RADIOCARBON, Vol 53, Nr 3, 2011, p 529–542

HIGH-PRECISION RADIOCARBON MEASUREMENTS OF TREE-RING DATED WOOD FROM NEW ZEALAND: 195 BC–AD 995

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ABSTRACT. The best means for correcting Southern Hemisphere (SH) radiocarbon measurements, which are significantly influenced by temporal variations in the interhemispheric offset, is by the construction of a SH-specific calibration curve from dendrochronologically dated wood. We present here decadal ^{14}C measurements on dendrochronologically secure New Zealand kauri (*Agathis australis*), covering the period 195 BC–AD 995, extending the range of calibration measurements from New Zealand tree rings to more than 2 millennia.

Recently published Tasmanian huon pine (*Lagarostrobos franklinii*) data for the interval 165 BC to AD 1095 measured at the Center for Accelerator Mass Spectrometry (CAMS) have underestimated standard errors, which need to be re-assessed before the data can be considered for a Southern Hemisphere calibration curve update. The CAMS huon data, unlike the Waikato kauri data presented here, show a significant reduction in the SH offset for the interval AD 775–855. Although these data points are being checked, it is unlikely this represents a temporal geographic location-dependent offset. With re-assessed errors, the huon data set from 165 BC to AD 995 closely matches the new kauri data, with the combined data sets producing a mean interhemispheric offset with IntCal09 of 44 ± 17 yr for the time interval 195 BC–AD 1845. This SH offset is lower than the modeled offset of 55–58 yr used in the construction of SHCal04, and we recommend the lower value be used in future SHCal updates. Although there is an apparent increase in higher frequency events in the SH offset (NZ kauri plus Tasmanian huon) from 200 BC–AD 1000, the reason for this remains unclear.

INTRODUCTION

Past global atmospheric radiocarbon levels have varied both temporally and spatially, as a result of fluctuating ^{14}C production rates and variations in the carbon cycle, particularly ocean atmosphere interactions. The temporal variations during the last 50 kyr have been detailed in the latest Northern Hemisphere (NH) internationally ratified calibration curve, IntCal09 (Reimer et al. 2009), which contains ^{14}C measurements accumulated over the last 3 decades, principally from tree rings, ocean sediments, marine varves, and corals. Definition of the geographic extent (and cause) of ^{14}C spatial variations has proved more elusive. The most extensive and widely recognized regional offset is the Southern Hemisphere (SH) or Interhemispheric offset, which results in SH samples being older than NH samples by a few decades. Although this natural offset was originally considered constant through time, studies on contemporaneous SH/NH wood decadal sample pairs for the time interval AD 950–1850 have shown the ^{14}C offset varies periodically (~130 yr periodicity) with amplitudes varying between 1 and 10‰ (i.e. 8–80 yr, McCormac et al. 2002). This offset is probably related to the larger expanse of the SH oceans and associated ocean atmosphere CO_2 exchange, but the exact mechanism determining the magnitude and variability of the offset remains unclear.

Hogg et al. (2009a) used Bayesian ^{14}C wiggle-matching techniques to analyze 5 accurate and precise floating Holocene SH data sets ranging in age from 1.9 to 10.2 kyr BP, and found interhemispheric offset levels similar to modern values. This approach cannot presently be used to investigate the offset for time periods earlier than 12.5 kyr BP, however, as IntCal09 is too imprecise, being based upon marine data sets with associated reservoir uncertainties (Turney et al. 2010).

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New SH ^{14}C measurements from dendrochronologically secure wood have been limited to 2 studies, one using New Zealand kauri (*Agathis australis*, this paper; see also Hogg et al. 2009b) and another using Tasmanian huon pine (*Lagarostrobos franklinii*, Zimmerman et al. 2010). The SH offset for the 1st millennium AD was investigated by Hogg et al. (2009b) using 20 dendrochronologically secure contemporaneous New Zealand kauri/British oak decadal sample pairs. They found an average interhemispheric offset of 35 ± 6 yr (or 35 ± 20 yr where the standard deviation is based on the spread in the differences) and noted that although this value was consistent with previous measurements, it was lower than the offset of 55–58 yr used in the construction of the SH calibration curve SHCal04 (McCormac et al. 2004). Measurements from Tasmanian huon pine for the interval 165 BC–AD 1095 (Zimmerman et al. 2010) showed evidence for a distinct but variable offset, including a zero offset for an 80-yr period (AD 775–855). The authors plan further work to verify the zero offset for this time interval.

The best means for correcting SH measurements, which are significantly influenced by the temporal variations in the interhemispheric offset, is construction of a SH-specific calibration curve from dendrochronologically dated wood (McCormac et al. 2004). The initial SH calibration curve, SHCal02 (McCormac et al. 2002), was restricted to the last millennium (AD 955–1955) and based upon data from New Zealand (Hogg et al. 2002), Chile and Tasmania (Stuiver and Braziunas 1998), and South Africa (Vogel et al. 1993). Its successor, SHCal04 (McCormac et al. 2004), used a random effects model that applied an offset from the NH IntCal04 data set of 55–58 yr, permitting calibration back to 11 kyr cal BP. Calibration beyond 11 kyr cal BP was not recommended because of the possibility of large-scale carbon reservoir changes. The authors, however, noted that the average offset for the last 500 yr of the modeled data set SHCal04 was 56 ± 24 yr (McCormac et al. 2004).

We present here 120 high-precision (~2‰) decadal ^{14}C measurements of dendrochronologically secure New Zealand kauri from 195 BC to AD 995 to extend the SH measured tree-ring data set and to assess the suitability of the modeled SHCal04 offset of 55–58 yr (McCormac et al. 2004) for the Holocene. The data will also be used for ^{14}C wiggle-match dating the Taupo Tephra, one of New Zealand's most widespread and important tephra marker beds. This research is an extension of the investigations into the interhemispheric offset for the 1st millennium AD presented by Hogg et al. (2009b). The paper also compares the New Zealand kauri and Tasmanian huon pine (Zimmermann et al. 2010) data sets in anticipation of their possible incorporation into a SH calibration update.

METHODS

Dendrochronology

A 1088-yr (AD 911–1998) tree-ring chronology from New Zealand kauri (*Agathis australis*) was originally built by Fowler et al. (2004) and strengthened and extended to 1724 BC by Boswijk et al. (2006). The tree-ring samples for this study were obtained from 3 sites, Maitahi, Chitty, and Harding (Table 1), near the town of Dargaville, Northland, New Zealand. All samples, which offer good cross-matches to other samples (Table 2), were cross-matched against other sequences from the same sites to develop site chronologies and calendar dated by comparison of site chronologies. Lower values were only obtained between series with short overlaps (where comparison was between "old" and "young" trees).

The samples cover 1200 calendar years from 195 BC to AD 995 (Figure 1). Sequential decadal (i.e. 10 annual rings) samples were extracted, following the protocol xx1 – xx0 with no zero year (i.e....BC 1–10; AD 1–10...).

Table 1 Site location details of the 4 kauri trees used in this study.

Site	Code	Latitude (S)	Longitude (E)	Nr kauri samples	ID of log used	Time range
Maitahi	MAIT	35°50′55″	173°45′08″	9	MAI001	576 BC–AD 370
Harding	HARD	36°00′04″	173°50′06″	13	HAR010	AD 610–1152
					HAR005	AD 124–686
Chitty	CHIT	35°57′38″	173°50′32″	15	CHI003	AD 252–842

Table 2 Summary cross-dating information of the 4 kauri trees used to provide samples for ^{14}C dating.[a]

	MAIT001 *576 BC* *AD 370*	**CHIT003** *AD 252* *AD 842*	**HARD010** *AD 610* *AD 1152*
CHIT003 *AD 252* *AD 842*	$t = 4.49$ $r = 0.39$		
HARD010 *AD 610* *AD 1152*		$t = 9.31$ $r = 0.53$	
HARD005 *AD 124* *AD 686*	$t = 8.63$ $r = 0.49$	$t = 11.28$ $r = 0.48$	$t = 3.3$ $r = 0.36$

[a] The t values are calculated based on Baillie and Pilcher (1973), and the r value is Pearson's correlation coefficient, as implemented in Dendro for 32-bit Windows (Tyers 2004).

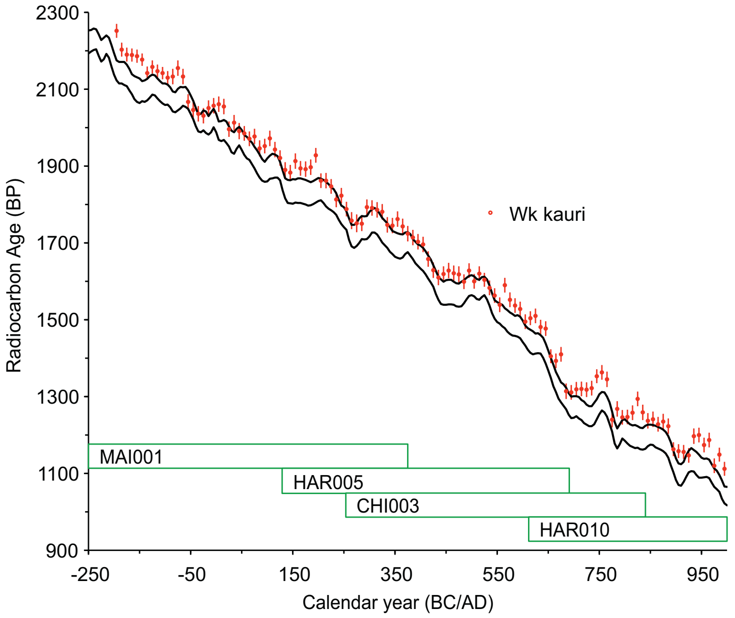


Figure 1 ^{14}C measurements (1σ errors) from dendrochronologically dated New Zealand kauri; overlain by the 95% probability envelope of IntCal09 (Reimer et al. 2009). The tree-ring periods covered by the 4 trees utilized in this study are also shown.

Sample Pretreatment

All samples in this study have been pretreated to α-cellulose, which represents about 40% by weight of total wood components and the most chemically resistant fraction. The wood was chipped and ground to pass a 20-mesh sieve, and then subject to a 4-step chemical pretreatment regime (Hogg et al. 2007):

1. Solvent extraction (3 steps: chloroform/ethanol, ethanol, distilled water);
2. Bleaching with acidified $NaClO_2$;
3. NaOH extraction under a N_2 gas atmosphere;
4. Acidification with HCl followed by rinsing in distilled water.

^{14}C Measurement

The ^{14}C dates were determined by liquid scintillation counting (LSC) of benzene using PerkinElmer Wallac 1220 Quantulus™ spectrometers and laboratory procedures optimized for high-precision measurement (Hogg et al. 2007). The precision of each decadal measurement is approximately ±20 yr. The higher levels of precision are achieved using "Waikato" large-volume synthetic silica counting vials (Hogg 1993) with higher benzene weights (7.5 g) and long measurement times (6–7k min per sample). Oxalic acid (HOxII) was used as the primary standard and $\delta^{13}C$ measured to enable fractionation correction. Every third high-precision benzene sample analyzed was the secondary standard ANU sucrose (IAEA C-6), which is used to monitor long-term vial and counter stability and for assessment of reproducibility. All of our measurements of ANU sucrose as a secondary standard over the last 3 yr result in an average value of 150.33 ± 0.05 pMC. This value is significantly lower than the IAEA C-6 standard value of 150.61 ± 0.11 (Rozanski et al. 1992) but statistically indistinguishable from the consensus value (with Waikato/Hogg data removed) of 150.23 ± 0.13 pMC (calculated from data published in Xu et al. 2010: Table 2, p 872).

Background blank correction, equivalent to an apparent age of 58.2 ^{14}C kyr (0.071 ± 0.005 pMC), was achieved by ^{14}C analysis of the α-cellulose component of OIS 7 (~170 kyr) kauri (Hogg et al. 2006).

RESULTS AND DISCUSSION

The 1200 yr of decadal data are given in Table 3 and Figure 1.

Comparison with Previous Measurements

We checked the consistency between the new Northland kauri measurements and published New Zealand West Coast silver pine measurements for the interval AD 955–995. The results are shown in Table 4. The weighted mean difference between the 2 data sets is 5.6 ± 10.1 yr based upon 5 sample pairs. Using the χ^2 test for paired samples, there is no difference between the new Waikato (Wk) New Zealand kauri measurements and previously published Wk/QUB (Queen's University Belfast, radiometric) New Zealand silver pine at the 95% confidence level.

Comparison with Tasmanian Huon Pine

Zimmerman et al. (2010) reported ^{14}C measurements from 127 decadal wood samples of dendrochronologically secure Tasmanian huon pine (*Lagarostrobus franklinii*) from the Stanley River Basin (145°E, 42°S) for the time interval 165 BC to AD 1095. The ^{14}C measurements were made at the CAMS Lawrence Livermore AMS facility on wood pretreated by a modified de Vries acid-base-acid method.

Table 3 Radiocarbon measurements on decadal samples of New Zealand kauri, from 195 BC to AD 995 (decadal midpoints).

Dendro age	Lab nr	Midpoint BC/AD	Midpoint cal yr BP	$\delta^{13}C^{a}$ (‰)	^{14}C age (yr BP)	1σ error[b]
191–200 BC	23108	–195	2145	–22.7	2252	18
181–190 BC	23107	–185	2135	–22.5	2203	18
171–180 BC	23106	–175	2125	–22.5	2190	18
161–170 BC	23105	–165	2115	–22.3	2189	17
151–160 BC	23104	–155	2105	–21.7	2186	17
141–150 BC	23103	–145	2095	–21.9	2177	16
131–140 BC	23102	–135	2085	–22.1	2142	17
121–130 BC	23101	–125	2075	–21.8	2158	17
111–120 BC	23100	–115	2065	–21.7	2147	17
101–110 BC	23099	–105	2055	–22.1	2142	16
91–100 BC	23090	–95	2045	–22.3	2130	17
81–90 BC	23089	–85	2035	–22.5	2133	20
71–80 BC	23088	–75	2025	–22.3	2155	20
61–70 BC	23087	–65	2015	–22.4	2133	20
51–60 BC	23086	–55	2005	–22.8	2067	20
41–50 BC	20466	–45	1995	–22.3	2046	20
31–40 BC	20467	–35	1985	–22.0	2036	20
21–30 BC	20468	–25	1975	–22.1	2031	20
11–20 BC	20469	–15	1965	–21.7	2051	20
1–10	20470	–5	1955	–21.8	2057	20
AD 1–10	20471	5	1945	–22.0	2061	20
AD 11–20	20472	15	1935	–21.6	2055	20
AD 21–30	20473	25	1925	–22.0	1996	20
AD 31–40	20474	35	1915	–21.6	2013	20
AD 41–50	20475	45	1905	–21.8	1991	21
AD 51–60	20476	55	1895	–21.9	1985	19
AD 61–70	20477	65	1885	–22.0	1971	19
AD 71–80	20478	75	1875	–21.7	1977	20
AD 81–90	20479	85	1865	–21.3	1946	21
AD 91–100	20480	95	1855	–22.1	1952	19
AD 101–110	20481	105	1845	–22.2	1972	20
AD 111–120	20482	115	1835	–21.9	1943	20
AD 121–130	20483	125	1825	–21.6	1921	20
AD 131–140	20484	135	1815	–22.0	1890	20
AD 141–150	20485	145	1805	–22.2	1883	20
AD 151–160	20486	155	1795	–21.7	1913	20
AD 161–170	20487	165	1785	–21.2	1894	19
AD 171–180	20488	175	1775	–22.4	1892	20
AD 181–190	20321	185	1765	–22.2	1897	20
AD 191–200	20322	195	1755	–22.1	1928	19
AD 201–210	20323	205	1745	–22.1	1862	19
AD 211–220	20324	215	1735	–21.8	1862	20
AD 221–230	20325	225	1725	–21.6	1847	19
AD 231–240	20326	235	1715	–22.4	1813	20
AD 241–250	20327	245	1705	–22.2	1823	20
AD 251–260	20328	255	1695	–22.1	1788	19
AD 261–270	20329	265	1685	–21.8	1758	22

Table 3 Radiocarbon measurements on decadal samples of New Zealand kauri, from 195 BC to AD 995 (decadal midpoints). *(Continued)*

Dendro age	Lab nr	Midpoint BC/AD	Midpoint cal yr BP	$\delta^{13}C^{a}$ (‰)	^{14}C age (yr BP)	1σ error^{b}
AD 271–280	20330	275	1675	–21.3	1751	23
AD 281–290	20331	285	1665	–21.6	1750	19
AD 291–300	20332	295	1655	–20.9	1793	20
AD 301–310	20373	305	1645	–21.5	1791	20
AD 311–320	20374	315	1635	–22.4	1786	20
AD 321–330	20375	325	1625	–22.3	1781	20
AD 331–340	20376	335	1615	–21.9	1747	20
AD 341–350	20377	345	1605	–21.6	1745	20
AD 351–360	22043	355	1595	–21.0	1762	20
AD 361–370	22044	365	1585	–21.0	1743	20
AD 371–380	22045	375	1575	–20.9	1724	20
AD 381–390	22046	385	1565	–21.1	1714	20
AD 391–400	22047	395	1555	–21.1	1703	20
AD 401–410	22048	405	1545	–21.0	1696	20
AD 411–420	22049	415	1535	–21.4	1658	20
AD 421–430	21033	425	1525	–21.0	1629	20
AD 431–440	21034	435	1515	–21.5	1610	20
AD 441–450	21035	445	1505	–21.8	1619	20
AD 451–460	21036	455	1495	–21.6	1628	20
AD 461–470	21037	465	1485	–22.1	1621	20
AD 471–480	21038	475	1475	–21.4	1618	21
AD 481–490	21039	485	1465	–21.4	1599	19
AD 491–500	21040	495	1455	–21.6	1628	19
AD 501–510	21041	505	1445	–21.3	1600	19
AD 511–520	21042	515	1435	–21.1	1620	19
AD 521–530	21043	525	1425	–20.8	1604	18
AD 531–540	21044	535	1415	–20.8	1583	19
AD 541–550	21045	545	1405	–20.0	1563	19
AD 551–560	21046	555	1395	–20.9	1539	19
AD 561–570	21047	565	1385	–20.5	1590	19
AD 571–580	21101	575	1375	–21.3	1552	19
AD 581–590	21102	585	1365	–21.0	1537	19
AD 591–600	21103	595	1355	–21.2	1528	19
AD 601–610	21104	605	1345	–20.9	1495	19
AD 611–620	21105	615	1335	–21.2	1504	18
AD 621–630	21106	625	1325	–21.1	1510	19
AD 631–640	21107	635	1315	–21.2	1481	19
AD 641–650	21108	645	1305	–21.0	1477	19
AD 651–660	21109	655	1295	–21.3	1405	18
AD 661–670	21110	665	1285	–20.8	1393	19
AD 671–680	21111	675	1275	–18.7	1410	19
AD 681–690	22102	685	1265	–22.5	1314	20
AD 691–700	22103	695	1255	–22.5	1311	19
AD 701–710	22104	705	1245	–22.2	1319	19
AD 711–720	22105	715	1235	–21.4	1320	19
AD 721–730	22106	725	1225	–20.2	1318	19
AD 731–740	22107	735	1215	–22.7	1322	19

Table 3 Radiocarbon measurements on decadal samples of New Zealand kauri, from 195 BC to AD 995 (decadal midpoints). *(Continued)*

Dendro age	Lab nr	Midpoint BC/AD	Midpoint cal yr BP	$\delta^{13}C$[a] (‰)	^{14}C age (yr BP)	1σ error[b]
AD 741–750	22108	745	1205	–22.5	1353	18
AD 751–760	22109	755	1195	–22.5	1363	19
AD 761–770	22110	765	1185	–22.5	1345	20
AD 771–780	22111	775	1175	–22.4	1240	20
AD 781–790	22112	785	1165	–22.0	1268	20
AD 791–800	22113	795	1155	–21.7	1246	19
AD 801–810	22114	805	1145	–21.7	1247	19
AD 811–820	22115	815	1135	–21.6	1258	19
AD 821–830	22116	825	1125	–21.7	1294	19
AD 831–840	22117	835	1115	–21.3	1259	20
AD 841–850	22118	845	1105	–21.6	1237	20
AD 851–860	22119	855	1095	–21.6	1241	20
AD 861–870	22120	865	1085	–21.7	1228	19
AD 871–880	22163	875	1075	–22.1	1235	20
AD 881–890	22164	885	1065	–21.6	1223	20
AD 891–900	22165	895	1055	–21.6	1163	18
AD 901–910	22166	905	1045	–22.2	1158	18
AD 911–920	22167	915	1035	–21.1	1156	18
AD 921–930	22168	925	1025	–21.3	1147	19
AD 931–940	22169	935	1015	–21.4	1197	20
AD 941–950	22170	945	1005	–21.9	1200	19
AD 951–960	25205	955	995	–22.5	1174	19
AD 961–970	25206	965	985	–22.5	1187	19
AD 971–980	25207	975	975	–22.3	1120	19
AD 981–990	25208	985	965	–22.6	1149	18
AD 991–1000	25209	995	955	–22.1	1112	18

[a] With respect to VPDB.

[b] Includes lab error multiplier of 1.2.

Table 4 Offsets between new Waikato (Wk) kauri (*K*) measurements and published Waikato/Queen's University Belfast (QUB) NZ pine (*P*) measurements for the interval AD 955–995.

Dendro age	Midpoint (AD)	New Wk *K* age (yr BP)	Wk/QUB *P* age[a] (yr BP)	Difference (yr) Wk *K* – Wk/QUB *P*
AD 951–960	955	1174 ± 19	1175 ± 13	–1 ± 23
AD 961–970	965	1187 ± 19	1167 ± 13	20 ± 23
AD 971–980	975	1120 ± 19	1153 ± 12	–33 ± 22
AD 981–990	985	1149 ± 18	1141 ± 12	8 ± 22
AD 991–1000	995	1112 ± 18	1077 ± 14	35 ± 23

[a] Data from Hogg et al. (2002).

More than half (55%) of the decadal samples were replicated (38% duplicates, 15% triplicates, and 2% quadruplicates, Zimmerman et al. 2010: Table 2) with replicate ^{14}C ages reported as a weighted mean. The authors unfortunately did not include replicate data, but support the very low standard errors on the replicate measurements by showing that 63% of the 99 replicate analyses overlap at 1σ uncertainty based upon the analytical errors. However, 2 lines of evidence suggest the CAMS huon errors reported in Zimmerman et al. (2010: Table 2) are significantly underestimated.

Firstly, 2 process standards (Belfast cellulose and Irish oak Q1323), analyzed in conjunction with the CAMS huon pine measurements, show standard deviations based upon the spread in the measurements of between 34 yr (11 repeats) and 26 yr (18 repeats), respectively (Zimmerman et al. 2010: Table 1). A weighted mean of these 2 values suggests a value of ~ ±29 yr may be more appropriate for single measurements than the mean value of ~ ±17 yr used by Zimmerman et al. (2010).

Secondly, for a given time interval, the mean standard error of the measurements should be reflected in the magnitude of the age-corrected Δ^{14}C population standard deviation. Using the time interval 165 BC–AD 945, the Waikato data have a mean standard error of ±19 yr (~2.4‰) and an age-corrected Δ^{14}C population standard deviation of 4.1‰. This contrasts with the CAMS huon data set, for the same time interval, which, despite the significantly lower quoted average standard error of ±13 yr (~1.7‰), has a much higher age-corrected Δ^{14}C population standard deviation of 5.1‰. Although it is not possible to quantify the additional variance in the CAMS data set (because some of the spread in both data sets is due to real variations in atmospheric age-corrected Δ^{14}C over the period 165 BC–AD 945), it is clearly higher than that of Waikato and supports elevation of the CAMS standard errors as indicated above. If the CAMS huon data is to be utilized in an SHCal update, the replicate ^{14}C measurements will require rigorous statistical analysis, to provide more definitive ^{14}C standard errors for this data set.

Comparison of Wk Kauri and CAMS Huon Measurements

We re-assessed the CAMS huon data and assigned individual ^{14}C standard errors of ±29 yr based on the analysis above in order to permit a valid comparison of the Wk kauri and CAMS huon measurements. The huon analyses have therefore been assigned mean errors of ±29 yr (for single measurements), and making the assumption that replicate measurements are not statistically different, using Ward and Wilson's Case 1 (Ward and Wilson 1978), variance on the pooled ages results in errors of ±21 yr (duplicates), ±17 yr (triplicates), and ±15 yr (quadruplicates).

Figure 2 shows the individual measurements on Waikato (Wk) kauri and CAMS huon for the period 195 BC to AD 945. There is good agreement between the data sets except for a 90-yr interval from AD 775–855 where the huon data shows younger values. The weighted mean difference between the 2 data sets for this interval is 39.6 ± 10.4 yr based upon 9 sample pairs (Table 5). The Tasmanian huon pine samples from this interval will be reanalyzed by both Waikato and CAMS laboratories to see if the variations could represent a location-dependent geographic offset.

We checked the consistency in the ^{14}C measurements between individual New Zealand kauri and Tasmanian huon pine decadal samples (with elevated standard errors as above) using the χ^2 test for paired samples, for the time interval common to both data sets i.e. 165 BC to AD 945. Only 1 decadal pair (AD 825) failed the t test at the 95% confidence level (χ^2 test: $df = 1$, $t = 9.0$ (5% 3.84)). The weighted mean difference between the 2 data sets, from 165 BC to AD 945, is 5.9 ± 2.8 yr, with Waikato kauri data older. The difference drops to 3.3 ± 2.9 yr if the interval AD 775–855 is omitted. This laboratory offset compares favorably with the Belfast-Waikato offsets for the 2nd millennium AD New Zealand cedar/pine and British oak series of 3.9 to 4.5 yr (Hogg et al. 2002).

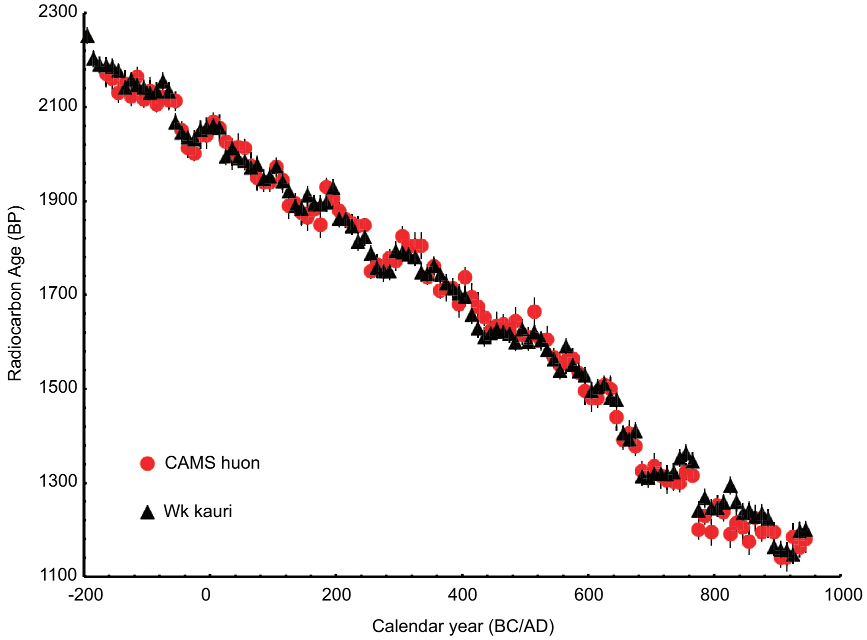


Figure 2 ^{14}C measurements (1σ errors) on decadal samples of dendrochronologically dated New Zealand kauri (Wk kauri) and Tasmanian huon pine (CAMS huon) for the interval 195 BC to AD 945.

Is there any other Evidence for Temporal ^{14}C Location-Dependent Geographic Offsets between Tasmania and New Zealand?

The CAMS huon data from AD 775–855 is 39.6 ± 10.4 yr younger than the Wk kauri data (Table 5) suggesting that temporal location-dependent offsets between Tasmania and New Zealand may be possible. To provide more data on this, we compared ANSTO ^{14}C ages from Tasmanian huon pine (Hua et al. 2004) with Wk/QUB ^{14}C ages from New Zealand cedar (Hogg et al. 2002) during a time period, the Little Ice Age, when perhaps climatic conditions might be expected to be more conducive to temporal location-dependent ^{14}C offsets. Sixteen decadal sample pairs from AD 1625–1775 are graphed in Figure 3. Only 1 decadal pair (AD 1655) failed the t test at the 95% confidence level (χ^2 test: $df = 1$, $t = 6.5$ (5% 3.84)). The weighted mean difference between the 2 data sets is 10.1 ± 6.5 yr with the ANSTO huon measurements older. Data from this time interval therefore does not support the contention of location-dependent offsets between Tasmania and New Zealand.

Interhemispheric Offset for the Interval 200 BC to AD 950

The mean differences (SH-NH) between the combined kauri/huon data set and IntCal09 from 185 BC to AD 945 are shown in Figure 4. The mean offset for the time interval 165 BC to AD 945 is 44 ± 18 yr (standard deviation based on the spread in the differences). This compares with mean offsets of 40 ± 13 yr (NZ cedar and pine minus British oak, AD 1850–950; Hogg et al. 2002), 41 ± 14 yr (SHCal02 minus IntCal98, AD 955–1955, McCormac et al. 2002), and 35 ± 20 yr (20 New Zealand kauri/British oak decadal sample pairs from 3 time periods in the 1st millennium AD, Hogg et al. 2009b). The interhemispheric offset for the combined kauri/huon data has amplitudes varying from –12 to 83 yr (compared with 8 to 80 yr for the 2nd millennium AD measurements, McCormac et al. 2002), but drops to –2 to 83 yr if the 9 decadal samples from AD 775–855 are omitted. The mean offset from 195 BC to AD 1845 is 44 ± 17 yr.

Table 5 Offsets between Wk kauri and CAMS huon pine measurements for the interval AD 775–855.

Dendro age	Midpoint (AD)	Wk kauri age (yr BP)	CAMS huon age[a] (yr BP)	Difference (yr) Wk kauri – CAMS huon
AD 771–780	775	1240 ± 20	1200 ± 21	40 ± 29
AD 781–790	785	1268 ± 20	1229 ± 17	39 ± 26
AD 791–800	795	1246 ± 19	1195 ± 29	51 ± 35
AD 801–810	805	1247 ± 19	1253 ± 21	–6 ± 28
AD 811–820	815	1258 ± 19	1238 ± 21	20 ± 28
AD 821–830	825	1294 ± 19	1190 ± 29	104 ± 35
AD 831–840	835	1259 ± 20	1215 ± 29	44 ± 35
AD 841–850	845	1237 ± 20	1205 ± 29	32 ± 35
AD 851–860	855	1241 ± 20	1175 ± 29	66 ± 35

[a] Data from Zimmerman et al. (2010) with single analysis CAMS errors set to ±29 yr—see text for more details. Wk = Waikato lab; CAMS = Center for Accelerator Mass Spectrometry.

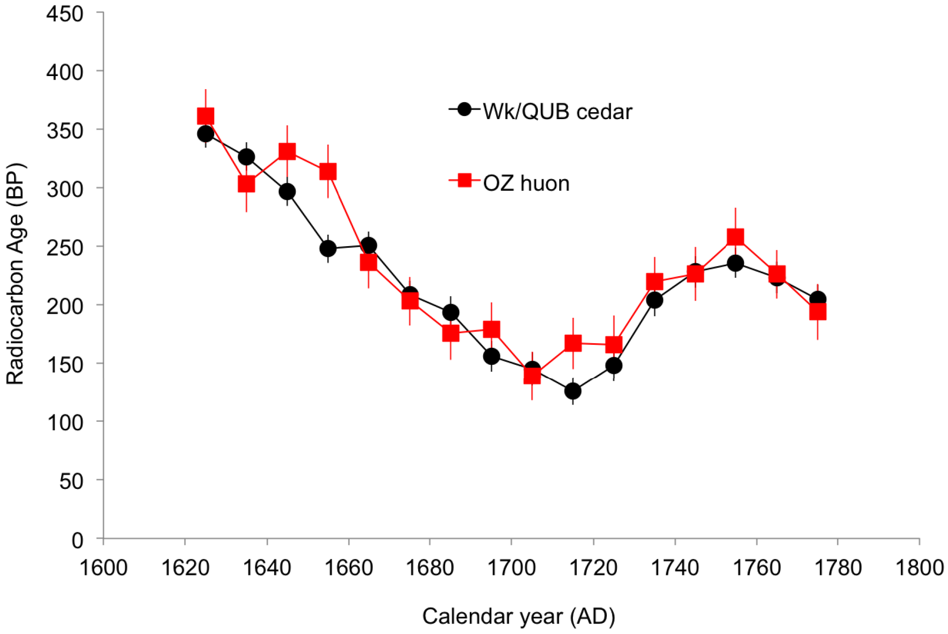


Figure 3 ^{14}C measurements (1σ errors) on decadal samples of dendrochronologically dated New Zealand cedar (mean Wk and QUB data; from Hogg et al. 2002) and Tasmanian huon pine (ANSTO - OZ huon data; from Hua et al. 2004) for the interval AD 1625 to 1775.

McCormac et al. (2004) utilized a random effects model to produce a modeled offset from the IntCal04 data set of 55–58 yr, with an uncertainty increasing from ±7.9 yr at 1000 cal BP to ±25 yr at 11.0 kyr cal BP (McCormac et al. 2004). A higher offset (i.e. 55–58 yr) than that measured (41 ± 14 yr) reflected the trend of the offset from 50–990 cal BP (McCormac et al. 2004). The 1150 yr of new SH measurements presented here suggests an offset of 55–58 yr may be too high, with a value of 44 ± 17 yr being more appropriate.

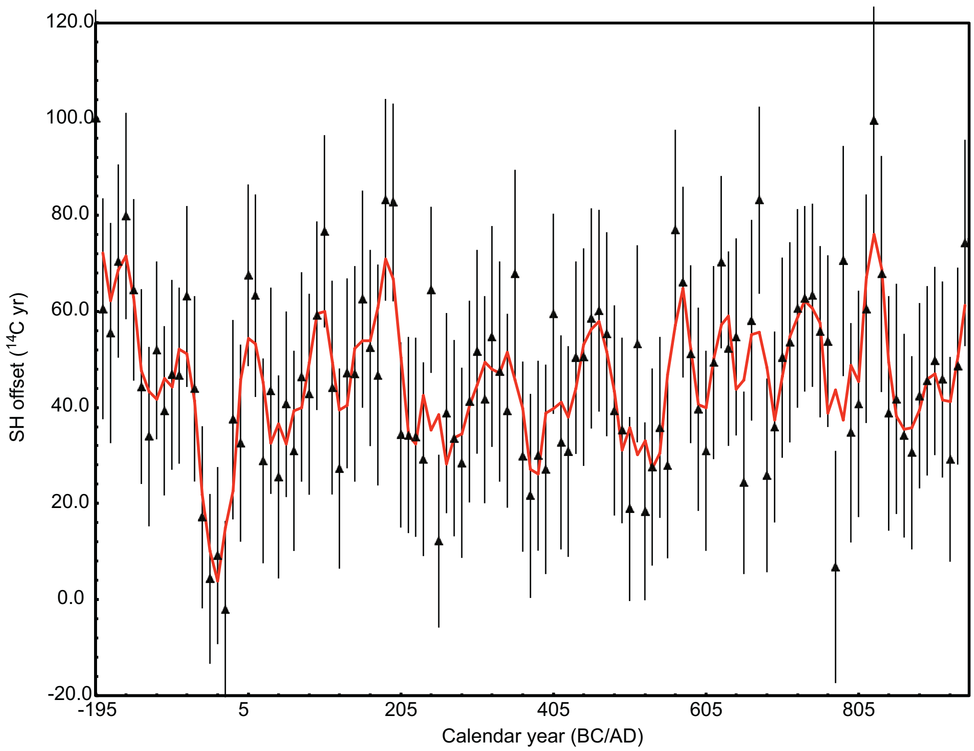


Figure 4 The mean differences (SH-NH) between the combined Wk kauri/CAMS huon data sets and IntCal09 are shown for the interval 185 BC to AD 945. The red line is a 3-point moving average (for interpretation of the references to color, the reader is referred to the online version of this article).

Periodicity for the Interval 200 BC to AD 950

McCormac et al. (2002) showed by measuring contemporaneous 2nd millennium AD NH and SH sample pairs, with samples duplicated in 2 laboratories, that an interhemispheric offset exists and varies with a periodicity of ~130 yr. Because contemporaneous SH/NH wood decadal sample pairs were limited to only 20 in this study (see Hogg et al. 2009b), analysis of periodicity during the 1st millennium AD is necessarily less robust, with the additional factor of unknown laboratory bias between the various NH and SH data sets. Summaries of NH and SH ^{14}C tree-ring data sets for the 1st and 2nd millennia are given in Tables 6A and 6B. NH tree rings, mainly from the US Pacific Northwest and Ireland/England, have been analyzed as single, decadal, or bidecadal samples by 3 laboratories. SH tree rings from Chile, New Zealand, Tasmania, and South Africa as either single-ring or decadal samples, have been analyzed by 5 laboratories. The multiplicity of laboratories and sample year spans, and paucity of SH/NH wood decadal sample pairs, makes analysis of the cyclicity of the 1st millennium AD interhemispheric offset problematic. For this reason, we have limited cyclicity analysis to general patterns, without attempting to identify predominant cycles. The data sets from Table 6 were amalgamated, ignoring potential laboratory offsets, and wavelet analysis (Torrence and Compo 1998) performed on the interhemispheric Δ^{14}C data from 200 BC to AD 1850 (Figure 5). The 1st millennium AD appears to contain a larger number of higher frequency events, but as this increased variability ceases about AD 1000, we are unsure if this is due to natural variations or is an artifact of combining the various data sets.

Table 6A ^{14}C tree-ring NH data sets (details from Reimer et al. 2009).

Tree-ring data set	Location, species, and year span (1st millennium AD)	Location, species, and year span (2nd millennium AD)
University of Washington (QL)	Mainly Pacific NW; Douglas fir and Californian sequoia, minor German oak; mainly decadal samples	Mainly Pacific NW; Douglas fir and Californian sequoia, minor German oak; single year and decadal samples
Queen's University Belfast (UB)	Irish oak; bidecadal and decadal samples	Irish and English oak; bidecadal and decadal samples
University of Waikato (Wk)	Irish and English oak; 20 decadal samples	Irish and English oak; decadal samples

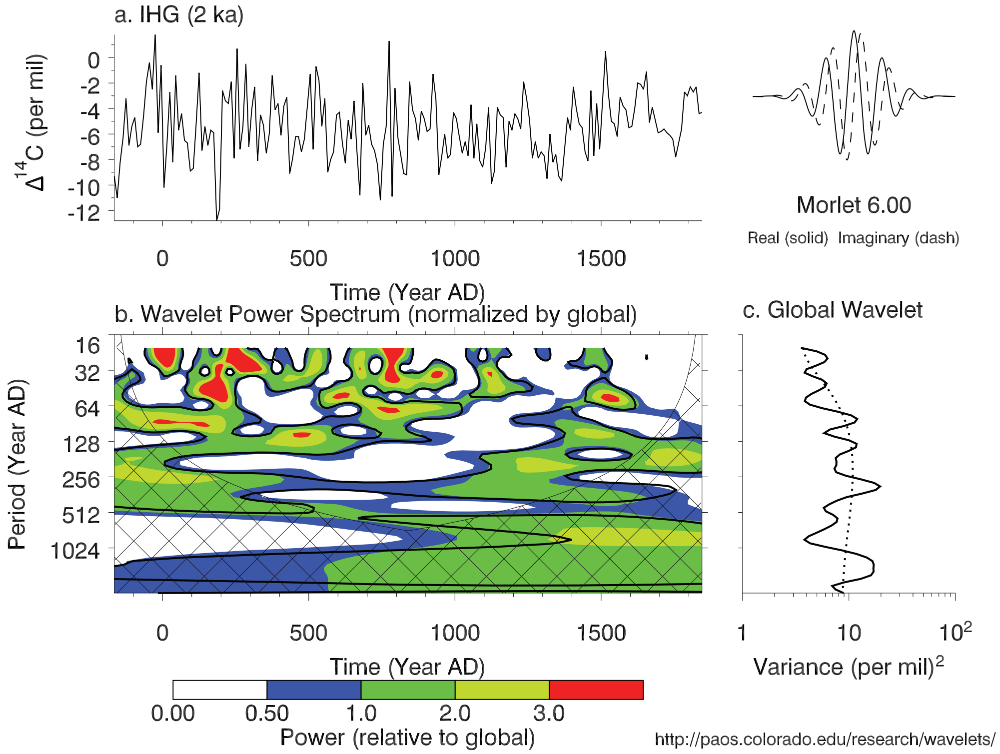
Table 6B ^{14}C tree-ring SH data sets (details in the supplemental information for SHCal04; http://www.radiocarbon.org/IntCal04%20files/shcal04.14c).

Tree-ring data set	Location, species, and year span (1st millennium AD)	Location, species, and year span (2nd millennium AD)
University of Washington (QL)		Chilean coihue and lenga and Tasmanian huon pine 1 to 5 rings per sample
Queen's University Belfast (UB)		New Zealand cedar and pine decadal samples
University of Waikato (Wk)	New Zealand kauri decadal samples (this paper)	New Zealand cedar and pine decadal samples
CSIR, Pretoria (Pta)		Cape Town pine tree 19 single-year samples
Center for Accelerator Mass Spectrometry (CAMS)	Tasmanian huon pine decadal samples	
ANSTO[a] (OZ)		Tasmanian huon pine 16 decadal samples

[a] ANSTO data set (Hua et al. 2004) not included in SHCal04 but shown here for completeness.

CONCLUSIONS AND FUTURE WORK

Decadal ^{14}C measurements on dendrochronologically secure New Zealand kauri covering the period 195 BC–AD 995 are presented. Recently published CAMS Tasmanian huon pine data covering a similar time interval have significantly underestimated standard errors and we recommend the replicate measurements be statistically analyzed to provide more reliable information about the precision of these data. With re-assessed errors, the huon data set from 165 BC to AD 995 closely matches the kauri data, with the combined kauri/huon SH measurements older than NH measurements by 44 ± 18 yr. When the new kauri/huon data are combined with 2nd millennium AD data (i.e. for the interval 195 BC–AD 1845), the mean offset becomes 44 ± 17 yr. This SH offset is lower than the modeled offset of 55–58 yr used in the construction of SHCal04 and we recommend the lower value be used in future SHCal updates. The Tasmanian huon data, unlike the kauri data, shows a significant reduction in the SH offset for the interval AD 775–855. Tasmanian huon pine and New Zealand kauri samples from this interval will be re-analyzed by both Waikato and CAMS laboratories to check the consistency of these results. Although there is an apparent increase in higher frequency events in the SH offset from 200 BC–AD 1000, the reason for this remains unclear.



http://paos.colorado.edu/research/wavelets/

Figure 5 a) The interhemispheric gradient (IHG) for Δ^{14}C (SH-NH) from 200 BC to AD 1850. b) The wavelet power spectrum. The power has been scaled by the global wavelet spectrum (at right). The cross-hatched region is the cone of influence, where zero padding has reduced the variance. Black contour is the 90% significance level, using a red noise (autoregressive lag1) background spectrum. c) The global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (b). See text for more details. Wavelet analysis after Torrence and Compo (1998).

ACKNOWLEDGMENTS

This work was supported by a grant to Dr A Hogg at the University of Waikato, Dr J Palmer from the Gondwana Tree-Ring Laboratory, and Dr G Boswijk from the Tree Ring Laboratory at the University of Auckland, by the Marsden Fund, grant number UOW-0606. Thanks go to Helen McKinnon, Margaret Rabjohns, Kathleen Dabell, and Anna Jenkins for the painstaking pretreatment and benzene syntheses of these samples. Thanks also to Dr Quan Hua (ANSTO) for supplying the ANSTO LIA huon pine data used in Figure 3, to Dr Ed Cook (Lamont-Doherty Earth Observatory) for assistance interpreting the periodicity data, and also to Drs John Southon (University of California at Irvine) and Paula Reimer (Queen's University Belfast) for their constructive reviews.

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