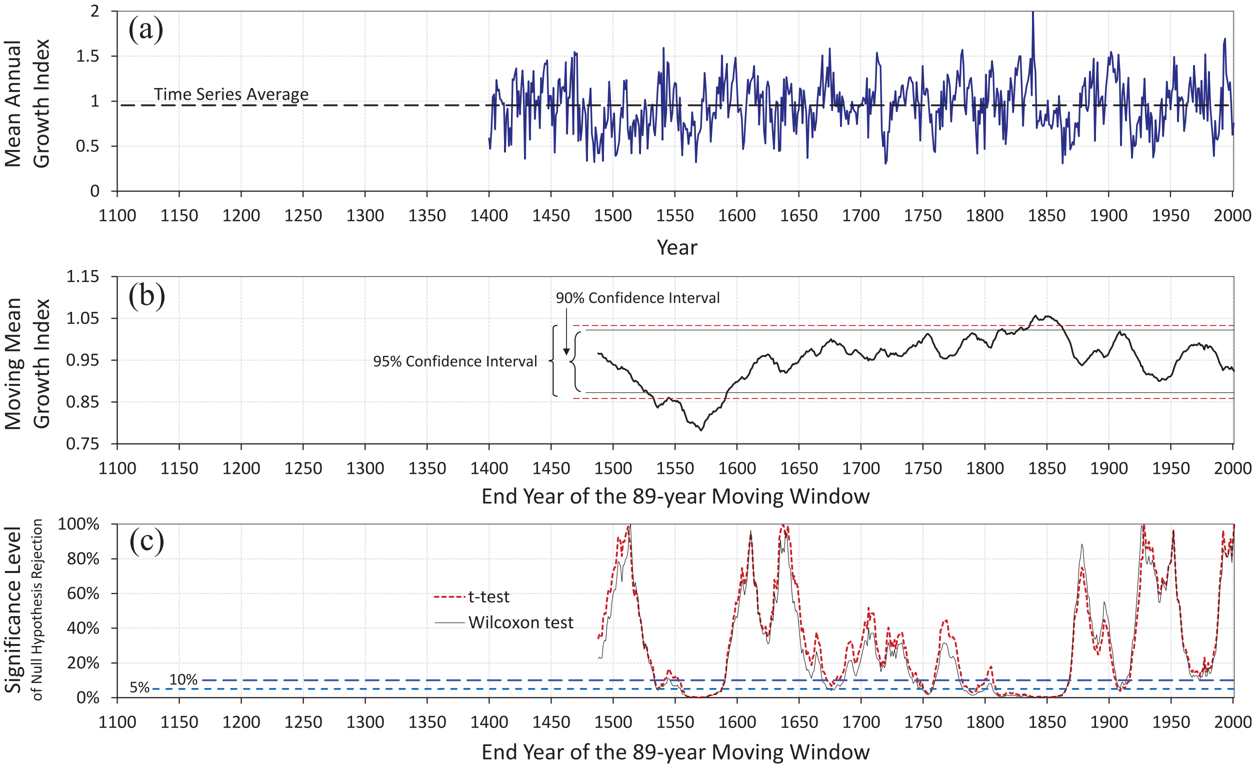

Figure 11. (a) Time series of annual growth averaged across the main clusters of chronologies of the Oldman basin, (b) 89 year moving mean of the time series shown in Figure 11a along with 90 and 95% confidence intervals of the mean statistic estimated through bootstrapping of data in the historical period, and (c) significance levels of *t* test and Wilcoxon rank sum test at which the null hypothesis is rejected—for any given time window of 89 years, the null hypothesis is that the 89 year sample and the historical period sample are from the same population.

For all the 89 year periods ending between 1910 and 1965, the lag-1 autocorrelation in the North Saskatchewan basin is significantly greater than the lag-1 autocorrelation of data in the historical period. Interestingly, the temporal patterns of the changes in lag-1 autocorrelations at the two basins are quite similar.

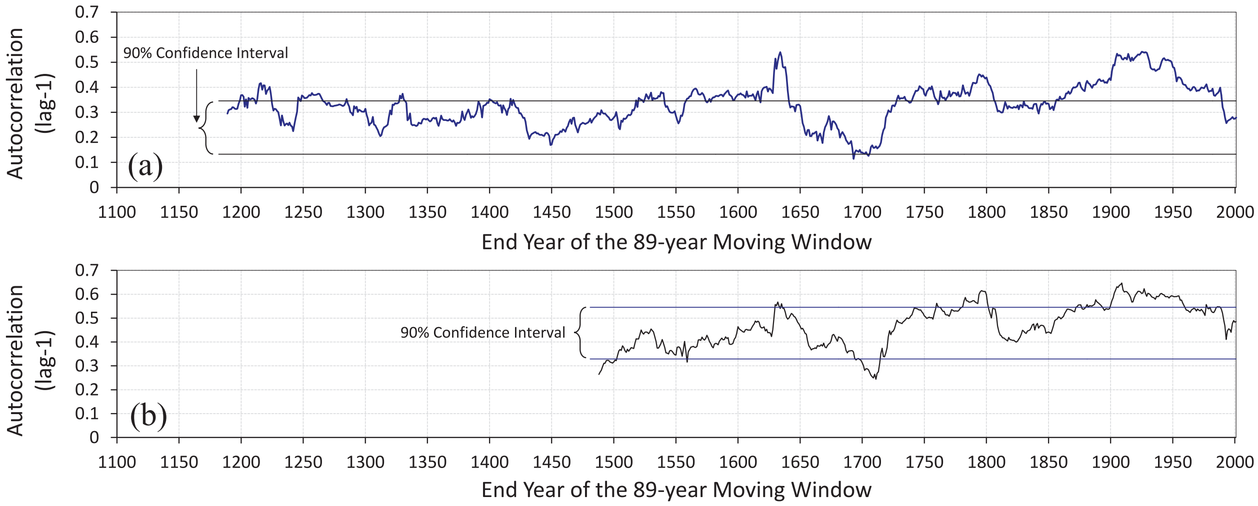

Figure 12. Time series of lag-1 autocorrelation of the index chronologies calculated based on the 89 year moving window for (a) North Saskatchewan and (b) Oldman Rivers, along with 90% confidence intervals on the autocorrelation based on bootstrapping the information available in the historical period.

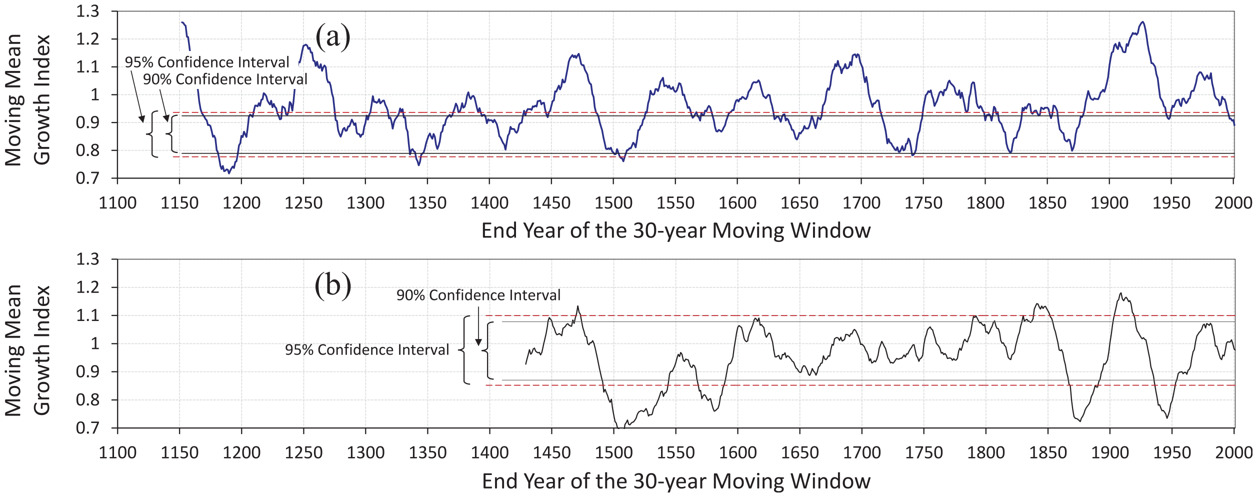

Figure 13. The 30 year moving mean of the growth time series in the (a) North Saskatchewan and (b) Oldman basins along with 90 and 95% confidence intervals of the mean statistic estimated through bootstrapping of data in the last 30 years of the historical period.

Similar to Figures 10b and 11b, Figure 13 shows the 30 year moving mean of the growth time series in the North Saskatchewan and Oldman basins benchmarked against 90 and 95% confidence intervals of the mean statistic estimated through bootstrapping of data in the last 30 years of the historical period. For further quantification of the extent of nonstationarity, a test is designed in which all possible pairs of sample periods (here each 30 years long) out of the full time series are tested for the null hypothesis that the two samples are from the same population. This test also explores the widely used assumption in the hydrologic

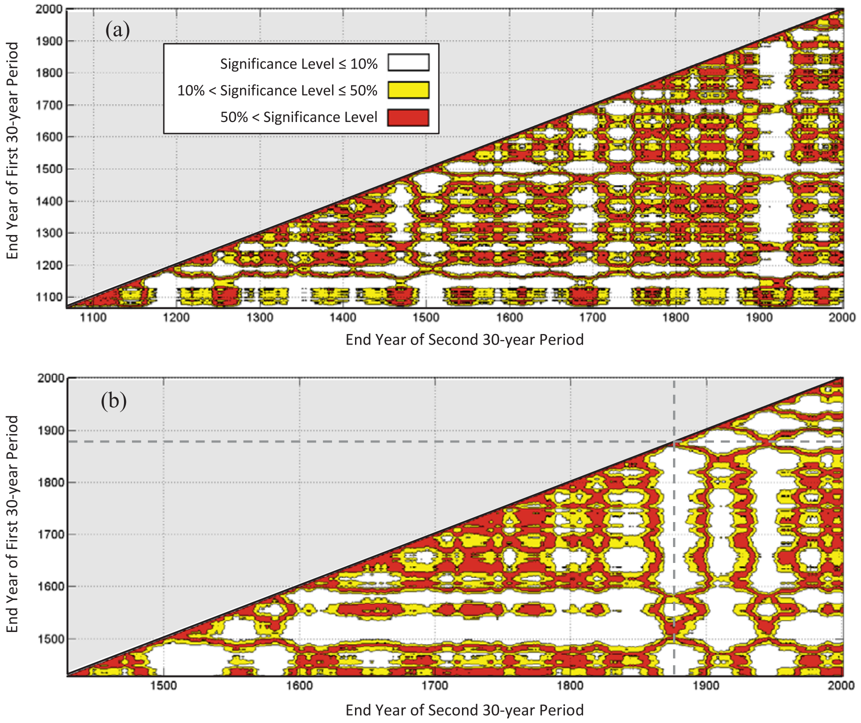

Figure 14. Nonstationarity maps demonstrating the significance of nonstationarity along the paleo-hydrologic proxy time series of the (a) North Saskatchewan and (b) Oldman river basins—two different 30 year periods are moved along the time series and the significance level of *t* test for every pair of periods at which the null hypothesis is rejected is plotted—the null hypothesis is that the two selected 30 year periods (samples) are from the same population.

engineering community that a period of 30 years is sufficiently long to capture the properties of the hydrologic regime in a region. Figure 14 shows the results of the new test for the North Saskatchewan and Oldman basins, which maps the significance level for any pair of periods at which the null hypothesis is rejected. As an example, in the Oldman basin, the 30 year period ending at 1875 possesses a mean which is significantly different from the mean of almost any other 30 year period (null hypothesis is rejected with significance level of 10% or lower). In Figures 14a and 14b, the ratios of the area representing the significance level of 10% and under to the total area are 37% and 44%, respectively. The ratios for the significance levels of 1% and under are 16% and 25% (these areas are not shown in the figures). These results highlight the large extent of nonstationarity in these time series. Also evidently, in this region, a period of 30 years is by no means representative of the long-term statistical properties of the hydrologic regime.

Note that the growth rates (and also hydrologic variables) in individual years are not *independent* of those of the other years in any period of the records, as there is significant short and long-term persistence in the time series. Also, the data in the periods specified by the moving window ending anywhere in the historical period have a portion (one or more years) in common with the historical period based on which the bootstrap and tests were conducted. In the analyses with *t* test and Wilcoxon test, such dependence is assumed negligible to facilitate the methods used.

5. Conclusions

The observed streamflows in the major tributaries of the Saskatchewan River Basin demonstrate significant correlations with the concurrent growth rates of trees in the basin. This is the basis of the *main assumption* in this study (and dendrohydrology in general) that index chronologies are reliable proxies for hydrologic conditions in centuries preceding the period of observational record. By providing empirical support for this assumption, our analysis implies that stationarity might never have existed in the hydrology of the region. The long-term mean property of streamflow time series in SaskRB has undergone significant changes over time. These changes in each major tributary in terms of the long-term mean were not always in harmony with the changes in other tributaries, indicating a time-varying cross-correlation structure across SaskRB.

There may also have existed significant nonstationarities in the autocorrelation structure of the streamflow time series over the last couple of centuries. Unlike the mean statistic, however, the changes in the autocorrelation structure over time are in complete harmony in the major tributaries of SaskRB. This suggests that the changes in autocorrelation are not an artifact of the changes in the mean in a tributary, which tends to change relatively independently from other tributaries. This is one of only a few studies investigating changes in the autocorrelation structure of observational or paleo-records. These findings may trigger further research on this topic and in other study areas. Note that biological uncertainty due to our incomplete mechanistic understanding of growth of most tree species should be kept in mind as a caveat [*Cook and Pederson*, 2011]. It has been shown that the autocorrelation structure of tree ring time series is partly biological and definitely partly climatic [*Wettstein et al*., 2011]. The physiological growth patterns of trees, which are a long-term product of evolution, may also partially explain the harmonious change in autocorrelation structure.

This study demonstrates that the available period of observational record (89 years) may not be an accurate representative of the hydrologic regime in the region (at least in annual time scale). Shorter period lengths, e.g., 30 years, can be seriously misleading in calculating the statistical properties of the hydrologic time series, due to the extensive nonstationarities observed in this time frame. Although the proper length of the time window to investigate the extent of nonstationarity in hydroclimatic time series remains an open question, for design purposes, it can be arguably related to the periods of observational record for the hydrologic variable of interest. The dependence of stationarity/nonstationarity conclusions on the window length suggests that the traditional statistical definition of stationarity may need to be improved and tailored in the hydrologic context to reflect such dependence. Given that shorter time windows may generally lead to stronger nonstationarity conclusions in a hydrologic time series and vice versa, attaching the analytical window length to the definition seems warranted. For example, a hydrologic time series can be 30 year nonstationary (i.e., nonstationary when the window length is 30 years), while being 200 year stationary. Paleo-hydrologic proxy records can be very helpful in this regard to properly contextualize the periods of observational record.

The possible existence of significant nonstationarities in the mean and autocorrelation has important implications for the research activities that attempt to stochastically generate realizations of long streamflow time series. Such stochastically generated streamflow time series are ideally intended to embed all possible hydrologic situations that can occur in a basin. Therefore, any technique used to simulate the underlying stochastic process in a basin needs to be capable of incorporating the nonstationarities, at least in the first and the second-order statistical properties. In this regard, the validity of the conventional autoregressive and autoregressive moving average models that are designed to simulate and preserve statistical properties of the (typically short) period of observational record in a static fashion needs to be treated with caution.

Acknowledgments
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