

32 **Abstract**

33 This is the first study to generate and analyze the climate signal in Blue Intensity (BI) tree-ring
34 chronologies from Alaskan yellow-cedar (*Callitropsis nootkatensis* D. Don; Oerst. ex D.P.
35 Little). The latewood BI chronology shows a much stronger temperature sensitivity than ring-
36 widths (RW), and thus can provide information on past climate. The well-replicated BI
37 chronology exhibits a positive January-August average maximum temperature signal for 1900-
38 1975, after which it loses temperature sensitivity following the 1976/77 shift in northeast Pacific
39 climate. The positive temperature response appears to recover and remains strong for the most
40 recent decades although the coming years will continue to test this observation. This temporary
41 loss of temperature sensitivity from about 1976 to 1999 is not evident in RW or in a change in
42 forest health, but is consistent with prior work linking cedar decline to warming. A confounding
43 factor is the uncertain influence of a shift in color variation from the heartwood/sapwood
44 boundary. Future expansion of the yellow-cedar BI network and further investigation of the
45 influence of the heartwood/sapwood transitions in the BI signal will lead to a better
46 understanding of the utility of this species as a climate proxy.

47 **Key words:** Yellow cedar, blue intensity, tree rings, dendroclimatology, Alaska

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53 1. Introduction:

54 Climate-driven, abiotic stresses are emerging as a major driver of forest decline in North
55 America (Cohen et al., 2016; Buma et al., 2017). Forest decline is defined as the loss of tree
56 vigor and eventual mortality triggered by complex biotic and abiotic factors (Manion and
57 Lachance 1992). Abiotic forest decline is a complex disorder driven by various non-living
58 physical stresses, including climate change, on a forest stand that results in growth decline and
59 can lead to mortality. Affected trees may recover once the stresses are removed. Identifying the
60 response of ecosystems to varying rates of climate change is a challenge as species may respond
61 linearly or non-linearly to anthropogenic warming as well as to the natural internal climate
62 dynamics of the North Pacific (Krapek et al., 2017). In the coastal northeast Pacific, of particular
63 interest are the Pacific related decadal fluctuations (ie., the Pacific Decadal Oscillation; PDO)
64 that dominate many aspects of the climate and ecosystems and have persisted for increasingly
65 long intervals over the observational record since CE 1900 (Boulton and Lenton, 2015; Gaglioti
66 et al., 2019). This decadal variability is superimposed on contemporary warming and has been
67 observed throughout the Little Ice Age (~CE 1250-1850; Wilson et al., 2007).

68 Decadal shifts have been recognized in climate data, climate indices and biological time
69 series (Overland et al., 2008). Determining the causes of shifts in North Pacific climate has been
70 an ongoing challenge, in part due to the large number of both instrumental and proxy time series
71 available, all of which capture different aspects of climate system on various timescales (ENSO,
72 decadal and century-scale warming). Efforts to extract the decadal signal from sea surface
73 temperature data suggest that in addition to the positive shift in PDO in 1975/76, a negative shift
74 occurred in 1998/99, although it may be too early to label this episode as a “regime shift” (Ding
75 et al., 2013; McAfee, 2014, 2016; Wills et al., 2018).

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

90 Yellow cedar has been the subject of intense study primarily because of the phenomenon
91 of widespread decline of this species in southeastern Alaska, which is relatively well understood.
92 In the early 1980s, foresters (led largely by the National Forest Service in Juneau, Alaska) ruled
93 out various pathogens and other abiotic factors (Hennon et al. 2006, 2012, 2016; Schaberg et al.,
94 2008). The current leading hypothesis for the decline has been factors related to warming
95 temperatures. Earlier spring snowmelt, and the associated shift in the transition from snow to
96 rain, both lead to a loss of spring snowpack, which can contribute to freezing of rootlets and to
97 decline. Snowpack provides insulation from cold surface air temperatures, protecting vulnerable
98 small roots from frost events especially when shallow root dehardening occurs in wet soils

99 (Schaberg et al., 2008, 2011; Hennon et al. 2012, 2016). Extensive work has been done testing
100 this hypothesis and exploring the forest dynamics and ecology associated with the decline
101 (Oakes et al., 2014, 2015; Krapek and Buma, 2017; Krapek et al., 2017) driven by concerns of
102 species loss and determination of whether the species is endangered (Buma et al., 2017; Barrett
103 and Pattison, 2017, Bidlack et al., 2017).

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

119 In a regional study examining yellow-cedar health across its entire range (Buma et al.,
120 2017) identified a critical threshold of mean winter temperatures above 0°C as snow turns to rain
121 (Buma et al., 2017) and rootlets become more susceptible to frost damage. Once winter

122 temperatures sufficiently warm, frosts may be less frequent and snowpack will not be as crucial a
123 factor in protecting root systems. This appears to be the case at the southern range of yellow-
124 cedar (Buma, 2018) in Washington and Oregon where healthy stands are flourishing. This
125 previous work provides a context for the present study, as our sites are entering the zone where
126 mean winter temperatures are between -2° and $+2^{\circ}\text{C}$ as mapped by Buma et al. (2017) and are
127 thus susceptible to future decline as warming proceeds.

128 Previous dendroclimatic investigations along the Gulf of Alaska (GOA) have used tree
129 rings from coastal sites for climate reconstruction focusing primarily on mountain hemlock RW
130 (*Tsuga mertensiana* (Bong.) Carr.; Barclay et al., 1999; D'Arrigo et al., 2001; Wilson et al.,
131 2007; Wiles et al. 2014). More recently BI records are showing promise for generating robust
132 climate reconstructions along the GOA (Wilson et al., 2017) and in the Yukon (Wilson et al, in
133 press). Thus far, BI chronologies for the GOA have only been developed for mountain hemlock
134 (Wilson et al., 2017). Wilson et al. (2017) used the delta BI (dBi; latewood BI (LBi) subtracted
135 from the earlywood BI (EBi) values) parameter to reconstruct climate, noting the stronger
136 relationship between summer temperature and dBi than with LBi or EBi for mountain hemlock.

137 Here we present the first BI tree-ring series for yellow-cedar and examine the strength
138 and stability of its climate signal. Both RW and LBi chronologies for yellow-cedar were
139 examined for their potential for climate reconstruction and our results are interpreted within the
140 context of the yellow-cedar decline outlined above (Buma et al., 2017; Hennon et al., 2016). We
141 generated ring-width (RW) and blue intensity (BI) measurements to document the climate
142 response over the past several centuries. Latewood blue intensity (LBi) is a similar tree-ring
143 measurement to maximum latewood density (MXD). BI measurements, in general, reflect the
144 combined hemi-cellulose, cellulose and lignin content in the latewood which are key components

145 of relative density (Björklund et al., 2014; Rydval et al., 2014). The utility of LBi as a summer
146 temperature proxy has been shown to improve climate reconstruction from multiple high
147 elevation and high latitude sites (Björklund et al., 2014, 2015; Campbell et al., 2007; Dolgova,
148 2016; Rydval et al., 2014, 2017; Wilson et al., 2014) and the use of dBi from the Gulf of Alaska
149 (Wilson et al., 2017). Significantly, blue intensity is a much less expensive parameter to generate
150 than MXD. One downside however, is that LBi chronologies generally require a larger sample
151 size than MXD to generate a robust mean chronology (Björklund et al., 2014; Wilson et al.,
152 2014, 2017).

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154 **2. Methods**

155 Trees were cored at the aforementioned three sites near Juneau: Cedar Lake, Bridget Cove and
156 East Glacier (Fig. 1). The sites range in elevation from 110 to over 480 m (Table 1). For the
157 Cedar Lake site, cores and ring-width data were obtained from other researchers (Beier et al.,
158 2008; Krapek et al., 2017) and combined with our collections from the summers of 2016 and
159 2017 (Charlton et al., 2017). The tree cores were immersed in acetone for 72 hours to remove
160 resins in the wood (Rydval et al., 2014; Fuentes et al., 2018), then glued onto wood mounts and
161 sanded to a high polish. An Epson V850 pro scanner, using an IT8.7/2 calibration card in
162 conjunction with SilverFast scanning software was used to scan the samples at a resolution of
163 2400 dpi. Scanning was done with a nonreflective black box covering the scanner window. BI
164 measurements were made using CDendro 8.1 and CooRecorder 8.1 (Larsson, 2016). Previously
165 generated ring-width chronologies facilitated calendar dating, and COFECHA (Holmes, 1983)
166 was used as a final quality control for the dating of the RW and LBi measurements.

167 Since BI measurements are color based, discoloration of the wood presents challenges.
168 One is the presence of a heartwood/sapwood boundary, which can cause a color shift in some
169 species that may impose a trend bias in the BI series (Björklund et al., 2014; 2015). In most of
170 the yellow-cedar cores we did not observe a strong color difference, although a subtle change
171 was noted in some series that might be enough to influence the measured values. To investigate
172 potential color change, we counted the number of rings at the transition from heartwood to
173 sapwood where we were able to discern the transition; counts ranged from 16 to 50 years in the
174 ~10% of samples in which we could detect the transition. The blue intensity parameters that
175 were evaluated included: LBi, earlywood BI (EBi) and the derived dBi (McCarroll et al., 2002;
176 Björklund et al., 2014, 2015; Rydval et al., 2014; Wilson et al., 2017). In our yellow cedar series,
177 EBi and LBi values are highly correlated with one another ($r=0.82$ for 1900-2014). The
178 application of dBi in the case of such a strong inter-correlation can lead to a loss in climate signal
179 (Björklund et al. 2014). The uniform density between the earlywood and latewood illustrated in
180 this high correlation is consistent with known wood properties that make the yellow cedar
181 desirable for its smoothly carved surfaces (Hennon et al., 2016). Given the high correlation
182 between the early and latewood measurements, and our strong results for our climate analyses
183 using LBi, we focused herein on only the LBi and RW signals from yellow-cedar for this paper.

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

189 Population Signal (EPS) of >0.85 (Fig. 2a; Wigley et al, 1984). The EPS is a measure of how
190 well a sample of tree-ring data (ie., number of tree ring series) represents an ideal population.

191 We followed the methodology of Wilson et al. (2017) in processing the ring-width and
192 LBi records into chronologies. Tree-ring series were standardized using the signal-free (SF), age
193 dependent spline (ADS) approach described in Melvin et al. (2007), and Melvin and Briffa
194 (2008, 2014; Fig. 2a). We used the signal free software RCSigFree, a freeware program
195 developed at the Tree-Ring Lab of the Lamont-Doherty Earth Observatory
196 (<http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>) that is based on the
197 program ARSTAN (Cook, 1985). The SF approach was used because of the complex growth
198 trends recognized in the individual tree ring series; both Wilson et al., (2017; in press) and
199 Buckley et al. (2018) similarly used SF standardization with favorable results.

200 The RW and LBi series were best correlated with GOA monthly maximum temperatures
201 (T_{max} , CRU TS4.01; Harris et al., 2014; Fig. 3). The temperature series was calculated by
202 averaging gridded data from within the coordinates $56^{\circ} - 62^{\circ} N$, $130^{\circ} - 140^{\circ} W$ (Fig. 1) for the
203 CE 1900-2014 interval. We used the T_{max} for analyses because of its stronger correlation with
204 the tree-ring record than with mean or minimum monthly temperatures. Wilson et al. (2017), in
205 their investigation of BI and RW series for mountain hemlock (using dBi), used mean monthly
206 temperatures from stations within $57^{\circ} - 61^{\circ} N$, $134^{\circ} - 153^{\circ} W$, a broader region than our study, as
207 they analyzed multiple sites across a larger swath of the GOA. Although we obtained marginally
208 better results with maximum temperatures from this larger area, we chose to use a more
209 restricted area to better represent the region surrounding our sampling sites (Fig. 1). It is difficult
210 to assess the temperatures at the tree-ring sites relative to the meteorological stations and we
211 have no records of frost frequency at the individual sites. January (coldest month) T_{max} values

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

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

220

221 **3. Results**

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

231 The final chronologies were created by combining the three individual sites into one RW
232 and one YCLBi regional series (Fig.2). The two series correlate with one another at 0.49 for the
233 period of overlap between 1400 and 1975 CE (Fig. 2a) after which they diverge. The RW and
234 YCLBi series match well with the exception of intervals in the mid 1500s, early to mid 1600s

235 and after about CE 1970 (Fig. 2a). About 1975, the YCLBi record strongly decreases and the
236 RW series declines marginally and then generally increases through recent decades (Fig. 2; Table
237 3). Comparisons of RW and YCLBi series with Tmax from the CRU gridded dataset were made
238 for the “dendroclimatic year” that consists of March through December of the previous year of
239 growth and January through October of the year of growth (Fig. 3). For the YCLBi, the strongest
240 correlations (Pearson two-tailed) were with mean January through August (J-A) maximum
241 temperatures at 0.64 for 1901-1975 ($p < 0.00001$), with a 1st differenced correlation of 0.71 (1902-
242 1975; $p < 0.00001$; Fig. 3a). After 1975, there is a marked decrease in correlation and loss of
243 significance ($r = 0.21$ $p > 0.34$) for the non-transformed series with a 1st differenced correlation of
244 0.33 ($p = 0.14$, also not significant) for the 1976-1999 interval (Figs. 3b, 4a). For the 2000-2014
245 interval, the correlation increases to 0.71 ($p = 0.004$) with an increase in the 1st differenced data
246 correlation to 0.64 ($p = 0.01$) (Fig. 4b) comparable to the pre-1975 relationship (Fig. 3c). RW was
247 positively correlated with temperature (J-A) prior to 1976 ($r = 0.30$, $p < 0.01$) and after that time
248 correlations with maximum temperatures are not significant (Fig. 3a).

249 A principal result of our analyses is that the YCLBi is more sensitive to, and thus
250 provides a much stronger proxy for maximum temperatures (January-August average) than RW.
251 Furthermore, decadal variations in climate along the GOA as inferred from the YCLBi record
252 appear nonstationary, especially during the climatic shift in the mid to late 1970s. This noted so-
253 called 1976/77 regime shift in the North Pacific is well-documented in terms of the physical and
254 biological changes that occurred in the region (Ebbesmeyer et al., 1991; Mantua et al., 1997;
255 Trenberth and Hurrell, 1994; Newman et al., 2016). In southeast Alaska, this shift brought
256 warmer temperatures with less snow but higher precipitation as rain (Wendler et al., 2017). The
257 loss of sensitivity in YCLBi to maximum temperature after this shift is consistent with the

258 hypothesis that warming decreases snowpack, thus potentially exposing the shallow roots to frost
259 (the decline hypothesis). This dropoff in correlation also corresponds with a peak of cedar
260 mortality in the late 1970s to the early 1980s elsewhere in southeast Alaska (Hennon et al., 2016;
261 Hennon and Shaw, 1994). The apparent recovery in climate signal after the 1999 negative shift
262 in climate discussed in Ding et al. (2013), analyzed in McAfee (2016) and reported by Wills et
263 al. (2018) is marked here by a strengthening in correlation with Tmax and is also consistent with
264 the decline hypothesis. A recovery of climate sensitivity with respect to Tmax after 1999 appears
265 to be strongest in the year-to-year, high frequency response (differenced data; Fig. 4b). It also
266 appears that the lower frequency (decadal) response is also in recovery, although this finding is
267 preliminary (Fig. 4).

268

269 **4. Discussion**

270 To explore these changes in climate response further we compared our new YCLBi series
271 with a published climate reconstructions based on ring widths (GOARW; Wiles et al., 2014).
272 This record is derived from coastal mountain hemlock sites along the Gulf of Alaska. The
273 GOARW record sustains a strong positive relationship with mean temperature throughout the
274 post 1976/77 regime shift (a so-called “divergence-free” reconstruction; Wiles et al., 2014). This
275 “divergence-free” series was constructed to minimize the effect of the changing climate response
276 of mountain hemlock RW recognized at some elevations along the southern Alaskan coast
277 (Jarvis et al., 2013; Wiles et al., 2014). As discussed above, the YCLBi record correlates best
278 with maximum average (January-August) temperatures, which is similar to the response of the
279 GOARW series that has been used to reconstruct mean February-August temperatures (Wiles et
280 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

304 peak wave of recent yellow-cedar mortality in southeast Alaska (Hennon et al., 2016). The 1976
305 threshold shift may have led to multiple years of successive injury altering climate sensitivity,
306 although mortality has not been observed at our sites. Furthermore, in the course of the analyses
307 we did not observe any evidence of injury in the wood such as traumatic resin ducts. Importantly,
308 yellow-cedar freezing injury is classified as a “forest decline” because it often takes multiple
309 freezing events and years of injury before eventual mortality.

310 The correspondence of YCLBi change with the mid-1970s regime shift from a
311 dominantly negative to dominantly positive PDO caused strong warming in coastal regions in
312 southeastern Alaska and thus a reduction in snowpack is consistent with the decline hypothesis.
313 This possible threshold crossing is likely associated with the physiological limits of yellow-
314 cedar, wherein its sensitivity to temperature becomes decoupled (D’Arrigo et al. 2004; Ohse et
315 al. 2012). Wang et al. (2014) documented an analogous divergence between temperature and RW
316 in five species from southeastern China, also in response to the 1976-77 regime shift. To our
317 knowledge, the Juneau YCLBi results presented here are the first tree ring studies to suggest the
318 effects of this relatively recent phenomenon on yellow-cedar populations in southeastern Alaska.

319 The favorable comparisons of the YCLBi series with the GOARW tree-ring series (Fig.
320 5a) prior to 1976 and then again after 1999 also suggest that the changes documented in yellow-
321 cedar in recent decades are unprecedented at least since CE 1400 (Fig. 5a; Table 3). Our results
322 indicate, therefore, that decadal shifts in addition to century-scale warming should be considered
323 when assessing the climate response of yellow-cedar. The strong coherence between the series
324 additionally, suggests that the conditions forcing the divergence after 1976 were likely not
325 experienced since at least 1400 CE. Furthermore, with the caveat that in some of our samples we
326 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.

349 Blue-intensity parameters measured in yellow-cedar could complement such studies of
350 divergent tree growth and warming temperatures in northern forests, which have been primarily
351 based on ring-widths (D'Arrigo et al., 2008). Here the YCLBi measurements show a change,
352 whereas the RW do not, suggesting that blue intensity, at least for yellow cedar, may experience
353 divergent phenomena. Thus, when the limiting factors on growth at a location change, it may
354 result in distinct challenges for using blue intensity from yellow-cedar in dendroclimatology. It is
355 possible that a band-pass approach could be performed with RW providing the low frequency
356 signal with the BI record providing the higher frequency signal (Wilson et al., 2014). However,
357 the challenge remains that the climate sensitivity of the RW is not as strong as the YCLBi record,
358 although the multi-decadal to century scale variability appears to be relatively coherent (Fig. 2).

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

372 Our YCLBi series is climatically sensitive to January through August maximum average
373 temperatures a broader climate window than the June-September sensitive GOAdBi study by
374 Wilson et al. (2019). We hypothesize that the broader climate window for the YCLBi record
375 compared with the more restricted summer signal found in Wilson et al (2017) may be due to the
376 ecophysiological tendency of yellow-cedar to dehardening earlier in the spring, thus responding
377 favorably to winter/spring temperatures. This early dehardening may allow yellow cedar to gain
378 a competitive advantage with respect to nutrient uptake (D'Amore et al., 2009) relative to other
379 conifer species and thus yellow-cedar respond to late winter/spring temperatures as well as
380 summer.

381 Finally, although the three sites in this investigation have not shown indications of
382 decline at the stand level or a marked decrease in radial growth (RW), they appear to have been
383 impacted by changes in climate in the mid to late 1970s, behaving similarly to stands that have
384 experienced extensive mortality (Beier et al., 2008). Since about 1999, these populations
385 recovered their climate sensitivity suggesting some level of resilience. This is consistent with the
386 concept that this population is “on the edge” of climatic vulnerability (Buma, 2018). Thus, it may
387 be that at some of the locations in the Juneau area, yellow-cedar sites remain healthy forests.
388 However, since they are near the leading edge of the decline and outside of the “historical
389 decline,” a slight warming in the region could push these trees closer toward conditions of
390 potential mortality as recognized farther south in coastal Alaska.

391 As Buma (2018) points out, across the range of yellow-cedar, if the rate of warming is
392 great enough to ameliorate the occurrence of frost, then the warming and loss of snowpack may
393 not influence cedar growth. Although the roots are vulnerable, frosts are less likely to occur in a
394 rapidly warming climate. A drop toward nonsignificant correlations in both the non-transformed

395 and first differenced series between 1976 and 1999 is consistent with stress-related changes,
396 perhaps related to warming temperatures and its interactions with snowpack and frost.
397 Furthermore, the secular increase as well as the decadal changes in the North Pacific emphasized
398 here will drive and modulate the tree response to climate.

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

410 Our results suggest that with further work YCLBi records could be used to reconstruct
411 past climate. Melting glaciers across the GOA continue to reveal ancient forests, and in at least
412 one case, have exposed sub-fossil wood that includes yellow-cedar (Gaglioti et al., unpublished
413 data). This presents the emerging possibility of extending these cedar series further back in time.
414 As in the case for mountain hemlock (Wilson et al., 2017), blue intensity tree-ring series in
415 yellow-cedar show promise to improve temperature reconstructions for the GOA and perhaps in
416 the future entering into multi-species climate reconstructions.

417

418 **5. Conclusions**

419 This analysis of yellow-cedar response to climate is the first to examine the latewood
420 blue intensity parameter. Previous work with ring-widths from yellow cedar of southeast Alaska,
421 although valuable in examining changing climate response, have been limited with respect to
422 reconstructing past climate. Our well-replicated YCLBi series has a strong temperature response
423 until the mid-1970s equal to or greater than many published ring-width series from the
424 traditionally used mountain hemlock from the region.

425 The trends in the observational climate records and in the YCLBi data suggest changes in
426 tree physiology around the mid-1970s shift in the PDO that may have been detrimental to tree
427 growth but do not necessarily appear to be affecting bioproductivity as inferred from ring-widths.
428 The presumed recovery in temperature sensitivity in YCLBi after a shift to a cooler regime in
429 1998/99 (Wills et al., 2018) is further evidence of a response to decadal climate change, although
430 additional years for comparison in the coming decades may strengthen or refute this observation.
431 The climate sensitivity of this economically, ecologically and culturally important species should
432 be coupled with the existing knowledge of past migrations and the mechanisms of decline when
433 anticipating its future range (Krapek et al., 2017), especially in the face of unprecedented
434 warming.

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

440

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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.

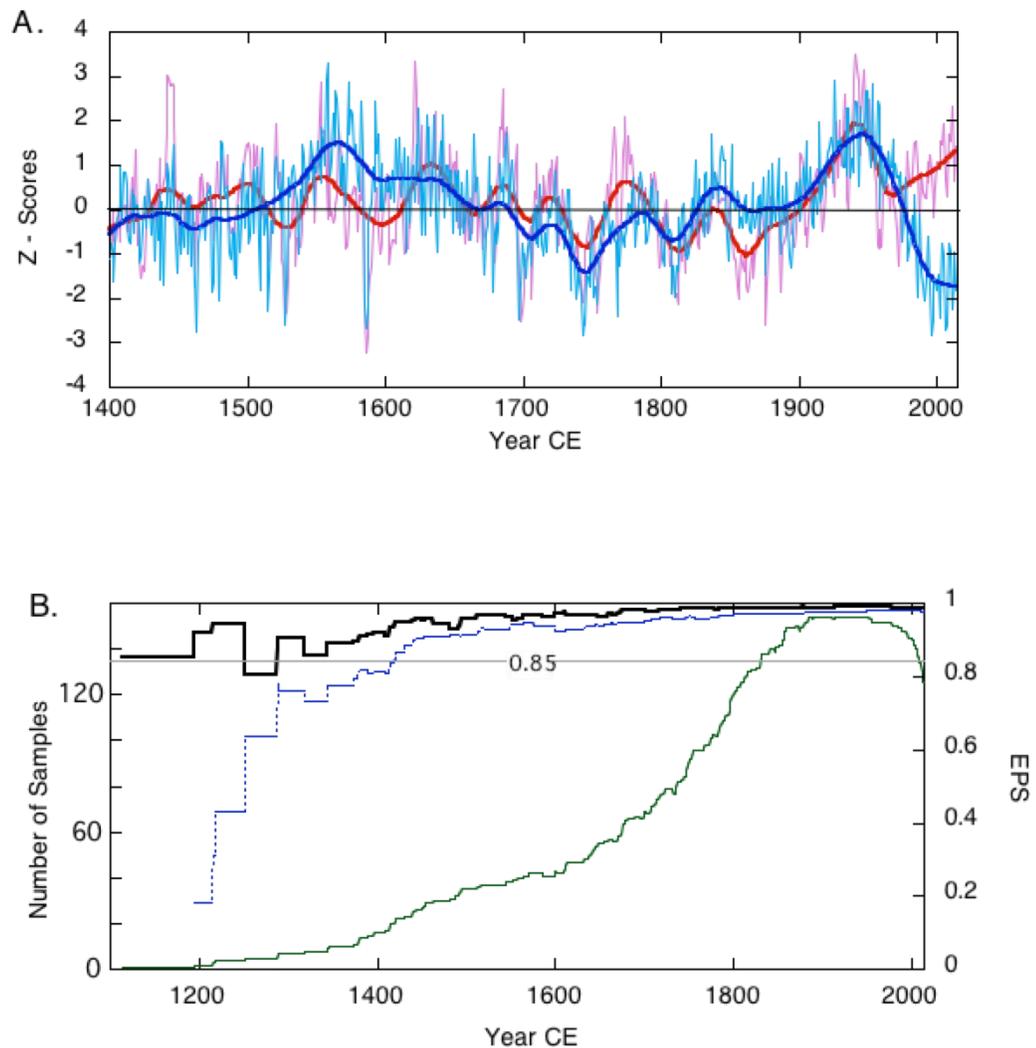


Fig. 2. (a) Z-scores (relative to the 1400-1900 interval) of the ring—width (red) and latewood blue intensity (YCLBi, blue) both chronologies are built from the composite of the three cedar sites (Figure 1). (b) Shows the sample size (green) and the EPS for each of the chronologies (black (RW) and blue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

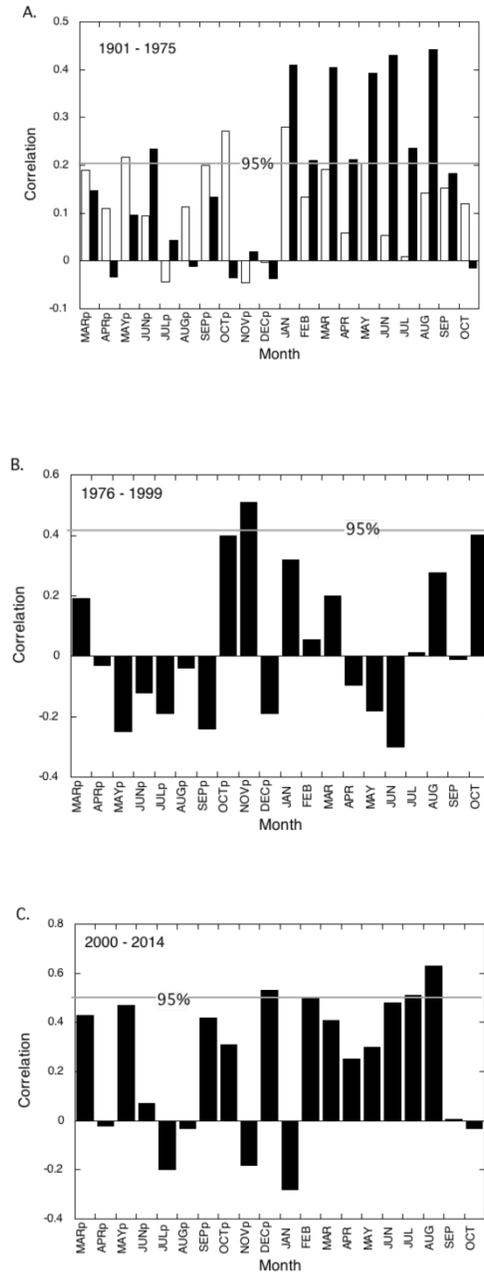


Fig. 3. (a) The temperature response (monthly correlations) for the ring-width (white) and blue intensity(black) cedar records for the dendroclimatic year. Note that for the 1901-1975 interval the YCLBi record correlates much more strongly with monthly temperatures than the RW. For the 1976-1999 interval, 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.

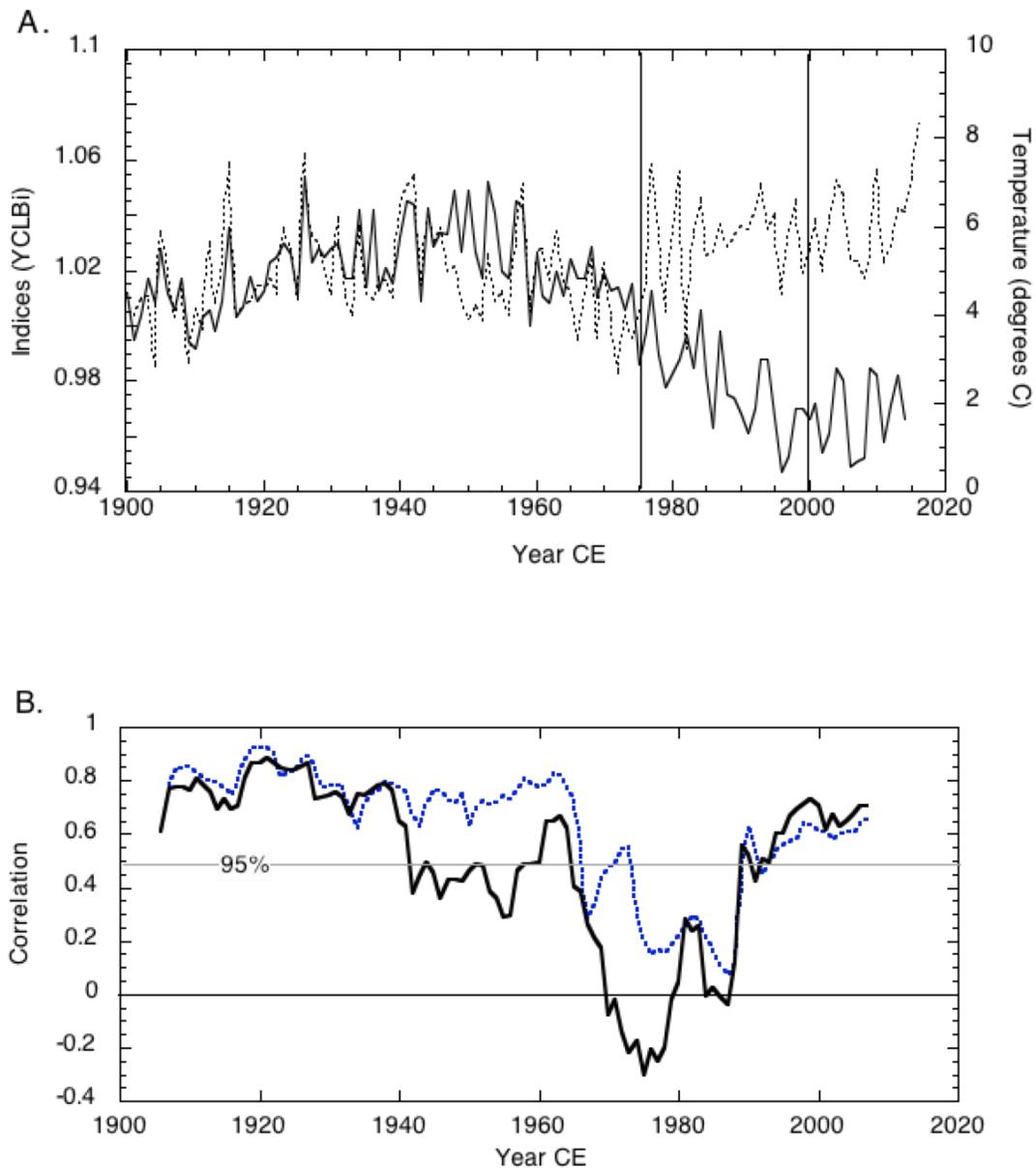


Fig. 4. Plots of (a) January through August average maximum temperatures (broken line) compared with YCLBi. Note how after 1975 the relationship diverges. (b) 15-year running correlations of the YCLBi series with maximum temperature (January-August average), with the non-transformed series (solid line)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

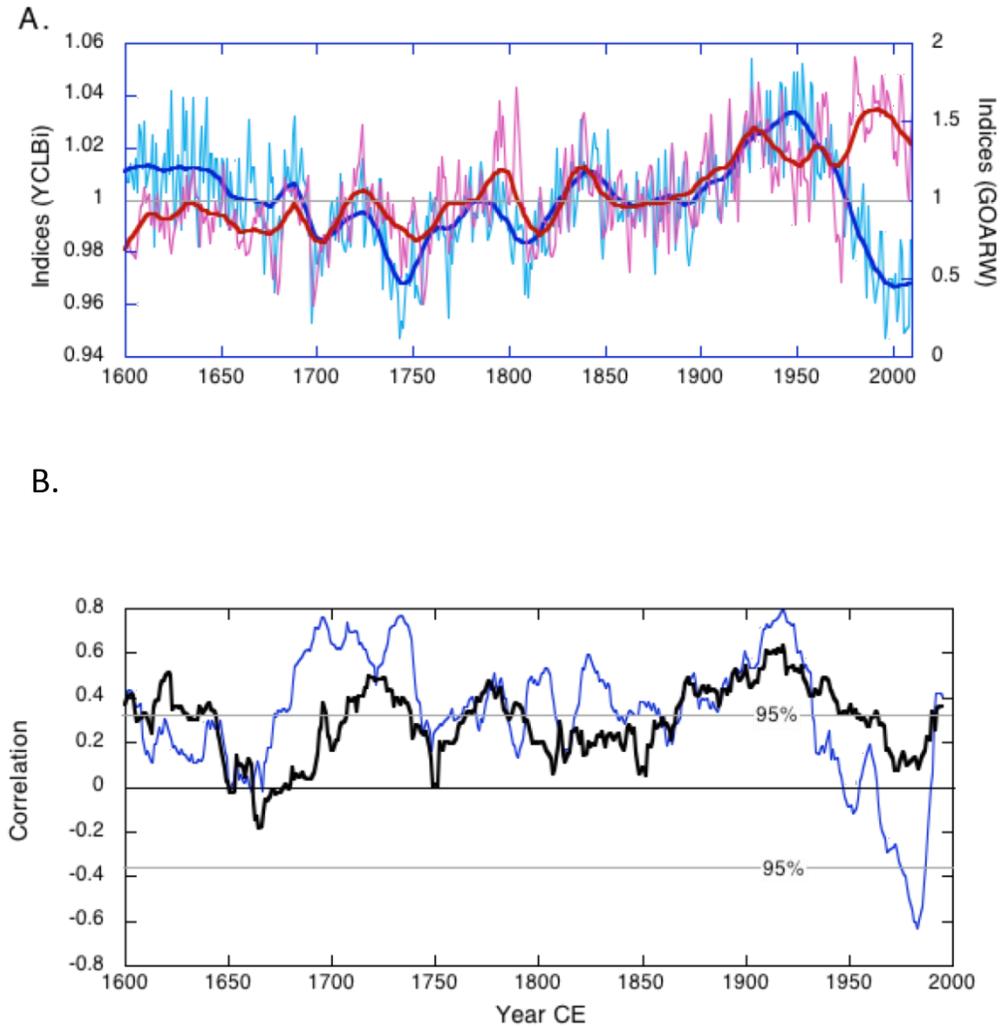


Fig. 5. YCLBi (blue) and GOARW (red) records compared. (a) Note the divergence of the two series in the last few decades. (b) 31-year running correlations between the two series (not transformed (blue) and the first differences (black)). These running correlations show the dramatic drop in correlation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