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Blue Intensity based experiments for reconstructing North Pacific temperatures along the Gulf of Alaska

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Abstract: Climate in the Gulf of Alaska (GOA) reflects large-scale ocean-atmosphere variability of the North Pacific climate system. Ring-width (RW) records from the GOA have yielded a valuable long-term perspective for North Pacific changes on decadal to longer time scales in prior studies, but express a broad winter to late summer seasonal response. Similar to the highly climate-sensitive maximum latewood density (MXD) proxy, the Blue Intensity (BI) parameter has recently been shown to correlate well with year-to-year warm-season temperatures for a number of sites at northern latitudes. Since BI records are much less expensive and labor intensive to generate than MXD, such data hold great potential value for future tree-ring studies in the GOA and other regions at mid-to-high latitudes. Here we highlight the potential for improving tree-ring based reconstructions using combinations of RW and BI-related parameters (latewood BI (LWB) and delta BI (DB)) from an experimental sub-set of samples from eight mountain hemlock (*Tsuga mertensiana*) sites along the GOA. This is the first such study for the hemlock genus using BI data. We find that using either LWB or DB can improve the amount of explained temperature variance by > 10% compared to RW alone although the optimal target season changes to June-September, which may have implications for studying ocean-atmosphere variability in the region. However, one challenge in building these BI records is that resin extraction did not remove colour differences between the heartwood and sapwood, so long term trend biases, expressed as relatively warm temperatures in the 18th century, were noted when using the LWB data. Using DB appeared to overcome these trend biases resulting in a reconstruction expressing 18th-19th century temperatures ca. 0.5°C cooler than the 20th/21st centuries. This cool period agrees well with previous dendroclimatic studies and the glacial advance record in the region. Continuing BI measurement in the GOA region must focus on sampling more trees per site (> 20) and more sites to overcome site specific factors effecting climate response while sub-fossil material will extend the reflectance records back over 1000 years. DB appears to capture long term secular trends that agree with other proxy archives in the region but great care is needed when implementing different detrending options. Finally, more experimentation is needed to assess the utility of DB for different conifer species around the Northern Hemisphere.

Keywords: Blue Intensity, Gulf of Alaska, Tree Rings, Reconstruction, North Pacific**; Short Title**: Gulf of Alaska Blue Intensity Tree-Ring Temperature Reconstruction

1. Introduction

The climate of the Gulf of Alaska (GOA) is strongly influenced by the atmosphere-ocean variability of the North Pacific sector (e.g. the Pacific Decadal Oscillation, Mantua et al. 1997), with profound socioeconomic implications for the region (Ebbesmeyer et al. 1991). However, the variability of such synoptic climate phenomena is more strongly expressed in winter. Ring-width (RW) data measured from montane treeline conifer trees in the GOA region often express a broad seasonal response window (e.g. January-September, Wilson et al. 2007; February-August, Wiles et al. 2014), which has allowed such data to provide information on cold season synoptic dynamics for almost two thousand years (Barclay et al. 1999, D'Arrigo et al. 2001, Wiles et al. 2004 and 2014, Wilson et al. 2007).

Maximum-latewood density (MXD) measurements have yielded long records of past summer temperatures for many regions in the northern mid-to-high latitudes (e.g. Schweingruber 1988, Briffa et al. 2002, Anchukaitis et al. 2013, Schneider et al. 2015), but such records do not yet exist for the GOA. MXD series are particularly desirable as such records often express stronger coherence with temperatures than RW and result in climate reconstructions with better skill and spectral fidelity (Anchukaitis et al. 2013, Esper et al. 2015, Wilson et al. 2016). This is partly because RW chronologies typically exhibit higher autocorrelation and lagged memory effects than MXD (Briffa et al. 2002; Anchukaitis et al. 2012), but also because RW may potentially integrate other ecological signals (e.g. disturbance and stand dynamics) which can obscure the climate signal (Rydval et al. 2015). Yet, only two millennial-length MXD records are currently published for all of northwestern North America (Icefields, British Columbia (BC), Canada - Luckman and Wilson 2005; Firth River, Alaska - Andreu-Hayles et al. 2011, Anchukaitis et al. 2013) and no traditionally measured MXD data have been generated to date for the entire GOA. This situation partly relates to the expensive and labor intensive nature of MXD measurement, but also because the wood of mountain hemlock (*Tsuga mertensiana*), the dominant conifer species in the GOA, is rather brittle and does not lend itself well to sample preparation for MXD measurement.

To help meet the need for additional climatically-sensitive density records from northwestern North America, we present herein an exploration of novel Blue Intensity (BI) parameters measured from scanned images of tree core samples from the GOA. Minimum latewood blue intensity (LWB) has recently been shown to express strong similarities to MXD, and is much cheaper and easier to generate (McCarroll et al. 2002; Björklund et al. 2014, 2015; Rydval et al, 2014; Wilson et al. 2014, 2017). LWB is closely related to MXD as they measure similar wood properties (combined hemicellulose, cellulose and lignin content related to cell wall thickness), and both are well correlated with warm-season temperatures (Campbell et al. 2007; Björklund et al. 2014, Rydval et al. 2014, Wilson et al. 2014). This correspondence between BI and temperature has recently been shown to hold true for several locations and tree species, including Scots pine (*Pinus sylvestris*) in Scotland, UK (Rydval et al. 2014) and Sweden (Björklund et al. 2014, 2015), Caucasian fir (*Abies nordmanniana*) in the Northern Caucasus' (Dolgova 2016), Stone pine (*Pinus cembra*) in Austria (Österreicher et al. 2015; Wilson et al. 2017), Engelmann spruce (*Picea engelmannii*) from the Canadian Rockies, British Columbia, Canada (Wilson et al. 2014) and our own analyses of white spruce (*Picea glauca*) in northwestern North America (Andreu-Hayles et al., ms. in prep.). Although BI often requires larger sample sizes than MXD to improve signal strength (Wilson et al. 2014), this is not a concern due to the low cost of the method.

The greatest limitation of LWB, however, is that any colour variation that does not represent year-to-year climate-driven cell wall thickness changes will bias the resultant raw reflectance measurements. For example, some conifer species (including Scots pine and mountain hemlock) show either a sharp or transitional colour change from the heartwood to sapwood, which, even after resin extraction using ethanol or acetone, can still impose a systematic change in reflectance around the heartwood/sapwood transition (Björklund et al. 2014, 2015). Further colour variations, often seen in dead but preserved snag or sub-fossil wood, can also result in systematic biases when combined with data measured from living samples (Björklund et al. 2014, 2015; Rydval et al. 2014). Björklund et al. (2014) proposed a potential solution to the heartwood/sapwood colour bias issue by effectively detrending the LWB measurements by removing the inherent common colour changes of the earlywood and latewood (i.e. those related to heartwood/sapwood colour change). This was done by subtracting the LWB value from the maximum blue reflectance value of the earlywood (EWB) for each year. The resulting new parameter, referred to as delta blue intensity (hereafter referred to as DB), should theoretically be less biased by such non-climatic related colour changes. Although Björklund et al. (2014, 2015) presented compelling DB results using Scots pine in Sweden, the method has not yet been tested elsewhere or on any other species. We hypothesis that DB can only theoretically work if the inter-annual signal between EWB and LWB is weakly correlated. If the correlation between these two parameters is high, then the method of deriving DB may remove the specific climate signal of interest.

Finally, although BI based variables hold great promise as an alternative proxy to MXD, another concern is their potential inability to capture low frequency information related to long term-climate changes. Wilson et al. (2014), working with Engelmann spruce from British Columbia, which does not express a visual colour difference, urged caution as both the MXD and LWB parameters were sensitive to different detrending options and there was some indication that LWB could not capture as much low frequency information as MXD. However, this observation could not be fully addressed due to the relatively short instrumental record in British Columbia.

In this paper, building upon previous RW based research (Wilson et al. 2007, Wiles et al. 2014), we measure BI variables (EWB, LWB and DB) from multiple sites in the GOA to evaluate: (a) whether BI can improve on previous RW-only based reconstruction, and (b) whether meaningful low frequency information can be gleaned from these data by exploiting the long monthly instrumental temperature records that go back into the mid-19th century to validate secular trends in the TR data.

2. Methods and Analysis

BI measurements were made on a sub-set (ca. 15 single tree cores per site) of crossdated core samples collected over the past few decades from living mountain hemlock (*Tsuga mertensiana* Bong. Carrière) trees located at eight sites near altitudinal treeline (around ~300-400 meters above sea level) along the GOA (Table 1, Figure 1). Data from these and additional sites were used previously to create coastal GOA RW based temperature-related reconstructions (D'Arrigo et al. 2001, Wilson et al. 2007, Wiles et al. 2014).

The tree core samples were immersed in acetone for 72 hours to remove excess resins in the wood (Rydval et al. 2014) and then finely sanded to 1200 grit to remove marks and abrasions prior to scanning. An Epson V850 pro scanner, using an IT-8 calibration card in conjunction with Silverfast scanning software, was used to scan the samples at 2400 dpi resolution. EWB and LWB variables were measured using the CooRecorder 8.1 software (Cybis 2016 - http://www.cybis.se/forfun/dendro/index.htm), which has state-of-the-art capabilities to acquire accurate reflectance intensity RGB colour measurements from scanned wood samples (see Rydval et al. 2014). DB values were calculated within CooRecorder by subtracting the LWB values from the EWB values for each year. Since LWB is negatively correlated to MXD (high density 'dark' latewood = low reflectance), values were inverted following the method detailed in Rydval et al. (2014) to allow for LWB to be detrended in a similar way to MXD (see also Wilson et al. 2014). The nature of the DB calculation results in this parameter being positively correlated with inverted LWB, so these data could also be theoretically detrended in a similar way.

For initial experiments comparing the different tree-ring (TR) variables, the RW, LWB, EWB and DB data were detrended using fixed 200-year cubic smoothing splines (Cook and Peter 1981) to retain the interannual to decadal signal and minimize any potential lower frequency biases due to heartwood/sapwood colour changes. These chronology versions were assessed by (1) signal strength statistics: both common signal (via mean inter-series correlation – RBAR) and expressed population signal (EPS - Wigley et al. 1984) statistics, (2) between variable correlation, (3) between site coherence using a rotated principal component analysis (PCA, varimax rotation using correlation matrices with eigenvectors retained with an eigenvalue > 1.0) and (4) climate response derived by correlations between regional composite TR variable mean series and the dominant PC scores against monthly and season variables of temperature (CRU TS 3.24 (Harris et al. 2012): 57-61ºN / 153-134ºW).

The 200-year spline chronology versions were also used to explore calibration (1901-1960) and validation (1961-1989) based principal component regression reconstruction experiments using the CRU TS data. For the PCA, a reasonably replicated common period (1792-1989) was used where tree series replication was > 5 trees. All site chronologies are replicated with > 10 trees from 1792 except for JM and SR (see Table 1) where replication is 6 and 5, respectively. Reconstruction validation was performed using the Pearson's correlation coefficient (r), the Reduction of Error (RE) and the Coefficient of Efficiency (CE - Cook et al., 1994). Further validation was performed over the 1850-1900 period using the gridded BEST instrumental data (Rohde et al., 2012), extracted for the same region as the CRU TS (57-61ºN / 153-134ºW), after these data were scaled to the CRU TS data over the

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1901-2015 period. CRU TS and BEST compare well to the original GOA 5-station mean record (Supplementary Figure 1) used in Wilson et al. (2007) confirming that the gridded products are good representations of the regional temperature signal. The higher variance of the pre-1950 period in the 5-station mean is related to the fact that variance stabilization (Frank et al. 2007a) was not performed when this mean series was originally developed (Wilson et al. 2007) and is therefore likely a less robust measure of GOA temperatures than the gridded products.

Finally, to explore the potential of reconstructing robust low frequency temperature changes in the region, the data from each of the eight sites were pooled to derive GOA regional composite records for each of the TR variables. These pooled composite variable datasets, with their greater overall replication, allowed detrending experiments to be performed to ascertain the sensitivity of the final parameter chronologies to different detrending choices. Specifically, RW detrending experiments were performed using (1) STD: negative exponential function or negative or zero slope linear function detrending via division; (2) NEPT: negative exponential function or negative or zero slope linear function detrending via subtraction after power transformation of the raw RW data (Cook and Peters 1997); (3) RCS: single group regional curve standardization (RCS - Briffa et al., 1996; Esper et al., 2003; Briffa and Melvin 2008) detrending via division. For each of these three approaches, the 'Signal-Free' (SF - Melvin and Briffa 2008) approach to detrending was also utilized. These different options resulted in 6 different RW composite chronologies. For LWB and DB, as they theoretically should behave more like MXD, detrending was performed using only two methods; (1) LINres: negative or zero slope linear function detrending via subtraction; (2) RCSres: single group RCS detrending via subtraction. As with the RW data, the SF approach was also performed leading to four chronology variants for both LWB and DB.

3. Results and Discussion

3.1 Common signal within the network

RW has the strongest common signal with a median overall RBAR of 0.44 (8 site range: 0.33 – 0.49 - Table 1), whereas LWB and DB both have weaker RBAR values of 0.24. EWB shows the weakest common signal with a median RBAR from the 8 sites of only 0.12. In order of decreasing between-series common signal, the number of series needed to attain an EPS of 0.85 are 7 (RW), 18 (LWB and DB), and 41 (EWB) for each TR variable respectively. Rydval et al. (2014) showed that as the within tree common signal was much weaker for LWB than RW, the between tree common signal improved more for LWB than RW as multiple radii from the same tree were measured (i.e. up to 3). For this exploratory analysis, only a single series was measured per tree, and therefore we hypothesise that the EPS of BI based chronologies would improve markedly, compared to RW, if at least 2 radii were measured from each tree.

The weak signal strength in EWB compared to RW, LWB and DB is also reflected in the PCA. The leading PC for RW, LWB and DB explains 59%, 53% and 57% of the overall variance, respectively, while just 39% is explained by the EWB PC1. In general, the loadings (based on a varimax rotation) of the chronologies on each PC for each variable are related to the geographical locations across the GOA with PC1 representing the eastern sites and PC2 the western ones (Figures 1 and 2).

3.2 Seasonal temperature sensitivity

EWB contains a weak response to summer temperature variability with almost no late summer temperature signal (Figure 2) although significant correlations (r = ~0.3 - 0.4) are found with May and previous October/November temperatures (supplementary Figure 2). In agreement with previous work (Wilson et al. 2007; Wiles et al. 2014), RW correlates well with a broad range of summer seasons, showing positive correlations for nearly all months from January through to September (Supplementary Figure 2) with June returning the strongest correlation. LWB and DB, on the other hand, show weaker responses with the late winter/spring months and strongest correlations with June, July and August (Figure 2). As LWB and DB should express similar growth/climate response properties to MXD, these observations are not surprising.

There appears to be a geographical difference in response with PC1 (eastern sites) showing stronger seasonal (Figure 2) and monthly (supplementary Figure 2) correlations with temperature than PC2 (western sites). This spatial pattern of response is also expressed in the RW data (Figure 2). However, correlations of the individual site chronologies for each TR variable (Table 2) against June-September temperatures (optimal season for reconstruction – see later) suggest that there is a degree of variability of the individual sites' response to summer temperatures across the GOA. As PC2 is weighted more towards the TBB site (see PCA loadings in Figure 2 for RW, LWB and DB) which correlates weakly with JJAS, it is therefore not surprising that this PC correlates weakly with summer temperatures. However, the correlation results of the mean composite chronologies (Figure 2) are marginally stronger than the PC1 results. This suggests that a regional mean composite approach is potentially optimal in the context of deriving a GOA wide reconstruction which can be extended further back in time using data generated from sub-fossil samples.

The positive correlation of RW, LWB and DB to summer temperatures (Figure 2 and Table 2) is also reflected in the inter-correlation between these different variables (Table 3). RW agrees most strongly with DB, followed by LWB. EWB has the weakest relationship with the other 3 variables. Importantly, the correlation between EWB and LWB is weak which we hypothesise is the theoretical ideal for the utilization DB to minimize potential heartwood/sapwood colour change biases (Björklund et al. 2014, 2015). Hereafter, due to the poor signal strength and weak climate signal, the EWB data alone was not used for further analysis except in the DB calculations.

3.3 Calibration/validation experiments

Calibration and validation statistics for various PC regression variable combinations for several summer target seasons are detailed in Table 4 along with results using the GOA RW composite of Wiles et al. (2014). Firstly, calibration of Wiles et al. (2014) to the CRU TS 3.24 data (February – August) over the 1901-1989 period (r^2 = 0.33) is stronger than the new sample sub-set based RW GOA composite (r^2 = 0.27) which also shows a significant

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trend in the model residuals. This residual trend possibly reflects the fact that there could be a longer term low frequency trend missing in the RW data due to the use of 200-year spline detrended chronologies when compared to the RCS processed version of Wiles et al. (2014). Also, the slightly weaker results of the new RW data likely reflect generally lower replication in the current study compared to Wiles et al. (2014).

The strongest calibration $_ar^2$ values for each BI parameter over the 1901-1960 period are 0.49 and 0.47 for LWB and DB respectively for the JJA season although DB fails validation with negative RE and CE values over the 1961-1989 period. Minimal model improvement is gained by including RW data. RW+LWB calibrates best ($_ar^2$ = 0.49) with JJA while RW+DB explains more temperature variance for MJJAS ($_ar^2$ = 0.51). However, in both cases, validation RE and CE are negative. Focussing on the full period (1901-1989) calibration, strongest results are found for the JJAS season for all parameters options (except Feb-Aug for RW) with $_ar^2$ values of 0.27 (RW), 0.43 (LWB), 0.38 (DB), 0.38 (RW+LWB) and 0.39 (RW+DB) with no 1st order autocorrelation noted for any version. Only the RW+DB version, however, shows no significant linear trend in the model residuals. The full period (1901-1989) calibrated reconstructions (Table 4) for each of the variable options are presented in Figure 3 along with independent validation (1850-1900) with the BEST gridded data. All parameter iterations fail validation (negative CE values) except for RW+DB which returns positive RE (0.57) and CE (0.19) values. Overall, using this subset of samples from these 8 sites, the calibration results (Table 4 and Figure 3) indicate that BI based parameters explain more temperature variance than using RW alone. However, assessing the fidelity of the resultant reconstructions appears sensitive to the periods of calibration and validation used and as the chronologies were limited in the frequency domain by using a fixed 200-year spline detrending option, it is not clear which of these parameters best represent longer term secular change.

The large-scale climate signal expressed by these data is illustrated by comparing the RW+DB JJAS reconstruction with gridded land/sea HadCRUT4 (Morice et al. 2012; Cowtan and Way 2014 – Figure 4a) and land only CRU TS 3.24 (Harris et al. 2012 – Figure 4b) temperatures for the GOA and North Pacific sector. Although the spatial correlations are stronger towards Juneau and Sitka (see Figure 1 for locations) in the east of the region it is clear that these new data represent very well the temperature variability of the wider GOA region and North Pacific. Continued measurement of BI based parameters from sub-fossil samples taken from each end of the GOA will allow long term summer temperature variability to be derived for at least the last millennium which will complement the long RW based temperature reconstructions expressing a broader seasonal window (Wilson et al. 2007; Wiles et al. 2014).

3.4 Potential low frequency bias

The main potential limitation to the use of BI based TR variables such as LWB is concerned with low frequency trend biases related to wood colour change. Mountain hemlock, in general, shows darker heartwood and lighter sapwood, a colour change which resin extraction appears to only minimise but not entirely remove. Also, this colour change is not a sharp transition and is expressed in raw EWB and LWB measurements as a steady increase in reflectance intensity. Non-detrended mean composite chronologies of EWB and LWB for the whole GOA region (Figure 5) clearly show the impact of the heartwood/sapwood colour change with increasing intensity values through time (see also Supplementary Figure S3 for a single tree example), especially since the late 18th century. However, MXD generally shows a linear decreasing trend with increasing cambial age (Esper et al. 2012). If LWB is indeed a comparable (but inverted) TR variable to MXD as a measure of latewood anatomical density properties, then we would expect, therefore, an increasing trend in raw LWB values. Figure 5 therefore poses a potential "mixed-signal" conundrum as the observed trend in the GOA raw mean LWB composite will incorporate both the true age-related trend of changing latewood density and the heartwood/sapwood colour change bias. Although using DB can theoretically overcome these colour bias issues, it has not been explored in any detail beyond the original concept papers (Björklund et al. 2014, 2015). The mean DB non-detrended GOA chronology (Figure 5) expresses minimal long term trends which could suggest that the colour change bias has been removed or at least minimised.

Mean cambial age-aligned curves of the LWB and DB data show very distinct trends (Supplementary Figure 4). LWB appears to show a general linear increase in values – a trend that would be expected if LWB indeed does reflect similar wood properties (inversely) to MXD. DB, however, has a more complex mean growth curve and shows an initial increasing juvenile trend for ~50 years, a period of stabilisation and then a decreasing trend from about ~200 to 300 years. These different age-aligned curves highlight that different detrending options may well be needed for these different TR variables.

A range of credible methodological choice options for detrending the RW, LWB and DB GOA regional composite data are presented in Figure 6. The outcome for the RW data appears extremely consistent even when using STD vs RCS based methods. However, the LWB and DB chronologies are extremely sensitive to the detrending method used. Compared to RW and DB, all LWB chronology variants show above zero z-score values in the 17th century, which likely reflects the low reflectance bias of the darker heartwood compared to the sapwood because the LWB data have been inverted. The RCS versions appear particular inflated and as LWB is positively correlated with summer temperatures (Figure 2), this would result in markedly warm temperature estimates during the LIA compared to the 20th century which is at odds with previous GOA dendroclimatic analyses (Wiles et al. 2014) and the geomorphological record, which indicates substantial glacial advance from the 17th to 19th centuries (Wiles et al., 2004; Solomina et al. 2016). RCS can impart significant low frequency bias when the assumptions and requirements of the method are not met (Melvin and Briffa 2014; Anchukaitis et al. 2013) and as the GOA composite utilises only living trees this is a far from optimal sample design for this detrending method. For DB, the LINsf version deviates markedly from LINres, RCSres and RCSsf variants with very low values (< -6 standard deviation from 1901-1989 mean) before 1700 followed by a strong linear increase until present. A similar observation was noted in Wilson et al. (2014) where signal free detrending of LWB and especially MXD resulted in much cooler LIA conditions than other detrending approaches.

3.5 JJAS GOA summer temperatures back to 1600

The long GOA instrumental record allows for additional assessment of how different reflectance based chronology variants track temperatures back through time. Using the extended BI based regional composite records, further reconstruction experiments against the JJAS season were performed using LWB and DB separately by calibrating against JJAS CRU TS3.24 (1901-2010) and separately validating using the BEST data (1850-1900). For the LWB data, RCSres and RCSsf calibrated poorly (Table 5: r^2 = 0.07 and 0.05 respectively) with negative CE values over the 1850-1900 period. The LINres and LINsf version, however, explained 41% of the temperature variance and validated reasonably well with positive RE and CE values. Significant 1st-order autocorrelation (DW range 1.28 to 1.37) and linear trends (LINr range 0.36 to 0.48) was however noted for all model residuals. The DB chronology variants on the whole performed better than their LWB counterparts, with RCSsf (RCSres) calibrating most strongly (r^2 = 0.43 (0.40)) and validating well (RE = 0.48 (0.50), CE = 0.15 (0.18)). The residuals for both versions show no 1st-order autocorrelation although a significant linear trend is still however observed.

The best reconstructions using LWB (LINres) and DB (RCSsf), identified using the calibration and verification results (Table 5), represent quite different histories of past GOA temperatures (Figure 7). Specifically, the LWB (LINres) reconstruction expresses temperature estimates from the late 17th to mid-19th century warmer than the 1961-1990 mean, while the DB (RCSsf) reconstruction exhibits generally cooler conditions. Both reconstructions explain a similar amount of summer temperature variance and validate well (Table 5) and from comparison to the instrumental data alone, one cannot objectively choose which of the two is most robust although there are arguably less problems with the model residuals using the DB data. Wilson et al. (2014) highlighted the difficulties of relying solely on the instrumental data to validate the long-term trend in any reconstruction. Moreover, there could be unknown homogeneity issues in early instrumental data series which are difficult to identify which would impact calibration and validation (see Frank et al. 2007b). Therefore, alternative sources of relevant information are needed for further validation. As the geomorphological record in the region suggests a prolonged period of glacial advance occurred in the GOA up to the early 20th century (Wiles et al., 2004; Solomina et al. 2016) when a substantial retreat started, we hypothesize that the pre-1900 period must therefore have been cooler. This would suggest that the DB based reconstruction is likely more representative of past GOA temperatures than the LWB driven one.

Figure 8 presents the RW + DB principal component reconstruction (Figure 3), the DB (RCSsf) extended reconstruction (Figure 6) and the Wiles et al. (2014) RW based reconstruction and compares them to the GOA regional glacial advance record (Wiles et al., 2004; Solomina et al. 2016). The TR reconstructions demonstrate centennial and multi-decadal agreement, although the extended DB reconstruction has a smaller amplitude of temperature change between the LIA period and the 20th century. Overall, temperatures in the GOA region were below the 1961-90 norm throughout most of the LIA with temperatures only rising to substantially higher values in the early 20th century. The coldest decadal periods are centred around the 1700s, 1750s, and 1810s. The glacial advance record clearly shows periods of advance through the LIA, peaking at the end of the 19th century. Despite the use of 200-year spline detrended chronologies, the RW+DB reconstruction has a similar amplitude change to the

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Wiles et al. (2014) record, which was derived from RCS processed RW data. It should however be noted also that this RW based reconstruction was calibrated against Feb-August temperatures which has a greater increasing temperature trend (0.81ºC/century vs 0.62ºC/century) and higher variance (0.79 vs 0.41) than JJAS (calculated using BEST data from 1850-2015), which will influence the amplitude of the reconstructions (Esper et al. 2005).

4. Conclusions

We have described a set of experimental temperature reconstructions based on RW, LWB and DB data measured from eight tree-ring sites along the Gulf of Alaska. Focusing on these data sets, the results demonstrate that inclusion of BI based variables can significantly improve the calibrated variance explained using RW alone by more than 10%.

RW, LWB and DB are strongly correlated with each other (Table 3) but the inclusion of LWB or DB shifts the calibrated signal from a broad (February-August, Wiles et al. 2014) season using RW alone to a late summer (JJAS) season. The influence of late winter and early spring temperatures on RW suggest that this variable may, in fact, still be the more optimal variable for studying important synoptic phenomena such as north Pacific variability, which dominates in the winter/spring months (Wilson et al. 2007).

The LWB data, for mountain hemlock, despite calibrating and validating in a similar way to DB, are clearly affected by heartwood/sapwood colour differences which impart a trend bias in the resultant chronologies and reconstructions (Figure 6 and 7). However, this bias may not necessarily always occur for other species showing a heartwood/sapwood colour change which could be removed through traditional resin extraction methods. For the first time since the original concept papers by Björklund et al. (2014, 2015), we have experimented with the DB variable and the resulting reconstruction agrees well with a previous RW based reconstruction (Wiles et al. 2014) and the glacial advance record (Wiles et al., 2004; Solomina et al. 2016) for the region.

The analyses presented herein must be viewed as a series of experiments to inform future dendroclimatologists of possible methodological strategies that need to be considered for improving TR based reconstructions using blue reflectance based variables. Specific to the GOA region, but likely relevant to other regions and species, we therefore detail the following recommendations:

- Although MXD typically has a higher expressed signal strength and climate responses than RW (Wilson and Luckman 2003), signal strength in LWB and DB in GOA hemlock is weaker than RW, so replication needs to be substantially increased (ideally > 20 trees – Table 1) to allow the development of robust chronologies. Rydval et al. (2014) also showed that substantial improvement in LWB signal strength could be gained by measuring 2 or even 3 radii per tree. Additional assessments of signal strength should be conducted as new species and sites are analysed using BI methods.
- For conifer species with a clear colour difference between the heartwood and sapwood, LWB may likely always express biased long-term trends. The DB variable could potentially minimize this effect as shown

here, but more experimentation with this parameter is needed before it can be commonly used as a solution to the LWB colour bias problem. Rydval et al. (2017) overcame the heartwood/sapwood colour bias by utilising a band-pass approach to calibration, where LWB drove the decadal and high frequency fraction of the Scottish temperature reconstruction, while RW drove the low frequency variability. This approach however assumes that (1) RW is predominantly controlled by summer temperatures (not necessarily the case in the GOA) and (2) meaningful longer-term secular information can be gleaned from RW data, which may not always be the case (Esper et al. 2012).

- The results presented herein highlighted substantial sensitivity of the final chronologies to varying methodological detrending approaches. Much more exploration of the impact of different detrending choices is needed for dendroclimatology as a whole. Locations with long instrumental records may help identify more optimal detrending options but care is needed, as it cannot be assumed that the quality of 19th century data is comparable to late 20th/early 21st century data. Utilizing other proxy observations of past climate (e.g. in this case the glacial record) may help further constrain TR estimates of past climate especially when different chronology variants (that validate well) portray quite different past temperature histories.

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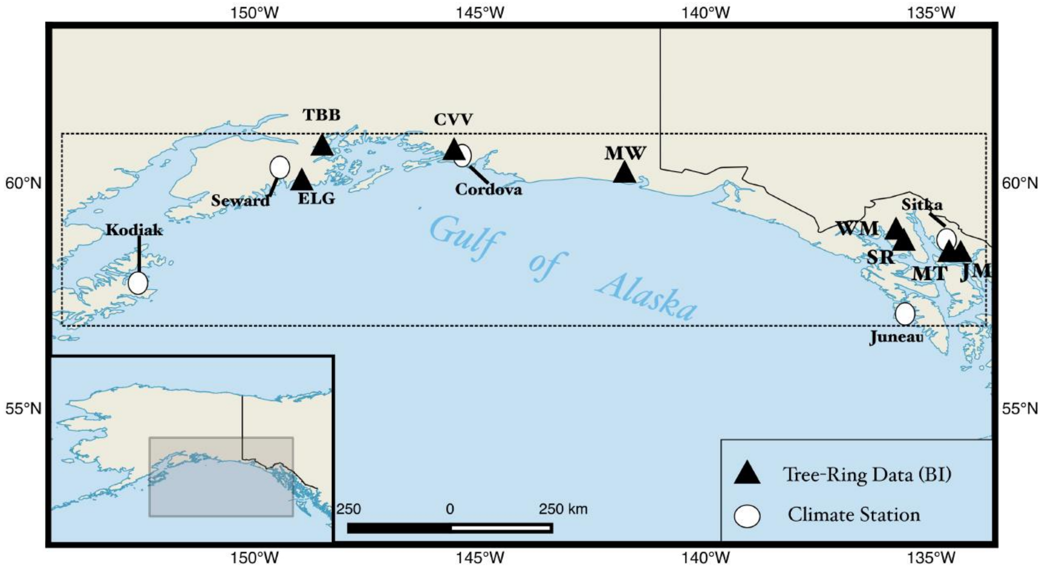

Figure 1: Location map of the eight GOA tree-ring sites used in this study (Table 1). Also indicated (dashed line box) is the domain (57-61°N / 153-134°W) of the gridded data (CRU TS 3.24, Harris et al. 2012; BEST, Rohde et al., 2012) used for calibration and the five coastal GOA temperature stations used in the original 5-station mean series (Wilson et al. 2007 – see supplementary Figure 1).

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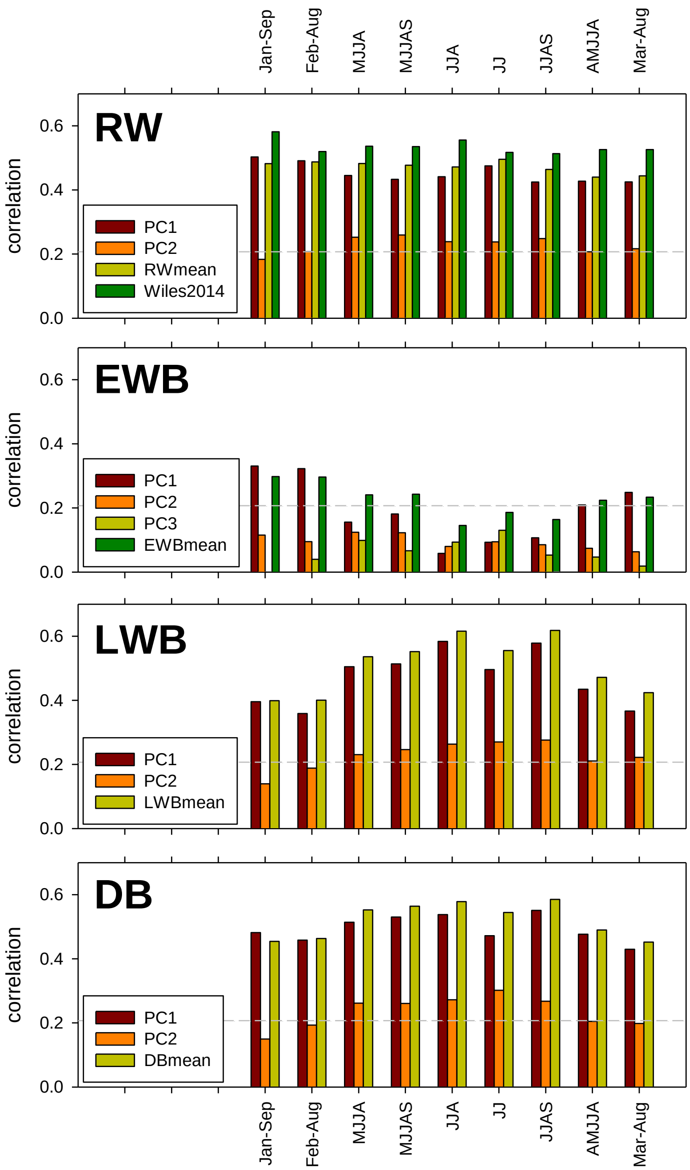

	PC1 (59.2%)	PC2 (17.2%)
WMrw	**0.90**	0.24
JMrw	**0.87**	0.08
SRrw	**0.84**	0.13
MWrw	**0.76**	0.33
MTrw	**0.75**	0.30
TBBrw	-0.03	**0.91**
ELGrw	0.36	**0.76**
CVVrw	0.47	**0.76**

	PC1 (38.5%)	PC2 (17.1%)	PC3 (13.0%)
JMewb	**0.85**	0.12	-0.14
MTewb	**0.84**	0.16	0.09
WMewb	**0.68**	0.24	0.17
TBBewb	0.17	**0.82**	-0.10
ELGewb	0.06	**0.75**	0.26
CVVewb	0.33	**0.55**	0.37
MWewb	-0.07	0.25	**0.84**
SRewb	0.60	-0.15	**0.62**

	PC1 (52.7%)	PC2 (17.2%)
JMlwb	**0.88**	0.11
WMlwb	**0.85**	0.23
SRlwb	**0.80**	0.16
MTlwb	**0.77**	0.23
MWlwb	**0.56**	0.46
TBBlwb	0.05	**0.85**
CVVlwb	0.35	**0.81**
ELGlwb	0.22	**0.80**

	PC1 (56.7%)	PC2 (15.6%)
WMdb	**0.85**	0.17
SRdb	**0.85**	0.06
JMdb	**0.81**	0.25
MTdb	**0.75**	0.37
MWdb	**0.71**	0.35
TBBdb	0.00	**0.90**
ELGdb	0.38	**0.75**
CVVdb	0.43	**0.75**

Figure 2: Left: Correlation response function analysis (1901-1989) using CRU TS3.24 mean temperatures with each tree-ring variable (RW = ring-width; EWB = early wood maximum blue intensity; LWB = inverted latewood minimum blue intensity; DB – Delta Blue). The bars represent correlations with seasonal temperature for each principal component (PC) score and the simple GOA mean composite. Also for RW, correlations are shown for the Wiles et al. (2014) RW based RCS reconstruction. Horizontal line denotes the 95% confidence limit. Correlations against individual months are presented in Supplementary Figure 2. **Right:** Varimax rotation principal component analysis results showing loadings of each chronology on each PC with an eigenvalue > 1.0. % values denote the explained amount of variance each PC explains of the original data input matrix.

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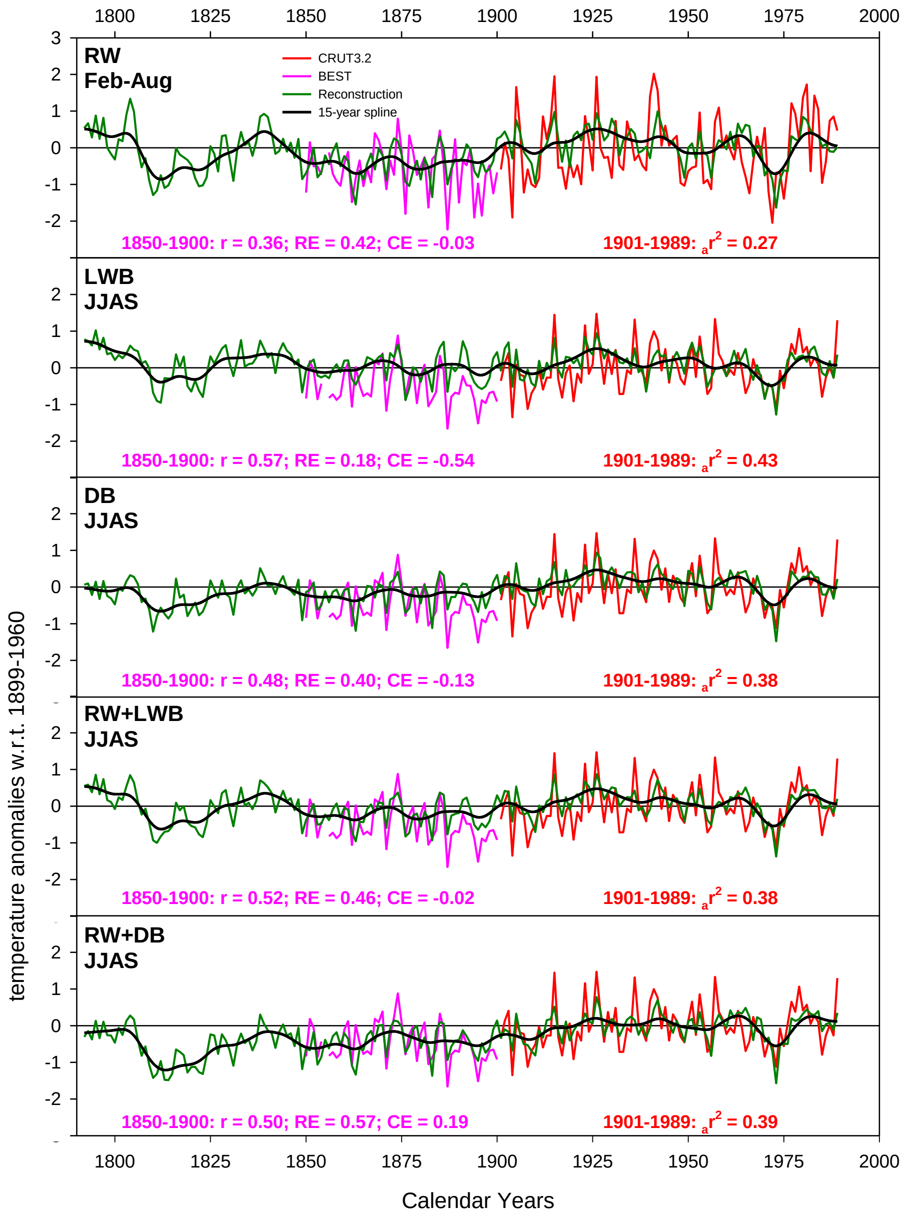

Figure 3: Illustration of the various PC regression experiments performed herein, with each reconstruction model compared against the June-September (Table 3). Feb-August is shown for RW as that was the reconstructed season in Wiles et al. (2014). Full period calibration is performed on the 1901-1989 period (Table 3 – CRU TS 3.24) while validation (Pearson's correlation coefficient (r), Reduction of Error (RE) and

Coefficient of Efficiency (CE)) is undertaken over 1850-1900 using the BEST gridded data after those data were scaled to the CRU TS 3.24 data over the 1901-1989 period.

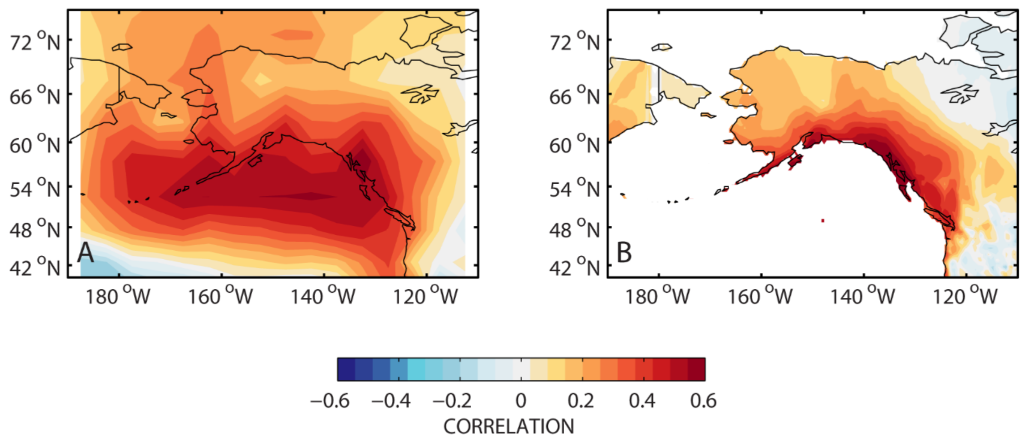

Figure 4: Spatial correlation (1901-1989) fields comparing the RW+DB GOA JJAS temperature reconstruction with larger-scale temperatures. **A:** for HADCRUT4 land/SST (Morice et al. 2012; Cowtan and Way 2014); **B:** for CRU TS3.24 land temperatures (Harris et al. 2012).

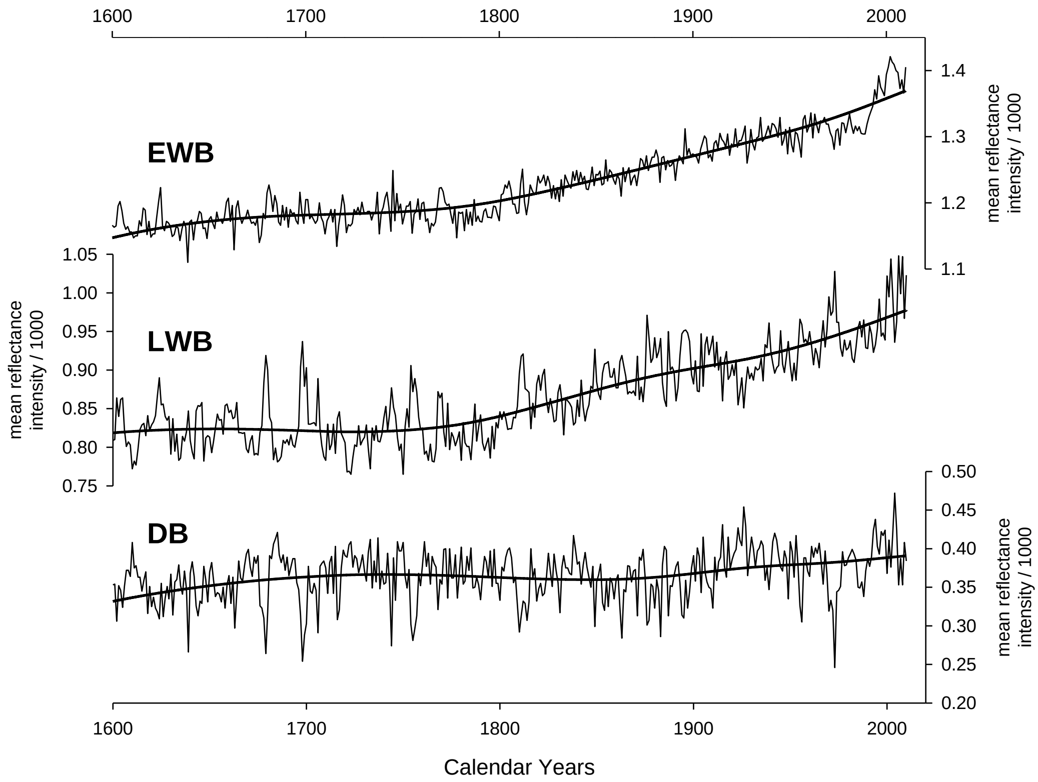

Figure 5: Mean non-detrended GOA wide composite chronologies since 1600 for EWB, LWB and DB. The LWB data have not been inverted for this figure.

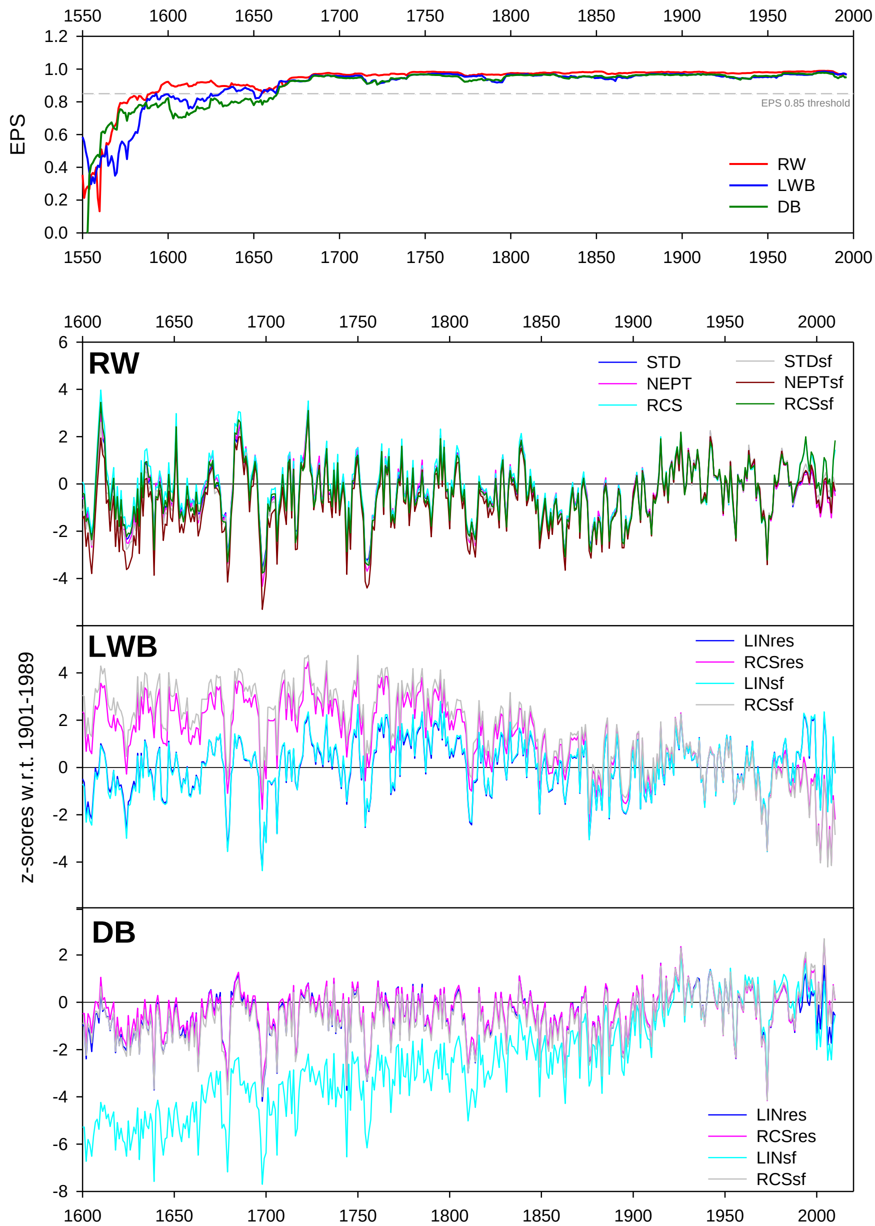

Figure 6: Detrending experiments for each TR variable using the full GOA regional composite (data from all 8 sites). Upper panel is 31-year moving EPS plots for RW, LWB and DB using 200-yr spline detrending. Low plots present chronology variants from 1600-2010. For RW - STD = negative exponential detrending (ratio) or regression function of zero or negative slope; NEPT = as STD but raw data have been power transformed and detrended via subtraction; RCS = single group RCS detrending (ratio); STDsf, NEPTsf, RCSsf = as previous three options but using signal free detrending. For LWB and DB – LINres – detrending via subtraction using

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linear functions (negative or zero slope); RCSres = as RCS above but detrending via subtraction; LINsf and RCSsf = as with LINres and RCSres but with signal free detrending.

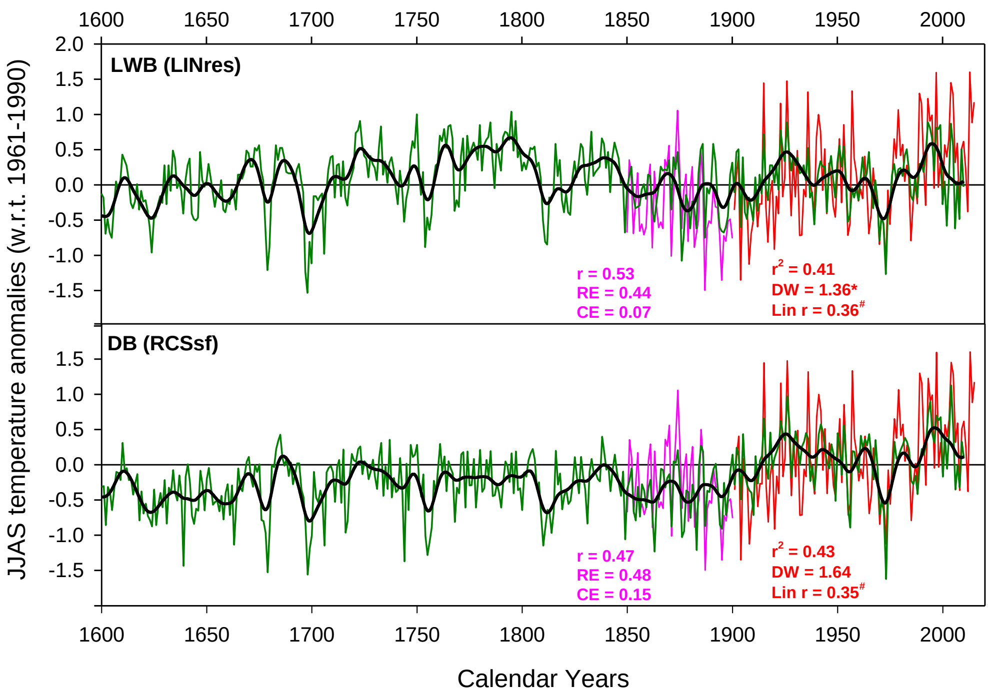

Figure 7: Extended reconstruction tests using LWB and DB. 1901-2010 period calibration uses CRU TS3.24 data while validation is performed using BEST data over the 1850-1900 period. * denotes significant 1st order autocorrelation in model residuals; # denotes a significant linear trend in the model residuals.

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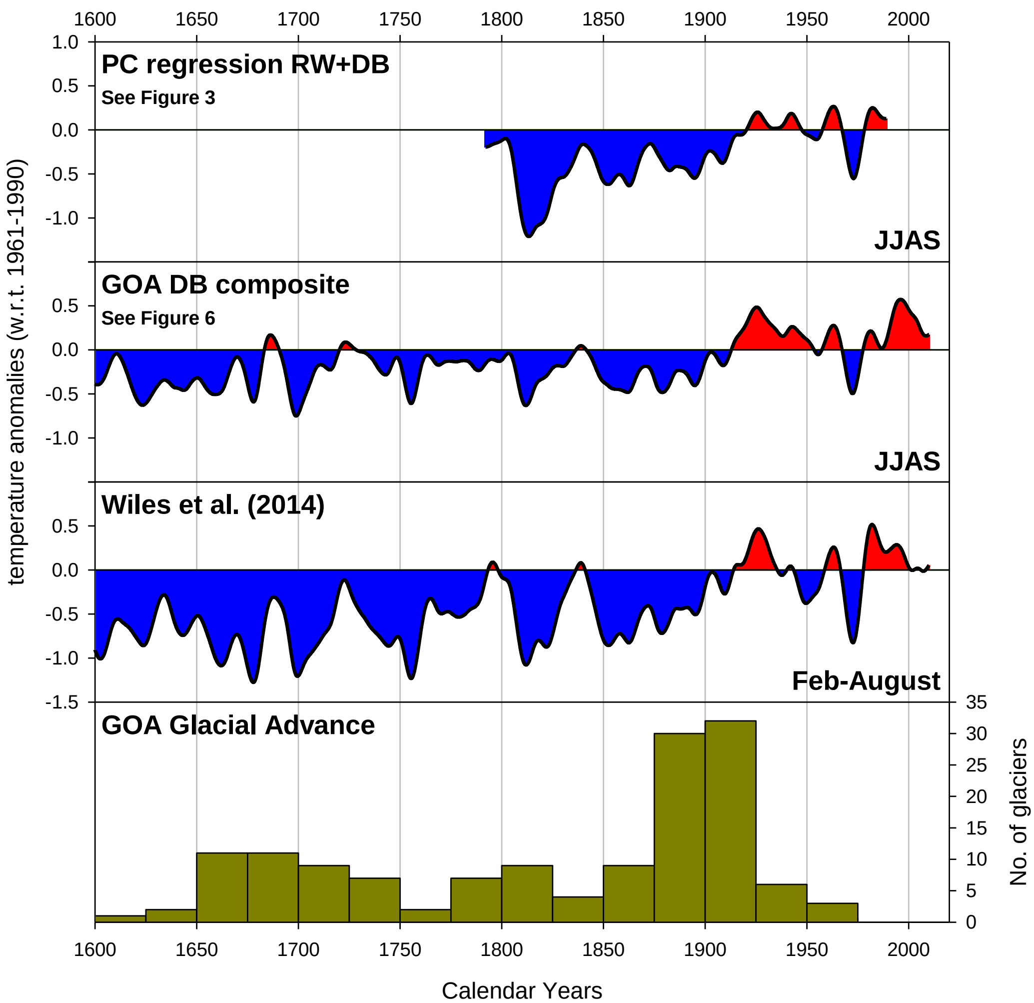

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611 **Figure 8:** Comparison of GOA reconstruction variants using DB and RW with Wiles et al. (2014). The lower
612 panel presents a histogram of glacial advance in the GOA region (Wiles et al., 2004; Solomina et al. 2016).

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Site Name	Timespan	No. of series	Period n > 5	MSL	RW RBAR	EWB RBAR	LWB RBAR	DB RBAR	N-RW EPS	N-EWB EPS	N-LWB EPS	N-DB EPS
Cordova Eyak Mtn (CVV)	1573-1992	17	1672-1992	280.6	0.46	0.15	0.32	0.29	6.5	32.1	12.0	14.2
Juneau Mtn (JM)	1558-1998	17	1604-1998	238.5	0.35	0.15	0.24	0.25	10.7	32.9	17.7	17.3
McGinnis (MT)	1485-1999	15	1584-1999	363.5	0.47	0.11	0.24	0.24	6.4	46.3	17.6	18.0
Miners Well (MW)	1479-1994	13	1640-1995	324.0	0.49	0.05	0.33	0.14	5.8	120.3	11.8	36.2
Son of Repeater (SR)	1713-2009	10	1792-2007	216.7	0.33	0.12	0.17	0.25	11.3	43.5	27.5	17.4
Wright Mtn (WM)	1610-2010	17	1738-2010	234.2	0.45	0.06	0.25	0.17	6.9	84.0	17.1	27.9
Ellsworth (ELG)	1636-1991	18	1750-1990	218.5	0.40	0.14	0.24	0.29	8.6	35.7	17.7	14.2
Tebenkof (TBB)	1357-1990	15	1605-1990	339.2	0.43	0.13	0.20	0.22	7.6	37.9	22.4	19.6
			median	259.6	0.44	0.12	0.24	0.24	7.2	40.7	17.6	17.7

Table 1: Metadata information for the eight GOA sites used in the study. All PCA and related analyses were performed on the 1792-1990 period for which there is replication for all eight sites of at least five series. Tree-ring data were detrended using a 200-year spline for these signal strength analyses. The final 4 columns denote the number of series needed to attain an EPS of 0.85 (Wigley et al. 1984).

RW								
	JM	**MT**	**SR**	**WM**	**MW**	**CVV**	**TBB**	**ELG**
1850-1900	0.45	0.22	0.49	0.22	0.27	0.30	0.30	0.38
1901-1990	0.49	0.26	0.42	0.41	0.36	0.41	0.20	0.34
1850-1990	0.50	0.37	0.47	0.43	0.39	0.47	0.33	0.39
LWB								
	JM	**MT**	**SR**	**WM**	**MW**	**CVV**	**TBB**	**ELG**
1850-1900	0.45	0.29	0.48	0.38	0.49	0.40	0.25	0.46
1901-1990	0.52	0.39	0.64	0.58	0.46	0.45	0.28	0.41
1850-1990	0.37	0.32	0.55	0.46	0.53	0.51	0.33	0.44
DB								
	JM	**MT**	**SR**	**WM**	**MW**	**CVV**	**TBB**	**ELG**
1850-1900	0.45	0.29	0.49	0.23	0.35	0.40	0.37	0.48
1901-1990	0.57	0.45	0.58	0.47	0.48	0.50	0.23	0.39
1850-1990	0.53	0.44	0.48	0.38	0.44	0.52	0.34	0.44

Table 2: Correlations (1850-1900, 1901-1990 and 1850-1990) for each site RW, LWB and DB chronology against JJAS temperatures. EWB correlations are not shown. The sites are ordered from east to west (see Figure 1).

mean r	**EWB**	**LWB**	**DB**
RW	0.27	0.68	0.81
EWB		-0.23	0.36
LWB			0.80

Table 3: Correlation matrix between the different tree-ring variable chronologies (200-year spline detrended. These values represent the averages for between TR variable correlations performed separately for each site.

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			1901-1960 Calibration		1961-1989 Validation			1901-1989 Full Calibration + Residuals			
Wiles14	**season**	**series entered**	**r**	**r2**	**r**	**RE**	**CE**	**r**	**r2**	**DW**	**Linr**
	MJJA	Wiles2014	0.60	0.36	0.48	0.11	0.10	0.55	0.30	1.62	0.15
	MJJAS	Wiles2014	0.55	0.30	0.53	0.21	0.20	0.53	0.28	1.72	0.17
	JJA	Wiles2014	0.58	0.34	0.47	0.06	0.05	0.53	0.28	1.75	0.17
	JJAS	Wiles2014	0.52	0.27	0.53	0.20	0.20	0.51	0.26	1.77	0.18
	Feb-Aug	Wiles2014	0.60	0.36	0.54	0.23	0.23	0.57	0.33	1.78	0.17
RW	**season**	**PCs entered**	**r**	**ar2**	**r**	**RE**	**CE**	**r**	**ar2**	**DW**	**Linr**
	MJJA	1, 2	0.60	0.34	0.40	0.03	0.03	0.52	0.26	1.60	0.21
	MJJAS	1, 2	0.56	0.29	0.46	0.15	0.14	0.52	0.25	1.70	0.23
	JJA	1, 2	0.58	0.31	0.42	-0.01	-0.02	0.51	0.24	1.74	0.23
	JJAS	2, 1	0.53	0.26	0.49	0.16	0.15	0.51	0.24	1.76	0.24
	Feb-Aug	2, 1	0.60	0.36	0.46	0.08	0.08	0.54	0.27	1.75	0.23
LWB	**season**	**PCs entered**	**r**	**ar2**	**r**	**RE**	**CE**	**r**	**ar2**	**DW**	**Linr**
	MJJA	1, 2	0.63	0.38	0.49	0.15	0.14	0.57	0.31	1.39	0.20
	MJJAS	1, 2	0.63	0.37	0.55	0.23	0.22	0.59	0.34	1.50	0.23
	JJA	1, 2	0.71	0.49	0.58	0.16	0.15	0.66	0.42	1.45	0.25
	JJAS	1, 2	0.69	0.46	0.64	0.27	0.27	0.66	0.43	1.51	0.27
DB	**season**	**PCs entered**	**r**	**ar2**	**r**	**RE**	**CE**	**r**	**ar2**	**DW**	**Linr**
	MJJA	1, 2	0.69	0.45	0.43	-0.01	-0.02	0.59	0.33	1.55	0.24
	MJJAS	1, 2	0.67	0.43	0.50	0.09	0.08	0.61	0.37	1.68	0.26
	JJA	1, 2	0.70	0.47	0.50	-0.05	-0.05	0.62	0.36	1.65	0.26
	JJAS	1, 2	0.68	0.44	0.58	0.11	0.11	0.63	0.38	1.72	0.29
RW + LWB	**season**	**PCs entered**	**r**	**ar2**	**r**	**RE**	**CE**	**r**	**ar2**	**DW**	**Linr**
	MJJA	1, 2	0.69	0.45	0.46	0.03	0.03	0.60	0.34	1.67	0.18
	MJJAS	1, 2	0.66	0.43	0.51	0.13	0.12	0.62	0.37	1.87	0.20
	JJA	1, 2, 3	0.72	0.49	0.52	-0.07	-0.08	0.63	0.37	1.56	0.26
	JJAS	1, 2, 3	0.68	0.43	0.59	0.12	0.12	0.63	0.38	1.63	0.28
RW + DB	**season**	**PCs entered**	**r**	**ar2**	**r**	**RE**	**CE**	**r**	**ar2**	**DW**	**Linr**
	MJJA	1, 2	0.71	0.49	0.44	-0.16	-0.16	0.62	0.36	1.69	0.04
	MJJAS	1, 2	0.72	0.51	0.49	-0.14	-0.15	0.61	0.36	1.78	-0.11
	JJA	1, 2, 3	0.72	0.50	0.49	-0.15	-0.15	0.56	0.32	1.89	-0.12
	JJAS	1, 2	0.71	0.49	0.52	-0.18	-0.18	0.64	0.39	1.84	0.05

Table 4: Calibration experiments for four dominant seasons (see Figure 2). Initial calibration (using CRU TS 3.24) was made over 1901-1960 and validation over 1961-1989. Full calibration (1901-1989) was also performed to allow for residual tests and extra validation using BEST (1850-1990 – see Figure 2). Shaded results do not pass significance. r = Pearson's correlation coefficient; r2 = coefficient of determination; ar2 = r2 adjusted for the number of predictors in the model; RE = Reduction of Error; CE = Coefficient of Efficiency; DW = Durbin-Watson test for residual autocorrelation; LINr = linear trend of the residuals.

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	1901-2010 Calibration					1850-1900 Validation		
	series entered	**r**	**r2**	**DW**	**LINr**	**r**	**RE**	**CE**
LWB	LINres	0.64	0.41	1.36	0.36	0.53	0.44	0.07
	RCSres	0.26	0.07	1.28	0.48	0.56	0.01	-0.64
	LINsf	0.64	0.41	1.37	0.36	0.53	0.43	0.06
	RCSsf	0.21	0.05	1.32	0.46	0.56	-0.05	-0.73

	1901-2010 Calibration					1850-1900 Validation		
	series entered	**r**	**r2**	**DW**	**LINr**	**r**	**RE**	**CE**
DB	LINres	0.55	0.31	1.37	0.50	0.50	0.52	0.21
	RCSres	0.64	0.40	1.59	0.40	0.48	0.50	0.18
	LINSF	0.54	0.29	1.35	0.38	0.43	0.40	0.00
	RCSsf	0.65	0.43	1.64	0.35	0.47	0.48	0.15

Table 5: Extended reconstruction Calibration experiments using different chronology versions (Figure 6) of LWB and DB. Shaded results do not pass significance.