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BAYESIAN EVALUATION OF THE SOUTHERN HEMISPHERE RADIOCARBON OFFSET DURING THE HOLOCENE

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ABSTRACT. While an interhemispheric offset in atmospheric radiocarbon levels from AD 1950–950 is now well established, its existence earlier in the Holocene is less clear, with some studies reporting globally uniform ^{14}C levels while others finding Southern Hemisphere samples older by a few decades. In this paper, we present a method for wiggle-matching Southern Hemisphere data sets against Northern Hemisphere curves, using the Bayesian calibration program OxCal 4.1 with the Reservoir Offset function accommodating a potential interhemispheric offset. The accuracy and robustness of this approach is confirmed by wiggle-matching known-calendar age sequences of the Southern Hemisphere calibration curve SHCal04 against the Northern Hemisphere curve IntCal04. We also show that 5 of 9 Holocene Southern Hemisphere data sets are capable of yielding reliable offset information. Those data sets that are accurate and precise show that interhemispheric offset levels in the Early Holocene are similar to modern levels, confirming SHCal04 as the curve of choice for calibrating Southern Hemisphere samples.

INTRODUCTION

This paper uses Bayesian wiggle-matching techniques to analyze published (and 2 unpublished) atmospheric Southern Hemisphere data sets to determine their suitability for providing information about the interhemispheric offset during the Holocene. The technique known as "wiggle-matching" refers to the fitting of several ^{14}C data points of unknown calendar age from a constrained sequence (e.g. tree rings) to a calibration curve. Bronk Ramsey et al. (2001) showed that the matching of the data to the wiggles in the curve not only significantly improved the precision of the calibration but also reduced the influence of minor offsets. They also warned about systematic offsets between the samples analyzed and the calibration curve and the additional concern of geographic offsets.

It is now well established, particularly for the last millennium, that ^{14}C dates on contemporaneous wood samples are generally older for the Southern Hemisphere than for the Northern (Hogg et al. 2002; McCormac et al. 2002). For example, McCormac et al. (2002) showed by measuring contemporaneous Northern Hemisphere and Southern Hemisphere sample pairs for the time interval AD 950–1950 that a Southern Hemisphere offset exists and varies from 8–80 yr.[5] However the persistence of an interhemispheric offset throughout the Holocene is less clear, with some studies showing an offset of the order of a few decades (Kromer et al. 1998; Barbetti et al. 2004), while others found no such offset (Barbetti et al. 1992, 1995; Sparks et al. 1995).

The principle focus of this paper is to describe a technique, based upon modern Bayesian methods, that is capable of analyzing floating Holocene Southern Hemisphere data sets, to determine whether or not they are sufficiently robust to identify interhemispheric offsets of the order of only a few decades.

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[5]Although reservoir offsets are in ^{14}C yr, we have followed McCormac et al. (2004) and used yr for brevity.

WIGGLE-MATCHING

^{14}C wiggle-matching of tree rings can be done in a number of ways; the χ^2 test, Monte Carlo wiggle-matching, and Bayesian methods (Bronk Ramsey et al. 2001). In this research, we have used the Bayesian calibration program OxCal 4.1 (Bronk Ramsey 1995, 2001, 2009a) to wiggle-match floating Southern Hemisphere data sets to the Northern Hemisphere calibration curve IntCal04 (Reimer et al. 2004), using the OxCal Reservoir Offset function to account for possible reservoir offsets (Bronk Ramsey 2009b). We set the level of the reservoir offset at 40 yr and have assigned it an uncertainty of 20 yr, on the basis of the offset observed from 50–1000 cal BP (McCormac et al. 2004). Uncertainties in the reservoir offset allow the data set to be wiggle-matched to float up and down in ^{14}C space as well as in calendar space to find the best fit.

Testing the Suitability of the Reservoir Offset Function to Provide the Correct Fit for Wiggle-Matched Sequences from Disparate Reservoirs

Decadal ^{14}C measurements are available for both the Northern and Southern hemispheres for the time interval AD 1950–950 (0–1000 cal BP) and we can use these data to test the ability of the Reservoir Offset function to compensate for the interhemispheric offset. By treating selected intervals of SHCal04 (McCormac et al. 2004) as floating sequences, a wiggle-match of this Southern Hemisphere data against IntCal04 using a reservoir offset with a wide uncertainty will allow calculation of the difference between the wiggle-matched date and the true date, as well as the most probable ΔR for the wiggle-matched sequence.

In Figure 1, we have emulated a typical floating ^{14}C data set composed of 20 decadal samples by wiggle-matching Southern Hemisphere data from SHCal04 for a 200-yr sequence for the interval 990–800 cal BP against IntCal04 using a reservoir offset of 40 ± 20 yr. The output from the OxCal 4.1 analysis indicates excellent agreement between the wiggle-matched date and the true date, with a difference of 1 ± 3 yr and an estimated ΔR of 55 ± 4 yr (mean value from the posterior of the ΔR). The true (measured) ΔR for this interval is 46 ± 14 yr (Hogg et al. 2002).

This wiggle-match, using SHCal04 data of known calendar age, demonstrates for this 200-yr interval that the Reservoir Offset function can adequately compensate for geographic offsets even as large as the interhemispheric offset. We tested the Reservoir Offset function for a whole range of different fits by wiggle-matching 200-yr sequences of SHCal04 data to IntCal04 from AD 1950–950, using 20-yr intervals, 5-yr resolution, and a reservoir offset of 40 ± 20 yr. For each wiggle-match, we have allowed the reservoir offset to take on a different value so that we can get an estimate for the variations in the reservoir offset as well as the fit and the offset to true age. Figure 2A shows the difference between the wiggle-matched date and the true date from D0 (AD 1950) to D800 (AD 1150) and Figure 2B the estimated ΔRs for the same time interval. The results are quite acceptable, with most within the 95% range, except for D0 (AD 1950). The estimated ΔRs in Figure 2B are also within measured ranges and show the same natural variability as the true (measured) interhemispheric offset values (Figure 2C, from Hogg et al. 2002).

Figure 3 shows the result of omitting a reservoir offset from a wiggle-match of Southern Hemisphere data to a Northern Hemisphere curve. Here, we have constrained the reservoir offset to be zero and we get a very strong systematic bias.

We tested the robustness of using the Reservoir Offset function by wiggle-matching 200-yr sequences of IntCal04 data against IntCal04 (i.e. against the same curve) with a reservoir offset of 40 ± 20 yr, to see if application of a prior reservoir offset value resulted in artificially elevated estimated ΔR values. Figure 4 (A and B) shows the results of this analysis. Despite the attempt to force

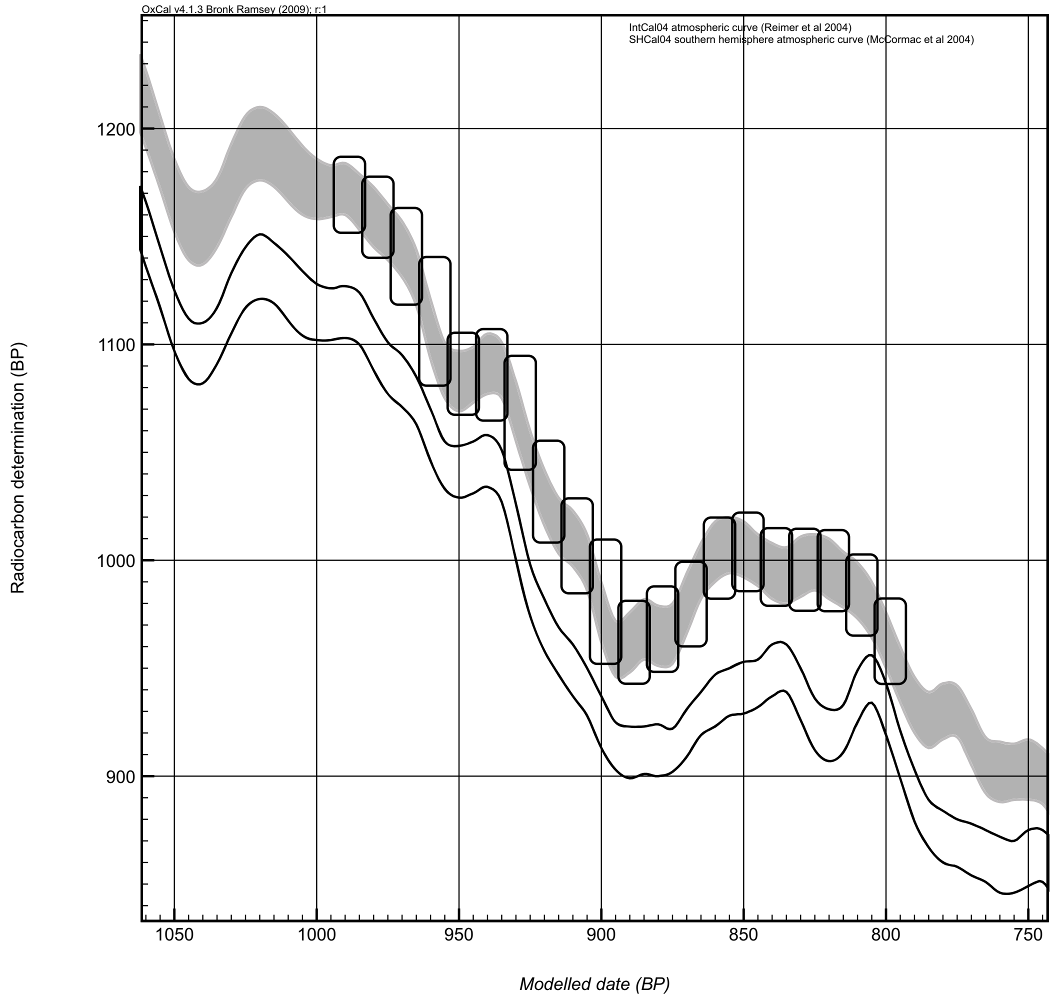

Figure 1 Wiggle-match of SHCal04 data for the time interval 990–800 cal BP against IntCal04 (transparent curve), using a reservoir offset of 40 ± 20 yr. SHCal04 (gray curve) is included to show the goodness of fit. Rectangle vertical height represents ^{14}C date ±2-σ errors; horizontal width represents 95.4% calibration range.

an incorrect fit by the application of the reservoir offset, all wiggle-matches have, with 1 exception—D20 (AD 1930), resulted in a difference between the wiggle-match age and the true age of 0 yr (Figure 4A), with an estimated ΔR of 0 yr (Figure 4B).

We can conclude that calibration using OxCal 4.1 combined with the Reservoir Offset function permits wiggle-matching data sets from disparate reservoirs, with the additional benefit of obtaining reasonably accurate reservoir offset information. We will now apply this technique to various floating Holocene Southern Hemisphere data sets to see if they can provide useful Southern Hemisphere offset data.

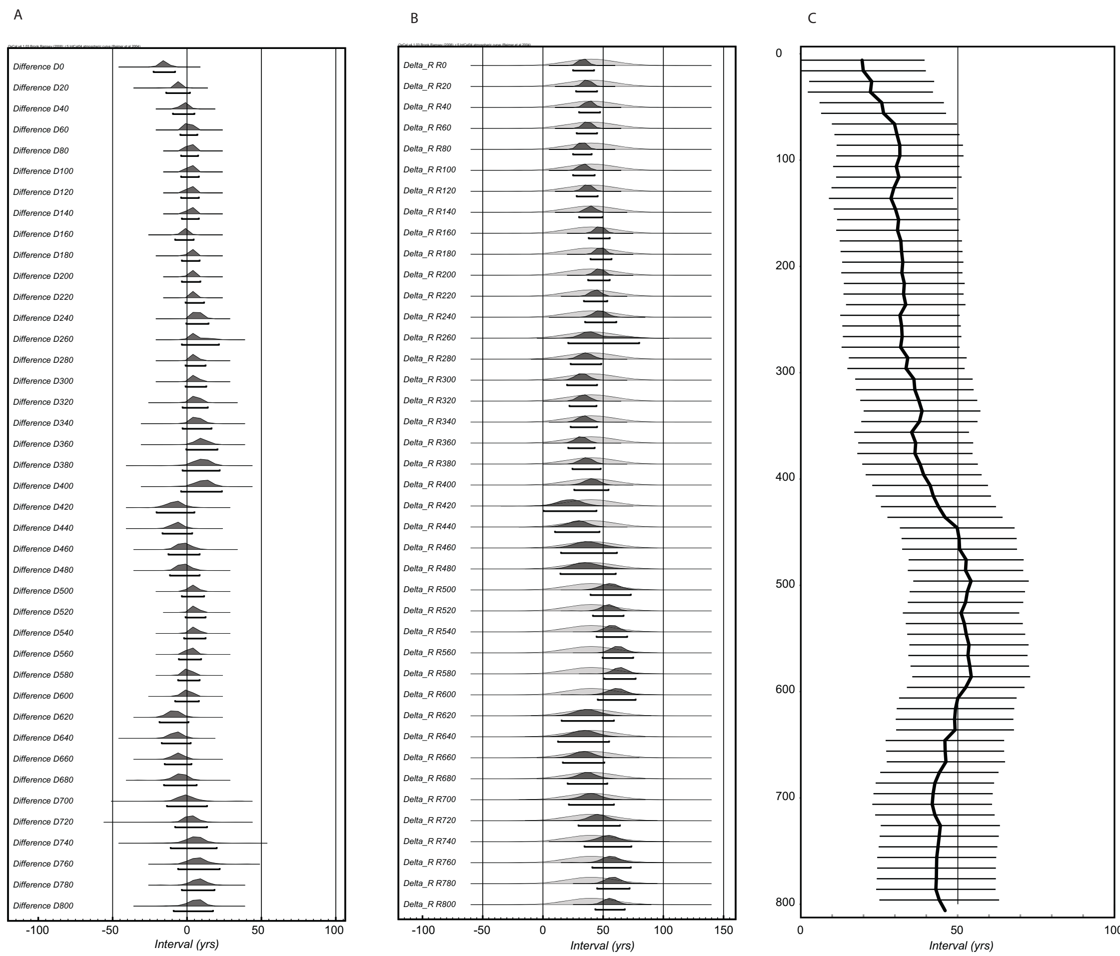

Figure 2 200-yr long SHCal04 data sets of known calendar age wiggle-matched against IntCal04, using a reservoir offset of 40 ± 20 yr, for different fits from 0 cal BP (cal AD 1950) to 800 cal BP (cal AD 1150). A—the difference between the wiggle-matched date and the true date; B—estimated ΔR values; C. True (measured) ΔR values smoothed by a 20-point moving average (data from Hogg et al. 2002). The light gray distribution in Figure 2B is the prior assumption for the reservoir offset. This use of known-calendar age SHCal04 data shows the Reservoir Offset function can provide the correct fit and accurate ΔR values for wiggle-matching Southern Hemisphere data to a Northern Hemisphere curve.

ANALYSIS OF HOLOCENE SOUTHERN HEMISPHERE DATA SETS

We wiggle-matched the 9 floating Holocene data sets as shown in Table 1 against curves suitable for both Southern Hemisphere and Northern Hemisphere samples to test the premise that if the data sets to be wiggle-matched are to resolve an interhemispheric offset of only a few decades, they should also be able to differentiate between these curves. We used 2 curves for the Southern Hemisphere; the Northern Hemisphere curve IntCal04 with a reservoir offset of 40 ± 20 yr (hereafter identified as IntCal04[40,20]) and the Southern Hemisphere curve SHCal04. The Northern Hemisphere curve IntCal04 without a reservoir offset is identified as IntCal04[0,0] for clarity. The results of the wiggle-matching of the 9 data sets against the 3 curves are given in Table 2.

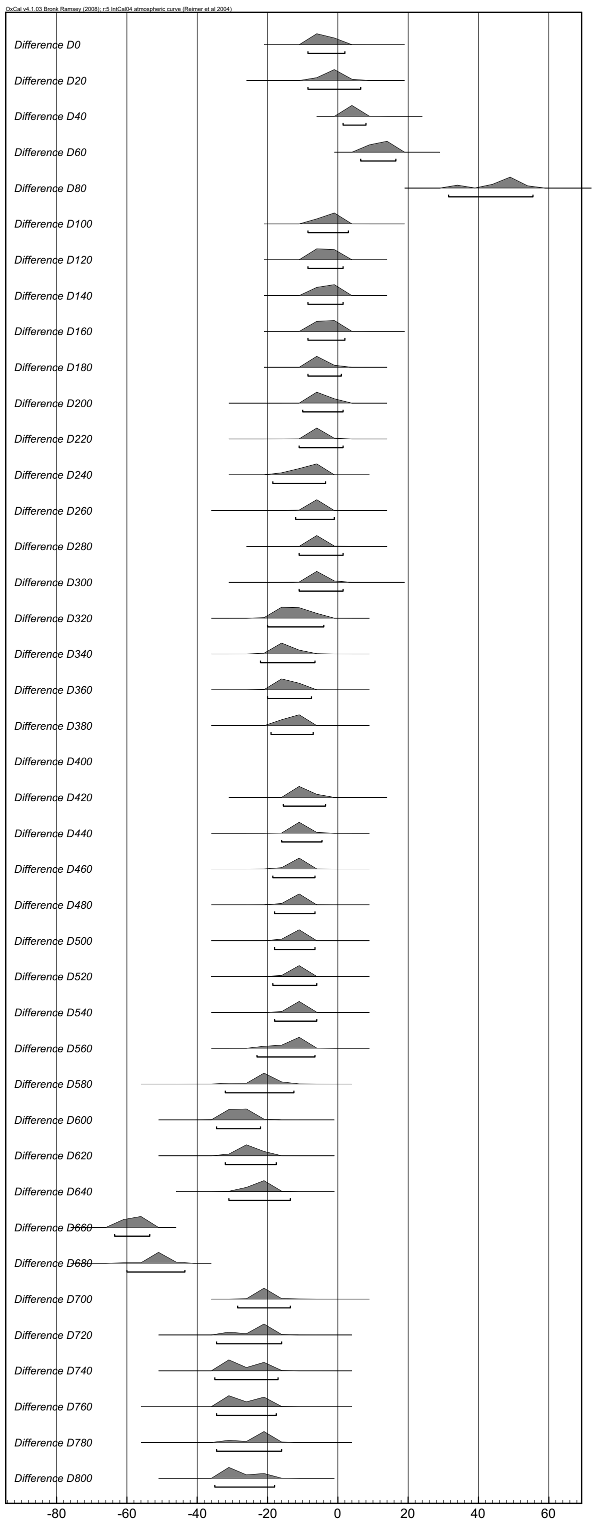

Figure 3 The difference between the wiggle-matched date and the true date for 200-yr SHCal04 data sets wiggle-matched against IntCal04 without applying a reservoir offset, for different fits from D0 (AD 1950) to D800 (AD 1150). A strong systematic error results from wiggle-matching Southern Hemisphere data against a Northern Hemisphere curve, if no provision is made for the interhemispheric offset.

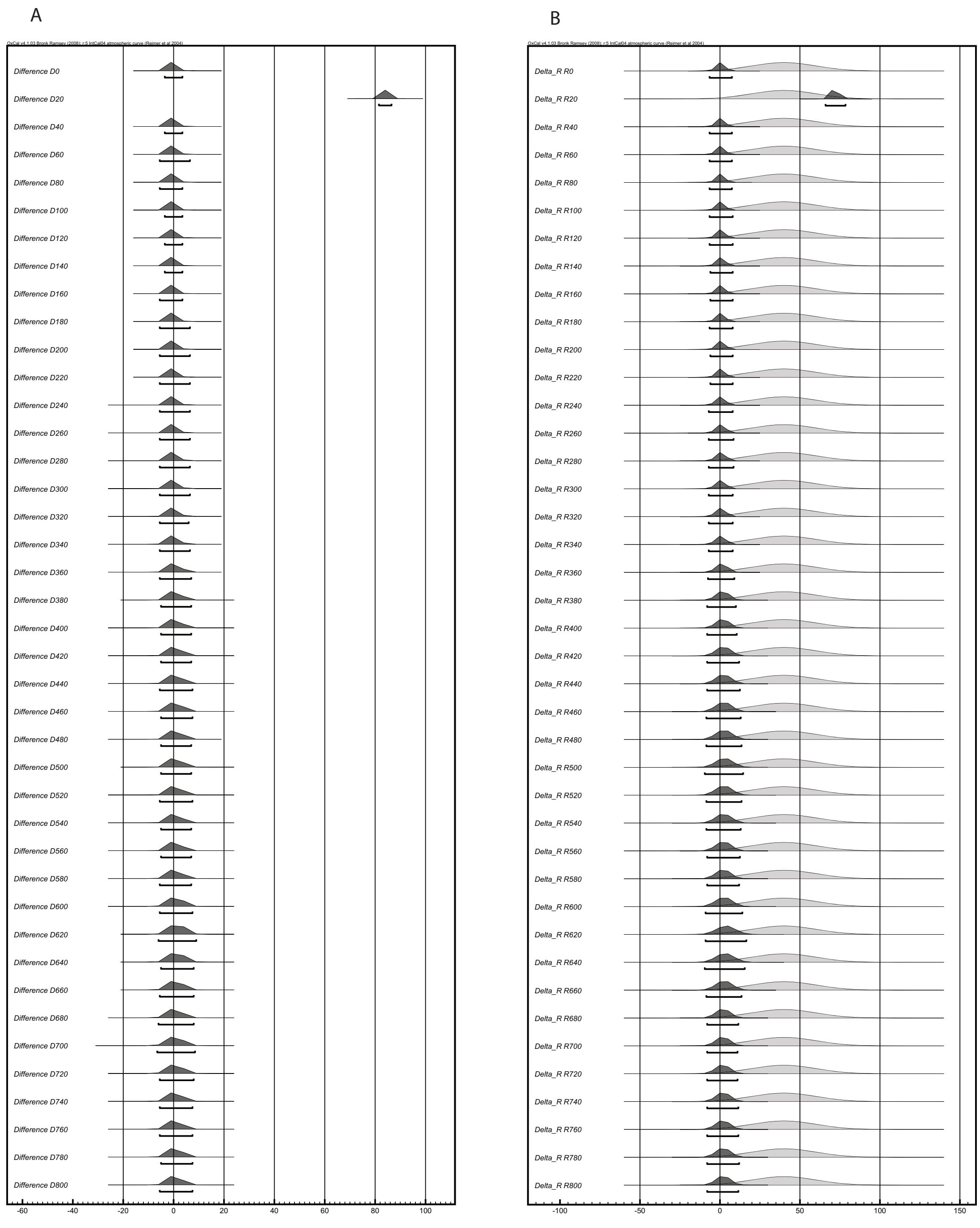

Figure 4 200-yr IntCal04 data sets of known calendar age wiggle-matched against IntCal04 (i.e. against the same curve), using a reservoir offset of 40 ± 20 yr, for different fits from D0 (AD 1950) to D800 (AD 1150). A—the difference between the wiggle-matched date and the true date; B—estimated ΔR values. Here we have attempted to force an incorrect fit by applying a reservoir offset where none exists. The wiggle-match successfully avoids errors in all cases except one, D20 (AD 1930).

Table 1 Summary of the Holocene Southern Hemisphere data sets to be analyzed in this study.

Data set	Average ^{14}C yr BP	Total nr of rings (nr observations)	Conclusions about Southern Hemisphere offset (for published data sets only)	Reference
1. R Sparks New Zealand *Phyllocladus trichomanoides*	1927	270 (21)	No systematic offset with respect to Stuiver and Becker (1993) NH data set.	Sparks et al. 1995
2. A Hogg New Zealand *Phyllocladus trichomanoides*	1952	250 (25)	—	Unpublished data
3. M Barbetti SRT-449 *Lagarostrobos franklinii*	8224	210 (25)	SH data set slightly but not significantly younger than NH data.	Barbetti et al. 1995
4. M Barbetti SRT-450a *Lagarostrobos franklinii*	8690	240 (16)	No significant latitudinal difference in ^{14}C; if anything, NH ^{14}C data sets (Kromer and Becker 1993) slightly older	Barbetti et al. 1995
5. M Barbetti SRT-416 *Lagarostrobos franklinii*	8758	340 (32)	than SH data.	Barbetti et al. 1995
6. M Barbetti SRT-444 *Phyllocladus aspleniifolius*	7300	350 (24)	Data slightly but not significantly younger than German oak data set. Little or no offset to NH data.	Barbetti et al. 1992
7. B Kromer SRT-416 *Lagarostrobos franklinii*	8862	440 (32)	^{14}C offset of several decades to the Hohenheim German oak and pine chronology for most of the data set.	Kromer et al. 1998
8. M Barbetti SRT-447 *Lagarostrobos franklinii*	9047	360 (35)	^{14}C offset varies: - "quite small" when rapidly increasing Δ^{14}C levels; 50 yr when rapidly decreasing Δ^{14}C levels.	Barbetti et al. 2004
9. A. Hogg New Zealand *Agathis australis*	10,180	200 (20)	—	Unpublished data

We used the OxCal 4.1 diagnostic tool A_{model} to test the goodness of fit for the wiggle-matches (Bronk Ramsey 1995, 2001, 2009a). We realize that the Model Agreement index A_{model} is not ideal for the case with curve 1 because it does not take into account the correlated nature of this kind of fit together with the reservoir uncertainty. However, it does allow us to compare the fits of the data to different curves and this is what we need to do in this case. For acceptable agreement in the context of wiggle-matching, A_{model} must be significantly higher than A_n (i.e. $1/\sqrt{2n}$), where *n* depends upon the number of observations in the floating data set (see Bronk Ramsey et al. 2001). We also used the individual Agreement index A to identify observations that are clearly aberrant in the fit. Although a threshold of 60% is usually applied, because this would typically reject 1 in 20 measurements anyway, we have adopted a more conservative approach (with fewer rejections) and halved this to 30%. The outliers were identified in the wiggle-match against the curve IntCal04[40,20],

Table 2 Summary of wiggle-match data for Holocene Southern Hemisphere data sets analyzed in this study.

Data set	**Curve 1** IntCal04[40,20] A_{model} (nr outliers)	**Curve 2** SHCal04 A_{model} (nr outliers)	**Curve 3** IntCal04[0,0] A_{model} (nr outliers)	Average 1-σ error (yr)	Useful for Southern Hemisphere offset? (est. ΔR yr)
1. R Sparks *Phyllocladus*	176.5 *n* = 21 A_n = 15.4 (0)	158.9 *n* = 21 A_n = 15.4 (0)	154.7 *n* = 21 A_n = 15.4 (0)	±37	**No.** A_{model} »15.4 for all 3 curves (n.a.)
2. A Hogg *Phyllocladus*	103.1 *n* = 25 A_n = 14.1 (0)	195.2 *n* = 25 A_n = 14.1 (0)	7.7 *n* = 25 A_n = 14.1 (0)	±18	**YES.** A_{model} «14.1 for curve 3 (**59 ± 6**)
3. M Barbetti SRT-449	129.1 *n* = 24 A_n = 14.4 (1)	164.4 *n* = 24 A_n = 14.4 (1)	97.6 *n* = 24 A_n = 14.4 (1)	±55	**No.** A_{model} »14.4 for all 3 curves (n.a.)
4. M Barbetti SRT-450a	98.5 *n* = 15 A_n = 18.3 (1)	99.3 *n* = 15 A_n = 18.3 (1)	73.4 *n* = 15 A_n = 18.3 (1)	±63	**No.** A_{model} »18.3 for all 3 curves (n.a.)
5. M Barbetti SRT-416	41.3 *n* = 27 A_n = 13.6 (5)	47.0 *n* = 27 A_n = 13.6 (5)	52.0 *n* = 27 A_n = 13.6 (5)	±59	**No.** A_{model} »13.6 for all 3 curves (n.a.)
6. M Barbetti SRT-444	57.2 *n* = 21 A_n = 15.4 (3)	70.4 *n* = 21 A_n = 15.4 (3)	4.4 *n* = 21 A_n = 15.4 (3)	±40	**YES.** A_{model} «15.4 for curve 3 (**51 ± 10**)
7. B Kromer SRT-416	93.5 *n* = 27 A_n = 13.6 (5)	66.3 *n* = 27 A_n = 13.6 (5)	0.1 *n* = 27 A_n = 13.6 (5)	±23	**YES.** A_{model} «13.6 for curve 3 (**46 ± 5**)
8. M Barbetti SRT-447	38.8 *n* = 31 A_n = 12.7 (4)	74.0 *n* = 31 A_n = 12.7 (4)	0.2 *n* = 31 A_n = 12.7 (4)	±39	**YES.** A_{model} «12.7 for curve 3 (**59 ± 7**)
9. A Hogg *Agathis*	100.3 *n* = 20 A_n = 15.8 (0)	n.a.[a]	11.0 *n* = 20 A_n = 15.8 (0)	±25	**YES.** A_{model} «15.8 for curve 3 (**50 ± 8**)

[a]Data set cannot be wiggle-matched against SHCal04 because SHCal04 does not extend beyond 11.0 cal kyr BP and all observations are out of range.

with the number of outliers shown in parentheses underlying the A_{model} data in Table 2. The justification for the rejection level is that with these rejections the fits have acceptable A_{model} values in all cases. The % of outliers removed for the analysis is generally small and ranges from 0% to 15.6% (Table 2).

Data sets 1 and 2 were obtained from a floating *Phyllocladus trichomanoides* tree-ring chronology (Palmer et al. 1988) with an average age of about 1.9 ^{14}C kyr BP. Data set 1 has an average 1-σ error of ±37 yr and shows high agreement (high A_{model} values) for all 3 curves and therefore cannot provide useful offset data. This contrasts with data set 2, which has a lower average 1-σ error (±18 yr) and high agreement with curves 1 and 2 only. The agreement with curve 3 is very low (A_{model} = 7.7) and the estimated value for ΔR (59 ± 6 yr) can therefore be considered reliable. Both data sets show high internal consistency with no clearly defined outliers (i.e. any observation where A < 30%).

Figures 5A and B show the wiggle-match for data set 2 against IntCal04[40,20] and IntCal04[0,0], respectively. In Figure 5A (with an applied reservoir offset of 40 ± 20 yr), the individual data points are in high agreement as seen by comparison with SHCal04. In Figure 5B (no applied reservoir off-

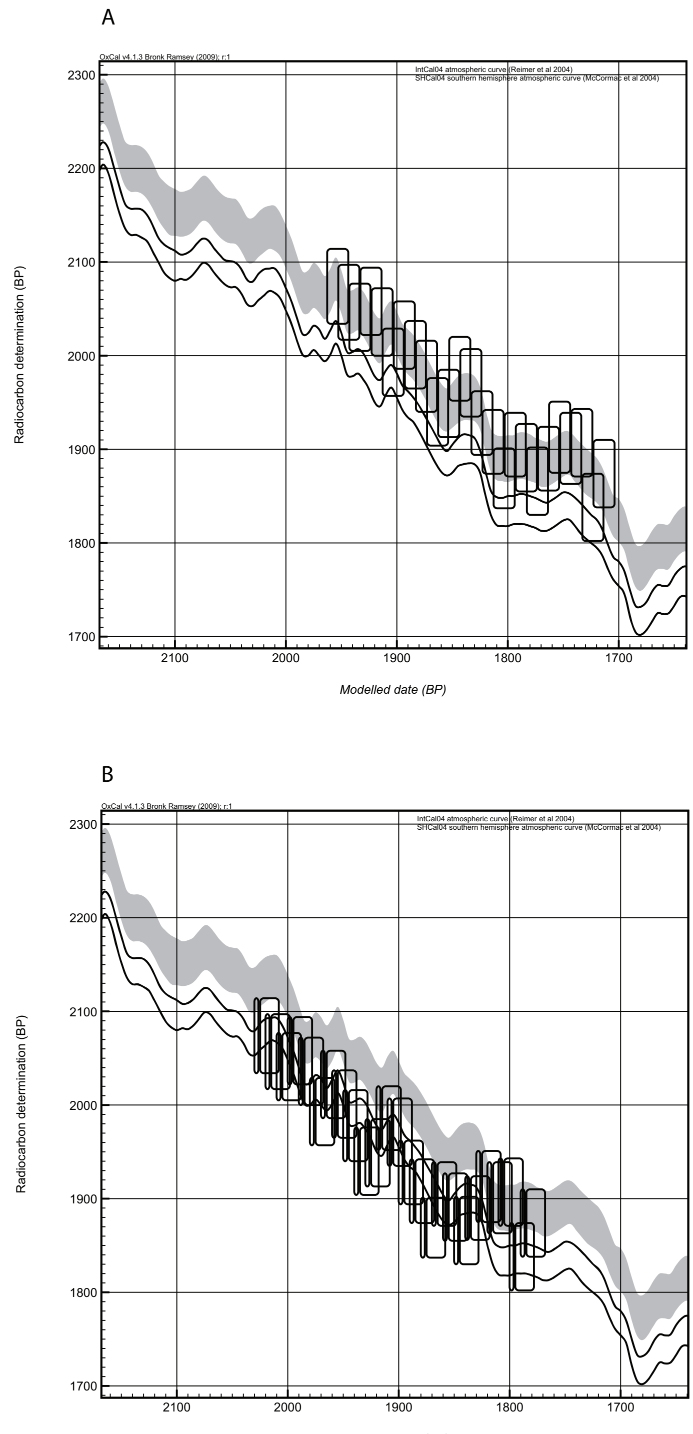

Figure 5 A wiggle-match for data set 2 (Hogg *phyllocladus*) against A: IntCal04[40,20] and B: IntCal04[0,0] – IntCal04 transparent in each plot. SHCal04 (gray curve) is included to show the goodness of fit. Agreement is high in 5A against curve IntCal04[40,20] as shown by comparison with SHCal04 but low in 5B against curve IntCal04[0,0]. Note the misaligned youngest 10 data points in 5B, causing the low agreement A_{model} values.

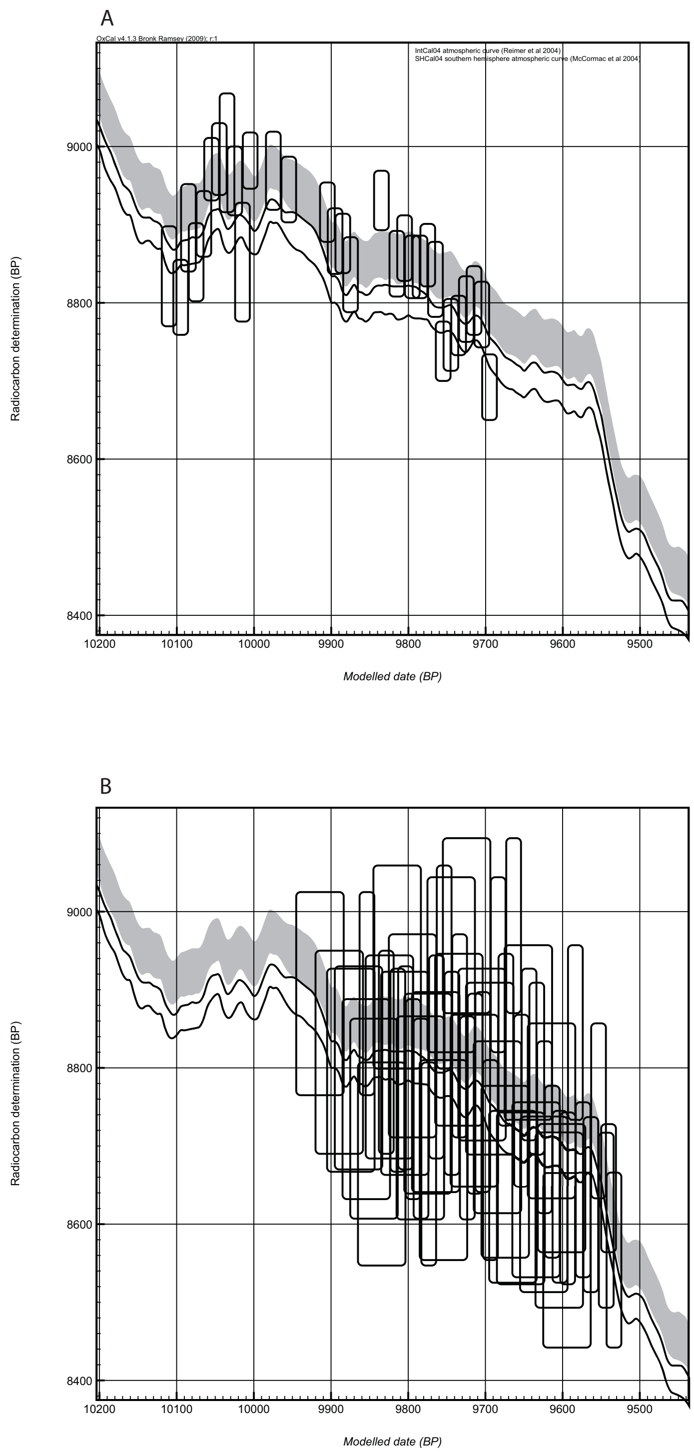

Figure 6 Wiggle-matches for Southern Hemisphere data sets against curve IntCal04[40,20], using a reservoir offset of 40 ± 20 yr. IntCal04 shown as transparent curve. SHCal04 (gray curve) shows goodness of fit. A: Example of a data set capable of providing reservoir offset information (Kromer SRT-416). B: Example of a data set that is incapable of providing reservoir offset information (Barbetti SRT-449). The large 1-σ errors result in calibrated ranges that span both curves.

set), agreement is high with the 15 older data points, but very low for the 10 youngest data points, which are clearly misaligned with the curve, thereby resulting in low A_{model} values. It is interesting to note that if an attempt to estimate the Southern Hemisphere offset was made on a subset of the older 15 data points, it would fail because of a lack of relief in the calibration curve for this restricted time interval—in this case, there is high agreement with both curves (IntCal04[40,20] – A_{model} = 95.1; IntCal04[0,0] – A_{model} = 111.6).

Data sets 3–5 (Barbetti SRT-449, Barbetti SRT-450a, and Barbetti SRT-416) have high A_{model} values with both IntCal04[40,20] and SHCal04 but also with IntCal04[0,0]. We think this is largely because of the lower precision of these data sets (average 1-σ errors of 55, 63, and 59 yr respectively), perhaps combined with insufficient relief in the curves for the relevant time periods.

Data sets 6–9 (Barbetti SRT-444, Kromer SRT-416, Barbetti SRT-447, and Hogg *Agathis*) are more precise (average 1-σ errors of 40, 23, 39, and 25 yr, respectively) and show significantly better agreement with IntCal04[40,20] and SHCal04 curves than with IntCal04[0,0]. The ability of these data sets to differentiate the Southern and Northern Hemisphere curves yields reliable interhemispheric offset information, with estimated ΔRs of 51 ± 10 yr at 7.3 ^{14}C kyr BP (Barbetti SRT-444), 46 ± 5 yr at 8.9 ^{14}C kyr BP (Kromer-SRT 416), 59 ± 7 yr at 9.0 ^{14}C kyr BP (Barbetti SRT-447), and 50 ± 8 yr at 10.2 ^{14}C kyr BP (Hogg *Agathis*).

These results gives us more confidence that the interhemispheric offset has indeed remained constant throughout the Holocene, with SHCal04 the curve of choice for calibrating Holocene Southern Hemisphere data sets.

Figure 6A shows an example (Kromer SRT-416) of a wiggle-match that results in reliable offset information, and Figure 6B an example (Barbetti SRT-449) that does not. The second example clearly shows the influence of higher standard errors, which cause the calibrated ranges of the ^{14}C dates to effectively span both curves.

CONCLUSIONS

The Bayesian calibration program OxCal 4.1 combined with the Reservoir Offset function is a powerful tool for calibrating ^{14}C data sets against a calibration curve where an offset is known or suspected. The reservoir offset function not only compensates for reservoir offsets to provide the correct fit, but also allows estimation of the magnitude of that offset i.e. an estimated ΔR value. A reservoir offset of 40 yr with an uncertainty of 20 yr provides a satisfactory wiggle-match for Southern Hemisphere data sets against Northern Hemisphere curves. A value of 0 ± 20 yr could also be appropriate for wiggle-matches in like reservoirs in situations where the level of fit is unexpectedly low and laboratory bias is suspected.

There are certain prerequisites to obtain accurate offset data by wiggle-matching floating data sets against disparate curves:

1. The floating data series must be sufficiently accurate and precise.
2. The calibration curve must also be accurate and precise for that time period.
3. There must be sufficient relief in the calibration curve to anchor at least part of the floating data series.

We tested the accuracy of the reservoir offset function by wiggle-matching known-calendar age sequences of the Southern Hemisphere calibration curve SHCal04 against the Northern Hemisphere curve IntCal04. The Reservoir Offset function provides a remarkably good fit with estimated ΔR values conforming with measured levels. The robustness of this approach is further indicated when a reservoir offset of 40 ± 20 yr is applied to a wiggle-match of IntCal04 data against the same curve i.e. IntCal04. The wiggle-match does not result in a poor fit or generate an artificial estimated ΔR, despite the attempt to force this.

Our evaluation of 9 Holocene Southern Hemisphere data sets shows that 5 are capable of yielding useful offset information. These indicate the interhemispheric offset is approximately 50 yr between 2–10 ^{14}C kyr BP and give us confidence in the use of SHCal04 for calibrating Holocene Southern Hemisphere ^{14}C dates. The remaining data sets are too imprecise for evaluation of the interhemispheric offset.

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