

the apparent phase relationship between the Auckland maar lake and Antarctic Isotope Maxima (AIM) warming intervals during the LGCP and their out-of-phase relationship with Greenland ice core Dansgaard-Oeschger events (Fig. 2) provides further support for interhemispheric asynchrony in rapid climate change.

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# Five centuries of ENSO history recorded in *Agathis australis* (kauri) tree rings

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Kauri (*Agathis australis* (D. Don) Lindley) is a canopy-emergent conifer endemic to northern New Zealand (north of latitude 38°S). Mature adults can achieve heights of 30 m and trunk diameters over 2 m are not uncommon. Trees often live for more than 600 years, and ages in excess of 1000 years are known (but rare). This longevity, strategic location in the data-deficient southern hemisphere, and an abundance of source material (living trees, logging relics, colonial-era buildings, sub-fossil wood preserved in swamps; Fig. 1), gives kauri considerable potential for paleoclimate applications. All four sources of material have been successfully exploited and an extensive kauri tree-ring database has been developed. This includes data from 17 modern (living tree) sites, collected in the 1980’s, late 1990’s and early 2000’s (Fowler et al., 2004); 16 colonial-era structures and a logging relic, collected since 2001; and numerous sub-fossil assemblages, collected in the 1980’s, late 1990’s and early 2000’s. The combined tree-ring data provide continuous coverage of the past 3700 years (Boswijk et al., 2006) with “floating” sequences of mid-Holocene date indicating the potential to extend the calendar-dated record back further in time. Large quantities of sub-fossil pre-Holocene wood (Palmer et al., 2006) will also enable paleoclimatic analyses for millennial-length windows over much longer time scales.

In the growing season, Kauri growth is enhanced by cool-dry conditions, yet suppressed by warm-wet conditions, particularly in the austral spring (Sep-Oct-Nov; SON). This relationship to climate is fortuitous in terms of El Niño Southern Oscilla-



Figure 1: Sources of kauri material. Tree-ring chronologies for the last 500 years have been developed from: **a,b** living trees; **c** a few logging relics (picture courtesy of Auckland Museum Collection); and **d,e** from colonial-era building timbers.

tion (ENSO) reconstruction potential, because such conditions are associated with El Niño and La Niña events, respectively, in the far north of New Zealand. Moreover, the strongest relationships between kauri growth and climate occur during SON, coincident with the peak strength of the teleconnection between ENSO and New Zealand climate. Recognition of these juxtapositions led to the identification of kauri’s potential as an ENSO proxy in the 1990’s (Fowler et al., 2000) and has been the primary impetus for research undertaken by the University of Auckland Tree-Ring Laboratory ever since. Fowler et al., (2007) summarized the current understanding,

derived from that research. They suggest there is a significant regional-scale forcing signal in the width of kauri tree rings and ENSO is the dominant contributor to that forcing. ENSO’s influence on kauri growth is predominantly via the western pole of the Southern Oscillation. Wide kauri tree rings tend to be associated with El Niño events (narrow with La Niña), with similar event registration strength. Strongest statistical relationships are for a five-season window from March, prior to growth initiation (in September), through to the following May. Growing season relationships are stronger when ENSO is most active (e.g., early and late 20th century), but otherwise

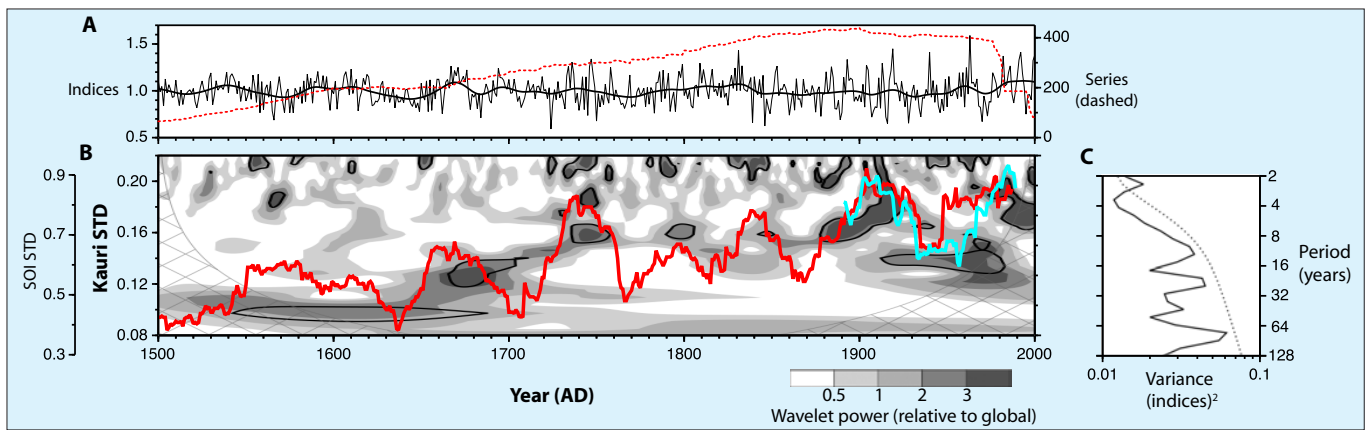


Figure 2: Kauri master chronology and associated analyses indicating 500 yr of evolving ENSO activity: **A**) Composite kauri master chronology built by combining archeological timbers and samples from living trees. Sample depth (Series, dashed red line) is the number of radii contributing to the master; **B**) Solid red line is running Standard Deviation (STD) (31-year window) for the kauri master. Blue line is the same for the Southern Oscillation Index (SOI) (July–June mean). Shading is the wavelet power spectrum, derived by Morlet wavelet analysis of the kauri master, using zero padding to reduce wrap around effects. Wavelet power is expressed relative to the global wavelet (shown in c), with significant periodicities (far right scale) enclosed by black lines (significance determined at the 10% level using a red-noise background spectrum); **C**) Global wavelet power spectrum (solid line). Dashed line is the significance for the global wavelet spectrum (same significance level and background spectrum as in b). Wavelet analyses were run using the online wavelet toolkit at <http://paos.colorado.edu/research/wavelets> (Torrence, C. and G. P. Compo, 1998).

appear to be stationary at the multi-decadal scale. About half of El Niño events are associated with wide kauri tree rings, with very few opposite associations (likewise for narrow rings and La Niña). Finally, kauri carries a multi-decadal signal of the evolving strength of ENSO activity (robustness) within the evolving variance of kauri master chronologies (derived by pooling data from across kauri's growth range).

Fowler (2007) investigated the potential of evolving kauri master chronology standard deviation (STD) as a proxy for ENSO robustness. Results indicated that evolving STD (31-year moving window) of the kauri master chronology is a robust index of the timing of multi-decadal ENSO activity, although the relative magnitude of that activity needs to be interpreted with caution, especially when sample depth (expressed as number of trees) is less than about 20. Based on these results, evolving STD was used to reconstruct ENSO activity back to AD 1580, with supporting evidence inferred from the occurrence of decadal-scale periodicity features (determined from wavelet analysis). Two key findings were: a) the 20th century was the most active ENSO century in at least the last 400 years, and, b) ENSO activity has been characterized by 50–80 year cyclicity in phases of relative robustness.

To extend our ENSO reconstruction prior to AD 1580, a new kauri master chronology was developed by combining archeological data with the living tree data set (Fig. 1). The increase in sample depth markedly improved the statistical quality of the kauri master chronology prior to AD 1700, and particularly prior to AD 1600. Here, we update the Fowler (2007) results, extending the ENSO reconstruction to AD 1500. Our methods essentially duplicate those described in detail in Fowler et al. (2007) and Fowler (2007), including the

key pre-processing step of standardizing each series by dividing ring-width values by a fitted low pass filter (spline curve with 50% frequency response at 200 yr). However, because the archeological timbers derive from unknown trees, the master chronology was built by combining individual radii, rather than first producing tree means from same-tree radii and then averaging these.

A notable feature of the kauri master chronology (Fig. 2A) is the trend towards increasing variance from the 16th to 20th centuries. Although this appears to follow the trend in sample depth, we have no reason to believe that this is a sampling artifact—indeed variance would be expected to decrease with increasing sample depth. Monte Carlo resampling of the period of high sample depth in the 19th to mid-20th centuries indicates that this assumption is reasonable and that variance changes associated with a range of 65–439 data series are minor. The 31-year running STD (Fig. 2B) shows the centennial-scale increase in variance over the last 500 kyr, but with a superimposed multi-decadal pattern of similar magnitude. Note the similar multi-decadal variance change in the comparable analysis of the Southern Oscillation Index. The underlying wavelet power spectrum shows strong coincidence between kauri STD peaks and periods of relatively strong inter-annual to decadal-scale periodicities. Based on our interpretation of high kauri STD as indicative of robust ENSO (especially when combined with strong periodicities), this suggests that ENSO was relatively quiescent in the 16th and 17th centuries, that there was pronounced ENSO activity centered around 1740, and that the 20th century was the most active in 500 yr.

A number of caveats should be made with the above interpretation. For exam-

ple, the north of New Zealand is outside the ENSO tropical core zone and subject to other forcing factors. Although ENSO forcing is dominant, other factors must also be influential—so some of the changes in variance in Figure 1 may be un-related to ENSO. Moreover, our interpretation implicitly assumes that the observed 20th century teleconnection is stationary. Finally, ENSO is a highly complex phenomenon and inferring evolving ENSO behavior based on a single proxy is always going to be problematic (especially when that proxy derives from a remote teleconnection region). Multi-proxy research is the obvious next step, at least for the latter half of the millennium, when several other proxy records (e.g., coral, other tree-rings, historical archives) are available. We hope that the kauri data set will be a valuable contribution to such research.

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