ELSEVIER

Global and Planetary Change 33 (2002) 209–220

GLOBAL AND PLANETARY CHANGE

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A multi-millennial palaeoclimatic resource from *Lagarostrobos colensoi* tree-rings at Oroko Swamp, New Zealand

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Abstract

We describe the first results of a new dendroclimatic study in New Zealand using *Lagarostrobos colensoi* (silver pine) growing at Oroko Swamp in the West Coast of the South Island. This research has produced the first millennium-length tree-ring chronology from New Zealand, covering the period AD 816–1998. Statistical analysis of the climate signal in the chronology indicates that it reflects Austral summer temperatures with a high degree of fidelity, except for the post-1957 period when a stand-wide disturbance apparently impacted the trees. Locally abundant sub-fossil wood on the swamp surface has been used to extend the present chronology back beyond the ages of the living trees. However, a large amount of material is still available, so the prospect of extending this chronology further back in time is good. A comparison of the pre-20th Century temperatures estimated using the chronology with instrumental data over the 1900–1999 period indicates a change in variability from that of the 20th century. In addition, it appears that summer temperatures estimated over the period of most reliable tree-ring data prior to the instrumental record (AD 1200–1865) were considerably more variable and persistent than those found in the "modern" record. This result has implications in detection and attribution studies of greenhouse gas forcing because it suggests that Austral summer temperatures in this sector of New Zealand have been anomalous during the 20th Century relative to earlier times.

Keywords: dendrochronology; *Lagarostrobos colensoi*; New Zealand; climate reconstruction

1. Introduction

The need for centuries-long records of past temperature variation is increasing as efforts are being made to better understand recent warming trends in the Northern and Southern Hemispheres. These trends are believed to be partly forced by radiatively active "greenhouse" gases injected into the atmosphere by fossil fuel burning and other human activities (Intergovernmental Panel of Climate Change (IPCC), 1996). Recent attempts to reconstruct long-term records of hemispheric and global temperatures from multi-proxy networks of palaeoclimatic data have been reasonably successful (e.g. Jacoby and D'Arrigo, 1989; Jones et al., 1998; Mann et al., 1998, 1999). These reconstructions are especially important in detection and attribu-

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0921-8181/02/$ - see front matter
PII: S0921-8181(02)00078-4

tion studies of global warming (e.g. Santer et al., 1995; Jones et al., 1998; Barnett et al., 1999) because they supply estimates of natural variability prior to the buildup of greenhouse gases in the 20th Century. These estimates can be used to determine if recent temperature increases exceed the natural variability of the climate system.

Understanding the role of the ocean-dominated Southern Hemisphere in attribution and detection studies of global climate change is critically important because of the impact of ocean circulation dynamics and processes on climate in both hemispheres. Yet, there are very few sources of long, high-resolution palaeoclimatic data from the Southern Hemisphere that cover the past millennium. Notable exceptions include the multi-millennial tree-ring reconstructions of warm-season temperatures in Tasmania and South America (Lara and Villalba, 1993; Villalba et al., 1996; Cook et al., 2000), the temperature-related tropical ice core records from South America (Thompson, 1996; Thompson et al., 1995, 1998), and the Law Dome ice core from Antarctica (Morgan and van Ommen, 1997). While these records are important contributions, more are needed in other areas of the Southern Hemisphere, such as New Zealand.

New Zealand has many long-lived tree species that can produce valuable records of past climate conditions from their ring-widths (e.g. Norton et al., 1989; Salinger et al., 1994; D'Arrigo et al., 1998; Xiong et al., 1998). Yet, until now, none have produced climatically sensitive tree-ring chronologies that span the past millennium. Here we report on the development of the first such record from New Zealand and its climatic interpretation. This work is in an early stage of development, but the results show that there is an excellent opportunity to develop a multi-millennial record of past temperatures from New Zealand from the endemic conifer *Lagarostobos colensoi* (silver pine) growing in Oroko Swamp on the South Island of New Zealand.

2. Area description, methods and material studied

2.1. Oroko Swamp

Oroko Swamp is located on the West Coast of South Island of New Zealand (lat. 43°14′ S, long. 170°17′ E, elev. 110 m.a.s.l.), south of the town of Hokitika. The map in Fig. 1 shows its location, along with that of Hokitika where instrumental temperatures are available to calibrate the climate information in the tree rings. The landform around Oroko Swamp consists of Pleistocene glacial moraines and outwash terraces. The soils experience high rainfall and have become very strongly leached, often podzolised, and of very low nutrient status. They tend to be accompanied by very poor drainage and aeration due to the presence of poorly structured, silty upper horizons and/or the occurrence of pans at depth (Almond, 1997). Oroko Swamp is infertile and acidic with a substrate consisting of structureless peat of varying depth. In some areas, the peat contains portions of buried logs and/or lenses of fine silt.

The vegetation pattern is similar to that described by Wardle (1977, 1991) for other infertile swamps and bogs of Central Westland lowlands. Distinct changes in species composition occur from the centre to the outer edges, often referred to as ecotones, which broadly reflect a moisture/drainage gradient. The *L. colensoi* trees tend to occur as a zone in transition between the *Leptospermum scoparium* (tea tree) monoculture near the swamp centre and the *Dacrydium cupressinum* (rimu) dominated forest on the surrounding moraines and terraces. Trees progressively increase in size with the stunted *L. scoparium* being only 2–3 m tall near the centre, while *D. cupressinum* reaches 30 m. *L. colensoi* were usually 12–15-m tall but some trees could be as tall as 20 m. In the area dominated by *L. colensoi*, other associated tree and shrub species included *Phyllocladus alpinus*, *Weinmannia racemosa*, *Elaeocarpus hookerianus*, *Quintinia acutifolia*, *Neomyrtus pedunculata*, *Podocarpus acutifolius*, *Coprosma* spp. and a few scattered clusters of *Libocedrus bidwillii*.

2.2. Lagarostrobos colensoi at Oroko Swamp

L. colensoi is in the family Podocarpaceae and is a very slow growing, long-lived conifer with a confirmed maximum age in excess of 800 years. This species was investigated for dendroclimatic potential by LaMarche et al. (1979) and D'Arrigo et al. (1998) at two sites: Ahaura on the South Island, and Mangawhero on the North Island (see Fig. 1). The tree-ring

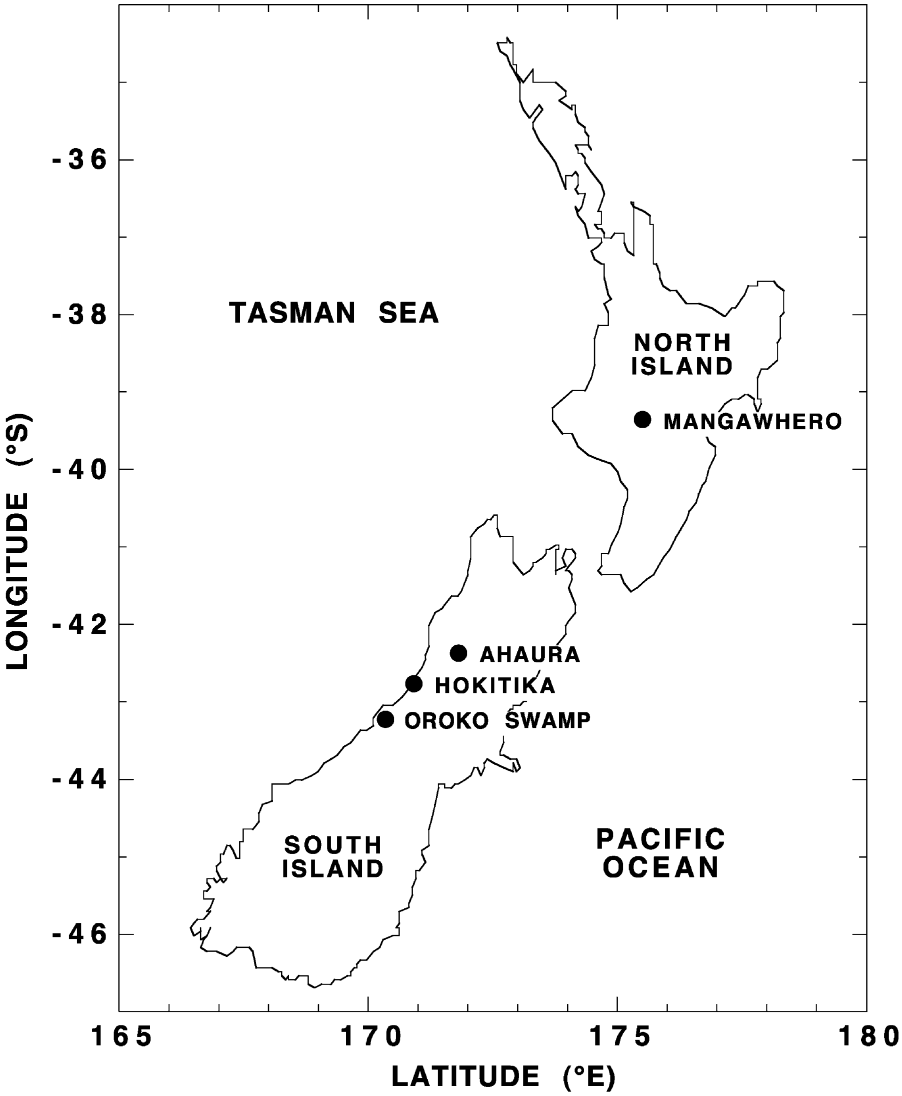

Fig. 1. Map of New Zealand showing the location of the Oroko Swamp *L. colensoi* site. Hokitika, where the temperature data come from for modeling the dendroclimatic signal, is northeast of the swamp. Two other *L. colensoi* sites at Ahaura and Mangawhero, previously studied by D'Arrigo et al. (1998), are also shown.

chronologies developed from those sites demonstrated that *L. colensoi* could be successfully cross-dated (LaMarche et al., 1979). In addition, the results of D'Arrigo et al. (1998) proved that ring-width variations of this species had a statistically significant correlation with warm-season (November–April) temperatures. Consequently, *L. colensoi* has proven dendroclimatic value in New Zealand.

The species has another attribute that makes it especially valuable for study. The wood is remarkably resistant to decay in the same way as the only other species in the genus, Huon pine (*Lagarostrobos franklinii*) in Tasmania (see Cook et al., 2000 and references therein). Thus, there is the potential for using well-preserved, sub-fossil *L. colensoi* wood to extend these dendroclimatic records back well beyond the ages of the living trees. As far as is known, Oroko Swamp is unique among the three sampled *L. colensoi* sites in New Zealand because of its supply of subfossil wood lying on or just below the surface.

Although the Oroko Swamp forest has living trees growing on it that are many centuries-old, it has not been immune from natural or human disturbances. In fact, there are the remains of a small-gauge tramline in part of the swamp that was used to log selected *L. colensoi* during the 20th Century. The presence of this known disturbance, along with patches of naturally fallen trees, prompted us to conduct a detailed disturbance history study in the swamp.

3. Results and analyses

3.1. Oroko Swamp disturbance history

In 1999, a 10-m-wide, 350-m transect was undertaken from east to west in Oroko Swamp. This transect followed a natural moisture/vegetation gradient from the relatively "drier" *D. cupressinum* dominated eastern end to the "wetter" *L. scoparium* dominated western end. Within this 10-m-wide transect, every fallen *L. colensoi* tree and any remnant log (with at least its root plate intact) within the corridor was sampled to allow the year of death to be determined. In total, 96 trees were sampled, either as a cross-section or increment core. Information on the presence or absence of bark was recorded. In the case where bark was not present, a corrected mortality date was estimated by adding the mean number of sapwood rings present in the living trees to the outer ring date of the dead tree as determined by cross-dating. The number of sapwood rings was 48 ± 17 years, so the corrected mortality dates are somewhat imprecise. However, they are probably more accurate than the uncorrected dates. Of the 96 trees sampled, only 71 were successfully cross-dated. Those that did not generally contained an insufficient number of tree rings (<200).

Mortality dates are being used here to infer severe disturbance history. If the distribution of mortality dates occurs more or less randomly along the transect line, and through time, it implies that local or endogenous processes were responsible for tree death. In contrast, a clustering of mortality dates would indicate the occurrence of a stand-level disturbance by exogenous or external processes, like wind-throw or seismic events.

The results of this disturbance study are shown in Fig. 2, with year of death plotted as a function of distance along the transect line. Two patterns are evident in this relationship. First, there appears to be a general trend in mortality dates from east (drier) to west (wetter), with mortality being greater in the more recent time in the wetter end of the transect. This suggests that *L. colensoi* is more susceptible to death in the wetter areas, perhaps because it is less root firm. Second, there appears to be another cluster of mortality dates that is independent of the trees' location along the transect line. The cluster occurs in the 20th Century and has a median mortality date of 1956. We interpret this clustering to be related to the logging activity known to have occurred around that time. Although there was no evidence of cut stumps along the transect line, the cutting nearby would have opened up the forest and perhaps made it more susceptible to wind-throw. *L. colensoi* is also known to form root grafts between individuals, producing an interlinked network (Moar, 1955). Alternatively, the hydrology of the swamp may have been altered when drains associated with road construction and light rail access for milling were put into the area.

The results of this study indicate that *L. colensoi* at Oroko Swamp has probably experienced a stand-wide disturbance in the 20th Century that is probably related to human activity. However, the exact mechanism that led to widespread mortality is presently unknown. As will be shown later, this effect is also evident in the response of the surviving *L. colensoi* to climate.

3.2. The *L. colensoi* tree-ring chronology

Using the tree-ring samples obtained from living trees, plus those obtained from the disturbance history analysis above, we developed a chronology suitable for dendroclimatic analysis covering the period AD 816–1998. This process involved the application of the usual procedures of tree-ring dating, followed by standardization (Cook, 1985) to remove growth trends in the individual ring-width series believed to be unrelated to climate. Because *L. colensoi* is a shade-tolerant species growing in a highly competitive

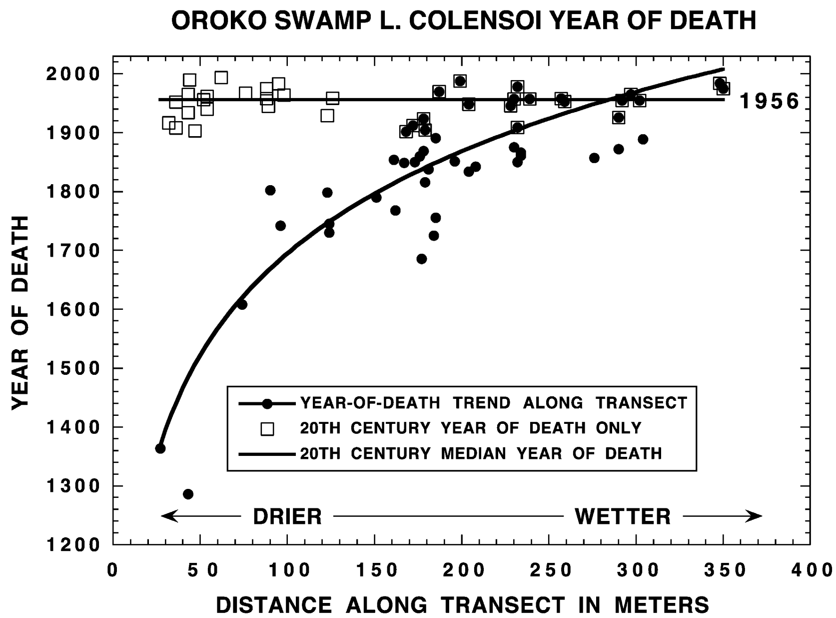

Fig. 2. *L. colensoi* mortality along the disturbance transect in Oroko Swamp. Two distinct patterns of mortality dates are indicated, one that appears related to transect location (●) from drier (older dates) to wetter (younger dates) and another that is independent of transect location (□). The latter is probably related to known logging activity during the 20th Century in the swamp.

closed-canopy forest, we detrended the data with cubic smoothing splines (Cook and Peters, 1981) with a 50% frequency response cutoff equal to 67% of the series length. This method preserves most of the resolvable low-frequency variance given the lengths of the series being detrended (Cook et al., 1995). In addition, we first stabilized the variance of the series before standardization by applying data-adaptive power transformations (Cook and Peters, 1997). This method avoids possible bias in the resulting tree-ring indices.

The mean tree-ring chronology is shown in Fig. 3. The top plot shows the annual chronology values in dimensionless tree-ring index form (Cook, 1985), with a low-pass filtered curve superimposed to illustrate inter-decadal variations. The median segment length used in creating this average series is 305 years. Given the smoothing spline method of detrending used, this means that the maximum useful low-frequency variance retained in this series is on the order of 200 years. The standardization process has removed any longer-term climatic fluctuations.

The bottom plot in Fig. 3 shows the number of tree-ring measurements that were used each year in creating the mean chronology. The sample size changes considerably and remains uniformly below 20 measurements per year prior to AD 1500. However, this information is not in itself sufficient to determine how reliable the time series is for interpretation prior to that time. Rather, it is useful in estimating the changing common signal strength of the tree-ring chronology over time.

The average correlation between all series (RBAR) in this chronology is 0.245, which is an expression of the percent variance in common. RBAR ranges from 0.0 to 1.0, i.e. from no common variance to perfect common variance. As such, it is an unbiased measure of common signal strength in the series, which is independent of sample size (Wigley et al., 1984). A second statistic that is very useful for assessing chronology reliability is the expressed population signal (EPS) statistic. It measures how well the finite-sample chronology compares with the theoretical population chronology based on an infinite number of trees (Wigley et al., 1984). Like RBAR, EPS ranges from 0.0 to 1.0, i.e. from no agreement to perfect agreement with the population chronology. EPS differs from RBAR because it depends on both

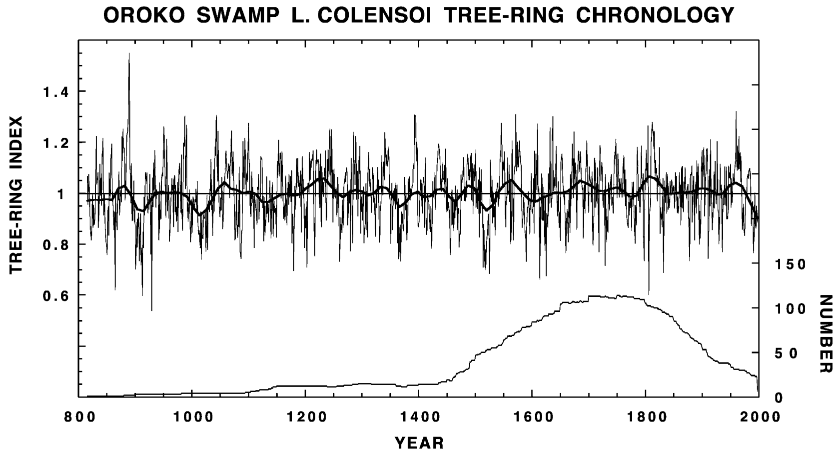

Fig. 3. The Oroko Swamp *L. colensoi* tree-ring chronology. The upper plot shows the annual tree-ring indices with a low-pass filtered version superimposed to highlight the inter-decadal fluctuations. The lower plot shows the changing sample size for each year.

the value of RBAR itself and the number of trees used in the mean chronology.

The signal strength of a tree-ring chronology usually changes with time as a function of fluctuations in the local value of RBAR and changing sample size (Briffa, personal communication), which in turn affects EPS. Therefore, it is useful to examine the temporal properties of RBAR and EPS to get a better understanding of where the chronology may become unreliable for interpretation. Fig. 4 shows a running series of RBAR and EPS, based on a 50-year moving window with 25-year overlaps. The mean RBAR quoted above is plotted for comparison in the upper running-RBAR plot. It differs from the mean of the running-RBARS (0.28) because of the overlapping nature of these statistics. In the lower running-EPS plot, a value of 0.85 is plotted as a rough cutoff point for accepting EPS. EPS values below 0.85 may be considered unacceptable. However, this 0.85 cutoff is rather arbitrary and should be used only as an approximate guide (Wigley et al., 1984).

The running-RBAR and EPS plots show that the reliability of the chronology is not constant through time. Prior to AD 1200, RBAR declines sharply in one period, but overall the variations in this measure of signal strength are reasonably stable. EPS also remains stable and mostly above 0.85 back to AD 1200 and then declines systematically to a value below 0.50. This result is due to the decline in sample size indicated in Fig. 3. So for purposes of interpretation, the *L. colensoi* chronology is reasonably reliable back to AD 1200 only. Further collections of subfossil wood from Oroko Swamp will undoubtedly improve the sample size in the period prior to AD 1500 and thus provide a more reliable record of past climate in the region.

3.3. Climate modeling results

As noted earlier, *L. colensoi* appears to be a useful candidate for dendroclimatic analysis and temperature reconstruction based on the results of D'Arrigo et al. (1998). We will show next that this is the case for the Oroko Swamp chronology as well. This will be done first through a series of simple correlation analyses between monthly mean instrumental temperatures and the tree-ring chronology. Once the response to climate has been identified, we will use that model in a predictive sense to demonstrate the stability of the dendroclimatic relationship. Similar analyses (not shown) were also performed using monthly total precipitation data form Hokitika, but no significant relationships were found.

The monthly temperature data used here come from Hokitika (see Fig. 1). This record covers the period from 1866-to-present, though there is a gap in the data in 1881–1893. Without knowing a priori the nature of the temperature response, we calculated simple correlations between monthly mean temperature series and tree rings. The temperatures represent

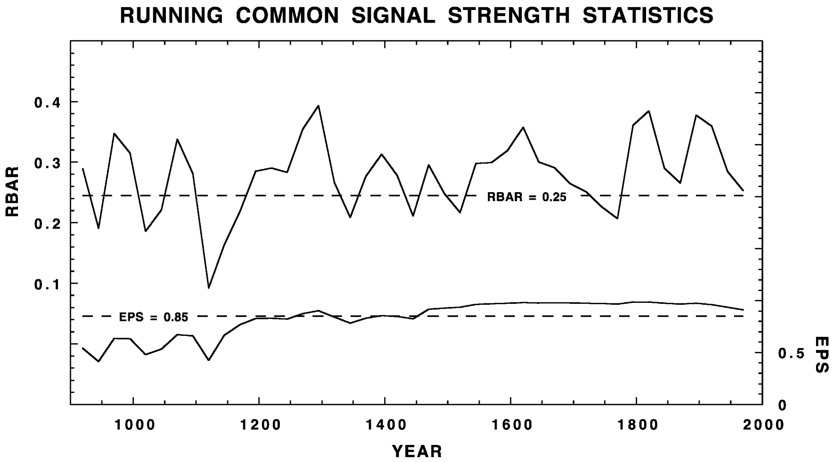

Fig. 4. Running RBAR and EPS plots of the *L. colensoi* chronology based on a 50-year window with 25-year overlaps. See the text for more details.

a 21-month "dendroclimatic year" from September prior to the radial growth year through to the current May. This broad dendroclimatic window was chosen to identify possible effects of antecedent climate on radial growth potential. See Fritts (1976) for many examples of this phenomenon in tree rings and a discussion of the physiological basis for its existence.

Separate correlations were computed over two time periods: 1894–1998 and 1894–1957. The latter (shortened) period was chosen after it was realized that the stand-level 20th Century mortality event shown in Fig. 2 had a pronounced non-climatic influence on the surviving *L. colensoi*. The correlations were also calculated using temperature and tree-ring data with (RED) and without (WHT) the presence of "red noise" or positive autocorrelation, which is commonly found in tree-ring series and temperature data. This was done to demonstrate that the significant correlations indicated below are not unduly influenced by autocorrelation in the data.

An examination of Fig. 5 shows that Oroko Swamp tree rings are positively correlated ($p < 0.05$) with monthly temperature over a broad window of months from September to May of the current growth year. This was the case whether the RED or WHT data were used. In addition, there is little evidence for strong preconditioning of radial growth by temperatures in the months prior to the current September, especially after autocorrelation was removed. This simplifies the use of this chronology for reconstructing past climate. The correlation plots also show the impact of the stand-level mortality event on the temperature response of the surviving trees. In every case, the September–May correlations are markedly lower if the post-1957 tree-ring data are included. Indeed, if the correlations are calculated for the post-1957 period of temperature (January–March), the results with either RED or WHT data never exceed $r = 0.09$. This catastrophic loss of climate correlation in the surviving trees confirms that a stand-level disturbance occurred. It is likely that the cause is the known logging activity described earlier. However, the exact effects of this disturbance on the surviving trees are unknown. The short-term growth release indicated in the chronology after 1957 may be related to the thinning of the stand caused by the logging. In addition, the water table of the swamp was probably lowered somewhat by culverts installed during road and tramway construction, which may have contributed to the prolonged growth reduction in the chronology following the release.

The results of the correlation analyses shown in Fig. 5 indicate that Oroko Swamp *L. colensoi* is responding to warm season (September–May) temperatures during the year concurrent with radial growth. The correlations in this overall 9-month response window are mostly significant ($p < 0.05$), with several exceeding the 99% confidence level, provided the analyses are

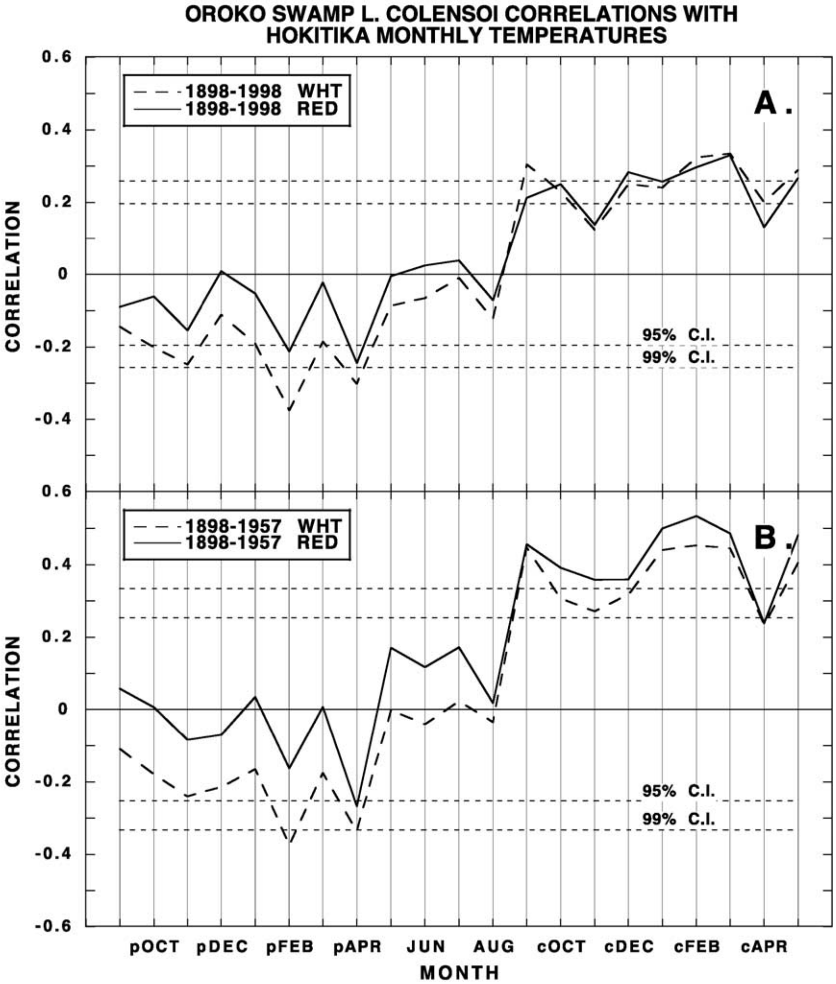

Fig. 5. The correlations between Oroko Swamp *L. colensoi* tree rings and Hokitika monthly temperatures. The dendroclimatic year is 21 months long and extends from September of the previous radial growth year to the May of the current growth year. See the text for further details.

restricted to the pre-disturbance period (Fig. 5B). However, correlations in some months like November and April are noticeably weaker, while in others, like January–March, they are noticeably stronger. For purposes of dendroclimatic interpretation, it would be useful to know if certain monthly combinations of temperature are more representative as growth predictors than others. Therefore, we performed three calibration/verification experiments, using different monthly temperature combinations: September–May, September–March, and January–March. These experiments were performed on the 1894–1957 pre-disturbance RED tree-ring data using the Hokitika temperature data. The early Hokitika data (1866–1880) not used in the previous correlation analyses were used to verify the three models.

Table 1 shows the results of these experiments. The calibration results are all significant ($p < 0.01$) and nearly identical for the September–May and September–March models ($r = 0.52$ and 0.53, respectively). In contrast, the January–March model is somewhat better ($r = 0.61$). This separation between the models is accentuated in the verification results where only the January–March season is significant ($r = 0.64$, $p < 0.01$). Consequently, the shorter January–March season appears to be the most stable and dependable

Table 1
Calibration/verification results of three competing temperature response models for Oroko Swamp *L. colensoi* based on the temperature correlations shown in Fig. 5

Season	Months	Calibration	Years	r	Verification	Years	r
September–May	9	1894–1957	64	0.52*	1866–1880	15	0.43
September–March	7	1894–1957	64	0.53*	1866–1880	15	0.41
January–March	3	1894–1957	64	0.61*	1866–1880	15	0.64*

The temperature data are from Hokitika. Note that the 1958–1998 tree-ring data have not been used because of the stand-wide disturbance that occurred in the late-1950s. In addition, the Hokitika temperature data for 1881–1893 are missing. Given these limitations, the January–March temperature season is the most stable temperature response model with nearly equal skill in both the calibration and verification periods.

* $p < 0.01$.

temperature response model for interpreting the climatic signal in the Oroko Swamp *L. colensoi* tree-ring chronology.

The strength and stability of the January–March temperature model is somewhat surprising considering that Oroko Swamp is a low-elevation site. D'Arrigo et al. (1998) found the highest correlations between *L. colensoi* tree rings and warm-season temperatures were for the high-elevation (1000 m) Mangawhero site on the North Island (RED $r = 0.73$ and WHT $r = 0.59$). In contrast, the low-elevation (200 m) Ahaura site on the South Island correlated much more weakly with warm-season temperatures (RED $r = 0.27$ and WHT $r = 0.27$). In Tasmania, where the only other *Lagarostrobos* species lives, the ring widths of Huon pine (*L. franklinii*) are only useful for dendroclimatic interpretation at high-elevation sites above 800 m (Buckley et al., 1997). Yet, the low-elevation (110 m) Oroko Swamp tree-ring chronology correlates as well with temperature as the high-elevation (950 m) Mt. Read Huon pine chronology (see Cook et al., 2000). Whether this is due to intrinsic genetic differences between these two related species or due to certain site characteristics at Oroko Swamp that cause *L. colensoi* to respond to climate in a "high-elevation way" is unclear.

4. Discussion and conclusions

The net result of the calibration exercises shows that Oroko Swamp *L. colensoi* can be used as a reliable proxy of high-summer (i.e. January–March) temperatures for this part of the New Zealand South Island. With the current chronology, this conclusion applies only to the AD 1200–1957 period. The weak chronology signal strength prior to AD 1200 and the disturbance impact after 1957 render those periods presently non-interpretable. Given these limitations, it is possible to compare the 20th Century with the prior seven centuries of inferred high-summer temperature. However, to do this for the full 20th Century requires that the instrumental data be spliced in with the tree-ring estimates to account for the loss of signal in the tree rings after 1957. This has been done in Fig. 6, with the actual temperatures scaled to have the same amplitude as the tree-ring estimates based on the 1866–1957 calibration period results.

Fig. 6 shows that 20th Century January–March temperatures on the West Coast of the South Island have not been very unusual relative to the past 700 years. There is little trend in the instrumental data up to 1999 and little in the way of long-term, low frequency behavior in the tree-ring estimates either in the overlap period with the instrumental data (Fig. 6B) or further back in time (Fig. 6A). This result might seem contrary to the expectation of a warming signal consistent with the hemispheric trend. However, it probably reflects both the more local nature of climate in the Tasman Sea area and the Austral summer season being reconstructed. This interpretation is supported by the rotated principal components (RPC) analysis of New Zealand instrumental temperature data published by Salinger and Mullan (1999). They found that the scores of RPC #3, which represented the South Island west and south, showed smaller increases in temperature compared to RPCs #1 and #2 representing the North Island and the East Coast. Further back in time, the reconstruction indicates that there have been several periods of above and below average temperature that have not been experienced in the 20th Century. This result indicates

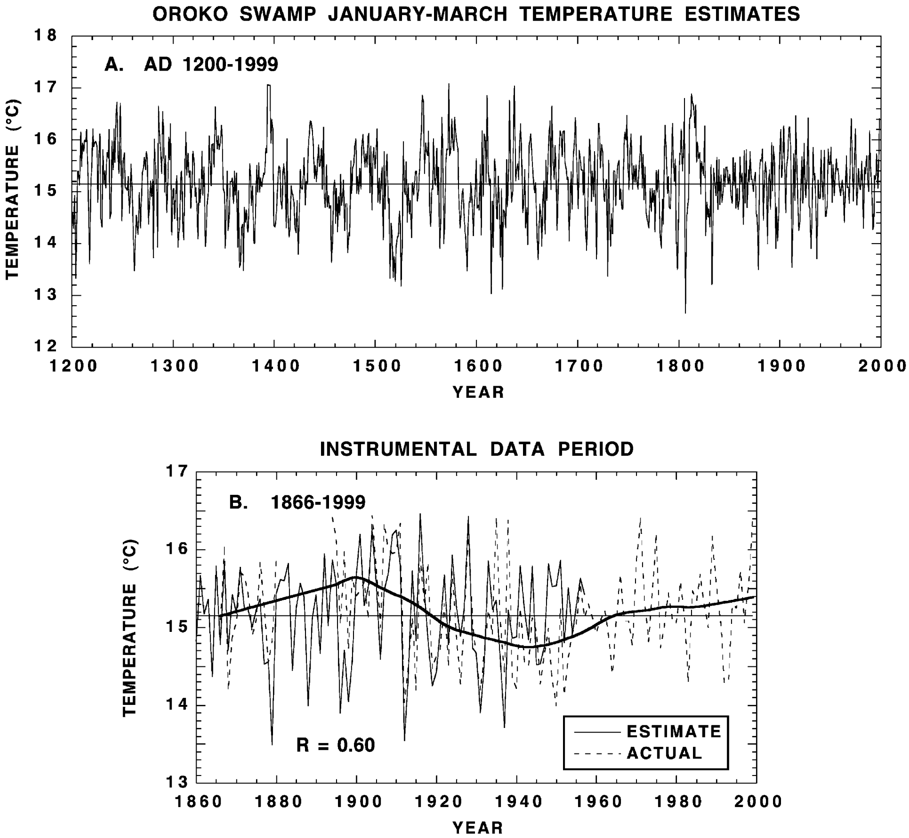

Fig. 6. Reconstruction of January–March temperatures from Oroko Swamp *L. colensoi* tree rings (A). The calibration is based on joint 1866–1957 tree-ring and temperature data only (B) because of the post-1957 disturbance in the tree rings. The actual temperatures, scaled to the same amplitude as the tree-ring estimates, have been appended to the tree-ring estimates to allow for an evaluation of temperatures up to 1999.

that natural variability has been larger in the past relative to recent decades, an important finding that relates to the problem of detection and attribution (Barnett et al., 1999).

Coupled with the abundant supply of well-preserved sub-fossil wood at this site, Oroko Swamp has the potential to be as significant to Southern Hemisphere palaeoclimatology as the Mt. Read site in Tasmania (Cook et al., 2000) has been. Literally hundreds of *L. colensoi* logs are scattered on the forest floor of Oroko Swamp, so it ought to be possible to both solidify and extend the present chronology back in time. Some of this surface sub-fossil wood is already being used in a highly detailed analysis of the inter-hemispheric offset in atmospheric radiocarbon concentrations back in time (McCormac et al., 1998). So, dendrochronologically dated wood from Oroko Swamp will have important uses in isotope geochemistry as well.

Many *L. colensoi* logs also exist beneath the surface of Oroko Swamp. Samples from two such logs were obtained from a shallow pit. These logs, one just under the surface and a second one beneath it, have radiocarbon dates of 3590 ± 55 and 5710 ± 60 years before present (Radiocarbon Dating Laboratory, University of Waikato, Hamilton). So, it is clear that a multi-millennial tree-ring chronology of *L. colensoi* can be developed from wood available at Oroko Swamp. This chronology would be an excellent complement to the multi-millennial Huon pine chronologies being developed in Tasmania and add another important location on the Southern Hemisphere map.

Acknowledgements

We thank Jon Pilcher and Mike Baillie (Queens University, Belfast), Kathy Allen (University of Tasmania), Xiong Limin and Sandy Hammond (Lincoln University), Brendan Buckley and Joan Basher (Lamont-Doherty Earth Observatory), and Ian James for their help in various stages of the fieldwork and laboratory processing of the tree-ring samples. We also thank Keith Briffa for correcting the senior author's "colonial English" and the comments of anonymous reviewers. This research was supported by the National Science Foundation (Grants ATM 96-27318 and ATM 96-16975) and the National Oceanic and Atmospheric Administration (Grant NA96GP0445). Lamont-Doherty Earth Observatory Contribution No. 6314.

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