Evidence for a 'Medieval Warm Period' in a 1,100 year tree-ring reconstruction of past austral summer temperatures in New Zealand

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[1] The occurrence of the Medieval Warm Period (MWP) in the Southern Hemisphere is uncertain because of the paucity of well-dated, high-resolution paleo-temperature records covering the past 1,000 years. We describe a new tree-ring reconstruction of Austral summer temperatures from the South Island of New Zealand, covering the past 1,100 years. This record is the longest yet produced for New Zealand and shows clear evidence for persistent above-average temperatures within the interval commonly assigned to the MWP. Comparisons with selected temperature proxies from the Northern and Southern Hemispheres confirm that the MWP was highly variable in time and space. Regardless, the New Zealand temperature reconstruction supports the global occurrence of the MWP. _INDEX TERMS:_ 4221 Oceanography: General: Dendrochronology; 4215 Oceanography: General: Climate and interannual variability (3309); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] The 'Medieval Warm Period' (MWP) was first described by _Lamb_ [1965] as an epoch of anomalously warm conditions over western Europe covering the approximate period A.D. 1000 to 1300. Since _Lamb_ [1965], considerable interest in the MWP has arisen because of its potential value as a 'natural' analogue of 20th century 'greenhouse' warming. Reconstructions of Northern Hemisphere (NH) temperatures (both mean annual and warm-season) that include the MWP [e.g., _Mann et al._, 1999; _Briffa_, 2000; _Crowley and Lowery_, 2000] can also be used in modeling experiments to test the relative importance of natural and anthropogenic forcings on past and present temperatures [e.g., _Jones et al._, 1998; _Crowley_, 2000]. Therefore, characterizing the temporal and spatial properties of the MWP worldwide is important to studies of global change.

[3] Because the MWP was first identified in Europe, there has been considerable debate concerning its true global extent. _Hughes and Diaz_ [1994] and _Folland et al._ [2001] found that the MWP was likely to have been highly variable in space and not strongly synchronous in time. A similar finding was reported by _Crowley and Lowery_ [2000] for the NH. Even so, _Folland et al._ [2001] noted that reconstructed NH temperatures were above-average during the MWP, but not as warm as those in the late 20th century. This conclusion is difficult to extend to the globe because temperature reconstructons of sufficient length and resolution are relatively few for the SH. Regardless, _Grove and Switsur_ [1994] argued for a global MWP based on glaciological evidence from both hemispheres. _Broecker_ [2001] likewise argued for a global MWP, even while admitting that the case "remains inconclusive" because of insufficient data. Since, as _Bradley_ [2001] points out, "the absence of evidence does not necessarily mean evidence of absence", more effort is needed to determine the true global nature of the MWP.

[4] One of the principal difficulties in determining the global extent of the MWP is the relative paucity of well-dated, high-resolution paleoclimatic time series that cover some or all of the MWP (i.e., those that extend back to at least A.D. 1200). For example, _Jones et al._ [1998] used only seven such series, _Mann et al._ [1999] twelve, _Briffa_ [2000] eight, _Crowley and Lowery_ [2000] fifteen, and _Esper et al._ [2002] ten in their studies of past temperature variability covering the past 1,000 years. Most of these records are based on annual tree-ring chronologies from sites located in the NH extra-tropics. In the Southern Hemisphere (SH), only three tree-ring reconstructions of past temperature have been used to characterize temperature variability and change over the past millennium. These records are from Argentina [_Villalba_, 1990], Chile [_Lara and Villalba_, 1993], and Tasmania [_Cook et al._, 2000]. Another SH location where additional millennia-long temperature reconstructions might be developed is New Zealand, with its large expanses of intact forest that support several tree species with known dendroclimatic potential. Here we present the first tree-ring reconstruction of past temperatures in New Zealand that extends back through the proposed A.D. 1000–1300 interval of the MWP. In so doing, we find evidence for an anomalous warm period that is consistent with the MWP in the NH.

2. Oroko Swamp

[5] The tree-ring site in New Zealand is Oroko Swamp (lat. 43° 14′S, long. 170° 17′E, elev. 110 m.a.s.l.), located on
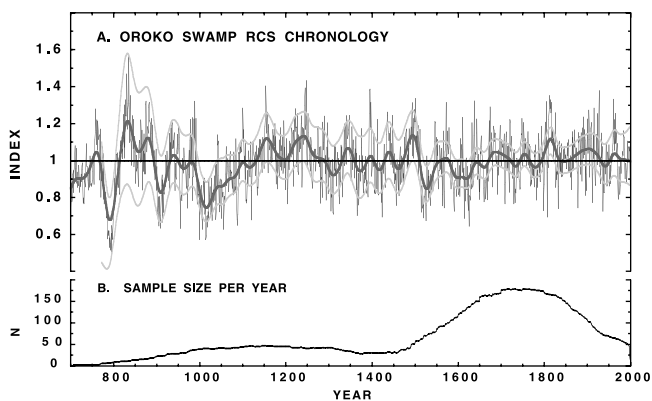
Figure 1. The Oroko Swamp silver pine tree-ring chronology (1a) covering the period A.D. 700–1999, with overlaid 50-year smoothing (thick red line) and bootstrap 95% confidence intervals (thin blue lines). The annual sample size used in computing the chronology is below (1b).

the west coast of the South Island approximately 70km southwest of Hokitika. This site supports a number of old-growth tree species, including the endemic conifer *Lagarostrobos colensoi* (silver pine). Silver pine is especially useful for our dendroclimatic studies in New Zealand because its maximum age can approach 1,000 years and its wood is virtually impervious to decay. Consequently, a large number of sub-fossil logs are available on the swamp floor for sampling. Over the past four years, a concerted effort has been made to utilize this dendroclimatic resource. *Cook et al.* [2002] describe the results of this work up to the point where the sub-fossil wood resource was beginning to be exploited. Their efforts resulted in a tree-ring reconstruction of past New Zealand Austral summer (January–March) temperatures covering the period A.D. 1200–1998. However, it was not well suited for MWP studies because of the way in which the ring-width series were detrended [*Cook et al.*, 2002].

[6] Following the success of *Cook et al.* [2002], we returned to Oroko Swamp and intensively sampled the sub-fossil wood. This resulted in a silver pine chronology with much greater sample depth (up from 145 to 260 ring-width series) covering the period A.D. 700–1999, which enabled us to use the Regional Curve Standardization (RCS) method [*Briffa et al.*, 1992] for developing the annual tree-ring chronology. The RCS method can potentially preserve multi-centennial tree-ring fluctuations related to climate and has been successfully used in dendroclimatic studies in both the NH [e.g., *Briffa et al.*, 1992; *Briffa et al.*, 1995; *Esper et al.*, 2002] and SH [*Cook et al.*, 2000].

[7] The Oroko Swamp RCS tree-ring chronology is shown in Figure 1. The chronology has also been low-pass filtered with a 50-year smoothing spline (red line) to highlight centennial timescale fluctuations, and 95% confidence limits (blue lines) for the filtered series have been estimated using the bootstrap method [*Efron*, 1987]. The confidence limits are acceptably narrow and stable back to A.D. 900, before which they expand rapidly. This identifies a natural breakpoint in the reliability of the chronology. Other measures of statistical signal strength in tree-ring chronologies

(not shown), such as the average correlation between series (RBAR) and expressed population signal (EPS) [*Briffa and Jones*, 1990], likewise confirm the usefulness of the RCS chronology back to A.D. 900. Figure 1b shows why this is so. The tree-ring chronology is based on the mean of 21 or more well-correlated tree-ring measurements per year back to A.D. 900.

3. The Temperature Reconstruction

[8] Following standard calibration/verification procedures used in dendroclimatology [*Fritts*, 1976; *Cook and Kairiukstis*, 1990] and the results from *Cook et al.* [2002], we calibrated the RCS chronology with homogenized Hokitika summer temperatures [*Salinger et al.*, 1992], using the 1894–1957 data for calibration and 1866–1893 data for verification (Figure 2). Hokitika did not record temperatures from 1881 to 1893. However, we were able to usefully fill in this gap with estimates from local sea surface temperature data [*Kaplan et al.*, 1998], which for the January–March season had a correlation of 0.73 with Hokitika temperatures. As before [*Cook et al.*, 2002], the post-1957 tree-ring data were severely affected by known logging of the stand and, therefore, not used for either calibration or verification.

[9] The linear regression of Hokitika temperatures on the tree-ring chronology produced a calibration R^2 of 0.38 (Pearson r = 0.62), a highly significant result ($p < 0.01$) even after taking into account a degrees of freedom correction for autocorrelation in the series. Over the 1866–1893 verification period, this relationship was strongly maintained with a Pearson r of 0.65. In addition, the reduction of error (RE) and coefficient of efficiency (CE) verification statistics (both measures of explained variance in the verification period; *Cook et al.* [1999]) were comparable to the calibration period R^2 (0.35 for both). These test results strongly support the validity of the temperature reconstruction, which allows it to be used to assess the occurrence of the MWP in New Zealand.
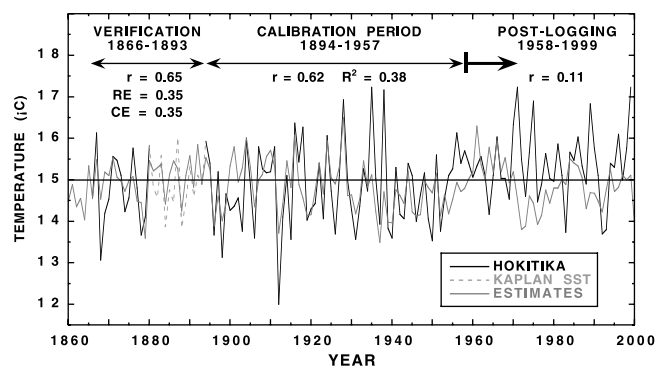

Figure 2. Calibration and verification results. The Oroko Swamp chronology has been calibrated against January–March mean temperatures from Hokitika, yielding a regression R^2 of 0.38. The correlation between actual and estimated temperatures in the 1866–1893 verification period indicates that the tree-ring estimates are valid. Tree growth after 1957 was severely disturbed by known selective logging of the site, which resulted in a collapse in the fidelity of the tree-ring response to climate.
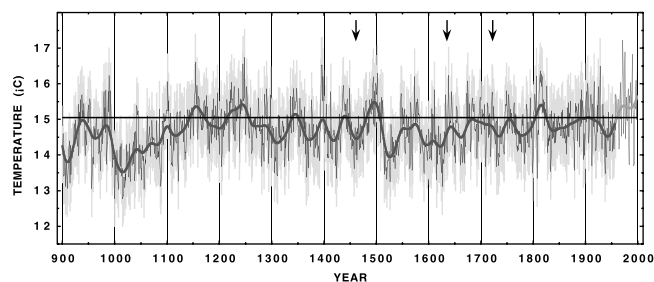
Figure 3. The Oroko Swamp Austral summer temperature reconstruction, with overlaid 40-year smoothing (thick red line). Annual error estimates in blue (±1 standard error of the estimate from regression) are also included (yellow). After 1957, the actual Hokitika data have been appended to the reconstruction (dark blue line) to allow the full 20th century to be compared to the previous 1,000 years. The thin black horizontal line is the 20th century mean of Hokitika instrumental temperatures. The three vertical arrows mark the years of Alpine fault earthquakes (1460, 1630, and 1717).

[10] The impact of logging on the temperature signal in the tree rings implies that earlier disturbances may have occurred and produced similar non-climatic effects on tree growth in Oroko Swamp. This suggestion can not be tested directly without having an independent data set for comparison. However, we conducted a disturbance transect analysis of silver pine in Oroko Swamp [*Cook et al.*, 2002] and found that the only evidence for anomalous mortality back to ca. 1300 was associated with the logging event. This result suggests that the recent breakdown in the temperature signal due to logging has not been repeated in the past.

[11] Figure 3 shows the full reconstruction with ±1 standard error limits of the regression model. The actual Hokitika data since 1958 have been appended to the reconstruction to provide a complete picture of how 20th century temperatures compare to the past. Also included in Figure 3 are arrows indicating the dates of earthquakes from the nearby Alpine fault in 1460, 1630, and 1717 [*Wells et al.*, 1999] that might have affected silver pine tree growth at Oroko Swamp and, consequently, the temperature estimates. The lack of any consistent change in the pattern of reconstructed temperatures following the inferred earthquakes suggests that they did not affect the sampled silver pines in any discernable way.

[12] The 20th century pattern of temperature variability in the reconstruction (and appended actual data) agrees qualitatively with analyses of New Zealand instrumental annual temperature data [*Folland and Salinger*, 1995; *Folland et al.*, 1997; *Salinger and Mullan*, 1999]. Summer and annual temperatures at Hokitika (1894–1998) are quite similar (r = 0.74) and have comparable warming trends (0.008°C/yr). However, the rate of 20th century warming on the west coast of the South Island is less then that for other parts of New Zealand [*Salinger and Mullan*, 1999], which affects the geographic interpretation of the reconstruction somewhat. Even so, summer temperatures have warmed since 1900, with most of the warming occurring somewhat abruptly after 1950. This change is accentuated by below-average temperatures in the 1940's and is superimposed on

a more general trend of increasing temperatures since the 16th century, which may be related to a recovery from the Little Ice Age. The rapid warming since 1950 is certainly unusual, but is not statistically unprecedented when compared to the previous 1000 years of reconstructed temperatures (Figure 3), especially the warm interval indicated in the first half of the 13th century. This early warm period, and another in the 12th century, fall within the generally accepted interval of the MWP based on evidence from the NH [*Lamb*, 1965; *Hughes and Diaz*, 1994; *Crowley and Lowery*, 2000; *Bradley*, 2001]. Similar to the NH, this SH expression of the MWP is not homogeneous in time. Rather, it is composed of two periods of generally above-average warmth, A.D. 1137–1177 and 1210–1260, that are punctuated by years of below-average temperatures and a middle period that is near average. Overall, this translates to a MWP that was probably 0.3–0.5°C warmer than the overall 20th century average at Hokitika and, for the A.D. 1210–1260 period, comparable to the warming that has occurred since 1950.

[13] Of equal interest in the reconstruction is the sharp and sustained cold period in the A.D. 993–1091 interval. This cold event is easily the most extreme to have occurred over the past 1,100 years. Interestingly, *Gellataly et al.* [1988] reported evidence for a significant glacier advance in the Mount Cook area around the period 1100–950 BP. The date of this event based on rock weathering-rind thickness is not precisely known (the error may be as great as ±300 years; see *Gellataly* [1984]), but its estimated timing is plausibly consistent with the reconstruction presented here. A sharp cooling is also indicated after A.D. 1500, followed by the long-term warming trend described earlier.

4. Conclusions

[14] We have described a 1,100 year long Austral summer temperature reconstruction for New Zealand from a silver pine tree-ring chronology developed at Oroko Swamp. The chronology is presently the longest, absolutely-dated, tree-ring record yet developed from New Zealand. Given the substantial quantities of sub-fossil silver pine wood yet unsampled in Oroko Swamp and in other low-land swamps and bogs on the west coast of the South Island, a multi-millennial temperature reconstruction similar to the 3,600 year record from Tasmania is clearly feasible [*Cook et al.*, 2002].

[15] The identification of a MWP *sensu lato* in New Zealand adds an important new datum to the debate concerning its large-scale occurrence and supports *Broecker's* [2001] argument that it was indeed global. The Oroko Swamp reconstruction may also prove valuable in determining the phasing between hemispheres of important global climate epochs like the MWP and LIA. This information may help determine the degree to which ocean circulation dynamics and seesawing of deep water production between the Atlantic and Southern Oceans [*Broecker et al.*, 1999; *Seidov et al.*, 2001] have contributed to the timing and development of the MWP and LIA between the hemispheres.

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