

Yellow-cedar blue intensity tree-ring chronologies as records of climate in Juneau, Alaska, USA

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Abstract: This is the first study to generate and analyze the climate signal in blue intensity (BI) tree-ring chronologies from Alaska yellow-cedar (*Callitropsis nootkatensis* (D. Don) Oerstr. ex D.P. Little). The latewood BI chronology shows a much stronger temperature sensitivity than ring width and can thus provide information on past climate. The well-replicated BI chronology exhibits a positive January–August mean maximum temperature signal for 1900–1975, after which it loses temperature sensitivity following the 1976–1977 shift in northeastern Pacific climate. The positive temperature response appears to recover and remains strong for the most recent decades, but the coming years will continue to test this observation. This temporary loss of temperature sensitivity from about 1976 to 1999 is not evident in ring width or in a change in forest health but is consistent with prior work linking cedar decline to warming. A confounding factor is the uncertain influence of a shift in color variation from the heartwood–sapwood boundary. Future expansion of the yellow-cedar BI network and further investigation of the influence of the heartwood–sapwood transitions in the BI signal will lead to a better understanding of the utility of this species as a climate proxy.

Key words: yellow-cedar, blue intensity, tree rings, dendroclimatology, Alaska.

Résumé : Cette étude est la première à générer et analyser le signal climatique dans des séries dendrochronologiques construites à partir de l'intensité de la lumière bleue (IB) reflétée par les cernes annuels du faux-cyprès de Nootka (*Callitropsis nootkatensis* (D. Don) Oerstr. ex D.P. Little). La chronologie IB reliée à la densité maximum du bois final est beaucoup plus sensible à la température que la largeur des cernes annuels et fournit par conséquent de l'information sur le climat passé. La chronologie IB bien répétée révèle un signal positif de la température maximum moyenne de janvier à août de 1900 à 1975, après quoi la sensibilité à la température disparaît à la suite du changement du climat dans le nord-est du Pacifique en 1976–1977. La réponse positive de la température semble se rétablir et demeure forte pour les plus récentes décennies mais cette observation devra subir l'épreuve du temps. Cette perte temporaire de sensibilité à la température de 1976 à 1999 environ n'est pas évidente dans la largeur des cernes annuels ni dans un changement dans l'état de santé de la forêt, mais elle correspond aux résultats de travaux antérieurs reliant le dépérissement du faux-cyprès au réchauffement. L'influence incertaine d'un changement dans la variation de la couleur à la limite entre le bois de cœur et le bois d'aubier est un facteur de confusion. L'expansion future du réseau IB du faux-cyprès de Nootka et la poursuite de l'étude de l'influence de la transition entre le bois d'aubier et le bois de cœur dans le signal IB mèneront à une meilleure compréhension de l'utilité de cette espèce comme indicateur indirect du climat. [Traduit par la Rédaction]

Mots-clés : faux-cyprès de Nootka, intensité de la lumière bleue, cernes annuels, dendroclimatology, Alaska.

1. Introduction

Climate-driven, abiotic stress is emerging as a major driver of forest decline in North America (Cohen et al. 2016; Buma et al. 2017). Forest decline is defined as the loss of tree vigor and eventual mortality triggered by complex biotic and abiotic factors (Manion and Lachance 1992). Abiotic forest decline is a complex disorder driven by various nonliving, physical stressors, including climate change, on a forest stand that results in growth decline and can lead to mortality. Affected trees may recover once the

stressors are removed. Identifying the response of ecosystems to varying rates of climate change is a challenge, as species may respond linearly or nonlinearly to anthropogenic warming and the natural internal climate dynamics of the North Pacific (Krapek et al. 2017). Of particular interest in the coastal northeastern Pacific are the Pacific-related decadal fluctuations (i.e., the Pacific Decadal Oscillation, PDO) that dominate many aspects of the climate and ecosystems and have persisted for increasingly long intervals over the observational record since 1900 CE (Boulton and Lenton 2015; Gaglioti et al. 2019). This decadal variability is super-

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Table 1. Parameters of the three tree-ring sites shown in Fig. 1.

Site	Latitude, Longitude	Elevation (m)	No. series/ No. trees	Interval (years CE)	RBAR LBI/RW
BC	58.6301, -134.9304	140	49/29	1644–2014	0.41/0.50
CL	58.6655, -134.9688	110	70/41	1611–2014	0.41/0.46
EG	58.4077, -134.5243	480	60/43	1114–2014	0.42/0.56

Note: BC, Bridget Cove; CL, Cedar Lake; EG, East Glacier. See Fig. 1 for locations of sites. RBAR is the mean correlation coefficient among tree-ring series. LBI, latewood blue intensity; RW, ring width.

imposed on contemporary warming and was observed throughout the Little Ice Age (~1250–1850 CE; Wilson et al. 2007).

Decadal shifts have been recognized in climate data, climate indices, and biological time series (Overland et al. 2008). Determining the causes of shifts in North Pacific climate has been an ongoing challenge, in part due to the large number of both instrumental and proxy time series available, all of which capture different aspects of the climate system on various timescales (El Niño–Southern Oscillation (ENSO), decadal, and century-scale warming). Efforts to extract the decadal signal from sea surface temperature data suggest that in addition to the positive shift in PDO in 1975–1976, a negative shift occurred in 1998–1999, although it may be too early to label this episode as a “regime shift” (Ding et al. 2013; McAfee 2014, 2016; Wills et al. 2018).

In this paper, we examine the climate response of a well-replicated tree-ring chronology of Alaska yellow-cedar (*Callitropsis nootkatensis* (D. Don) Oerst. ex D.P. Little; hereafter referred to simply as yellow-cedar) composited from three sites near Juneau, Alaska, United States (Table 1; Fig. 1). Yellow-cedar is an economically and culturally important species that grows along the northwestern coast of North America (Oakes 2018; Hennon et al. 2016). Yellow-cedar wood is strong and resistant to decay and is used for canoe paddles and in carvings, and its inner bark is utilized for fiber in weavings. The three sites composited in this study have shown limited evidence of cultural modification, with the exception of Cedar Lake, which shows evidence of bark stripping on a few trees that have been utilized over the past few decades (up to a century). Our three sites have been discussed in previous publications, including analyses of ring-width (RW) data from Cedar Lake (Beier et al. 2008) and investigations of forest ecology at all three sites (Krapek et al. 2017). Krapek and Buma (2017) showed that the timing of yellow-cedar establishment in these stands occurred during cool, wet intervals during the Little Ice Age and that cedar could not colonize areas where other species outcompeted this long-lived, slow-growing, and slow-migrating species.

Yellow-cedar has been the subject of intense study primarily because of the phenomenon of its widespread decline in southeastern Alaska, which is relatively well understood. In the early 1980s, foresters (led largely by the National Forest Service in Juneau) ruled out various pathogens and other abiotic factors as reasons for the decline (Hennon et al. 2006, 2012, 2016; Schaberg et al. 2008). The current leading hypothesis for the decline focuses on factors related to warming temperatures. Earlier spring snowmelt and the associated shift in the transition from snow to rain lead to a loss of spring snowpack, which can contribute to the freezing of rootlets and decline of the species. Snowpack provides insulation from cold surface air temperatures, protecting small, vulnerable roots from frost events, especially when shallow root dehardening occurs in wet soils (Schaberg et al. 2008, 2011; Hennon et al. 2012, 2016). Extensive work has been done to test this hypothesis and explore the forest dynamics and ecology associated with the decline (Oakes et al. 2014, 2015; Krapek and Buma 2017; Krapek et al. 2017), driven by concerns of species loss and conservation status (Buma et al. 2017; Barrett and Pattison 2017, Bidlack et al. 2017).

Dendroclimatic studies of RW in southeastern Alaska have shown that the growth response of yellow-cedar can be spatially and temporally complex (Beier et al. 2008; Wiles et al. 2012), and

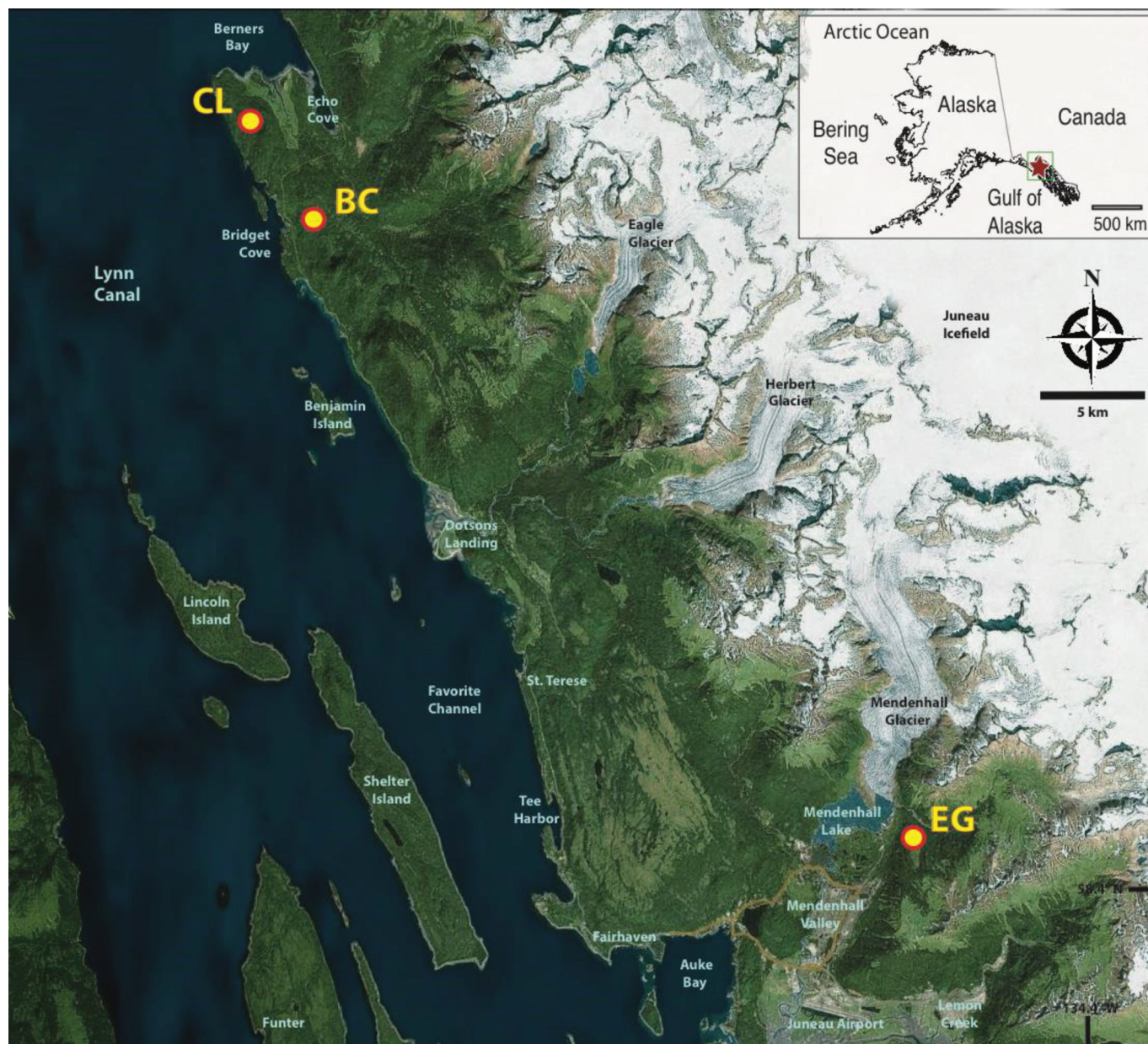
results have generally not been promising for climate reconstruction. Beier et al. (2008) analyzed RW from declining cedar sites in southeastern Alaska and the healthy stand at Cedar Lake, one of our study sites. At Cedar Lake, they noted a general decrease in RW over the past several decades, whereas at sites that were experiencing substantial decline and tree death (farther to the southeast of Juneau), a reduced-competition growth release in surviving trees was detected. Another RW study examined two healthy yellow-cedar stands in Glacier Bay National Park and Preserve in Alaska (Wiles et al. 2012). This work showed a marked nonstationary response to climate, with a notable shift in temperature sensitivity from positive (more growth with warmer temperatures) to negative (less growth with warmer temperatures) after 1950 CE, presumably as warming occurred (Wiles et al. 2012). Wiles et al. (2012) also documented decreased radial growth for decades without any visible evidence of decline in the crowns of the trees. Similarly, Hennon et al. (1990) observed a decrease in RW, sometimes for decades, prior to noticeable decline in the outward appearance of the trees.

In a regional study examining yellow-cedar health across its entire range, Buma et al. (2017) identified a critical threshold of mean winter temperatures above 0 °C as snow turns to rain and rootlets become more susceptible to frost damage. Once winter temperatures sufficiently warm, frosts may be less frequent and snowpack will not be as crucial a factor in protecting root systems. This appears to be the case at the southern range of yellow-cedar (Buma 2018) in Washington and Oregon, United States, where healthy stands are flourishing. This previous work provides a context for the present study, as our sites are entering the zone where mean winter temperatures are between -2 and +2 °C, as mapped by Buma et al. (2017), and yellow-cedar stands are thus susceptible to future decline as warming proceeds.

Previous dendroclimatic investigations along the Gulf of Alaska (GOA) have used tree rings from coastal sites for climate reconstruction, focusing primarily on RW of mountain hemlock (*Tsuga mertensiana* (Bong.) Carrière) (Barclay et al. 1999; D'Arrigo et al. 2001; Wilson et al. 2007; Wiles et al. 2014). More recently, records of blue intensity (BI) are showing promise for generating robust climate reconstructions along the GOA (Wilson et al. 2017) and in Yukon, Canada (Wilson et al. 2019). Thus far, BI chronologies for the GOA have only been developed for mountain hemlock (Wilson et al. 2017). Wilson et al. (2017) used the delta BI (DBI; latewood BI (LBI) subtracted from the earlywood BI (EBI) values) parameter to reconstruct climate, noting the stronger relationship between summer temperature and DBI than with LBI or EBI for mountain hemlock.

In this paper, we present the first BI tree-ring series for yellow-cedar and examine the strength and stability of its climate signal. Both RW and LBI chronologies for yellow-cedar were examined for their potential for climate reconstruction, and our results are interpreted within the context of the yellow-cedar decline previously outlined (Buma et al. 2017; Hennon et al. 2016). We generated RW and BI measurements to document the climate response over the past several centuries. LBI is a tree-ring measurement similar to maximum latewood density (MXD). BI measurements, in general, reflect the combined hemicellulose, cellulose, and lignin content in latewood, which are key components of relative density (Björklund et al. 2014; Rydval et al. 2014). The utility of LBI

Fig. 1. Location of the three yellow-cedar sites in Alaska, United States, used in the composite chronology of ring-width and latewood blue intensity (CL, Cedar Lake; BC, Bridget Cove; EG, East Glacier). The red star on the inset map shows the location of the Juneau area, and the green box outlines the region over which the maximum temperature (T_{\max}) series were averaged. Map data Google, Image Landsat/Copernicus. [Color online.]



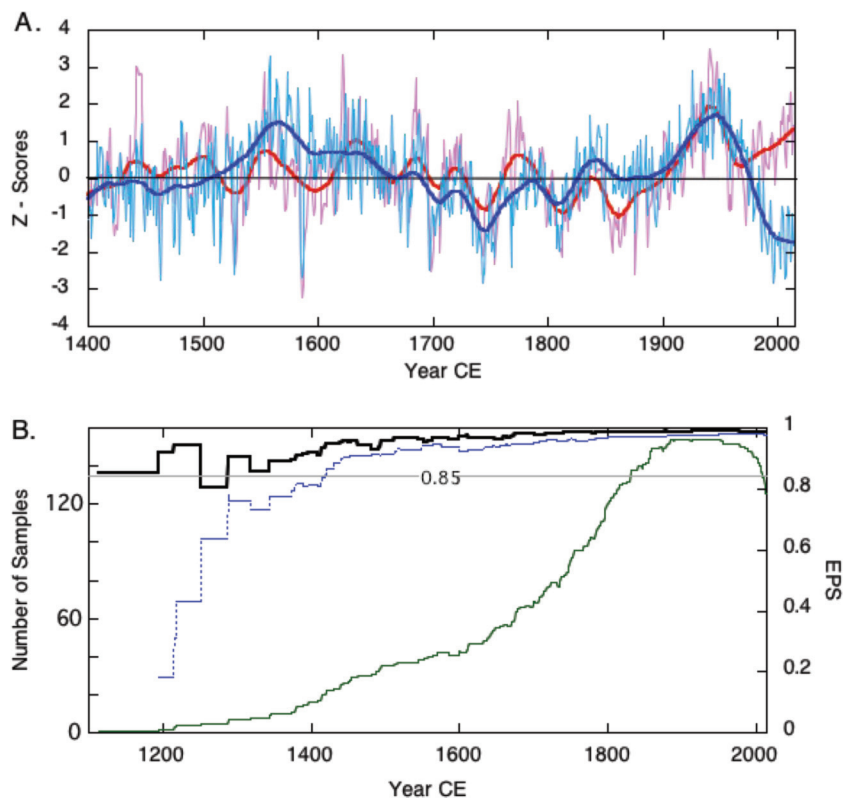
as a summer temperature proxy has been shown to improve climate reconstruction from multiple high-elevation and high-latitude sites (Björklund et al. 2014, 2015; Campbell et al. 2007; Dolgova 2016; Rydval et al. 2014, 2017; Wilson et al. 2014) and the use of DBI from the GOA (Wilson et al. 2017). BI is much less expensive to generate than MXD. One downside, however, is that LBI chronologies generally require a larger sample size than MXD to generate a robust mean chronology (Björklund et al. 2014; Wilson et al. 2014, 2017).

2. Methods

Trees were cored at the three aforementioned sites near Juneau: Cedar Lake, Bridget Cove, and East Glacier (Fig. 1). The sites range from 110 to 480 m in elevation (Table 1). For Cedar Lake, cores and RW data were obtained from other researchers (Beier et al. 2008;

Krapek et al. 2017) and combined with our collections from the summers of 2016 and 2017 (Charlton et al. 2017). The tree cores were immersed in acetone for 72 h to remove resins in the wood (Rydval et al. 2014; Fuentes et al. 2018), then glued onto wood mounts and sanded to a high polish. An Epson V850 pro scanner (Epson, Suwa, Japan), using an IT8.7/2 calibration card in conjunction with SilverFast scanning software (LaserSoft Imaging, Kiel, Germany), was used to scan the samples at a resolution of 2400 dpi. Scanning was done with a nonreflective black box covering the scanner window. BI measurements were made using CDendro version 8.1 and Coorecorder version 8.1 (Larsson 2016). Previously generated RW chronologies facilitated calendar dating, and COFECHA (Holmes 1983) was used as a final quality control for the dating of the RW and LBI measurements.

Fig. 2. (A) Z scores (relative to the interval 1400–1900 CE) of the ring-width (RW, red) and latewood blue intensity (YCLBI, blue) chronologies. Both chronologies are built from the composite of the three yellow-cedar sites (Fig. 1). (B) Sample size (green line) and the expressed population signal (EPS) for each of the chronologies (RW, black line; YCLBI, blue line). Note that the EPS statistic for both series exceeds the critical 0.85 value around the year 1400 CE.



Because BI measurements are color based, discoloration of the wood presents challenges. One such challenge is the presence of a heartwood–sapwood boundary, which can cause a color shift in some species that may impose a trend bias in the BI series (Björklund et al. 2014, 2015). In most of the yellow-cedar cores, we did not observe a distinct color difference, although a subtle change was noted in some series that might be enough to influence the measured values. To investigate potential color change, we counted the number of rings at the transition from heartwood to sapwood where we were able to discern the transition; counts ranged from 16 to 50 years in the ~10% of samples in which we could detect the transition. The BI parameters that were evaluated included LBI, EBI, and the derived DBI (McCarroll et al. 2002; Björklund et al. 2014, 2015; Rydval et al. 2014; Wilson et al. 2017). In our yellow-cedar series, EBI and LBI values are highly correlated with one another ($r = 0.82$ for 1900–2014). The application of DBI in the case of such a strong intercorrelation can lead to a loss in climate signal (Björklund et al. 2014). The uniform density between earlywood and latewood illustrated in this high correlation is consistent with known wood properties that make the yellow-cedar desirable for its smoothly carved surfaces (Hennon et al. 2016). Given the high correlation between the earlywood and latewood measurements and our strong results for climate analyses using LBI, we focused herein on only the LBI and RW signals from yellow-cedar.

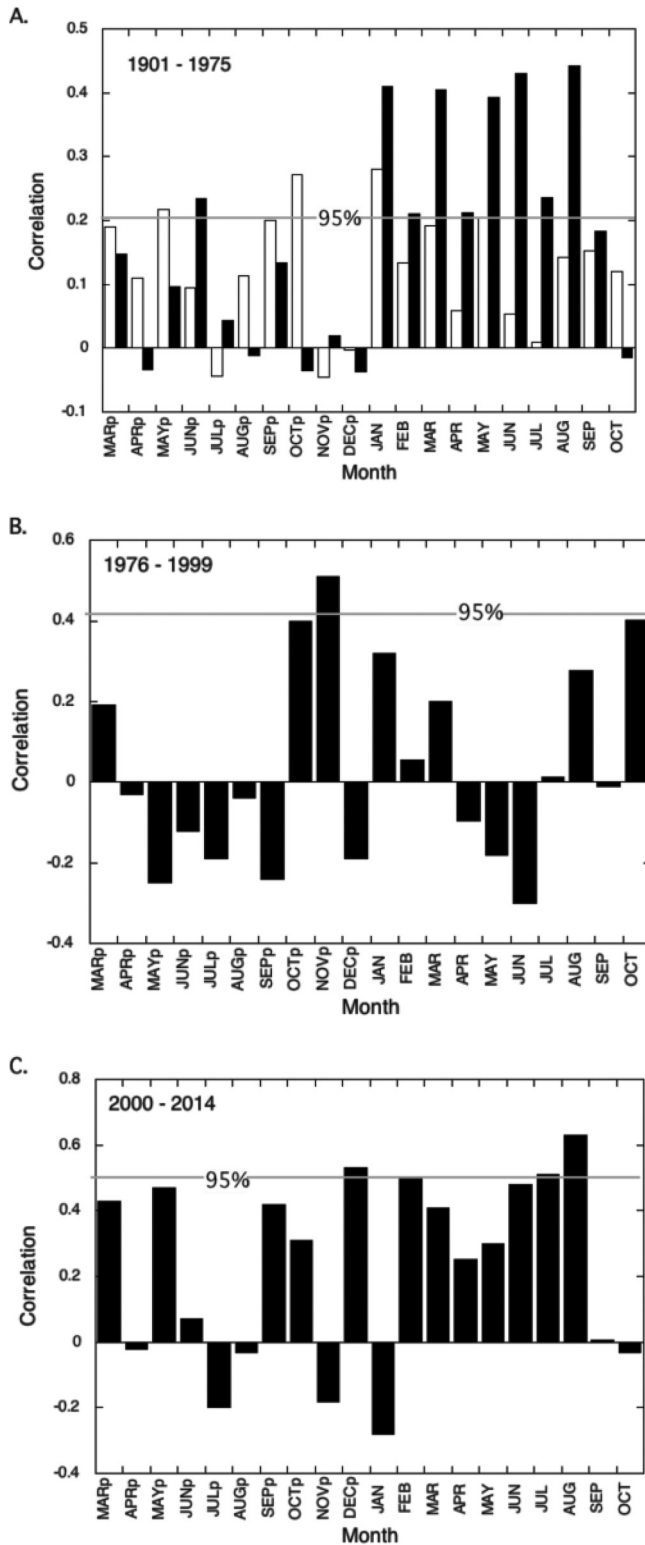
We combined the individual series from the three sites into a regional master chronology based on the strong correlations and coherent low-frequency features among the sites. The combined final RW and LBI chronologies are well replicated and both incorporate 179 series from 113 trees. Although individual sites have trees that date back to 1114 CE (East Glacier; Table 1), we examined the combined record back to 1400 CE based on a critical expressed

population signal (EPS) of >0.85 (Fig. 2A; Wigley et al. 1984). The EPS is a measure of how well a sample of tree-ring data (i.e., number of tree-ring series; Fig. 2B) represents an ideal population.

We followed the methodology of Wilson et al. (2017) in processing the RW and LBI records into chronologies. Tree-ring series were standardized using the signal-free, age-dependent spline approach described by Melvin et al. (2007) and Melvin and Briffa (2008, 2014) (Fig. 2A). We used the signal-free software RCSIgFree, a freeware program developed at the Tree-Ring Lab of the Lamont-Doherty Earth Observatory at Columbia University (Palisades, N.Y., USA; <http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>) that is based on the program ARSTAN (Cook 1985). The signal-free approach was used because of the complex growth trends recognized in the individual tree-ring series; both Wilson et al. (2017, 2019) and Buckley et al. (2018) similarly used signal-free standardization with favorable results.

The RW and LBI series were best correlated with GOA monthly maximum temperatures (T_{\max} ; Climatic Research Unit time-series data, version 4.01 (CRU TS4.01); Harris et al. 2014; Fig. 3). The temperature series was calculated by averaging gridded data from within the coordinates 56°N–62°N, 130°W–140°W (Fig. 1) for the interval of 1900–2014 CE. We used the T_{\max} for analyses because of its stronger correlation with the tree-ring record compared with mean or minimum monthly temperatures. In their investigation of BI and RW series for mountain hemlock (using DBI), Wilson et al. (2017) used mean monthly temperatures from stations within 57°N–61°N, 134°W–153°W, a broader region than our study, as they analyzed multiple sites across a larger swath of the GOA. Although we obtained marginally better results with maximum temperatures from this larger area, we chose to use a more restricted area to better represent the region surrounding our sampling sites (Fig. 1). It is difficult to assess the temperatures at

Fig. 3. (A) The temperature response (monthly correlations) for the ring-width (RW, white bars) and latewood blue-intensity (YCLBI, black bars) records for yellow-cedar for the dendroclimatic year. Note that for the 1901–1975 interval, the YCLBI record correlates much more strongly with monthly temperatures compared with RW. (B) For the 1976–1999 interval, there is a significant loss of temperature sensitivity for YCLBI, and (C) for the 2000–2014 interval, correlations recover. The 95% confidence level is shown for each data set. A lowercase “p” following the month denotes the previous year of growth.



the tree-ring sites relative to the meteorological stations, and we have no records of frost frequency at the individual sites. January (coldest month) T_{\max} values correlated at 0.95 ($N = 96$ years) with temperatures at the Juneau station, near sea level and south of the study sites; however, the T_{\max} series is ~ 6 °C colder than Juneau values, which may be closer to the actual temperatures at the sites up to 480 m in elevation.

To assess the temporal stability of the tree-ring series and T_{\max} , we performed running correlations between series, using 15-year and 31-year windows. To account for autocorrelation in the series, we examined correlations among the first-differenced data. We also compared running correlations between the yellow-cedar LBI series (YCLBI) and published climate reconstructions based on tree rings for the GOA (Wiles et al. 2014).

3. Results

The RW series at the three sites span a common period of 1400–1975 CE (prior to a divergence of the LBI and RW series; Fig. 2A) and correlate between 0.65 and 0.81 with one another, whereas for LBI, correlations among the three sites ranged from 0.39 to 0.53 (Table 2). The lower correlation among the LBI series is consistent with our observations of mountain hemlock along the GOA (Wilson et al. 2017), white spruce (*Picea glauca* (Moench) Voss) in Yukon (Wilson et al. 2019), and Scots pine (*Pinus sylvestris* L.) in Scotland (Rydval et al. 2014). As is found here, these cited studies found a weaker common signal among the BI series relative to the RW series but a stronger climate signal in BI than RW. This paradox is not well understood at the present time.

The final chronologies were created by combining the three individual sites into one RW and one YCLBI regional series (Fig. 2). The two series correlate with one another at 0.49 for the period of overlap between 1400 and 1975 CE (Fig. 2A), after which they diverge. The RW and YCLBI series match well, with the exception of intervals in the mid-1500s, early to mid-1600s, and after ~ 1970 CE (Fig. 2A). Around 1975, the YCLBI record strongly decreases and the RW series declines marginally and then generally increases through recent decades (Fig. 2; Table 3). Comparisons of RW and YCLBI series with T_{\max} from the CRU gridded data set were made for the “dendroclimatic year” that consists of March through December of the previous year of growth and January through October of the current year of growth (Fig. 3). For YCLBI, the strongest correlations (Pearson two-tailed) are with January–August mean maximum temperatures at 0.64 for 1901–1975 ($p < 0.00001$), with a first-differenced correlation of 0.71 for 1902–1975 ($p < 0.00001$; Fig. 3A). After 1975, there is a marked decrease in correlation and loss of significance ($r = 0.21$, $p > 0.34$) for the nontransformed series, with a first-differenced correlation of 0.33 ($p = 0.14$, also not significant) for the 1976–1999 interval (Figs. 3B and 4A). For the 2000–2014 interval, the nontransformed correlation increases to 0.71 ($p = 0.004$) and the first-differenced data correlation increases to 0.64 ($p = 0.01$) (Fig. 4B), which is comparable to the pre-1975 relationship (Fig. 3C). RW is positively correlated with January–August temperature prior to 1976 ($r = 0.30$, $p < 0.01$), after which time correlations with maximum temperatures are not significant (Fig. 3A).

A principal result of our analyses is that the YCLBI is more sensitive to, and thus provides a much stronger proxy for, January–August mean maximum temperatures compared with RW. Furthermore, decadal variations in climate along the GOA, as inferred from the YCLBI record, appear nonstationary, especially during the climatic shift in the middle to late 1970s. This so-called 1976–1977 regime shift in the North Pacific is well documented in terms of the physical and biological changes that occurred in the region (Ebbesmeyer et al. 1991; Mantua et al. 1997; Trenberth and Hurrell 1994; Newman et al. 2016). In southeastern Alaska, this shift brought warmer temperatures with less snow but increased precipitation as rain (Wendler et al. 2017). The loss of sensitivity in

Table 2. Correlations among chronologies of ring width (RW) and latewood blue intensity (LBI) for the interval 1750–1975 CE at individual tree-ring sites.

Chronology	CL RW	CL LBI	BC RW	BC LBI	EG RW	EG LBI
CL RW	—	0.43 (–0.03)	0.81 (0.78)	0.36 (–0.04)	0.65 (0.63)	0.57 (0.32)
CL LBI		—	0.37 (0.05)	0.53 (0.47)	0.34 (–0.02)	0.39 (0.28)
BC RW			—	0.44 (–0.02)	0.76 (0.53)	0.54 (0.31)
BC LBI				—	0.42 (–0.05)	0.41 (0.57)
EG RW					—	0.51 (0.19)

Note: Values are nontransformed series correlations, followed by first-differenced series correlations in parentheses. BC, Bridget Cove; CL, Cedar Lake; EG, East Glacier. See Fig. 1 for locations of sites. Values in boldface type indicate comparisons between RW series, and values in italic type indicate comparisons between LBI series.

Table 3. Correlations among key tree-ring series relative to yellow-cedar latewood blue intensity (YCLBI) and those used in climate reconstruction along the Gulf of Alaska.

Series	1600–1975 CE	1976–1999 CE	2000–2014 CE
RW_Cedar	0.53 (0.34)	0.07 (–0.41)	0.42 (0.15)
GOADBI	0.50 (0.04)	0.18 (0.56)	0.80 (0.82)
GOARW	0.48 (0.29)	–0.19 (0.16)	0.70 (0.72)

Note: Values are nontransformed series correlations, followed by first-differenced series correlations in parentheses. Correlations in boldface type are significant ($p < 0.01$). RW, ring width; GOADBI, Gulf of Alaska delta blue intensity; GOARW, Gulf of Alaska ring width.

YCLBI to maximum temperature after this shift is consistent with the hypothesis that warming decreases snowpack, thus potentially exposing the shallow roots to frost (the decline hypothesis). This drop-off in correlation also corresponds with a peak of cedar mortality in the late 1970s to early 1980s elsewhere in southeastern Alaska (Hennon et al. 2016; Hennon and Shaw 1994). The apparent recovery in climate signal after the negative shift in climate in 1999 discussed by Ding et al. (2013), analyzed by McAfee (2016), and reported by Wills et al. (2018) is marked here by a strengthening in correlation with T_{\max} and is also consistent with the decline hypothesis. A recovery of climate sensitivity with respect to T_{\max} after 1999 appears to be strongest in the interannual, high-frequency response (first-differenced data; Fig. 4B). It appears that the lower-frequency (decadal) response is also in recovery, although this finding is preliminary (Fig. 4).

4. Discussion

To further explore these changes in climate response, we compared our new YCLBI series with a published climate reconstruction based on RWs in the GOA (GOARW) (Wiles et al. 2014). This record is derived from coastal sites of mountain hemlock along the GOA. The GOARW record sustains a strong positive relationship with mean temperature throughout the period after the 1976–1977 regime shift (a so-called divergence-free reconstruction; Wiles et al. 2014). This divergence-free series was constructed to minimize the effect of the changing climate response of mountain hemlock RW recognized at some elevations along the southern Alaskan coast (Jarvis et al. 2013; Wiles et al. 2014). As previously discussed, the YCLBI record correlates best with January–August mean maximum temperatures, which is similar to the response of the GOARW series that has been used to reconstruct mean February–August temperatures (Wiles et al. 2014). Thus, the two compare favorably (Fig. 5A), with the YCLBI record correlating with the GOARW series (Wiles et al. 2014; Fig. 5A) at 0.43 ($p < 0.00001$) for the interval 1400–1975 (Fig. 5A). The 31-year running correlations of these two series show generally good agreement, except for the 1976–1999 interval (Fig. 5B). Correlations are strongest for the 1670–1930 period (Fig. 5B). Subsequently, there is a dramatic drop after 1975 (not significant ($r = -0.19$) for the 1976–1999 interval) and then a marked recovery in correlation between the two series after 1999 ($r = 0.70$, $p < 0.05$; Table 3; Fig. 5B), which persists to the present (2014). First-differenced transformations

(detrended) agree more strongly for that interval (1976–1999); however, they also do not match well in the mid-1600s (Fig. 5B).

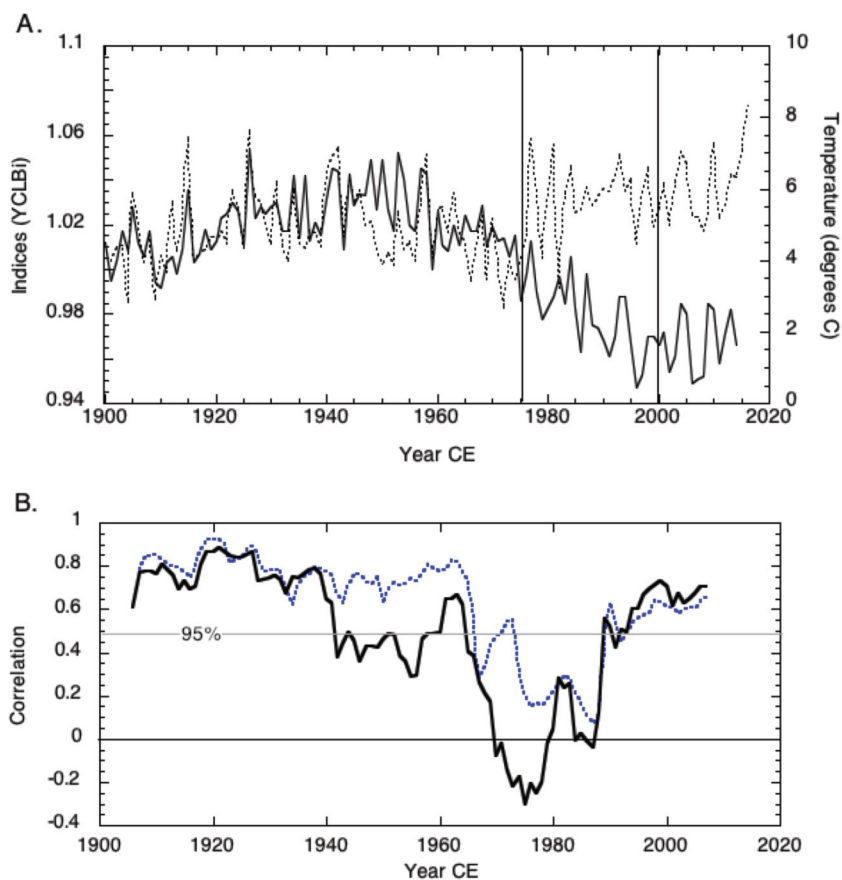
A similar comparison was made with YCLBI and the Gulf of Alaska delta blue intensity (GOADBI) series of Wilson et al. (2017) (Table 3). Similar to GOARW, the GOADBI series shows no signs of divergence. Many of the same tree-ring sites included in the GOADBI series are also incorporated into the GOARW reconstruction; however, GOADBI also includes DBI series that responded strongly to June–September mean temperatures. The comparison of the pre-1976, 1976–1999, and 2000–2014 intervals yielded consistent but somewhat stronger correlations (Table 3) to those of the YCLBI and GOARW comparisons. The two series agree especially well for the 2000–2014 interval, with a correlation of 0.80 for the nontransformed series and 0.82 for the first-differenced series, which are both highly significant ($p < 0.01$; Table 3).

Taken together, the changing climate response and comparison of the YCLBI series with the T_{\max} series (Fig. 4) and the GOARW (Fig. 5) and GOADBI (Table 3) reconstructions suggest that yellow-cedar may have crossed a temperature threshold around 1976 (Fig. 3), which then altered the interannual climate response of the species for about 20 years. The negative trend in the YCLBI series for this interval may now be in recovery, as suggested by the strong positive response to T_{\max} in recent decades. As noted, the late 1970s and early 1980s also represent a peak wave of recent yellow-cedar mortality in southeastern Alaska (Hennon et al. 2016). The 1976 threshold shift may have led to multiple years of successive injury that altered climate sensitivity; however, mortality has not been observed at our sites. Furthermore, in the course of the analyses, we did not observe any evidence of injury in the wood such as traumatic resin ducts. Importantly, yellow-cedar freezing injury is classified as forest decline because it often takes multiple freezing events and years of injury before eventual mortality.

YCLBI change corresponded to the mid-1970s regime shift from a dominantly negative to dominantly positive PDO that caused strong warming in coastal regions in southeastern Alaska, thus a reduction in snowpack is consistent with the decline hypothesis. This possible threshold crossing is likely associated with the physiological limits of yellow-cedar, wherein its sensitivity to temperature becomes decoupled (D'Arrigo et al. 2004; Ohse et al. 2012). Wang et al. (2014) documented an analogous divergence between temperature and RW in five species from southeastern China, also in response to the 1976–1977 regime shift. To our knowledge, the Juneau YCLBI results presented here are the first tree-ring studies to suggest the effects of this relatively recent phenomenon on yellow-cedar populations in southeastern Alaska.

The favorable comparisons of the YCLBI series with the GOARW tree-ring series (Fig. 5A) prior to 1976 and then again after 1999 also suggest that the changes documented in yellow-cedar in recent decades are unprecedented, at least since 1400 CE (Fig. 5A; Table 3). Our results therefore indicate that decadal shifts, in addition to century-scale warming, should be considered when assessing the climate response of yellow-cedar. Additionally, the strong coherence between the series suggests that the conditions

Fig. 4. (A) January–August mean maximum temperatures (dashed line) compared with yellow-cedar latewood blue intensity (YCLBI, solid line). Note that the relationship diverges after 1975. (B) Fifteen-year running correlations of the YCLBI series with January–August mean maximum temperature, with the nontransformed series (solid black line) and first-differenced data (dashed blue line), showing the decadal loss of climate signal and then recovery. [Color online.]



forcing the divergence after 1976 were likely not experienced since at least 1400 CE. Furthermore, with the caveat that in some of our samples we detected a change in color in the heartwood-sapwood transition, the temporary loss of climate signal (1976–1998) suggests that the divergence here has, at least to some degree, recovered.

Previous work has focused on the secular warming since the Little Ice Age as a dominant driver in cedar decline, and this is clearly consistent with the data. However, decadal shifts superimposed on this warming can also be instrumental in changing growing conditions and subsequent stressors. For southeastern Alaska, a ~ 1.1 °C warming during the period of 1976–1999 relative to the previous 1951–1975 interval (Hartmann and Wendler 2005) occurred. At the time of this shift, the amount of annual snowfall decreased by 36%, whereas overall total precipitation increased by 7%, with approximately 7% increase in rain during the late summer to early fall months (July–September) (Hartmann and Wendler 2005). This higher percentage of precipitation falling as rain after the mid-1970s shift, forced by the increased warming, may have also influenced the simultaneous marked shift in YCLBI.

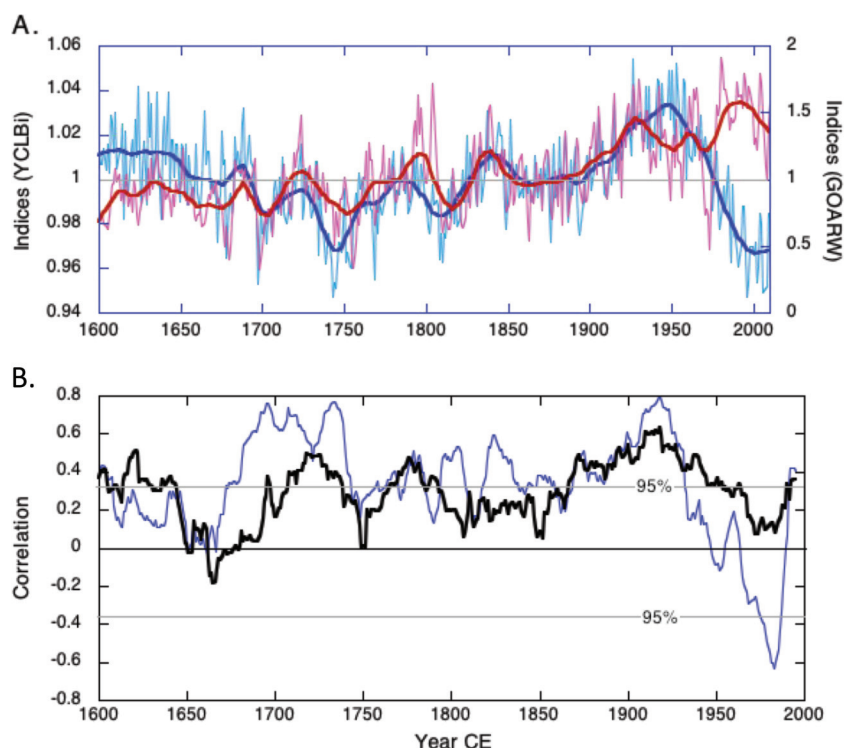
Sullivan et al. (2017) noted a response driven by summer temperatures to a more moisture-limited signal in white spruce in Alaska and, similar to our work, did not detect a widespread decrease in radial growth (RW). These results from Interior Alaska are in contrast to earlier work at some interior sites (i.e., Barber et al. 2000; Juday et al. 2003; Juday and Alix 2012; D'Arrigo et al. 2008), which identified a recent reduction in radial growth that was likely due to moisture stress. Additionally, for white spruce in the interior of Alaska, Ohse et al. (2012) pointed out that growth is

further complicated by regional gradients in climate and site-specific attributes, as well as Pacific decadal climate shifts, which have also been implicated for these transitions. Finally, Wright et al. (2018) identified the role of stand dynamics in southwestern Alaska in driving varying degrees of temperature-related stress responses.

Blue-intensity parameters measured in yellow-cedar could complement such studies of divergent tree growth and warming temperatures in northern forests, which have been primarily based on RWs (D'Arrigo et al. 2008). In the current study, the YCLBI measurements show a change, whereas the RW measurements do not, suggesting that BI, at least for yellow-cedar, may experience divergent phenomena. Thus, when the limiting factors on growth at a location change, it may result in distinct challenges for using BI from yellow-cedar in dendroclimatology. It is possible that a band-pass approach could be performed, with RW providing the low-frequency signal and the BI record providing the high-frequency signal (Wilson et al. 2014). However, the challenge remains that the climate sensitivity of the RW record is not as strong as the YCLBI record, although the variability on a scale of multiple decades to a century appears to be relatively coherent (Fig. 2).

Further investigation is required to understand the divergence in the BI record that may be influenced by heartwood-sapwood color differences, even though we did not observe a distinct visual color change in many of the cores. Such factors warrant more detailed evaluation to ensure that BI data can adequately capture climatic variability through the last several decades. Although this needs to be investigated more fully for yellow-cedar, the coincidence of loss of signal (nonsignificant correlations) at times of

Fig. 5. (A) Comparison of records of yellow-cedar latewood blue intensity (YCLBI, blue) and Gulf of Alaska ring width (GOARW, red). Note the divergence of the two series in the last few decades. (B) Thirty-one-year running correlations between the two series (nontransformed, blue line; first-differenced, black line). These running correlations show the dramatic drop in correlation after the 1976–1977 regime shift in the North Pacific and a recovery in correlation after ~1999.



known shifts in climate (1976–1977 and 1999) supports a climate-driven response of tree growth. Further work could include investigating other chemical treatments of the wood prior to analysis (Rydval et al. 2014). DBI proposed to ameliorate the heartwood-sapwood transition also shows a strong divergence (not shown), but DBI is much less sensitive to temperature variability in this study, perhaps because of the strong intercorrelation between the LBI and EBI series, so it is not helpful here. In contrast, for the GOA mountain hemlock, DBI seems to be a more climatically sensitive parameter than LBI (Wilson et al. 2017).

Our YCLBI series is climatically sensitive to January–August mean maximum temperatures, which is a broader climate window than the GOADBI study by Wilson et al. (2019) that was sensitive to June–September temperatures. We hypothesize that the broader climate window for the YCLBI record compared with the more restricted summer signal found by Wilson et al. (2017) may be due to the ecophysiological tendency of yellow-cedar to de-harden earlier in the spring, thus responding favorably to winter and spring temperatures. This early dehardening may allow yellow-cedar to gain a competitive advantage with respect to nutrient uptake (D'Amore et al. 2009) relative to other conifer species. Thus, in addition to summer temperatures, yellow-cedar respond to late winter and early spring temperatures.

Finally, although the three sites in this investigation have not shown indications of decline at the stand level or a marked decrease in radial growth (RW), they appear to have been impacted by changes in climate during the middle to late 1970s, behaving similarly to stands that have experienced extensive mortality (Beier et al. 2008). Since about 1999, these populations recovered their climate sensitivity, suggesting some level of resilience. This is consistent with the concept that this population is “on the edge” of climatic vulnerability (Buma 2018). Thus, it may be that at some of the locations in the Juneau area, yellow-cedar sites remain healthy forests; however, because they are near the leading

edge of the decline and outside of the “historical decline”, a slight warming in the region could push these trees closer toward conditions of potential mortality, as recognized farther south in coastal Alaska.

As Buma (2018) pointed out, across the range of yellow-cedar, if the rate of warming is great enough to ameliorate the occurrence of frost, then the warming and loss of snowpack may not influence cedar growth. Although the roots are vulnerable, frosts are less likely to occur in a rapidly warming climate. A drop toward nonsignificant correlations in both the nontransformed and first-differenced series between 1976 and 1999 is consistent with stress-related changes, perhaps related to warming temperature and its interactions with snowpack and frost. Furthermore, the secular increase, as well as the decadal changes in the North Pacific emphasized here, will drive and modulate the tree response to climate.

Clearly, decade-scale variability needs to be considered in the context of forest health. It is difficult to separate the effect of secular warming and the decadal shifts from one another, and it is likely that they have worked synergistically to cause the decoupling of tree growth and maximum temperature. Hennon et al. (2016) pointed out that although yellow-cedar competes well on saturated soils relative to other species, trees rooted in saturated soils tend to have more shallow rootlets, making them more vulnerable to freezing damage. The species' preference and its ability to outcompete other tree species on wetter soils can increase its vulnerability to freezing if the insulating layer of snow disappears so that shallow roots can freeze. Even though the primary driver in the decline remains temperature, increased precipitation may also exacerbate the tree stress related to warmer temperatures, loss of snowpack, and the detrimental impact of frosts on root systems. These factors need to be explored more fully.

Our results suggest that with further work, YCLBI records could be used to reconstruct past climate. Melting glaciers across the

GOA continue to reveal ancient forests and, in at least one case, have exposed subfossil wood that includes yellow-cedar (B.V. Gaglioti et al., unpublished data). This presents the emerging possibility of extending these cedar series further back in time. As in the case for mountain hemlock (Wilson et al. 2017), BI tree-ring series in yellow-cedar show promise to improve temperature reconstructions for the GOA and may perhaps enter into multispecies climate reconstructions in the future.

5. Conclusions

This analysis of yellow-cedar response to climate is the first to examine the LBI parameter. Previous work with RWs from yellow-cedar of southeastern Alaska, although valuable in examining changing climate response, has been limited with respect to reconstructing past climate. Our well-replicated YCLBI series has a strong temperature response until the mid-1970s that is equal to or greater than many published RW series from the traditionally used mountain hemlock from the region.

The trends in the observational climate records and in the YCLBI data suggest changes in tree physiology around the mid-1970s shift in the PDO that may have been detrimental to tree growth but do not necessarily appear to be affecting bioproductivity as inferred from RWs. The presumed recovery in temperature sensitivity in YCLBI after a shift to a cooler regime in 1998–1999 (Wills et al. 2018) is further evidence of a response to decadal climate change, although additional years for comparison in the coming decades may strengthen or refute this observation. The climate sensitivity of this economically, ecologically, and culturally important species should be coupled with the existing knowledge of past migrations and the mechanisms of decline when anticipating its future range (Krapek et al. 2017), especially in the face of unprecedented warming.

Further study of the impact of decadal shifts and secular warming in yellow-cedar across its range, together with monitoring, could help anticipate the risks that these sites may experience in the future. This work emphasizes the findings of previous studies on the ecology of yellow-cedar (Krapek and Buma 2017), supporting the observation that this species has not responded linearly to secular warming.

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