REGIONAL OFFSET OF RADIOCARBON CONCENTRATION AND ITS VARIATION IN THE KOREAN ATMOSPHERE FROM AD 1650–1850

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ABSTRACT. A series of annual tree-ring measurements has been performed in order to reconstruct the radiocarbon concentration variation in the Korean atmosphere from AD 1650 to 1850. The absolute ages of the samples were determined using dendrochronology. Alpha-cellulose extraction was applied to prepare the tree-ring samples for precise ^{14}C measurement. The ^{14}C concentrations of the tree rings were then plotted with the dendrochronological ages and showed that during the period AD 1650–1850, the discrepancy in ^{14}C concentration in the Korean atmosphere from IntCal data is small enough to use IntCal data without any further correction. This is nearly one third of the average offset of the 400 yr from AD 1250 to 1650. One of the probable causes for the regional offset around Korea is the contribution of ^{14}C-depleted CO_2 released from the northern Pacific Ocean, where old deep water upwells to the surface. It is likely that the release rate of ^{14}C-depleted CO_2 decreased due to the temperature change during the Little Ice Age.

INTRODUCTION

Radiocarbon concentration variations in the atmosphere depend on variations of natural activities such as the ^{14}C production rate, climate change, and volcanic eruptions, as well as anthropogenic behaviors such as fossil fuel consumption and nuclear bomb tests. Among these factors, volcanic eruptions and local fossil fuel releases can cause regional offsets in ^{14}C concentrations. In particular, the contribution of CO_2 released from the deep ocean is notable because oceans contain old carbon due to the long periods of seawater circulation. Previous studies reported that the ^{14}C concentrations in tree rings grown in east Asia are slightly lower than those of western Europe and North America (Nakamura et al. 2007; Hong et al. 2013). It appears that the low concentration is due to the migration of ^{14}C-depleted CO_2 into the Korean and Japanese atmosphere when it is released from the northern Pacific Ocean. The calendar age obtained by calibration using IntCal09 data (Reimer et al. 2009) may include offsets for the samples collected in the east Asian region because IntCal04 data after 12.4 cal kyr BP were obtained from tree-ring measurements of trees grown in Europe and North America, despite the fact that the IntCal04 data were provided after very careful cross-checking with European tree rings (German pines, German oaks, Belfast oaks, and Irish oaks) and North American rings (from Washington, Oregon, California and Alaska and bristlecone pine trees) (Reimer et al. 2004). To confirm the consistency in IntCal data used for calibrating the ^{14}C ages of local samples in the Far East, careful and precise ^{14}C concentration measurements of tree rings grown in this area are very important.

Since 2009, the 1MV accelerator mass spectrometry (AMS) system of the Korea Institute of Geoscience and Mineral Resources (KIGAM) has been dedicated to ^{14}C measurements of tree rings grown on the Korean Peninsula in order to study the regional characteristics of atmospheric isotopic concentration. ^{14}C variations of tree-ring samples that grew in Korea from AD 1250 to 1650 were initially reported at the 12th AMS Conference held in Wellington (Hong et al. 2013). This article builds on that work and reports ^{14}C concentrations of tree rings spanning the next 200 yr, from AD 1650 to 1850.

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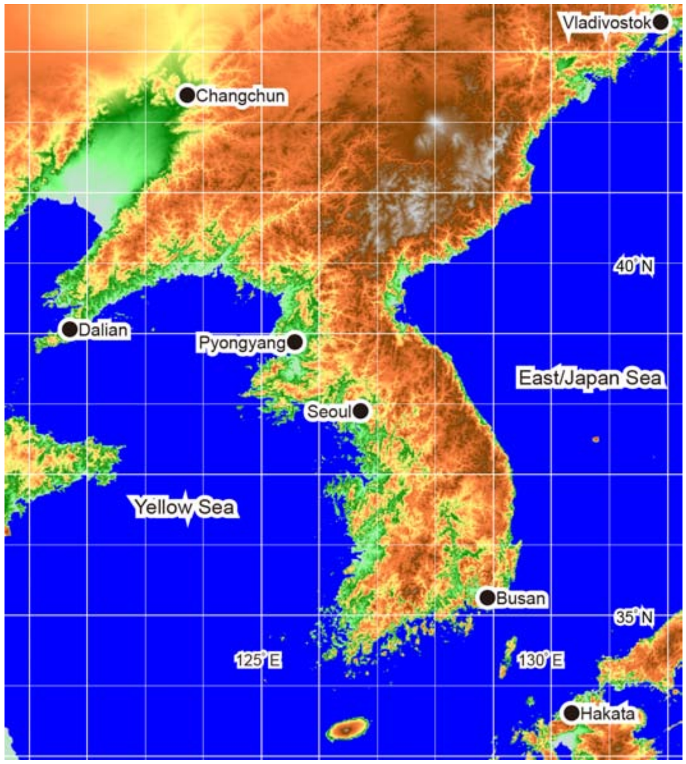

Figure 1 The location of the sampling sites in the Korean Peninsula

SAMPLE COLLECTION AND DENDROCHRONOLOGY

The tree-ring samples used in this work were collected from Tongmyeongjeon (37°34′46.98″N, 126°59′37.60″E; see Figure 1), which is an annex of the Changdeok Palace in Seoul. This building was built in AD 1484 during the Choseon Dynasty, the last dynasty in Korea. In 2002, Tongmyeongjeon was renovated and wooden building materials were collected. Among them, 3 samples (TMJS017A, TMJS079A, and TMgt215A) were used for tree-ring measurements of pine wood (*Pinus densiflora*: Japanese red pine). Dendrochronological ages of the tree-ring samples were obtained from the Tree-Ring Material Bank of Chungbuk National University using Baillie's method (Baillie 1982). The ring-width plots of the samples were cross-dated by matching their patterns with the master chronologies that had already been absolutely dated through matches with living trees. The correlation coefficient r between the sample and its reference is given as

$$r = \frac{\sum[(S_i - S)(R_i - R)]}{\sqrt{\sum[(S_i - S)^2 (R_i - R)^2]}} \tag{1}$$

where S_i is the i^{th} ring width of a sample, S is the average ring width of the sample, R_i is the i^{th} ring width of a reference, and R is the average ring width of the reference (Baillie and Pilcher 1973). The t value in the dating results is therefore defined as

$$t = \frac{r\sqrt{n-2}}{1-r^2} \tag{2}$$

where *n* is the number of overlapped years in both the sample and reference. The age range of TMJS017A is 186 yr (AD 1619–1804). The master chronology for this sample was P3P1001M, and the *t* value was 5.9. TMJS079A was a roof packing log with an age range of 135 yr (AD 1699–1833). The master for this was KNNNUNP1, and the *t* value was 6.7. Another roof packing log, TMgt215A, was found to have an age range of 139 yr (AD 1757–1895) using the master, SINSUNP1. Its *t* value was calculated to be 9.5. The sample information is summarized in Table 1. Tree-ring chronologies of Japanese red pine in Korea, which were used as masters, were described in previous papers (Park and Lee 2001; Park et al. 2007).

Table 1 List of samples used for tree-ring measurements and chronology masters. *t* values were calculated using the formula given by Baillie and Pilcher (1973).

Sample	Master	Age range	Ranges used in this work	*t* value
TMJS017A	P3P1001M	AD 1619–1804 (186 yr)	AD 1650–1749 (100 yr)	5.9
TMJS079A	KNNNUNP1	AD 1699–1833 (135 yr)	AD 1750–1790 (41 yr)	6.7
TMgt215A	SINSUNP1	AD 1757–1895 (139 yr)	AD 1791–1850 (60 yr)	9.5

SAMPLE PREPARATION AND MEASUREMENT OF RADIOCARBON

After obtaining the absolute ages using dendrochronology, the samples were cut into annual rings to perform single-year measurements. An alpha-cellulose extraction procedure was utilized on 201 samples with ages from AD 1650 to 1850. Each tree ring was powdered by a mixer mill with a diameter smaller than 0.5 mm. The tree-ring powders were heated to 80 °C in a Soxhlet system with a mixed solution of 120 mL of cyclohexane and 60 mL of ethanol for 6 hr to remove gums, resins, waxes, sugars, oils, starches, alkaloids, tannins, and fats, followed by rinsing at 90 °C in a Soxhlet system with 180 mL of ethanol for 6 hr to remove cyclohexane, which contains dead carbon, and a final rinse at 100 °C in a Soxhlet containing 180 mL of deionized water for 6 hr to remove ethanol, which may contain modern carbon. After the rinsing process, the samples were moved to flasks with a solution of 105 mg of $NaClO_2$ in 50 mL of 1M HCl solvent, and the flasks were heated to 100 °C in an ultrasonic water bath for 1 hr to remove lignin from the samples. During this step, the sample color typically changes to light brown. When the sample color was still dark, 50 mg of $NaClO_2$ was added to the solution, followed by additional heating for 1 hr. The samples were then rinsed with deionized water until neutral. Alpha-cellulose was extracted from the samples by an ultrasonic treatment at 60 °C for 1 hr in 50 mL of a 12% NaOH solution with nitrogen bubbling. The solution was changed to a 7% NaOH solution and the same procedure was repeated. The alpha-cellulose was rinsed so that it was neutralized. To remove any atmospheric CO_2 contamination during the extraction process, the alpha-cellulose was treated with 2M HCl at room temperature for 30 min. Finally, the alpha-cellulose was rinsed with deionized water until neutral, after which it was dried at 40 °C for 2 days. All of these processes took a total of 5 days.

The conversion of alpha-cellulose to graphite was done using an automatic 24-fold reduction system directly connected to an elemental analyzer (EA; Hong et al. 2010a). The samples were sequentially combusted in the EA and the CO_2 gases were transferred to the reduction system and trapped cryogenically in reduction tubes. Some 3–4 mg of Fe catalyst and hydrogen gas with a volume 2.1 times larger than that of CO_2 was used for the reduction reactions at 600 °C. Typically, the reduction yields were 93% after a 3-hr reduction process. Around 1 mg of graphite was obtained for each tree ring, and the graphite samples were pelletized for AMS measurements. $^{14}C/^{12}C$ ratios were measured using the 1MV AMS at KIGAM (Hong et al. 2010b). Each sample was measured 3 times for 1050 s. The total counting time per tree-ring sample was 53 min and the total collected charge of

^{12}C was ~300–400 µC. To monitor the counting conditions, known samples (IAEA C7 and C8 reference materials) were measured every 25 tree-ring measurements.

RESULTS AND DISCUSSION

Results of the ^{14}C measurements of the annual tree-ring samples are presented in Table 2 with their dendrochronological ages. The ^{14}C concentration deviations ^{14}C of the tree rings grown on the Korean Peninsula during AD 1650–1850 were calculated by

$$\Delta^{14}C = [pMC \cdot \exp\{(1950 - y)/\lambda\} - 1] \times 1000 \quad (3)$$

where y is the year the ring was grown and $\lambda = t_{1/2}/\ln(2) = 8267$. $t_{1/2}$ is the half-life of ^{14}C, 5730 yr. pMC was calculated by comparing the measured activity of a tree-ring sample to that of NIST oxalic acid after background subtraction, followed by $\delta^{13}C$ correction following Stuiver and Polach (1977). $^{13}C/^{12}C$ ratios were measured by AMS, and the errors given in the Table 2 were evaluated by the statistical errors of the ^{14}C counts and ^{12}C and ^{13}C values of tree-ring samples, oxalic acids, and blank samples. Though the $\delta^{13}C$ values of the AD 1657, 1677, 1682, and 1728 samples were too high in terms of our $\delta^{13}C$ criteria for terrestrial samples (–30‰ < $\delta^{13}C$ ≤ –20‰), their ages were consistent with the adjacent ages. The annual ^{14}C values of the tree rings measured are plotted in Figure 2 with the IntCal04 data. Because the IntCal04 data are the average values for every 10 yr (Reimer et al. 2004), our tree-ring data were also averaged every 10 yr to calculate the deviations in the Korean tree-ring data from the IntCal04 data. They are plotted every 5 yr in Figure 2.

Table 2 Results of ^{14}C and dendrochronological age measurements of tree-ring samples grown in Korea from AD 1650 to 1850. Ages (AD) were determined by the dendrochronological method, and $\delta^{13}C$ values were measured by AMS.

Lab code	Age (AD)	Year BP	pMC (%)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
KGM-TWd091535	1650	190 ± 30	97.68 ± 0.38	12.93 ± 3.80	–23.83 ± 0.16
KGM-TWd091534	1651	220 ± 30	97.31 ± 0.38	8.89 ± 3.81	–24.78 ± 0.15
KGM-TWd091533	1652	269 ± 30	96.71 ± 0.36	2.60 ± 3.60	–21.39 ± 3.40
KGM-TWd091532	1653	302 ± 31	96.31 ± 0.37	–1.67 ± 3.66	–22.95 ± 3.81
KGM-TWd091531	1654	240 ± 31	97.06 ± 0.38	5.98 ± 3.73	–23.18 ± 3.33
KGM-TWd091530	1655	254 ± 32	96.89 ± 0.38	4.10 ± 3.80	–23.55 ± 3.24
KGM-TWd091529	1656	283 ± 32	96.54 ± 0.38	0.35 ± 3.81	–23.01 ± 3.31
KGM-TWd091528	1657	323 ± 31	96.06 ± 0.36	–4.74 ± 3.62	–19.39 ± 3.60
KGM-TWd091527	1658	275 ± 30	96.63 ± 0.37	1.04 ± 3.63	–21.63 ± 1.36
KGM-TWd091526	1659	293 ± 31	96.42 ± 0.37	–1.26 ± 3.70	–23.29 ± 0.27
KGM-TWd091525	1660	345 ± 32	95.79 ± 0.38	–7.90 ± 3.80	–22.95 ± 0.66
KGM-TWd091524	1661	283 ± 31	96.54 ± 0.38	–0.25 ± 3.74	–21.53 ± 0.44
KGM-TWd091523	1662	245 ± 32	96.99 ± 0.39	4.28 ± 3.83	–24.70 ± 1.44
KGM-TWd091522	1663	293 ± 32	96.42 ± 0.38	–1.74 ± 3.80	–22.99 ± 0.87
KGM-TWd091521	1664	255 ± 31	96.87 ± 0.38	2.80 ± 3.73	–21.72 ± 0.97
KGM-TWd091520	1665	206 ± 31	97.47 ± 0.38	8.89 ± 3.79	–23.23 ± 1.31
KGM-TWd091519	1666	199 ± 30	97.55 ± 0.37	9.59 ± 3.65	–24.01 ± 0.62
KGM-TWd091518	1667	214 ± 31	97.37 ± 0.37	7.61 ± 3.70	–22.92 ± 0.73
KGM-TWd091517	1668	198 ± 31	97.57 ± 0.38	9.56 ± 3.78	–20.65 ± 1.05
KGM-TWd091516	1669	212 ± 32	97.40 ± 0.39	7.68 ± 3.87	–23.71 ± 0.29
KGM-TWd091515	1670	206 ± 32	97.47 ± 0.39	8.28 ± 3.89	–25.15 ± 0.86
KGM-TWd091514	1671	166 ± 32	97.95 ± 0.39	13.12 ± 3.83	–23.78 ± 1.19
KGM-TWd091513	1672	174 ± 32	97.86 ± 0.39	12.07 ± 3.85	–23.40 ± 1.01
KGM-TWd091512	1673	214 ± 31	97.37 ± 0.37	6.88 ± 3.68	–20.19 ± 0.93
KGM-TWd091511	1674	170 ± 32	97.91 ± 0.38	12.34 ± 3.82	–23.48 ± 2.11
KGM-TWd091510	1675	203 ± 33	97.51 ± 0.40	8.08 ± 3.96	–22.68 ± 1.34

Table 2 Results of ^{14}C and dendrochronological age measurements of tree-ring samples grown in Korea from AD 1650 to 1850. Ages (AD) were determined by the dendrochronological method, and $\delta^{13}C$ values were measured by AMS. *(Continued)*

Lab code	Age (AD)	Year BP	pMC (%)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
KGM-TWd091509	1676	119 ± 32	98.53 ± 0.39	18.50 ± 3.90	–21.67 ± 0.84
KGM-TWd091508	1677	159 ± 31	98.04 ± 0.38	13.32 ± 3.78	–17.51 ± 1.17
KGM-TWd091507	1678	146 ± 32	98.20 ± 0.40	14.85 ± 3.93	–24.08 ± 1.02
KGM-TWd091506	1679	134 ± 31	98.35 ± 0.38	16.27 ± 3.73	–20.92 ± 0.85
KGM-TWd091505	1680	130 ± 32	98.39 ± 0.39	16.56 ± 3.87	–22.56 ± 0.59
KGM-TWd091504	1681	191 ± 32	97.65 ± 0.39	8.80 ± 3.85	–20.39 ± 0.66
KGM-TWd091503	1682	150 ± 31	98.15 ± 0.38	13.84 ± 3.76	–18.51 ± 3.04
KGM-TWd091502	1683	131 ± 31	98.39 ± 0.38	16.20 ± 3.77	–20.20 ± 1.58
KGM-TWd091501	1684	101 ± 31	98.75 ± 0.39	19.79 ± 3.83	–20.47 ± 2.92
KGM-TWd091500	1685	195 ± 31	97.60 ± 0.38	7.79 ± 3.73	–23.09 ± 0.44
KGM-TWd091499	1686	190 ± 31	97.66 ± 0.38	8.29 ± 3.73	–24.53 ± 0.82
KGM-TWd091498	1687	189 ± 31	97.67 ± 0.38	8.27 ± 3.73	–21.31 ± 0.75
KGM-TWd091497	1688	158 ± 31	98.05 ± 0.38	12.07 ± 3.74	–24.58 ± 0.34
KGM-TWd091496	1689	127 ± 31	98.43 ± 0.38	15.87 ± 3.76	–23.16 ± 0.71
KGM-TWd091495	1690	133 ± 31	98.36 ± 0.38	15.03 ± 3.75	–22.69 ± 1.08
KGM-TWd091494	1691	150 ± 31	98.16 ± 0.38	12.84 ± 3.76	–22.65 ± 0.66
KGM-TWd091493	1692	147 ± 31	98.19 ± 0.38	13.03 ± 3.75	–24.04 ± 0.81
KGM-TWd091492	1693	160 ± 31	98.03 ± 0.38	11.25 ± 3.74	–22.04 ± 1.17
KGM-TWd091491	1694	197 ± 31	97.57 ± 0.38	6.39 ± 3.73	–21.29 ± 0.62
KGM-TWd091490	1695	104 ± 31	98.71 ± 0.38	18.02 ± 3.78	–22.84 ± 0.54
KGM-TWd091489	1696	182 ± 31	97.75 ± 0.38	8.00 ± 3.73	–23.02 ± 0.94
KGM-TWd091488	1697	64 ± 31	99.20 ± 0.38	22.83 ± 3.79	–22.36 ± 0.28
KGM-TWd091487	1698	83 ± 31	98.97 ± 0.38	20.33 ± 3.77	–22.15 ± 0.77
KGM-TWd091486	1699	83 ± 31	98.97 ± 0.38	20.21 ± 3.78	–21.43 ± 1.16
KGM-TWd091485	1700	111 ± 31	98.63 ± 0.38	16.58 ± 3.77	–22.39 ± 0.61
KGM-TWd091484	1701	93 ± 31	98.85 ± 0.38	18.73 ± 3.78	–21.47 ± 0.38
KGM-TWd091483	1702	106 ± 31	98.69 ± 0.38	16.95 ± 3.77	–25.92 ± 1.16
KGM-TWd091482	1703	106 ± 31	98.69 ± 0.38	16.83 ± 3.78	–26.31 ± 1.32
KGM-TWd091481	1704	105 ± 31	98.70 ± 0.38	16.81 ± 3.78	–24.49 ± 0.85
KGM-TWd091480	1705	112 ± 31	98.62 ± 0.38	15.86 ± 3.76	–22.29 ± 0.75
KGM-TWd091479	1706	97 ± 31	98.80 ± 0.38	17.60 ± 3.78	–22.92 ± 0.90
KGM-TWd091478	1707	76 ± 31	99.06 ± 0.38	20.15 ± 3.78	–25.12 ± 0.92
KGM-TWd091477	1708	136 ± 31	98.32 ± 0.38	12.41 ± 3.75	–23.24 ± 0.83
KGM-TWd091476	1709	–26 ± 34	100.32 ± 0.43	32.88 ± 4.25	–21.27 ± 0.08
KGM-TWd091475	1710	–112 ± 34	101.40 ± 0.43	43.87 ± 4.26	–20.25 ± 0.13
KGM-TWd091474	1711	–62 ± 34	100.77 ± 0.42	37.26 ± 4.19	–23.44 ± 0.13
KGM-TWd091473	1712	–6 ± 34	100.07 ± 0.42	29.93 ± 4.18	–23.97 ± 0.44
KGM-TWd091472	1713	173 ± 35	97.87 ± 0.42	7.16 ± 4.17	–24.20 ± 0.39
KGM-TWd091471	1714	–21 ± 34	100.27 ± 0.43	31.74 ± 4.26	–22.68 ± 0.10
KGM-TWd091470	1715	31 ± 30	99.61 ± 0.38	24.82 ± 3.73	–23.26 ± 2.28
KGM-TWd091469	1716	108 ± 31	98.67 ± 0.38	15.03 ± 3.73	–25.00 ± 2.27
KGM-TWd091468	1717	88 ± 31	98.91 ± 0.38	17.37 ± 3.78	–22.51 ± 0.55
KGM-TWd091467	1718	43 ± 31	99.47 ± 0.38	23.01 ± 3.79	–21.52 ± 0.81
KGM-TWd091466	1719	80 ± 31	99.01 ± 0.38	18.16 ± 3.79	–23.95 ± 1.11
KGM-TWd091465	1720	116 ± 31	98.57 ± 0.38	13.51 ± 3.75	–23.27 ± 0.64
KGM-TWd091464	1721	114 ± 31	98.59 ± 0.38	13.59 ± 3.77	–22.45 ± 1.27
KGM-TWd091463-1	1722	146 ± 32	98.20 ± 0.39	9.46 ± 3.83	–21.44 ± 0.50
KGM-TWd091462-1	1723	185 ± 32	97.73 ± 0.38	4.51 ± 3.80	–21.79 ± 0.41
KGM-TWd091461-1	1724	180 ± 33	97.79 ± 0.39	5.00 ± 3.92	–23.22 ± 0.55
KGM-TWd091460	1725	84 ± 31	98.97 ± 0.38	17.01 ± 3.74	–23.96 ± 2.16
KGM-TWd091459	1726	165 ± 31	97.97 ± 0.38	6.61 ± 3.74	–22.84 ± 1.99
KGM-TWd091458	1727	88 ± 31	98.91 ± 0.38	16.14 ± 3.74	–24.36 ± 3.18
KGM-TWd091457	1728	221 ± 31	97.29 ± 0.37	–0.62 ± 3.70	–19.91 ± 2.95

Table 2 Results of ^{14}C and dendrochronological age measurements of tree-ring samples grown in Korea from AD 1650 to 1850. Ages (AD) were determined by the dendrochronological method, and $\delta^{13}C$ values were measured by AMS. *(Continued)*

Lab code	Age (AD)	Year BP	pMC (%)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
KGM-TWd091456	1729	123 ± 31	98.48 ± 0.38	11.48 ± 3.80	–21.66 ± 0.93
KGM-TWd091455	1730	143 ± 31	98.24 ± 0.38	8.89 ± 3.72	–21.26 ± 0.84
KGM-TWd091454	1731	60 ± 32	99.25 ± 0.39	19.14 ± 3.88	–24.17 ± 0.87
KGM-TWd091453	1732	80 ± 31	99.00 ± 0.38	16.45 ± 3.75	–23.10 ± 0.55
KGM-TWd091452	1733	121 ± 31	98.51 ± 0.39	11.30 ± 3.82	–23.03 ± 0.29
KGM-TWd091451	1734	112 ± 31	98.62 ± 0.38	12.31 ± 3.79	–22.26 ± 0.69
KGM-TWd091450	1735	173 ± 32	97.87 ± 0.38	4.49 ± 3.80	–22.78 ± 0.76
KGM-TWd091449	1736	201 ± 30	97.53 ± 0.37	0.88 ± 3.66	–21.26 ± 0.61
KGM-TWd091448	1737	200 ± 32	97.55 ± 0.38	0.96 ± 3.80	–23.02 ± 0.75
KGM-TWd091447	1738	222 ± 30	97.28 ± 0.37	–1.93 ± 3.65	–21.11 ± 0.49
KGM-TWd091446	1739	191 ± 31	97.65 ± 0.37	1.74 ± 3.69	–21.87 ± 0.20
KGM-TWd091445	1740	224 ± 31	97.24 ± 0.37	–2.58 ± 3.68	–22.83 ± 0.40
KGM-TWd091444	1741	230 ± 31	97.18 ± 0.37	–3.32 ± 3.66	–23.34 ± 0.57
KGM-TWd091443	1742	222 ± 31	97.28 ± 0.37	–2.41 ± 3.69	–20.87 ± 0.30
KGM-TWd091442	1743	181 ± 33	97.78 ± 0.40	2.59 ± 3.95	–25.29 ± 0.34
KGM-TWd091441	1744	220 ± 31	97.30 ± 0.37	–2.45 ± 3.66	–22.05 ± 0.24
KGM-TWd091440	1745	191 ± 32	97.66 ± 0.39	1.12 ± 3.89	–24.32 ± 0.91
KGM-TWd091439	1746	200 ± 33	97.55 ± 0.40	–0.13 ± 3.94	–24.29 ± 0.37
KGM-TWd091438	1747	232 ± 31	97.15 ± 0.38	–4.35 ± 3.77	–23.04 ± 0.35
KGM-TWd091437	1748	201 ± 30	97.53 ± 0.37	–0.58 ± 3.64	–22.28 ± 0.34
KGM-TWd091436	1749	196 ± 30	97.59 ± 0.37	–0.08 ± 3.65	–21.08 ± 0.68
KGM-TCe110001	1750	191 ± 30	97.65 ± 0.37	0.41 ± 3.63	–22.20 ± 0.80
KGM-TCe110002	1751	223 ± 41	97.26 ± 0.50	–3.70 ± 4.93	–22.57 ± 0.38
KGM-TCe110003	1752	200 ± 40	97.53 ± 0.49	–1.06 ± 4.82	–23.57 ± 0.16
KGM-TCe110004	1753	270 ± 41	96.70 ± 0.49	–9.68 ± 4.91	–23.69 ± 0.14
KGM-TCe110005	1754	255 ± 40	96.87 ± 0.48	–8.06 ± 4.73	–23.30 ± 0.10
KGM-TCe110006	1755	266 ± 41	96.74 ± 0.49	–9.51 ± 4.91	–24.89 ± 0.26
KGM-TCe110007	1756	270 ± 40	96.69 ± 0.48	–10.14 ± 4.73	–22.34 ± 0.21
KGM-TCe110008	1757	247 ± 41	96.97 ± 0.49	–7.40 ± 4.84	–23.37 ± 0.20
KGM-TCe110009	1758	189 ± 41	97.68 ± 0.50	–0.25 ± 4.99	–22.81 ± 0.17
KGM-TCe110010	1759	171 ± 41	97.89 ± 0.50	1.78 ± 4.97	–22.59 ± 0.38
KGM-TCe110011	1760	195 ± 41	97.60 ± 0.50	–1.31 ± 4.94	–21.93 ± 0.39
KGM-TCe110012	1761	272 ± 40	96.68 ± 0.48	–10.84 ± 4.80	–20.95 ± 0.41
KGM-TCe110013	1762	203 ± 31	97.51 ± 0.38	–2.47 ± 3.76	–23.43 ± 0.37
KGM-TCe110014	1763	193 ± 31	97.63 ± 0.38	–1.36 ± 3.74	–22.92 ± 0.49
KGM-TCe110015	1764	179 ± 31	97.79 ± 0.38	0.15 ± 3.79	–22.51 ± 0.38
KGM-TCe110016	1765	169 ± 32	97.92 ± 0.38	1.36 ± 3.82	–24.24 ± 0.37
KGM-TCe110017	1766	180 ± 31	97.79 ± 0.37	–0.09 ± 3.70	–22.66 ± 1.45
KGM-TCe110018	1767	226 ± 32	97.23 ± 0.39	–5.94 ± 3.86	–22.78 ± 1.52
KGM-TCe110019	1768	207 ± 31	97.45 ± 0.38	–3.81 ± 3.77	–21.89 ± 1.19
KGM-TCe110020	1769	146 ± 31	98.20 ± 0.38	3.74 ± 3.77	–23.95 ± 1.33
KGM-TCe110021	1770	171 ± 31	97.90 ± 0.38	0.55 ± 3.80	–23.16 ± 1.06
KGM-TCe110022	1771	155 ± 32	98.09 ± 0.39	2.37 ± 3.84	–23.94 ± 1.82
KGM-TCe110023	1772	198 ± 33	97.57 ± 0.40	–3.06 ± 4.00	–23.58 ± 0.32
KGM-TCe110024	1773	167 ± 31	97.94 ± 0.38	0.60 ± 3.72	–22.30 ± 0.17
KGM-TCe110025	1774	218 ± 31	97.32 ± 0.38	–5.86 ± 3.75	–20.95 ± 0.65
KGM-TCe110026	1775	156 ± 31	98.08 ± 0.38	1.78 ± 3.77	–22.48 ± 0.39
KGM-TCe110027	1776	194 ± 31	97.61 ± 0.38	–3.14 ± 3.73	–22.24 ± 0.21
KGM-TCe110028	1777	192 ± 31	97.64 ± 0.37	–2.95 ± 3.69	–20.96 ± 0.58
KGM-TCe110029	1778	146 ± 32	98.20 ± 0.39	2.65 ± 3.86	–21.19 ± 0.44
KGM-TCe110030	1779	250 ± 31	96.94 ± 0.38	–10.34 ± 3.74	–21.90 ± 0.42
KGM-TCe110031	1780	189 ± 31	97.68 ± 0.37	–2.91 ± 3.72	–20.86 ± 0.58
KGM-TCe110032	1781	184 ± 32	97.74 ± 0.39	–2.41 ± 3.91	–23.30 ± 0.33

Table 2 Results of ^{14}C and dendrochronological age measurements of tree-ring samples grown in Korea from AD 1650 to 1850. Ages (AD) were determined by the dendrochronological method, and $\delta^{13}C$ values were measured by AMS. *(Continued)*

Lab code	Age (AD)	Year BP	pMC (%)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
KGM-TCe110033	1782	209 ± 32	97.43 ± 0.39	–5.70 ± 3.89	–21.13 ± 0.16
KGM-TCe110034	1783	250 ± 32	96.93 ± 0.39	–10.92 ± 3.88	–22.18 ± 0.21
KGM-TCe110035	1784	194 ± 32	97.62 ± 0.38	–4.00 ± 3.80	–22.20 ± 0.15
KGM-TCe110036	1785	124 ± 29	98.46 ± 0.35	4.45 ± 3.51	–23.33 ± 0.38
KGM-TCe110037	1786	197 ± 28	97.57 ± 0.34	–4.75 ± 3.35	–23.42 ± 0.63
KGM-TCe110038	1787	121 ± 27	98.50 ± 0.33	4.61 ± 3.27	–22.17 ± 0.11
KGM-TCe110039	1788	114 ± 27	98.59 ± 0.33	5.41 ± 3.26	–21.88 ± 0.19
KGM-TCe110040	1789	56 ± 27	99.31 ± 0.34	12.63 ± 3.35	–23.43 ± 0.41
KGM-TCe110041	1790	194 ± 28	97.61 ± 0.34	–4.82 ± 3.36	–22.77 ± 0.40
KGM-TCe110042	1791	175 ± 27	97.85 ± 0.33	–2.50 ± 3.31	–22.95 ± 0.35
KGM-TCe110043	1792	213 ± 31	97.38 ± 0.38	–7.41 ± 3.74	–22.99 ± 0.53
KGM-TCe110044	1793	282 ± 27	96.55 ± 0.32	–15.99 ± 3.22	–22.55 ± 0.14
KGM-TCe110045	1794	265 ± 27	96.75 ± 0.33	–14.07 ± 3.24	–21.53 ± 0.56
KGM-TCe110046	1795	216 ± 28	97.35 ± 0.34	–8.08 ± 3.41	–23.23 ± 0.40
KGM-TCe110047	1796	234 ± 30	97.12 ± 0.36	–10.54 ± 3.56	–23.64 ± 0.59
KGM-TCe110048	1797	216 ± 28	97.35 ± 0.34	–8.32 ± 3.39	–22.20 ± 0.29
KGM-TCe110049	1798	172 ± 28	97.88 ± 0.35	–3.04 ± 3.44	–22.26 ± 0.52
KGM-TCe110050	1799	149 ± 28	98.16 ± 0.34	–0.31 ± 3.35	–21.80 ± 0.25
KGM-TCe110051	1800	135 ± 29	98.33 ± 0.35	1.30 ± 3.48	–21.93 ± 0.19
KGM-TCe110052	1801	166 ± 28	97.95 ± 0.34	–2.69 ± 3.38	–21.59 ± 0.22
KGM-TCe110053	1802	167 ± 28	97.95 ± 0.34	–2.81 ± 3.41	–22.64 ± 0.30
KGM-TCe110054	1803	181 ± 27	97.77 ± 0.33	–4.76 ± 3.27	–21.90 ± 0.18
KGM-TCe110055	1804	149 ± 28	98.17 ± 0.35	–0.81 ± 3.43	–23.69 ± 0.31
KGM-TCe110056	1805	157 ± 28	98.07 ± 0.34	–1.95 ± 3.36	–22.07 ± 0.44
KGM-TCe110057	1806	155 ± 27	98.08 ± 0.33	–1.97 ± 3.32	–22.49 ± 0.21
KGM-TCe110058	1807	147 ± 28	98.18 ± 0.34	–1.07 ± 3.33	–22.54 ± 0.27
KGM-TCe110059	1808	127 ± 28	98.44 ± 0.34	1.45 ± 3.36	–22.73 ± 0.38
KGM-TCe110060	1809	209 ± 28	97.44 ± 0.34	–8.84 ± 3.38	–23.68 ± 0.17
KGM-TCe110061	1810	175 ± 28	97.85 ± 0.34	–4.79 ± 3.40	–23.99 ± 0.34
KGM-TCe110062	1811	183 ± 28	97.75 ± 0.34	–5.93 ± 3.33	–21.86 ± 0.49
KGM-TCe110063	1812	81 ± 31	99.00 ± 0.38	6.66 ± 3.78	–22.95 ± 0.37
KGM-TCe110064	1813	182 ± 31	97.76 ± 0.37	–6.06 ± 3.69	–21.60 ± 0.33
KGM-TCe110065	1814	50 ± 30	99.37 ± 0.38	10.18 ± 3.74	–22.24 ± 0.36
KGM-TCe110066	1815	79 ± 30	99.02 ± 0.37	6.50 ± 3.70	–21.02 ± 0.20
KGM-TCe110067	1816	93 ± 30	98.85 ± 0.37	4.65 ± 3.69	–21.17 ± 0.61
KGM-TCe110068	1817	71 ± 30	99.12 ± 0.37	7.28 ± 3.71	–23.20 ± 0.36
KGM-TCe110069	1818	118 ± 31	98.54 ± 0.38	1.26 ± 3.72	–22.79 ± 0.45
KGM-TCe110070	1819	54 ± 30	99.33 ± 0.37	9.17 ± 3.72	–22.23 ± 0.36
KGM-TCe110071	1820	80 ± 31	99.01 ± 0.38	5.79 ± 3.76	–24.42 ± 0.57
KGM-TCe110072	1821	46 ± 30	99.43 ± 0.37	9.94 ± 3.71	–22.38 ± 0.66
KGM-TCe110073	1822	63 ± 31	99.22 ± 0.38	7.68 ± 3.74	–24.37 ± 0.70
KGM-TCe110074	1823	86 ± 30	98.94 ± 0.37	4.72 ± 3.69	–20.98 ± 0.58
KGM-TCe110075	1824	86 ± 30	98.94 ± 0.37	4.60 ± 3.69	–23.36 ± 0.14
KGM-TCe110076	1825	51 ± 31	99.36 ± 0.38	8.74 ± 3.76	–23.41 ± 0.28
KGM-TCe110077	1826	101 ± 31	98.75 ± 0.38	2.42 ± 3.74	–23.91 ± 0.90
KGM-TCe110078	1827	126 ± 31	98.44 ± 0.38	–0.84 ± 3.74	–25.85 ± 1.04
KGM-TCe110079	1828	60 ± 30	99.26 ± 0.37	7.36 ± 3.72	–22.31 ± 0.63
KGM-TCe110080	1829	105 ± 30	98.70 ± 0.37	1.55 ± 3.69	–22.54 ± 0.38
KGM-TCe110081	1830	84 ± 31	98.96 ± 0.38	4.07 ± 3.77	–27.41 ± 0.20
KGM-TCe110082	1831	70 ± 31	99.13 ± 0.38	5.67 ± 3.75	–23.85 ± 0.39
KGM-TCe110083	1832	96 ± 31	98.81 ± 0.38	2.30 ± 3.82	–21.79 ± 0.63
KGM-TCe110084	1833	106 ± 30	98.69 ± 0.37	0.97 ± 3.68	–22.00 ± 1.43
KGM-TCe110085	1834	166 ± 31	97.96 ± 0.37	–6.56 ± 3.70	–23.25 ± 1.17

Table 2 Results of ^{14}C and dendrochronological age measurements of tree-ring samples grown in Korea from AD 1650 to 1850. Ages (AD) were determined by the dendrochronological method, and $\delta^{13}C$ values were measured by AMS. *(Continued)*

Lab code	Age (AD)	Year BP	pMC (%)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)
KGM-TCe110086	1835	169 ± 30	97.92 ± 0.37	–7.08 ± 3.66	–22.29 ± 1.57
KGM-TCe110087	1836	101 ± 31	98.75 ± 0.38	1.21 ± 3.77	–22.50 ± 1.26
KGM-TCe110088	1837	79 ± 30	99.02 ± 0.37	3.83 ± 3.69	–23.64 ± 0.61
KGM-TCe110089	1838	89 ± 30	98.89 ± 0.37	2.39 ± 3.69	–23.16 ± 0.20
KGM-TCe110090	1839	118 ± 30	98.54 ± 0.37	–1.28 ± 3.64	–23.12 ± 0.41
KGM-TCe110091	1840	185 ± 31	97.72 ± 0.37	–9.71 ± 3.68	–25.31 ± 0.98
KGM-TCe110092	1841	180 ± 29	97.78 ± 0.36	–9.22 ± 3.53	–23.21 ± 0.16
KGM-TCe110093	1842	180 ± 31	97.78 ± 0.38	–9.34 ± 3.73	–25.06 ± 0.69
KGM-TCe110094	1843	184 ± 30	97.74 ± 0.36	–9.87 ± 3.60	–24.53 ± 0.36
KGM-TCe110095	1844	121 ± 30	98.51 ± 0.37	–2.19 ± 3.62	–25.00 ± 0.20
KGM-TCe110096	1845	136 ± 30	98.32 ± 0.37	–4.23 ± 3.65	–24.55 ± 0.25
KGM-TCe110097	1846	139 ± 30	98.29 ± 0.36	–4.66 ± 3.59	–24.40 ± 0.20
KGM-TCe110098	1847	70 ± 29	99.13 ± 0.36	3.73 ± 3.58	–24.16 ± 0.80
KGM-TCe110099	1848	135 ± 29	98.33 ± 0.36	–4.49 ± 3.55	–23.18 ± 1.14
KGM-TCe110100	1849	126 ± 29	98.45 ± 0.36	–3.40 ± 3.55	–22.57 ± 0.98
KGM-TCe110101	1850	131 ± 30	98.38 ± 0.37	–4.23 ± 3.66	–22.80 ± 0.18

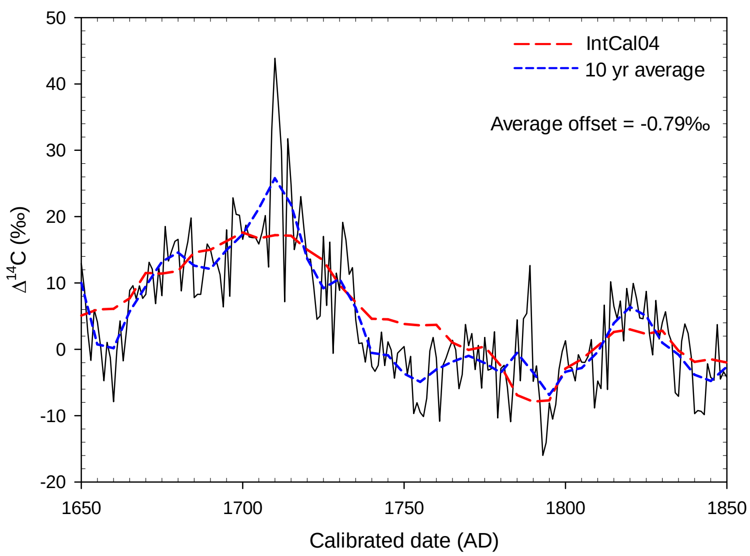

Figure 2 Variation curve (solid line) of ^{14}C concentration in the Korean atmosphere from AD 1650 to 1850. The dashed line represents IntCal04 data and the dotted line, the Korean measurements smoothed by averaging every 10 yr. The average offset is –0.79‰.

The average deviation of the ^{14}C concentrations of Korean tree rings from the IntCal data for AD 1650 to 1850 was calculated as –0.79 ± 3.81‰, which is a much smaller value than the statistical error. Hence, the deviation can be ignored when IntCal data are used for calibration of the ^{14}C ages of Korean samples. Our previous work showed that the average deviation of ^{14}C concentration of Korean tree rings from AD 1250 to 1650, –2.13 ± 4.32‰, was a much larger value than –0.79‰ (Hong et al. 2013). A remarkable change between the offsets of the 2 age ranges was observed. The low ^{14}C concentration in the east Asian atmosphere is thought to be due to the release of ^{14}C-depleted CO_2 from the Kuroshio Current in the northern Pacific Ocean, which is a warm current starting near the Taiwanese islands and passing through the straits between the Korean Peninsula and Japan, i.e. the Korea Strait. During the summer season, when most tree growth occurs, southeasters containing the ^{14}C-depleted CO_2 affect this country dominantly. Thus, the ^{14}C concentrations in the Korean trees are strongly affected by the Kuroshio. It is known that the temperature during the Little Ice Age (LIA) from AD 1550 to 1850 was lower by at least 1 °C than the temperature before and after (Mann 2002). The Maunder minimum (AD 1650–1700), a well-known period of minimum solar activity (Eddy 1976), is suggested as a cause for the cold period. The LIA includes the age range of tree rings used in this work. The release rate of CO_2 from the northern Pacific Ocean increases along with the temperature. The small offset of ^{14}C concentration of Korean trees from IntCal from AD 1650 to 1850 can be interpreted by understanding that the release rate of ^{14}C-depleted CO_2 from the Kuroshio Current decreased during the LIA such that the migration of ^{14}C-depleted CO_2 to the Korean atmosphere also decreased during this period. Also, a cold climate could make the intensity of the warm monsoon from the south small, while the influence of the cold continental high pressure from the north to the Korean climate could be relatively large. This could be another reason of the small offset of the period.

The relationship between the ^{14}C ages of the Korean tree rings and the dendrochronological ages is plotted in Figure 3 as a comparison to the IntCal04 calibration curve. The ^{14}C ages of the Korean tree rings around AD 1710 and 1787 deviate from those in the IntCal04 data. The average ^{14}C offset from IntCal in these periods is +5.93‰ (–47 ^{14}C yr) around AD 1710 and +3.24 ‰ (–25 ^{14}C yr) around AD 1787, which are larger by 6.72‰ and 4.03‰, respectively, than the average of the entire period. Because the 2 periods are included in both timespans of TMJS017A (AD 1619–1804) and TMJS079A (AD 1699–1833), the ^{14}C concentrations during the periods will be cross-checked. A proper correction may then be necessary when the ages of samples around AD 1710 and 1787 are calibrated.

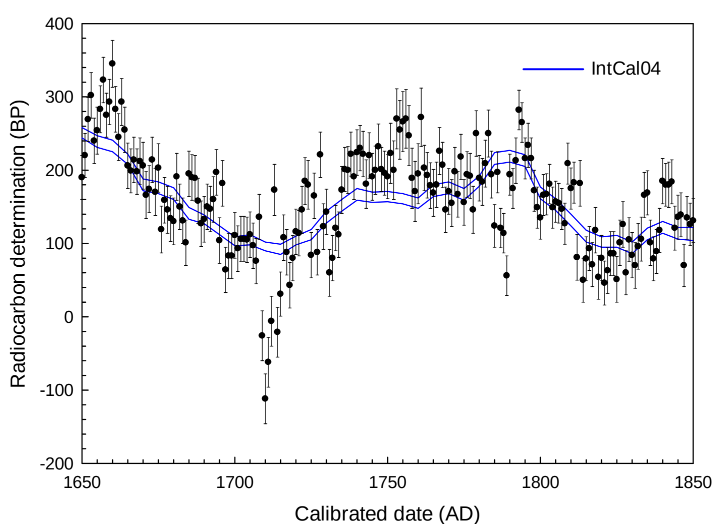

Figure 3 Comparison of ^{14}C ages of Korean tree rings grown AD 1650–1850 and their dendrochronological ages with the calibration curve of IntCal04 (solid line).

CONCLUSION

Tree rings with ages spanning AD 1650 to 1850 were measured to verify the consistency of the IntCal data with data from local samples of Korea. Three samples were collected from an historic wooden building (Tongmyeongjeon) in Korea, because a live tree with such a long age range is rare in this country. Tongmyeongjeon is located in Seoul, and the woods used as building materials are thought to have grown at a close site to Seoul, in the center of the Korean Peninsula.

The ^{14}C concentration offset during AD 1650 to 1850 from the IntCal data was found to be remarkably reduced compared to the corresponding previous value of 400 yr. The climate was colder during this period and the CO_2 release rate of the northern Pacific Ocean occurred at a lower rate. This is in good agreement with the contention that the Little Ice Age began around AD 1650 and ended around AD 1850. The possibility that a global event can induce a regional variation of ^{14}C concentration should be noted.

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