

Nonstationary temporal response of mountain hemlock growth to climatic variability in the North Cascade Range, Washington, USA

Kailey Marcinkowski, David L. Peterson, and Gregory J. Ettl

Abstract: A stationary response of tree radial growth to climatic variables is assumed as a basis for climatic reconstructions and future growth projections in response to climate change. Mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière) trees on the western slopes of the North Cascade Range (Washington, USA) were examined for stability in growth response to climatic influences at a small spatial scale. Moving correlation functions demonstrate that climate–growth interactions are nonstationary over time, alternating between periods of significant and nonsignificant responses. Correlations between growth and winter precipitation have weakened, becoming statistically insignificant in the last decade, but correlations with spring temperature and previous-year summer temperature have strengthened, becoming statistically significant. The Pacific Decadal Oscillation influences patterns in climate–growth correlations but does not seem to account for the most recent changes in correlation strength. At an interannual scale, growth differs between El Niño Southern Oscillation phases, specifically between El Niño and La Niña years and between La Niña and neutral phase years. The variability in growth response to climate at interannual and interdecadal time frames, especially with the climate changes emerging in recent decades, will challenge the reliability and accuracy of reconstruction and predictive models.

Key words: dendrochronology, mountain hemlock, North Cascades, limiting factors, climate.

Résumé : À la base des reconstitutions du climat et des projections de la croissance future en réaction aux changements climatiques, on assume que la réaction de la croissance aux variables climatiques est stationnaire. Des tiges de pruche subalpine (*Tsuga mertensiana* (Bong.) Carrière) sur les pentes occidentales de la section nord de la chaîne des Cascades (Washington, É.-U.) ont été examinées à petite échelle pour déterminer la stabilité de leur croissance en réaction aux influences du climat. Des fonctions de corrélation mobile démontrent que les interactions entre la croissance et le climat ne sont pas stationnaires dans le temps : elles alternent entre des périodes où la réaction de la croissance est significative et des périodes où elle ne l'est pas. Les corrélations entre la croissance et les précipitations hivernales se sont estompées pour devenir statistiquement non significatives durant la dernière décennie alors que les corrélations avec la température printanière et la température estivale de l'année précédente se sont renforcées et sont devenues statistiquement significatives. L'oscillation décennale du Pacifique influence l'allure des corrélations entre le climat et la croissance mais ne semble pas expliquer les plus récents changements dans la force des corrélations. Sur une base interannuelle, la croissance diffère entre les phases de l'oscillation australe El Niño, spécifiquement entre les années El Niño et La Niña et entre les années La Niña et en phase neutre. La variabilité de la réaction de la croissance au climat sur une base interannuelle et interdécennale, particulièrement avec les changements qui sont apparus au cours des dernières décennies, vont remettre en question la fiabilité et la précision des reconstitutions et des modèles de prévision. [Traduit par la Rédaction]

Mots-clés : dendrochronologie, pruche subalpine, section nord de la chaîne des Cascades, facteurs limitants, climat.

Introduction

Forest environments can often be classified on a gradient from energy limited, in which growth is influenced by climatic factors such as light, temperature, or length of growing season, to water limited, in which growth is limited by climatic factors that affect water availability. Radial tree growth in energy-limited forest environments is most often negatively correlated with winter precipitation and positively correlated with summer temperature (Ettl and Peterson 1995a), *Abies lasiocarpa* (Hook.) Nutt. (subalpine fir); Peterson (1998), review of climate–growth trends in various subalpine studies), and radial growth in water-limited forests is generally positively correlated with summer and winter precipi-

tation and negatively correlated with summer temperature (Littell et al. 2008, *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir)). Some forests such as those in the continental climate of the Mediterranean Basin fall into the middle of the gradient, often containing characteristics of both energy and water limitations (DeSoto et al. 2012). High-elevation forests at or near the tree line in the Pacific Northwest region of North America (PNW) are generally considered to be at the energy-limited end of the gradient, because growth is mainly influenced by the effects of temperature (McKenzie et al. 2003; Albright and Peterson 2013) and duration of snowpack on the length of the growing season (Peterson and Peterson 1994, 2001; Ettl and Peterson 1995b; Peterson et al. 2002; Case and Peterson 2007). Temperatures have increased over the

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past century and are expected to continue to increase, potentially affecting the growth of subalpine tree species (Fischlin et al. 2007).

In the PNW, temperatures increased by 0.8 °C during the 20th century (Mote 2003), with an expected average increase of 0.3 °C per decade in the 21st century (Mote and Salathé 2010). Summers are projected to be warmer and drier, and winters will likely be warmer and slightly wetter (Mote and Salathé 2010). Warmer winter temperatures are already apparent, with spring snow-covered area, snowpack, and snow–water equivalent (SWE) decreasing in the region (Mote et al. 2005; McCabe and Wolock 2010; Pederson et al. 2011). Warmer temperatures, decreased snow accumulation, and more precipitation falling as rain will likely result in a longer growing season for subalpine forest ecosystems. In response to warming temperatures, high-elevation trees are expected to increase growth and productivity (Latta et al. 2010). This has been documented at some locations in western North America where growth has increased over the past century concurrent with temperature increases (Graumlich et al. 1989), *Tsuga heterophylla* (Raf.) Sarg. (western hemlock), *Abies amabilis* Douglas ex J. Forbes (Pacific silver fir), and *Tsuga mertensiana* (Bong.) Carrière (mountain hemlock) forest zones; Peterson et al. (1990), *Pinus contorta* Douglas ex Loudon (lodgepole pine) and *Pinus albicaulis* Engelm. (whitebark pine); Peterson (1994), review of growth trends in various studies; McKenzie et al. (2001), chronologies composed mainly of *Pinus ponderosa* Douglas ex P. Lawson & C. Lawson (Ponderosa pine), *P. menziesii*, and *Picea engelmannii* Parry ex Engelm. (Engelmann spruce); Millar et al. (2004), *P. albicaulis* and *Pinus monticola* Douglas ex D. Don (western white pine)). Projected warmer temperatures and lower snowpack in the next century will likely lead to changes in known limiting factors at higher elevation sites, possibly shifting energy-limited, high-elevation forests to more water-limited ecosystems (Williams et al. 2010; Albright and Peterson 2013).

Climate–growth relationships (e.g., correlations between radial growth and climatic variables) have been shown to vary over time (Jacoby and D'Arrigo 1995; Briffa et al. 1998; Biondi 2000; Carrer and Urbinati 2006; Trindade et al. 2011; Griesbauer and Green 2012), and recent investigations at high-latitude, high-elevation locations have found that recent tree growth is showing a decreasing sensitivity to temperature (Jacoby and D'Arrigo (1995) and D'Arrigo et al. (2004), *Picea glauca* (Moench) Voss (white spruce); Briffa et al. (1998), boreal forests at high elevations and northern latitudes; D'Arrigo et al. (2008), review of many studies and species around the world; Coppola et al. (2012), *Larix decidua* Mill. (European larch)). This anomaly, known as the “divergence problem” (D'Arrigo et al. 2008), is focused on temperature-limited northern forests that have weakening trends in growth response to temperature in the last few decades. Several explanations have been proposed for this phenomenon, the main one being that the increased temperature is causing soil moisture stress that, in turn, reduces climatic sensitivity (Briffa et al. 1998; D'Arrigo et al. 2008). This temporal variation in climate–growth relationships affects the robustness of climatic reconstructions, as well as projections of tree growth in models of climate change effects.

Mountain hemlock, a common conifer species in the subalpine forests of coastal mountains in western North America, has been the focus of several climate–growth investigations (Taylor 1995; Smith and Laroque 1998; Gedalof and Smith 2001a; Peterson and Peterson 2001) and the basis for different climatic reconstructions (Graumlich and Brubaker 1986; Gedalof and Smith 2001b; Marcinkowski 2012). At high elevations, winter precipitation and snowpack are negatively correlated with mountain hemlock growth (Smith and Laroque 1998; Peterson and Peterson 2001; Marcinkowski 2012). Growth is positively correlated with current-year summer temperature and negatively correlated with previous-year summer temperature (Smith and Laroque 1998; Gedalof and Smith 2001a; Peterson and Peterson 2001; Marcinkowski 2012). At lower elevations, mountain hemlock growth is negatively correlated with previous-year summer temperature and positively correlated with previous-year summer

precipitation, suggesting a water-limited response that is opposite to the response of energy-limited, high-elevation sites (Peterson and Peterson 2001).

Climatic modes of variability at different time scales such as the El Niño Southern Oscillation (ENSO; interannual) and the Pacific Decadal Oscillation (PDO; multidecadal) also influence mountain hemlock growth in the PNW. Cool phases of PDO and ENSO (La Niña) are characterized by cool, wet winters in the PNW, and warm phases of PDO and ENSO (El Niño) are generally warmer and drier — warmer and drier phases of both indexes have higher values. At high elevations, mountain hemlock growth in the PNW is positively correlated with the winter PDO index (Gedalof and Smith 2001b; Peterson and Peterson 2001; Marcinkowski 2012) and the spring ENSO index (Marcinkowski 2012), and at low elevations, growth is negatively correlated with the winter PDO index (Peterson and Peterson 2001). Although much is known about the response of mountain hemlock growth to climate, previous studies have not investigated if or how these climate–growth relationships change over time, particularly in response to the recent warming.

In this study, we use a multidecadal time frame to examine climate–growth correlations for mountain hemlock at tree line locations on the western slopes of the North Cascade Range (Washington, USA). This was done to (i) explore the temporal variability of mountain hemlock climate–growth correlations, (ii) better understand how short-term, annual, and interannual, climatic phenomena influence radial tree growth, and (iii) investigate longer term patterns of growth.

Methods

Study area

Sampling was conducted on the west side of the North Cascade Range (Washington, USA). The North Cascade Range spans two climatic zones, with the eastern side having a drier, continental climate and the western side having a wet, more maritime climate. Total precipitation can reach up to 250 cm annually on the western side. Snow can accumulate as early as October, reach depths of more than 5 m, and persist into June or July at high elevations. Moist subalpine forests are dominated by mountain hemlock and Pacific silver fir, with occurrences of subalpine fir (Douglas 1972), and trees transition from closed canopy forests to more open forests, with trees clumped together at increasing elevations.

Six high-elevation stands on the western slopes of the North Cascade Range were sampled in summer 2011 (Table 1; Fig. 1). These sites were all above 1200 m, i.e., near the tree line where radial growth was considered to be limited by persistent snowpack. No preference was given to slope or aspect, because the overwhelming effect of snow diminishes the importance of these factors at the tree line. Sites were located within the North Cascades National Park Complex, Mount Baker-Snoqualmie National Forest, and Okanogan-Wenatchee National Forest boundaries.

Chronology construction

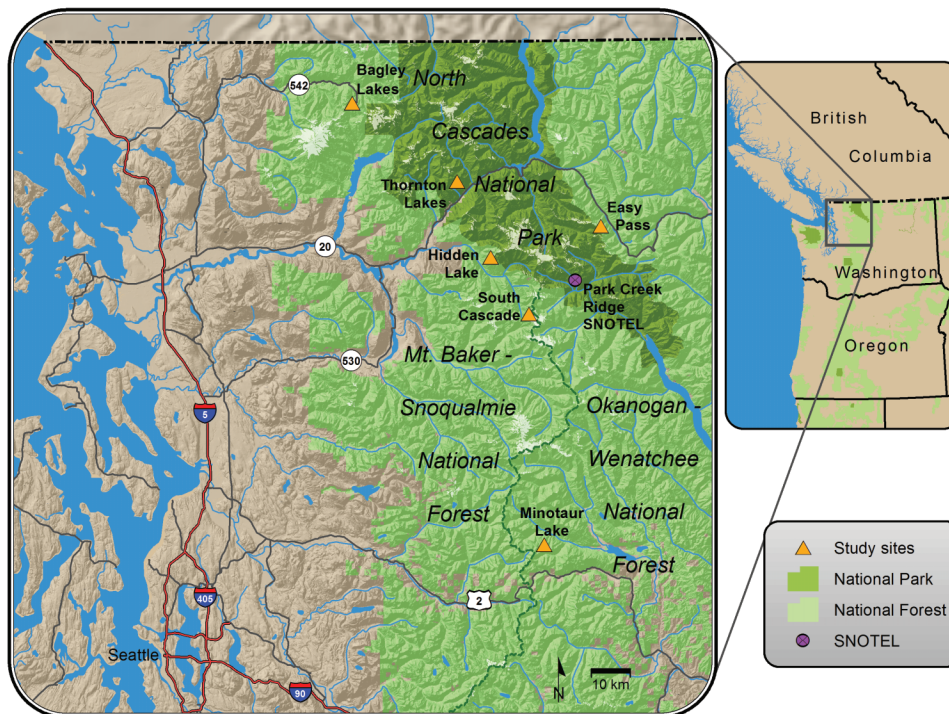
Twenty mountain hemlock trees were sampled at each site, and preference was given to dominant or codominant trees without obvious disturbances (e.g., apparent fire, insect, or wind effects). Trees were sampled at breast height (1.3 m) with an increment borer at the cross-slope position of the bole to reduce the likelihood of encountering compression wood. Two cores were collected per tree. Tree rings were cross-dated using standard dendrochronological procedures (Stokes and Smiley 1968). For each tree, the longest or most intact core was chosen, and the ring widths were measured and recorded to the nearest 0.001 mm using a measuring stage (Velmed, Inc., Bloomfield, New York), MeasureJ2x software (version V4.2, VoorTech Consulting, Holderness, New Hampshire), and an Olympus DF PLAN 1.5× measuring

Table 1. Summary of site characteristics.

Site	Mean elevation (m)	Longitude	Latitude	Mean DBH (SD) (cm)	Year range	Median age (years)	Mean age (years)
Hidden Lake (HL)	1769	-121.208797	48.5047562	51.7 (5.7)	1346–2010	371	385
South Cascade (SC)	1613	-121.078867	48.3736037	76.8 (12.6)	1392–2010	349	367
Bagley Lakes (BL)	1297	-121.685031	48.8606919	68.6 (8.1)	1659–2010	298	302
Minotaur Lake (ML)	1703	-121.035864	47.8443795	51.3 (8.6)	1615–2010	296	293
Easy Pass (EP)	1540	-120.826407	48.5732920	61.7 (12.7)	1623–2010	227	243
Thornton Lakes (TL)	1473	-121.322671	48.6797718	66.5 (10.3)	1746–2010	211	204

Note: DBH, diameter at breast height (1.3 m); SD, standard deviation.

Fig. 1. Region where mountain hemlocks were sampled. Triangles represent locations of sampling sites, the circle represents the SNOTEL used in this study, dark green shading represents National Park Service land, and light green shading represents U.S. Forest Service national forest land.



scope. Only one core per tree was measured, because the sample size was sufficiently large to achieve appropriate signal quality (Mäkinen and Vanninen 1999). Cross dating was verified by creating time-shifted correlation coefficients for cores with mean chronologies for each site using the program COFECHA (Holmes 1983).

Tree-ring series were detrended with ARSTAN (Cook and Holmes 1996) to remove age-related trends in growth. Several detrending methods were explored, but examination of descriptive curve statistics (Fritts 1976) showed that results were not sensitive to the detrending method. A cubic spline with a 50% cutoff of 150 years was chosen, because most growth series were older than 250 years and did not show age-related negative exponential decline.

Each detrended series was standardized by dividing the measured observations by the fitted curve values to create a unitless index. Autoregressive modeling was done to prewhiten the indices and generate residual chronologies, removing the biological persistence and autocorrelation and strengthening the climate-related growth signal in the series. A biweight robust mean was used to average the individual series into site chronologies.

A regional chronology was also created from 109 individual tree cores. The cores were detrended with a 50% cutoff of 150 years, standardized into a unitless index, and prewhitened. A biweight

robust mean was used to average all the individual cores into a regional chronology.

Climate data

The following climatic variables were used in this study: (i) current growth year winter (November–March) precipitation, SWE (measured 1 April), and previous growth year summer (June–August) temperature, and (ii) current growth year spring (April–May) temperature, current growth year summer (June–August) temperature, current growth year summer precipitation, current growth year summer Palmer Drought Severity Index (PDSI), winter (November–March) PDO index, and spring (April–May) ENSO index. Although this is not a precise classification, variables in group *i* are negatively correlated with growth in high-elevation, energy-limited forests, with some being positively correlated with growth at water-limited sites, and variables in group *ii* are positively correlated with growth in high-elevation, energy-limited environments, with some being positively correlated with growth in water-limited forests. Divisional climatic records for monthly precipitation, temperature, and PDSI were obtained from the National Climate Data Center (available from <http://www.ncdc.noaa.gov/oa/ncdc.html>, accessed September 2011) for 1896–2010; divisional data are a compilation of individual stations within similar climatic regions. Measurements

for seasonal variables (definitions above) were averaged to create a mean for winter and summer precipitations, spring and summer temperatures, and summer PDSI. The sites that were sampled had no long-term weather stations, and because the divisional data are a combination of many stations, they better represent the regional climate and have a longer record than any one station. Interpolated records such as those available through the PRISM Climate Group were considered for use, but preliminary analyses showed that there was no clear advantage to using interpolated site-specific climatic data. Two climatic divisions were used: the Hidden Lake (HL), South Cascade (SC), Thornton Lakes (TL), Easy Pass (EP), and Bagley Lakes (BL) sites all fell within the boundaries of the Cascade Mountains West division, and the Minotaur Lake (ML) site was located in the boundaries of the East Slope Cascades division. The Cascade Mountain West division was used for comparisons with the regional chronology, because the majority of the sites were located within this division. SWE values for 1936–2010 came from the Park Creek Ridge SNOWTEL station, which is situated at a central location to the six sampling sites. The PDO index, spanning 1901–2010, was obtained from the University of Washington Joint Institute for the Study of the Atmosphere and Ocean climate data archives (available from <http://jisao.washington.edu/pdo/PDO.latest>, accessed September 2011), and the Niño Region 3.4 Index (ENSO), spanning 1872–2007, was obtained from the National Center for Atmospheric Research (available from http://www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/index.html#Sec5, accessed September 2011).

Moving correlations

Moving Pearson product–moment correlations were calculated between climatic variables and each of the six growth chronologies and the regional chronology. The growth chronologies were truncated to match the available record for the climatic variables, and the lengths varied from 74 to 135 years. Moving correlation functions calculate correlations between two time series over a defined window of time, which progressively moves forward by 1 year over the length of the series (Biondi 2000). Moving correlation functions were chosen because the fixed window length provides a constant sample size in which statistical significance is established and comparisons between sites and climatic variables are equitable. The result of a moving correlation function is a time series that visually tracks variability in the correlations.

Inferences from moving correlations may depend on the window length and alignment, and different window lengths were tested to determine what effect, if any, alternative window lengths have on results. Four window lengths (20, 25, 30, and 35 years) were compared, and patterns in the moving correlations and periods of significance were similar. Longer window lengths were not tested, because the purpose of this study was to examine multidecadal trends, and window lengths longer than 40 years could obscure these trends. A 25-year, right-aligned window was selected to highlight multidecadal patterns in climate–growth correlations, and significance ($p < 0.05$) is based on the 25-year window length. Because the window progressively moves forward, many Pearson product–moment correlation tests were performed. Depending on the length of the climate record, calculations between one climatic variable and one growth chronology resulted in approximately one-hundred 25-year Pearson product–moment correlations. It is important to note that the large number of correlation tests could possibly result in spurious correlations.

No statistical corrections were made to the significance level of the moving correlations. This analysis relies on classification of both significant and nonsignificant correlation values. Common techniques to correct the type I error rate (e.g., Bonferroni) tend to be overly conservative, decreasing the type I error rate and inflating the type II error rate. In this case, we would be trading possible misclassification of significant correlations with misclassification of nonsignificant correlations. To better understand why the correlations might be changing over time, relationships

between correlation values and climatic variables were evaluated. Cross correlations between climatic variables using Pearson product–moment correlations and plots of moving correlations and climatic variables were first examined. Many of the climatic variables examined in this study are related, and changes in one variable may affect changes in other climatic variables. Plotting the climate–growth relationship determined by the moving correlations with related climatic variables will identify any patterns that could be caused by interactions in the climatic variables. Considering the connections between climatic variables provides a more robust analysis of trend in climate–growth relationships over time and helps reduce the potential for misinterpretation of spurious correlations.

Basal area increment

Raw tree-ring width data were converted to basal area increment (BAI) to examine changes in growth rate through time and provide a context for the moving correlations. Diameter inside the bark was calculated using the following equation:

$$D_{t-1} = \frac{[D_t - (B_s D_t)] - R_t}{1 - B_s}$$

where D_{t-1} is the diameter inside the bark, D_t is the measured diameter at breast height, R_t is twice the ring width at year t , and B_s is the species-specific bark thickness coefficient (0.914) for western hemlock (Smith and Kozak 1967), because a coefficient for mountain hemlock is not available. Using the bark thickness of western hemlock might introduce some error into the BAI calculations, but the error is consistent across all individual-tree BAI transformations. After calculating D_{t-1} , annual diameter was calculated by subtracting twice the tree-ring width from the previous year. The diameters were then converted to BAI with the following equation:

$$\text{BAI} = \pi \left(\frac{D_t}{2} \right)^2 - \pi \left(\frac{D_{t-1}}{2} \right)^2$$

Transforming ring widths to BAI eliminates the need for detrending, because BAI accounts for the increase in circumference as a tree ages and is considered a more accurate approximation of relative tree growth than tree-ring width (Visser 1995). BAI was used to explore growth trends and characteristics at the six sampling sites by averaging individual BAI series into a mean BAI time series for each site, and simple linear regressions of the mean BAI over time were calculated.

Short-term growth trends were examined using linear regression models of BAI over the 1950–2010 time period on each individual series within a site to provide a picture of overall trends within the region. If the slope of the regression model was significant ($p < 0.05$), then the individual BAI series had a linear trend. Mean change over the 1950–2010 time period was calculated to determine if each site had, on average, increased or decreased in growth.

ENSO phase comparisons

Differences in tree radial growth between El Niño, La Niña, and neutral phase years were also explored. El Niño years were categorized as any year in which the Niño Region 3.4 Index was above a threshold value of 0.4 for six consecutive months, and La Niña years were similarly categorized for the threshold value below -0.4 (Trenberth 1997). Years between those cutoff values were considered neutral. Several different ways to categorize ENSO phases were examined, but changing the threshold value or number of months required at the value did not have a noticeable effect on phase classification. A linear mixed model analysis with the ENSO phase as a fixed effect and sampling sites as random

Table 2. Summary of chronology statistics.

Site	<i>n</i>	Series mean first-order autocorrelation	Mean interseries correlation (\bar{r})	Mean sensitivity	Autoregressive order	Autoregressive R^2	EPS
Hidden Lake	17	0.480	0.294	0.231	4	0.24	0.88
South Cascade	17	0.371	0.318	0.186	2	0.15	0.89
Bagley Lakes	19	0.386	0.299	0.191	2	0.17	0.89
Minotaur Lake	18	0.549	0.307	0.191	2	0.33	0.89
Easy Pass	18	0.479	0.304	0.254	5	0.29	0.89
Thornton Lakes	20	0.327	0.355	0.221	2	0.12	0.92
Regional	109	0.394	0.239	0.168	1	0.16	0.97

Note: Series mean first-order autocorrelation and mean interseries correlation values are prior to autoregressive modeling. Mean sensitivity values are calculated after autoregressive modeling. *n*, number of cores per site chronology; EPS, expressed population signal; regional, a chronology created from 109 individual tree cores.

effects was used to test for differences in growth between ENSO phases; however, initial testing determined that there was no between-site variability. Therefore, an analysis of variance (ANOVA) test was conducted to examine if differences in mean growth during ENSO phases were significant ($p < 0.05$). The assumptions of an ANOVA were tested and met. If a significant difference was found between growth and ENSO phases, then Tukey's honestly significant difference (HSD) test was used as a post hoc test to further identify which phases differed.

All calculations and graphs in this study were created using R (version 0.94.110; R Development Core Team 2010), unless otherwise noted.

Results

Chronology descriptions

Chronology statistics show the quality and suitability of use for the six site chronologies and the regional chronology (Table 2). Mean interseries correlation (\bar{r}), which measures the similarity in growth among trees in a chronology, ranged from 0.294 to 0.355 (mean, 0.313), indicating a likely common growth response to climatic variability within the sites. Expressed population signal (EPS), which is a measure of how closely a chronology portrays a hypothetical perfect chronology, ranged from 0.88 to 0.92, above the common threshold of 0.85 (Wigley et al. 1984). The regional chronology had a slightly lower \bar{r} of 0.239 and an EPS of 0.97 due to the number of individual cores contained in the chronology.

Sample depth varied by the analysis, but cutoff dates were not chosen for the site chronologies. The entire length of the chronologies was used for the BAI analysis, but the chronologies were truncated to match the time series length of the climatic variables for all other analyses. Sample depth for the moving correlation analysis and ENSO phase analysis ranged from 17 to 20 cores for the series. The regional chronology included in the moving correlation analysis ranged from 108 to 109 cores depending on the time series length of the climatic variable.

Moving correlations

Moving correlations between each of the six sampling sites, the regional chronology, and the nine climatic variables and indices describe changes in mountain hemlock growth (Fig. 2). The six site chronologies and the regional chronology show a nonstationary response to all climatic variables, with correlation values increasing and decreasing over time and changing significance. The regional chronology highlights similarities in site growth responses over time.

Correlations of radial growth with winter precipitation are non-significant until the mid-1970s, except for one outlier at the Minotaur Lake site in the early 1940s. Correlations are significantly negative from the mid-1970s to 2000, but after 2000, correlations are nonsignificant again. Agreement among the sites is high, with all six chronologies having negative correlations from the 1970s to 2000 and decreasing correlation values in the last decade. Correlations between growth and SWE are negative and significant

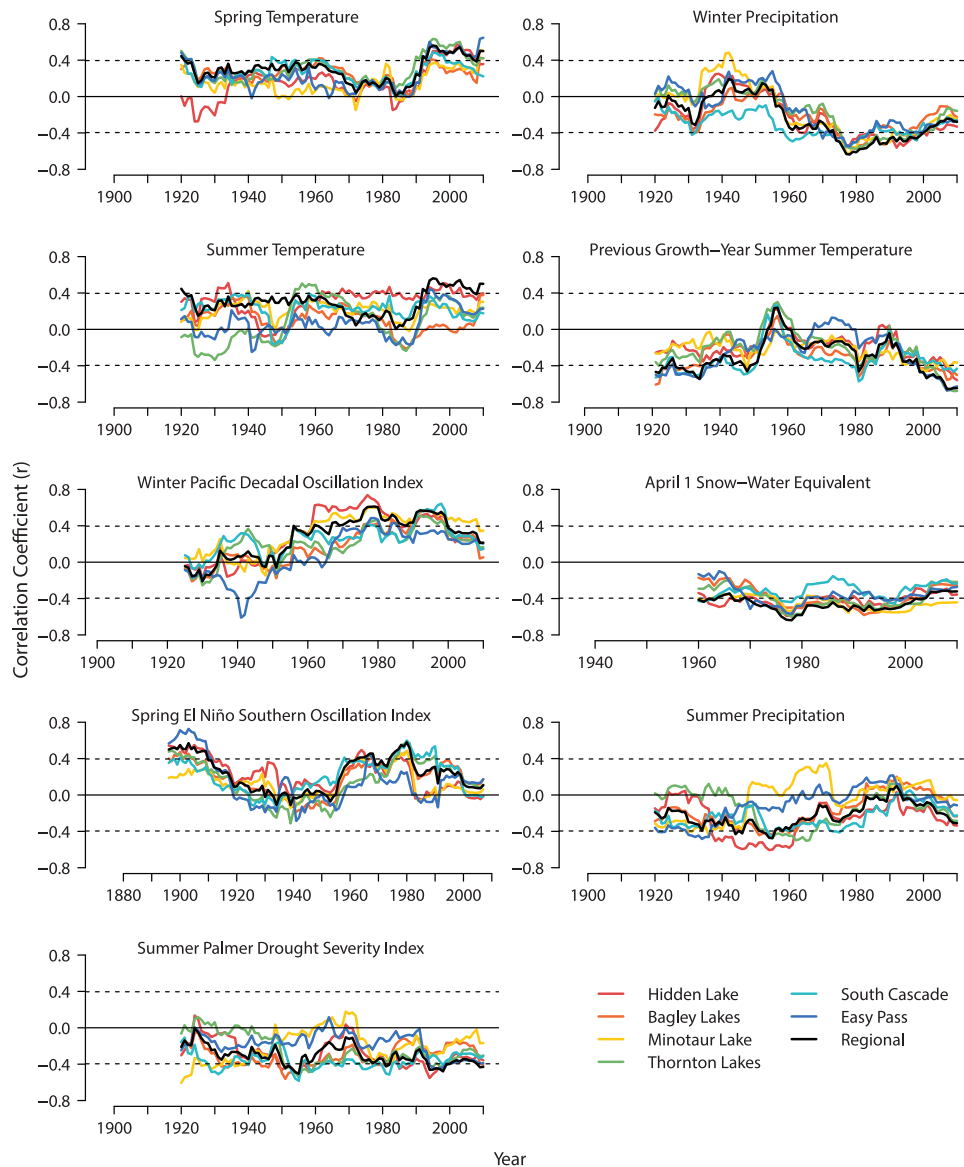
until about 2000, when correlation values between growth and SWE decrease and become nonsignificant. Correlations with previous growth year summer temperature show significant correlations in the 1920s and 1930s and again from the late 1990s into the 2000s. Agreement in correlations among sites is high, particularly as the correlation values become significant in the 1990s.

Correlations of radial growth with spring temperature are non-significant until the late 1980s when there is a large increase in magnitude of the correlation values. Spring temperature has significant positive correlations from 1990 to 2010. Summer temperature has few significant positive correlations over the time period but is mainly nonsignificant. Summer precipitation and summer PDSI correlations are generally nonsignificant. Spring ENSO correlations are nonsignificant except for about a decade at the beginning of the 20th century and again around 1980. Correlation values between growth and winter PDO increase in magnitude over the study period, with significant positive correlations from 1960 to 2000 and decreasing, nonsignificant correlations after 2000.

Graphing the PDO cycle averaged over the same 25-year window as the moving correlations shows that some climate-growth correlations appear to follow a similar pattern of peaks and troughs as the smoothed PDO (Fig. 3). The correlations between growth and spring temperature are significant during the most recent positive PDO phases and nonsignificant during negative phases, and correlations between growth and winter precipitation and growth and winter PDO are significant during cool phases and are generally nonsignificant during warm phases. Variability in the PDO phase was examined to see if it provided a possible explanation for patterns of significance in the climate-growth correlations. The PDO index used in this study spans 1901–2010, with cool (negative) phases during 1901–1924 and 1947–1976 and warm (positive) phases during 1925–1946 and 1977–1998 (Mantua and Hare 2002). Variability was determined by calculating the percentage of out-of-phase years during each PDO phase, with out-of-phase years being defined as years in which the sign of the mean PDO index was opposite of its determined phase: 1901–1924 cool phase (63%), 1925–1946 warm phase (27%), 1947–1976 cool phase (13%), and 1977–1998 warm phase (14%). The most recent phase, 1999–2010, is being considered a cool phase, but index values are still variable between warm- and cool-phase years.

Many of the climatic variables used in the moving correlation analysis are correlated, as evidenced by the cross correlations (Table 3). The significant correlations found were expected, based on knowledge of seasonal climate in high-elevation sites. Winter precipitation was significantly correlated with SWE, summer PDSI, winter PDO, and spring ENSO. Spring temperature was significantly correlated with SWE, summer temperature, summer PDSI, winter PDO, and spring ENSO. Summer PDSI was also significantly correlated with summer precipitation and summer temperature. Winter PDO and spring ENSO were correlated with all climatic variables except previous growth year summer temperature.

Fig. 2. Moving correlations over a 25-year window between mountain hemlock radial growth and climatic variables at each of the six sites. Horizontal, dashed lines indicate a significance ($p < 0.05$) cutoff of ± 0.396 . Variables in the left-hand plots are generally positively correlated with growth in energy-limited forests, and some are positively correlated with growth in water-limited forests, whereas variables in the right-hand plots are commonly negatively correlated with growth in energy-limited forests, with some being positively correlated with growth at water-limited sites.



The moving correlation analysis showed several interesting patterns (results for significant and (or) changing correlations are shown in Fig. 4). The relationship between growth and spring temperature gets weaker as SWE increases. Correlations between growth and SWE become stronger with more winter precipitation, but correlations between growth and winter precipitation do not have a compelling trend with raw SWE values. Plotting correlations between growth and SWE with the winter PDO index shows that the growth relationship with SWE becomes more negative when PDO values are higher. The relationship between growth and spring temperature gets weaker when PDO index values are higher, but the relationship between winter precipitation and growth becomes slightly stronger when winter PDO values are higher.

BAI

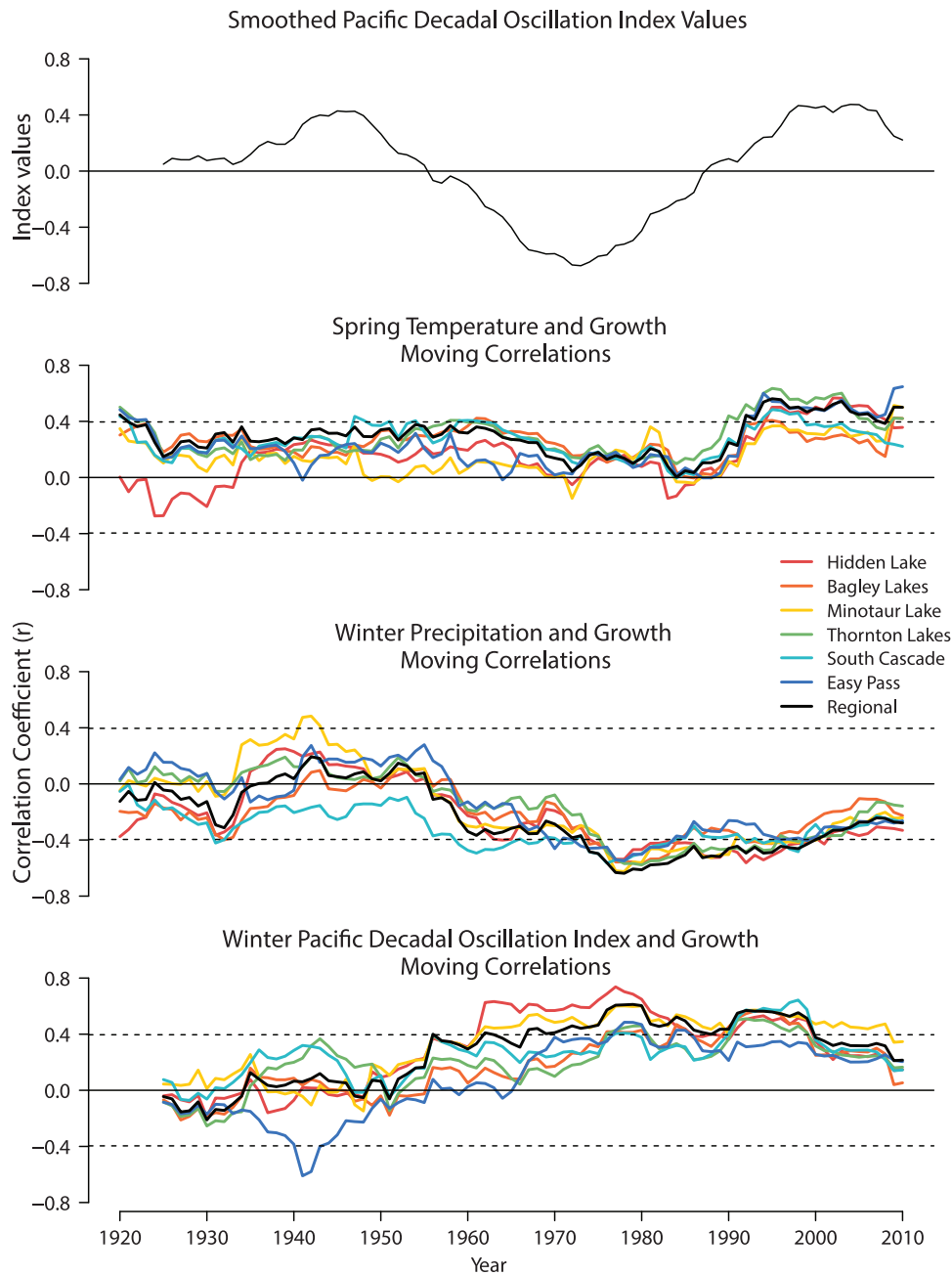
To better visualize growth and provide a context for the moving correlation results, individual BAI were averaged by year to create

a site BAI series (Fig. 5). All linear regression trend lines on the plots are significant and show that the majority of sampling sites have increased growth over the time series. Short-term trends in growth since 1950 were also explored with linear regression models. At each of the sites, about half of the individual trees had significant ($p < 0.05$) trends in growth (Table 4). Using the regression trend line, mean change in growth was calculated for each site. Trees at the EP and HL sites, on average, increased growth over the last 60 years, whereas trees at the TL and SC sites decreased in growth. Growth at the BL and ML sites also decreased over this time period, but these decreases were smaller in magnitude than at the TL and SC sites.

ENSO phase comparisons

Boxplots of growth during El Niño, La Niña, and neutral phases show that the distribution of mean growth is not very different among phases (Fig. 6). Visually, the largest difference in growth appears to be between La Niña (lower growth) and El Niño (higher

Fig. 3. The winter (November–March) Pacific Decadal Oscillation (PDO) index smoothed with a 25-year window, and the moving correlation functions between mountain hemlock growth chronologies and spring temperature, winter precipitation, and winter PDO. Horizontal, dashed lines indicate a significance ($p < 0.05$) cutoff of ± 0.396 .



growth). The assumptions for ANOVA testing were met, and the simple ANOVA was significant ($p < 0.05$), rejecting the null hypothesis of equal mean growth during ENSO phases. Tukey's HSD test was used to determine which phases had differences in mean growth. At a significance level of $p < 0.05$, Tukey's HSD test showed that there was a difference in mean growth between La Niña and El Niño years and also between La Niña and neutral years. There is no significant difference in growth between El Niño and neutral years.

Discussion

Climatic influences on mountain hemlock growth are nonstationary, and correlations between climate and growth are not consistently significant over the climate record. Visual observa-

tions from Fig. 2 suggest that climatic variables that are known to influence mountain hemlock growth through their effect on duration of growing season such as winter precipitation and SWE (Smith and Laroque 1998; Gedalof and Smith 2001a; Peterson and Peterson 2001; Marcinkowski 2012) have longer periods of significant correlations than variables that might have a smaller influence on growth (e.g., summer temperature). Correlations between growth and the climatic variables that mainly influence growth (e.g., winter precipitation) tend to be in close agreement, with very similar correlation values among the six sites, as highlighted by the regional chronology (Fig. 2).

The tree line location of the mountain hemlock sites may be sensitive to shifts in climate–growth responses. The relatively consistent negative correlation of SWE through time expresses

Table 3. Cross correlations between climatic variables.

	Winter precipitation	SWE	Previous growth year summer temperature	Spring temperature	Summer temperature	Summer precipitation	Summer PDSI	Winter PDO index	Spring ENSO index
Winter precipitation	1								
SWE	0.84	1							
Previous growth year summer temperature	0.054	-0.066	1						
Spring temperature	-0.1	-0.26	0.32	1					
Summer temperature	-0.023	-0.13	0.38	0.4	1				
Summer precipitation	0.07	0.03	0.07	-0.07	-0.35	1			
Summer PDSI	0.40	0.20	-0.01	-0.32	-0.36	0.67	1		
Winter PDO index	-0.38	-0.57	0.17	0.21	0.29	-0.06	-0.11	1	
Spring ENSO index	-0.29	-0.32	0.13	0.39	0.21	0.10	-0.03	0.35	1

Note: Bold font indicates significance ($p < 0.05$). SWE, snow-water equivalent (measured 1 April); PDSI, Palmer Drought Severity Index; PDO, Pacific Decadal Oscillation; ENSO, El Niño Southern Oscillation.

Fig. 4. Moving correlations of spring temperature, snow-water equivalent, and winter precipitation plotted again raw climatic variables. The black line is the trend line resulting from a simple linear regression of climatic variables and climate-growth relationships; none of the regressions are significant.

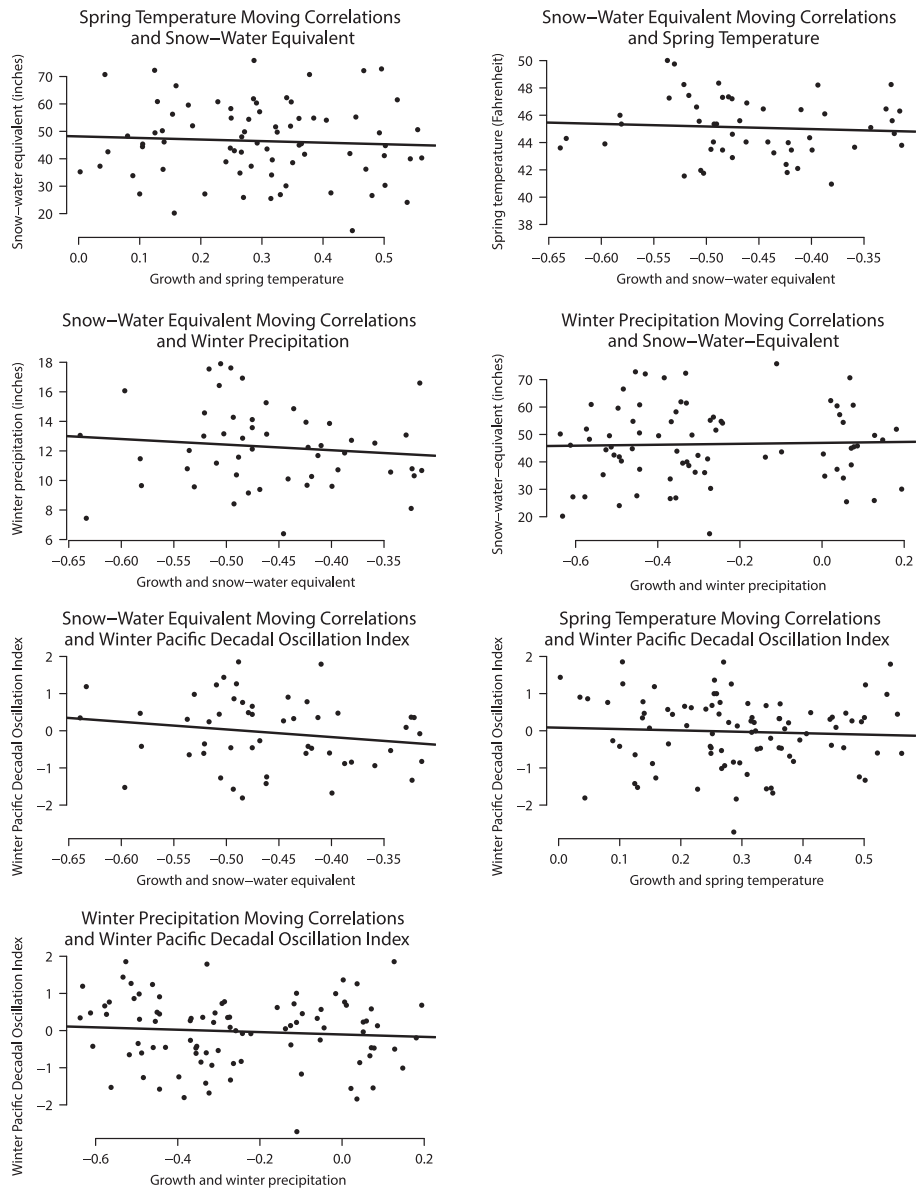


Fig. 5. Time series plots of mean basal area increment (BAI, cm²) by site. The x axis (years) is restricted to the site with the shortest mean BAI time series (Thornton Lakes, 1746). The thick black line is the trend line resulting from a simple linear regression of each site over time, and all regressions were significant.

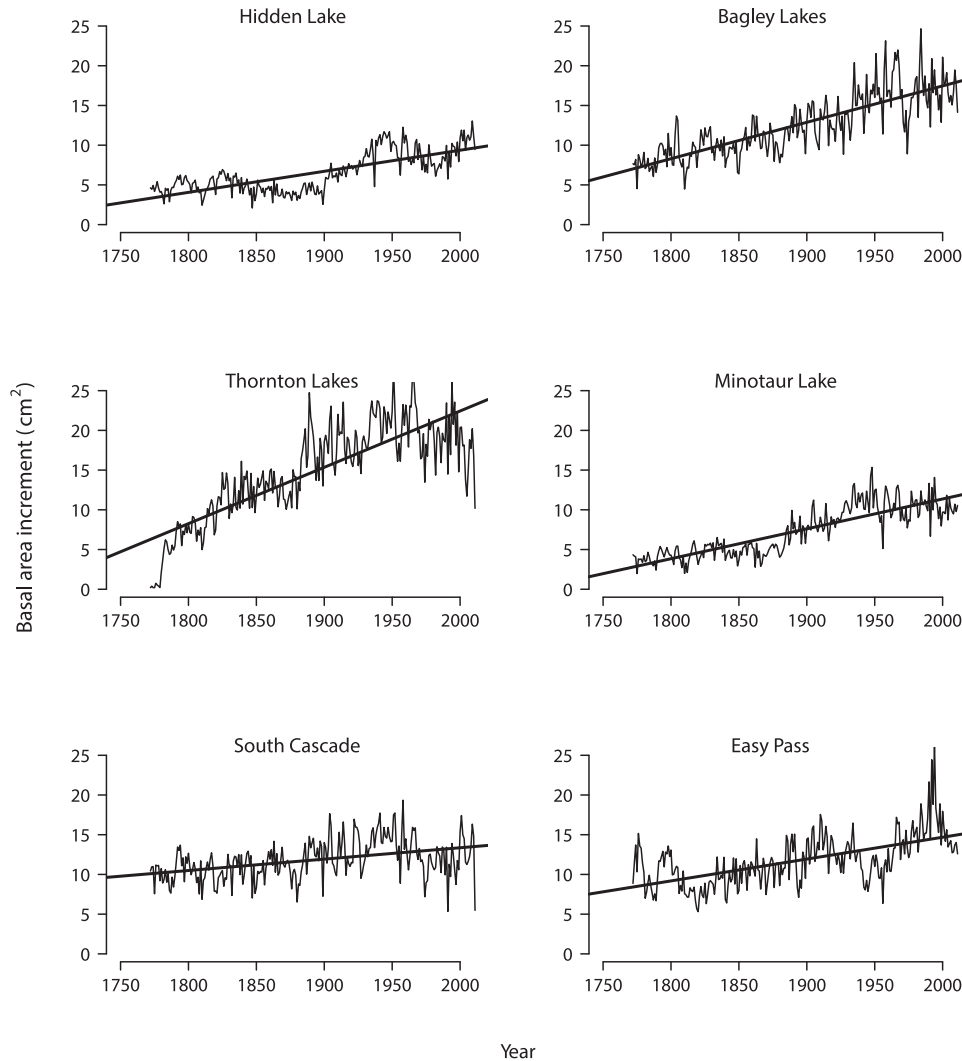


Table 4. Recent short-term (1950–2010) growth trends.

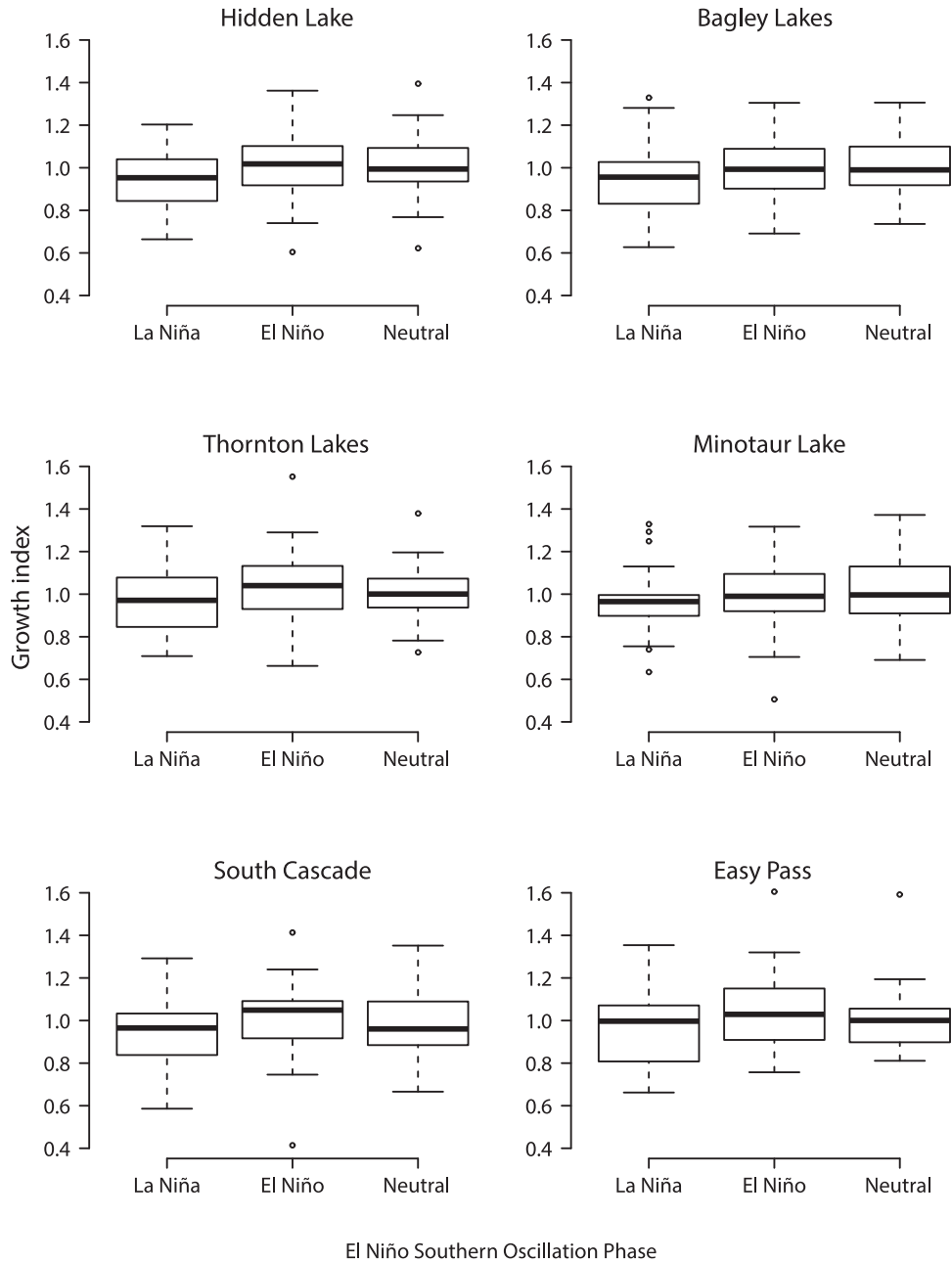
	Site					
	Hidden Lake	South Cascade	Bagley Lakes	Minotaur Lake	Easy Pass	Thornton Lakes
Mean change	1.29	-2.15	-0.54	-0.22	5.49	-4.80
Percent significant change	44	56	40	58	53	71

Note: Mean change indicates the average change over time from 1950 to 2011 for each site from the basal area increment chronologies. Percent significant change indicates the percentage of individual cores that experienced significant ($p < 0.05$) change (either positive or negative) in growth over the time period at each site.

the importance of this factor in limiting growth at the tree line. However, correlations between growth and winter PDO, winter precipitation, and SWE have decreased below significance within the last decade. During this time, correlations with spring temperature and previous growth year summer temperature both change from being nonsignificant throughout the record to being significant, which suggests a change in factors modifying growth. It appears that winter precipitation, a surrogate for growing season length, is being replaced by spring and summer temperatures, possibly indicative of an earlier start to the growing season. The increased importance of these variables in the most recent decades might suggest a change in limiting factors and a possible shift in these tree line sites from energy limited (persistent snowpack and short growing sites with cool temperatures) to water

limited. Although the sites are recently significantly correlated with temperature variables, moisture variables such as summer precipitation and PDSI are not significant. The sites are not exhibiting all of the climate–growth responses expected for water-limited sites (i.e., significant correlations with summer moisture). The changes found in limiting factors could indicate movement along the gradient from energy limited to water limited, rather than a direct shift from one limiting environment to another. Peterson and Peterson (2001) examined mountain hemlock climate–growth correlations for different elevation levels of mountain hemlocks, i.e., low, medium, and high. High-elevation sites such as those sampled in this study exhibited an energy-limited growth response, and low-elevation sites exhibited more of a water-limited growth response. However, mid-level sites did not show a

Fig. 6. Boxplots of growth during different El Niño Southern Oscillation phase years by site.



strong climate–growth response. It may be that these high-elevation sites are shifting to a more intermediary response, as usually exhibited by mid-level sites, and the climate–growth responses of mountain hemlock are moving down the mountain.

Plotting the spring temperature moving correlation with raw SWE values (Fig. 4) shows that this relationship is stronger with lower SWE values and weaker with higher SWE values (although nonsignificant). Spring temperature and SWE are correlated (Table 3), and it is likely that changes in SWE affect the relationship between spring temperature and growth. For example, a very high SWE might suppress growth to a point at which changes in spring temperature and other variables may not have a noticeable influence. A high SWE, indicating deep snowpack, would likely persist even with high spring temperatures, affecting growth and the relationship between growth and spring temperature. Similarly, low snowpack might mean that spring temperature has a greater impact on growth. Changes in the winter PDO index also

affect the moving correlations between spring temperature and growth, with the relationship becoming weaker when winter PDO values are higher. The increase in significance between spring temperature and growth could be partially related to its interactions with other climatic variables.

The relationship between mountain hemlock growth and climatic variables during the year has been investigated in other studies, which have found that high-elevation mountain hemlock growth generally has negative correlations with precipitation during the fall and winter months and positive correlations with temperature during the fall, winter, and spring months (Gedalof and Smith 2001a; Peterson and Peterson 2001; Marcinkowski 2012). The negative correlation between growth and previous growth year summer temperature is also a dominant feature of conifers in the PNW and has been found in subalpine fir, white-bark pine, mountain hemlock, and Douglas-fir and is more common on the warmer and drier sites for the range of each species

(Ettl and Peterson 2011), where water availability may be more of an issue. The increase in significance of a climatic variable more strongly associated with water-limited environments supports the suggestions of a move along the gradient away from energy limitations. However, the increasing significance of previous growth-year summer temperature could also be explained differently. Rather than a change in limiting factors, the increased importance of temperatures could indicate a change in the timing of limiting factors. The length of the frost-free period has increased by two weeks in the Northwest (Melillo et al. 2014), and the changes observed could indicate a longer growing season. Carbohydrate storage and cone production could explain the significance of previous-year summer temperatures. A relationship between previous-year July temperatures and cone production during the next year has been found for mountain hemlocks in northern Oregon and British Columbia (Ebell and Schmidt 1964; Woodward et al. 1994), and years with large cone productions could divert resources from radial growth. These possible explanations are based on the climatic variables that were examined in this study. A larger range of climatic variables or monthly variables rather than seasonal means could pinpoint why the observed changes in climate–growth correlations are happening.

The PDO influences temperature and precipitation in the PNW and affects climate–growth correlations (Gedalof and Smith 2001a, 2001b; Peterson and Peterson 2001; Holman and Peterson 2006; Nakawatase and Peterson 2006; Case and Peterson 2007; Marcinkowski 2012). Similarly, growth at tree line locations in Alaska has varied over time, likely due to shifts in the PDO phase (Ohse et al. 2012). Upon visual inspection, the significance of growth correlations with winter precipitation, winter PDO, and spring temperature appears to vary based on the PDO phase (Fig. 3). Plots of winter PDO values with the moving correlations between growth and spring temperature, SWE, and winter precipitation show that PDO does influence climate–growth correlations (Fig. 4), and the PDO phase could account for some of the temporal changes in the significance of climate–growth correlations.

The variability in the PDO phase was observationally compared with the climate–growth moving correlations. Many of the climate–growth correlations appear to have closer agreement in correlation values among the six sites during recent decades when compared with the earliest decades in the time series (Fig. 2). The variability in the PDO phase has decreased over the record from the 1901–1924 cool phase to the 1977–1998 warm phase. This decrease in variability of PDO index values during a specific phase could offer an explanation for the observed increase in correlation value agreement among sample sites. However, the recent 1999–2010 timeframe is being considered a cool phase, but index values alternate between warm- and cool-phase years. The PDO could explain some patterns in climate–growth correlations such as the close agreement among sites, but the most recent shifts in correlations from nonsignificant to significant or vice versa appear to be unusual over the record and could indicate a change in limiting factors as described above.

Energy-limited trees in North American boreal forests have been exhibiting decreased sensitivity to temperature signals since the 1960s and 1970s, a trend known as the “divergence problem” (Jacoby and D’Arrigo 1995; D’Arrigo et al. 2004, 2008; Griesbauer and Green 2012; Ohse et al. 2012). The high-elevation sites sampled in this study were also energy limited but have been experiencing weakening correlations with variables related to winter precipitation. The divergence problem is a complex issue that has been found only at high latitudes, but our findings of a decrease in sensitivity to important limiting factors are somewhat similar. However, our sites are at high elevations, rather than high latitudes, and the weakening climate–growth correlations have occurred only within the last decade. More high-elevation sites will

need to be sampled to find determine if the changes in correlations over time are supported elsewhere.

Hessl and Peterson (2004) examined productivity in the PNW using mean BAI and found that mountain hemlock dominated forests were productive and climatically sensitive, similar to this study in which long-term growth increased over time at most sites (Fig. 5). The increases in BAI occurred differently at each site, at least partially based on individual site characteristics. The TL site, which has the steepest trend line, is the youngest site and has experienced rapid growth. The SC site was older (1392–2010), had large trees in a more closed canopy setting, and experienced less growth. Similarly, the HL site was also old (1346–2010) and experienced less growth than other sites. Sites that were mostly open canopy (EP, BL, and ML) but not as young as the TL site steadily increased in growth over the time period. There could be different explanations for the increasing trend in growth since the late 1700s. For example, sampled trees at the different sites could have been experiencing reduced competition, or these trees might have had more favorable climatic conditions for growth. The HL, BL, TL, and ML sites all have a step-like increase in growth around 1900, which could be an indication of the start of the recent warming in surface temperature or an emergence from the slightly cooler Little Ice Age. However, it is important to note that all sampled trees were dominant or codominant in the canopy without apparent defects, and this sampling choice could partly explain the increasing trends in BAI.

Recent growth trends (Table 4) at the six sites examined in this study are variable. As evidenced by the mean change in growth from 1950 to 2010, two of the six sites increased in growth, two sites decreased in growth, and two sites had very small decreases in growth. Different locations have different microsite conditions and perhaps different genetic composition that may be the cause of variable growth trends at sites in the same general region. The tree line is presumed to be a place where tree growth and regeneration will increase, as evidenced by climate–growth correlations and tree establishment in subalpine meadows (Rochefort and Peterson 1996). Ettl and Peterson (1995a) showed a similar individualistic response for subalpine fir, with weaker consistency in the correlations at lower elevations and drier sites. The 0.8 °C increase in temperatures in the PNW during the 20th century (Mote 2003) and the current weakening of winter precipitation correlations do not seem to be reflected in recent growth patterns, and this raises the question of the relative importance of genotypic variation or microsite variation in determining differences in climate–growth correlations and the potential of some individuals to thrive. The most important implication may be that the high-elevation growth response to climate change is likely to be more variable than previously thought.

Differences in growth between ENSO phase years were identified. Further tests showed that differences in growth were significant between La Niña and El Niño years and between La Niña and neutral years; however, mean growth was not significantly different between El Niño and neutral years. Radial growth is correlated with the ENSO index in the PNW (Case and Peterson 2007; Marcinkowski 2012); however, it is unlikely that this short-term variability in growth would affect long-term climate–growth relationships. A study design aimed specifically at examining fine-scale interannual changes in growth could further expand on the growth differences between ENSO phases found in this study and the effect that these have on long-term trends.

Variability in mountain hemlock growth at high-elevation sites in the North Cascade Range exists at different temporal scales, and climate–growth relationships are nonstationary, changing in significance throughout the time series. If temporal variability in climate–growth relationships is indeed the norm, this will reduce the accuracy of climatic reconstructions (e.g., for precipitation or streamflow), because the reconstruction process assumes that climate–growth relationships are relatively stationary (Fritts 1976).

Specifically, the recent temperature warming and changes in growth correlations can cause an overestimation in reconstructed temperatures (Briffa et al. 1998). Recent decades in which divergence in climate–growth correlations is observed could be corrected for or left out of the reconstruction period, but this would miss important years of climatic warming and potentially weaken reconstructions (D'Arrigo et al. 2008). Although climate–growth relationships do change in significance over time, the sign of the relationship is generally the same. The consistent direction of the relationships may help stabilize long-term correlations and reconstructions in dendrochronological studies, unless extended periods of nonsignificance persist.

Variability in climate–growth interactions increases the difficulty in estimating future tree growth in a changing climate. Limitations on growth may differ in the future compared with the recent past (Williams et al. 2010; Albright and Peterson 2013), and this change is being manifested by changing climate–growth relationships at high latitudes (Jacoby and D'Arrigo 1995; Briffa et al. 1998; Biondi 2000; D'Arrigo et al. 2004, 2008; Coppola et al. 2012). Mountain hemlock growth is mainly influenced by the effects of winter climate on the duration of the growing season (Gedalof and Smith 2001a; Peterson and Peterson 2001; Marcinkowski 2012), and the decline in snowpack over the last few decades (McCabe and Wolock 2010) is likely to continue. As the snowpack declines, the relationship between high-elevation growth and winter precipitation might also continue to change. Weakening in snowpack-related growth correlations and strengthening of spring and previous summer temperature correlations in the most recent decades could suggest that a change in limiting factors is already emerging. More information on temporal patterns of climate–growth correlations, with a focus on the effects of changing climatic conditions, will improve our understanding of growth and productivity at high elevations. Reliable forest growth projections are important for modeling purposes, and the complexity of growth patterns and climatic drivers will need to be considered when modeling forest growth in subalpine ecosystems.

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