

**Yellow-Cedar Blue Intensity Tree Ring Chronologies as Records of Climate, 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 Alaskan yellow-cedar (*Callitropsis nootkatensis* D. Don; Oerst. ex D.P. Little). The latewood BI chronology shows a much stronger temperature sensitivity than ring-widths (RW), and thus can provide information on past climate. The well-replicated BI chronology exhibits a positive January-August average maximum temperature signal for 1900-1975, after which it loses temperature sensitivity following the 1976/77 shift in northeast Pacific climate. The positive temperature response appears to recover and remains strong for the most recent decades although the coming years will continue to test this observation. This temporary loss of temperature sensitivity from about 1976 to 1999 is not evident in RW 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

1. Introduction:

Climate-driven, abiotic stresses are 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 non-living physical stresses, including climate change, on a forest stand that results in growth decline and can lead to mortality. Affected trees may recover once the stresses are removed. Identifying the response of ecosystems to varying rates of climate change is a challenge as species may respond linearly or non-linearly to anthropogenic warming as well as to the natural internal climate dynamics of the North Pacific (Krapek et al., 2017). In the coastal northeast Pacific, of particular interest are the Pacific related decadal fluctuations (ie., 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 CE 1900 (Boulton and Lenton, 2015; Gaglioti et al., 2019). This decadal variability is superimposed on contemporary warming and has been observed throughout the Little Ice Age (~CE 1250-1850; 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 climate system on various timescales (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 1975/76, a negative shift occurred in 1998/99, 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).

Here we examine the climate response of a well-replicated tree-ring chronology of yellow-cedar (*Callitropsis nootkatensis* D. Don; Oerst. ex D.P. Little) composited from three sites near Juneau, Alaska (Table 1, Fig. 1). Yellow-cedar is an economically and culturally important species, which grows along the northwest coast of North America (Oakes, 2018; Hennon et al., 2016). The wood is strong and resistant to decay, 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 had limited evidence of cultural modification with the exception of one of them, Cedar Lake, which shows evidence of bark stripping on a few trees that have been utilized over the past few decades to a century. Our three sites have been discussed in previous publications including analyses of ring-width data (RW) 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 of the Little Ice Age and that cedar could not colonize where other species out-competed this long-lived, slow growing and slow migrating species.

Yellow cedar has been the subject of intense study primarily because of the phenomenon of widespread decline of this species in southeastern Alaska, which is relatively well understood. In the early 1980s, foresters (led largely by the National Forest Service in Juneau, Alaska) ruled out various pathogens and other abiotic factors (Hennon et al. 2006, 2012, 2016; Schaberg et al., 2008). The current leading hypothesis for the decline has been factors related to warming temperatures. Earlier spring snowmelt, and the associated shift in the transition from snow to rain, both lead to a loss of spring snowpack, which can contribute to freezing of rootlets and to decline. Snowpack provides insulation from cold surface air temperatures, protecting vulnerable small 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 testing this hypothesis and exploring 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 determination of whether the species is endangered (Buma et al., 2017; Barrett and Pattison, 2017, Bidlack et al., 2017).

Dendroclimatic studies of RW in southeast 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, in general, results have not been promising for climate reconstruction. Beier et al. (2008) analyzed RW from declining cedar sites in southeast Alaska and from 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 (Wiles et al., 2012). This latter 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 CE 1950, presumably as warming occurred (Wiles et al. 2012). Wiles et al. (2012) also documented decreased radial growth for decades but 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 (Buma et al., 2017) 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 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 $+2^{\circ}\text{C}$ as mapped by Buma et al. (2017) and 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 mountain hemlock RW (*Tsuga mertensiana* (Bong.) Carr.; Barclay et al., 1999; D'Arrigo et al., 2001; Wilson et al., 2007; Wiles et al. 2014). More recently BI records are showing promise for generating robust climate reconstructions along the GOA (Wilson et al., 2017) and in the Yukon (Wilson et al, in press). 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.

Here 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 outlined above (Buma et al., 2017; Hennon et al., 2016). We generated ring-width (RW) and blue intensity (BI) measurements to document the climate response over the past several centuries. Latewood blue intensity (LBi) is a similar tree-ring measurement to maximum latewood density (MXD). BI measurements, in general, reflect the combined hemi-cellulose, cellulose and lignin content in the latewood which are key components

of relative density (Björklund et al., 2014; Rydval et al., 2014). The utility of LBi 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 Gulf of Alaska (Wilson et al., 2017). Significantly, blue intensity is a much less expensive parameter 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 aforementioned three sites near Juneau: Cedar Lake, Bridget Cove and East Glacier (Fig. 1). The sites range in elevation from 110 to over 480 m (Table 1). For the Cedar Lake site, cores and ring-width 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 hours 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, using an IT8.7/2 calibration card in conjunction with SilverFast scanning software 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 8.1 and CooRecorder 8.1 (Larsson, 2016). Previously generated ring-width chronologies facilitated calendar dating, and COFECHA (Holmes, 1983) was used as a final quality control for the dating of the RW and LBi measurements.

Since BI measurements are color based, discoloration of the wood presents challenges. One 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 strong 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 blue intensity parameters that were evaluated included: LBi, earlywood BI (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 inter-correlation can lead to a loss in climate signal (Björklund et al. 2014). The uniform density between the 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 early and latewood measurements, and our strong results for our climate analyses using LBi, we focused herein on only the LBi and RW signals from yellow-cedar for this paper.

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 CE 1114 (East Glacier; Table 1) we examine the combined record back to CE 1400 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 (ie., number of tree ring series) represents an ideal population.

We followed the methodology of Wilson et al. (2017) in processing the ring-width and LBi records into chronologies. Tree-ring series were standardized using the signal-free (SF), age dependent spline (ADS) approach described in 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 (<http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>) that is based on the program ARSTAN (Cook, 1985). The SF approach was used because of the complex growth trends recognized in the individual tree ring series; both Wilson et al., (2017; in press) and Buckley et al. (2018) similarly used SF standardization with favorable results.

The RW and LBi series were best correlated with GOA monthly maximum temperatures (Tmax, CRU TS4.01; Harris et al., 2014; Fig. 3). The temperature series was calculated by averaging gridded data from within the coordinates 56° - 62° N, 130° - 140° W (Fig. 1) for the CE 1900-2014 interval. We used the Tmax for analyses because of its stronger correlation with the tree-ring record than with mean or minimum monthly temperatures. Wilson et al. (2017), in their investigation of BI and RW series for mountain hemlock (using dBi), used mean monthly temperatures from stations within 57° - 61° N, 134° - 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 the tree-ring sites relative to the meteorological stations and we have no records of frost frequency at the individual sites. January (coldest month) Tmax values

correlated at 0.95 (N=96 years) with temperatures at the Juneau station, near sea level south of the study sites. However, the Tmax series is about 6°C colder than Juneau values, which may be closer to the actual temperatures at the sites up to 480 meters in elevation.

To assess the temporal stability of the tree-ring series and Tmax we performed running correlations between series using 15-year and 31-year windows. To account for autocorrelation in the series we examined correlations between the first differenced data. We also compared running correlations between the yellow-cedar latewood BI series (YCLBi) and a published tree-ring based temperature reconstructions for the Gulf of Alaska (Wiles et al., 2014).

3. Results

The RW series at the three sites span a common period of CE 1400-1975 (prior to a divergence of the LBi and RW series; Fig. 2a) and correlate between 0.65 and 0.81 with one another, whereas the three sites for LBi, correlations ranged from 0.39 to 0.53 (Table 2). The lower correlation among the LBi series is consistent with our observations of mountain hemlock BI along the GOA (Wilson et al, 2017), white spruce (*Picea glauca* (Moench) Voss) in the Yukon (Wilson et al., in press), and scots pine (*Pinus sylvestris* L.) in Scotland (Ryvdaal et al., 2014). As is found here, these cited studies found a weaker common signal among BI series relative to the RW, but a stronger climate signal in the BI than the 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 about CE 1970 (Fig. 2a). About 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 Tmax from the CRU gridded dataset were made for the “dendroclimatic year” that consists of March through December of the previous year of growth and January through October of the year of growth (Fig. 3). For the YCLBi, the strongest correlations (Pearson two-tailed) were with mean January through August (J-A) maximum temperatures at 0.64 for 1901-1975 ($p < 0.00001$), with a 1st differenced correlation of 0.71 (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 non-transformed series with a 1st differenced correlation of 0.33 ($p = 0.14$, also not significant) for the 1976-1999 interval (Figs. 3b, 4a). For the 2000-2014 interval, the correlation increases to 0.71 ($p = 0.004$) with an increase in the 1st differenced data correlation to 0.64 ($p = 0.01$) (Fig. 4b) comparable to the pre-1975 relationship (Fig. 3c). RW was positively correlated with temperature (J-A) prior to 1976 ($r = 0.30$, $p < 0.01$) and after that 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 maximum temperatures (January-August average) than RW. Furthermore, decadal variations in climate along the GOA as inferred from the YCLBi record appear nonstationary, especially during the climatic shift in the mid to late 1970s. This noted so-called 1976/77 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 southeast Alaska, this shift brought warmer temperatures with less snow but higher precipitation as rain (Wendler et al., 2017). The loss of sensitivity in 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 dropoff in correlation also corresponds with a peak of cedar mortality in the late 1970s to the early 1980s elsewhere in southeast Alaska (Hennon et al., 2016; Hennon and Shaw, 1994). The apparent recovery in climate signal after the 1999 negative shift in climate discussed in Ding et al. (2013), analyzed in McAfee (2016) and reported by Wills et al. (2018) is marked here by a strengthening in correlation with Tmax and is also consistent with the decline hypothesis. A recovery of climate sensitivity with respect to Tmax after 1999 appears to be strongest in the year-to-year, high frequency response (differenced data; Fig. 4b). It also appears that the lower frequency (decadal) response is also in recovery, although this finding is preliminary (Fig. 4).

4. Discussion

To explore these changes in climate response further we compared our new YCLBi series with a published climate reconstructions based on ring widths (GOARW; Wiles et al., 2014). This record is derived from coastal mountain hemlock sites along the Gulf of Alaska. The GOARW record sustains a strong positive relationship with mean temperature throughout the post 1976/77 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 discussed above, the YCLBi record correlates best with maximum average (January-August) 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

281 the GOARW (Wiles et al., 2014; Fig. 5a) series at 0.43 ($p < 0.00001$) for the interval 1400-1975
 282 (Fig. 5a). The 31-year running correlations of these two series show generally good agreement
 283 except for the 1976-1999 interval (Fig. 5b). Correlations are strongest for the 1670-1930 period
 284 (Fig. 5b). Subsequently, there is a dramatic drop after 1975 (not significant ($r = -0.19$) for the
 285 1976-1999 interval) and then a marked recovery in correlation between the two series after 1999
 286 ($r = 0.70$ ($p < 0.05$); Table 3; Fig. 5b), which persists to the present (2014). First differenced
 287 transformations (detrended) agree better for that interval (1976-1999); however, they also do not
 288 match well in the mid 1600s (Fig. 5b).

289 A similar comparison was made with the YCLBi and the Gulf of Alaska dBi (GOAdBi)
 290 series of Wilson et al. (2017; Table 3). Similar to the GOARW the GOAdBi series shows no
 291 signs of divergence. Many of the same tree-ring sites included in the GOAdBi series are also
 292 incorporated into the GOARW reconstruction, however GOAdBi also include dBi series that
 293 responded strongly to June-September mean temperatures. The comparison of the pre-1976,
 294 1976/99 and 2000/14 intervals yielded consistent but somewhat stronger correlations (Table 3) as
 295 those of the YCLBi and GOARW comparisons. The two series agree especially well for the
 296 2000/14 interval with a correlation of 0.80 for the non-transformed series and 0.82 for the first
 297 differenced series, both highly significant ($p < 0.01$; Table 3).

298 Taken together, the changing climate response and comparison of the YCLBi series with
 299 the Tmax series (Fig.4), and the GOARW (Fig.5) and GOAdBi (Table 3) reconstructions suggest
 300 that yellow-cedar may have crossed a temperature threshold about 1976 (Fig. 3), which then
 301 altered the interannual climate response of the species for about 20 years. The negative trend in
 302 the YCLBi series for this interval may now be in recovery as suggested by the strong positive
 303 response to Tmax in recent decades. As noted, the late 1970s and early 1980s also represent a

peak wave of recent yellow-cedar mortality in southeast Alaska (Hennon et al., 2016). The 1976 threshold shift may have led to multiple years of successive injury altering climate sensitivity, although 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 a “forest decline” because it often takes multiple freezing events and years of injury before eventual mortality.

The correspondence of YCLBi change with the mid-1970s regime shift from a dominantly negative to dominantly positive PDO caused strong warming in coastal regions in southeastern Alaska and 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 1976-77 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 CE 1400 (Fig. 5a; Table 3). Our results indicate, therefore, that decadal shifts in addition to century-scale warming should be considered when assessing the climate response of yellow-cedar. The strong coherence between the series additionally, suggests that the conditions 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

327 signal (between 1976-1998) suggests that the divergence here at least to some degree has
328 recovered.

329 Previous work has focused on the secular warming since the Little Ice Age as a dominant
330 driver in cedar decline and this is clearly consistent with the data. However, decadal shifts
331 superimposed on this warming can also be instrumental in changing growing conditions and
332 subsequent stresses. For southeast Alaska, a $\sim 1.1^{\circ}\text{C}$ warming during the period 1976-1999
333 relative to the previous 1951-1975 interval (Hartmann and Wendler, 2005) occurred. At the time
334 of this shift, the amount of annual snowfall decreased by 36% while overall total precipitation
335 increased by 7% with an approximately 7% increase in rain during the late summer to early fall
336 months (JAS) (Hartmann and Wendler 2005). This higher percentage of precipitation falling as
337 rain after the mid-1970s shift, forced by the increased warming, may also have influenced the
338 simultaneous marked shift in YCLBi.

339 Sullivan et al. (2017) noted a summer temperature driven response to a more moisture-
340 limited signal in Alaskan white spruce (*Picea glauca*) and, similar to our work, did not detect a
341 widespread decrease in radial growth (RW). These results from interior Alaska are in contrast to
342 earlier work at some interior sites, (ie., Barber et al., 2000; Juday et al., 2003; Juday and Alix,
343 2012; D'Arrigo et al., 2008) which identified a recent reduction in radial growth likely due to
344 moisture stress. Additionally, for white spruce in the interior of Alaska, Ohse et al. (2012) point
345 out that growth is further complicated by regional gradients in climate and site-specific
346 attributes, as well as Pacific decadal climate shifts, which also have been implicated for these
347 transitions. Finally, Wright et al. (2018) identified the role of stand dynamics in southwestern
348 Alaska can drive varying degrees of temperature 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 ring-widths (D'Arrigo et al., 2008). Here the YCLBi measurements show a change, whereas the RW do not, suggesting that blue intensity, 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 blue intensity from yellow-cedar in dendroclimatology. It is possible that a band-pass approach could be performed with RW providing the low frequency signal with the BI record providing the higher frequency signal (Wilson et al., 2014). However, the challenge remains that the climate sensitivity of the RW is not as strong as the YCLBi record, although the multi-decadal to century scale variability appears to be relatively coherent (Fig. 2).

Requiring further investigation is the divergence in the BI record that may be influenced by heartwood-sapwood color differences even though we did not observe a strong visual color change in many of the cores. Such factors warrant more detailed evaluation to ensure that BI data are able to adequately capture climatic variability through the last several decades. Whereas this needs to be investigated more fully for yellow-cedar, the coincidence of loss of signal (non-significant correlations) at times of known shifts in climate (1976/77 and 1999) supports a climate-driven response of the tree growth. Further work could include investigating other chemical treatments of the wood prior to analysis (Rydval et al., 2014). Delta BI (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 LWBi and EWBi series, and so is not helpful here. In contrast, for the GOA mountain hemlock dBi seems to be a more climatically sensitive parameter than LWBi (Wilson et al., 2017).

Our YCLBi series is climatically sensitive to January through August maximum average temperatures a broader climate window than the June-September sensitive GOAdBi study by Wilson et al. (2019). We hypothesize that the broader climate window for the YCLBi record compared with the more restricted summer signal found in Wilson et al (2017) may be due to the ecophysiological tendency of yellow-cedar to dehardening earlier in the spring, thus responding favorably to winter/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 and thus yellow-cedar respond to late winter/spring temperatures as well as summer.

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 in the mid 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, since 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) points 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 non-transformed

and first differenced series between 1976 and 1999 is consistent with stress-related changes, perhaps related to warming temperatures 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, decadal-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) point out that although the 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 out-compete other tree species on wetter soils can increase their 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 snow pack, 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 sub-fossil wood that includes yellow-cedar (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), blue intensity tree-ring series in yellow-cedar show promise to improve temperature reconstructions for the GOA and perhaps in the future entering into multi-species climate reconstructions.

5. Conclusions

This analysis of yellow-cedar response to climate is the first to examine the latewood blue intensity parameter. Previous work with ring-widths from yellow cedar of southeast Alaska, although valuable in examining changing climate response, have been limited with respect to reconstructing past climate. Our well-replicated YCLBi series has a strong temperature response until the mid-1970s equal to or greater than many published ring-width 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 ring-widths. The presumed recovery in temperature sensitivity in YCLBi after a shift to a cooler regime in 1998/99 (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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Table 1. Parameters of tree-ring sites shown in Figure 1.

Site*	Lat./Long.	Elev. (m)	# series/trees	Interval (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

*BC – Bridget Cove; CL – Cedar Lake; EG – East Glacier (see Figure 1 for locations). RBAR is the mean correlation coefficient among tree-ring series.

Table 2. Correlations among ring-width (*RW*) and latewood blue intensity (LBI) chronologies for the interval CE1750-1975 at individual tree-ring sites for non-transformed and first difference series (parens.).

Chron	<i>CL (RW)</i>	<u>CL (LBI)</u>	<i>BC (RW)</i>	<u>BC (LBI)</u>	<i>EG (RW)</i>	<u>EG (LBI)</u>
<i>CL (RW)</i>	----	0.43(-0.03)	0.81 (0.78)	0.36(-0.04)	0.65 (0.63)	0.57 (0.32)
<u>CL (LBI)</u>		----	0.37 (0.05)	<u>0.53 (0.47)</u>	0.34(-0.02)	<u>0.39 (0.28)</u>
<i>BC (RW)</i>			----	0.44(-0.02)	0.76 (0.53)	0.54 (0.31)
<u>BC (LBI)</u>				----	0.42(-0.05)	<u>0.41 (0.57)</u>
<i>EG (RW)</i>					----	0.51 (0.19)

* BC – Bridget Cove; CL – Cedar Lake; EG – East Glacier (see Figure 1 for locations). **Bold** are comparisons between RW series and underlined are comparisons between LBI.

Table 3. Correlations among key tree-ring series relative to YCLBi and those used in climate reconstruction along the GOA. The first value is the non-transformed correlation and those in parentheses are 1st differenced.

<i>YCLBi_Cedar*</i>	1600-1975	1976/99	2000/14
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)

***Bold** correlations are significant <0.01 level.

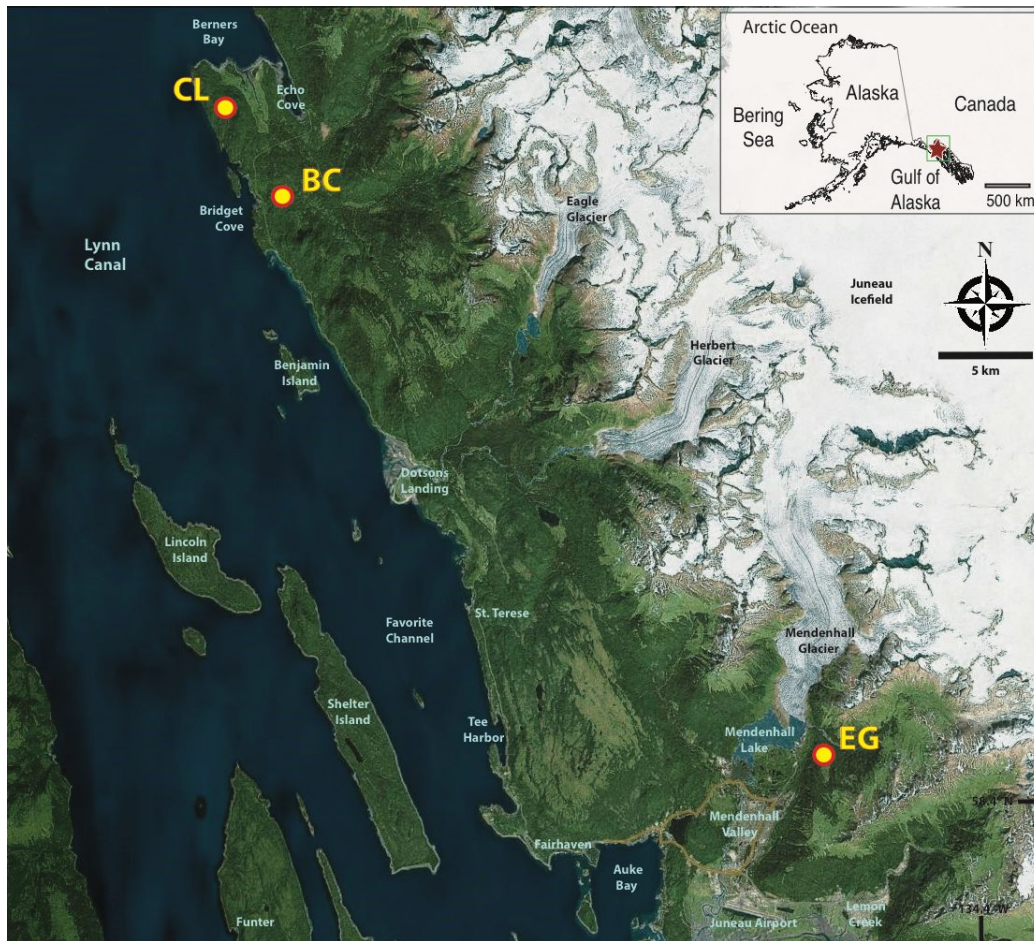


Fig. 1. Location of the three yellow-cedar sites used in the composite ring-width and latewood blue intensity (YCLBi) chronology (CL = Cedar Lake, BC = Bridget Cove, EG = East Glacier). The inset map shows the location of the Juneau area and the box includes the region over which the maximum temperature (T_{max}) series were averaged.

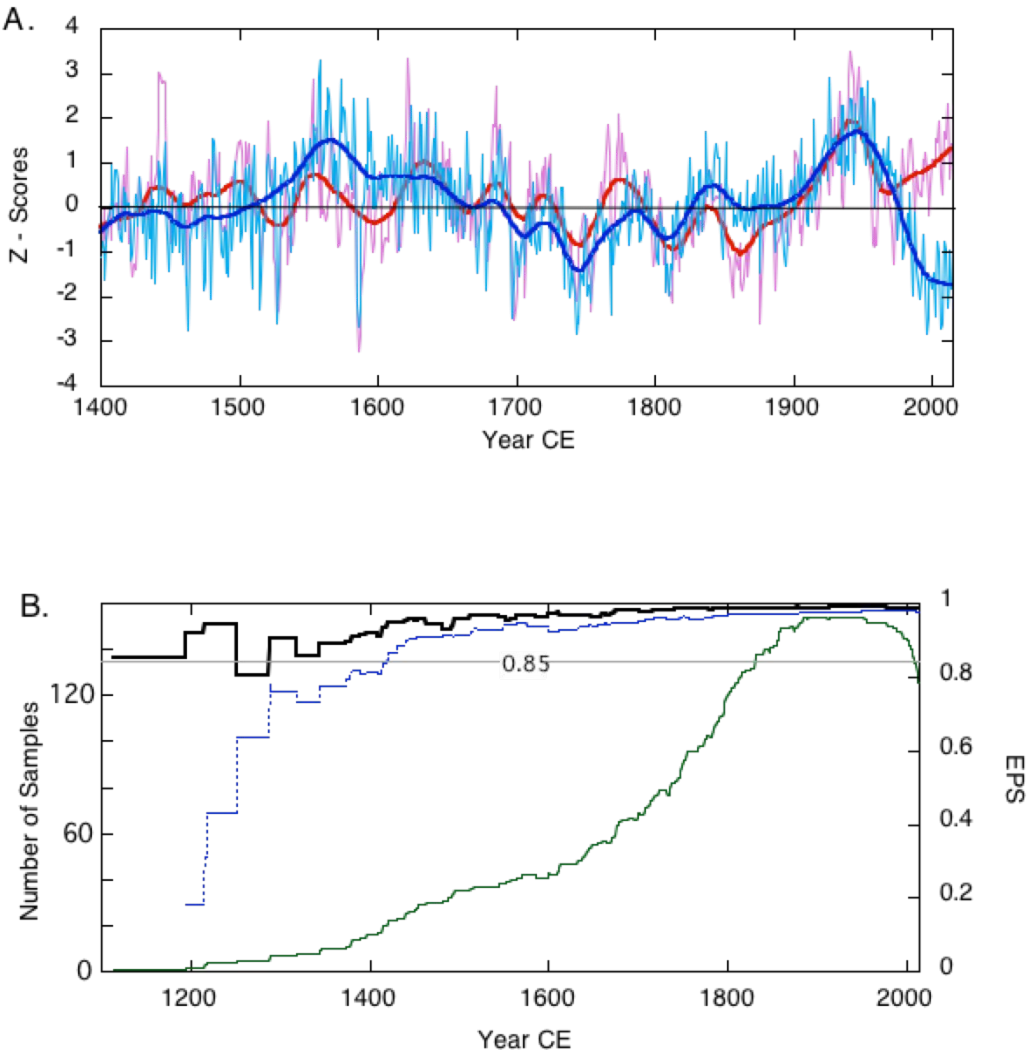


Fig. 2. (a) Z-scores (relative to the 1400-1900 interval) of the ring—width (red) and latewood blue intensity (YCLBi, blue) both chronologies are built from the composite of the three cedar sites (Figure 1). (b) Shows the sample size (green) and the EPS for each of the chronologies (black (RW) and blue (YCLBi)). Note that the EPS statistic for both sites exceeds the critical 0.85 value about CE 1400.

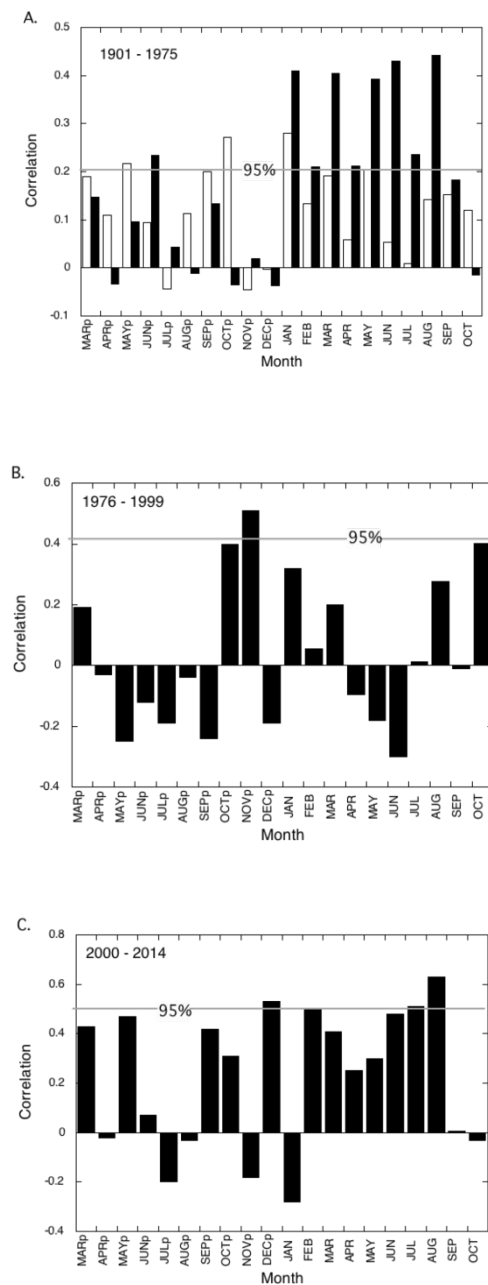


Fig. 3. (a) The temperature response (monthly correlations) for the ring-width (white) and blue intensity(black) cedar records for the dendroclimatic year. Note that for the 1901-1975 interval the YCLBi record correlates much more strongly with monthly temperatures than the RW. For the 1976-1999 interval, there is a significant loss of temperature sensitivity for YCLBi (b) and for the 2000-2014 interval correlations recover. The 95% confidence level is shown for each data set.

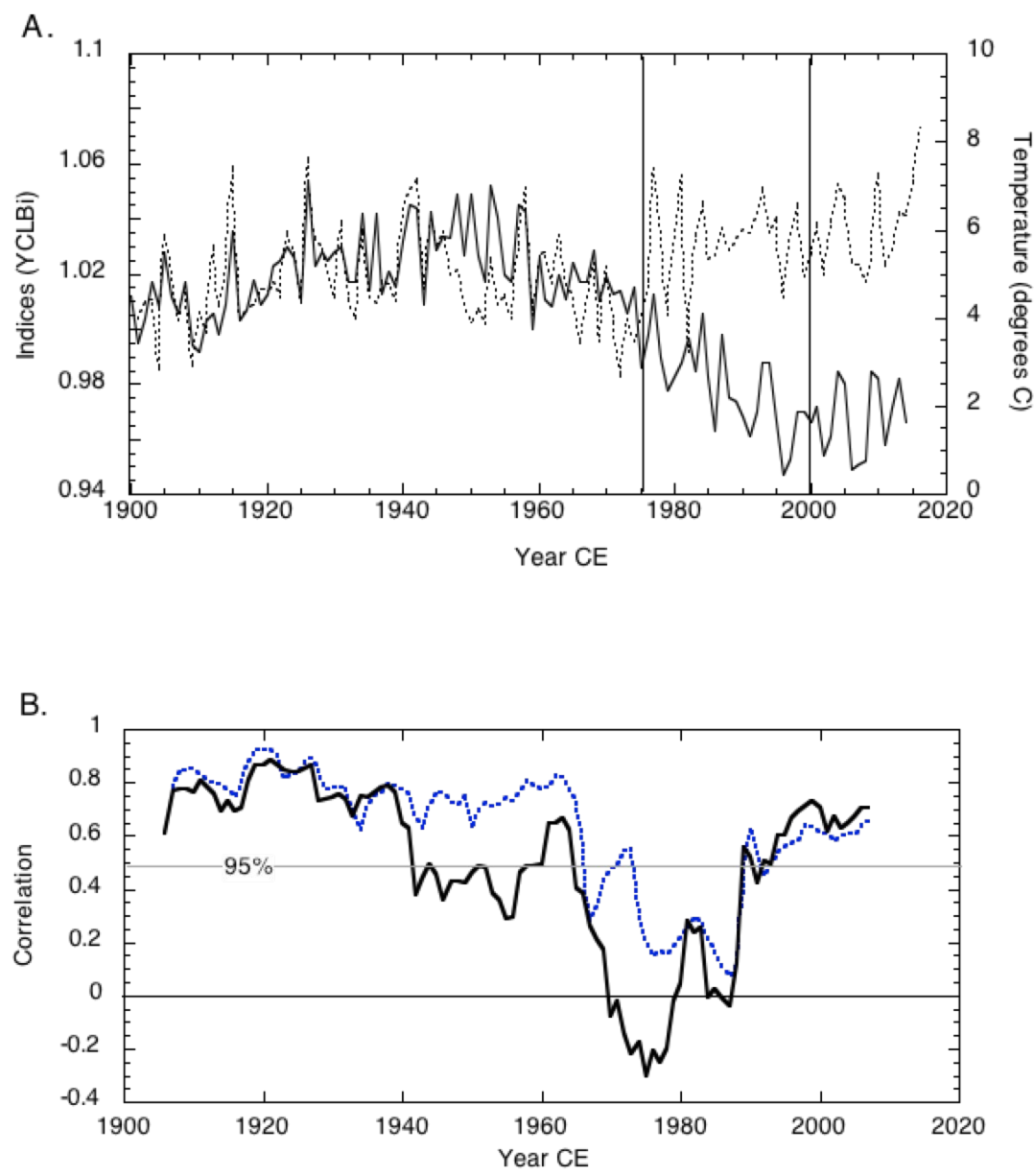


Fig. 4. Plots of (a) January through August average maximum temperatures (broken line) compared with YCLBi. Note how after 1975 the relationship diverges. (b) 15-year running correlations of the YCLBi series with maximum temperature (January-August average), with the non-transformed series (solid line) and with the first differenced data (broken line) showing the decadal loss of climate signal and then recovery.

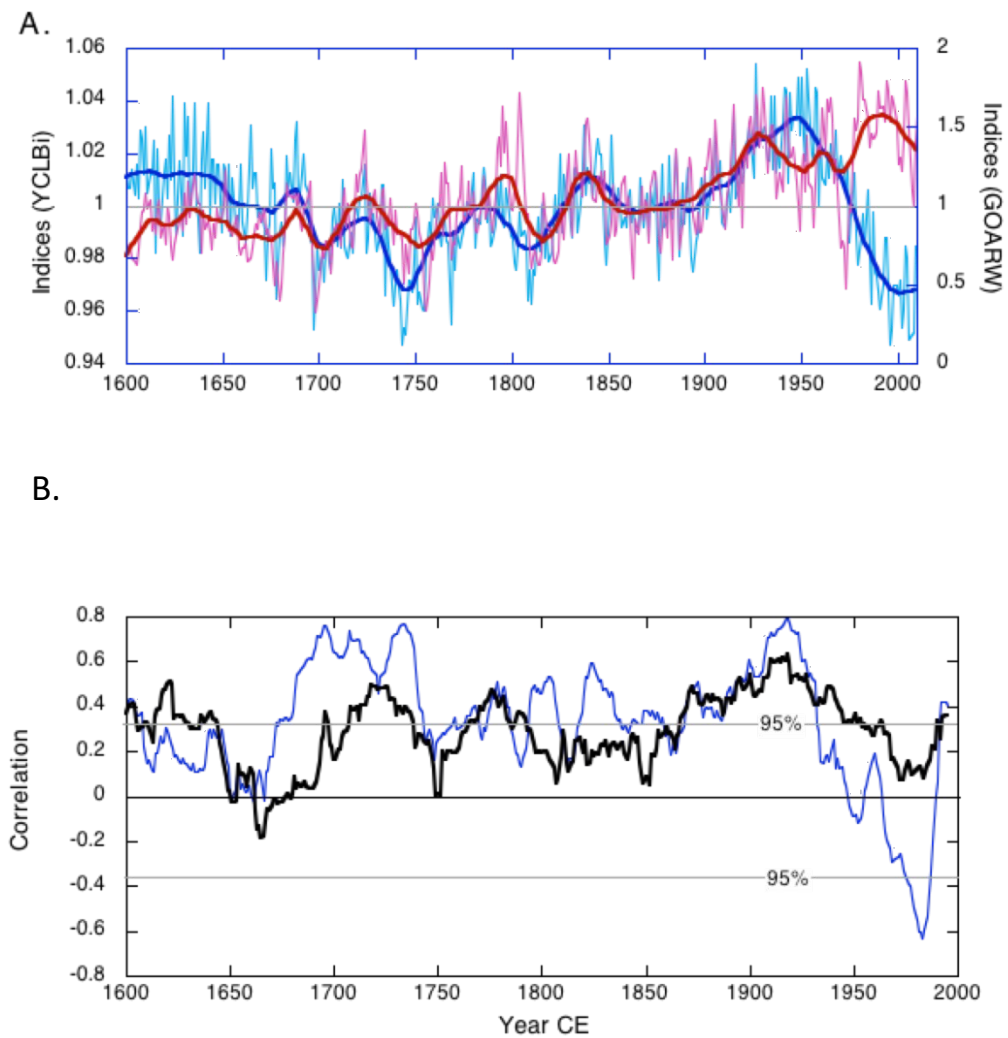


Fig. 5. YCLBi (blue) and GOARW (red) records compared. (a) Note the divergence of the two series in the last few decades. (b) 31-year running correlations between the two series (not transformed (blue) and the first differences (black)). These running correlations show the dramatic drop in correlation after the 1976/77 regime shift in the North Pacific and a recovery in correlation after ~1999.