Long Hydroclimate Records from Tree-Rings in Western Canada: Potential, Problems and Prospects

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Abstract: Tree-ring chronologies from moisture-sensitive sites can provide annually resolved proxy records for precipitation, streamflow and other hydrological variables for periods several hundred years longer than available instrumental records. This paper reviews some previous North American work in this field (concentrating on western Canada), examining the limitations and potential of these studies with specific examples from ongoing research in the Canadian Cordillera. Although they cannot be used to predict future flows or precipitation, proxy data can document the long-term natural variability and periodicities of these phenomena—information vital for better approximations of future probabilities. In addition, by establishing relationships between hydrometeorological variables and persistent modes of atmospheric and oceanic circulation, such research may provide some predictive skill in short-term forecasting.

Résumé : Les dendrochronologies obtenues dans les zones sensibles à l’humidité peuvent fournir des relevés climatiques indirects avec une résolution annuelle pour les précipitations, les débits des cours d’eau et les autres variables hydrologiques pour des périodes plus longues, de centaines d’années, que les relevés instrumentaux disponibles. Le présent article s’intéresse à certaines études nord-américaines antérieures dans le domaine (en mettant l’accent sur l'Ouest canadien) et examine les limites et le potentiel de ces études à l’aide d’exemples précis tirés de recherches permanentes dans la Cordillère canadienne. Bien qu’ils ne puissent servir à prédire les précipitations ou les débits futurs, les relevés climatiques indirects peuvent attester de la variabilité naturelle à long terme et des périodicités de ces phénomènes. Il s’agit là de données essentielles à de meilleures approximations des probabilités futures. De plus, grâce à l’établissement de liens entre les variables hydrométéorologiques et les modes persistants de circulation atmosphérique et océanique, de telles recherches peuvent donner lieu à des capacités prévisionnelles dans les prévisions à court terme.

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Introduction

Fresh water will be an increasingly scarce resource in the more crowded, warmer world we will experience with ongoing Global Changes. Future changes in the amount, seasonality and quality of water will be critical determinants of human activities: increasing demand coupled with changes in both the volume and timing of runoff will create severe water supply problems that will require effective management and mitigation strategies (Barnett et al., 2004). Warmer winter temperatures are expected to result in reduced snowpacks and greater winter rainfall, changing seasonal hydrograph characteristics for many rivers (Beniston et al., 2003; Detttinger et al., 2004; Stewart et al., 2004). Continued reduction of glacier areas will have considerable effects on late summer flows in glacier-fed streams from the mountains (Beniston, 2004). Realistic estimates or models of probable changes are urgently required as the basis for informed management decisions. However, future changes will be superimposed on existing natural variability and it is therefore necessary to have better estimates of the full range of that variability than existing instrumental records can provide. Mountains have been described as the “Water Towers of the Continents” (Mountain Agenda, 1997) providing water to adjacent, often drier, lowlands. Tree-ring records from mountain areas can provide long, annually resolved, proxy records of precipitation, streamflow and glacier mass balance for the last 200 to 600 years. These proxy records allow the exploration of linkages between sea surface temperatures (SSTs), atmospheric circulation, precipitation and streamflow over longer intervals than instrumental records providing critical information for long-term planning of water resources that are vital to many economic activities.

This paper outlines the types and quality of information that can be obtained from tree-ring based records of past moisture conditions using examples from western Canada. The paper begins with a brief introduction to dendrochronology and dendroclimatology. This is followed by a brief synopsis of previous dendrohydrological work conducted in western Canada. The balance of the paper focuses primarily on examples from our own work reconstructing precipitation, streamflow and winter glacier mass balance (discussed here as a proxy for snowpack) and details some of the complexities encountered in reconstructing streamflow generated by snowmelt.

Background

Tree-Ring Reconstructions

Tree-ring chronologies from carefully selected environments can correlate highly with records of local and large scale climate phenomena (e.g., Figure 1a). Standard reviews of the basic sampling and statistical techniques used in dendrochronology are given in Stokes and Smiley (1968), Fritts (1976; 1991) and Cook and Kairiukstis (1990). Chronologies are typically developed by averaging records from duplicate cores from a minimum of ten or more trees at a site. In areas with strongly seasonal growth, each tree ring corresponds to a single growing season with a clear boundary provided by the contrast between the latewood formed near the end of the current growing season (small, dark coloured cells in conifers) and the larger, lighter coloured earlywood cells formed in the subsequent spring. Following the measurement of the width (or density) of each annual ring in the cores, non-climatic growth trends are removed from each series (Cook, 1985). Earlywood and latewood width can also be measured separately to develop chronologies sensitive to conditions during different parts of the current and/or previous growing season (Meko and Baisan, 2001). The measured series are averaged to produce a site chronology. The great strength of tree-ring chronologies is that they are annually resolved, well replicated and rigorous crossdating (Stokes and Smiley, 1968) ensures that they are precisely dated. Correlation coefficients or more complex multivariate response functions (Fritts, 1976; 1991) are used to evaluate the strength and nature of the relationship between the chronology and climate variables. Once these relationships are identified, stepwise multiple linear regression is usually employed to develop a transfer function that can be used to hindcast the climate variable of interest (i.e., the dependent variable in the regression equation). The temporal stability and quality of most reconstruction models are evaluated through rigorous calibration and verification procedures. This cross-validation usually involves splitting the instrumental record in half and developing the model on one-half and verifying it on the other using a suite of statistical tests (Gordon, 1982; Fritts et al., 1990; Cook et al., 1994).

Moisture-stressed trees have been used in many successful hydroclimatic reconstructions in the United States. These include reconstructions of: streamflow
Figure 1. Examples of relationships between tree-growth variability and precipitation from western Canada. (a) Lytton instrumental precipitation plotted with a latewood ring-width chronology from Lytton. (b) Banff instrumental precipitation plotted with a tree-ring reconstruction of precipitation. In both cases, the tree-ring based series clearly depict the timing of positive and negative departures but the magnitude of the variation is not as well captured in the reconstruction (i.e., the variance is somewhat muted). Recent studies have attempted to compensate for this by expanding the variance of the reconstruction to match that of the instrumental period (Cook et al., 2004).
for large and small rivers (Cook and Jacoby, 1983; Meko et al., 2001; Woodhouse, 2001; Woodhouse et al., 2006); spring (Stahle and Cleaveland, 1992) and summer (Meko and Baisan, 2001; Woodhouse and Overpeck, 1998) precipitation; the Palmer Drought Severity Index (PDSI) (Cook et al., 1999); and winter snowpack (Woodhouse, 2003). Perhaps the most widely cited example (Fye et al., 2003) and strongest justification for the long-term perspective that tree-ring reconstructions can provide is for the Colorado River. The Colorado Compact allocated water resources of the Colorado River between the seven American basin states in 1922 and was based on a mean flow of $22 \times 10^9$ m$^3$yr$^{-1}$ from about 15 years of available record. The mean measured flow from 1906 to 2000 is approximately $18.7 \times 10^9$ m$^3$yr$^{-1}$ (Woodhouse et al., 2006), equivalent to the U.S. allocation under the agreement, and the long-term mean (1520 to 1961), based on a tree-ring based reconstruction originally developed by Stockton (1975), is only $16.7 \times 10^9$ m$^3$yr$^{-1}$. The abnormality of the high flows during this reference period (probably the wettest in the last 500 years) gave rise to serious and continuing issues of appropriate water allocation. Woodhouse et al. (2006) have recently developed several new flow reconstructions for the Colorado River using more extensive tree-ring and hydrological databases. Their four long-term reconstructions use different models and yield higher mean flows (range $17.6$ to $18.1 \times 10^9$ m$^3$yr$^{-1}$) than those of Stockton (1975). These differences are ascribed to the data sets and modelling techniques used in the different reconstructions. Nevertheless the underlying message for management is unchanged. These long reconstructions are invaluable in assessing the full range of flow variability, provide context for available instrumental records and can therefore contribute significantly to decisions on future long-term water management strategies.

Long tree-ring based precipitation reconstructions have also proved useful for studying periodicities in drought that may be related to solar and lunar cycles (Cook et al., 1997). Tree-ring chronologies from appropriately targeted areas (i.e., “centres of action” where a significant proportion of local climate variance is related to a large-scale forcing) have been used to reconstruct the long-term behaviour of large-scale oceanic and atmospheric circulation patterns that affect moisture delivery patterns over vast regions and hence impact water resources (Stahle et al., 1998; Gedalof and Smith, 2001; Biondi et al., 2001; Gray et al., 2004). Millennial length tree-ring reconstructions of precipitation and temperature can also be evaluated to examine moisture conditions during warm intervals before the period of instrumental record. An example is the period between 900 and 1300 AD often characterized as the “Medieval Warm Period” (MWP), although this concept has come under strong criticism (Hughes and Diaz, 1994) as climate seems to have been quite variable in the 9th to 13th centuries and we use this term only where used by the authors cited. Several long regional and northern hemispheric temperature reconstructions identified intervals almost as warm as temperatures of the late 20th to early 21st century during the 11th to 13th centuries (Luckman and Wilson, 2005; D’Arrigo et al., 2006; Osborn and Briffa, 2006). Cook et al. (2004) identified “epic drought” in PDSI reconstructions for the western United States during the so-called MWP suggesting that increasing future temperatures may also cause increased aridity.

**Dendrohydrology in Western Canada**

Comparatively few dendrohydrologic studies have been carried out in Canada because the most moisture-stressed environments (e.g., the Prairies) contain few suitable trees and, traditionally, the more northern, cooler and wetter environments in Canada were not considered to have high dendroclimatological potential. The short growing season also restricts the climatic window and therefore the types of parameters that can be reconstructed. Nevertheless, the number of successful studies, often from ‘non-traditional’ environments (Szeicz and MacDonald, 1996), is increasing, providing key information on past variability in western Canada. We briefly outline some of this work below (from Manitoba westward to British Columbia).

Tree-ring chronologies developed from *Quercus macrocarpa* (bur oaks) growing along the Red River in Manitoba have been used to reconstruct annual precipitation for Winnipeg back to 1409 and, in conjunction with an assessment of wood anatomical features, study pre-instrumental floods in the Red River Basin (St. George and Nielsen, 2000; 2002; 2003). Ferguson and St. George (2003) were able to extend records of groundwater levels for Winnipeg...
using estimates derived from a subset of the moisture sensitive bur oak chronologies. In adjacent Saskatchewan, the University of Regina tree-ring laboratory has established a network of moisture-sensitive chronologies beginning with white spruce (*Picea glauca*) in the Cypress Hills area that now extends south into Montana and west into the Rocky Mountain foothills (http://www.parc.ca/urtreelab/). Precipitation and PDSI reconstructions have been developed from this work (Sauchyn and Beaudoin, 1998; Sauchyn and Skinner, 2001; Sauchyn et al., 2003) and more recent work by Beriault (2005) and Beriault and Sauchyn (2006) has resulted in the development of discharge reconstructions for hydrometric stations in the Churchill River Basin using tree-ring chronologies from northern Saskatchewan.

Case and MacDonald (1995) developed four moisture-sensitive *Pinus flexilis* (limber pine) chronologies in the Rocky Mountain foothills of southwestern Alberta that were used to reconstruct local precipitation. These data, in conjunction with a *Picea mariana* (black spruce) chronology from Prince Albert, Saskatchewan, were used to make the first, preliminary reconstructions of streamflow for three sites in the Saskatchewan drainage basin (Case and MacDonald, 2003). Earlier, Stockton and Fritts (1973) used moisture-stressed white spruce ring-width chronologies to develop a 158-year reconstruction of summer lake levels on Lake Athabasca in northeastern Alberta. These reconstructions were recently updated and improved by Meko (2005; 2006) and provide a useful context for evaluating human impacts on water levels. Recently, Bonin and Burn (2005) used novel techniques to develop and evaluate a streamflow reconstruction for the Athabasca River at Athabasca. The reconstruction includes tree-ring data sampled by the Laboratory of Tree-Ring Research (LTRR: University of Arizona) in the 1960s for the Stockton and Fritts study and obtained from the International Tree Ring Databank.

The initial work in the western Cordillera was carried out by researchers from the LTRR who sampled a few chronologies in Alberta and British Columbia in the 1940s and mid-1960s (Schulman, 1947; Drew, 1975; Fritts and Shatz, 1975). Robertson and Jozsa (1988) subsequently developed a long *Pseudotsuga menziessii* (Douglas-fir) chronology from one of these sites in Banff National Park. The LTRR sites in Canada and many new sites were sampled by researchers from the University of Western Ontario to develop an updated and expanded network of moisture-sensitive chronologies across the southern Cordillera (Watson and Luckman, 2001; 2002) that form the basis of the specific examples discussed later. Gedalof et al. (2004) incorporated a limited number of chronologies from western Canada into a reconstruction of discharge of the Columbia River at The Dalles in Oregon.

Larocque and Smith (2005a) have developed reconstructions of a number of climate-related parameters including hydrologically important April 1 snowpack and glacier mass balance (Larocque and Smith, 2005b) from a set of tree-ring chronologies in the Mt Waddington region of the British Columbia Coast Mountains. In the latter study, tree-ring chronologies from a number of species were calibrated against measured seasonal mass balance records for three individual glaciers and for regional mass balance series. The reconstructions range from 164 to 530 years in length. On Vancouver Island, Lewis and Smith (2004) developed a tree-ring based net mass balance proxy for glaciers in Strathcona Provincial Park (1600 to 1994) based on relationships with four maritime glaciers in the Coast and Cascade Mountains.

The absence of relict material (i.e., dead wood used to extend living tree chronologies back in time) at many moisture-sensitive chronology sites means we know less about precipitation than temperature variability before ~1500 in western Canada. Recent isotopic work on long-lived trees by Tom Edwards and colleagues (e.g., Wolfe et al., 2005) offers the potential of exploring pre-1500s moisture variability (i.e., the trees do not need to be growing in traditionally moisture stressed environments to contain useful information). Other work with long records includes the development of an almost continuous 4000 year chronology from sub-fossil Douglas-fir from Heal Lake, Vancouver Island that is thought to be sensitive to growing season precipitation (Zhang et al., 2000; Zhang and Hebda, 2004; 2005). The most prolonged period of below normal growth in this chronology spans much of the mid-late 15th century through the 16th century (Zhang and Hebda, 2005) corresponding with the 16th century ‘megadrought’ identified for much of North America (Stahle et al., 2000).
Establishing the Long-Term Context and Large Scale Controls of Moisture Availability: Some Examples from Western Canada

Drought

Prior to a discussion of drought in this region it is important to discriminate between meteorological/climatological droughts and hydrological droughts. Meteorological/climatological droughts result from a deficit in precipitation in a region; hydrological drought is a deficit in water storage and streamflow. While in many regions the two are connected (where streamflow is strongly linked to local, largely contemporaneous rainfall periodicities) elsewhere, the two are not linked directly as streamflow may come from precipitation in adjacent, upstream regions (e.g., the Nile in Egypt) or may be linked to other forms of water provision such as snow or glacier melt. Although the climate and vegetation of the Cordillera and Canadian prairies differ, much of the precipitation and streamflow in the Prairie Provinces comes from atmospheric systems that traverse the Cordillera and therefore there are strong linkages in hydroclimates between the two regions.

Tree-ring reconstructions developed for individual climate stations (e.g., Figure 1b) can be used to examine the severity and duration of dry and wet periods from the instrumental record of the last 50 to 100 years and place them in the context of the last 200 to 600 years. Networks of precipitation reconstructions provide an even more powerful tool to evaluate the spatial extent and characteristics of past and present events. This type of spatial information provides data on the distribution of past events and supplies clues to their possible cause (e.g., do certain spatial patterns of drought have a unique climatic forcing). For example, a gridded network of Palmer Drought Severity (PDSI) records assembled for the coterminous United States (Cook et al., 1996; 1999) and parts of Canada (Cook et al., 2004) has been used to investigate past drought occurrences and their causes over a longer period that provided by the instrumental record (Cole and Cook, 1998; Cole et al., 2002).

Watson and Luckman (2001; 2002) built a network of 53 moisture sensitive Douglas-fir and Pinus ponderosa (Ponderosa pine) ring-width chronologies across the southern Canadian Cordillera from which 13 precipitation reconstructions were developed. The reconstructions range from 165 to 688 years in length and capture 39 to 64 percent of the variance in the instrumental records used for calibration (Watson and Luckman, 2004a). Time series of these reconstructions can be plotted to examine the occurrence, severity and duration of dry and wet events and to get a better idea of their frequency (Figure 2). In this paper we concentrate on the dry events. The 13 reconstructions have also been combined with precipitation reconstructions of other drought metrics from the adjacent Prairies (Case and MacDonald, 1995; Sauchyn and Beaudoin, 1998) and United States (Cook et al., 1999) to evaluate the spatial extent and characteristics of past events (Watson and Luckman, 2005a).

Annual maps displaying precipitation anomalies back to 1700 have been developed from this dataset. Composite maps developed for pronounced dry and wet periods greater and less than ten years in length (Figure 3) reveal that extended periods when dry or wet conditions prevail across the entire study region are not uncommon. These data suggest that the dry period from 1917 to 1941, which corresponds with the infamous dust bowl drought in the western United States (Fye et al., 2003) and Canada and some of the highest temperatures of the last millennium (Luckman and Wilson, 2005; D’Arrigo et al., 2006), was the most prolonged and spatially extensive dry event to have occurred in the region over the past 350 years (Figure 3; Watson and Luckman, 2004a). However, these records indicate that the intensity of this event was not unprecedented at individual sites within the region (it is the driest event in only three out of 13 reconstructions) and most reconstructions show dry periods of equivalent or greater magnitude as frequently as once or twice per century (Figure 2). The composite maps also reveal prolonged dry conditions in the 1840s to 1850s, the early 18th century and the mid-17th century. Shorter and occasionally more severe dry periods (e.g., the 1750s and 1790s) are identified for a number of intervals (Figure 3a).

Many of these dry events are corroborated by independent evidence. For example, the timing and apparent severity and extent of the 1790s dry event corresponds well with a period of sand dune reactivation in the Great Sand Hills region of the Palliser Triangle in Saskatchewan in the early 1800s that is also attributable to the dry conditions that prevailed throughout much of the 18th century (Wolfe et al., 2001; Figure 3). The 1850s dry period coincides with drought on the western Great Plains of the
Figure 2. Low frequency variation in 13 annual precipitation reconstructions for the southern Canadian Cordillera (Figure 4 from Watson and Luckman, 2004a, with permission of Springer Science and Business Media). All series are expressed in standard deviation units from their long-term mean and are smoothed with a 25-year spline. The thick vertical black line in each reconstruction indicates the first year for which chronology signal strength is considered reliable (see Watson and Luckman, 2004a). The vertical shading highlights intervals greater than four years in duration when below mean annual precipitation is identified in the majority of the available reconstructions (at least 60 percent prior to 1700 and greater than 50 percent post 1700) based on the annual series. Single years within some intervals fall below the 50% criterion.
Figure 3. Widespread dry periods (defined as in Figure 2) in the southern Canadian Cordillera after 1650 (after Watson and Luckman, 2005a, Figure 6). The standardized anomalies plotted are based on the mean and standard deviation over the common period of all 25 precipitation/drought reconstructions (1831 to 1978). Dry intervals less and greater than ten years are plotted sequentially (a and b) and the number of years in each period is given in brackets.
United States that may have contributed to the decline of the bison population of the area (Woodhouse et al., 2002). A well-known Canadian example for the context provided by tree-ring records involves the settlement of the Palliser Triangle region of the Canadian Prairies. An expedition to the area led by John Palliser during the period 1857 to 1860 reported unfavourable drought conditions (Rannie, 2006) but the Macoun expedition of the 1870s reported suitable conditions and settlement followed. The tree-ring based precipitation reconstructions (particularly Banff and Jasper, Figure 2) corroborate both periods and suggest that the major settlement of the area during the 1890s to 1920s occurred during one of the wettest periods of the last 500 years (Figure 2). The most severe individual dry year identified (1868 to 1869) corresponds with grasshopper plagues and crop failure on the Canadian Prairies (Phillips, 1990) and a severe fire year in interior British Columbia (Gray et al., 2002; Daniels and Watson, 2003) indicating that short-term, as well as long-term, dry events occur frequently in this region and can have significant impacts on the natural landscape.

The spatial scale of the dry periods identified suggests that large-scale circulation anomalies and related feedbacks are responsible for initiating and perpetuating these types of events. Conditions in the Pacific Ocean (primarily wintertime SSTs) are often implicated as triggers of large-scale drought in western North America (Bonsal et al., 1993; Ting and Wang, 1997; Fye et al., 2004; Shabbar and Skinner, 2004; Schubert et al., 2004). Several studies have noted links between wintertime El Niño and La Niña events and summer drought which are thought to relate to lags in the system (e.g., winter effects on summer soil moisture) and are consistent with wintertime North American moisture patterns associated with these events (Shabbar et al., 1997). Composite maps of summer precipitation in the southern Cordillera for El Niño and La Niña events in the 20th century show moderately drier and wetter conditions, respectively that are on average within ±0.5 standard deviations of the 1920 to 1994 mean (Watson and Luckman, 2005a). Correlations between a tree-ring based regional dryness series for summers in the southern Canadian Cordillera (Watson and Luckman, 2004a) and summertime (June to August) SSTs are presented in Figure 4a. The strongest correlations are negative and are centred in the eastern north Pacific at about 45°N, 150°W indicating that anomalously cool (warm) SSTs in this region generally coincide with more extensive (less extensive) dry summers in the southern Cordillera. The correlations in the equatorial Pacific are weaker but essentially show an effect of opposite sign to the relationship with wintertime SSTs (i.e., negative correlations indicate that cool, La Niña-like (warm, El Niño-like) tropical conditions are weakly associated with more (less) extensive dry events).

Barlow et al. (2001) identified three dominant modes of Pacific SST variability, the third of which is strongest in the North Pacific and identifiable in annual and summer SSTs. They demonstrate the impact of this “North Pacific mode” on drought, precipitation and streamflow in the United States. The temporal expression of this mode (i.e., the rotated principal component scores) is correlated with June to August Pacific SSTs in Figure 4b. The pattern of correlations of the dryness index with summertime SSTs (Figure 4a) resembles those with the North Pacific mode (Figure 4b) identified by Barlow et al. (2001). The correlation between the dryness series and the temporal expression of this mode is 0.41 (p < 0.05) over the period 1945 to 1993 (used in Barlow et al., 2001) but drops to 0.15 (p > 0.05) when a longer record that extends back to 1900 is used (downloaded from http://iri.ldeo.columbia.edu/~mattb/pdv.html). This may reflect a diminution of the quality of SST records back in time or more complex changes in large scale patterns (Gedalof et al., 2002) including those in the Atlantic Ocean that have recently (Shabbar and Skinner, 2004) been associated with drought in Canada. Causes of summertime drought in the region clearly require further investigation.

**Streamflow**

Some of the moisture sensitive tree-ring chronologies described above have also been useful for reconstructing streamflow. Watson and Luckman (2005b) describe the development of a discharge reconstruction for the Bow River at Banff, Alberta (51°10’N, 115°34’W). The Bow River flows for 623 km eastward from its headwaters at the Bow Glacier in the Canadian Rockies through Calgary, serving as an important water source for prairie agriculture (Figure 5). Flow upstream of the gauging station at Banff is unregulated...
Figure 4. Correlations between summer (June to August) Pacific SSTs and (a) the dryness series for the southern Canadian Cordillera (1948 to 1996) and (b) the time series representing the North Pacific mode (1948 to 1991; Barlow et al., 2001, time series from http://iri.ldeo.columbia.edu/~mattb/pdv.html). (a) The dryness series is simply the percentage of reconstructions from the southern Cordillera (n = 13) that have below normal (defined as the common period mean: 1831 to 1978) precipitation in each year. Positive values indicate that dryness was more spatially extensive not that wetter conditions occurred. Dry conditions in the southern Cordillera (positive dryness values) correlate with cooler SSTs in the north and, less strongly, the equatorial Pacific (the opposite is true for wet conditions). Note that correlations in (b) are naturally higher because the time series representing the North Pacific mode is generated from the Pacific SSTs. For n = 55 statistically significant correlations at the 90 and 95 percent levels exceed ±0.22 and ±0.27 respectively (not accounting for any spatial or serial correlation in the dataset). SST data are from the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) and the correlation map was generated at http://www.cdc.noaa.gov/ provided by NOAA-CIRES Climate Diagnostics Center, Boulder, CO.
and the record extends from 1912 to 1996 (source: HYDAT CD, version 2000–2.01, Environment Canada). The reconstruction is for the economically and agriculturally important summer flow period (April to August) when an average of 76 percent of annual flow occurs. Over the 1912 to 1996 period only 54 percent of annual precipitation occurs between April and August and the delayed release of winter snowpack is a key contributor to flow in the spring and summer months. The instrumental streamflow record (and subsequently the reconstruction) for the Bow River at Banff correlates highly with local records of snow water equivalent (SWE) and with those from a much larger set of snowpack records located along the continental divide (Figure 5). These results demonstrate the large-spatial scale of coherence in snowpack variability across the region.

Winter (November to March) and summer (April to August) precipitation at Banff are uncorrelated \( (r = -0.14, n = 99, p > 0.05) \). Therefore, the primarily summer sensitive Douglas-fir and ponderosa pine chronologies (described above) are not able to capture this winter snowpack signal. It was therefore necessary to include a winter snowfall proxy in the reconstruction (see Watson and Luckman, 2004b; 2005b). Watson and Luckman (2005b) note that statistically significant but physically unrealistic streamflow reconstructions can be developed using chronologies that are primarily sensitive to summer precipitation warranting careful interpretation of published results. In these cases it is important to recognize that, for these mountain-fed rivers, low flows (hydrological droughts) may be unrelated to periods of low growing season rainfall.

The Bow River streamflow reconstruction is presented over the period of calibration/verification (Figure 6a) and over its full length (Figure 6b; 1619 to 1995 with 95 percent standard error limits) in Figure 6. The reconstruction suggests that the magnitude of high and low flow periods during the 20th century are not unprecedented but that the duration of low flows are atypical: the only other interval with prolonged low flows was during the early 1600s. Statistically significant (95 percent level, tested with red noise background spectrum) spectral peaks are found at 73, 24, 2.6 and 2 years (not shown) with the 73 and 24 year peaks corresponding with periods of significant variability in the Pacific Ocean (Minobe, 1997; 1999). The Pacific Decadal Oscillation time series (1900 to 1995; Mantua et al., 1997) corresponds well with variability in the instrumental and reconstructed Bow River discharge records (Figure 6b) over the twentieth century but there is some debate about the strength and representativeness of this ‘oscillation’ back in time (Gedalof et al., 2002). The spatial patterns of correlations between winter SSTs and the measured summer flow record (1949 to 1995; Figure 7a) also resemble the interdecadal mode (Mantua et al., 1997; Zhang et al., 1997). The tree-ring based reconstruction (Figure 7b) captures a very similar pattern over the same period.

**Glacier Mass Balance**

It is important to consider glacial and snowmelt inputs to many rivers with headwaters in the mountains when discussing the flow regimes of rivers in western Canada. Mountain glaciers provide important contributions to streamflow, particularly during the late summer months when summer melting is at a peak and snowmelt water from the spring, stored temporarily as ice, is released (Fountain and Tangborn, 1985). Studies suggest that the percentage of flow contributed by glaciers increases during drought years and that glaciers can also store water during times of positive mass balance (Fountain and Tangborn, 1985; Hopkinson and Young, 1998).

Glacier mass balance studies are the primary tool used to evaluate climate-glacier relationships and were initiated at a number of representative glaciers in western Canada and the United States during the International Hydrological Decade (1965 to 1974). Although these records are short and sparsely distributed, they have been extremely valuable for assessing climate-glacier relationships (Lertréguilly, 1988; Walters and Meier, 1989; Bitz and Battisti, 1999; McCabe et al., 2000; Demuth and Keller, in press) and glacial contributions to streamflow (Hopkinson and Young, 1998; Moore and Demuth, 2001). However it has been difficult to evaluate the long-term variability of annual and seasonal glacier mass balance (mean, range, periodicities) using these short records as, in many cases, the climate variables that force changes in mass balance occur at timescales approaching the length of record. Proxy estimates of glacier mass balance from appropriate tree-ring chronologies (Nicolussi and Patzelt, 1996; Lewis and Smith, 2004; Pederson et al., 2004; Larocque and Smith, 2005b) can be used to evaluate the representativeness of contemporary...
glacier-climate relationships (both locally and with larger-scale patterns) and to evaluate the significance of the primarily negative late 20th century balances which have resulted in widespread recession and downwasting of glaciers (Dyurgerov and Meier, 2000; Meier et al., 2003).

Most of the North American studies that have generated net mass balance proxies from tree-ring chronologies have used species where high (low) growth is associated with lower (higher) winter snow accumulation and higher (lower) summer temperatures (Lewis and Smith, 2004; Larocque and Smith, 2005b). Many of these utilize glacier proximal *Tsuga mertensiana* (mountain hemlock) stands; this species has also been used to reconstruct variations in the Pacific Decadal Oscillation (PDO) index (D’Arrigo et al., 2001; Gedalof and Smith, 2001). The PDO is the leading mode of North Pacific sea surface temperatures poleward of 20°N (Mantua et al., 1997; Zhang et al., 1997) and represents a persistent ENSO-like pattern that alternates between ‘warm’ and ‘cool’ phases roughly every 20 to 30 years. These net mass balance reconstructions show a strong linkage with winter precipitation and the PDO but lack an independent summer temperature estimator (summer temperatures are an important control of net mass balance particularly for continental glaciers). The only studies to date that generate separate estimates for summer and winter balances are Pederson et al. (2004) and Watson and Luckman (2004b). Although both of these studies use PDO linked chronologies to estimate winter balance, Pederson et al. (2004) use drought indices rather than temperature sensitive chronologies to estimate summer balance. The seasonal reconstructions in Pederson et al. (2004) are not calibrated against measured mass balance data (see Watson et al., in press for further discussion) and we therefore use the Watson and Luckman (2004b) reconstructions to demonstrate the utility of long calibrated seasonal estimates of mass balance for assessing
Figure 6. Bow River at Banff April to August flow over the (A) 1912 to 1995 period (used for calibration) and (B) reconstructed for the period 1619 to 1995. Notes: Full calibration and verification statistics are given in A. For the calibration $R$, $R^2_{\text{adj}}$, SE and DW-d are the multiple correlation value from the regression model, $R^2$ adjusted for the number of samples, the standard error of the estimate and the Durbin-Watson d statistic, respectively. For the two verification periods, $r$, RE, CE, ST are the correlation coefficient, reduction of error statistic, the coefficient of efficiency and the sign test (agree/disagree), respectively (Cook et al., 1994; Fritts, 1976; 1991). Two standard error (95 percent) confidence limits from the full calibration are given in B. A 15-year filter (thick red line) fitted to the reconstruction highlights prolonged low and high flow periods. The November to March instrumental PDO time series smoothed with a 15-year filter (sign inverted) is plotted for comparison (Mantua et al., 1997; downloaded from http://jisao.washington.edu/pdo/PDO.latest). The first order autocorrelation in the tree-ring data was adjusted to match that in the streamflow time series using the method described by Meko et al. (2001). The variance in the flow estimates has been scaled to match that in the instrumental record over the calibration period (Cook et al., 2004). Figure revised and reworked from Watson and Luckman (2005b).
Figure 7. Correlations between winter (November to March) Pacific SSTs and (a) instrumental and (b) reconstructed summer (April to August) streamflow for the Bow River at Banff (1949 to 1995). For $n = 55$ statistically significant correlations at the 90 and 95 percent levels exceed $\pm 0.22$ and $\pm 0.27$, respectively (not accounting for any spatial or serial correlation amongst the data). SST data are from the NCEP/NCAR reanalysis dataset (Kalnay et al., 1996) and the correlation map was generated at http://www.cdc.noaa.gov/ provided by NOAA-CIRES Climate Diagnostics Center, Boulder, CO.
the significance of recent trends and assessing the stability of contemporary climate relationships.

Watson and Luckman (2004b) used tree-ring data from the Cordillera to reconstruct the mass balance of Peyto Glacier from 1673 to 1994. The reconstruction was calibrated against measured seasonal mass balance records for 1966 to 1995 (Demuth and Keller, in press; Dyurgerov, 2002). Separate seasonal balance reconstructions were developed using a set of tree-ring chronologies sensitive to both winter precipitation and summer temperatures. The net mass balance reconstruction compares well with independent morphological evidence of glacier fluctuations (i.e., periods of positive mass balance coincide with or precede the formation of dated moraines). The reconstructions indicate that the negative mass balances that dominate the measured record are part of a longer trend that began in the 1880s (Watson and Luckman, 2004b). Watson et al. (2006) use this proxy reconstruction to explore the influence of Pacific SSTs on mass balance over the last 124 years. This study demonstrated the strong influence of shifts in precipitation regime on winter balance, snowpack and thereby summer flows from these mountain areas.

These proxy mass balance data have also been used in conjunction with reconstructed summer precipitation to evaluate the controls of streamflow of the Bow River over periods of differing glacier extent (e.g., during the LIA maximum when mass balance was predominantly positive; Watson and Luckman, 2005b). The rationale for the analysis is that this suite of reconstructions should capture major meteorological inputs to the river: winter balance as a proxy for snowpack, summer balance as a proxy for glacier melt and summer precipitation inputs represented by a summer precipitation reconstruction. The analysis identified winter snowpack and summer precipitation as important contributors corresponding with the instrumental records but failed to detect any variability in reconstructed flow that could be clearly attributed to summer melting. This may be because the basin under study is not highly glacierized or because tree-growth is almost complete (or may have terminated) by the time these inputs become important (late summer). The analysis also relied on correlations measuring the degree of covariation between these variables over entire seasons not actual contributions—glacial melt inputs can be high in individual months (e.g., for the Bow River 56 percent of flow in August 1970 was attributed to glacier wastage (Hopkinson and Young, 1998)) and essentially represent a non-linear relationship with flow. Latewood ring-width chronologies generally have a stronger relationship with conditions in the current summer (Watson and Luckman, 2002) than total ring-width chronologies and use of these chronologies may improve these analyses.

Conclusions

In this paper we have demonstrated that tree-ring chronologies from carefully selected species and sites can be used to develop high quality (i.e., well verified internally and corroborated by independent data) records of a number of hydrological variables for western Canada over the last 200 to 600 years. Precipitation, PDSI and streamflow may all be successfully reconstructed and attempts at glacier mass balance reconstructions using a variety of species show promise. This work has been most successful in the Cordillera and foothills of the Rockies where a number of moisture-sensitive conifer species are found that attain ages of greater than 500 years. These proxy precipitation and streamflow records are clearly important for managing water supplies for agriculture and hydropower in these areas. The driest parts of the prairies are adjacent to the Cordillera and are watered by streams flowing out of the mountains. These reconstructions therefore provide important information on the long-term hydrological variability of mountain fed streams. In the prairies and adjacent boreal forest, suitable species are less readily found; available species often have a much shorter life span or fire restricts the length of potential records. Nevertheless chronologies of 150 to 200 years can yield valuable records and in some places records of suitable species may be extended by the use of wood from archeological sites or old buildings. Although ongoing work is expanding chronology networks in western Canada, more work is needed to explore the potential of ‘new’ species that could improve this situation.

Several of the studies outlined herein have demonstrated the sensitivity of mountain hemlock tree-ring series from the coastal ranges of western Canada and the United States to snowpack and winter precipitation amounts. There is a need to explore
other tree species or sites with tree-ring series that contain a winter precipitation and/or snowfall signal at interior sites as snowmelt remains the prime flow generator in many environments. Reconstructing snowfall is essential if hydrologically meaningful streamflow reconstructions are to be developed for snowmelt dominated regimes. It will also be important to seek out possible moisture-sensitive sites from more northern environments within the Cordillera and in the northern boreal forest to the east. The recent study by Cook et al. (2004) demonstrates that 20th century droughts in the western United States are much less extensive than during the period of increased aridity from 900 to 1300 AD. This is an excellent example of the context long proxy data can provide. It is important to recognize that the reconstructions are much better in some regions than others and that the footprint of drought is regionally variable. Although difficult to find, additional long, moisture-sensitive records from western Canada are required to evaluate the spatial extent of past dry events such as the “epic droughts” described from the United States (Stahle et al., 2000; Cook et al., 2004).

The examples discussed in this paper have demonstrated that networks of chronologies provide a powerful tool for the evaluation of spatial patterns in reconstructed climate data, particularly drought. Networks of drought reconstructions allow the pattern and magnitude of 20th century droughts to be compared with those that occurred in the pre-instrumental period (Fye et al., 2003). Extensive droughts with differing spatial patterns can be compared with oceanic and atmospheric datasets to link them to their causes. Several recent studies have identified periods of coincident drought over much of the western United States and parts of the Canadian west (Stahle et al., 2000; Cook et al., 2004). Relationships with the Pacific, particularly La Niña-like conditions in the equatorial Pacific, have been suggested as a trigger of these widespread droughts. However, studies of contemporary climate data suggest that the pattern of precipitation during cool equatorial SSTs (La Niña-like conditions) in western Canada is opposite to that over much of the southwestern United States. Future work is needed to explore relationships between precipitation in western Canada, Pacific SSTs (over winter and summer) and possible feedback mechanisms responsible for drought propagation.

Ongoing studies based on tree-rings and other proxy climate data are revealing considerable information about the spatial and temporal variability of precipitation and streamflow and the linkages with recurrent atmospheric and oceanic circulation patterns. As these patterns may persist for periods of several years to decades there is also the potential to use these relationships for forecasting. Long reconstructions of variables with short measured records, such as glacier mass balance (typically ~30 years), allow more extended and robust analyses of climate-related causes of variability. Long reconstructed records can also provide useful data to place current variability in context, establishing more realistic probability estimates for the return interval for drought at individual locations and, when networks are used, the recurrence of large-scale drought patterns across a region. Long reconstructions are also important for evaluating the significance of trends identified in the instrumental record. For example, an increasing number of studies in the west are showing that flow regimes are strongly influenced by both ENSO and the PDO (Gobena and Gan, 2006). The PDO was in a negative phase from 1947 to 1976 (generally higher winter precipitation in western Canada) and a positive phase (lower winter precipitation) from 1976 to the end of the century. Given the strong influence of PDO on streamflow and snowmelt in the west, most snowmelt dominated streamflow records from the region less than 50 years in length will show a declining linear trend due to the effects of the PDO (see, for example the last 50 years of record shown in Figure 6). Although a 50-year record may seem to be a statistically adequate sample, analysis of these records must recognize that they may consist of at least two “populations” stratified by the phase of the PDO. Understanding that this trend may well reverse in the near future, or determining the precursors for such a shift, is important in long-term forecasting.

Most of the research reported in this paper has been developed and carried out for both academic interest and the need for water managers to understand past and thereby present natural climate variability. Some of this material has important implications for water management but it is necessary to establish a common language that makes these data available in a form that is usable for water research managers and modellers (see Woodhouse and Lukas (2006) for an example). The paleo record of the last millennium indicates that
there has been considerable variation of hydroclimate including extremes that considerably exceed those in the modern instrumental record. Prudent practice would suggest that the range and duration of past events need to be taken into account in planning future water resource allocations and usage. Tree-ring data can only produce information on annual or in some cases, seasonal, timescales and are generally not as useful for the reconstruction of individual extreme events, except perhaps for flood records where dendrogeomorphic techniques may be appropriate (St. George and Nielson, 2000; 2003). Such historical studies cannot be used to predict future flow or climate conditions directly because of uncertainties with respect to global warming scenarios. However, dendroclimatologic/dendrohydrologic reconstructions provide strong, clear evidence of long term, low frequency natural climatic/hydrologic variability that cannot be recovered from available instrumental records. Moreover, any future anthropogenic climate changes will be superimposed on this natural variability. Understanding the controls of that variability is one of the main keys to the successful development and modelling of future water use scenarios.

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