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A multi-species dendroclimatic reconstruction of Chilko River streamflow, British Columbia, Canada

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Abstract:

Dendroclimatological data were used to reconstruct the discharge history of Chilko River, which drains a glacierized watershed in the Coast Mountains of British Columbia. We correlated ring-width records from Engelmann spruce (ES) (*Picea engelmanni*) and mountain hemlock (MH) (*Tsuga mertensiana*) trees to historical hydroclimate data. Over the period of record, spruce and hemlock radial growth correlates significantly with temperature and snow depth, respectively. We found that a multi-species approach provided a better model fit and reconstructive power. Using these relationships, we developed generalized linear models for mean June, July, and June-July discharge. The proxy records provide insights into streamflow variability of a typical Coast Mountains river over the past 240 years and confirm the long-term influence of the Pacific Decadal Oscillation (PDO) on hydroclimatic regimes in the region. A relationship also exists between the reconstructed June-July discharge record and the North Pacific (NP) Index, suggesting that winter atmospheric patterns over the North Pacific influence the hydrology of coastal British Columbia. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS British Columbia; Chilko River; tree-ring; Engelmann spruce; mountain hemlock; streamflow reconstruction; Pacific Decadal Oscillation

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INTRODUCTION

The Homathko Icefield has an area of over 2000 km^2 and is one of the largest icefields in the British Columbia Coast Mountains (Figure 1). Outlet glaciers flowing from the icefield, like mountain glaciers elsewhere in the world, have thinned and retreated dramatically in the past few decades (Schiefer *et al.*, 2007; Vanlooy and Forster, 2008). Meltwater streams issuing from these glaciers have significant hydrological influences on the downstream flow regimes of tributaries of the Fraser and Homathko rivers, which drain most of southern British Columbia (Fleming *et al.*, 2007). Given the environmental and economic importance of these rivers, increasing attention is being given to understanding how recent climate change and glacier recession are influencing their hydrology (Fleming and Clarke, 2003; Moore *et al.*, 2009).

Shifts in large-scale ocean-atmospheric circulation, notably the Pacific Decadal Oscillation (PDO; Mantua and Hare, 2002), are known to influence glacier mass balance and streamflow in the Coast Mountains (Moore and Demuth, 2001; Whitfield, 2001; Fleming *et al.*, 2006), but records of long duration are required to elucidate these relationships and assess fully the hydroclimatic impact of historic and ongoing climate change. The hydrology of glacier-fed rivers in this region is typically evaluated from the historic time series of discharge maintained by the Water Survey of Canada (2009). Research has shown that the hydrologic regime of these rivers is climatically driven (Melack *et al.*, 1997; Kiffney *et al.*, 2002; Morrison *et al.*, 2002), but available hydrometric records are of short duration and commonly contain data gaps (Fleming and Clarke, 2002). These deficiencies limit the identification and understanding of possible relationships between low-frequency climate modes described by PDO, the El Niño-Southern Oscillation (ENSO) and streamflow (Fleming *et al.*, 2007).

Tree rings provide an opportunity to develop long-term proxy records of streamflow (Stockton and Fritts, 1973; Meko *et al.*, 2001; Case and MacDonald, 2003; Watson and Luckman, 2005; Woodhouse *et al.*, 2006). We capitalize on this opportunity by using climatically sensitive tree-ring records to reconstruct summer mean streamflow of Chilko River, a major tributary of Fraser River (Figure 1). We use this proxy to assess the influence of large-scale climate variability on streamflow regimes over the past two centuries.

Previous prehistoric streamflow reconstructions in British Columbia have been developed from precipitation-sensitive tree species (Gedalof *et al.*, 2004; Watson and Luckman, 2005). In this study, we use mountain hemlock (MH) (*Tsuga mertensiana*), a species that typically shows a radial growth relationship to snow depth (Gedalof and Smith, 2001a; Peterson and Peterson, 2001; Larocque and Smith, 2005) and Engelmann spruce (ES) (*Picea engelmanni* Parry), a species that characteristically shows a radial growth response to summer

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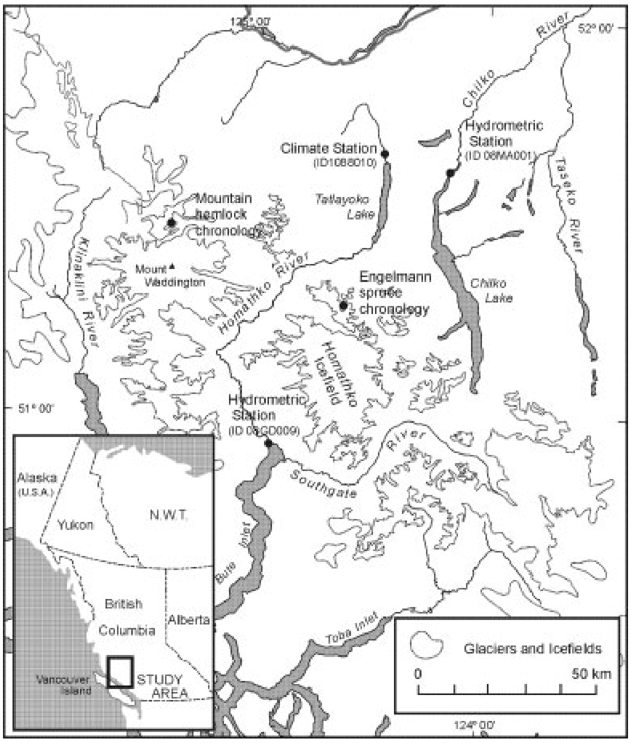

Figure 1. Locations of climate station, tree-ring chronologies and hydrometric stations used in this study

temperatures (Ettl and Peterson, 1995; Peterson *et al.*, 2002; Wilson and Luckman, 2003), to reconstruct proxy records of summer discharge for a snowpack-dominated basin within the Coast Mountains.

STUDY AREA

The study area is located in the south-central Coast Mountains, which has extensive snow and ice cover and the highest peaks in British Columbia (Figure 1). Three major rivers drain this part of the Coast Mountains—Homathko and Kliniklini rivers flow to the west into Bute and Knight Inlets, respectively, and Chilko River flows north from Chilko Lake and joins Chilcotin River near the east margin of the Coast Mountains. Hydrometric records for Chilko River at Chilko Lake are the longest in the region (1928 to present).

The climate of the region is transitional from wet and maritime on the west side of the range to drier and more continental on the east side. Climate normals for Tatlayoko Lake (Table I) indicate daily temperature ranges from −11·7 °C in January to 22·5 °C in August (1971–2000) Annual total precipitation at Tatlayoko Lake averages 434·1 mm, of which approximately 30% falls as snow from November through March (Meteorologic Service of Canada, 2009).

The study area is located within the Engelmann spruce–subalpine fir (ESSF) biogeoclimatic zone (Meidinger and Pojar, 1991). Homogenous stands of MH can be found on many mid-elevation slopes throughout the Homathko and Waddington ranges (Larocque and Smith, 2005). Higher elevations are characterized by subalpine fir, except dry, disturbed sites which are favoured by whitebark pine (*Pinus albicaulis*) (Meidinger and Pojar, 1991). Two tree-ring sampling sites were selected for this study—an ES site and a MH site.

ES site

Cores were collected from ES on an alluvial fan adjacent to the west branch of Nostetuko River at the edge of the Homathko Icefield in July 2008 (Figure 1, Table I). The west branch of Nostetuko River is a glacier-fed stream in a valley that was affected by repeated catastrophic glacial outburst floods in the 20th century (Blown and Church, 1985; Clague and Evans, 2000; Kershaw *et al.*, 2005). The forest at the study site consists of a mixed stand of ESSF and whitebark pine. Trees were selected within continuous forest *ca* 100 m below the local treeline.

MH site

A MH chronology was established from tree cores collected by the University of Victoria Tree-Ring Lab (UVTRL) at Oval Glacier (historically known as Parallel Glacier) in the summer of 2000 (Figure 1, Table I). Oval Glacier presently calves into proglacial Oval Lake and drains into Homathko River (Laroque and Smith, 2003). The steep mountain slopes above Oval Lake are characterized by a mixed stand of MH and subalpine fir.

DATA AND METHODS

Hydrometric data

Mean, maximum and minimum monthly streamflow data for Chilko River at Chilko Lake were obtained from the Water Survey of Canada website (Water Survey of Canada, 2009). Missing values were replaced with long-term monthly average values. Chilko River mean monthly discharge was examined graphically and statistically to assess trends, normality and persistence in the time series.

Table I. Locations of study sites

Station	Type	ID	Latitude (N)	Longitude (W)	Elevation (m asl)
Tatlayoka Lake	Meteorologic	1088010	51°40′	124°24′	870
Chilko Lake	Hydrologic	08 MA001	51°37′	124°08′	2110
Tatlayoka Lake	Snow	3A13	51°36′	124°20′	1710
Nosetuko River	Engelmann spruce		51°17′	124°30′	1390
Oval Glacier	Mountain hemlock		51°29′	125°15′	1445

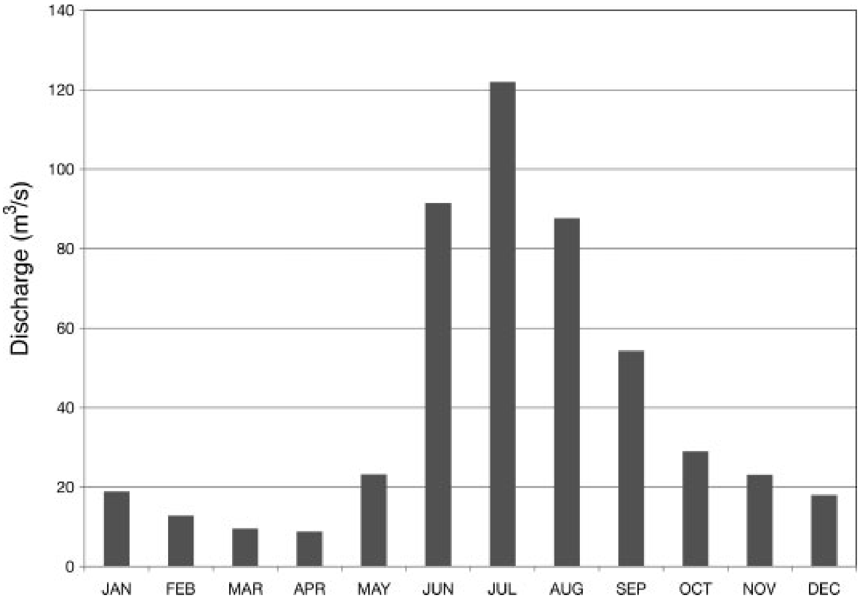

Figure 2. Average monthly discharge of Chilko River at Chilko Lake (1928–2007)

Peak flows occur in summer months in response to seasonal melt of the snowpack in the Coast Mountains (Figure 2; Whitefield, 2001). Streamflow is also likely augmented by glacier melt in the Homathko Icefield in July and August (Moore *et al.*, 2009). No significant autocorrelation was found in summer discharge data (Table II). Summer water flows were either normal or skewed and found to be lognormal (Table II).

Climate data

We used monthly temperature and precipitation data from the nearest meterological station at Tatlayoko Lake (Figure 1, Table I) to provide regional indices of climate variability. These data were obtained from the Adjusted Homogenized Canada Climate Data website (AHCCD, 2009). Missing data were replaced with long-term monthly average values. April 1 snowpack data for Tatlayoko Lake were acquired from the B.C. Environment Historical Snow Survey Data website (B.C. Environment, 2009).

Chilko River, like other rivers in coastal British Columbia, is expected to show a systematic response to large-scale climate variability (Fleming and Quilty, 2006; Fleming *et al.*, 2007). In this study, we use various indexes to represent large-scale climate variability—the southern oscillation index (SOI), NINO3·4 index, PDO index, North Pacific (NP) index and Pacific North America (PNA) index (Moore and Demuth, 2001). Monthly index data were obtained from the following web sites: SOI, http://www.cru.uea.ac.uk/cru/data/soi/; NINO3·4, http://climexp.knmi.nl/data/inino5.dat; PDO, http://jisao. washington.edu/pdo/PDO.latest; NP, http://gcmd.nasa.gov/records/GCMD_NCAR_NP.html; PNA, http://jisao.washington.edu/data/pna/

The SOI and NINO3·4 indices are indicators of ENSO, a complex atmosphere–ocean interaction that causes cyclical warming and cooling of sea surface temperatures in the tropical Pacific Ocean. ENSO events over the past century have occurred, on average, every 5–7 years, resulting in an alternation of warm and cool climate states in PNA (Ware, 2007). The SOI measures the difference in sea level pressure between Darwin and Tahiti, whereas the NINO3·4 index is the average sea surface temperature anomaly for the region 5 °S–5°N and 170–120 °W.

The PDO is an atmosphere–ocean interaction in the NP that describes ENSO-like variability at both interdecadal and decadal scales. The PDO index is calculated from time series scores related to the first leading principle component of Pacific Ocean sea surface temperature north of 20°N. During the 20th century, the PDO has switched states about every 15–25 years (Mantua and Hare, 2002), but proxy reconstructions back to 1600 AD suggest the presence of secondary PDO cycles with a periodicity ranging from 50 to 75 years (Gedalof and Smith, 2001b).

The PNA pattern is a mode of winter atmospheric circulation in the NP. The PNA index reflects atmospheric pressure for the zone 20–55°N and 85–165 °W (Wallace and Gutzler, 1981). Positive phases of the PNA coincide with enhanced Rossby waves and southerly airflow over western North America. Negative phases of the PNA result in northwesterly airflow in western North America. The NP index, another measure of the PNA pattern, is defined as the anomaly of area-weighted mean sea level

Table II. Flow statistics for the Chilko River

Variable	Flow statistics					
	Mean	Minimum	Maximum	cv	Skew	r_1
June	76·8	42·4	157·0	0·293	1·266*	0·057
July	113·1	72·0	175·0	0·184	0·250	0·067
June–July	189·9	118·4	289·0	0·197	0·676*	0·0364

* Significant skewness calculated using the function dagoTest in R.

pressure over the zone 30–65°N and 160 °E to 140 °W relative to the 1925–1988 mean (Trenberth and Hurrell, 1994).

Tree-ring data

Standard dendrochronological techniques were used in collecting samples in the field (Stokes and Smiley, 1964). Two increment cores were taken from 20 trees to ensure adequate replication at each study site. The cores were taken at breast height 180° from each other to account for differences in growth.

The cores were transported to UVTRL where they were air-dried, glued into slotted mounting boards and sanded to a 600-grit polish (Stokes and Smiley, 1964). Ring-widths of each core were measured to the nearest 0·01 mm along a single path using WinDendro software and a high-resolution flatbed scanner (Guay *et al.*, 1992). For series with exceptionally narrow rings, a Velmex stage equipped with a microscope and video display was used in conjunction with MeasureJ2X (VoorTech Consulting, 2008) to measure the ring widths to the nearest 0·01 mm.

The ring-width series were both visually cross-dated by comparing marker years between the series (Stokes and Smiley, 1964) and statistically using the International Tree Ring Database (ITRDB) computer program COFECHA (Holmes *et al.*, 1986). COFECHA correlations were calculated using a 50-year segment length lagged successively by 25 years at a one-tailed 99% confidence level (Grissino-Mayer, 2001). Ring-width series that were not significantly correlated to the group were removed from the data set.

Master tree-ring chronologies were constructed using the R package dplR (Bunn, 2008). Chronologies were conservatively detrended using a negative exponential curve followed by a cubic smoothing spline to remove biological growth trends (Holmes *et al.*, 1986). A spline rigidity of 95 years with a 50% frequency response level was chosen to generate the highest inter-series correlations and preserve trends that might relate to low-frequency oscillations in climate (Gedalof and Smith, 2001b). Low-order autocorrelation was removed using an autoregressive model in dplR (Bunn, 2008).

Expressed population signal (EPS) values were calculated for each chronology (Wigley *et al.*, 1984). EPS is a statistic that expresses the amount of noise in a chronology. EPS values were calculated at 25-year moving periods for each chronology using the computer program ARSTAN to quantify signal strength through time (Cook and Holmes, 1986).

Hydroclimatic relationships

Typically, dendrohydrological reconstructions make use of precipitation-limited tree-ring series (Fritts, 1976). However, in the Coast Mountains, trees typically exhibit complex radial-growth relations to both temperature and precipitation (Laroque and Smith 1999, 2003; Zhang and Hebda, 2004). We hypothesized that the climate variables driving tree growth and discharge in this environment are sufficiently similar that we could use radial growth indices as proxies for climate predictors in our discharge model. To test this hypothesis, we first identified relationships between monthly climate and hydrometric data using correlation analysis. Relationships between the annual tree-ring series and monthly climate data were then analysed using bootstrapped correlation and response function techniques with the R package bootRes (Zang, 2009). Tree growth was compared with mean monthly temperature and precipitation for the current and previous years. Data for the months of September to December of the current year were excluded from the analysis because most tree growth occurs before these months (Laroque and Smith, 2003). Correlations between April 1 snowpack and tree growth were then calculated.

Climatic variables significantly related to both tree growth and discharge were used to identify discharge response variables. Correlations between the discharge response variables and radial growth variables were calculated to determine whether radial growth indices could serve as proxy predictor variables for climate.

Reconstruction

We used generalized linear modelling to examine the relationships between three different discharge response variables and four continuous predictor variables: radial growth of MH and ES; and the lagged radial growth of hemlock (MH_t) and spruce (Es_{t-1}). We used a generalized linear modelling approach because previous research indicated that a linear relationship generally exists between tree rings and hydroclimatic variables and it is sufficiently flexible to allow for different distributions (Hughes, 2002). We examined 14 simple additive models that represent all possible combinations of the predictor variables (discharge Q as a function of the radial growth of MH_t, Es_t, MH_{t-1}, and Es_{t-1}).

We divided the response and predictor variable time series into two periods, an early period (1928–1962) and a late period (1963–1999). Parameters for each model were fit using the late-period time series by minimizing the model's negative log likelihood (R Development Core Team, 2009). We then assessed model fit and reconstructive power by comparing Akaike information criterion (AIC; Akaike, 1973), coefficient of error (CE; Fritts, 1976), reduction of error (RE), and correlation statistics. To ensure model stability, the early period time series was then used to calibrate the model. The best model was selected based on: (1) similar statistics and parameter estimates from both early and late period calibration and (2) optimal model fit and model power estimates. The best model was then run backwards through the period of overlap between the two chronologies to reconstruct past summer discharge.

Detecting modes of variability

We used time-series correlations and wavelet analysis to determine the relative importance of large-scale climate variability in the Chilko River discharge record.

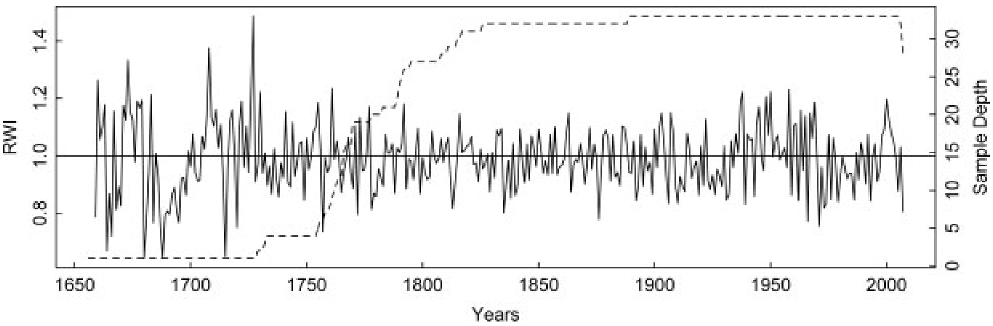

Figure 3. ES residual chronology from the west branch of Nostetuko River. Dashed line indicates sample depth

Table III. Tree-ring chronology statistics

Site	Interval	No. series	Average series intercorrelation[a]	Average mean sensitivity
Engelmann spruce	1656–2007	38	0·468	0·174
Mountain hemlock	1762–1999	37	0·624	0·237

[a] Calculated using computer program COFECHA with a segment length of 50 years and 25-year overlap.

Correlation analysis was conducted on all discharge reconstructions and winter (November–April) average climate indices. Wavelet analysis was used to determine whether dominant modes of variability and localized variations in power exist within the Chilko River discharge record (http://paos.colorado.edu/research/wavelets/). A Gaussian 2 function with a 5% red noise reduction was used as the base function (Torrence and Compo, 1998; Woodhouse *et al.*, 2006).

RESULTS

Tree-ring chronologies

The ES master chronology spans 352 years (1656–2007 AD; Table III). Prior to 1785, the chronology displays considerable annual variability due to limited sample depth (Figure 3). Anomalously narrow tree rings, which served to anchor the series, date to 1835, 1876, 1966, 1971 and 1979.

The MH master chronology spans 237 years (1762–1999 AD; Table III). It shows considerable annual variability prior to 1845, which is attributed to low sample depth (Figure 4). Narrow marker rings date to 1872, 1887, 1894, 1911, 1912, 1913, 1916, 1921, 1976 and 1991.

Dendroclimatic relationships

Several climate variables significantly correlate to instrumented Chilko River discharge. The strongest relationships are between early summer discharge, temperature and snowpack. June–July discharge is significantly correlated to April 1 snowpack at Tatlayoko Lake ($r = 0{\cdot}568$). June–July temperature, an index of the energy available to melt snow in the basin, is significantly correlated to Chilko River mean summer streamflow ($r = 0{\cdot}518$). Warmer summer temperatures drive snowmelt and increase the amount of runoff carried by alpine streams (Whitfield, 2001).

Correlation and response function analyses show that both the ES and MH chronologies significantly correlate with air temperature (Figure 5). The ES chronology shows a significant negative relationship to the previous year's summer air temperature, consistent with findings of previous research in the Pacific Northwest (Ettl and Peterson, 1995; Peterson *et al.*, 2002). The MH chronology also shows a weak, but significant negative correlation with previous summer temperature, similar to that reported by Gedalof and Smith (2001b). Higher-than-average summer temperatures can cause increase evapotranspiration and water loss, decrease nutrient storage and foliage efficiency, and initiate cone production earlier,

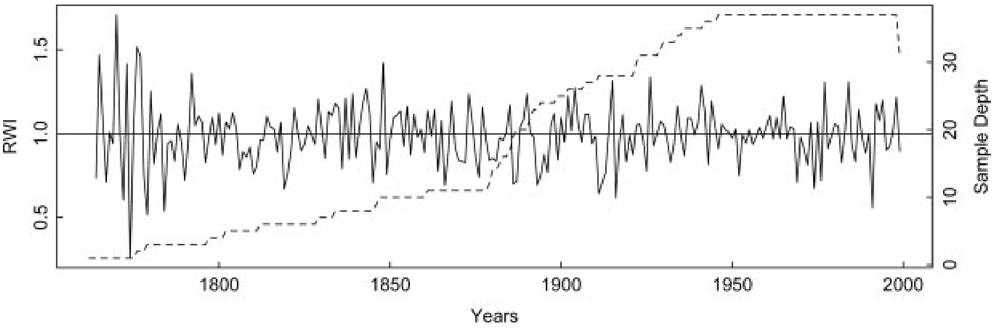

Figure 4. MS residual chronology from Oval Glacier. Dashed line indicates sample depth

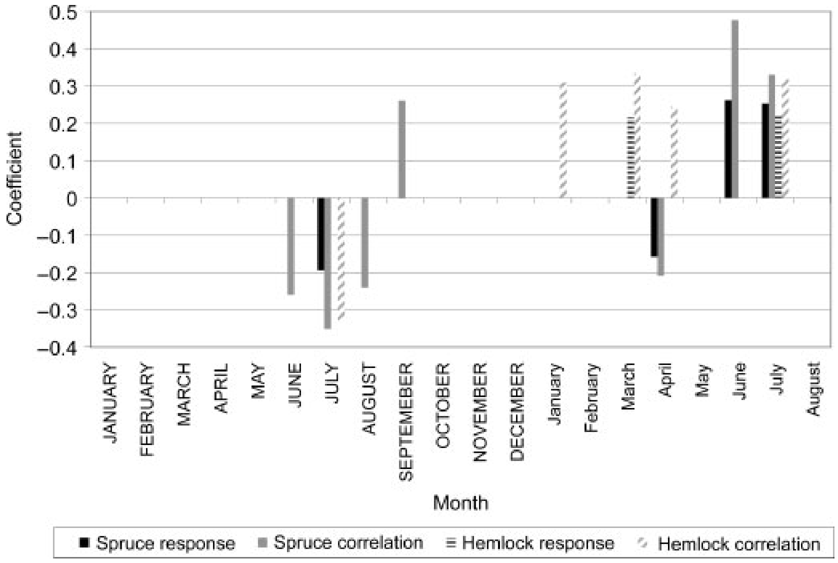

Figure 5. Response function and correlation coefficients for chronologies and mean temperature time series (1929–1999) for each month from Tatlayoko Lake derived using the R package bootRes. Months in block letters are from the previous year

all of which decrease cambial activity and reduce radial growth in the following growth year (Ettl and Peterson, 1995; Klinka and Spelchtna, 1998; Zhang *et al.*, 1999; Rossi *et al.*, 2006; Thibeault-Martel *et al.*, 2008).

MH ring-width is significantly correlated to winter air temperature (Figure 5). Warmer-than-average winter temperatures probably increase survival of vegetative buds, leading to an increase in the photosynthetic potential of the trees. This finding is consistent with results of other dendroclimatic research conducted in the Coast Mountains (Larocque and Smith, 2005). The hemlock chronology is negatively correlated with April 1 snowpack ($r = -0{\cdot}452$). Photosynthesis activity and cambial production are delayed by late-lying snow, thereby limiting the annual growth increment. Late-lying snow also can reduce the effective length of the growing season by lowering soil temperature (Hansen-Bristow, 1986). Although few spring phenology data are available for MH, this species likely behaves similarly to subalpine fir by not initiating leaf and shoot growth until after spring snowmelt (Peterson and Peterson, 2001).

The strongest climate signal for both chronologies is a positive correlation to summer temperature (Figure 5). Warmer temperatures during summer result in earlier needle maturation and increased photosynthesis (Schmidt and Lotan, 1980). High early summer temperatures may melt lingering snow, thereby increasing the length of the growth season. Similar conclusions have been drawn from dendroclimatological research on ES in the Canadian Rocky Mountains (Luckman and Wilson, 2005) and interior British Columbia (Wilson and Luckman, 2003). Previous research has also identified positive correlations between hemlock and summer temperatures in the Pacific Northwest (Gedalof and Smith, 2001a; Peterson and Peterson, 2001; Larocque and Smith, 2005).

No significant correlations were found between monthly precipitation and the spruce chronology, suggesting that moisture is not limiting radial growth. The hemlock chronology, however, shows a significant negative relationship to previous November precipitation. November precipitation is snowfall, which adds to the seasonal snowpack and delays the start of the next growing season.

We hypothesize that summer temperature and winter snowpack correlate to both early summer Chilko River discharge and tree growth. We selected three discharge response variables for potential reconstruction—mean June discharge, mean July discharge and summed mean June–July discharge. The spruce chronology was selected as a summer temperature proxy. The spruce chronology significantly correlates to June–July discharge ($r = 0{\cdot}49$, $p = 0{\cdot}00001$, $n = 72$). The MH chronology is sensitive to both April 1 snowpack and temperature. We performed a partial correlation analysis to determine if the MH could be used as proxy predictor variable for April 1 snowpack. Specifically, the hemlock ring series and summer discharge were correlated while holding the spruce ring series constant. The hemlock chronology and mean summer discharge are significantly negatively correlated ($r = -0{\cdot}24$, $p = 0{\cdot}45$, $n = 72$).

Dendrohydrological reconstructions

The relationships between the radial growth of MH and ES allowed us to develop models for mean June, July, and June–July discharge (Table IV). The best models for each response variable used both the spruce and hemlock chronologies as predictors (Table IV), suggesting that multi-species models better capture the temperature and snowpack variability that drives early summer Chilko River discharge. The model for mean June discharge includes the lagged spruce variable, which is a proxy for current year summer temperature. The second best models of July and June–July discharge also include the lagged spruce variable. The incorporation of a second proxy predictor for summer temperature likely reflects

Table IV. Linear models used to estimate summer discharge of Chilko River and model fit statistics

	Model	Link function	AIC[a]	CE[b]	RE[c]	Correlation[d]
June	$Q_t \sim \mathrm{ES}_t + \mathrm{MH}_t + \mathrm{ES}_{t-1}$	Logarithm	320·10	0·28	0·28	0·40*
July	$Q_t \sim \mathrm{ES}_t + \mathrm{MH}_t$	None	323·10	0·27	0·27	0·12
June–July	$Q_t \sim \mathrm{ES}_t + \mathrm{MH}_t$	Logarithm	360·04	0·37	0·38	0·52*

[a] Akaike information criterion.

[b] Coefficient of error.

[c] Reduction of error.

[d] Correlations for normal distributions were calculated using a Pearson's correlation. Correlations for non-normal distributions were calculated using a Spearman's rank correlation. Significant correlations are indicated by asterisks.

the importance of high summer temperature variability in driving early snowmelt and thus discharge.

Of the three response variables examined in this study, mean June–July discharge was modelled the best (Figure 6). This model expresses summer discharge (Q_t) as a function of current year spruce (ES_t) and hemlock (MH_t) growth, and was most successful at optimizing CE, RE and correlation statistics (Table IV). The model was run backwards over the length of the common period between the two chronologies (Figure 7). It predicts anomalously high stream flows in 1958, 1947, 1939, 1883, 1876, 1875, 1835, 1808 and 1773; and low stream flows in 1973, 1962, 1915, 1824, 1818, 1769 and 1765. The increase in extreme values in the later part of the record likely reflects noise in the data and should be interpreted in combination with the decreasing confidence expressed by the EPS statistic (Figure 7).

Identifying modes of variability

We found significant correlations between our discharge reconstructions and large-scale climate indices (Table V). Specifically, we identified a negative relationship between PDO and summer discharge, which suggests that greater Chilko River summer flow occurs

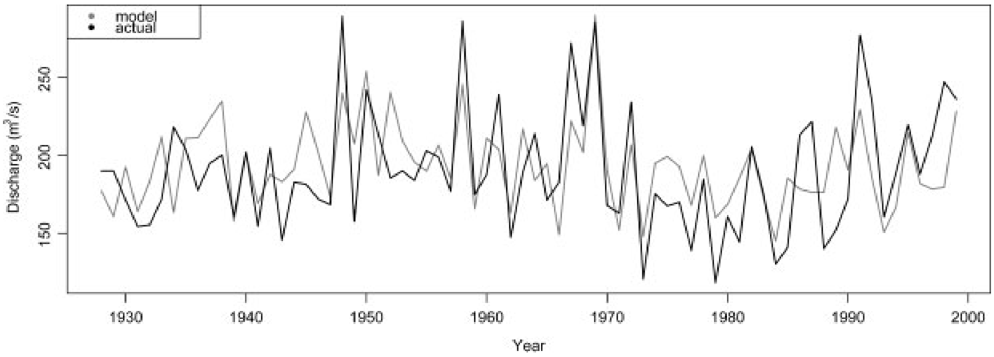

Figure 6. Best model of June–July discharge for Chilko River. The model is based on current year growth of MH and ES as predictors in a generalized linear model using a lognormal distribution

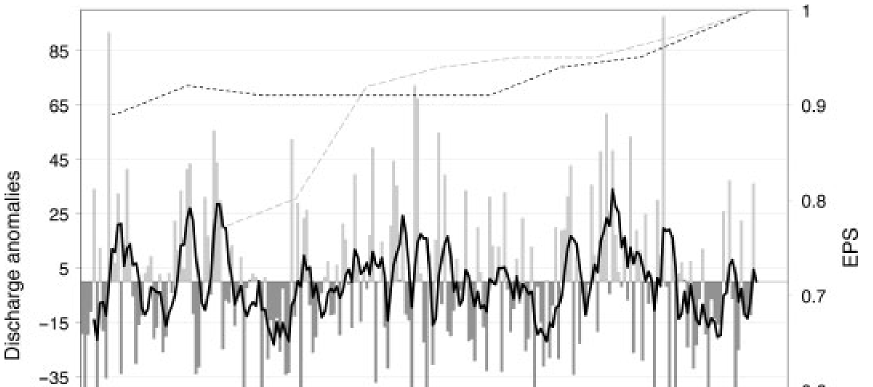

Figure 7. Reconstructed discharge for Chilko River, 1764–1999. The black line is a 10-year running mean. The dashed black and dashed gray lines show EPS statistics at 25-year intervals for the ES and MH chronologies, respectively

Table V. Correlations between reconstructed June–July discharge and large-scale climate indices

Reconstructed variable	SOI	NINO3·4	PDO	NP	PNA
June					
r	0·16	−0·14	−0·36*	0·11	−0·25
p (*n*)	0·07 (133)	0·10 (143)	0·0003 (98)	0·27 (98)	0·08 (48)
July					
r	0·142	−0·14	−0·321*	0·11	−0·25
p (*n*)	0·10 (133)	0·09 (143)	0·001 (98)	0·26 (98)	0·08 (48)
June–July					
r	0·15	−0·14	−0·37*	0·24*	−0·25
p (*n*)	0·08 (133)	0·09 (143)	0·0003 (98)	0·01 (98)	0·08 (48)

* Correlations significant at $\alpha = 0{\cdot}05$.

during negative phases of the PDO when the Coast Mountains experience a cooler and wetter climate than normal (Kiffney *et al*., 2002). Greater flows are also more likely to occur when the NP index is positive; at these times, the Coast Mountains are subject to greater advection of cool moist air and increased storminess (Moore and Demuth, 2001).

Wavelet analysis revealed dominant low- and high-frequency modes of variability within the reconstructed 225-year streamflow record (Figure 8). Wavelet spectra are characterized by multi-decadal variability (30–70 years) over most of the proxy record. Significant energy in decadal to bidecadal bands appears during the early and late 18th century. The wavelet analysis also reveals weakened power in the multi-decadal band from 1850 to 1910 (Figure 8). This dampening of the multi-decadal signal appears in independent reconstructions of the PDO over the past 200 years (Gedalof and Smith, 2001b; MacDonald and Case, 2005).

DISCUSSION

Most previous tree-ring-based streamflow reconstructions have focused on records derived from precipitation-sensitive trees (Case and MacDonald, 2003). In the southern Coast Mountains, tree growth is related to both temperature and precipitation, reflecting the broad-scale hydroclimatic teleconnections that characterize this region (Stahl *et al*., 2006; Ware, 2007).

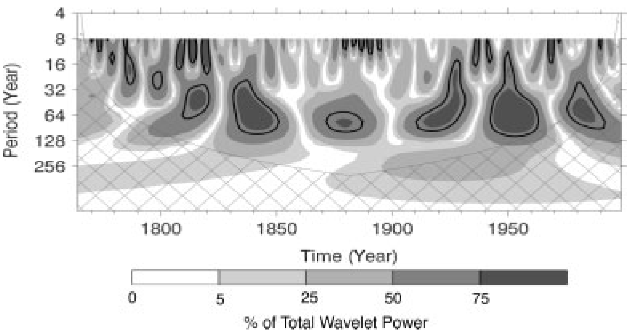

Figure 8. Wavelet power spectrum of reconstructed June–July discharge of Chilko River. A Gaussian 2 wavelet was used. The cross-hatched region represents the cone of influence where zero padding has reduced the variance. The black contours are the 5% significance levels, using a red noise (autoregressive lag 1) background spectrum (Torrence and Compo, 1998)

We have confirmed and extended previously reported complex climatic relationships between tree growth and climate. From these relationships, we developed proxy models of Chilko River summer streamflow. Our models demonstrate that an information theoretics approach can be used to reconstruct streamflow from tree-ring data. This approach proved useful in identifying the multi-species model that best fit the historical data and optimized the model's reconstructive power. The best models for each of the three response variables are similar and models provide insight into the long-term variability of summer discharge of a typical Coast Mountains stream.

Our reconstruction has identified low-frequency variation that we attribute to large-scale climate variability. Correlation analysis showed that Chilko River summer flow is related to complex atmosphere–ocean variability associated with the PDO and NP index. Our dendrohydrologic reconstruction is the first in the Coast Mountains to identify an influence of PDO-like variability in streamflow over the past 200 years.

Although ENSO is known to affect streamflow in British Columbia (Fleming and Quilty, 2006; Fleming *et al*., 2007), we were unable to distinguish variability at the annual to decadal level that we could attribute to ENSO. This outcome may be the result of the detrending method we used, which was selected to preserve low-frequency variability. However, previous work on large-scale climate variability has shown that the relation between ENSO-like decadal and PDO-like multi-decadal variability is complex. In British Columbia, discharge is most affected when PDO and ENSO are in phase (Hamlet and Lettenmaier, 1999). Although we found no significant correlations of our records with either of the ENSO indices, the NINO3·4 index was nearly significant in all three reconstructions. The near-significance of the NINO3·4 index correlation and periodic power in the annual to decadal bands may be related to ENSO events.

CONCLUSION

We used dendroclimatological techniques to establish relationships between annual growth of two tree species in the British Columbia Coast Mountains and historical climate data. We identified relationships between historical discharge of Chilko River and climate data and showed that climatically sensitive tree-ring chronologies could be used as proxy climate predictors to model streamflow. We developed generalized models of June, July, and June–July discharge for Chilko River using an information theoretics approach. A multi-species approach provided better model fit and reconstructive power than an approach based on a single species. We then reconstructed June–July discharge, our best response variable, back to AD 1764.

Our paleo-discharge record is the first to be developed from tree-ring data for a river draining a glacierized watershed in the Coast Mountains. It provides insights into streamflow variability over the past 240 years, and confirms the long-term influence of PDO teleconnections on the hydroclimatic regime in the region. We also found a relationship between reconstructed June–July discharge and the NP index, suggesting that winter atmospheric patterns over the NP may influence the region's hydrology. This record demonstrates that a carefully selected temperature-sensitive tree-ring chronology can be used in conjunction with a snowpack-sensitive species to provide a proxy record of summer discharge in rivers that are strongly affected by snowmelt.

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