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REVIEW OF TROPOSPHERIC BOMB ^{14}C DATA FOR CARBON CYCLE MODELING AND AGE CALIBRATION PURPOSES

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ABSTRACT. Comprehensive published radiocarbon data from selected atmospheric records, tree rings, and recent organic matter were analyzed and grouped into 4 different zones (three for the Northern Hemisphere and one for the whole Southern Hemisphere). These ^{14}C data for the summer season of each hemisphere were employed to construct zonal, hemispheric, and global data sets for use in regional and global carbon model calculations including calibrating and comparing carbon cycle models. In addition, extended monthly atmospheric ^{14}C data sets for 4 different zones were compiled for age calibration purposes. This is the first time these data sets were constructed to facilitate the dating of recent organic material using the bomb ^{14}C curves. The distribution of bomb ^{14}C reflects the major zones of atmospheric circulation.

INTRODUCTION

A large amount of artificial radiocarbon was injected mostly into the stratosphere in the late 1950s and early 1960s by atmospheric nuclear detonations (Enting 1982). As a result, the concentration of ^{14}C in the troposphere dramatically increased in these periods, as depicted in Figure 1. Since the Nuclear Ban Treaty came into effect in 1963, the ^{14}C concentration in the troposphere has been decreasing due to rapid exchange between the atmosphere and other carbon reservoirs (mainly the oceans and biosphere). The large pulse of artificial ^{14}C injected to the atmosphere enables us to use ^{14}C as a unique and powerful tracer for studying exchanges between carbon reservoirs and the global carbon cycle (Nydal 1968; Oeschger et al. 1975; Broecker et al. 1980; Druffel and Suess 1983; Levin and Hesshaimer 2000). A few laboratories conducted early measurements to document changes in atmospheric and oceanic ^{14}C, e.g., Vogel and Marais (1971), Manning and Melhuish (1994) for atmospheric samples; and Broecker et al. (1960), Bien et al. (1960), Rafter (1968) for oceanic samples. Tans (1981) compiled bomb ^{14}C data for use in global carbon model calculations. Part of his compilation dealt with tropospheric ^{14}C based on limited data derived from atmospheric, tree-ring, and organic samples in terms of temporal and spatial distribution. Since then, more atmospheric ^{14}C data from many more different sites in the world have become available. Today, more than 50 yr after the first atmospheric nuclear detonation, there is a need for a comprehensive compilation of atmospheric bomb ^{14}C for calibrating and comparing carbon cycle models. In addition, different atmospheric ^{14}C levels between consecutive years during the bomb period offer the possibility of dating recent organic materials by ^{14}C with a variable resolution of one to a few years. The growing demand in this field (Worbes and Junk 1989; Wild et al. 1998; Searson and Pearson 2001) also necessitates comprehensive bomb ^{14}C data sets for age calibration over the past 50 yr. Therefore, this paper contains a new compilation of tropospheric bomb ^{14}C data for modeling and calibration purposes.

The construction of bomb ^{14}C data sets was based on comprehensive and reliable ^{14}C data derived from atmospheric samples, tree rings, and organic material. For atmospheric records, data sets which were strongly influenced by local anthropogenic CO_2 were not used for the compilation, such as those of Smilde (53°N, 6°E; Meijer et al. 1995) and Melbourne (38°S, 145°E; Manning et al. 1990). For ^{14}C data from tree rings, only data sets that are demonstrably reliable, as reported in Hua

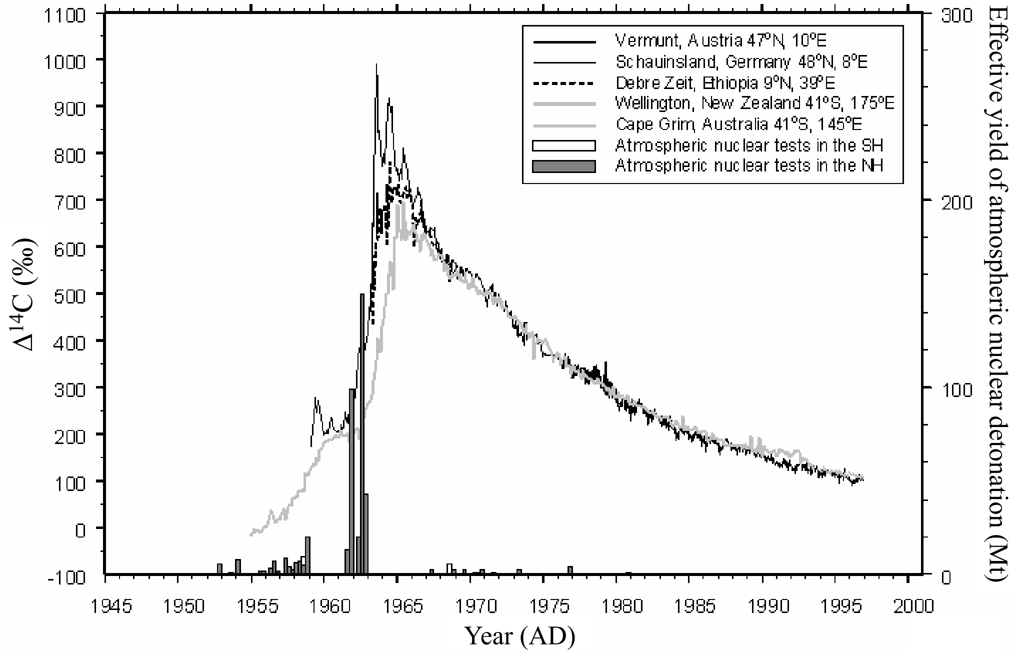

Figure 1 Atmospheric ^{14}C for the last 50 yr and the magnitude of atmospheric nuclear detonation. Lines represent atmospheric ^{14}C data. Data sources are Levin et al. (1994) for Vermunt and Schauinsland, Nydal and Lövseth (1996) for Debre Zeit, Manning and Melhuish (1994) for Wellington, and Levin et al. (1996, 1999) for Cape Grim. Bars represent effective yield of atmospheric nuclear detonations for 3-month periods (for 1950–1976, Enting 1982; for 1977–1980, Yang et al. 2000).

et al. (1999), were employed for the construction of the bomb data sets. One measured ^{14}C value from a very recent morphine sample (Zoppi et al. 2004) was also used for the compilation.

ZONAL TROPOSPHERIC ^{14}C DERIVED FROM TREE RINGS AND ATMOSPHERIC CO_2 SAMPLES

The excess ^{14}C produced by atmospheric nuclear detonation was mostly injected into the northern stratosphere, then returned to the northern troposphere through the mid- to high-latitude tropopause gap during the spring and summer. Injection of a large amount of artificial ^{14}C from the stratosphere during the late 1950s and 1960s created a great ^{14}C disequilibrium between the troposphere and other carbon reservoirs, and within the troposphere (north vs south, and high vs low latitudes). This caused the transfer of bomb ^{14}C from the atmosphere to the oceans and biosphere. For the troposphere, excess ^{14}C was transferred southwards by atmospheric circulation and its distribution depended on regional wind patterns, the resistance of atmospheric cell boundaries, and the Intertropical Convergence Zone (ITCZ) (Hua and Barbetti 2003). The highest ^{14}C level was in northern mid to high latitudes, where the input of bomb ^{14}C from the stratosphere occurred. The ^{14}C level was significantly lower in the subtropics to mid-latitudes. As excess ^{14}C was transferred to the tropics, monsoons mixed air masses from the Northern Hemisphere with those from the Southern Hemisphere (Hua and Barbetti 2003; Hua et al. 2004a,b). As a consequence, the ^{14}C level for the tropics was noticeably lower in magnitude. Across the Equator in the Southern Hemisphere, the ^{14}C excess was lower again in magnitude but nearly uniform for the whole hemisphere (Manning et al. 1990; Hua et al. 2003). The reason for small ^{14}C gradients in the Southern Hemisphere is that the sources of bomb ^{14}C, which are mainly in the Northern Hemisphere, are far from the south (Manning et al. 1990), and the ^{14}C excess becomes diffused as it is transported over the broad and seasonally-moving ITCZ (Hua et al. 1999, 2003). As bomb ^{14}C (more or less) reached a global equilibrium in the late 1960s (Telegadas 1971), there has not been much difference between locations in terms of ^{14}C for the period from 1970 onwards.

The above spatial and temporal distribution of bomb ^{14}C is well illustrated by $\Delta^{14}C$ values measured in tree rings from different locations, which are depicted in Figure 2. The diagram shows a large gradient in terms of ^{14}C from 1955 to the late 1960s, illustrating 4 different levels of ^{14}C, namely, Northern Hemisphere (NH) zones 1, 2, and 3, and one Southern Hemisphere (SH) zone. The issue arising here is "do atmospheric ^{14}C records have a pattern similar to that recorded in tree rings?".

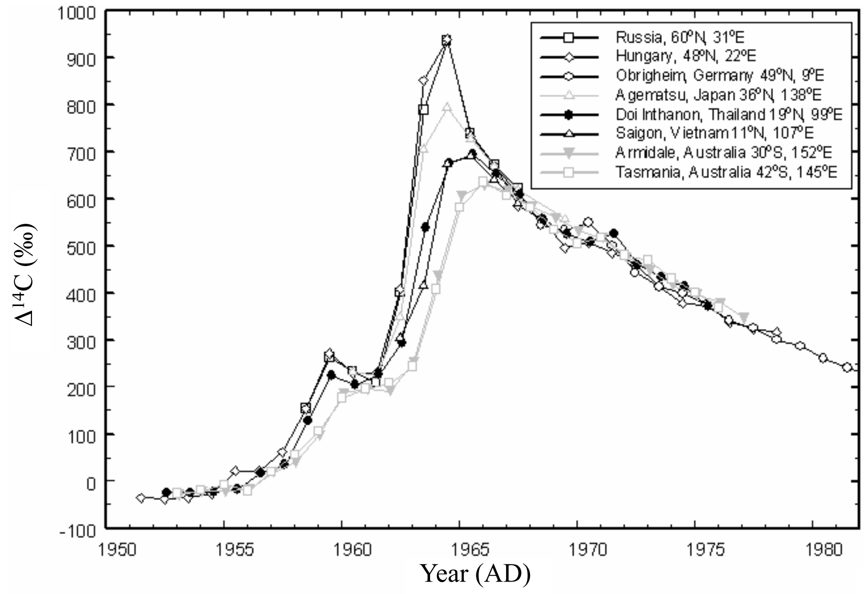

Figure 2 ^{14}C in tree rings at different locations. Data sources are Kolesnikov et al. (1970) for Russia, Hertelendi and Csongor (1982) for Hungary, Levin et al. (1985) for Obrigheim (Germany), Muraki et al. (1998) for Agematsu (Japan), Kikata et al. (1992, 1993) for Saigon (Vietnam), Hua et al. (2000) for Doi Inthanon (Thailand) and Tasmania (Australia), and Hua et al. (2003) for Armidale (Australia).

Because one atmospheric record is not much different from the others for the Southern Hemisphere, the maximum difference in ^{14}C within the hemisphere would indicate the magnitude of variations that one can expect for a group of atmospheric ^{14}C data. Using the strategy employed by Manning et al. (1990), the monthly differences between stations in the Southern Hemisphere were calculated and summarized in Table 1. The calculation consisted of 2 stages: calculation of monthly values for each record and calculation of the mean difference. For each month, the monthly value for each record was the weighted mean of a number of individual samples if more than 1 sample was available for that month. The weights for the calculation of monthly values were the ^{14}C uncertainties and the sampling duration (if available) of individual samples. The uncertainty associated with a monthly mean was the larger value of the error of the mean and the standard error. For details of the calculation of weighted mean and its error, see Bevington and Robinson (1992). Similarly, the mean difference of 2 atmospheric records was the weighted mean of the difference based on uncertainties associated with individual differences. The maximum mean difference between stations in the

Southern Hemisphere is ~15‰ (Funafuti 9°S, 179°E–Scott Base 78°S, 167°E; see Table 1). Note that in this paper, atmospheric ^{14}C levels are expressed as Δ^{14}C values after corrections for isotopic fractionation using δ^{13}C and radioactive decay [Hua et al. 1999; and the Δ and $\Delta^{14}C_{CORR}$ terms of Stuiver and Polach (1977) and Nydal and Gislefoss (1996), respectively].

Table 1 Monthly differences in ^{14}C between sites in the Southern Hemisphere.

Sites	Nr of common months	Period	Weighted mean difference (‰)
Funafuti (9°S, 179°E)–Wellington (41°S, 145°E)	34	Aug 66–Mar 72	9.1 ± 2.9
Suva (18°S, 178°E)–Wellington	85	July 59–Jun 75	9.9 ± 2.1
Fianarantsoa (21°S, 47°E)–Wellington	111	Nov 64–May 78	6.3 ± 1.3
Pretoria (26°S, 28°E)–Wellington	237	Apr 57–Jun 93	0.5 ± 1.1
Campbell Island (53°S, 169°E)–Wellington	50	Jan 70–Feb 77	–3.4 ± 2.0
Scott Base (78°S, 167°E)–Wellington	27	Nov 61–Mar 76	–4.7 ± 3.2

For the Northern Hemisphere, the ^{14}C gradient is large for the period from 1955 to the late 1960s, but small for the period from 1970 onwards. The monthly differences between stations in the Northern Hemisphere were therefore calculated for the 2 different periods and are summarized in Table 2.

The atmospheric ^{14}C records for the Northern Hemisphere were grouped into 3 different zones, similar to the classifications used for tree rings. For the period 1955–1969, the maximum intrazonal mean differences are ~18‰ (Fruholmen 71°N, 24°E–Vermunt 47°N, 10°E) for stations within zone 1, and ~23‰ (N'Djamena 12°N, 16°E–Izaña 28°N, 17°W) for stations within zone 2. Regarding zone 2, however, for an unknown reason, values for N'Djamena (12°N, 16°E) are higher than those from Mas Palomas (28°N, 16°W) and significantly higher than those from Izaña (28°N, 17°W). The mean differences for N'Djamena versus Izaña and N'Djamena versus Mas Palomas are 23‰ and 13‰, respectively. The surprisingly high ^{14}C level for low-latitude N'Djamena is unexpected in the bomb ^{14}C context. If this record is disregarded, the maximum mean difference between stations within zone 2 is ~16‰ (Mas Palomas–Santiago de Compostela). The maximum differences for stations within zone 1 (of 18‰) and within zone 2 (of 16‰) are very similar to the Southern Hemisphere value of 15‰. For zone 3, the only record available is from Debre Zeit at 9°N, 39°E. Meanwhile, the interzonal mean differences are much larger. They are 30–53‰ between zones 1 and 2, and 40–55‰ between zones 2 and 3 (except for the mean difference between N'Djamena and Debre Zeit of 18‰). Therefore, it is clear that atmospheric ^{14}C for the Northern Hemisphere for the period from 1950 to 1969 is well separated into 3 different zones. Note that these NH zones are not simply latitude-dependent, as China Lake (36°N, 118°W) belongs to zone 1, while Santiago de Compostela (43°N, 8°W) belongs to zone 2. For the period from 1970 onwards, the mean differences within a zone and between zones are similar and smaller compared to those for the former period, respectively (see Table 2). The maximum difference is ~16‰ between Fruholmen and China Lake over a 6-yr period (AD 1977–1983). Therefore, all atmospheric records from 1970 onwards can be treated as one group.

The pattern of bomb ^{14}C obtained from atmospheric ^{14}C records is similar to that derived from tree rings. This allows us to compile bomb ^{14}C data using a combination of atmospheric ^{14}C records and ^{14}C data from tree rings.

Table 2 Monthly differences in ^{14}C between sites in the Northern Hemisphere.[a]

Sites	Bomb peak periods (up to AD 1969)			From AD 1970 onwards		
	Nr of common months	Period	Weighted mean difference (‰)	Nr of common months	Period	Weighted mean difference (‰)
NH zone 1						
Spitsbergen (78°N, 14°E)–Fruholmen (71°N, 24°E)	6	Jun 63–Jul 64	–0.1 ± 10.4			
Trondheim (63°N, 10°E)–Fruholmen	6	Dec 62–Aug 63	–7.1 ± 5.2			
Lindesness (58°N, 7°E)–Fruholmen	20	Jan 63–Sep 64	–1.3 ± 4.3			
Vermunt (47°N, 10°E)–Fruholmen	79	Jan 63–Dec 69	–18.3 ± 3.4	128	Jan 70–Jun 83	–12.2 ± 1.4
Schauinsland (48°N, 8°E)–Fruholmen				178	Dec 76–Jun 93	–7.3 ± 0.7
China Lake (36°N, 118°W)–Fruholmen	44	Oct 63–Apr 68	–13.1 ± 5.0	47	Jan 77–May 83	–16.3 ± 2.0
Vermunt–Schauinsland				68	Dec 76–Jun 83	–1.8 ± 0.8
China Lake–Vermunt	47	Oct 63–Apr 68	6.9 ± 3.4	53	Jan 77–May 83	–8.1 ± 1.2
China Lake–Schauinsland				52	Jan 77–May 83	–8.5 ± 1.2
NH zone 2						
Santiago de C. (43°N, 8°W)–Izaña (28°N, 17°W)	43	Mar 63–Dec 66	–13.3 ± 6.4			
Mas Palomas (28°N, 16°W)–Izaña	45	Apr 63–Mar 67	13.1 ± 6.0			
Dakar (15°N, 17°W)–Izaña	43	Mar 63–Mar 67	6.9 ± 4.9			
N'Djamena (12°N, 16°E)–Izaña	6	Oct 66–Mar 67	22.5 ± 5.6			
Santiago de C.–Mas Palomas	45	Apr 63–Dec 66	–16.0 ± 6.5			
Dakar–Mas Palomas	52	Apr 63–Jan 68	–5.3 ± 5.5			
N'Djamena–Mas Palomas	35	Oct 66–Nov 69	13.4 ± 3.9	38	Feb 70–Aug 73	5.1 ± 3.7
Santiago de C.–Dakar	44	Mar 63–Dec 66	–8.0 ± 9.5			
N'Djamena–Dakar	12	Oct 66–Jan 68	7.5 ± 9.7			
NH zone 3						
Debre Zeit (9°N, 39°E)						

Table 2 Monthly differences in ^{14}C between sites in the Northern Hemisphere.[a] *(Continued)*

	Bomb peak periods (up to AD 1969)			From AD 1970 onwards		
Sites	Nr of common months	Period	Weighted mean difference (‰)	Nr of common months	Period	Weighted mean difference (‰)
Between NH zones 1 and 2						
Fruholmen (71°N)–Izaña (28°N)	46	Mar 63–Mar 67	42.9 ± 6.5	116	Mar 76–Dec 90	3.1 ± 1.1
Fruholmen (71°N)–Santiago de C. (43°N)	46	Mar 63–Dec 66	53.2 ± 5.8			
Fruholmen (71°N)–Mas Palomas (28°N)	76	Apr 63–Dec 69	31.1 ± 4.0	43	Feb 70–Dec 73	14.2 ± 4.6
Vermunt (47°N)–Izaña (28°N)	46	Mar 63–Mar 67	29.2 ± 5.1	40	Mar 76–Jun 83	–0.3 ± 1.9
Schauinsland (48°N)–Izaña (28°N)				116	Feb 77–Dec 90	–4.3 ± 0.8
China Lake (36°N)–Izaña (28°N)	33	Oct 63–Mar 67	30.6 ± 5.1	25	Feb 77–May 83	–5.9 ± 1.9
China Lake (36°N)–Santiago de C. (43°N)	32	Oct 63–Dec 66	38.4 ± 6.6			
Vermunt (47°N)–Santiago de C. (43°N)	46	Mar 63–Dec 66	37.9 ± 6.7			
Between NH zones 2 and 3						
Santiago de C. (43°N)–Debre Zeit (9°N)	38	May 63–Dec 66	49.9 ± 15.7			
Izaña (28°N)–Debre Zeit (9°N)	38	May 63–Mar 67	39.8 ± 10.4			
Mas Palomas (28°N)–Debre Zeit (9°N)	49	May 63–Jul 69	55.3 ± 11.8			
Dakar (15°N)–Debre Zeit (9°N)	40	May 63–Nov 67	38.9 ± 8.3			
N'Djamena (12°N)–Debre Zeit (9°N)	13	Oct 66–Jul 69	18.4 ± 6.1			

[a] Note: Atmospheric ^{14}C data used for the above calculations were reported in Nydal and Lövseth (1996) for Spitsbergen, Fruholmen, Trondheim, Lindesness, Santiago de Compostela, Izaña, Mas Palomas, Dakar, N'Djamena, and Debre Zeit; Levin et al. (1994) for Vermunt and Schauinsland; and Berger et al. (1987) for China Lake for AD 1977–1983. For China Lake for AD 1963–1968, the data used for these calculations were original data reported in Berger et al. (1965) and Berger and Libby (1966, 1967, 1968, 1969) after correction for δ^{13}C (using an assumed value of –23.2‰, which is the average δ^{13}C value for this site for the period AD 1977–1983) and decay correction.

COMPILED TROPOSPHERIC ^{14}C DATA SETS FOR MODELING PURPOSES

In this section, we describe data sets we have compiled and which are representative of zonal, hemispheric, and global ^{14}C levels in the troposphere for the past 50 yr. In order to have fully comparable values for atmospheric ^{14}C records and tree-ring ^{14}C (or ^{14}C in some terrestrial organic materials), only atmospheric data for the summer of each hemisphere (the growing seasons for tree rings—May to August for the Northern Hemisphere and November to February for the Southern Hemisphere) were used for the compilation. The advantage of this strategy is twofold: (1) There is a minimal contamination of fossil-fuel CO_2 devoid of ^{14}C in the summer time (Meijer et al. 1995; Levin and Kromer 1997), so this strategy therefore largely avoids possible discrepancies in ^{14}C between stations in the Northern Hemisphere due to local or regional fossil-fuel CO_2 emissions, which mostly occur in winter months; and (2) this strategy allows an extension of the atmospheric ^{14}C records, using the ^{14}C data from tree rings or terrestrial organic matter, when atmospheric ^{14}C data are sparse, such as at the beginning of atmospheric nuclear detonations during the 1950s and the most recent period.

Zonal or Hemispheric Data Set for the Southern Hemisphere

For the Southern Hemisphere, the ^{14}C data sets employed for the construction of atmospheric ^{14}C included records for Suva (18°S, 178°E), Campbell Island (53°S, 169°E), and Scott Base (78°S, 167°E) from Manning et al. (1990); Fianarantsoa (21°S, 47°E; Nydal and Lövseth 1996); Pretoria (26°S, 28°E; Vogel and Marais 1971); Wellington (41°S 175°E; Manning and Melhuish 1994); and Cape Grim (41°S, 145°E; Levin et al. 1996, 1999). We also included tree-ring data sets for Armidale (30°S, 152°E; Hua et al. 2003) and Tasmania (42°S, 145°E; Hua et al. 2000), and a ^{14}C datum derived from very recent Tasmanian morphine (Zoppi et al. 2004).

For the atmospheric record, the mean value for summer months (November–February) for a particular year was calculated only if there were data available for at least 3 out of 4 months for the season. The Funafuti record (9°S, 179°E; Manning et al. 1990) does not meet this criterion. This record was therefore not used in the compilation of Southern Hemisphere ^{14}C. The summer mean values for the atmospheric record are weighted averages based on the ^{14}C uncertainty and on the sampling duration of an individual sample (if the latter was available). The uncertainty associated with the summer mean value is the larger of the error of the mean and the standard error. The compiled atmospheric Δ^{14}C data for the Southern Hemisphere are presented in Table 3. The average value for the Southern Hemisphere for a particular year is the weighted average value based on the uncertainty associated with the summer mean of the individual record (or the measurement uncertainty associated with the tree-ring or organic ^{14}C value of an individual sample). The uncertainty for the average yearly value is the larger of the error of the mean and the standard error. These criteria and methods were also employed for calculation of Northern Hemispheric and global data sets. The average yearly values for the Southern Hemisphere and their associated uncertainties are shown in the far right column of Table 3.

Table 3 Δ^{14}C (‰) for the Southern Hemisphere.

Year AD	Suva 18°S, 178°E[a]	Fianarantsoa 21°S, 47°E[a]	Pretoria 26°S, 28°E[a]	Wellington 41°S, 175°E[a]	Cape Grim 41°S, 145°E[a]	Campbell Is. 53°S, 169°E[a]	Scott Base 78°S, 167°E[a]	Armidale 30°S, 152°E[b]	Tasmania 42°S, 145°E[b]	Tasmanian morphine[c]	SH average
1955								–22.0 ± 4.3	–8.3 ± 5.1		–16 ± 7
1956								–17.0 ± 4.6	–20.1 ± 5.7		–18 ± 4
1957								18.7 ± 4.5	19.4 ± 5.4		19 ± 3
1958								40.5 ± 3.3	56.0 ± 4.8		45 ± 7
1959								98.1 ± 4.2	105.5 ± 5.7		101 ± 4
1960			188 ± 5	178.3 ± 3.5				186.8 ± 4.2	177.0 ± 5.4		182 ± 3
1961				195.7 ± 2.6				195.5 ± 3.4	196.7 ± 5.1		196 ± 2
1962	203.2 ± 8.3			210.0 ± 12			196.3 ± 4.2	191.2 ± 4.1	208.1 ± 6.1		198 ± 3
1963				263.2 ± 4.3				251.6 ± 4.6	242.7 ± 5.4		254 ± 6
1964				418.7 ± 21				435.8 ± 5.2	407.2 ± 6.4		424 ± 10
1965		649.0 ± 6.1		629.2 ± 11				606.6 ± 5.9	581.3 ± 7.4		617 ± 15
1966	654.9 ± 6.3	631.7 ± 3.6		636.0 ± 6.3				628.2 ± 5.7	636.0 ± 8.1		635 ± 4
1967		622.3 ± 4.3	601 ± 6	613.6 ± 5.0				615.4 ± 5.6	606.3 ± 6.8		614 ± 4
1968		567.7 ± 6.2	566 ± 22	582.4 ± 2.1			569.4 ± 7.6	583.7 ± 3.8	581.1 ± 8.5		581 ± 2
1969	544.6 ± 5.6	570.5 ± 6.0	565 ± 5	539.9 ± 1.7			542.2 ± 1.9	559.8 ± 5.4	533.7 ± 5.9		544 ± 3
1970			532 ± 4	514.5 ± 4.3			502.8 ± 23	531.6 ± 5.7	504.7 ± 9.0		524 ± 5
1971		498.2 ± 9.4	501 ± 10	497.1 ± 1.9				516.1 ± 5.1	517.2 ± 7.3		500 ± 4
1972	492.8 ± 2.9	489.5 ± 5.0		485.0 ± 3.4				475.6 ± 6.0	478.4 ± 6.9		487 ± 3
1973		461.4 ± 6.8	467 ± 4					448.1 ± 5.3	468.6 ± 6.7		462 ± 5
1974	434.4 ± 7.5	432.8 ± 7.0	433 ± 4	416.6 ± 5.9		405.9 ± 1.7		416.7 ± 5.4	428.7 ± 6.4		413 ± 5
1975			399 ± 4	397.6 ± 1.8		393.0 ± 6.4		396.0 ± 5.6	400.9 ± 7.8		398 ± 2
1976		368.3 ± 6.4	380 ± 5	369.0 ± 2.0		366.8 ± 1.7	364.1 ± 2.4	377.7 ± 4.4	368.8 ± 6.7		368 ± 2
1977		337.9 ± 4.2	333 ± 12	338.4 ± 4.5		337.2 ± 2.0		346.2 ± 5.2			338 ± 2
1978		333.6 ± 6.2	335 ± 4								335 ± 3
1979			312 ± 10								312 ± 10
1980			293 ± 4	286.0 ± 7.8							292 ± 4
1981			286 ± 5	267.6 ± 2.5							271 ± 7
1982			260 ± 5								260 ± 5
1983			238 ± 4	232.4 ± 2.4							234 ± 2
1984			226 ± 5								226 ± 5
1985			218 ± 3	209.7 ± 3.2							214 ± 4
1986			203 ± 3	204.5 ± 3.0							204 ± 2

Table 3 $\Delta^{14}C$ (‰) for the Southern Hemisphere. *(Continued)*

Year AD	Suva 18°S, 178°E[a]	Fianarantsoa 21°S, 47°E[a]	Pretoria 26°S, 28°E[a]	Wellington 41°S, 175°E[a]	Cape Grim 41°S, 145°E[a]	Campbell Is. 53°S, 169°E[a]	Scott Base 78°S, 167°E[a]	Armidale 30°S, 152°E[b]	Tasmania 42°S, 145°E[b]	Tasmanian morphine[c]	SH average
1987			191 ± 2								191 ± 2
1988			184 ± 3								184 ± 3
1989			170 ± 8	172.7 ± 2.8							172 ± 3
1990			162 ± 4	168.7 ± 8							163 ± 4
1991			148 ± 5	158.6 ± 2.3							157 ± 4
1992			149 ± 3	153.0 ± 2.3							152 ± 2
1993			137 ± 7								137 ± 7
1994			134 ± 4		122.0 ± 1.0						123 ± 3
1995					120.3 ± 1.2						120 ± 1
1996					116.0 ± 1.0						116 ± 1
1997					106.5 ± 1.4						107 ± 1
1998											
1999											
2000											
2001										80.6 ± 4.0	81 ± 4

[a] Mean atmospheric ^{14}C for Nov–Feb derived from the data of Manning et al. (1990) for Suva, Campbell Island, and Scott Base; Manning and Melhuish (1994) for Wellington; Nydal and Lövseth (1996) for Fianarantsoa; Vogel and Marais (1971) for Pretoria; and Levin et al. (1996, 1999) for Cape Grim.

[b] ^{14}C data from tree rings from Armidale (Hua et al. 2003) and Tasmania (Hua et al. 2000).

[c] Datum from Tasmanian morphine (Zoppi et al. 2004).

Zonal and Hemispheric Data Sets for the Northern Hemisphere

For the period 1955–1969, 3 separate data sets of atmospheric ^{14}C were compiled for the 3 different NH zones, namely, zones 1, 2, and 3. Note that the distribution of bomb ^{14}C strongly depended on atmospheric circulation and seasonal positions of Hadley cell boundaries and the ITCZ (Hua and Barbetti 2003). The NH zones are not just latitudinally dependent. Zone 1 covers the area from ~40°N to the North Pole. Because most atmospheric ^{14}C data for NH zones 1 and 2 are from Europe and northwestern Africa, the boundary between the 2 zones are not accurately determined by the analyses presented in Table 2. This boundary is estimated around 40°N, but may vary from one place to another. For example, this boundary has to be south of China Lake (36°N, 118°W) but north of Santiago de Compostela (42°N, 8°W) (see analyses in Table 2). NH zone 2 extends from the summer maximum position of the summer ITCZ to ~40°N, and zone 3 from the Equator to the position of the summer ITCZ. Figure 3 shows the areas covered by NH zones 1, 2, and 3, and the SH zone.

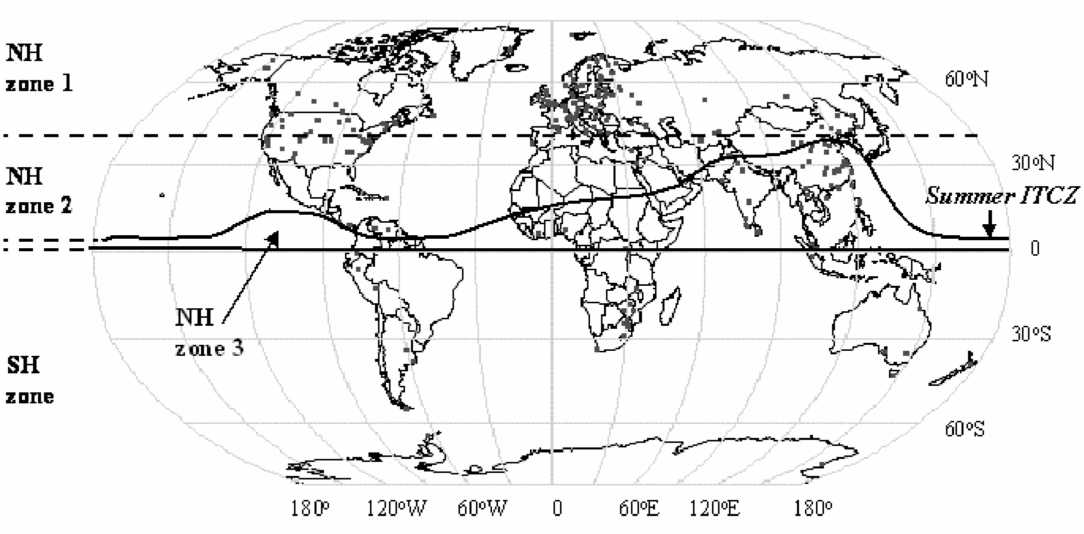

Figure 3 World map showing the areas covered by NH zones 1, 2, and 3, and the SH zone. The position of the summer ITCZ is adapted from Linacre and Geerts (1997).

The ^{14}C data sets employed for the construction of atmospheric ^{14}C for NH zone 1 included atmospheric records for Fruholmen (71°N, 24°E), Trondheim (63°N, 10°E), and Lindesness (58°N, 7°E) from Nydal and Lövseth (1996); Vermunt (47°N, 10°E; Levin et al. 1994); and China Lake (36°N, 118°W; Berger et al. 1965; Berger and Libby 1966, 1967, 1968, 1969). We also included tree-ring data for Russia (60°N, 31°E; Kolesnikov et al. 1970); Kiel (54°N, 10°E; Willkomn and Erlenkeuser 1968); Obrigheim (49°N, 9°E; Levin et al. 1985); Hungary (48°N, 22°E; Hertelendi and Csongor 1978); and Bear Mountain, New York (41°N, 74°W; Cain and Suess 1976).

For NH zone 2, ^{14}C data sets used for compilation were atmospheric records for Santiago de Compostela[1] (43°N, 8°W), Israel (32°N, 35°E), Izaña (28°N, 17°W), Mas Palomas (28°N, 16°W), and Dakar (15°N, 17°W) from Nydal and Lövseth (1996). Due to the surprisingly high ^{14}C level for N'Djamena (12°N, 16°E; Nydal and Lövseth 1996) as mentioned above, this record was not employed in the compilation. There is a long atmospheric ^{14}C record for New Jersey (40°N) for AD 1959–1966 reported in Feely et al. (1963; 1966a,b); however, ^{14}C measurement uncertainties for this record are large (~5%; Feely et al. 1966a). This record was therefore not used for the compilation. We also included tree-ring data for Gifu (36°N, 138°E; Nakamura et al. 1987a,b), Agematsu (36°N, 138°E; Muraki et al. 1998), and Mts Chiak and Kyeryong (36–37°N, 127–128°E; Park et al. 2002).

Regarding NH zone 3, ^{14}C data sets employed for the compilation included atmospheric records for Debre Zeit (9°N, 39°E; Nydal and Lövseth 1996), and tree-ring ^{14}C from India (23°N, 81°E; Murphy et al. 1997), Saigon (11°N, 107°E; Kikata et al. 1992, 1993), and Doi Inthanon (19°N, 99°E; Hua et al. 2000).

The compiled atmospheric $\Delta^{14}C$ data for NH zones 1, 2, and 3 for 1955–1969 are presented in Tables 4a, 4b, and 4c, respectively. The compiled data set for the Northern Hemisphere for 1955–1969 is shown in Table 5a. Weighted yearly mean values for the Northern Hemisphere were calculated from the 3 yearly zonal means, with weights consisting of uncertainties associated with yearly zonal value and zonal surface area. The percentages of zonal surface areas within the Northern Hemisphere for NH zones 1, 2, and 3 were taken as 17%, 46%, and 37%, respectively.

For the period from 1970 onwards, ^{14}C data sets used for the compilation consisted of atmospheric records for Fruholmen, the Canary Islands (including Izaña and Mas Palomas), Debre Zeit (Nydal and Lövseth 1996), Vermunt and Schauinsland (Levin et al. 1994), and China Lake (36°N, 118°W; Berger et al. 1987); and tree-ring ^{14}C from Obrigheim (Levin et al. 1985), Schauinsland (48°N, 8°E; Levin and Kromer 1997), Hungary (Hertelendi and Csongor 1978), Agematsu (Muraki et al. 1998), Mts Chiak and Kyeryong (Park et al. 2002), India (Murphy et al. 1997), and Doi Inthanon (Hua et al. 2000). The compiled atmospheric $\Delta^{14}C$ data for the Northern Hemisphere for 1970–1999 is presented in Table 5b.

Compiled zonal atmospheric ^{14}C data sets for the summer season for 1955–1999 together with individual data sets available in each zone are shown in Figures 4–8.

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[1] Nydal and Lövseth (1983) reported unusual ^{14}C minima in September–December for the Santiago de Compostela record for the period AD 1963–1966. The authors argued that local fossil-fuel consumption was the cause for these minima, as accumulation of CO_2 free of ^{14}C near the ground became significant on calm days and contaminated atmospheric samples. However, these September–December troughs in ^{14}C were also observed in Izaña, Dakar, and New Jersey records during 1963–1966, indicating that the effect must therefore be regional. We infer that temporary changes in the regional wind systems, rather than just the local weather of the Spanish station, are responsible for the presence of these ^{14}C troughs in the Santiago de Compostela and other records (Hua and Barbetti, unpublished data). The Spanish ^{14}C record was therefore considered to be regionally significant and used in the compilation.

Table 4a $\Delta^{14}C$(‰) NH zone 1 for the period of 1955 to 1969.

Year AD	Fruholmen 71°N, 24°E[a]	S. Norway 58–63°N, 7–10°E[a]	Vermunt 47°N, 10°E[a]	China Lake 36°N, 118°W[a]	Russia 60°N, 31°E[b]	Kiel 54°N, 10°E[c]	Obrigheim 49°N, 9°E[c]	Hungary 48°N, 22°E[c]	New York 41°N, 74°W[b]	NH zone 1 average
1955.5						16 ± 6		21.6 ± 11.7	40	21 ± 6
1956.5						27 ± 10		20.9 ± 11.5	69	38 ± 15
1957.5						117 ± 9		61.7 ± 12.6	108	101 ± 16
1958.5					154	171 ± 6		153.1 ± 13.8	174	167 ± 5
1959.5			257 ± 10		263	293 ± 7		271.2 ± 14.6	278	278 ± 8
1960.5			227 ± 4		233	256 ± 9		229.3 ± 13.0	244	232 ± 5
1961.5			233 ± 7		208	238 ± 8		230.7 ± 13.2	237	232 ± 4
1962.5		400.8 ± 10	392 ± 14		400	407 ± 22		407.5 ± 12.7	360	398 ± 6
1963.5	822.2 ± 47	858.1 ± 47	802 ± 47		788	844 ± 10		851.0 ± 13.9	734	812 ± 18
1964.5	912.4 ± 19	948.5 ± 3	901 ± 6	880 ± 19	935	906 ± 15		939.1 ± 16.3	887	933 ± 9
1965.5	798.9 ± 6		780 ± 13	776 ± 10	738			732.9 ± 15.8	788	781 ± 10
1966.5	707.5 ± 6		715 ± 4	696 ± 13	671		667 ± 5	670.9 ± 15.4	714	697 ± 9
1967.5	661.1 ± 6			639 ± 7	622		614 ± 4	584.5 ± 15.9	634	628 ± 9
1968.5	604.0 ± 9		569 ± 5				543 ± 9	558.2 ± 15.5	600	572 ± 10
1969.5	569.5 ± 5		550 ± 5				533 ± 4	495.6 ± 16.6	543	547 ± 8

[a] Mean atmospheric ^{14}C for May–August derived from the data of Nydal and Lövseth (1996) for Fruholmen and southern Norway (Trondheim and Lindesness), Levin et al. (1994) for Vermunt, and Berger et al. (1965) and Berger and Libby (1966, 1967, 1968, 1969) for China Lake. The China Lake data used for this compilation were the original data reported in Berger and colleagues after correction for $\delta^{13}C$ (using an assumed value of –23.2‰, which is the average $\delta^{13}C$ value for this site for the period AD 1977–1983) and decay correction.

[b] ^{14}C in tree rings from Kolesnikov et al. (1970) for Russia, and Cain and Suess (1976) for Bear Mountain, New York. These data were taken from diagrams because tabulated data were not reported in the above publications. Therefore, the uncertainties associated with these data used for this compilation were chosen to be the larger uncertainty of the Kiel and Hungarian data.

[c] ^{14}C in tree rings from Willkomn and Erlenkeuser (1968) for Kiel, Levin et al. (1985) for Obrigheim, and Hertelendi and Csongor (1978) for Hungary.

Table 4b $\Delta^{14}C$(‰) for NH zone 2 for the period of 1955 to 1969.

Year AD	Santiago de C. 43°N, 8°W[a]	Israel 32°N, 35°E[a]	Izaña 28°N, 17°W[a]	Mas Palomas 28°N, 16°W[a]	Dakar 15°N, 17°W[a]	Agematsu 36°N, 138°E[b]	Gifu 36°N, 138°E[b,c]	Mts Chiak & Kyeryong 36–37°N, 122–128°E[b]	NH zone 2 average
1955.5							–5.2 ± 15.6	22.4 ± 11.3	13 ± 13
1956.5							49.8 ± 17.5		50 ± 18
1957.5							81.3 ± 14.0		81 ± 14
1958.5							187.2 ± 12.5		187 ± 13
1959.5							235.1 ± 18.3		235 ± 18
1960.5						232.3 ± 5.0		225.1 ± 11.7	231 ± 5
1961.5						222.7 ± 5.8			223 ± 6
1962.5						349.5 ± 3.7		381.0 ± 12.7	352 ± 9
1963.5	783 ± 59		761.3 ± 56	806.2 ± 34	701.9 ± 15	706.3 ± 3.2		707.6 ± 42.9[d]	707 ± 5
1964.5	821 ± 18		844.9 ± 12	861.8 ± 21	816.4 ± 23	794.1 ± 3.9		825.5 ± 12.6[d]	804 ± 8
1965.5	710 ± 7		739.0 ± 6	799.2 ± 14	750.0 ± 4	726.5 ± 6.4		679.7 ± 29.1	738 ± 9
1966.5	663 ± 12		689.6 ± 9	664.3 ± 4	701.1 ± 8	668.3 ± 4.2		641.1 ± 13.9	671 ± 6
1967.5		627.7 ± 6		606.3 ± 9		618.6 ± 2.6			620 ± 3
1968.5				563.6 ± 14					564 ± 14
1969.5				554.2 ± 6		556.7 ± 3.4			556 ± 3

[a] Mean atmospheric ^{14}C for May–August derived from the data of Nydal and Lövseth (1996) for Santiago de Compostela, Israel, Izaña, Mas Palomas, and Dakar.

[b] ^{14}C in tree rings from Muraki et al. (1998) for Agematsu, Nakamura et al. (1987a,b) for Gifu, and Park et al. (2002) for Mts Chiak and Kyeryong.

[c] Only data for 1955–1959 were used for the compilation as the remaining data of this record are less reliable (see Hua et al. 1999).

[d] Average value derived from the data of Park et al. (2002).

Table 4c $\Delta^{14}C$ (‰) for NH zone 3 for the period of 1955 to 1969.

Year AD	Debre Zeit 9°N, 39°E[a]	Mandla 23°N, 81°E[b]	Doi Inthanon 19°N, 99°E[b]	Saigon 11°N, 107°E[c]	NH zone 3 average
1955.5		15.7 ± 5.5	–17.8 ± 5.8		0 ± 17
1956.5			16.8 ± 4.4		17 ± 4
1957.5			34.7 ± 5.6		35 ± 6
1958.5			127.7 ± 5.3		128 ± 5
1959.5			224.6 ± 7.2		225 ± 7
1960.5		205.5 ± 6.9	204.1 ± 7.3		205 ± 5
1961.5			226.5 ± 6.3		227 ± 6
1962.5			292.6 ± 6.6	305.0 ± 43	293 ± 7
1963.5	578.5 ± 31	565.4 ± 8.0	538.4 ± 7.5	415.7 ± 17[d]	552 ± 10
1964.5	711.4 ± 11		675.7 ± 7.6	673.1 ± 22	681 ± 9
1965.5	716.5 ± 6	704.7 ± 8.6	694.1 ± 7.0	691.8 ± 16	705 ± 6
1966.5			652.5 ± 9.0	640.7 ± 17	650 ± 8
1967.5			607.9 ± 10.0	589.6 ± 23	605 ± 9
1968.5	560.2 ± 17		554.9 ± 7.1		555 ± 7
1969.5			523.3 ± 6.6		523 ± 7

[a] Mean atmospheric ^{14}C for May–August derived from the data of Nydal and Lövseth (1996) for Debre Zeit.

[b] ^{14}C in tree rings for Mandla (Murphy et al. 1997) and for Doi Inthanon (Hua et al. 2000).

[c] ^{14}C in tree rings for Saigon from Kikata et al. (1992, 1993). No $\delta^{13}C$ data were reported in the papers; therefore, no $\delta^{13}C$ correction was applied for these $\Delta^{14}C$ data.

[d] This value is too low compared to corresponding values from Debre Zeit, Mandla, and Doi Inthanon, and might not be reliable. This datum was therefore not used for this compilation.

Table 5a $\Delta^{14}C$ (‰) for the Northern Hemisphere for 1955–1969.[a]

Year AD	NH zone 1	NH zone 2	NH zone 3	NH average
1955.5	21 ± 6	13 ± 13	0 ± 17	15 ± 6
1956.5	38 ± 15	50 ± 18	17 ± 4	20 ± 6
1957.5	101 ± 16	81 ± 14	35 ± 6	45 ± 15
1958.5	167 ± 5	187 ± 13	128 ± 5	148 ± 16
1959.5	278 ± 8	235 ± 18	225 ± 7	239 ± 16
1960.5	232 ± 5	231 ± 5	205 ± 5	222 ± 9
1961.5	232 ± 4	223 ± 6	227 ± 6	226 ± 3
1962.5	398 ± 6	352 ± 9	293 ± 7	337 ± 30
1963.5	812 ± 18	707 ± 5	552 ± 10	686 ± 41
1964.5	933 ± 9	804 ± 8	681 ± 9	785 ± 62
1965.5	781 ± 10	738 ± 9	705 ± 6	723 ± 17
1966.5	697 ± 9	671 ± 6	650 ± 8	668 ± 10
1967.5	628 ± 9	620 ± 3	605 ± 9	618 ± 3
1968.5	572 ± 10	564 ± 14	555 ± 7	559 ± 6
1969.5	547 ± 8	556 ± 3	523 ± 7	551 ± 8

[a] Weights for calculation of the Northern Hemisphere average for a particular year are uncertainties associated with zonal ^{14}C values and zonal surface areas. The percentages of zonal surface areas within the Northern Hemisphere for NH zones 1, 2, and 3 are taken as 17%, 46%, and 37%, respectively.

Table 5b Δ^{14}C (‰) for the Northern Hemisphere for the period from 1970 onwards.

Year AD	Fruholmen 71°N[a]	Vermunt 47°N[a]	Schauinsland 48°N[a]	China Lake 36°N[a]	Canary Is. 28°N[a]	Obrigheim 49°N[b]	Schauinsland 48°N[b]	Hungary 47°N[b]	Doi Inthanon 19°N[b]	Agematsu 36°N[b]	Mts Chiak, Kyeryong 36–37°N[b]	NH average
1970.5	558.9 ± 11	533 ± 5			511.1 ± 14	549 ± 5		506.6 ± 15.9	507.6 ± 7.3		526.1 ± 15	534 ± 8
1971.5	552.0 ± 6	511 ± 6			492.5 ± 10	501 ± 5		484.0 ± 15.4	525.9 ± 7.2			518 ± 10
1972.5	481.1 ± 5	472 ± 5			474.0 ± 4	442 ± 4		461.3 ± 14.5	458.3 ± 9.3			464 ± 7
1973.5	458.5 ± 5				443.7 ± 4	413 ± 3		413.2 ± 14.2	432.9 ± 8.3			430 ± 9
1974.5	423.6 ± 4					399 ± 5	427 ± 3	377.8 ± 14.4	412.2 ± 5.5			419 ± 6
1975.5	397.3 ± 5					375 ± 5	390 ± 3	375.3 ± 14.9	371.7 ± 8.7		393.0 ± 28	387 ± 4
1976.5	362.3 ± 4	348 ± 4			348.6 ± 3	340 ± 3	352 ± 3	336.7 ± 14.7				349 ± 3
1977.5	343.0 ± 5	338 ± 2	336 ± 2	325.8 ± 2.0		325 ± 4	336 ± 3	322.9 ± 10.3				333 ± 2
1978.5	334.7 ± 5	325 ± 4	336 ± 3	316.8 ± 3.2		300 ± 4	336 ± 3	316.3 ± 9.4				326 ± 5
1979.5	309.8 ± 4	296 ± 5	299 ± 7			287 ± 5	290 ± 3				259.4 ± 13	295 ± 4
1980.5	285.8 ± 4	266 ± 4	272 ± 2	266.9 ± 1.9	264.0 ± 5	260 ± 5	271 ± 3				279.7 ± 15	270 ± 2
1981.5		263 ± 2	261 ± 9			240 ± 4	263 ± 3				240.6 ± 15	259 ± 4
1982.5	246.3 ± 4	239 ± 2	245 ± 2	233.0 ± 2.8	242.2 ± 5	226 ± 4	242 ± 3					240 ± 2
1983.5	239.3 ± 2		223 ± 4		229.7 ± 2		218 ± 2					228 ± 5
1984.5	223.3 ± 2		208 ± 1		210.7 ± 2		204 ± 2					210 ± 3
1985.5	209.3 ± 3		200 ± 2		206.3 ± 2		200 ± 3				198.1 ± 11	204 ± 2
1986.5	198.7 ± 3		187 ± 1		195.8 ± 3							189 ± 3
1987.5	186.6 ± 2		181 ± 2		191.0 ± 2							187 ± 3
1988.5	169.3 ± 4		170 ± 1		178.1 ± 2							172 ± 2
1989.5	161.1 ± 2		159 ± 2		165.3 ± 2							162 ± 2
1990.5	157.9 ± 3		149 ± 2		144.7 ± 2						155.9 ± 11	149 ± 3
1991.5	142.5 ± 3		137 ± 2									138 ± 2
1992.5	137.9 ± 2		135 ± 2									136 ± 1
1993.5			125 ± 2									125 ± 2
1994.5			119 ± 1									119 ± 1
1995.5			112 ± 2							115 ± 3.9	114.1 ± 14	113 ± 2
1996.5			104 ± 2									104 ± 2
1997.5												—
1998.5												—
1999.5											91.4 ± 20	91 ± 20
2000.5											56.1 ± 9[c]	—

[a] Mean atmospheric ^{14}C for May–August derived from the data of Levin et al. (1994) for Vermunt and Schauinsland, Berger et al. (1987) for China Lake, and Nydal and Lövseth (1996) for Fruholmen and Canary Islands (including Izaña and Mas Palomas).

[b] ^{14}C in tree rings from Levin et al. (1985) for Obrigheim, Levin and Kromer (1997) for Schauinsland, Hertelendi and Csongor (1978) for Hungary, Muraki et al. (1998) for Agematsu, Park et al. (2000) for Mts Chiak and Kyeryong, and Hua et al. (2000) for Doi Inthanon.

[c] Average value derived from the data of Park et al. (2000). This value may be too low and was not used for this compilation.

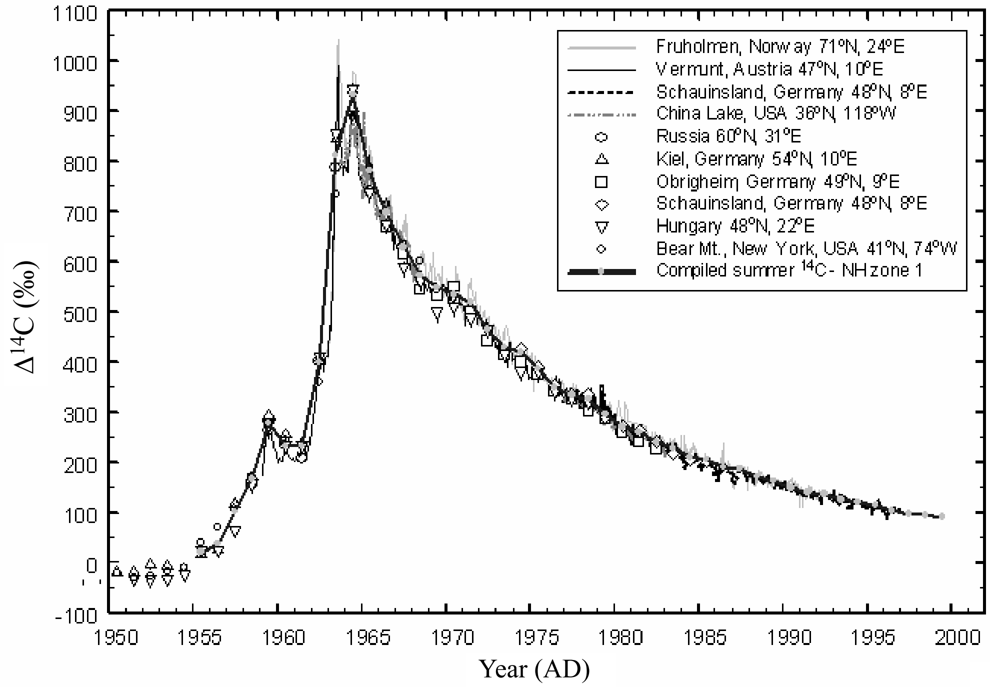

Figure 4 Compiled summer atmospheric ^{14}C curve for NH zone 1 versus atmospheric ^{14}C records (lines) and tree-ring ^{14}C data (symbols) available for the zone. Data sources are given in Tables 4a and 5b.

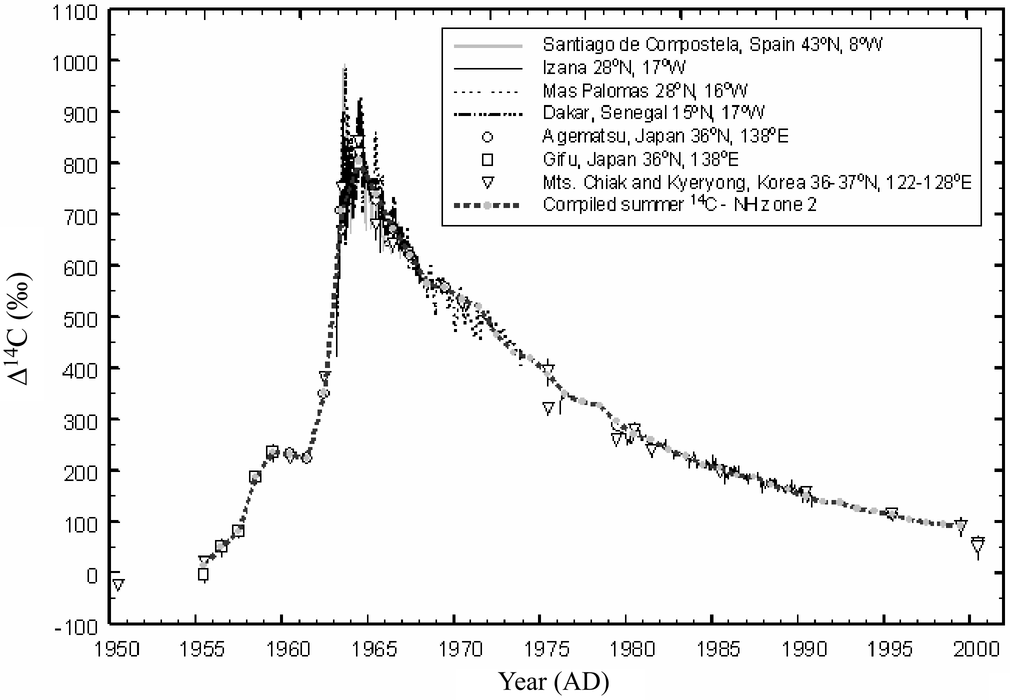

Figure 5 Compiled summer atmospheric ^{14}C curve for NH zone 2 versus atmospheric ^{14}C records (lines) and tree-ring ^{14}C data (symbols) available for the zone. Data sources are given in Tables 4b and 5b.

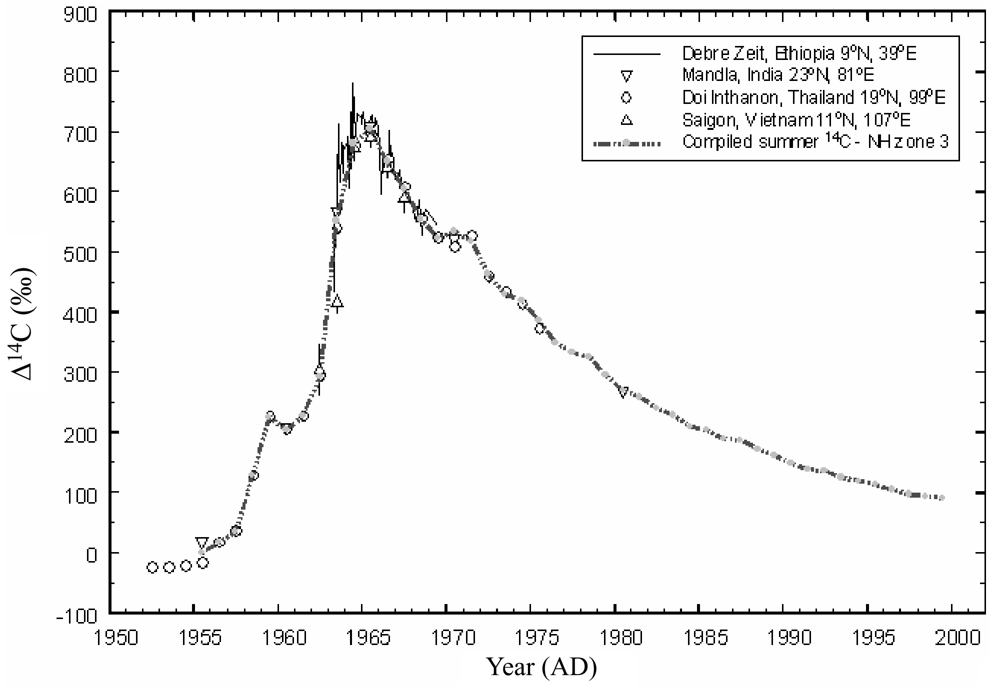

Figure 6 Compiled summer atmospheric ^{14}C curve for NH zone 3 versus atmospheric ^{14}C record (line) and tree-ring ^{14}C data (symbols) available for the zone. Data sources are given in Tables 4c and 5b.

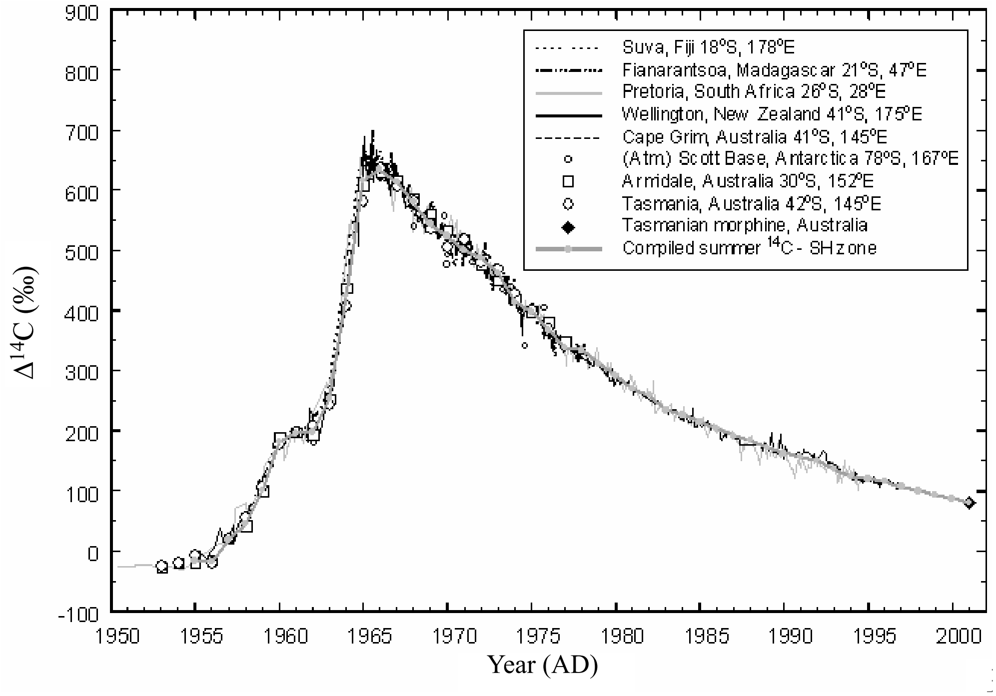

Figure 7 Compiled summer atmospheric ^{14}C curve for the SH zone versus atmospheric ^{14}C records (lines; but small dots for Scott Base) and tree-ring ^{14}C data (open symbols), and the ^{14}C datum from a morphine sample (solid symbol) available for the zone. Data sources are given in Table 3.

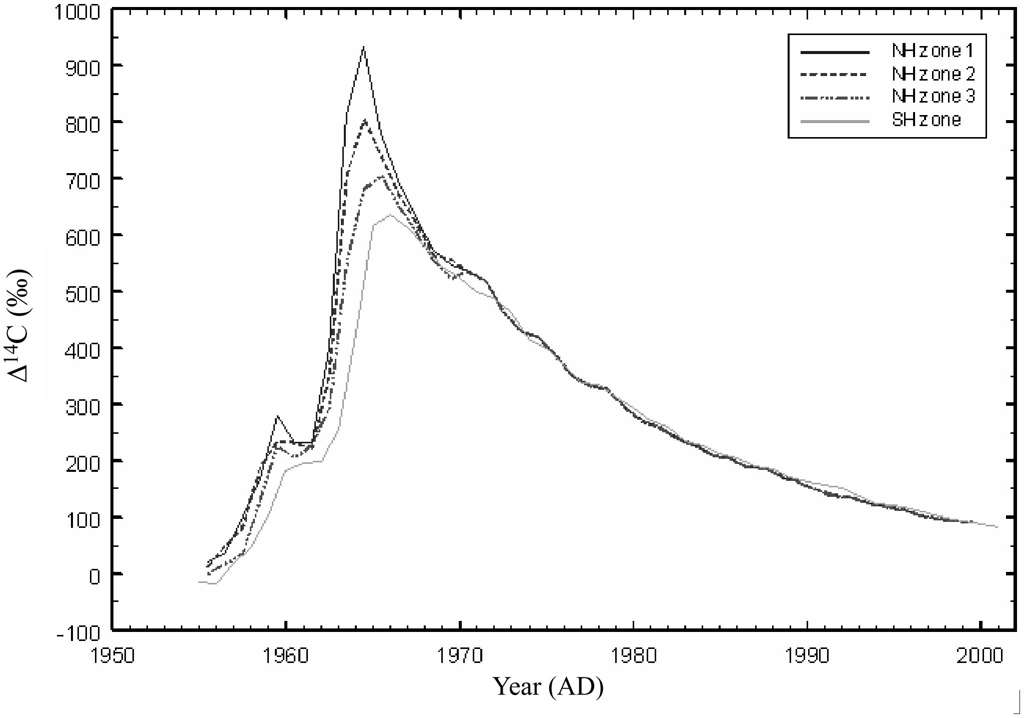

Figure 8 Compiled summer atmospheric ^{14}C curves for 4 different zones (NH zones 1–3, and the SH zone). These compiled data are presented in Tables 3, 4a–c, and 5a–b.

Global Atmospheric ^{14}C Data Set

The temporal spans of the compiled ^{14}C data sets for the Northern and Southern Hemisphere are not the same: they are effectively the middle of a calendar year for the Northern Hemisphere and the beginning of the following year for the Southern Hemisphere. In order to construct a global data set, the same temporal spans have to be employed. Because bomb ^{14}C in the Southern Hemisphere has lower seasonal variations during the bomb peak, ^{14}C values for the Southern Hemisphere for the middle of a calendar year were estimated by linear interpolation of the compiled data set for the Southern Hemisphere presented in Table 3. From now on, this Southern Hemispheric data set is called the estimated Southern Hemispheric winter data set.

For the period 1955–1969, there are 2 different methods which can be used to construct the picture of global atmospheric ^{14}C. The first method employs the 2 hemispheric data sets for the compilation: the Northern Hemispheric mean values reported in Table 5a, and the estimated Southern Hemispheric winter data set. The second method estimates the global values from 4 zonal data sets: 3 zonal data sets for the Northern Hemisphere presented in Tables 4a–c, and the estimated Southern Hemispheric winter data set. As a result of the large ^{14}C gradient in the northern troposphere for the period 1955–1969, the uncertainties associated with the compiled Northern Hemispheric values (see Table 5a) are larger than those for the estimated Southern Hemispheric values. If the first method were employed, the global weighted means would be close to the Southern Hemispheric values when the weights are the ^{14}C uncertainties mentioned above. The mean values therefore might not reflect the true global values. Meanwhile, the uncertainties associated with the 3 zonal values for the Northern Hemisphere (see Tables 4a–c) are almost comparable to those for the estimated Southern

Hemispheric values. Thus, the global means derived from the second method would not be biased by the method of calculation and would reflect the true values. The compiled data of atmospheric ^{14}C for 1955–1969 were estimated using the second method and are presented in Table 6a.

Table 6a Global average $\Delta^{14}C$ (‰) for the period of 1955 to 1969.[a]

Year AD	NH zone 1	NH zone 2	NH zone 3	SH zone (winter data)[b]	Global average
1955.5	21 ± 6	13 ± 13	0 ± 17	–17 ± 5	–11 ± 7
1956.5	38 ± 15	50 ± 18	17 ± 4	0 ± 4	5 ± 5
1957.5	101 ± 16	81 ± 14	35 ± 6	32 ± 5	36 ± 7
1958.5	167 ± 5	187 ± 13	128 ± 5	73 ± 5	103 ± 23
1959.5	278 ± 8	235 ± 18	225 ± 7	141 ± 3	151 ± 18
1960.5	232 ± 5	231 ± 5	205 ± 5	189 ± 2	195 ± 8
1961.5	232 ± 4	223 ± 6	227 ± 6	197 ± 3	202 ± 7
1962.5	398 ± 6	352 ± 9	293 ± 7	226 ± 5	258 ± 32
1963.5	812 ± 18	707 ± 5	552 ± 10	339 ± 8	549 ± 101
1964.5	933 ± 9	804 ± 8	681 ± 9	521 ± 12	699 ± 83
1965.5	781 ± 10	738 ± 9	705 ± 6	626 ± 10	687 ± 29
1966.5	697 ± 9	671 ± 6	650 ± 8	625 ± 4	635 ± 12
1967.5	628 ± 9	620 ± 3	605 ± 9	597 ± 3	603 ± 6
1968.5	572 ± 10	564 ± 14	555 ± 7	562 ± 3	562 ± 3
1969.5	547 ± 8	556 ± 3	523 ± 7	534 ± 4	543 ± 7

[a] Weights for calculation of the global average for a particular year are uncertainties associated with zonal ^{14}C values and zonal surface areas. The percentages of zonal surface areas estimated for NH zones 1, 2, and 3, and the SH zone are 17, 46, 37, and 100%, respectively.

[b] Data were estimated by linear interpolation of the Southern Hemisphere average summer values shown in Table 3.

For the period 1970 onwards, the global mean values were constructed from 2 hemispheric data sets: the Northern Hemispheric means presented in Table 5b, and the estimated Southern Hemispheric winter values. The compiled data of global atmospheric ^{14}C for 1970 onwards are shown in Table 6b. A summary of global and hemispheric mean values of atmospheric $\Delta^{14}C$ for the summer for AD 1955–2001 is presented in Table 7 and illustrated in Figure 9. Atmospheric ^{14}C records for Vermunt and Schauinsland (central Europe; Levin et al. 1994) and Wellington (New Zealand; Manning and Melhuish 1994) are also plotted in Figure 9 for comparison. These records are usually used to represent atmospheric ^{14}C for the Northern and Southern Hemispheres, respectively. Because the gradient of bomb ^{14}C was not large for the Southern Hemisphere, there is a good agreement between the Wellington record and the compiled summer ^{14}C curve for the Southern Hemisphere. Meanwhile, there is a large difference between the Vermunt record and the compiled summer ^{14}C values for the Northern Hemisphere for the bomb peak, the period which saw a large ^{14}C gradient within the Northern Hemisphere. This indicates that Vermunt, belonging to NH zone 1, and its ^{14}C values may represent this zone (see Figure 4), but may not be an appropriate representation of the whole Northern Hemisphere, at least for the bomb peak period AD 1963–1966.

Table 6b Global average Δ^{14}C (‰) for the period from 1970 onwards.

Year AD	NH	SH winter data[a]	Global average	Year AD	NH	SH winter data[a]	Global average
1970.5	534 ± 8	512 ± 4	517 ± 10	1986.5	189 ± 3	197 ± 2	194 ± 4
1971.5	518 ± 10	494 ± 3	496 ± 7	1987.5	187 ± 3	188 ± 3	187 ± 2
1972.5	464 ± 7	475 ± 4	472 ± 4	1988.5	172 ± 2	178 ± 3	175 ± 3
1973.5	430 ± 9	438 ± 5	436 ± 4	1989.5	162 ± 2	168 ± 3	164 ± 3
1974.5	419 ± 6	405 ± 3	408 ± 5	1990.5	149 ± 3	160 ± 4	154 ± 5
1975.5	387 ± 4	383 ± 2	383 ± 1	1991.5	138 ± 2	154 ± 3	145 ± 8
1976.5	349 ± 3	353 ± 2	352 ± 2	1992.5	136 ± 1	144 ± 4	137 ± 2
1977.5	333 ± 2	336 ± 2	335 ± 2	1993.5	125 ± 2	130 ± 5	126 ± 2
1978.5	326 ± 5	323 ± 7	325 ± 4	1994.5	119 ± 1	121 ± 2	119 ± 1
1979.5	295 ± 4	302 ± 7	297 ± 3	1995.5	113 ± 2	118 ± 1	117 ± 2
1980.5	270 ± 2	281 ± 5	272 ± 4	1996.5	104 ± 2	111 ± 1	109 ± 3
1981.5	259 ± 4	266 ± 6	261 ± 3	1997.5	100 ± 8[b]	103 ± 2	103 ± 2
1982.5	240 ± 2	247 ± 4	242 ± 3	1998.5	96 ± 14[b]	97 ± 2	97 ± 2
1983.5	228 ± 5	230 ± 4	229 ± 3	1999.5	91 ± 20	90 ± 3	90 ± 3
1984.5	210 ± 3	220 ± 5	213 ± 5	2000.5	—	84 ± 4	84 ± 4
1985.5	204 ± 2	209 ± 3	206 ± 2				

[a] Data were estimated by linear interpolation of the Southern Hemisphere average summer values reported in Table 3.
[b] Estimated value from adjacent data by linear interpolation.

Table 7 Summary of global and hemispheric average Δ^{14}C (‰) for 1955–2001.

Year AD	SH average	Year AD	NH average	Global average
1955.0	–16 ± 7	1955.5	15 ± 6	–11 ± 7
1956.0	–18 ± 4	1956.5	20 ± 6	5 ± 5
1957.0	19 ± 3	1957.5	45 ± 15	36 ± 7
1958.0	45 ± 7	1958.5	148 ± 16	103 ± 23
1959.0	101 ± 4	1959.5	239 ± 16	151 ± 18
1960.0	182 ± 3	1960.5	222 ± 9	195 ± 8
1961.0	196 ± 2	1961.5	226 ± 3	202 ± 7
1962.0	198 ± 3	1962.5	337 ± 30	258 ± 32
1963.0	254 ± 6	1963.5	686 ± 41	549 ± 101
1964.0	424 ± 10	1964.5	785 ± 62	699 ± 83
1965.0	617 ± 15	1965.5	723 ± 17	687 ± 29
1966.0	635 ± 4	1966.5	668 ± 10	635 ± 12
1967.0	614 ± 4	1967.5	618 ± 3	603 ± 6
1968.0	581 ± 2	1968.5	559 ± 6	562 ± 3
1969.0	544 ± 3	1969.5	551 ± 8	543 ± 7
1970.0	524 ± 5	1970.5	534 ± 8	517 ± 10
1971.0	500 ± 4	1971.5	518 ± 10	496 ± 7
1972.0	487 ± 3	1972.5	464 ± 7	472 ± 4
1973.0	462 ± 5	1973.5	430 ± 9	436 ± 4
1974.0	413 ± 5	1974.5	419 ± 6	408 ± 5
1975.0	398 ± 2	1975.5	387 ± 4	383 ± 1
1976.0	368 ± 2	1976.5	349 ± 3	352 ± 2
1977.0	338 ± 2	1977.5	333 ± 2	335 ± 2
1978.0	335 ± 3	1978.5	326 ± 5	325 ± 4
1979.0	312 ± 10	1979.5	295 ± 4	297 ± 3

Table 7 Summary of global and hemispheric average Δ^{14}C (‰) for 1955–2001. *(Continued)*

Year AD	SH average	Year AD	NH average	Global average
1980.0	292 ± 4	1980.5	270 ± 2	272 ± 4
1981.0	271 ± 7	1981.5	259 ± 4	261 ± 3
1982.0	260 ± 5	1982.5	240 ± 2	242 ± 3
1983.0	234 ± 2	1983.5	228 ± 5	229 ± 3
1984.0	226 ± 5	1984.5	210 ± 3	213 ± 5
1985.0	214 ± 4	1985.5	204 ± 2	206 ± 2
1986.0	204 ± 2	1986.5	189 ± 3	194 ± 4
1987.0	191 ± 2	1987.5	187 ± 3	187 ± 2
1988.0	184 ± 3	1988.5	172 ± 2	175 ± 3
1989.0	172 ± 3	1989.5	162 ± 2	164 ± 3
1990.0	163 ± 4	1990.5	149 ± 3	154 ± 5
1991.0	157 ± 4	1991.5	138 ± 2	145 ± 8
1992.0	152 ± 2	1992.5	136 ± 1	137 ± 2
1993.0	137 ± 7	1993.5	125 ± 2	126 ± 2
1994.0	123 ± 3	1994.5	119 ± 1	119 ± 1
1995.0	120 ± 1	1995.5	113 ± 2	117 ± 2
1996.0	116 ± 1	1996.5	104 ± 2	109 ± 3
1997.0	107 ± 1	1997.5	100 ± 8[a]	103 ± 2
1998.0	100 ± 2[a]	1998.5	96 ± 14[a]	97 ± 2
1999.0	94 ± 3[a]	1999.5	91 ± 20	90 ± 3
2000.0	87 ± 3[a]	2000.5	—	84 ± 4
2001.0	81 ± 4			

[a] Estimated value from adjacent data by linear interpolation.

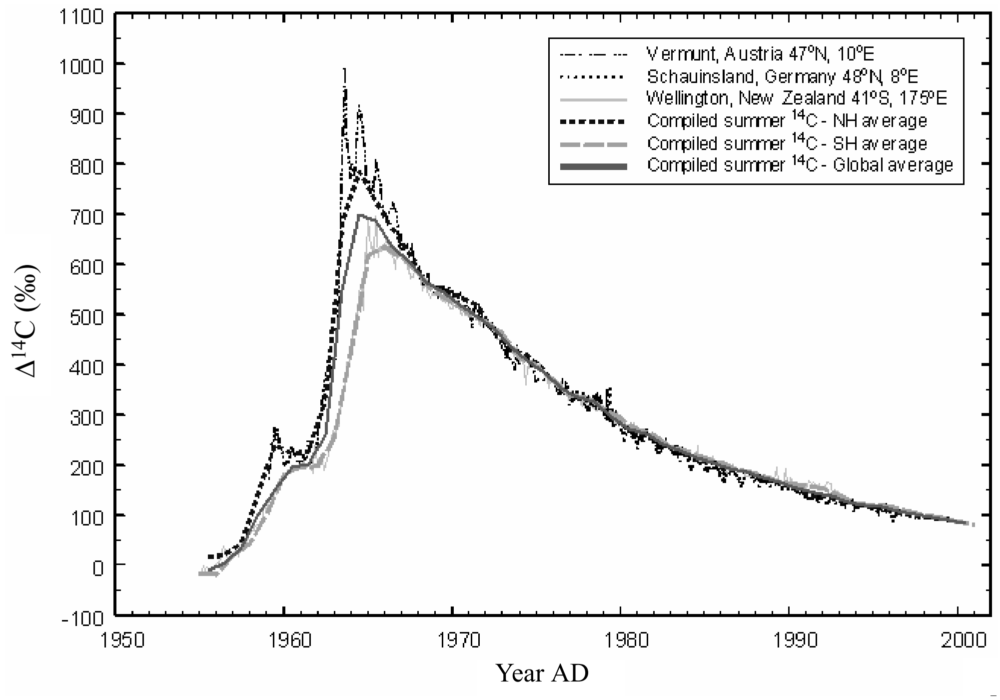

Figure 9 Compiled summer hemispheric and global ^{14}C curves versus atmospheric ^{14}C records for Vermunt and Schauinsland (central Europe; Levin et al. 1994) and Wellington (New Zealand; Manning and Melhuish 1994). The compiled data sets are presented in Tables 5a–b, 6a–b, and 7.

COMPILED TROPOSPHERIC ^{14}C DATA SETS FOR AGE CALIBRATION PURPOSES

The zonal summer ^{14}C data sets, described in the last section, represent ^{14}C levels in tree rings and other short-lived plant materials (leaves, grains, seeds, etc.), which in some cases grow in a single summer season. However, in general these data sets do not well reflect ^{14}C levels in woody materials and plant products such as grass, paper, textiles, etc. For example, most trees in the tropics grow all year round. In addition, some datable animal products (bones, teeth, skins, and hairs) do not receive new ^{14}C on a seasonal basis. Therefore, the zonal summer ^{14}C data sets may not be suitable for age calibration purposes.

Four different data sets for the troposphere (NH zones 1, 2, and 3, and SH) were compiled for age calibration. The data sets were compiled mainly from monthly mean values derived from atmospheric ^{14}C records. These data sets were extended to the beginning of the nuclear age using ^{14}C data from tree rings and to very recent years using a ^{14}C datum derived from morphine. The ^{14}C data from tree rings and morphine were yearly data showing the value in the middle of the growing period (middle of the year for the Northern Hemisphere and beginning of the year for the Southern Hemisphere). The method of calculation of the monthly mean values and their associated uncertainties was the same as that described in the last section.

For the Southern Hemisphere, the ^{14}C data sets employed for the construction of monthly atmospheric ^{14}C for the hemisphere were atmospheric records for Funafuti, Suva, Campbell Island, and Scott Base (Manning et al. 1990); Fianarantsoa (Nydal and Lövseth 1996); Pretoria (Vogel and Marais 1971); Wellington (Manning and Melhuish 1994); and Cape Grim (Levin et al. 1996, 1999). These monthly data, from February 1955 to December 1996, were extended to the beginning of 2001 by the ^{14}C datum derived from very recent Tasmanian morphine (Zoppi et al. 2004).

For 1955–1969, monthly atmospheric ^{14}C data for NH zone 1 were constructed from atmospheric records from Fruholmen (Nydal and Lövseth 1996), Vermunt (Levin et al. 1994), and China Lake (36°N, 118°W; Berger et al. 1965; Berger and Libby 1966, 1967, 1968, 1969). The monthly data, from February 1959 to December 1969, were extended to mid-1955 using tree-ring data from Russia (Kolesnikov et al. 1970), Kiel (Willkomn and Erlenkeuser 1968), Hungary (Hertelendi and Csongor 1978), and Bear Mountain, New York (Cain and Suess 1976).

For NH zone 2, ^{14}C data sets used for construction of monthly data (March 1963–December 1969) were atmospheric records from Santiago de Compostela, Israel, Izaña, Mas Palomas, and Dakar (Nydal and Lövseth 1996). Tree-ring ^{14}C data for Gifu (Nakamura et al. 1987a,b), Agematsu (Muraki et al. 1998), and Mts Chiak and Kyeryong (Park et al. 2002) were used to extended the monthly data back to mid-1955.

For NH zone 3, the ^{14}C data set used for construction of monthly data (May 1963–July 1969) was the atmospheric record from Debre Zeit (Nydal and Lövseth 1996). Tree-ring ^{14}C data for India (Murphy et al. 1997), Saigon (Kikata et al. 1992, 1993), and Doi Inthanon (Hua et al. 2000) were used to extend the monthly data back to mid-1955.

For 1970 onwards, monthly atmospheric ^{14}C data for the Northern Hemisphere (January 1970–January 1997) were constructed from atmospheric records from Fruholmen, Canary Islands (Nydal and Lövseth 1996), Vermunt and Schauinsland (Levin et al. 1994), and China Lake (Berger et al. 1987). The monthly data were extended to mid-1999 using tree-ring data from Mts Chiak and Kyeryong (Park et al. 2002).

Compared to individual ^{14}C atmospheric records, these compiled data sets have at least 2 advantages in terms of age calibration: (1) an even distribution of data in the compiled data sets, which are mostly based on monthly data, and (2) longer data sets, which almost span the complete bomb period. For example, the compiled data set for the Southern Hemisphere is from 1955–2001, whereas individual records for the Southern Hemisphere cover shorter periods of time [Funafuti (9°S) for 1966–1972, Suva (18°S) for 1958–1975, Fianarantsoa (21°S) for 1964–1978, Pretoria (26°S) for 1955–1994, Wellington (41°S) for 1955–1993, Campbell Island (53°S) for 1970–1977, or Scott Base (78°S) for 1961–1976] with an uneven distribution of data points (Fianarantsoa, 2 samples per month for 1964–1966, and less than 1 sample per month for 1967–1978; Pretoria, 8–10 samples per year for 1960–March 1965, and no sample between April 1965–June 1966; Scott Base, only data for the summer season are available).

The 4 compiled data sets almost cover the past 50 yr of atmospheric ^{14}C (1955.5–1999.5 for the Northern Hemisphere and 1955–2001 for the Southern Hemisphere). They are presented in Tables 8a–d (www.radiocarbon.org/IntCal04), as both Δ^{14}C and δ^{13}C-corrected F^{14}C (fraction modern; Reimer et al. 2004a) values. These compiled data sets can be used to extend the IntCal04 calibration curve (Reimer et al. 2004b) to cover the bomb period. Using one of the calibration data sets together with the calibration program CaliBomb of Reimer et al. (2004a), one can easily determine the calibrated age for a particular sample having an F^{14}C value in the bomb period. The appropriate extended monthly data set, which should be chosen for age calibration, will depend on the geographic location of the ^{14}C sample (see Figure 3). These (compiled) extended monthly ^{14}C data sets in F^{14}C are shown in Figure 10.

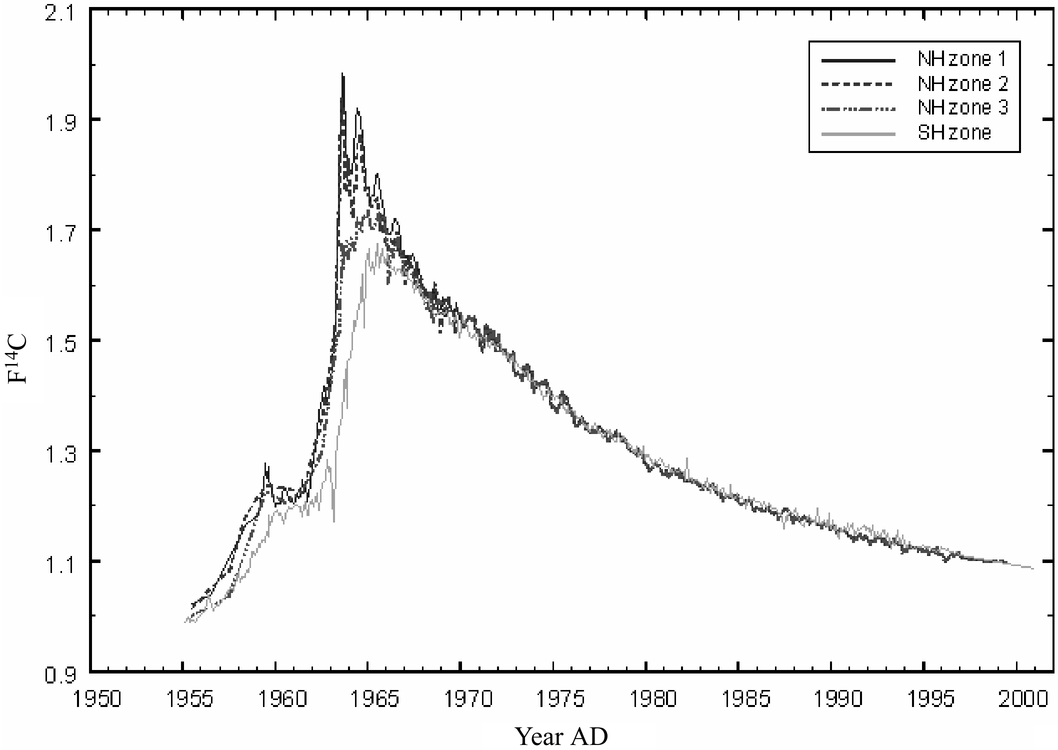

Figure 10 Compiled atmospheric ^{14}C curves for 4 different zones (NH zones 1–3, and the SH zone) for age calibration. The compiled data sets are presented in Tables 8a–d (www.radiocarbon.org/IntCal04).

CONCLUSION

A comprehensive compilation of bomb ^{14}C data for the troposphere from selected atmospheric records, tree rings, and recent organic material is presented. The compilation consists of zonal, hemispheric, and global ^{14}C data sets for the summer, and zonal atmospheric ^{14}C curves at (mostly) monthly resolution. The former can be employed for calibrating and comparing carbon cycle models, while the latter can be used for age calibration of recent organic matter dated by the ^{14}C method. These compiled ^{14}C data sets are available on the *Radiocarbon* Web site at http://www.radiocarbon.org/IntCal04 and the ANSTO Web site at http://www.ansto.gov.au/ansto/environment1/ams/.

We find that the distribution of bomb ^{14}C reflects the major zones of atmospheric circulation and their boundaries in a logical and understandable way. This should provide a valuable key to the interpretation of changing regional and interhemispheric ^{14}C offsets in the past.

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