INTEGR98 radiocarbon age calibration, 24,000-0 cal BP
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INTRODUCTION

The radiocarbon age time frame has been used extensively during the past 50 years in many disciplines. Because uncorrected $^{14}C$ ages and calibrated (cal) ages differ in a time-dependent fashion, the conversion of $^{14}C$ ages to cal ages is especially important for improving the validity of time estimates. Participants at the 16th International Radiocarbon Conference at Groningen (16–20 June 1997) discussed and recommended an update of previous calibration publications (Stuiver and Kromer 1986; Stuiver, Long and Kra 1993). Following the advice of the international radiocarbon community, we present here an extended $^{14}C$ calibration data set, INTCAL98, that caps the 20th century $^{14}C$ age calibration efforts.

Dendrochronology provided the cal ages of the wood used for $^{14}C$ dating; their accuracy is established through standard dendrochronological checks and counterchecks for double or missing tree rings. The Irish oak (Pilcher et al. 1984) and the German oak and pine chronologies (Spurk et al. 1998) play a crucial role. The German oak chronology provides absolute counts of dendroyears back to ca. 10,300 cal BP. $^{14}C$ matching of the latest part of a floating German pine chronology to the earliest absolutely dated German oak extends this chronology to 11,857 cal BP. Errors in the matching may amount to 20 cal years (Kromer and Spurk 1998).

Uranium-thorium (U-Th) dating of corals extends the cal age range (Bard et al. 1998; Burr et al. 1998; Edwards et al. 1993). Whereas tree-ring $^{14}C$, via the photosynthetic cycle, equilibrates with atmospheric carbon dioxide, corals equilibrate with mixed-layer ocean bicarbonate. The slightly lower $^{14}C$ activity (per gram of carbon) of the mixed layer, relative to the atmosphere, results in an offset (the $^{14}C$ reservoir age correction) between “atmospheric” and “oceanic” $^{14}C$ ages of samples with identical cal age. The reservoir correction ($509 \pm 25$ $^{14}C$ yr over the 12,000–10,000 cal BP interval) was fixed by comparing Early Holocene tree-ring and coral $^{14}C$ activities of contemporaneous samples. Adding coral results extends the calibration curve to 24,000 cal BP. Although only two
Terrestrial varve chronologies, to be discussed in a future issue of Radiocarbon, have not been used for construction of INTCAL98. A floating marine varve chronology, however, was used to strengthen the coral information from the 14,500–11,700 cal BP interval. To fix absolute time, the younger varve ¹⁴C ages were matched with tree-ring ¹⁴C ages (normalized on marine ¹⁴C level).

Decadal wood samples were emphasized in Radiocarbon’s 1986 and 1993 calibration issues. The ¹⁴C content of a 10-yr wood sample, however, is not necessarily a perfect reflection of the atmospheric ¹⁴C level of that decade. Tree-ring ¹⁴C does not represent the seasons equally because a major portion of the wood is formed in spring and early summer. Tree-ring thickness also differs from year to year, causing variable annual ¹⁴C contributions to the decadal average.

Decadal results were used in 1986 and 1993 for the construction of a (mostly) decadal Seattle calibration curve (Stuiver and Becker 1986, 1993). Combining these results with those obtained by Belfast for bidecadal samples led to a 20-yr calibration curve which has until now been used for most age calibrations (Pearson and Stuiver 1993; Pearson, Becker and Qua 1993; Stuiver and Reimer 1993).

Many ¹⁴C ages have been determined on dendrodated wood covering only a couple of years. Instead of disregarding these high-precision measurements, we used a different approach for the INTCAL98 calibration curve. INTCAL98 “decadal” ¹⁴C is obtained by averaging full-decadal and part-decadal (single- or multiple-year) results. ¹⁴C ages of samples covering 20 yr also are included by allocating to each decade the bidecadal age with a standard deviation (σ) multiplied by 1.4. Adding these data to the pool of “actual” decadal information ultimately produces ¹⁴C ages with a smaller σ.

**Decadal versus single-year age calibration**

The smaller INTCAL98 σ comes at a price, of course, because ¹⁴C dates of single years and decadal averages need not be identical. The impact on the decadal averages can be assessed by comparing single-year ¹⁴C ages (Stuiver, Reimer and Braziunas 1998: Table 2) to decadal ones.

Part of single-year Δ¹⁴C (expressed as the per mil (‰) deviation of tree-ring ¹⁴C activity from NBS oxalic acid activity, corrected for isotope fractionation, Stuiver and Polach 1977) is tied to 11-yr-cycle solar modulation of atmospheric ¹⁴C production. Pacific Northwest single-year data (when averaged with those of a Kodiak Island tree) yield a three-year moving average for the AD 1897–1945 interval with 11-yr-cycle Δ¹⁴C modulation averaging 2.5‰ (peak to peak) over four cycles (Stuiver and Braziunas 1998). Twenty ¹⁴C years appears to be an upper limit for single-yr ¹⁴C age change induced by the 11-yr cycle. The standard deviation introduced by 11-yr modulation around the long-term (e.g., decadal average) trend is a much smaller 8 ¹⁴C yr (as derived from a 2.5‰ peak-to-peak sinusoidal Δ¹⁴C cycle).

A frequency distribution of single-year (AD 1510–1950) ¹⁴C age differences around a smoothing spline (the spline closely resembles a 10-yr moving average) agrees with a Gaussian scatter σ₂ of 14.4 ¹⁴C yr (Fig. 1). The laboratory errors reported with the data predict an average measurement standard deviation σ₁ of 13.4 ¹⁴C yr for these ¹⁴C age differences. If the additional variability σₙ is attributed to natural causes (e.g., the 11-yr cycle) then, since σₙ² = σ₁² + σ₂², the increase in sigma from 13.4 to 14.4 ¹⁴C yr would be accounted for by σₙ = 5 ¹⁴C yr. The same technique, when applied to a three-year (instead of single-year) moving average, again produces natural ¹⁴C variance with σₙ = 5 ¹⁴C yr (σ₁ = 8.4 ¹⁴C yr and σ₂ = 10 ¹⁴C yr).
The above calculations suggest single-year and three-year natural variability (around long-term decadal trends) with σ's in the 5 to 8 14C yr range (the frequency distribution and solar considerations are for different time intervals). Natural variability plays a role in constructing INTCAL98 “decades” from a mixture of decadal and single (or multiple) year results. Given the above considerations, most INTCAL98 decades should deviate, on average, by only a couple of 14C years from “pure” decadal ones. This statement, of course, only applies to INTCAL98 decades constructed from multiple measurements. When constructing a (hypothetical) INTCAL 98 decade from only one nondecadal 14C age, the INTCAL 98 decadal value would contain, relative to actual decadal values, an additional σn in the 5 to 8 14C yr range.

Information contained in single-year (and three-year) results will be lost to the tune of 5 to 8 14C yr (σ's) when constructing decadal data. Conversely, when calibrating single-year results against the decadal INTCAL98 curve, the single-year 14C ages will differ from decadal 14C ages (σ in the 5 to 8 14C yr range). Here we recommend, prior to calibration, an increase of sample standard deviation σx to \( \sqrt{\sigma_x^2 + \sigma^2} \). The correction is very minor for most samples and only plays a role in high-precision determinations (a σx of, e.g., 10 14C yr transforms into 13 14C yr).
TREE-RING $^{14}$C AGE OFFSETS, "ERROR MULTIPLIERS" AND MINOR ADJUSTMENTS

The major laboratories involved in the determination of tree-ring $^{14}$C for INTCAL98 purposes are Seattle (S), Belfast (B), Heidelberg (H), and Pretoria/Groningen (P/G). For the tree-ring cal age portion of the INTCAL98 calibration curve we used the data sets reported in this calibration issue (Stuiver, Reimer and Brazilunas 1998; Kromer and Spurk 1998; and McCormac et al. 1998a), and previously reported $^{14}$C sequences (Vogel and van der Plicht 1993; Pearson, Becker and Qua 1993; Kromer et al. 1986; McCormac et al. 1998b). When applicable, the older German oak and pine chronologies were adjusted in conformity with the Spurk et al. (1998) corrections.

The $^{14}$C age differences of samples of identical cal age yield an average offset and (scatter) standard deviation $\sigma_2$. The $\sigma_2$ can be compared to the standard deviation ($\sigma_1$) predicted for the $^{14}$C age differences from the laboratory reported errors. The increase in variance (excess variance) $\sigma_E$ is derived from $\sigma_E^2 = \sigma_2^2 - \sigma_1^2$, whereas the ratio $\sigma_2/\sigma_1$ yields the "error multiplier" $k$ (Stuiver 1982).

The above statistical considerations are valid for $^{14}$C determinations of identical samples. However, the samples to be compared here are rarely fully identical, because the time over which the sample was formed may differ (e.g., 10 yr vs. 3 yr). Furthermore, cal ages (time-midpoints) of the wood used by different laboratories samples differ. Different selection criteria (e.g., should two samples be compared if one is a 10-yr and the other a 3-yr sample, and the difference in midpoints is ten years) yield variations in $\sigma_E$ (and $k$) estimates. Given these uncertainties, the $\sigma_E$ and $k$ calculations are only approximate.

The interlaboratory comparisons provide information on the sum total of uncertainty tied to the processes of wood allocation, dendroage determination, sample pretreatment, laboratory $^{14}$C determination, regional $^{14}$C differences and individual tree $^{14}$C differences.

$^{14}$C results determined in different laboratories for samples of the "same" dendroage usually yield offsets in the 0–20 $^{14}$C yr range. Values twice as large are occasionally encountered. The larger offsets are, for reasons unknown, over shorter (century-scale) intervals.

Offset information can be derived from $^{14}$C age comparisons when results are available from three or more laboratories over an identical time interval. Because average S $^{14}$C ages between 6600 and 5800 cal BC differed more than 2$\sigma$ from those reported by H and B, we increased the S $^{14}$C ages over this interval by 27 $^{14}$C yr for INTCAL98 purposes. The offset correction is relatively mild: we allow a 2$\sigma$ difference between the corrected S average and the average of the other laboratories. The same technique reduces Heidelberg $^{14}$C ages by 31, 27, and 26 yr for, respectively, 4400–4200, 5200–5000, and 7200–7000 cal BC. The $^{14}$C age offsets (number of comparisons = n) between the individual laboratory data sets used for INTCAL98 construction (the minor corrections discussed above are included), as well as $\sigma_1$, $\sigma_E$, and $k$, are listed in Table 1.

The trees forming the dendrodated portion of the INTCAL98 curve are predominantly from South Germany, Ireland, California and Washington. For the data sets used for INTCAL98 construction we list in Table 2 tree species, regions, offsets, $\sigma_1$, $\sigma_E$ and $k$ (relative to Seattle). The offsets need not be specifically species-related, and $^{14}$C results for trees from different regions may reflect laboratory, as well as regional, influences.

Time-dependent millennium offsets, relative to the INTCAL98 curve, are listed in Table 3. The largest millennium offset of 26 $^{14}$C yr, based on a small number of points, is not very significant given the ±10 $^{14}$C yr standard deviation. The complete data sets of individual laboratories differ only marginally (up to 11 $^{14}$C yr) from INTCAL98.
TABLE 1. A comparison of Seattle, Belfast, Pretoria/Groningen (P/G) and Heidelberg 14C ages of dendrodated wood. The offset equals the weighted mean 14C age difference of samples for which the midpoint cal ages fall within the same decade. n is the number of comparisons, σ₁ is the predicted average standard deviation in single 14C age comparisons (based on quoted laboratory errors), σₑ represents the difference between the observed standard deviation in the age difference (σ₂) and σ₁ (see text). The σ₂/σ₁ ratio = k. Offset, σ₁ and σₑ are in 14C yr.

<table>
<thead>
<tr>
<th>Laboratories</th>
<th>Offset</th>
<th>σ₁</th>
<th>σₑ</th>
<th>k</th>
<th>n</th>
<th>Cal yr interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belfast – Seattle</td>
<td>12 ± 1</td>
<td>27</td>
<td>22</td>
<td>1.29</td>
<td>866</td>
<td>7745 BC–AD 1935</td>
</tr>
<tr>
<td>Heidelberg – Seattle</td>
<td>19 ± 2</td>
<td>40</td>
<td>22</td>
<td>1.14</td>
<td>230</td>
<td>9665–4085 BC</td>
</tr>
<tr>
<td>P/G – Seattle</td>
<td>17 ± 1</td>
<td>22</td>
<td>17</td>
<td>1.26</td>
<td>194</td>
<td>3905–1935 BC</td>
</tr>
<tr>
<td>Heidelberg – Belfast</td>
<td>30 ± 3</td>
<td>43</td>
<td>30</td>
<td>1.22</td>
<td>142</td>
<td>7715–4075 BC</td>
</tr>
<tr>
<td>P/G – Belfast</td>
<td>−2 ± 2</td>
<td>26</td>
<td>23</td>
<td>1.33</td>
<td>194</td>
<td>3905–1935 BC</td>
</tr>
</tbody>
</table>

TABLE 2. A comparison of tree-ring 14C results of laboratories involved in the INTCAL98 project. (See Table 1 for nomenclature.) Offset, σ₁ and σₑ are in 14C yr.

<table>
<thead>
<tr>
<th>Laboratories</th>
<th>Offset</th>
<th>σ₁</th>
<th>σₑ</th>
<th>k</th>
<th>N</th>
<th>Cal yr interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belfast – Seattle</td>
<td>14 ± 2</td>
<td>24</td>
<td>11</td>
<td>1.1</td>
<td>202</td>
<td>150 BC–AD 1940</td>
</tr>
<tr>
<td>Irish oak – U.S. conifers</td>
<td>11 ± 1</td>
<td>26</td>
<td>22</td>
<td>1.3</td>
<td>501</td>
<td>5210 BC–AD 30</td>
</tr>
<tr>
<td>Belfast – Seattle</td>
<td>17 ± 2</td>
<td>22</td>
<td>17</td>
<td>1.3</td>
<td>194</td>
<td>3910–1930 BC</td>
</tr>
<tr>
<td>Irish oak – German oak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3910–1930 BC</td>
</tr>
<tr>
<td>P/G – Seattle</td>
<td>10 ± 2</td>
<td>32</td>
<td>35</td>
<td>1.5</td>
<td>181</td>
<td>7750–5260 BC</td>
</tr>
<tr>
<td>both German oak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7750–5260 BC</td>
</tr>
<tr>
<td>Belfast – Seattle</td>
<td>21 ± 3</td>
<td>41</td>
<td>28</td>
<td>1.2</td>
<td>128</td>
<td>7720–4080 BC</td>
</tr>
<tr>
<td>both German oak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7720–4080 BC</td>
</tr>
<tr>
<td>Heidelberg – Seattle</td>
<td>16 ± 4</td>
<td>38</td>
<td>12</td>
<td>1.0</td>
<td>102</td>
<td>9670–8000 BC</td>
</tr>
</tbody>
</table>

A portion of the variance increase (expressed by σₑ or k) is tied to factors unrelated to the laboratory operation (e.g., variable regional 14C differences). Previously (in 1993) k = 1.6 was used to calculate the errors in the decadal Seattle 14C age calibration curve. The Table 1 data suggest k values of 1.14 to 1.33. A conservative k = 1.3 was chosen for the calculation of the errors in decadal INTCAL98 tree-ring 14C ages.

HEMISPHERIC AND REGIONAL OFFSETS

Latitude-dependent differences in ocean surface area, and ocean circulation, cause corresponding latitude-dependent 14C transfer to and from the oceans. Rapid tropospheric mixing of air masses counteracts the oceanic influence but does not fully nullify the atmospheric response. As suggested by an atmospheric transport model (GISS GCM), regional atmospheric Δ14C gradients may amount to several per mil, especially between Northern and Southern Hemispheric localities (Braziunas, Fung and Stuiver 1995).

The INTCAL98 tree-ring data set is based on a mix of mid-latitude Northern Hemispheric trees (Germany, Ireland, Washington, Oregon and California). The atmospheric transport model predicts Δ14C...
TABLE 3. Offsets (millennial time separation) between individual laboratory and INTCAL98 (I) results. P/G is Pretoria/Groningen. All parameters following the cal age interval are in $^{14}$C yr. (See Table 1 for nomenclature.)

<table>
<thead>
<tr>
<th>Cal age interval</th>
<th>I – Seattle</th>
<th>I – Heidelberg</th>
<th>I – Belfast</th>
<th>I – P/G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Offset $\sigma_1$</td>
<td>Offset $\sigma_1$</td>
<td>Offset $\sigma_1$</td>
<td>Offset $\sigma_1$</td>
</tr>
<tr>
<td>10 – 9 ka BC</td>
<td>3 ± 4 29</td>
<td>-4 ± 5 36</td>
<td>-7 ± 4 33</td>
<td>-12 ± 5 39</td>
</tr>
<tr>
<td>9 – 8 ka BC</td>
<td>0 ± 3 28</td>
<td>-11 ± 5 41</td>
<td>11 ± 4 31</td>
<td>11 ± 4 31</td>
</tr>
<tr>
<td>8 – 7 ka BC</td>
<td>2 ± 2 23</td>
<td>-26 ± 10 40</td>
<td>-16 ± 3 26</td>
<td>2 ± 2 26</td>
</tr>
<tr>
<td>7 – 6 ka BC</td>
<td>9 ± 2 23</td>
<td>-19 ± 4 34</td>
<td>0 ± 3 27</td>
<td>0 ± 3 27</td>
</tr>
<tr>
<td>6 – 5 ka BC</td>
<td>7 ± 2 21</td>
<td>-8 ± 2 24</td>
<td>-5 ± 2 16</td>
<td>-8 ± 2 24</td>
</tr>
<tr>
<td>5 – 4 ka BC</td>
<td>10 ± 2 17</td>
<td>-6 ± 2 21</td>
<td>-7 ± 2 19</td>
<td>-6 ± 2 21</td>
</tr>
<tr>
<td>4 – 3 ka BC</td>
<td>9 ± 2 18</td>
<td>0 ± 2 24</td>
<td>3 ± 6 18</td>
<td>0 ± 2 24</td>
</tr>
<tr>
<td>3 – 2 ka BC</td>
<td>2 ± 2 18</td>
<td>-4 ± 2 23</td>
<td>-4 ± 2 23</td>
<td>-4 ± 2 23</td>
</tr>
<tr>
<td>2 – 1 ka BC</td>
<td>3 ± 2 18</td>
<td>-9 ± 3 26</td>
<td>-9 ± 3 26</td>
<td>-9 ± 3 26</td>
</tr>
<tr>
<td>1 – 0 ka BC</td>
<td>1 ± 1 11</td>
<td>-13 ± 2 19</td>
<td>-13 ± 2 19</td>
<td>-13 ± 2 19</td>
</tr>
<tr>
<td>AD 0 – 1 ka</td>
<td>3 ± 1 21</td>
<td>-11 ± 2 37</td>
<td>-6 ± 1 25</td>
<td>-11 ± 2 37</td>
</tr>
<tr>
<td>AD 1 – 2 ka</td>
<td>1 ± 1 11</td>
<td>-6 ± 1 18</td>
<td>-6 ± 1 18</td>
<td>-6 ± 1 18</td>
</tr>
</tbody>
</table>

Differences of $\pm1\%$ for these areas. Such differences are at the limit of $^{14}$C dating and difficult to measure. The fine structure in ocean circulation (e.g., in coastal waters) and differences in regional carbon cycle sources and sinks (e.g., permafrost areas, Damon et al. 1996) increase Northern Hemisphere $^{14}$C variability. The location-dependent $\Delta^{14}$C offsets also need not be constant over time. Measurements (not necessarily covering identical time intervals but mostly of the 19th century) of Northern Hemispheric localities yield differences (relative to Washington) of ca. $-21$, $+22$, $16 \pm 9$, $-26 \pm 6$ (AD 1545–1615), $2 \pm 6$ (AD 1615–1715), and $14 \pm 3$ $^{14}$C yr for, respectively, the Santa Catalina Mountains in Arizona (Damon 1995), Mackenzie River Valley, Canada (Damon 1995), Dean of Forest oak, England (Stuiver and Quay 1981), Russia (high latitude, two comparisons) and Kodiak Island, Alaska (Stuiver and Brazunas 1998). Furthermore, Irish oak yielded $41 \pm 9$ $^{14}$C yr younger dates than bristlecone pine of Nevada (McCormac et al. 1995) and German oak was $23 \pm 6$ $^{14}$C yr younger than California sequoia (Stuiver 1982).

Southern Hemisphere offset measurements (Stuiver and Brazunas 1998) yield $25 \pm 7$ $^{14}$C yr for Tasmania–Washington (19th century), and $38 \pm 5$ $^{14}$C yr and $21 \pm 5$ $^{14}$C yr for South Chile–Washington (respectively, AD 1670–1722 and 19th century). Other offsets are $40 \pm 5$ $^{14}$C yr for South Africa–the Netherlands (AD 1835–1900, Vogel et al. 1993) and $27 \pm 5$ $^{14}$C yr for New Zealand–British Isles (AD 1720–1885, McCormac et al. 1998a).

For the 1993 calibration program (Stuiver and Reimer 1993), a $40$ $^{14}$C yr correction was recommended for the entire Southern Hemisphere. The recent measurements of 19th century wood (Tasmania, New Zealand, South Chile) are in line with a smaller Southern Hemispheric offset of $24 \pm 3$ $^{14}$C yr.

The above Southern Hemisphere–Washington offset is for “natural” conditions. During the first half of the 20th century, fossil fuel CO$_2$ release depressed atmospheric $^{14}$C levels to a greater extent in the Northern Hemisphere. Whereas 19th century Chile/Tasmania $^{14}$C ages are about 23 yr older than those of Washington, the offset is reduced during the first half of the 20th century. There is even a switch to younger Southern Hemispheric ages ca. AD 1940 (Stuiver and Brazunas 1998; McCormac et al.1998b).
Tropical paleo-R values to Late have decay during is ratio. The TREE-RING ogy. Future adjustments tree-ring the of, Between 10,000-8,000 \(-300\) \(^{14}\text{C}\) omitted). However, there Differences between oceans (1993) coral data yield For and coral and coral data generate and coral results of, respectively, 414 \(\pm 31\) \(^{14}\text{C}\) yr (n = 12) and 509 \(\pm 25\) \(^{14}\text{C}\) yr (n = 21). Omitting the outlier reduces the latter to R = 451 \(\pm 26\) \(^{14}\text{C}\) yr. The older sample ages appear to have slightly larger R's, as depicted by the 1000 yr averages in Figure 2. Good agreement between mixed-layer corrected coral dates and tree-ring \(^{14}\text{C}\) dates (Fig. 3) is obtained when using R = 500 and 400 \(^{14}\text{C}\) yr for, respectively, the 12,000–10,000 cal BP and 10,000–8000 cal BP intervals.

Future adjustments of the pine–oak chronology, if any, will influence the derived R values. The 100 \(^{14}\text{C}\) yr R “increase” is perhaps tied to missing rings in the earliest part of the pine tree-ring chronology. Given our current state of knowledge, however, we do accept an R value of 500 \(^{14}\text{C}\) yr for the 12,000–10,000 cal BP interval, and postulate the same tropical R for the Late Glacial ocean.
Fig. 2. Reservoir ages (\(^{14}\)C age difference between coral and tree-ring samples of similar cal age) between 12,000 and 8000 cal BP. Coral measurements given here and in the following figures are from Bard et al. 1998 (○), Burr et al. 1998 (×), Edwards et al. 1993 (△). R values averaged over millennia are represented by the solid line. The dashed line is the R value for the 11,000–10,000 cal BP millennium when omitting the 900 \(^{14}\)C yr data point. Vertical bars represent the calculated error in the \(^{14}\)C age difference calculation, based on a 2σ error in the coral \(^{14}\)C age determination, and a 1.3σ error in the tree-ring \(^{14}\)C age determination.

CORAL \(^{14}\)C AGE VARIABILITY

The corals are assumed to be ideal closed systems with regard to \(^{14}\)C, \(^{234}\)U and \(^{234}\)Th exchange. The overall agreement (Fig. 3) between reservoir-corrected coral (with the reservoir correction averaged over millennia), and tree-ring \(^{14}\)C dates suggests that this condition is fairly well adhered to for carefully collected samples. Nevertheless, the scatter \(\sigma_2\) of INTCAL98 tree-ring minus reservoir-corrected coral \(^{14}\)C ages (12,000–8000 cal BP, \(n = 33\)) is 260 \(^{14}\)C yr, whereas the quoted measuring precision alone produces a \(\sigma_1 = 69\) \(^{14}\)C yr, resulting in \(\sigma_E = 255\) \(^{14}\)C yr and error multiplier \(k = 3.7\). Similar comparisons between tree-ring data sets yield an average \(k\) value of only \(\sim 1.3\).

The above calculation uses a fixed R of 500 and 400 yr for, respectively, 12,000–10,000 cal BP and 10,000–8000 cal BP. Normalizing each individual data set on its own R value (which aligns the average of each individual coral data set with that of the INTCAL98 tree-ring record) yields an improved \(k = 2.3\) when the INTCAL98 reservoir-corrected \(^{14}\)C ages are subtracted from the tree-ring ages.

To generate a pre-12,000 cal BP atmospheric record, one has the choice of 1) assuming R to be constant for each individual site, or 2) assuming average tropical R to be constant (the 500 \(^{14}\)C yr dis-
Fig. 3. Position of coral $^{14}$C ages (○), relative to INTCAL 98 tree-ring $^{14}$C ages (solid line), after a reservoir deficiency correction of the coral $^{14}$C ages by 400 and 500 $^{14}$C yr for, respectively, 10,000–8000 cal BP and 12,000–10,000 cal BP. Vertical bars equal 2$\sigma$ in the coral $^{14}$C age measurement.

cussed previously). It is likely (but not proven) that prior to 12,000 cal BP single-site R variability was larger than average R variability. We decided to generate the pre-12,000 cal BP atmospheric record by deducting an average tropical R = 500 $^{14}$C yr from all coral data.

The atmospheric and mixed-layer $^{14}$C records are filtered differently by natural processes. Mixed-layer response to postulated decadal atmospheric forcing resembles a ~100–200 yr moving average (e.g., Stuiver, Reimer and Braziunas 1998). Using a similar 200-yr moving average for tree rings, however, does not reduce the coral $^{14}$C–tree-ring $\sigma_E$. Mechanisms resulting in increased variance could be 1) varying tropical reservoir deficiency R, 2) post-depositional $^{14}$C activity modification and 3) U/Th age uncertainty.

Post-depositional $^{14}$C modification can be accounted for by using twice the standard deviation of the measurement. Many investigators routinely double the measuring precision of coral $^{14}$C determinations (Edwards et al. 1993; Bard et al. 1990). For INTCAL98 purposes the assigned standard deviation of coral $^{14}$C ages is based on a 2$\sigma$ error in the coral $^{14}$C age determination, and a $k = 1.3$ error multiplier similar to the one used for tree-ring derived $^{14}$C ages. The combined multiplier of 2.6 accounts for most of the variance actually observed.
MARINE RESERVOIR AGE CONSIDERATIONS

Causes for century-scale atmospheric $^{14}$C variability include solar modulation of the cosmic-ray flux and ocean circulation change. Model calculated $R$ values depend on the forcing mechanism. Switching from a solar to an oceanic mode produced century-scale global $R$ change of $\sim 150$ $^{14}$C yr in a global carbon reservoir model (Stuiver, Reimer and Brazunas 1998).

Splining of the reservoir-corrected coral $^{14}$C ages ($R = 500$ $^{14}$C yr) generates the pre-11,850 cal BP portion of the "atmospheric" INTCAL98 calibration curve. Before 11,850 cal BP, tropical ocean $R$ is assumed to be identical for the Atlantic, Pacific and Indian Ocean, as well as nonvariable over time. It is difficult to estimate the limits of tropical $R$ change. Figure 2 suggests tropical $R$ change of only $\sim 100$ $^{14}$C yr for millennia-scale oceanic changes between the end of the Ice Age and 8000 cal BP. A comparison of Cariaco Basin (Hughen et al. 1998) varve and INTCAL98 tree-ring chronologies (discussed in the following section) suggests that decadal- to century-scale tropical $R$ variability is restricted to $\sim 100$ $^{14}$C yr (11,700–9000 cal BP interval). Larger millennia-scale tropical $R$ changes further back in time cannot be excluded, but are not very likely given the limited tropical $R$ variability between the end of the Pleistocene and the present.

The globally integrated atmospheric $^{14}$C levels, and global $R$, depend on a globally integrated ocean circulation and ocean-atmospheric exchange rate. To derive global INTCAL98 atmospheric values, we used a constant late-glacial tropical $R$ value of 500 $^{14}$C yr. Implied in the switch from tropical to global conditions is the notion that tropical $R$ and global $R$ parallel each other over the 24,000–11,850 cal BP interval.

The corals discussed so far were formed in the mixed surface layer of the tropical ocean. Deep-sea corals, on the other hand, live mostly between 500 and 2000 m depth and are not confined to tropical latitudes. These corals exhibit substantial century-scale deepwater $R$ change in the Atlantic (16,000–12,000 cal BP interval: Adkins et al. 1998; Mangini et al. 1998). Atlantic deepwater $^{14}$C levels are tied to specific deepwater masses (e.g., Stuiver and Östlund 1980) and the deepwater $R$ changes are most likely caused by shifts in their depths. These relatively fast regional ocean circulation changes have the potential to modify (to an unknown extent) the values of both late-glacial atmospheric $^{14}$C and mixed-layer $R$.

MARINE VARVE CHRONOLOGY

Marine sediments of the Cariaco Basin in the Atlantic Ocean (at the northern continental margin of Venezuela) yield a $^{14}$C–varve count sequence (Hughen et al. 1998) useful for INTCAL98 construction. The floating chronology is tied to the absolute time scale by matching marine $^{14}$C ages to the INTCAL98 tree-ring data (the tree-ring data are increased by 500 and 400 $^{14}$C yr for, respectively, 12–10 and 10–8 ka cal BP). The best fit between the $^{14}$C ages of the adjusted tree-ring record and the Cariaco Basin is shown in Figure 4. The absolute time scale produced in this manner for the floating varves reduces the Hughen et al. (1998) varve count time scale by 40 yr. The latest tree-ring and $R$ adjustments cause this minor difference. The matching is secure within a statistical error (one $\sigma$) of 15 yr.

Applying $R = 400$ (10–8 ka cal BP) and 500 (14.5–10 ka cal BP) $^{14}$C yr to the corals and calibrated varve series yields the Figure 5 "atmospheric" values. Relative to the INTCAL 98 tree-ring record, the varve-derived $^{14}$C ages scatter less ($k = 1.3$) than the coral $^{14}$C ages. The observed varve scatter $\sigma$ of $\sim 95$ $^{14}$C yr (11,700–9000 cal BP interval) suggests a $\sim 100$ $^{14}$C yr limit on tropical $R$ change on decadal/century time-scales.
Fig. 4. Cal BP calibration of a floating marine varve record. The varve data given here, and in the following figures, are from Hughen et al. (1998). Shown is the best fit between the marine equivalent of the INTCAL98 tree-ring record (solid line; R values as noted with Fig. 3 were applied) and the measured varve results (□, with 1σ bars).

ATMOSPHERIC AND MARINE INTCAL98 CONSTRUCTION

The atmospheric INTCAL 98 curve consists of two segments, each derived from diverse materials and techniques. The materials used are wood (tree rings), coral and marine sediment. The $^{14}$C activity measurement is common to all but the cal BP time scale determination differs. The wood samples (back to 11,850 cal BP) are dated through dendrochronological means, the corals through U-Th determinations, and the marine sediment through $^{14}$C matching of (floating) varve and tree-ring chronologies. Marine coral and varve data, normalized on atmospheric levels, yield a 24,000–11,850 cal BP extension of the directly measured atmospheric values. Only two coral measurements are available for the 40,000–24,000 cal yr interval, resulting in rather speculative age “calibration” over this interval.

The 11,850–0 cal BP segment was constructed from $^{14}$C age measurements reported by the Belfast, Heidelberg, Pretoria/Groningen and Seattle laboratories (Stuiver, Reimer and Braziunas 1998; Kromer and Spurk 1998; McCormac et al. 1998a and b; Pearson, Becker and Qua 1993; Vogel and van der Plicht 1993; Kromer et al. 1986). Decadal $^{14}$C ages back to 11,614 cal BP were constructed by taking the average $^{14}$C age of all samples with cal midpoints within the cal decade. The rationale for this approach can be found in the introduction. The 11,624–11,854 cal BP interval is covered by the measurements of a single laboratory (Heidelberg; Kromer and Spurk 1998) of 20- to 30-yr tree-ring samples. The segments of Figure A8–A19 (Appendix) depict for 1000 cal yr intervals the “dec-
Fig. 5. INTCAL 98 tree-ring $^{14}$C ages (solid line) and the atmospheric equivalent (obtained by using the R values noted with Fig. 3) of 1) coral $^{14}$C ages (O, bar = 2$\sigma$) and 2) marine varve ages (□, bar = 1$\sigma$). The cal BP ages of the corals were determined by U/Th dating and the cal BP ages of the varves by a floating varve count that was shifted to the position given in Fig. 4.

The primary data of the 24,000–11,850 cal BP segment are coral and varve measurements (Bard et al. 1998; Burr et al. 1998; Edwards et al. 1993; Hughen et al. 1998). The $^{14}$C ages of the 12,500–11,850, 15,000–12,500, 19,500–15,000, and 24,000–19,500 cal BP intervals, adjusted to atmospheric levels by deducting a reservoir deficiency of 500 $^{14}$C yr (the rather minor 25 $^{14}$C yr standard deviation was neglected) from the marine ages, are depicted in Figures 6–9 with vertical bars representing 1$\sigma$ in the varve $^{14}$C determinations, and 2$\sigma$ for the coral $^{14}$C determinations. The "atmospheric" $^{14}$C ages of the 40,000–15,000 cal BP interval are given in Figure 10. Coral and varve data coverage is excellent for 16,000–11,850 cal BP, less so for 24,000–16,000 cal BP, and marginal for 40,000–24,000 cal BP.

The minimum smoothing spline (Reinsch 1967) of Figures 6–9, anchored at the last tree-ring point at 11,854 cal BP, was used to generate the atmospheric INTCAL98 $^{14}$C ages of the 11,850–16,000 cal BP period. Due to the scarcity of coral samples, INTCAL 98 lacks detail between 24,000 and 16,000 cal BP. Here the spline is essentially linear, with cal BP = 1.15 $^{14}$C BP + 680.
Fig. 6. "Atmospheric" coral (●, bar = 2σ) and varve (□, bar = 1σ) 14C ages. The minimum smoothing spline (solid line), anchored at the last tree-ring point (11,854 cal BP), was used to derive the INTCAL 98 14C ages of the 12,500–11,854 cal BP time interval.

The 24,000–11,850 cal BP coral- and varve-derived segment of atmospheric INTCAL 98 is part of the Figure A calibration curve. For the marine-derived atmospheric ages we used, as discussed, a spline with minimum smoothing. The INTCAL98 standard deviation (width of the calibration curve) was derived by using a standard deviation of 2σ for the coral 14C ages, 1σ for the varve 14C ages, and a k=1.3 error multiplier for both (σ = standard deviation in the measurement).

There are only two data points between 40,000 and 24,000 cal BP, and a linear relationship is automatic (Fig. 10). This interval, due to the lack of corroborating data points, generates an error-prone calibration curve. The 40,000–24,000 cal BP interval, as a consequence, was not considered for INTCAL98 inclusion.

The conversion of marine 14C age to atmospheric 14C age (by deducting 500 14C yr from the marine age) is an approximation only. The marine record also contains less detail than the atmospheric one, especially for cosmic-ray induced 14C production rate change (e.g., Stuiver, Reimer and Braziunas 1998). Only the 15,000–12,000 cal BP interval, with a large number of marine data points, produces a century-scale fine structure.

The marine INTCAL98 curve (Fig. B) of the 8800–0 cal BP interval contains marine 14C ages derived from the tree-ring record via carbon reservoir modeling (Stuiver, Reimer and Braziunas 1998). Coral and marine varve 14C ages were used for the 24,000–8800 cal BP marine INTCAL98
Fig. 7. Splined "atmospheric" coral and varve data 15,000–12,500 cal BP (solid line; see Fig. 6 caption for symbols). The inset compares three-point moving averages of "atmospheric" (marine derived) INTCAL'98 $^{14}$C ages (solid line) to a similar moving average of terrestrial $^{14}$C ages (dashed line) dated by varves (Kitagawa and van der Plicht 1998).

segment. Here we splined the available marine $^{14}$C dates of the 15,585–8800 cal BP interval (Figs. 5–7), and used a linear approximation for the 24,000–15,585 cal BP interval (Figs. 8 and 9). The calculated INTCAL98 standard deviation (width of the calibration curve, not given in Fig. A) was derived from the measured 2σ deviation for the coral $^{14}$C ages, 1σ for the varve $^{14}$C ages, and a k=1.3 error multiplier for both ($\sigma =$ standard deviation in the measurement). The connection between the splined and carbon reservoir calculated marine $^{14}$C ages is depicted in Figure 11.

The INTCAL98 marine calibration curves (Fig. B) reflect global open ocean conditions. Regional departures from the global values can be expressed in a $\Delta R$ parameter, as discussed in Stuiver, Reimer and Braziunas 1998.

**INTCAL98 $\Delta^{14}$C**

Converting the atmospheric $^{14}$C ages into $\Delta^{14}$C values yields Figure 12. The long-term trend in $\Delta^{14}$C is usually attributed to geomagnetically induced $^{14}$C production rate change.

An interesting $\Delta^{14}$C comparison can be made with the recently published 45,000 cal BP atmospheric varve chronology (Kitagawa and van der Plicht 1998). Although for the 15,000–12,000 cal BP interval the long-term trends of the Kitagawa and van der Plicht atmospheric record and the INTCAL98 atmospheric record derived from marine data are similar, century-scale detail is less fine in the varve...
Fig. 8. Splined "atmospheric" coral data (19,500–15,000 cal BP; see Fig. 6 for symbols). The number of data points is too small to generate detail in the dashed curve.

record (the inset in Fig. 7 compares three-point moving averages of both data sets). The varve curve, on the other hand, is more detailed for pre-15,000 cal BP ages where the coral curve (due to the limited number of data points) appears linear.

Given a perfect varve chronology, the 175-yr offset (Fig. 7 inset) would indicate a marine reservoir correction of 325 14C yr instead of 500 14C yr. Because a zero-error varve chronology is unlikely, however, this cannot be definitely concluded.

The century- and millennium-scale Δ14C variations (residual Δ14C, in per mil) of Figure 13 were obtained by deducting a 2000 yr moving average.

Reduced North Atlantic deepwater formation is tied to reduced surface-water transport toward the North (the "warm" Gulf Stream), causing Northern regions (e.g., Western Europe and Greenland) to become colder. Reduced deepwater formation is also tied to atmospheric 14C increase. Because lower δ18O values9 accompany reduced atmospheric precipitation temperatures, one expects an inverse relationship between δ18O and Δ14C for oceanic-induced climate perturbations. The relationship (correlation coefficient r = −0.54, Δ14C/δ18O = −20.4) is depicted in Figure 14, where residual INTCAL98 Δ14C (U/Th time scale) is compared to inverted δ18O (ice layer count time scale) of the GISP2 Greenland ice core (Stuiver, Grootes and Braziunas 1995) for the 15,500–10,500 cal BP interval.

9 δ18O is the per mil deviation of the sample 18O/16O ratio from that of the SMOW standard.
Fig. 9. Splined “atmospheric” coral data (24,000–19,500 cal BP; see Fig. 6 for symbols). The number of data points is too small to generate detail in the dashed curve.

The reduction of residual $\Delta^{14}C$ during the 15,000–14,500 cal BP interval suggests that the temperature increase of the Bølling (which starts ca. 14,670 cal BP) is tied to increased deepwater formation. The increase is followed by a two-step reduction and reverses again to increased deepwater formation (Broecker 1997, 1998; Hughen et al. 1998; Stuiver and Braziunas 1993) at the beginning of the Younger Dryas (~12,890 cal BP). This increase in deepwater formation ultimately leads to the relatively stable temperatures of the Holocene. To complicate matters, a Younger Dryas bipolar seesaw also may be operating (Broecker 1998). The Holocene itself has several century-scale oceanic and solar-induced (the solar connection yields $\Delta^{14}C = 60 \delta^{18}O$) $\Delta^{14}C$ perturbations (Stuiver and Braziunas 1993; Stuiver et al. 1997).

Oceanic-induced atmospheric $\Delta^{14}C$ changes ($\Delta^{14}C$/yr) are caused by $^{14}C$ exchange rate variations between the mixed layer and deep ocean. For a complete cessation of $^{14}C$ transfer between mixed layer and deep ocean, the cosmic-ray-produced $^{14}C$ (global production rate Q in atoms/yr) will be distributed over a much smaller atmosphere, biosphere and mixed layer (ABM) reservoir. Present-day carbon reservoirs contain $^{14}C$ totaling 8260 yr of production (8260Q). The ABM reservoir contains only 7% of the total amount of exchangeable carbon (e.g., Lal 1985), or 580 yr of $^{14}C$ production (580Q). When completely separated from the deep ocean, the atmospheric $^{14}C$ level of the ABM reservoir will double in ca. 650 yr (without radioactive decay the doubling time would be 580 yr). Thus the fastest rate of $^{14}C$ change in the atmosphere will be ~1% per 7 yr for a hypothetical deep ocean suddenly disconnected from the ABM reservoir. Rates of change of similar magnitude
will occur when fully reconnecting the mixed layer and deep ocean (the downward flux (0.93Q) is nearly identical to the production rate Q).

There are two modes of $^{14}$C transport from the mixed layer to the deep ocean. Diffusion (including isopycnal advection) and deepwater formation play a key role. For the Holocene, deepwater formation transports about two-thirds of the global $^{14}$C to the deep ocean (Toggweiler, Dixon and Bryan 1989). This yields a maximum $\Delta^{14}$C change of 1% per 10.5 yr for full cessation of deepwater formation alone. The fastest observed century-scale $\Delta^{14}$C change of 1% per 17 yr (near 13810, 13140 and 12720 cal BP, Fig. 14) delivers a 60% change in the rate of global deepwater formation. The well-defined maxima and minima in Figure 14 also suggest decadal switching times. And fast switching between the two modes of deepwater formation agrees with the symmetrical shape of several century-scale $^{14}$C maxima and minima in Figure 14.

The $\Delta^{14}$C decline near the start of the Bølling produces a fairly long plateau (15,000–14,400 cal BP) in the $^{14}$C age–cal age relationship (Fig. 7 and 8). There are several Bølling-type oscillations in the GISP2 oxygen isotope record between 40,000 and 15,000 cal BP. Assuming similarity in atmospheric $^{14}$C response, one expects ca. 600-yr-long $^{14}$C age plateaus near 38,400, 35,300, 33,600, 32,300 and 29,100 cal BP (GISP2 time scale).
Fig. 11. Coral (○, bar = 2σ) and varve (□, bar = 1σ) ¹⁴C ages splined (solid line) over the 12,000–8800 cal BP interval. The spline is connected to the carbon reservoir calculated decadal marine ¹⁴C ages (solid line) of the 8800–7000 cal BP interval. The solid lines form the INTCAL98 calibration curve for marine samples.

**CALIBRATION**

It is not possible to suggest guidelines for specific regional (non-hemispheric) offsets due to the lack of precise information on time-dependent regional ¹⁴C differences. Offsets (see “Hemispheric and Regional Offsets”) introduce uncertainties of one or two decades in the age calibration process of atmospheric samples. Because the ¹⁴C level of the Southern Hemisphere is, on average, below that of the Northern Hemisphere, we recommend for Southern Hemispheric samples a ¹⁴C age reduction of 24 ± 3 ¹⁴C yr prior to calibration (pre-AD 1900 atmospheric samples only).

As noted previously, the atmospheric calibration curve is based on 1) a linear connection of the tree-ring generated decadal data points (11,850–0 cal BP) and 2) a spline with minimum smoothing of reservoir-corrected coral and varve data (24,000–11,850 cal BP).

The marine calibration curve consists of 1) a linear connection of carbon reservoir calculated decadal marine ages (8800–0 cal BP) and a 2) a spline of measured coral and varve ages (24,000–8800 cal BP) with a degree of smoothing similar to the atmospheric calibration curve.

The standard deviation in the curves is not drawn in Figures A (atmospheric) and B (marine). For the tree-ring based portion of the atmospheric curve, the width of the curve (the one standard deviation includes a 1.3 error multiplier) starts with an average 9 yr for the youngest millennium and increases...
Fig. 12. Atmospheric $\Delta^{14}C$ profile for 1) 15,500-0 cal BP and 2) 40,000-0 cal BP (inset, with $\Delta^{14}C$ per mil scale). Tree-ring data were used for the 11,854–0 cal BP construction and marine (coral and varve) information for the remaining part. The solid line represents $\Delta^{14}C$ values derived from the INTCAL98 $^{14}C$ age–cal age relationship; the dashed portion is based on the splining of a limited number of data points (see Figs. 7 and 8). The double dashed curve is based on only two measurements.

to 23 yr for the older part (11,000–10,000 cal BP). The width of the spline, derived from the coral and varve $^{14}C$ age errors, is one standard deviation (as discussed, we use for the calculation of the actual standard deviation 2$\sigma$ for the coral $^{14}C$ ages, 1$\sigma$ for the varve $^{14}C$ ages, and a $k=1.3$ error multiplier for both) and ranges from an average 100 $^{14}C$ yr for the 13,000–12,000 cal BP interval to 300 $^{14}C$ yr for the 24,000–20,000 cal BP interval.

In its simplest form, the calibration process is a straightforward reading of the calibration curves (Stuiver and Pearson 1993). Because Figures A and B lack uncertainty estimates, we recommend the use of computer programs that include the error margin for age calibration. Computer programs (e.g., CALIB, Stuiver and Reimer 1993; cal15, van der Plicht 1993; and OxCal v2.18, Bronk Ramsey 1994) also generate additional information, such as probability distributions vs. cal age. To avoid confusion, we recommend that all computer programs, as of 1999, incorporate the INTCAL98 database for marine and terrestrial age calibration. The INTCAL98 calibration data (atmospheric as well as marine, with one standard deviation uncertainty), the atmospheric $\Delta^{14}C$ and residual $\Delta^{14}C$ values, the CALIB 4.0 computer program based on INTCAL98 data, and $^{18}O$ of the GISP2 ice core can be downloaded from the Quaternary Isotope Laboratory web site at <http://depts.washington.edu/qil/>. 
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Fig. 14. The upper curve depicts the inverted GISP2 oxygen isotope ratio ($\delta^{18}O$) record with bidecadal time separation (Stuiver, Grootes and Braziunas 1995). The lower curve is based on INTCAL98 residual $\Delta^{14}C$. The cal BP scale of the oxygen isotope record is based on ice layer counts (Alley et al. 1997). B = Bolling, YD = Younger Dryas.

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Fig. A1–19. INTCAL98 atmospheric calibration curve with decadal resolution back to 11,850 cal BP. The remaining part of INTCAL98 was constructed from coral data with a time resolution of about one century near 12,000 cal BP, and about one millennium near 24,000 cal BP. The dashed portions are based on the splining of a limited number of data points (see Figs. 7 and 8).
Fig. B1-10. INTCAL98 marine calibration curve based on 1) carbon reservoir derived 14C ages for the 8800-0 cal BP interval and 2) coral/varve 14C age determinations for the 8800-24,000 cal BP interval. The dashed portions are based on the spinning of a limited number of data points (see Figs. 7 and 8). The very substantial 10,900 cal BP perturbation is dashed because its maximum, generated by a single data point, lacks corroboration.
Fig. B3

Fig. B4
Fig. B19