ENSO history recorded in *Agathis australis* (kauri) tree rings. Part B: 423 years of ENSO robustness

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ABSTRACT: Part A of this study identified the potential of kauri tree rings for reconstructing the history of past ENSO activity. Plausible indices of multidecadal to centennial-scale ENSO activity (phase dominance and robustness) that could be derived from kauri regional master chronologies are hypothesized here, and they are tested against the instrumental SOI record, using partitioning and graphical analyses. The subset of the indices passing this first screening are then tested for sensitivity to the complex evolving sample depth and site-composition mix that characterizes regional tree-ring chronologies. Corrections for evolving sample depth are developed where possible. The two indices of ENSO activity remaining after these two screening phases (evolving chronology time-series variance and decadal-scale spectral signature) are used to infer 423 years of ENSO robustness and the results are compared to two multiproxy ENSO reconstructions. Results suggest that ENSO robustness (1) peaked in the 20th century, (2) is characterized by persistent 55–80 year cyclicity, (3) was low in the mid-20th century only relative to robust ENSO activity at the beginning and end of that century, (4) reached a pre-20th century peak in the mid-18th century, and (5) was weakest near the beginning of the 19th century. Copyright © 2007 Royal Meteorological Society

KEYWORDS: El Niño-Southern Oscillation; ENSO; tree rings; kauri; *Agathis australis*; New Zealand; palaeoclimatology; dendroclimatology

1. Introduction

Kauri (*Agathis australis* (D. Don) Lindley) is a long-lived conifer endemic to New Zealand. Because of its longevity, its strategic location in the data-deficient southern hemisphere, and its abundant availability as source material (living trees, logging relics, colonial-era buildings, subfossil wood preserved in swamps), kauri has considerable potential for palaeoclimate applications. All four sources of material have been successfully exploited and an extensive kauri tree-ring database is now available for palaeoclimate research. This includes 17 modern tree-ring chronology sites, summarized in Fowler et al. (2004) and in Part A of this study (Fowler et al., 2007), and a composite 3722 year chronology (Boswijk et al., 2006). Recent work has advanced the understanding of kauri’s seasonal growth characteristics (Fowler et al., 2005) and of its growth relationships to climate (Fowler et al., 2000, 2005).

Kauri’s potential as a proxy for El Niño-Southern Oscillation (ENSO) was first recognized by Fowler et al. (2000). Part A of this research represents the current state of understanding of the relationship between ENSO and kauri tree rings, based on the analysis of 17 modern kauri site chronologies and two regional master chronologies for the period of instrumental records. Key findings are listed below.

(1) There is a significant regional-scale forcing signal in the width of kauri tree rings.
(2) ENSO is a significant contributor to that forcing.
(3) ENSO’s influence on kauri growth is predominantly via the western pole of the Southern Oscillation.
(4) Wide (narrow) kauri tree rings tend to be associated with El Niño (La Niña) events, with similar event registration strength.
(5) Strongest statistical relationships are for a five-season window from March, prior to growth initiation (in September), through to the following May.
(6) Growing season relationships are stronger when ENSO is most active, but otherwise appear to be stationary at the multidecadal scale.
(7) About half of the El Niño (La Niña) events are associated with wide (narrow) kauri tree rings, with few opposite associations.
(8) Kauri appears to carry a multidecadal signal of the evolving strength of ENSO activity (robustness).
(9) Kauri may carry a multidecadal signal of the evolving relative frequency of El Niño and La Niña events (phase dominance).

This paper explores kauri’s potential for reconstructing ENSO robustness and phase dominance and presents a 423-year interpretation of ENSO activity. How ENSO robustness and phase dominance are likely to be registered in kauri tree rings is hypothesized, based on the results of Part A, and several time-evolving indices are interpreted (Section 3). The indices are tested against the...
corresponding instrumental measures derived from the Southern Oscillation Index (SOI) (Section 4). Indices that do not adequately mirror observed ENSO activity in the instrumental record are eliminated. Index sensitivity to the complex evolving sample depth characteristic of kauri regional tree-ring chronologies is then tested and corrections derived where necessary and possible (Section 5). Surviving indices are used to infer ENSO activity for the period 1580–2002 (Section 6). This kauri-based interpretation is compared with other proxy reconstructions and a synthesis assessment of multidecadal ENSO activity is deduced and interpreted.

2. Data

The kauri tree-ring data set used here is identical to that used in Part A. It consists of standardized time series for several hundred cores taken from over 200 trees at 17 sites. The standardized core series were averaged to produce tree chronologies, which in turn were averaged to produce site chronologies. A regional master chronology was built by averaging all the tree chronologies, except those from one anomalous high altitude site. Chronology building used a standardization with 50% frequency response at 200 years and the analysis was restricted to the ‘high-quality’ period 1580–2002. See Part A for site, standardization, and quality assessment details. For consistency with Part A, ‘K200’ is used to refer to the master chronology (officially AGAUm05b).

Monthly values of the SOI (1876–2002) were obtained from the Australian Bureau of Meteorology. These are the standardized departures (1933–1992 base period) of the difference in the mean sea-level pressure between Tahiti and Darwin.

3. Hypothesized Relationships and Potential Indices

During the years when the SOI is near-neutral, most kauri site chronologies have near-normal tree-ring indices. A tendency towards either slightly wider or narrower rings is common (suggestive of regional-scale forcing independent of ENSO), but few, if any, sites have notably wide or narrow rings, and some usually display an opposite tendency. In contrast, a stronger and more consistent growth response is typical during ENSO-event years. Wide or narrow rings are more common and it is unusual for sites to have an opposite growth response. This is the pervasive regional-scale ENSO forcing of kauri growth, as previously noted. Assuming that this forcing is dominant, and that ENSO teleconnection to the New Zealand region is stationary, it follows that any significant changes in either ENSO phase dominance or ENSO robustness should have a discernible impact on kauri tree rings. If the relevant signal can be isolated, then it should be possible to reconstruct the time-evolving character of ENSO from kauri tree rings. Potential indices of ENSO activity that might be derived from kauri tree rings are presented in Table I, with the associated rationale.

The temporally evolving mean of a kauri master chronology is probably the most obvious index of ENSO phase dominance. Provided that standardization retains decadal-scale variance in the kauri chronology, multidecadal deviations in average tree-ring indices may represent associated changes in the relative frequency of El Niño and La Niña events. However, because the ENSO signal in kauri is so strongly related to ENSO-event years (Part A), a more sensitive index may be the relative frequency of wide and narrow rings. A measure of relative frequency (e.g. frequency count difference) is necessary because simple counts of wide and narrow rings are also likely to be affected by ENSO robustness (see below).

The first three robustness indices are based on the premise that fluctuations in ENSO robustness will

| Table I. Potential kauri-based indices of evolving decadal-scale ENSO activity. |
|-----------------------|------------------|
| Index                 | Rationale         |
| **Phase-dominance indices** |                  |
| 1. Mean               | Multidecadal periods dominated by El Niño (La Niña) |
| 2. Relative frequency of wide and narrow tree rings (wide minus narrow) | Preponderance of wide (narrow) tree rings |
| **Robustness indices** |                  |
| 3. Combined frequency of wide and narrow tree rings | Robust ENSO |
| 4. Variance           | More and/or larger ENSO events |
|                       | Higher frequency and/or magnitude of wide and narrow tree rings |
|                       | Higher chronology variance |
| 5. Spectral signature | Robust ENSO |
|                       | Stronger ENSO signal in kauri chronologies |
|                       | Stronger ENSO-like spectral signature |
| 6. Inter-site correlation | Robust ENSO |
|                       | More consistent growth response across sites |
|                       | Stronger inter-site correlations |

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have corresponding impacts on ENSO-sensitive proxies. Because kauri is sensitive to both ENSO phases, more frequent and/or larger ENSO events should increase the combined frequency of wide and narrow rings (Index 3) and thus amplify chronology variance (Index 4). The associated strengthening of the ENSO signal in kauri chronologies would also amplify the ENSO component of kauri’s spectral signal (Index 5). Moreover, an increase in ENSO robustness may amplify the common signal across kauri’s growth range, resulting in stronger inter-site correlations (Index 6).

4. Testing Indices against the Instrumental Record

The merits of five of the six proposed kauri-based indices (spectral signature excluded) of ENSO activity were assessed using two approaches. The first involved partitioning the kauri time series data for the period 1876–2002 into composite subsets, based on July–June SOI quintiles. The rationale is if the proposed indices have merit for assessing time-evolving ENSO phase dominance and robustness, a comparable pattern should emerge across the quintile composites. For example, if decadal-scale mean tree-ring indices are interpretable in terms of ENSO phase dominance, it follows that the mean tree-ring index should be highest for the El Niño composite (Q1) and lowest for the La Niña composite (Q5). The second approach is direct graphical comparison of the evolving characteristics of SOI and kauri time series, using a moving 31-year window. The premise is that good agreement with the instrumental record is a prerequisite for accepting any kauri-based index of ENSO that is sensitive to both ENSO phase dominance and robustness, and is therefore ambiguous, although it may still have value as a generic index of ENSO activity.

The partitioning analysis results indicate that both the proposed ENSO phase-dominance statistics have potential. As hypothesized, mean tree-ring indices (#1) are notably higher (lower) for the El Niño (La Niña) composites (Q1, Q5) and the number of wide minus the number of narrow tree rings (#2) differs as expected. The lack of sensitivity of both statistics across Q2 to Q4 is consistent with the previous findings (Part A) that kauri sensitivity to ENSO is primarily event based. Larger changes for Q1 than Q5 suggests a small El Niño bias.

Results for the proposed robustness indices are mixed. The relative frequency of wide plus narrow rings (#3) is sensitive to ENSO activity, but systematic variability across the SOI Q1 to Q5 range indicates that the sensitivity is as likely to relate to ENSO phase dominance as it is to ENSO robustness. This is because the increase in the number of wide (narrow) tree rings in the case of the El Niño (La Niña) composites is greater than the decline in narrow (wide) rings. The index is therefore ambiguous. In contrast, the standard deviation (STD, #4) results show sensitivity to robustness (Q2,3,4 STD < Q1,5 STD) but insensitivity across Q1 to Q5. Mean inter-site correlation (#6) is also sensitive to robustness (Q2,3,4 R < Q1,5 R), with highly variable, nonsystematic, changes across Q1 to Q5. The fact that Q1 and Q5 correlations are not the highest of the five partitions suggests that, although ENSO events affect the mean and the frequency

Table II. Partitioning analysis results (1876–2002). Statistics are for K200, except for the inter-site mean correlation (R), which was derived from site chronologies. ‘Narrow’ and ‘wide’ rings are defined as those in the upper and lower quintiles of K200. ‘Q1’ through ‘Q5’ are composite partitions of K200, based on mean July–June SOI quintiles (see text for explanation). ‘Q1,5’ and ‘Q2,3,4’ are composites of two or three quintiles. The numbers in brackets are the years in each composite and the statistically significant values (p < 0.05) are in bold. Significance was determined with reference to the frequency distribution of 250 nonpartitioned random samples, repeated for sample sizes equivalent to each of one, two, and three quintiles. It is this difference in sample size that explains why 52% of the wide plus narrow rings is significant for Q1,5 but 54% is not significant for Q5.

<table>
<thead>
<tr>
<th>Index (from Table I)</th>
<th>Q1 (26)</th>
<th>Q2 (25)</th>
<th>Q3 (25)</th>
<th>Q4 (25)</th>
<th>Q5 (26)</th>
<th>Q1,5 (52)</th>
<th>Q2,3,4 (75)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Mean index</td>
<td>1.15</td>
<td>1.01</td>
<td>1.01</td>
<td>0.97</td>
<td>0.91</td>
<td>1.03</td>
<td>1.00</td>
</tr>
<tr>
<td>#2 Count of wide minus narrow rings</td>
<td>13</td>
<td>1</td>
<td>−2</td>
<td>−2</td>
<td>−10</td>
<td>3</td>
<td>−3</td>
</tr>
<tr>
<td>#3 Percent of wide plus narrow rings</td>
<td>50</td>
<td>44</td>
<td>24</td>
<td>32</td>
<td>54</td>
<td>52</td>
<td>33</td>
</tr>
<tr>
<td>#4 Standard deviation</td>
<td>0.17</td>
<td>0.18</td>
<td>0.17</td>
<td>0.15</td>
<td>0.17</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>#6 R (inter-site mean)</td>
<td>0.36</td>
<td>0.49</td>
<td>0.45</td>
<td>0.26</td>
<td>0.40</td>
<td>0.50</td>
<td>0.38</td>
</tr>
</tbody>
</table>
of wide and narrow rings, they do not seem to reduce the influence of factors responsible for inter-site variability.

4.2. Graphical analysis

Figure 1(A) shows the time series plots of K200 and mean July–June SOI (inverted). Comparison of the 10-year means (symbols) indicates strong agreement in evolving decadal-scale trend, the conjoint late 20th century departures from the mean being particularly noteworthy, and indicative of El Niño phase dominance. Departures from the mean prior to this are smaller but are all in the same direction (i.e., the 10-year mean tree-ring index consistently rises (falls) as the SOI falls (rises)). The only exception to this pattern is the 1990s when the mean SOI and K200 indices both declined relative to the 1980s.

Late 20th century El Niño phase dominance is also indicated by a higher frequency of El Niños than La Niñas (SOI Q1–Q5) (Figure 1(B)). As hypothesized, this coincides with a higher frequency of wide than narrow kauri tree rings (K200 Q5–Q1). However, prior to about the 1970s, the relationship between the relative number of ENSO events (SOI Q1–Q5) and the evolving decadal-scale mean SOI is weaker. For example, the negative 1960 count anomaly (−6) is larger than the positive 1980 anomaly (+5), even though the mean SOI at about 1960 is near zero. More importantly, whereas the SOI-based event difference count is near zero prior to 1950, broadly in agreement with the evolving mean, the K200-based statistic incorrectly indicates La Niña phase dominance. Further analysis (not shown) indicates that this is primarily because El Niño events are underestimated (i.e., the frequency of wide rings is too low).

Two SOI-based time-evolving indices of ENSO robustness (Figure 2(A), (B) dotted lines) show increasing activity late in the 19th century, reaching a peak in the first two decades of the 20th century. Activity then declines to a relatively quiescent 30-year period (1930s through 1950s) before increasing again to a second, slightly higher, peak at the end of the century. The corresponding time series for equivalent statistics calculated for K200 (Figure 2(A), (B) solid lines) mimic the general SOI trends well, in particular the two activity peaks and mid-20th century quiescence. However, late 20th century activity is underestimated and mid-20th century quiescence does not extend into the 1950s, the latter discrepancy being most clearly evident in the STD plots. Note that the abrupt increase in K200 STD in 1948 corresponds to the first entry of the very wide 1963 tree-ring (Figure 1(A)) into the 31-year moving window used for STD calculation. The thin line in Figure 2(B) shows the effect of changing the value of the 1963 tree-ring index to one (from 1.568) and demonstrates high STD sensitivity to outliers (1963 was identified as a significant outlier in Part A).

Inter-site correlations show similar decadal-scale patterns (Figure 2(C)) to the other indices, consistent with the hypothesis that periods of more robust ENSO activity (early and later 20th century) result in stronger inter-site correlations. The period of weakest correlations in the 1930s coincides with beginning of the quiescent period in the mid-20th century, but, as with the other two kauri-based indices, the 1950s is somewhat anomalous relative to the SOI-based statistics. Relatively large correlation fluctuations in the late 20th century occur at a time when the sample depth is declining from 14 sites to only 6 with complete data in the 31-year window by 1970, and to only 3 by 1985.
Figure 2. Comparison of three hypothesized K200-based indices of ENSO robustness with comparable statistics for the instrumental SOI. (A) 31-year running percentage of years falling below the first or above the fifth quintile, a measure of the relative frequency of extreme years. (B) 31-year running standard deviation (STD). The thin line with square symbols shows the effect of changing the 1963 K200 tree-ring index from 1.568 to 1.0. Solid and dotted lines in (A) and (B) are for the K200 master chronology and the mean July–June SOI, respectively. (C) Mean inter-site correlations for 31-year periods with 5-year steps, calculated for 13 tree-ring site chronologies. This figure is available in colour online at www.interscience.wiley.com/joc

4.3. Critique of indices

Both the partitioning and graphical analyses for the period of instrumental record are consistent with the hypothesis that the evolving mean of K200 is an index of ENSO phase dominance. An essential prerequisite is met in that the most significant decadal-scale anomaly in the SOI (El Niño phase dominance in the late 20th century) is also the most significant positive decadal-scale anomaly in K200. Also, neither series has any other noteworthy decadal-scale anomalies. However, this also highlights the difficulties in assessing the validity of the proposed phase-dominance indices, because the late twentieth century is the only period of El Niño phase dominance in the instrumental record (1876–2002) and there are no periods of sustained La Niña activity. Although it is promising that even relatively subtle decadal-scale changes in the decadal mean SOI are mirrored by K200, the little information available permits only provisional acceptance of the evolving K200 mean as an ENSO phase-dominance index.

Partitioning analysis indicates that the count of wide minus narrow rings (Index 2 in Table II) is sensitive to ENSO phase dominance. However, the graphical analysis (Figure 1(B)) clearly shows that the index is flawed, so it is not considered further here. Partitioning analysis also suggests that the combined frequency of wide plus narrow rings is highly sensitive to both ENSO phase dominance and robustness. The statistic is therefore rejected as a robustness index, although it may have value as a generic index of ENSO activity.

The STD and inter-site correlation statistics both have potential as ENSO robustness indices. Both are sensitive to ENSO robustness and neither is sensitive to ENSO phase dominance (Table II). Moreover, both mirror time-evolving ENSO robustness (Figure 2) and both have the same most notable deficiency (overestimated activity in the 1950s). Overall, STD is probably the superior statistic because (1) it is easier to calculate, (2) partitioning results suggest that it is less volatile than the inter-site correlation, and (3) abrupt late 20th century changes in inter-site correlation hint at possible sample depth issues that may affect its usefulness as an ENSO index.

5. Sensitivity to Sample Depth

Sensitivity to sample depth is a critical issue in the context of this research. The reconstruction of decadal-scale ENSO activity here uses a kauri tree-ring data set that increases from 20 trees (7 sites) in 1580, to a peak of 191 trees (17 sites) in 1900. Sample size then declines gradually to 136 trees (13 sites) by 1981, after which there is an abrupt decrease to a low of 29 trees (4 sites) in 1999. Clearly, there are two closely related issues here: the number of trees, and how many sites those trees are drawn from. An ideal index of time-evolving ENSO activity will be either insensitive to both sources of sample depth fluctuation, or be capable of appropriate adjustments to accommodate the complex sample depth changes through time.
To investigate the impacts of the variable numbers of contributing sites through time on the four remaining indices (mean, variance, inter-site correlation, spectral signature), the tree-ring data set was split into two subsamples, each of six sites. Sample A comprised those sites used to construct K200, which have data extending back to 1580 (one tree of unknown provenance was excluded), and Sample B comprised the six best quality remaining sites. These 12 sites are a subset of the 13 used in the earlier inter-site correlation analysis (Figure 2(C)). Two sub-master chronologies (K200_6A, K200_6B) were built from the data subsamples by pooling all trees across qualifying sites (the same method used to construct K200). The impact of the number of trees used to build the kauri master on the mean and STD statistics was investigated using a Monte Carlo subsampling approach (Appendix).

Figure 3(A) shows the evolving sample depth of the two subsamples. Subsample A has less than six sites prior to 1770 and 20+ trees from all six sites is not attained until 1750. Both sub-masters decline rapidly in sample depth after about 1980. The unequal quality of the two subsets is an unintended consequence of the data split, and implies that differences between the results for the two subsamples are not solely due to site selection, but also due to variable numbers of sites (pre-1770, post-1976) and trees (throughout). However, the data split has the important benefit of permitting direct assessment of the implications of the reduced data set actually available in 1580 for the proposed ENSO indices. In the analyses presented below, the most relevant comparisons are between the two subsamples (especially 1770–1976), and between Sample A and K200 during periods of high sample depth in the 19th and 20th centuries.

5.1. Mean

Running 31-year means for the two sub-masters (Figure 3(B)) show some agreement at the centennial scale. For example, both have periods of relatively wide rings centered around 1680, 1820, and 1980. There is also agreement at the decadal scale in terms of near-synchronous peaks and troughs. However, multidecadal patterns show important differences, including notable divergence in each century, suggesting sensitivity of the evolving mean to the specific subset of sites contributing trees to the kauri master chronology. This is supported by Monte Carlo experiments (Appendix) showing that, although divergence of the running means around 1660 may be a result of very low sample depth in K200_6B,
low sample depth is unlikely to explain divergences during later periods. It follows that any interpretation of the K200 31-year running mean in terms of ENSO phase dominance would be sensitive to the specific composite of sites contributing trees. At its most extreme (e.g. around 1885 in Figure 3(B)), opposite interpretations are possible. The evolving mean is therefore regarded as a flawed index of ENSO phase dominance, at least at the multidecadal scale, and is not pursued further here.

5.2. STD

Comparison of running 31-year STD for the two independent sub-master chronologies (Figure 3(C)) indicates remarkable agreement in terms of multidecadal to centennial-scale patterns for the last three centuries. Both have STD peaks and troughs at nearly identical locations, both show highest values in the 20th century, and, in both cases, the mid-20th century STD trough is comparable in scale to peaks in the previous two centuries (suggesting a 20th century variance ‘step up’). However, there are also three multidecadal periods of notable divergence (pre-1720, mid-to-late 19th century, late 20th century). These are discussed below and corrections devised where possible.

Late 20th century divergence is a 31-year block (1948–1978), and is a consequence of the size of the outlier 1963 tree-ring index. Because the 1963 tree-ring index is larger in K200_6B than in K200_6A, STD is relatively inflated in the former sub-master from 1948 (when the 1963 tree ring first enters the 31-year STD calculation window) and for the next 30 years. This is a clear demonstration of the sensitivity of temporal STD to outliers. Because outliers prior to the period of instrumental record cannot be identified as such (extreme rings may be associated with ENSO events), no correction is applicable.

The largest divergence between the STD plots for the two sub-masters is prior to 1720. This occurs at a time of low and rapidly evolving sample depth in K200_6B and is an anticipated consequence of the small sample size, especially before 1670 (<6 trees). Correcting the K200_6B subset prior to 1750 (<20 trees) for this (see Appendix) brings the results into closer agreement with those for K200_6A (Figure 3(C)).

Apart from the pre-1720 and the late 20th century divergences discussed above, the STD plot for K200_6A mostly plots above that for K200_6B. Divergence is greatest in the 19th century, with the STD for K200_6A at least 10% higher than K200_6B from 1837 to 1874 (peaking at 32% higher in 1855). The divergence cannot be attributed to differences in sample size, because, with at least 92 (55) trees used to build the K200_6A (K200_6B) sub-masters across 1837–1874, associated differences in STD (from Figure A1(B)) are less than 2% and in the opposite direction (i.e. K200_6B would be expected to have a slightly higher STD). There are two other plausible explanations. First, we may simply be seeing a subdued, but more prolonged, version of the late 20th century divergence, associated with inter-sub-master differences in a small number of extreme tree-ring indices. Second, divergence may result from temporally evolving differences in the strength of the climate signal in the respective chronologies, caused by differences in the ‘quality’ of the material used to build the respective sub-masters. The logic here is that for higher quality chronologies, the climate signal will be more consistently expressed, leading to a more emphatic tree-ring representation of climate forcing, with an associated increase in STD. The fact that the ‘Expressed Population Signal’ (Briffa and Jones, 1990) of K200_6A reaches its highest values over 1837–1874 (and K200_6B does not) is consistent with this idea.

Whatever the cause of the divergence in the sub-master STD plots, an important conclusion is that the STD (and any climate interpretation placed upon the statistic) is affected by the specific mix of sites. This is most obvious for the 20th century where the relative importance of the two STD peaks is different for the two subsets. However, it is important to emphasize that this sensitivity is limited to relatively small changes in the magnitude of STD peaks and troughs, and that the site mix has negligible impact on the timing of periods of high and low variance.

This suggests that a 31-year moving window of the STD of kauri master chronologies may be a remarkably robust index of the timing of multidecadal ENSO activity, but it also suggests that the relative magnitude of that activity should be interpreted with caution, even after correcting STD for sample size. A further caveat is that the results become notably less stable when sample depth drops below about 20 trees.

Comparison of the K200 and K200_6A STD plots for the 19th and 20th century indicates that the subset of sites available in 1580 (K200_6A) represents the full data set very well, especially in terms of the timing of STD peaks and troughs. Moreover, sample depth is not problematic since at least 20 trees are used to build K200, and 30+ from 1625. However, the fact that the STD for K200_6A plots above that for K200 for most of the last two centuries suggests that the K200 plot for the 16th through 18th centuries may be biased by about +10%. This is because the early part of the record is overwhelmingly dominated by data from the six K200_6A sites. Although this is too speculative to warrant any attempt at correction, it is worth keeping in mind when interpreting centennial-scale trends.

5.3. Inter-site correlations

Mean inter-site correlations for 13 sites (Figure 3(D)) show good agreement with evolving STD patterns (Figure 3(C)). Specifically, correlations and STDs are highest in the 20th century and the peak correlation periods at the multidecadal scale coincide with STD peaks. Following the hypothesized relationships proposed in Table I, conjoint high STD and mean inter-site correlation indicate a stronger regional-scale climate signal and, by implication, more robust ENSO activity. However, comparison of the inter-site correlation results for
the two independent subsets of six sites indicates substantial disagreement prior to the 20th century. This is most extreme at about 1740, when Sample A has its highest mean inter-site correlation and Sample B its lowest, resulting in opposite interpretations of ENSO robustness. In view of this extreme sensitivity to the mix of sites, mean inter-site correlation is rejected as an ENSO robustness index.

5.4. Spectral signature
Wavelet analysis was used in Part A to investigate whether kauri carries an ENSO-like spectral signature. That analysis showed that kauri lacks power in the 2–8 year spectral band, where ENSO power is focused (Torrence and Webster, 1999), perhaps because of the sensitivity of this high frequency signal to missed events and false positives in the kauri tree-ring record. However, decadal-scale periodicity features are better preserved and joint occurrence of kauri and SOI power at decadal-scale periodicities early and late in the 20th century was noted.

Figure 4 shows the extension of the wavelet analysis back to 1638 (first year in K200_6B) for K200 and for each of the two independent sub-master chronologies. The K200 and K200_6A plots are nearly identical over the last two centuries, indicating that the wavelet analysis results for K200 are not significantly affected by the reduction of sites contributing trees from 16 (most of the 18th and 19th centuries) to about half that number in 1580. It is also noteworthy that K200_6A and K200_6B carry similar decadal-scale periodicity patterns (i.e. concentrations of power in the 8–16 year band at about 1745, 1800, 1850, 1890, 1915, 1935, and 1995). Decadal-scale features are weaker in both sub-master tree-ring chronologies pre-1750, but agree back to at least 1690. The fact that K200_6B sample depth in 1690 is nine trees from three sites suggests that the evolutive kauri spectral signature is relatively robust to significant sample size degradation and to the mix of sites contributing trees.

6. 423 Years of ENSO Activity
Of the six potential kauri-based indices of multidecadal ENSO activity proposed in Table I, four were eliminated by the screening analyses (Sections 4, 5). Both phase-dominance indices were rejected – the relative frequency of wide versus narrow tree rings (#2) because of poor representation of the instrumental record, and the mean
(#1) because of uncorrectable bias associated with the mix of sites used to build the kauri master chronology. Of the four proposed ENSO robustness indices, the relative frequency of wide and narrow tree rings (#3) was rejected because the index is also significantly affected by phase dominance (although its usefulness as a nonspecific index of ENSO activity was noted), and inter-site correlation (#6) was rejected because of major uncorrectable bias associated with the specific mix of available sites.

Of the two remaining ENSO-robustness indices, evolving chronology variance (#4) appears to have most potential. This is because there is a clear rationale to its relationship to ENSO (Table I), and because the bias associated with changing sample depth is relatively easily corrected (Appendix). In contrast, although spectral signature (#5) also has a clear rationale and appears to be robust to major changes in sample depth and the mix of sites, it is arguably fundamentally flawed because it lacks power in the sub-decadal ENSO periodicities, which are generally considered to be ENSO’s key spectral signature (Kestin et al., 1998). Moreover, although ENSO does have periodicities at the decadal scale (Torrence and Compo, 1998), where power in K200 is concentrated, other plausible climate forcing mechanisms (e.g., solar activity) also have strong spectral signatures at these periodicities. In light of the consequent potential ambiguity, spectral signature is treated conservatively. This is done by reducing it to a supporting role for evolving chronology variance in the interpretation of the multidecadal ENSO activity that follows.

Figure 5(A) shows K200 kauri tree-ring indices (1580–2002). Dashed lines are the 5th and 95th percentiles for the relatively high sample depth period 1790–1974 (123 trees). Centennial counts of tree-ring indices below and above these thresholds differ by up to a factor of four, with a marked increase in the frequency of wide and narrow tree rings late in the record (especially in the 20th century). Particularly noteworthy is the relatively high frequency of wide rings in the 20th century, including the five largest tree-ring indices in 423 years. This indicates that regional-scale climate forcing was stronger in the 20th century, particularly forcing that was favorable to kauri growth. We can infer from this that ENSO activity was relatively strong in the 19th and 20th centuries.

It has been argued in this paper that the K200 evolving STD (Figure 5(B)) can be directly interpreted as an index of ENSO robustness. Interpreting Figure 5(B) in this

![Figure 5](https://www.interscience.wiley.com/ijoc)

way gives rise to five tentative conclusions about ENSO activity over the last 423 years.

(1) The 20th century was the most active ENSO century in at least the last 400 years.
(2) ENSO is characterized by 50–80 year cyclicity in phases of activity.
(3) The mid-20th century period of relatively low ENSO activity was quiescent only relative to robust activity early and late in that century.
(4) ENSO activity prior to the 20th century peaked in the four decades straddling 1740.
(5) ENSO was least active at about the beginning of the 19th century.

Post-1700 evolving spectral patterns in K200 (Figure 5(C)) are consistent with the above five conclusions. Power in the 4–16 year periodicity band is much stronger in the 20th century than at any earlier time, power peaks (in the 8–16 year frequency band) are 55–80 years apart, mid-20th century power is similar to that of pre-20th century peaks, the strongest pre-20th century power peak is at 1745, and 1800 is the weakest of the five post-1700 power peaks. Pre-1700, the wavelet analysis results are not consistent with those from the running 31-year STD. The STD peaks at 1600 and 1660 do not correspond with noteworthy spectral power peaks in the 4–16 year frequency band, and the weak 8–16 year frequency power peak at 1620 coincides with a variance trough.

To test the veracity of kauri-based interpretations of preinstrumental ENSO activity, the kauri results were compared with those from the multiproxy ENSO reconstructions of Mann et al. (2000, MBH00 hereafter) and Cook (2000, C00 hereafter), the latter reported in D’Arrigo et al. (2005). MBH00 is October–March surface air temperature (1650–1980) for a subset of the global multiproxy network of Mann et al. (2000). C00 is December–February Niño-3 Pacific SSTs (1998). C00 is December–February Niño-3 Pacific SSTs (1408–1978), derived from tree-ring records from the southwestern USA and Mexico. Note that, although MBH00 and C00 are the best multicentury and multiproxy ENSO reconstructions currently available, both are oceanic eastern pole ENSO reconstructions, making them imperfect tests for kauri (an atmospheric western pole proxy).

Symbols in Figure 5(B) show variance peaks in the SOI (from Figure 2(B)) and for the two Niño-3 reconstructions (from 31-year running variance plots in D’Arrigo et al. (2005)). All seven K200 variance peaks coincide with a variance peak in at least one of the other three sources, and no other source has a variance peak within a K200 variance trough. Neither MBH00 nor C00 has data extending into the last two decades of the 20th century, but high ENSO variance in the late 20th century is clearly represented in the instrumental data. All four sources indicate robust ENSO activity near the beginning of the 20th century, although MBH00 suggests peak activity in the last decade of the 19th century. This is a time of rapidly rising STD in K200, but with levels as high as the maximums achieved at prior peaks. The variance peak in K200 at about 1840 coincides with a peak in MBH00, but not in C00. D’Arrigo et al. (2005) attributed this discrepancy between MBH00 and C00 to a breakdown in the North American ENSO teleconnection, previously noted by Mann et al. (2000). The weak K200 variance peak at about 1800 coincides with a similarly weak peak in C00. MBH00 variance is relatively high at this time, but continues to increase to the aforementioned 1840 peak. K200 variance peaks centered on 1660 and 1740 coincide with peaks in both MBH00 and C00. However, the MBH00 peak in 1667 is at the beginning of the series, and so it could be too late (because unknown prior variance may be higher).

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Triangle symbols in Figure 5(C) mark eight significant spectral power peaks in the 2–6 year frequency band (indicative of robust ENSO activity), identified in the D’Arrigo et al. (2005) wavelet analysis of C00. Seven of these peaks coincide with six of the periods of robust ENSO activity indicated by the K200 analyses. Two of them (1783, 1887) precede the K200 STD peaks, but, in both cases, power in C00 continues for some decades after the indicated years. Two C00 spectral peaks coincide with each of the K200 variance peaks at 1740 and 1915, consistent with the contention that these are periods of relatively intense ENSO activity. Absence of a strong power peak at 1840 is not surprising, in light of the previously noted breakdown of the North American teleconnection.

Also shown in Figure 5(C) is a schematic representation of periods of strong spectral power in the Mann et al. (2000) 80-year window evolutive spectral analysis of MBH00 (their Figure 10.20). Solid lines represent the most significant power (log spectrum > cu 5.5) and dashed lines show periods of weaker power (5.0–5.5).

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ENSO. Encouragingly, centennial-scale changes in the running mean seem reasonably robust to changes in sites contributing to K200 (Section 5.1), so it is reasonable to accept that these are robust features. The fact that there is some agreement with the centennial-scale features shown in the MBH00 analysis is also encouraging. However, although the possibility of centennial-scale reconstruction of ENSO activity is flagged, it is not pursued further here. This is because further research is required to convincingly link centennial-scale forcing of kauri growth to (poorly understood) centennial-scale ENSO activity. Such work is also probably best undertaken and presented in the context of centennial- to millennial-scale signals in the 3722 year long kauri chronology (Boswijk et al. 2006).

The ENSO robustness message emerging from investigation of the kauri-based indices is consistent in the 18th through 20th centuries, but there are inconsistencies prior to 1700. As noted at the beginning of this section, the running STD is probably the stronger index, and it is noteworthy in this regard that the results for the Mann et al. (2000) and D’Arrigo et al. (2005) multiproxy analyses agree with the STD results. In fact, agreement between ENSO-robust periods identified by the kauri running STD and those for the two multiproxy analyses is very strong, with no significant unexplained inconsistencies. It is therefore reasonable to conclude that kauri is indeed a useful proxy for multidecadal to century-scale ENSO robustness (but not multidecadal phase dominance) and that the five tentative conclusions about ENSO activity derived from the running STD plot can be confirmed as a kauri-based assessment of 423 years of ENSO activity.

7. Discussion

7.1. Kauri indices of ENSO activity

Rejection of both ENSO phase-dominance indices was disappointing, especially in the case of the mean. It is of concern that very different multidecadal trends were obtained for independent sub-master tree-ring chronologies, even when these were built from scores of trees from at least six sites. This has serious implications for interpreting multidecadal trend in kauri master chronologies, especially when only a few sites contribute trees, or when a master chronology is composed of a temporally evolving mix of sites. For example, if the contributing sites change, or if there is a significant change in the relative contribution of sites, then the observed multidecadal trends may reflect changing site composition rather than climate forcing. This is of utmost concern prior to 1580, as the number of sites declines and modern (living tree) sites are replaced by subfossil wood and building timbers of unknown origin (as living trees). Note, though, that centennial and decadal trends appear to be less sensitive.

The impact of ENSO on kauri growth is primarily associated with El Niño and La Niña events (Part A). Consistent with this, both indices based on relatively extreme tree rings (Table I, #2, #3) are highly sensitive to ENSO activity. However, neither index is usable in the manner intended, one (#3) because it is jointly sensitive to ENSO phase dominance and robustness (Section 4.1), and the other (#2) because it indicates multidecadal La Niña phase dominance at a time when the instrumental record does not (Section 4.2). Consequently, although the conjoint frequency of the 5% widest and 5% narrowest tree rings (centennial counts in Figure 5(A)) can be taken as generally indicative of ENSO activity (robustness and phase dominance combined), the relative frequency cannot reasonably be interpreted in terms of the changing phase dominance.

Evolving variance of K200 emerged as the most promising index of ENSO robustness. The rationale for the index is simple (Table I), results are relatively insensitive to the mix of sites contributing trees to the kauri master chronology, and corrections for the impact of evolving sample depth are straightforward (Appendix). For the minimum of 20 trees available for the 1580–2002 period investigated here, the required STD adjustments are minor (Figure 5(B)), consistent with the theoretical analysis of Osborn et al. (1997), which showed that chronology variance increases strongly as the number of contributing series drops below about 10 (depending on the mean inter-series correlation).

The validity of using K200 running variance as an index of ENSO robustness is based on the premise that ENSO is the dominant decadal-scale forcing of kauri growth. Part A presented the case for ENSO dominance, and it is noteworthy that no other forcing factor has emerged that explains any significant amount of inter-decadal variance. It is also encouraging that D’Arrigo et al. (2005, p. 3) found ‘... remarkably good agreements in variance changes in recent centuries’, using an essentially identical running variance method, applied to several ENSO-sensitive proxies. On the basis of the combination of (1) strong ENSO–kauri relationships in the instrumental record, (2) consistency with comparable results for other ENSO-sensitive proxies, and (3) the lack of alternative forcing factors, the evolving K200 variance can reasonably be accepted as a useful index of ENSO robustness. However, it is important to recognize that ENSO explains only a portion of kauri growth (ca 50% of the 20% widest and 20% narrowest rings (Part A)). Although no other significant contributor has been identified, and any that does exist must be a relatively minor contributor (compared to ENSO), that inference is derived from the analysis of a period of strong ENSO activity in the 20th century. Because ENSO was weaker prior to this, other forcing factors may have been more important. Agreement between kauri and other ENSO proxies (Section 6) suggests that ENSO was not supplanted in influence, but the possibility cannot be ruled out.

Although the running variance of ENSO-sensitive proxies is a valuable index of ENSO robustness, there are several sensitivity issues that should be recognized. First, results presented in Figure 2(B) show that the STD
measure of chronology variance used here is highly sensitive to even single outliers. Second, variance is sensitive to decadal-scale trend. For example, the STD peak at 1660 (Figure 5(B)) partly relates to the fact that there is a notable decadal-scale trend in the data at this time. Third, because of this sensitivity to trend, running variance indices are sensitive to how tree ring-time series have been standardized. Although the timing of variance peaks and troughs is unlikely to change, small changes in their relative sizes can result from applying different standardizations. However, the index is not sensitive to centennial- and millenial-scale trends.

The registration of ENSO’s 2–8 year spectral signature in a proxy record is likely to depend on a sufficient proportion of ENSO events being faithfully recorded by the proxy (the strike rate), coupled with a low frequency of false positives. Part A found that kauri’s 50% ENSO-event strike rate was insufficient in this regard, but noted decadal-scale spectral features that might be ENSO-related. However, although a plausible connection was identified, the close association between these decadal-scale features and ENSO-robust periods was a surprise. Part of the explanation may be the strengthening of decadal-scale ENSO spectral features during periods of high robustness (Torrence and Compo, 1998). Whatever the reasons, there are two implications. The most obvious is that decadal-scale power provides a second kauri-based index of ENSO robustness that complements temporal variance. Second, the result may have implications for other researchers. It is natural to look for the 2–8 year ENSO spectral signal in proxies and perhaps to dismiss proxies that do not exhibit it. However, this may be an unrealistic standard that could lead to the rejection of proxies that have an insufficient strike rate to retain the 2–8 year power, but which, nevertheless, carry a useful signal of ENSO’s long-term evolution.

7.2. ENSO activity

The kauri tree-ring record suggests that the 20th century was the most active ENSO century for at least four centuries. The idea that the 20th century was an active ENSO century is not new, but the contention that it was the most active century is certainly controversial. This is consistent with the multiproxy reconstruction of Mann et al. (2000), which found the 20th century to have the strongest spectral features and highest frequency of extreme ENSO events, since 1650. However, Cobb et al. (2003) identify the mid-17th century as more active than the 20th century, based on a single 2–7 year bandpass filtered spliced coral record from the central tropical Pacific. High ENSO activity at this time is identified by the kauri record, by Mann et al. (2000) and D’Arrigo et al. (2005), but in none of these studies is the inferred ENSO activity comparable to that in the early 20th century. However, it is also noteworthy that D’Arrigo et al. (2005) identify the mid-18th century as a period of ENSO activity on par with the early 20th century. The kauri record and findings of Mann et al. (2000) are in agreement that the mid-18th century was the most ENSO-active period prior to the 20th century, but both studies clearly indicate less robust activity.

The non-kauri ENSO reconstructions referred to above are all eastern pole reconstructions and have focused on ENSO’s oceanic component. This contrasts with kauri, which is essentially a western pole atmospheric proxy. Therefore, the agreement between kauri and the Mann et al. (2000) and D’Arrigo et al. (2005) reconstructions has additional significance because it indicates that most ENSO features identified for the eastern pole in previous ENSO reconstructions are (as assumed) Pacific Basin wide and conjoint atmosphere–ocean phenomena.

The coincidence of late 20th century global warming and enhanced ENSO activity has previously been noted (e.g. Trenberth and Hoar, 1996, 1997). Although the link between these trends is not explored in this paper, the contention that ENSO activity was highest in the 20th century might be interpreted as being consistent with the argument that enhanced ENSO activity may be associated with a warmer world. In turn, this may lead to an inference that anthropogenic forcing may be a causal factor. Comparing the kauri running STD (Figure 5(B)) with the Southern Hemisphere instrumental and proxy-reconstructed surface air temperature (Mann and Jones, 2003) indicates agreement at the centennial scale. Both series show relative centennial stability from the late-16th through mid-19th centuries, followed by a strong rising trend. This is consistent with the idea that ENSO may be more active in a warmer world, but it is not feasible to deduce whether that relationship pertains to natural and/or anthropogenic forcing. While it is plausible that we are seeing the impact of anthropogenic forcing, it is also possible that it is not the 20th century that is unusual but that the previous three centuries have unusually low ENSO variance, and that the increase in the 20th century variance represents a return to ‘normal’ conditions after several relatively cool centuries (Mann and Jones, 2003). Analysis of the evolving variance of the multimillennial kauri long chronology (Boswijk et al., 2006) should be informative in this regard.

The second important result emerging from this study is the apparent 55–80 year cyclicality to periods of ENSO robustness. This suggests that the two observed phases of ENSO robustness in the instrumental record are a continuation of at least a multicentury cyclicality pattern. As noted in Section 6, each of the seven robust ENSO phases inferred from Figure 5(B) is consistent with the results of one or both of ENSO reconstructions of Mann et al. (2000) and D’Arrigo et al. (2005), and no robust ENSO phase suggested by either reconstruction is missed. This provides confidence that the observed cyclicality is a real ENSO feature. Nevertheless, it is significant that the K200 multidecadal cycles are much more pronounced than in any other ENSO reconstruction. Because the kauri proxy is located in a teleconnection region distant from the tropical ENSO core zone, caution is required in interpreting this particular feature. This is because it seems improbable that such a pronounced feature would
manifest more strongly in a teleconnection region than at the core ENSO eastern pole. It is possible that we are seeing a predominantly western pole and/or atmospheric feature, with a muted signal in the eastern pole SSTs. We know from analysis of the instrumental record that this is a plausible explanation, firstly because there are notable differences in the evolving spectral features of the SOI and Niño3 SSTs (Torrence and Webster, 1999, their Figure 8), and secondly because there are significant differences in evolving spectral power at the eastern and western ENSO poles (Torrence and Compo, 1998, their Figure 10). However, an alternative explanation is that we may be seeing a regional (southern ocean?) modulation of the primary ENSO signal, which decays in influence towards the tropical ENSO core zone. Additional work is required to resolve this critical question.

8. Conclusions

Part A identified kauri’s potential as an ENSO proxy and suggested that regional-scale kauri master tree-ring chronologies may be suitable for reconstructing ENSO robustness and (possibly) phase dominance. Two phase-dominance indices and four robustness indices were proposed here. These six indices were tested against the instrumental record and for sensitivity to evolving sample depth. Both phase-dominance indices and two of the robustness indices failed in the validation. 423 years of ENSO robustness was inferred from the two remaining robustness indices (evolving time series variance and evolving spectral signature).

With respect to kauri as an ENSO proxy, the conclusions of this study are given below.

(1) Kauri regional master chronologies can be used to reconstruct multidecadal to centennial-scale ENSO robustness.
(2) Evolving time series variance (corrected for sample depth) is the best available kauri-based index of ENSO robustness (of the six investigated).
(3) Evolving decadal-scale spectral features in the regional kauri masters signal robust ENSO periods and complement evolving variance.
(4) Kauri may carry centennial-scale information about ENSO activity.

The conclusions related to 423 years of ENSO history inferred from kauri tree rings are continued below.

(5) The 20th century was the most robust ENSO century.
(6) Evolving ENSO robustness in the instrumental period may be a continuation of a persistent 55–80 year cyclicity pattern extending back to at least 1580.
(7) The mid-20th century was ENSO quiescent only relative to the beginning and end of that century.
(8) ENSO robustness prior to the 20th century peaked in the mid-18th century.
(9) ENSO was least active near the beginning of the 19th century.

Kauri has two likely future courses as an ENSO proxy. First, it can be incorporated into multiproxy ENSO reconstructions. Notwithstanding the event capture deficiencies identified in Part A, with a 50% ENSO-event strike rate, kauri ranks high among the available centennial-scale proxies. It also has clear merits in terms of geographical location with respect to the under-represented ENSO western pole and the proxy-deficient southern ocean. Moreover, the fact that kauri seems to preserve decadal-scale ENSO variance complements the performance of other high-quality proxies, in which sub-decadal variance is strongly represented (e.g. C00, D’Arrigo et al., 2005).

Millennial-scale ENSO reconstruction is kauri’s second future prospect. Some high resolution ENSO proxies are superior to kauri in terms of their ENSO-event-capture strike rate (C00), and others are superior in terms of their location within the tropical ENSO core zone (corals), but none has the millennial-scale reconstruction potential of kauri. With a continuous calendar-dated chronology extending back 3722 years and numerous other floating chronologies providing multicentury climate ‘windows’ over many tens of thousands of years, kauri clearly has a reconstruction potential that is beyond the centennial-scale multiproxy applications. The research presented here provides the foundation for such work in terms of identifying the appropriate indices and necessary corrections for the complex and evolving sample depth and chronology composition characteristic of kauri tree rings. It is apparent from the conclusions listed here that evolving sample-depth-corrected time series variance (magnitude, cyclicity patterns), coupled with decadal-scale spectral patterns, are the most promising avenues to explore ENSO activity in such multimillennial investigations.

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A1. Appendix

The complex changes in sample depth, typical of tree-ring chronologies (e.g. Figure 3(A)), result in associated complex changes in the error of evolutive statistics such as the mean and variance. Moreover, in the case of variance, there is an additional problem of systematic bias. Recall that the tree-ring chronologies were built by averaging tree chronologies (to enhance common signal and suppress tree-specific noise). The influence of tree-specific variance is reduced as the number of trees...
used to build a chronology increases, with a consequent systematic decrease in temporal variance (Osborn et al., 1997).

Monte Carlo experiments were undertaken to quantify the errors and bias noted above and to investigate the feasibility of correcting the variance bias. For a 31-year window, within a period of relatively high sample depth, 100 sub-master chronologies were built by averaging \(N\) randomly drawn trees, where \(N\) ranged from 1 tree (100 single tree chronologies) up to one less than the total number of trees available in the window (100 chronologies each with one tree dropped). Selected statistics (minimum, mean, maximum, STD) of the mean and STD were calculated for each set of 100 sub-master chronologies. These statistics were compared with those for the full available data set to estimate bias and error associated with evolving sample depth. The analyses were repeated for each of six 31-year windows, starting in 1790 (Figure 3(C)), using the full data set used to construct K200, then recalculated again using the reduced K200_6A data set (to test sensitivity to site composition).

Results for the 1883–1913 window are shown in Figure A1 (Panels A, B). The open circles to the right of these two panels show the mean (0.979) and STD (0.175) for all 174 trees with complete data for this window. Solid lines show the mean results for each set of 100 sub-master chronologies (dots). These indicate that, although the mean is an unbiased estimate (as expected), STD clearly is biased, with a nonlinear trend of increasing STD with reducing sample depth. Initially, the impact of sample depth reduction is small (e.g. reducing the sample depth to 20 trees increases mean STD by 6%), but the impact is noticeably larger for fewer than about 10 trees. For the extreme case where sub-masters are single trees, the mean STD is about a factor of two larger (0.352 compared to 0.175). Dotted lines in Panels A and B are \(\pm 2\) STD error envelopes around the mean and also show increasing divergence with reduced sample depth. For 50 trees the two STD error (Panel B) is 10% of the mean value, climbs to 20% for 20 trees, then increases more rapidly to a peak of 60% for one tree. Comparable errors about the mean (Panel A) are about half of this.
STD results for the other five windows (not shown) are very similar to those for 1883–1913. The number of trees available differs and the all-tree baseline STD varies with the position of the window (Figure 3(C)), but the patterns of bias and error divergence are essentially the same as those shown in Panel B. Agreement is particularly strong when the mean STD results are standardized for baseline STD by proportioning mean STD for 30 trees (STD30) against the STD for sub-master chronologies built from 50 trees (STD50, Panel C). (The choice of STD50 is arbitrary and inconsequential – any large value of N would suffice.) The thick line in Panel C is a fourth-order polynomial regression of the median STDN/STD50 across the six analysis windows against the logarithm of the number of trees. This confirms a relatively minor mean STD bias for sub-master chronologies built from 30+ trees (<3% difference from STD50). This rises to about 5% for 20-tree chronologies, climbs to 27% for five trees, and peaks at 108% for single trees.

Repeating the above analysis for the K200 6A subset of six sites produced nearly identical results in terms of mean STD bias (circles in Figure A1 (Panel C)). This suggests that STD bias is insensitive to which sites contribute the trees and that a first-order correction of mean STD bias can be achieved by applying the regression analysis results of Panel C (i.e. dividing the actual STD for N trees by STDN/STD50).

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