RADIOCARBON, Vol 55, Nr 2, 2013, p 1–15

SHCAL13 SOUTHERN HEMISPHERE CALIBRATION, 0–50,000 YEARS CAL BP

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ABSTRACT. The Southern Hemisphere SHCal04 radiocarbon calibration curve has been updated with the addition of new data sets extending measurements to 2145 cal BP and including the ANSTO Younger Dryas Huon pine data set. Outside the range of measured data, the curve is based upon the Northern Hemisphere data sets as presented in IntCal13, with an interhemispheric offset averaging 43 ± 23 yr modeled by an autoregressive process to represent the short-term correlations in the offset.

INTRODUCTION

Numerous studies have shown that the radiocarbon ages of tree rings formed at the same time in opposite hemispheres are different, with Southern Hemisphere (SH) samples being older by an average of about 40 yr. This age difference is known as the interhemispheric (or North-South) offset and varies periodically (~130 yr periodicity, McCormac et al. 2002) with amplitudes ranging from –2 to 83 ^{14}C yr for the time interval 200 BC–AD 1850 (Hogg et al. 2011). The relatively older ages in the SH are considered due to a higher sea-air $^{14}CO_2$ flux from the larger expanse of SH oceans, with temporal perturbations resulting from variable Southern Ocean wind strength (Rodgers et al. 2011).

Although the ^{14}C calibration curves from the Northern Hemisphere (NH) and SH are broadly similar, there are subtle differences between the structural forms of each curve. For this reason, calibration, and especially ^{14}C wiggle-matching, is best achieved using a dendrochronologically secure calibration data set derived from the appropriate hemisphere (McCormac et al. 2004). The conventions for calibrating SH terrestrial samples have evolved over time with the addition of new data. Mook (1986) recommended decreasing terrestrial SH ^{14}C dates by 30 yr before calibration with a NH curve. McCormac et al. (2002) published the first SH calibration curve, SHCal02, composed of data from New Zealand, Chile, and South Africa for the 2nd millennium AD, and recommended using a value of 41 ± 14 yr for correction of IntCal98 (Stuiver et al. 1998) data for the period outside this range. McCormac et al. (2004) used the same SHCal02 data sets, and extended the calibration curve beyond the range of the SH measurements to 11,000 cal BP by using a random effects model (Buck and Blackwell 2004) to account for the interhemispheric offset varying slowly over time, within the constraints of the offset observed from 50–1000 cal BP. The modeled offset varied from 55 to 58 yr, with an uncertainty increasing from ±7.9 yr at 1000 cal BP to ±25 yr at 11,000 cal BP. They warned against calibrating samples older than 11,000 cal BP because of the possibility that large-scale carbon reservoir changes may have altered the interhemispheric offset before the Holocene.

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INTCAL12 WORKSHOP AND RADIOCARBON CONFERENCE 2012 RECOMMENDATIONS

New SH calibration data sets were recently discussed at a meeting of the IntCal Working Group (IWG) convened in Paris in July 2012. The data discussed included the results currently included in SHCal04 covering 0–1000 cal BP (McCormac et al. 2004); ANSTO data from Tasmanian wood from 325–175 cal BP shown graphically in Hua et al. (2004); results from CAMS Lawrence Livermore National Laboratory from Tasmanian wood from 2115–855 cal BP from Zimmerman et al. (2010); University of Waikato measurements on New Zealand wood from 2145–955 cal BP from Hogg et al. (2011); University of Waikato measurements on Tasmanian wood from 1205–1075 cal BP (Hogg et al. 2013a, this issue); and the ANSTO floating Younger Dryas (YD) Tasmanian Huon pine chronology (12,679 ± 11 to 12,073 ± 11 cal BP) of Hua et al. (2009).

It was agreed that the Hua et al. (2004) data could be included with the 0–1000 cal BP data sets as long as the interlaboratory offsets were small. Similarly, the Zimmerman et al. (2010) Huon data, Hogg et al. (2011) kauri data and Hogg et al. (2013a) Huon data for the 1000–2000 cal BP interval could be used to extend the measured range of SHCal data as long as the laboratories showed good relative consistency. Given that few calibration data sets directly sample the atmospheric reservoir before the onset of the Holocene tree-ring record at 11,560 cal BP, it was also decided to include the floating YD Tasmanian Huon pine chronology of Hua et al. (2009).

Ratification was obtained at the International Radiocarbon Conference in Paris, France (2012) to recommend the use of the SH data from the data sets given here from 0–2145 cal BP, with an extension to 50,000 cal BP using IntCal13 data, adjusted by a modeled offset.

NEW SOUTHERN HEMISPHERE DATA SETS

0–1000 cal BP

The SH data given in SHCal04 (McCormac et al. 2004) covering 0–1000 cal BP includes results from McCormac et al. (1998) and Hogg et al. (2002) on New Zealand trees covering 0–1000 cal BP; data from the University of Washington Quaternary Isotope Laboratory from Chilean and Tasmanian wood from 0–290 cal BP and 0–55 cal BP, respectively (Stuiver and Braziunas 1998; McCormac et al. 2002); and South African measurements from 51–115 cal BP from Pretoria (Vogel et al. 1993). In addition to these data, a few measurements of 17th and 18th century Little Ice Age (LIA) wood from Tasmania, previously published in graphical form in Hua et al. (2004), have been added (Table 1).

The decadal samples were obtained from a cross-dated tree-ring section (SRT-225) of Huon pine (*Lagarostrobos franklinii*) from western Tasmania (42°S, 145°E). The samples were pretreated to α-cellulose and analyzed by accelerator mass spectrometry (AMS) at ANSTO using the ANTARES facility (see Hua et al. 2004 for details). The ANSTO LIA Tasmanian Huon pine data set compares favorably with the combined Waikato (Wk) and Queen's University Belfast (QUB) decadal analyses on New Zealand cedar (Hogg et al. 2002), with the Huon measurements being older by 10.1 ± 6.5 yr.

1000–2000 cal BP

Three new data sets extend the range of measured SH data to 2145 cal BP: CAMS measurements from Tasmanian Huon pine; Waikato measurements on New Zealand kauri (*Agathis australis*); and Waikato measurements on Tasmanian Huon pine.

Table 1 ANSTO measurements on decadal Tasmanian Huon pine samples: 325–175 cal BP (AD 1625–1775) presented graphically in Hua et al. (2004).

Lab code	yr BP (midpoint)	yr AD (midpoint)	Nr of rings	^{14}C age (BP)	^{14}C error	δ^{13}C (‰)
OZF930	325	1625	10	361	23	–23.5
OZF931	315	1635	10	303	24	–22.6
OZE978	305	1645	10	331	22	–21.8
OZE979	295	1655	10	314	23	–21.3
OZE980	285	1665	10	236	22	–20.6
OZE981	275	1675	10	203	21	–20.5
OZE982	265	1685	10	176	23	–20.7
OZE983	255	1695	10	179	23	–20.7
OZE984	245	1705	10	139	21	–21.5
OZE985	235	1715	10	167	22	–20.4
OZE986	225	1725	10	166	25	–20.4
OZE987	215	1735	10	220	21	–19.9
OZE988	205	1745	10	226	23	–20.0
OZF932	195	1755	10	258	25	–20.4
OZF933	185	1765	10	226	21	–21.4
OZF934	175	1775	10	194	24	–20.6

CAMS Measurements of Tasmanian Huon Pine (2115–855 cal BP)

Zimmerman et al. (2010) reported measurements on 127 dendrochronologically secure decadal Tasmanian Huon pine samples for the interval 2115–855 cal BP (165 BC–AD 1095). The ^{14}C analyses were made at the CAMS Lawrence Livermore AMS facility on wood pretreated by a modified de Vries acid-base-acid method. The data showed a similar structure to the NH curve but are generally older, with a distinct but variable offset to IntCal04 (Reimer et al. 2004) averaging 42 ± 26 yr. They report a zero interhemispheric offset for an 80-yr period (1175–1095 cal BP; AD 775–855) but also note the need to replicate these data to confirm this. Although the interhemispheric offset calculated from the CAMS data utilizes IntCal04 and not IntCal09 (Reimer et al. 2009) as used for the Wk data by Hogg et al. (2011), the calculated offsets are directly comparable as the IntCal04 and IntCal09 data sets are identical for the late Holocene.

The CAMS Huon data set is compiled from a total of 222 measurements, including repeat determinations, analyzed over ~3.5 yr, with the first set of 40 measurements (~18% of the 222 individual analyses made) analyzed with protocols designed to ensure higher levels of precision, with standard errors typically ±15 yr (T Guilderson, personal communication). The remaining 182 measurements did not follow the same protocols and are less precise, with the standard errors as reported by Zimmerman et al. (2010) considered too low (Hogg et al. 2011). To check the findings of Hogg et al. (2011), and with the added advantage of having CAMS individual measurements, the standard errors of the CAMS Huon data set were re-assessed independently by Quan Hua, using the methods outlined below.

According to Scott et al. (2007) and Russell et al. (2011), the quoted error associated with a single analysis should be comparable to the standard deviation of the reference standards, with TIRI wood, Belfast cellulose, and Irish oak (Q1323) utilized in the CAMS study. The population standard deviations of these standards are 28 yr (11 analyses), 34 yr (11 analyses), and 26 yr (18 analyses), respectively. The average value of these standard deviations is 29 yr, which is much larger than most of the original errors quoted for single CAMS Huon measurements. We have therefore assigned a minimum value of ±29 yr for single analyses from the lower-precision data set, while retaining the ±15-yr errors for the higher-precision data.

Although more than half of the decadal samples were replicated, the methods Zimmerman et al. (2010) used to calculate a decadal weighted mean (X_{mean} in Equation 1) and its associated error (E_{stat} in Equation 2) did not take into account the scatter of the data:

$$X_{mean} = \left(\Sigma \frac{X_i}{E_i^2}\right) \Big/ \left(\Sigma \frac{1}{E_i^2}\right) \tag{1}$$

$$E_{stat} = \sqrt{1 \Big/ \Sigma \frac{1}{E_i^2}} \tag{2}$$

where X_i and E_i are ^{14}C age and its associated uncertainty for each single measurement, respectively.

To calculate a standard error that does take into account the dispersion of the data for each replicated sample, we have used Equation 3 (see Burr et al. 2007):

$$E_{std} = \sqrt{\frac{\Sigma\left((X_i - X_{mean})^2 / E_i^2\right)}{(n-1)\,\Sigma\left(1/E_i^2\right)}} \tag{3}$$

Using this method, the error (E_{final}) associated with each replicated sample is the larger of E_{stat} and $E_{std.}$ The CAMS data set with revised errors is reported in Table 2. In addition to the higher errors, 14 decadal measurements are likely to be erroneous and have been omitted (see discussion below).

Table 2 Revised CAMS measurements on Tasmanian Huon pine: 2115–855 cal BP (165 BC–AD 1095). Original data from Zimmerman et al. (2010). E_{final} ^{14}C error for replicated samples is the larger of E_{stat} (Equation 2) and E_{std} (Equation 3).

yr BP (midpoint)	yr AD (midpoint)	^{14}C age (BP)	^{14}C error (E_{final})
2115	–165	2170	29
2105	–155	2160	29
2095	–145	2144	20
2085	–135	2150	29
2075	–125	2123	11
2065	–115	2165	21
2055	–105	2122	12
2045	–95	2135	29
2035	–85	2104	10
2025	–75	2118	27
2015	–65	2100	21
2005	–55	2113	21
1995	–45	2049	10
1985	–35	2013	21
1975	–25	2018	28
1965	–15	2040	29
1955	–5	2040	15
1945	5	2065	21
1935	15	2055	15

Table 2 Revised CAMS measurements on Tasmanian Huon pine: 2115–855 cal BP (165 BC–AD 1095). Original data from Zimmerman et al. (2010). E_{final} ^{14}C error for replicated samples is the larger of E_{stat} (Equation 2) and E_{std} (Equation 3). *(Continued)*

yr BP (midpoint)	yr AD (midpoint)	^{14}C age (BP)	^{14}C error (E_{final})
1925	25	2025	29
1915	35	1995	15
1905	45	2015	29
1895	55	2012	24
1885	65	1975	29
1875	75	1950	15
1865	85	1940	21
1855	95	1940	11
1845	105	1969	17
1835	115	1945	15
1825	125	1890	29
1815	135	1895	11
1805	145	1875	29
1795	155	1865	15
1785	165	1882	17
1775	175	1850	15
1765	185	1921	21
1755	195	1905	11
1745	205	1880	31
1735	215	1861	10
1725	225	1860	30
1715	235	1846	13
1705	245	1840	22
1695	255	1755	12
1685	265	1773	28
1675	275	1770	11
1665	285	1780	22
1655	295	1774	13
1645	305	1815	35
1635	315	1804	12
1625	325	1805	29
1615	335	1805	15
1605	345	1730	21
1595	355	1760	11
1585	365	1715	18
1575	375	1715	15
1565	385	1715	21
1555	395	1680	15
1545	405	1738	21
1535	415	1695	29
1525	425	1675	29
1515	435	1643	17
1505	445	1625	29
1495	455	1635	29
1485	465	1638	23
1475	475	1623	28
1465	485	1645	29
1455	495	1613	21
1445	505	1615	21
1435	515	1665	29
1425	525	1603	21

Table 2 Revised CAMS measurements on Tasmanian Huon pine: 2115–855 cal BP (165 BC–AD 1095). Original data from Zimmerman et al. (2010). E_{final} ^{14}C error for replicated samples is the larger of E_{stat} (Equation 2) and E_{std} (Equation 3). *(Continued)*

yr BP (midpoint)	yr AD (midpoint)	^{14}C age (BP)	^{14}C error (E_{final})
1415	535	1605	29
1405	545	1568	28
1395	555	1555	21
1385	565	1560	29
1375	575	1553	43
1365	585	1528	19
1355	595	1495	29
1345	605	1480	29
1335	615	1480	21
1325	625	1513	15
1315	635	1500	29
1305	645	1440	29
1295	655	1392	21
1285	665	1405	29
1275	675	1378	21
1265	685	1318	21
1255	695	1308	21
1245	705	1335	29
1235	715	1315	29
1225	725	1305	29
1215	735	1300	21
1065	885	1200	30
1055	895	1195	25
1045	905	1140	21
1035	915	1140	29
1025	925	1185	29
1015	935	1163	21
1005	945	1180	29
995	955	1200	29
985	965	1145	21
975	975	1135	29
965	985	1160	29
955	995	1035	29
945	1005	1113	33
935	1015	1075	21
925	1025	1025	60
915	1035	965	29
905	1045	980	29
895	1055	1025	29
885	1065	1025	29
875	1075	945	29
865	1085	985	29
855	1095	940	29

Waikato Measurements of New Zealand Kauri (2145–955 cal BP)

Hogg et al. (2011) reported 120 high-precision measurements on dendrochronologically secure decadal kauri samples from the Maitahi and Harding sites in Northland, New Zealand, for the interval 2145–955 cal BP (195 BC–AD 995). The analyses were made at the University of Waikato by liquid scintillation spectroscopy using LKB Wallac Quantulus™ 1220 spectrometers with laboratory protocols and counting parameters optimized for high-precision measurement. All samples were pretreated to α-cellulose, comprising a 4-step process including solvent extraction, bleaching with acidified $NaClO_2$, NaOH extraction, and acidification with HCl. The Waikato kauri data set has an average offset to IntCal09 of 48 ± 2 yr and varies between –5 and 100 yr.

Waikato Measurements of Huon Pine (1205–1075 cal BP)

While the CAMS measurements showed a zero interhemispheric offset for the interval 1175–1095 cal BP, the Wk kauri measurements found a consistent offset (~48 yr) with IntCal09 (Reimer et al. 2009) over the entire 1200-yr range of the measurements. To investigate the discrepancies between these 2 data sets and the possibility of real differences in atmospheric ^{14}C concentration between Tasmania and Northland from 1175–1095 cal BP (the period showing the largest Huon-kauri differences), the Waikato laboratory measured 9 decadal Tasmanian Huon pine samples from SRT-440, the same Huon pine tree used by Zimmerman et al. (2010). As with previous Waikato measurements, samples were pretreated to α-cellulose, with the same measurement protocols used to determine the kauri data set. The 9 Waikato Huon measurements are 53 ± 7 yr older than the equivalent CAMS Huon data but only 4 ± 8 yr older than the equivalent Waikato kauri data (Hogg et al. 2013a, this issue), and we agree with the authors who concluded it was unlikely that a local offset exists between Tasmania and New Zealand. Given the consistency of the interhemispheric offset for New Zealand wood (New Zealand kauri, cedar, and silver pine) over the last 2000 yr, and the Waikato measurements of Tasmanian Huon pine, we concur with Hogg et al. (2011) that the younger 1175–1095 cal BP CAMS Huon data are likely to be incorrect. Indeed, as a result of our re-assessment of these SH data sets, we consider 14 CAMS Huon decadal analyses (1205–1075 cal BP) are erroneous and these have been omitted in Table 2. The revised CAMS Huon data set has an average offset to IntCal09 of 42 ± 2 yr and a range of –12 to 113 yr. The Waikato kauri measurements are on average 4 ± 3 yr older than the revised CAMS Huon measurements.

~12,100–12,700 cal BP

Hua et al. (2009) obtained 134 high-precision measurements from 4 Tasmanian Huon pine subfossil logs extracted from alluvial sediments along Stanley River in NW Tasmania, Australia, spanning the time interval 10,350 to 10,760 ^{14}C yr BP. The AMS measurements were obtained from wood pretreated to α-cellulose (Hua et al. 2004) at ANSTO using the ANTARES facility. Spectroscopic-grade powdered graphite from Union Carbide Corporation was used as blank material for evaluating accelerator and chemistry backgrounds. The original or unprocessed graphite (UPG) was employed for estimating accelerator background, while a mass-dependent chemistry blank was derived from processed (combusted and graphitized) graphite (PG) of different sizes. For every 15 samples, 2 blanks (1 UPG and 1 PG) were included for AMS measurement. The typical analytical AMS precision was 0.3–0.4%, including standard normalization and corrections for backgrounds (accelerator and chemistry) and isotopic fractionation using measured $\delta^{13}C$. Although each of the 4 subfossil logs showed clearly defined and measured annual tree rings, the logs could not be uniquely cross-matched by ring-width correlations alone. ^{14}C wiggle-matching was therefore used to supplement ring-width data to correlate the 4 logs and produce a 617-yr-long floating chronology. The timespan of the floating Huon chronology of 12,679 ± 11 to 12,072 ± 11 cal BP was determined by linking it to the NH extended absolute tree-ring chronology using ^{14}C wiggle-matching with a 40-yr constant interhemispheric offset.

Hogg et al. (2013b, this issue) recently reported a new initiative to obtain atmospheric ^{14}C data from kauri tree rings for the time interval ~13,100–11,700 cal BP. Initial intercalibration studies for this project showed that the calendar position of the Swiss larch sequence Ollon (VOD) 505 in IntCal04 and IntCal09 might not be correct. While the extended NH tree-ring series is dendro-dated independent of VOD505, this series did make an important contribution to the shape of IntCal between ~12,130–11,950 cal BP. The VOD505 shift indicates that YD ^{14}C calibration data based on tree-ring series are still a work in progress. Future work to strengthen ^{14}C and dendrochronology in both NH and SH sequences could produce additional decadal-scale changes affecting the positioning of the Hua et al. (2009) Huon data set.

CALIBRATION CURVE CONSTRUCTION

Measured SH Curve

The new SH calibration curve utilizes the SH data sets incorporated into SHCal04 from 0–1000 cal BP and ANSTO Huon data from 325–175 cal BP, and extended to 2145 cal BP with the Waikato kauri and Huon data sets and modified CAMS Huon data set (Figures 1A and B).

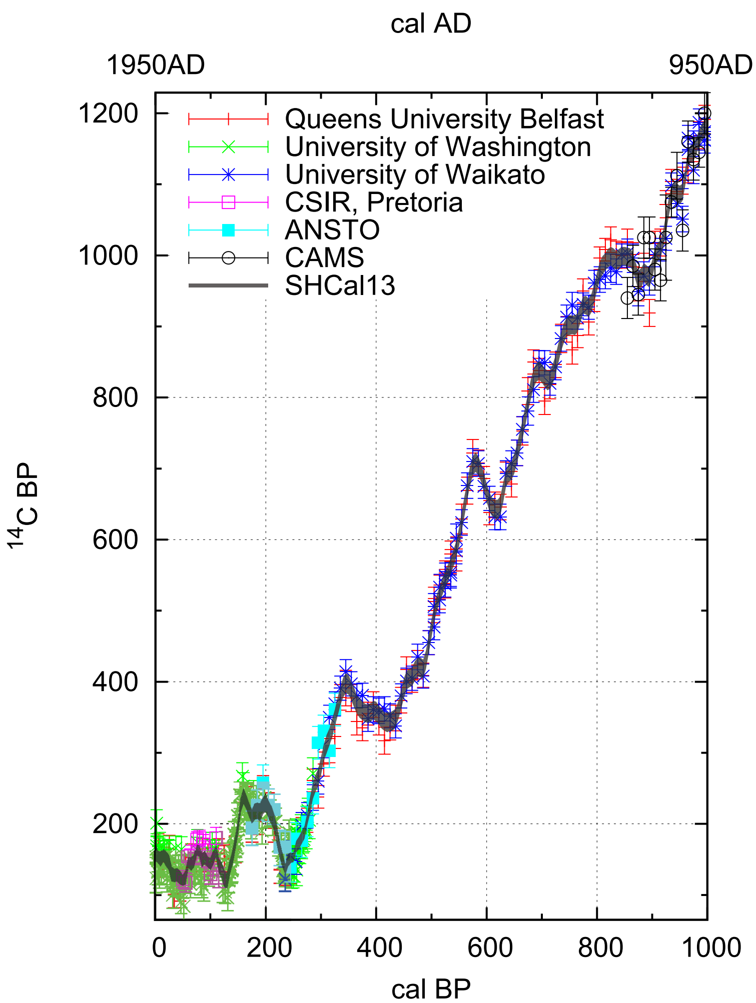

Figure 1A SHCal13 terrestrial calibration curve (1-standard deviation envelope) and data with 1-standard deviation uncertainty in the ^{14}C and calendar ages. Color-coded individual data sets can be seen in the online version of this article.

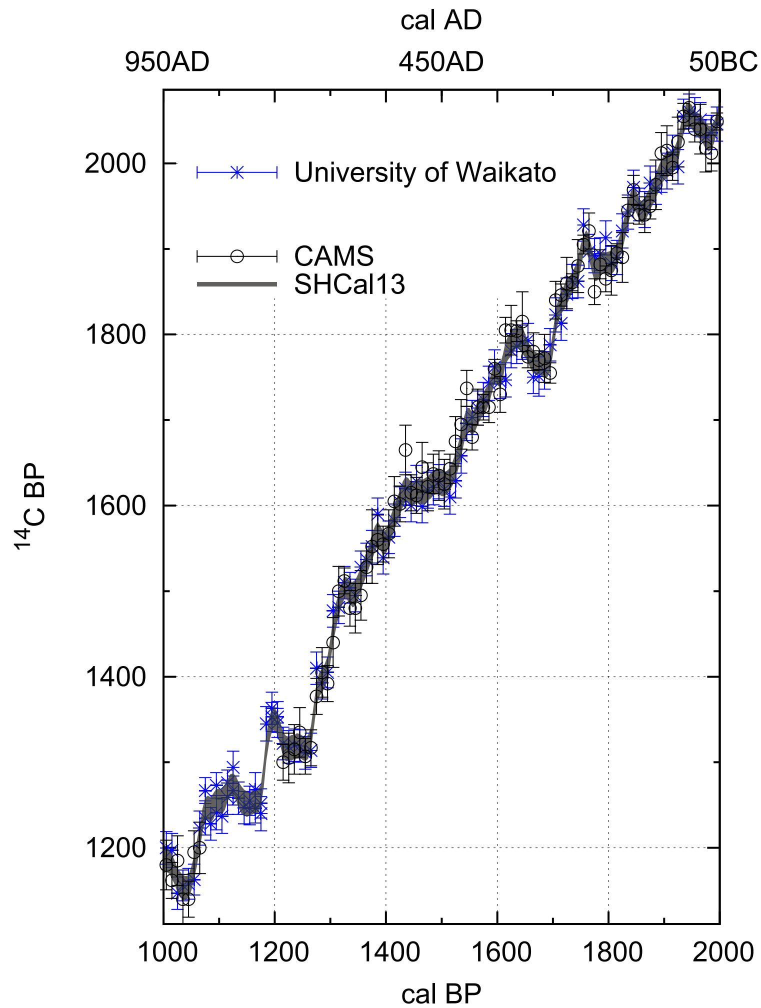

Figure 1B SHCal13 terrestrial calibration curve (1-standard deviation envelope) and data with 1-standard deviation uncertainty in the ^{14}C and calendar ages. Color-coded individual data sets can be seen in the online version of this article.

The new SH curve also uses the measured ANSTO YD Huon data set from 12,679 ± 11 to 12,072 ± 11 cal BP (Figure 2), inserted into the modeled reconstruction (see below), using transitional regions where the variance depends upon both the ANSTO data and the modeled SH data.

The underlying calibration curve was constructed using the same approach as IntCal13, using a Markov chain Monte Carlo (MCMC) implementation of the random walk model (Blackwell and Buck 2008; Heaton et al. 2009; Niu et al. 2013).

Modeled Southern Hemisphere Curve

Beyond the range of the measured data sets, SHCal13 is based upon NH data as given in IntCal13, corrected for an interhemispheric offset, which results in contemporaneous SH dates being older than NH dates by a few decades.

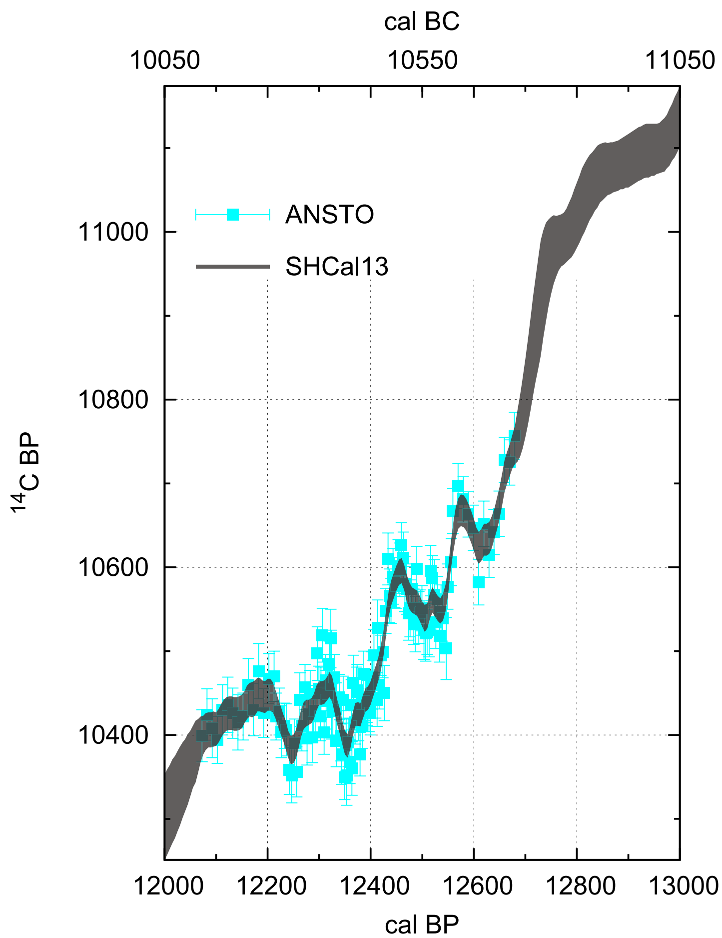

Figure 2 SHCal13 terrestrial calibration curve (1-standard deviation envelope) and data with 1-standard deviation uncertainty in the ^{14}C and calendar ages. Color-coded individual data sets can be seen in the online version of this article.

Value of the Interhemispheric Offset

The interhemispheric ^{14}C offset has been variously measured at 8 to 80 ^{14}C yr for the last 1000 yr (average = 41 ± 14 yr; McCormac et al. 2002) to –2 to 83 ^{14}C yr for the last ~2000 yr (average = 44 ± 17 yr; Hogg et al. 2011). Kromer et al. (1998) and Barbetti et al. (2004) measured floating early Holocene Tasmanian Huon pine and German oak-pine tree rings and also found interhemispheric offset ranges from 0–100 yr. Hogg et al. (2009) determined the interhemispheric offset in 4 accurate and precise SH data sets between 7300 and 10,200 ^{14}C yr BP, and found offset levels of ~50 yr.

The 617-yr-long early YD Huon pine chronology of Hua et al. (2009) was used to link the floating NH pre-YD Late Glacial Pine Chronology (Kromer et al. 2004) with the NH extended absolute tree-ring chronology (Hua et al. 2009). The authors subtracted 40 yr from the Huon measurements to account for the interhemispheric offset and found a smooth transition between the NH and SH data sets. Their conclusion, that ocean circulation reorganization was mainly responsible for the onset of the YD, makes an unchanging interhemispheric offset all the more remarkable. It also provides some confidence that large-scale carbon reservoir changes may not have significantly impacted the interhemispheric ^{14}C offset before this time, as originally feared by McCormac et al. (2004), who limited SHCal04 to 11,000 cal BP for this reason.

For SHCal13, the offset has been estimated from the intervals where the SH curve is measured directly, by calculating the difference between the SH curve and IntCal13, at the 5-yearly "grid points" on which IntCal13 is reported. A stationary first-order autoregressive model (see e.g. Brockwell and Davis 2002) was then fitted to the differences, giving an estimated mean offset of 43 yr, with a standard deviation of 23 yr, broadly consistent with the range reported for 2150–100 cal BP by Hogg et al. (2011).

Although the variability in the offset (SHCal13 minus IntCal13) for the interval 0–2000 cal BP accurately reflects changes in the distribution of ^{14}C between the hemispheres because all measurements are derived from dendrochronologically secure chronologies, this may not be the case for the interval 12,000–13,000 cal BP. SH data may contain extra noise as the Tasmanian Huon pine chronology is mainly based upon ^{14}C wiggle-matching and, in addition, the NH data sets have a paucity of measurements around 12,250 and 12,600 cal BP (B Kromer, personal communication). We would therefore warn against a literal interpretation of the interhemispheric offset distribution for the YD as derived from SHCal13 and IntCal13.

Offsetting IntCal13

For calendar ages that are far from the direct measurements of the SH curve, we constructed SHCal13 by adjusting the mean for IntCal13 by the mean offset calculated above; the uncertainty on SHCal was obtained by adding the uncertainty on the offset to the uncertainty on IntCal (adding variances, or equivalently adding standard deviations "in quadrature").

For calendar ages that are outside, but close to, the directly measured ranges, we have additional information on the offset, since it varies relatively slowly. We used the fitted autoregressive model, and the local value of the offset estimated from the direct measurements, to obtain predictions of the offset nearby, with associated uncertainty; these were used to offset IntCal13, as above. Further back in time from the direct measurements, the local estimate of the offset tends towards a value approximating the long-term estimate of 43 yr, and the uncertainty in the prediction increases, eventually reaching the long-term standard deviation of 23 yr. Thus, this modeling and prediction of the offset provides a statistically principled way of achieving a smooth transition between direct and indirect estimation of the SH curve. For further details, see Niu et al. (2013, this issue).

Figure 3 shows an example at 2145 cal BP, where the main direct measurements of the SH curve come to an end. The curve is estimated purely from SH data back to 2145 cal BP, where the offset is approximately 29 yr. Beyond that, the offset is predicted from the fitted model, with the uncertainty increasing as we look further beyond the direct data. This modeling of the offset has an effect over a period of roughly 250 yr; so for the part of the plot beyond about 2400 cal BP, SHCal13 is essentially IntCal13 adjusted by 43 yr.

Range of SHCal13

Following the lead shown by IntCal09 (Reimer et al. 2009) and IntCal13 (Reimer et al. 2013, this issue), we have extended SH calibration to 50,000 cal BP, assuming interhemispheric offset levels similar to those measured for the past ~2000 yr. However, we also note that a significant component of the pre-YD ^{14}C data sets are compiled from surface ocean-based records, which are subject to errors resulting from changes in marine reservoir ages (*R*). With this caveat, the IWG has generated a new SH calibration curve back to 50,000 cal BP, with ratification by the international carbon dating community at the 21st International Radiocarbon Conference.

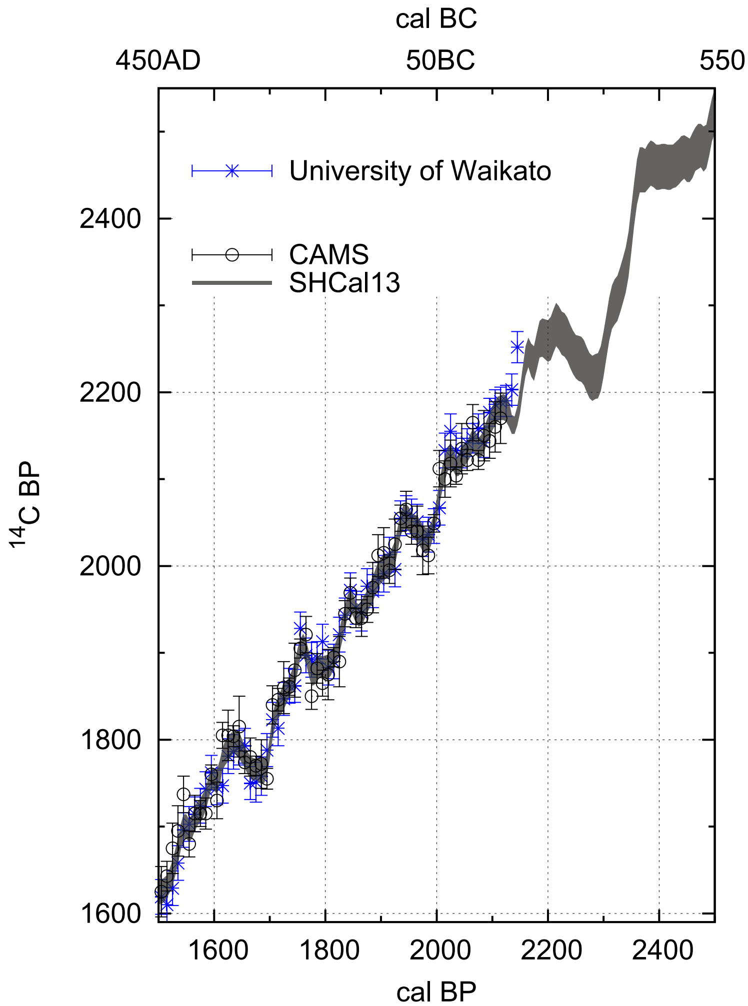

Figure 3 SHCal13 terrestrial calibration curve (1-standard deviation envelope) and data with 1-standard deviation uncertainty in the ^{14}C and calendar ages. The calibration curve beyond the end of the tree-ring data set at 2145 cal BP (but excluding the YD data shown in Figure 2) is based on the offset from the NH data set (IntCal13) calculated with a random effects model (see text for more details). Color-coded individual data sets can be seen in the online version of this article.

FUTURE RESEARCH

Following McCormac et al. (2004), we define the NH-SH boundary as south of the Intertropical Convergence Zone (ITCZ), which experiences seasonal shifts of atmospheric CO_2, creating additional uncertainties in ^{14}C calibration in tropical or neotropical sites. Further research is needed to identify the most appropriate curves for these regions and funding agencies should be encouraged to support this work.

ACKNOWLEDGMENTS

Thanks to Dr John Southon (Keck laboratory UCI) and Drs Warren Beck and George Burr (University of Arizona) for helpful comments in their reviews of this paper.

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APPENDIX: SOUTHERN HEMISPHERE CALIBRATION DATA SETS

A summary of the ^{14}C data sets used for SHCal13 is given below with references to the original data sets. These are cataloged by the institute where the ^{14}C measurements were made. Data set number is a historical construct and makes no reflection on the date of publication. Lab codes can be found on the Radiocarbon Web site at http://www.radiocarbon.org.

The SHCal13 database can be accessed at http://intcal.qub.ac.uk/shcal13/.

1. CSIR, Pretoria (lab code: Pta)

Data set number: 1

Tree rings from Cape Town pine tree.

Vogel JC, Fuls A, Visser E, Becker B. 1993. Pretoria calibration curve for short-lived samples, 1930–3350 BC. *Radiocarbon* 35(1):73–85.

2. University of Washington (lab code: QL)

Data set number: 2

Tree rings from Chilean coihue (*Nothofagus dombeyi*) and lenga (*N. pumilio*) and Tasmanian Huon pine (*Lagarostrobos franklinii*).

Stuiver M, Braziunas TF. 1998. Anthropogenic and solar components of hemispheric ^{14}C. *Geophysical Research Letters* 25(3):329–32.

3. University of Waikato (lab code: Wk)

Data set number 3

Division 1: 0–1000 cal BP

Tree rings from New Zealand cedar (*Libocedrus bidwillii*) and silver pine (*Lagarostrobos colensoi*) chronology.

Hogg AG, McCormac FG, Higham TFG, Reimer PJ, Baillie MGL, Palmer JG. 2002. High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850–950. *Radiocarbon* 44(3):633–40.

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Division 2: 2150–950 cal BP

Tree rings from New Zealand kauri (*Agathis australis*) chronology.

Hogg A, Palmer J, Boswijk G, Turney C. 2011. High-precision radiocarbon measurements of tree-ring dated wood from New Zealand: 195 BC–AD 995. *Radiocarbon* 53(3):529–42.

Division 3: 1205–1075 cal BP

Tree rings from Tasmanian Huon pine (*Lagarostrobos franklinii*) chronology.

Hogg A, Turney C, Palmer J, Cook E, Buckley B. 2013a. Is there any evidence for regional ^{14}C offsets in the Southern Hemisphere? *Radiocarbon* 55(2), this issue.

4. Queen's University Belfast (lab code: UB)

Data set number: 4

Tree rings from New Zealand cedar (*Libocedrus bidwillii*) and silver pine (*Lagarostrobos colensoi*) chronology.

Hogg AG, McCormac FG, Higham TFG, Reimer PJ, Baillie MGL, Palmer JG. 2002. High-precision radiocarbon measurements of contemporaneous tree-ring dated wood from the British Isles and New Zealand: AD 1850–950. *Radiocarbon* 44(3):633–40.
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5. Australian Nuclear Science and Technology Organisation (lab code: OZ)

Data set number: 5

Division 1: ~12,100–12,700 cal BP

Tree rings from 4 Tasmanian Huon pine (*Lagarostrobos franklinii)* trees.

Hua Q, Barbetti M, Fink D, Kaiser K, Friedrich M, Kromer B, Levchenko V, Zoppi U, Smith A, Bertuch F. 2009. Atmospheric ^{14}C variations derived from tree rings during the early Younger Dryas. *Quaternary Science Reviews* 28(25–26):2982–990.

Division 2: 325–175 cal BP

Tree rings from Tasmanian Huon pine (*Lagarostrobos franklinii*) chronology.

Hua Q, Barbetti M, Zoppi U, Fink D, Watanasak M, Jacobsen G. 2004. Radiocarbon in tropical tree rings during the Little Ice Age. *Nuclear Instruments and Methods in Physics Research B* 223–224:489–94.
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6. Center for Accelerator Mass Spectrometry (lab code: CAMS)

Data set number: 6

Tree rings from Tasmanian Huon pine (*Lagarostrobos franklinii*) chronology.

Zimmerman S, Guilderson T, Buckley B, Cook E. 2010. Extension of the Southern Hemisphere atmospheric radiocarbon curve, 2120–850 years BP: results from Tasmanian Huon pine. *Radiocarbon* 52(2–3):887–94.
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