The Holocene 12,1 (2002) pp. 1–6

Evidence from northwest European bogs shows 'Little Ice Age' climatic changes driven by variations in solar activity

Dmitri Mauquoy,[1]* Bas van Geel,[1] Maarten Blaauw[1] and Johannes van der Plicht[2]

([1]Institute for Biodiversity and Ecosystem Dynamics and Centre for Geo-ecological Research, University of Amsterdam, Kruislaan 318, 1098 SM Amsterdam, The Netherlands; [2]Centre for Isotope Research and Centre for Geo-ecological Research, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands)

Received 2 April 2001; revised manuscript accepted 1 June 2001

A
HOLOCENE
FAST-TRACK
REPORT

Abstract: Fluctuations in Holocene atmospheric radiocarbon concentrations have been shown to be due to variations in solar activity. Analyses of both ^{10}Be and ^{14}C nuclides confirm that production-rate changes during the Holocene were largely modulated by solar activity. Analyses of peat samples from two intact European ombrotrophic bogs show that climatic deteriorations during the 'Little Ice Age' are associated with transitions to increasing atmospheric ^{14}C content due to greater ^{14}C production. Both ombrotrophic mires, which are positioned *c.* 800 km apart, register reactions to globally recorded ^{14}C fluctuations between AD 1449 and 1464 and an almost identical reaction between AD 1601 and 1604.

Key words: Solar forcing, Δ^{14}C, wiggle-match dating, 'Little Ice Age', *Sphagnum*, mires.

Introduction

The value of atmospheric radiocarbon content as a solar variability proxy has been confirmed through analyses of both ^{14}C and ^{10}Be (Stuiver and Braziunas, 1989; Bard *et al.*, 1997; Beer *et al.*, 1988; Beer, 2000). The central Greenland GISP2 ice core background dust concentration also appears to be modulated with a period of 11 years from at least 100000 years BP (Ram *et al.*, 1997). This period coincides with the 11-year Schwabe sunspot cycle (Cohen and Lintz, 1974). Evidence for solar forcing of climate has been detected in European peat bogs at *c.* 850 cal. BC (van Geel *et al.*, 1999), using wiggle-match dating (van Geel and Mook, 1989; van der Plicht, 1993; Kilian *et al.*, 2000; Speranza *et al.*, 2000) to precisely establish the timing and relation of wet-shifts to changes in the production of ^{14}C. The direct link between mire hydroclimatic changes and changes in the production of atmospheric ^{14}C (solar activity) has not yet, however, been detected during the 'Little Ice Age' series of climatic deteriorations.

Ombrotrophic mires are closely coupled to the atmosphere, since they receive all their water through precipitation alone. In addition, plants growing on these mires are sensitive to changes in effective precipitation (the balance of precipitation remaining after evapotranspiration processes). Rainfed peat bogs are therefore excellent ecosystems to investigate potential sun/climate links, since exceptional preservation of subfossil material upon burial, combined with high accumulation rates (a mean value of 1 mm yr^{-1}) and relative ease of radiocarbon dating, allows high-resolution reconstructions of Holocene palaeoenvironments to be made using these records (Aaby, 1976; van Geel, 1978; Barber, 1981; Barber *et al.*, 1994; Kilian *et al.*, 1995; van Geel *et al.*, 1996; Mauquoy and Barber, 1999; Hughes *et al.*, 2000).

Materials and methods

In order to investigate the timing and nature of climate change during the 'Little Ice Age' (LIA), peat monoliths of 1 m depth

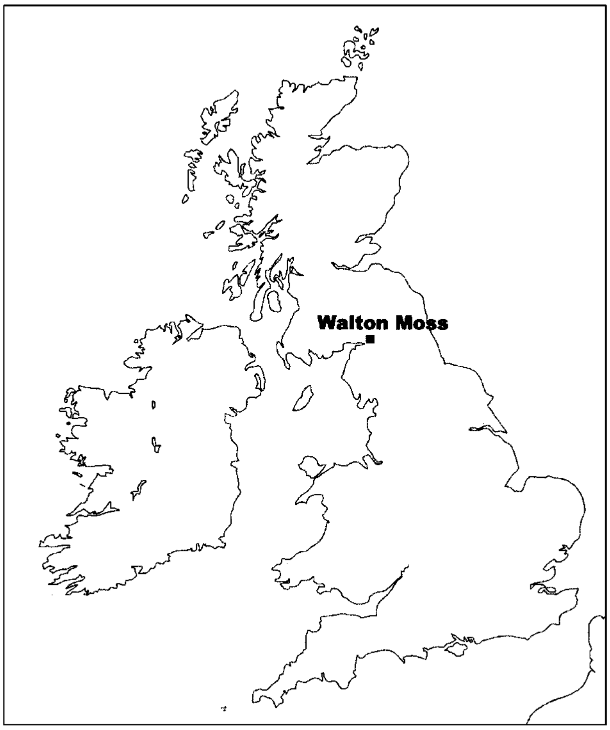
---

*Author for correspondence (e-mail: dmitri.mauquoy@geo.uu.se)

10.1191/0959683602hl514rr

were taken from Lille Vildmose (LVM), Denmark (56°50′N, 10°15′E; Figure 1) and Walton Moss (WLM19), UK (54°59′N, 02°46′W). These ombrotrophic mires are positioned *c.* 800 km apart, and offer the possibility of detecting supraregional changes in climate. Both of these rainfed peat bogs are remarkably intact and possess abundant *Sphagnum magellanicum,* principally in lawn microforms, while *Sphagnum capillifolium* and *Sphagnum tenellum/cuspidatum* are encountered in hummocks and low lawns/pools respectively. Increases in mire surface wetness were detected by increased representation of *Sphagnum tenellum,* and *Sphagnum cuspidatum* leaves (Figures 2b and 3b). Increases in the representation of these subfossil bryophyte components unequivocally illustrate high local water tables (Barber, 1981), which in raised peat bogs indicates increased effective precipitation (cool, moist climatic conditions).

A single 92 cm monolith of peat was taken from Lille Vildmose (LVM) using a Wardenaar corer (Wardenaar, 1987). The top 25 cm of this monolith was compressed by the Wardenaar corer; therefore a small pit was dug immediately adjacent to the Wardenaar borehole, and a replicate core taken with a metal box (50 × 15 × 10 cm). Samples from the box sample were taken from 0–25 cm depth, then from 25–92 cm samples from the Wardenaar monolith were used. The Wardenaar borehole taken from Walton Moss (WLM19) was positioned 7.3 m northwest from Walton Moss Core 11 (see Figure 2 in Barber *et al.,* 1998). WLM19 did not suffer from any visible compression, therefore the complete monolith was investigated. Vegetative macrofossils taken at contiguous 1 cm sample intervals in each monolith were examined using light microscopy. Abundances of each peat component were expressed as volume percentages of the subsample (*c.* 5 cm^3).



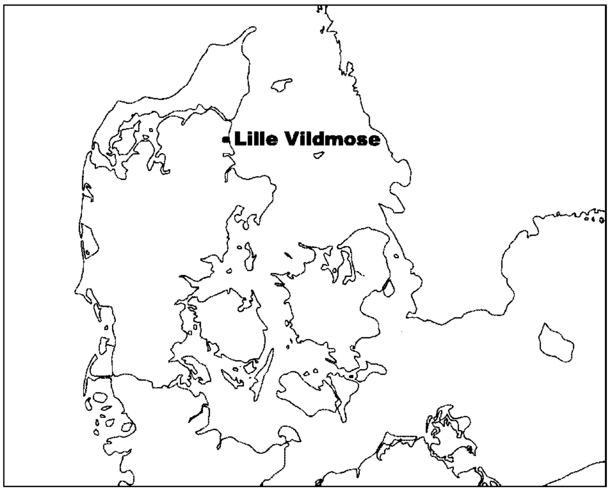


Figure 1 Study sites in northern England (above) and Denmark (below).

A closely spaced series of ^{14}C AMS dated samples immediately preceding and following each of the identified wet-shifts was closely matched to century-scale fluctuations (wiggles) in the ^{14}C tree-ring calibration curve (INTCAL98 calibration data set; Stuiver *et al.*, 1998) using CAL25 (van der Plicht, 1993). By using this wiggle-match dating strategy (van Geel and Mook, 1989), the precise timing and relation of wet-shifts to changes in the production of ^{14}C was determined. During the Holocene, production of ^{14}C is mainly dependent upon incident cosmic rays (Figures 2a and 3a), while the intensity of cosmic rays is anticorrelated with solar activity (Beer *et al.*, 1990; Leftus, 2000). Changes in deep-water formation (reduced CO_2 exchange at the air/sea interface and/or reduced upwelling of ^{14}C deficient deep ocean water) appear to be an unlikely candidate for the marked changes in ^{14}C production during the 'Little Ice Age' (Stuiver and Braziunas, 1993). In addition, there is no indication from experimental data that Holocene ^{14}C wiggles are due to changes in the geomagnetic field intensity (Jürg Beer, personal communication).

Results

The calendar and ^{14}C ages of the samples dated from LVM and WLM19 are presented in Tables 1 and 2. In LVM (Figure 2b), the wiggle-match fit of the 19 ^{14}C AMS dates to the tree-ring calibration curve is excellent, with the exception of a single outlier (date 16). The two wet-shifts identified in this peat bog using leaf abundances of *Sphagnum tenellum* and *Sphagnum cuspidatum* were initiated at *c.* AD 1449 (date 14) and AD 1604 (date 11). The wiggle-match dating results for WLM19 (Figure 3b) again show an outlier (date 20), but, with the exception of this date, the 30 dated levels closely follow the wiggles in the calibration curve. The first climatic deterioration registered at date 23 suggests that the inception of *Sphagnum tenellum* and *Sphagnum* section *Cuspidata* occurred at *c.* AD 1215. The start of the second and third wet-shifts identified (dates 13, AD 1464, and 8, AD 1601) again occur during periods of rapid increases in Δ^{14}C (at a transition point between low and high Δ^{14}C).

Discussion

The first climatic deterioration in LVM at *c.* AD 1449 occurred during a period of rapid increase in Δ^{14}C (Figure 2a), while the second one at *c.* AD 1604 was initiated at a transition point between low and high Δ^{14}C. Both of these wet-shifts occurred when production of ^{14}C increased rapidly at the beginning of the Spörer (S) and Maunder (M) Minima respectively. During these periods of reduced solar activity cosmic rays were less effectively deflected by the solar wind, allowing more ^{14}C production in the atmosphere. The deepest part of the LVM peat stratigraphy postdates the beginning of the Wolf (W) Minimum, so it was not possible to explore the peat proxy climate/Δ^{14}C relation before *c.* AD 1340. Increased mire surface wetness did not occur during the Dalton Minimum.

The wet-shifts identified in WLM19 (*c.* AD 1215, 1464 and 1601) appear to have occurred during the Wolf, Spörer and

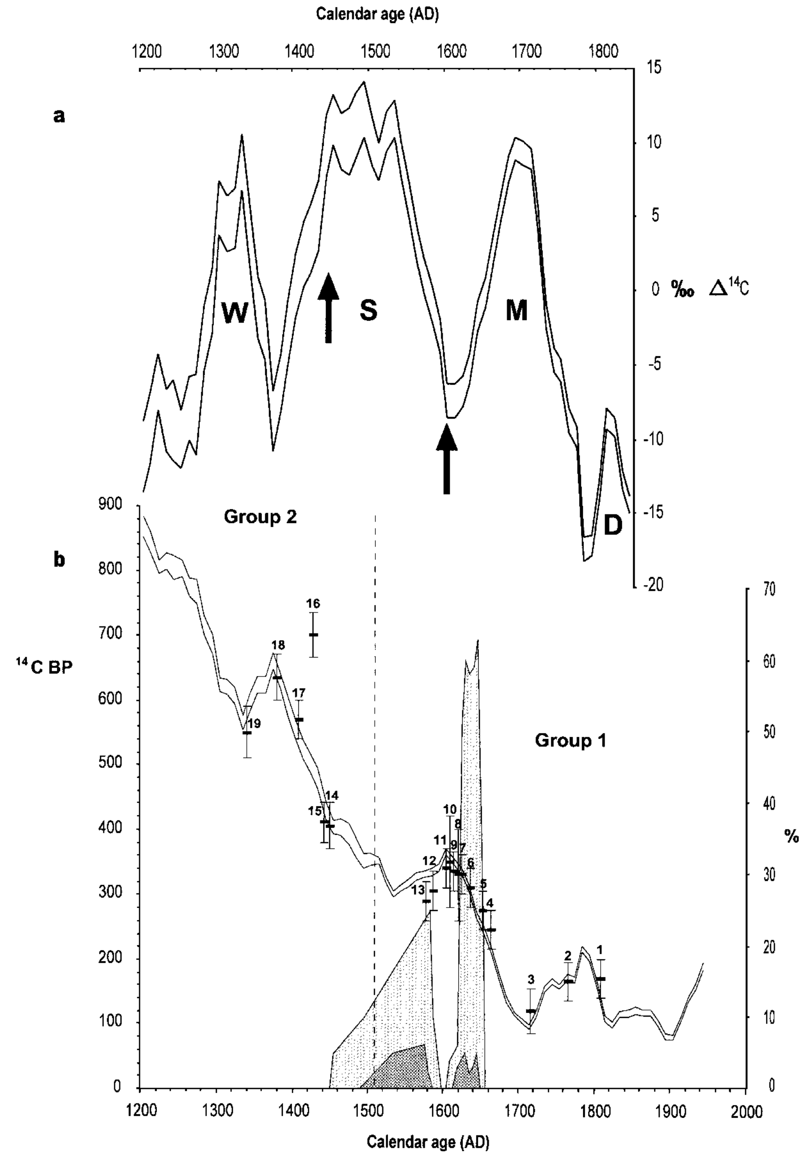


Figure 2 (a) Detrended $\Delta^{14}C$ presented with 1 σ error bars versus calendar age. W = Wolf, S = Spörer, M = Maunder and D = Dalton Minimum (periods of reduced solar activity). Black arrows on the $\Delta^{14}C$ curve indicate the initiation of climatic deteriorations as recorded by *Sphagnum tenellum* and *Sphagnum cuspidatum.* (b) Radiocarbon versus calendar ages of *Sphagnum* samples wiggle-match dated from Lille Vildmose (LVM). Both the ^{14}C dates and the INTCAL98 calibration curve (Stuiver *et al.,* 1998) are presented with 1 σ error bars. Two subgroups of the ^{14}C dated samples were independently wiggle-matched to the tree-ring calibration curve (van Geel and Mook, 1989; van der Plicht, 1993) on the basis of pronounced changes in peat bulk density (dry mass cm^{-3}). These changes reflect variations in peat accumulation rate. Abundances of *Sphagnum tenellum* (light shading) and *Sphagnum cuspidatum* (dark shading) are superimposed and register increases in mire surface wetness (cool, moist climatic conditions). Volume abundances of these vegetative macrofossils are expressed as percentages in the *c.* 5 cm^3 samples investigated.

Maunder Minima respectively (Figure 3a). WLM19 mirrors the climatic response of LVM, since increased mire surface wetness did not occur during the Dalton Minimum. The five wet-shifts identified in the peat stratigraphy of LVM and WLM19 are all correlated with steep increases in $\Delta^{14}C$, which are highly likely to have been driven by increased ^{14}C production, i.e., solar forcing changes. The identification of the Spörer and Maunder Minima in both LVM (*c.* AD 1449 and 1604) and the Wolf, Spörer and Maunder Minima in WLM19 (ca. AD 1215, 1464 and 1601 respectively), suggests that these climatic deteriorations had widespread effects, since these two mires are positioned *c.* 800 km apart. These time intervals correspond to periods of peak cooling in 1000-year Northern Hemisphere climate records (Crowley and Lowery, 2000). Further evidence for the widespread registration of the 'Little Ice Age' is presented in the Greenland GISP2 ice core by O'Brien *et al.* (1995) based on sea salt and terrestrial dust fluxes. The diatom-based record of Korhola *et al.* (2000) for northern Fennoscandia also suggests that regional changes in climate occurred during the 'Little Ice Age' (400 cal. BP). The sudden increase in $\Delta^{14}C$ during the Dalton Minimum is smaller (8.8‰) than the Wolf, Spörer and Maunder Minima, which were major increases in $\Delta^{14}C$ (around 20‰). Solar activity changes during the Dalton Minimum may therefore not have been as severe as the antecedent 'Little Ice Age' changes, which may explain the failure of the peat stratigraphy to record climatic changes during this time.

The *direct* link identified here between changes in ^{14}C production and the occurrence of regional climate change signals in ombrotrophic peat bogs during the LIA, suggests that solar forcing during this period may well have been an important driving factor

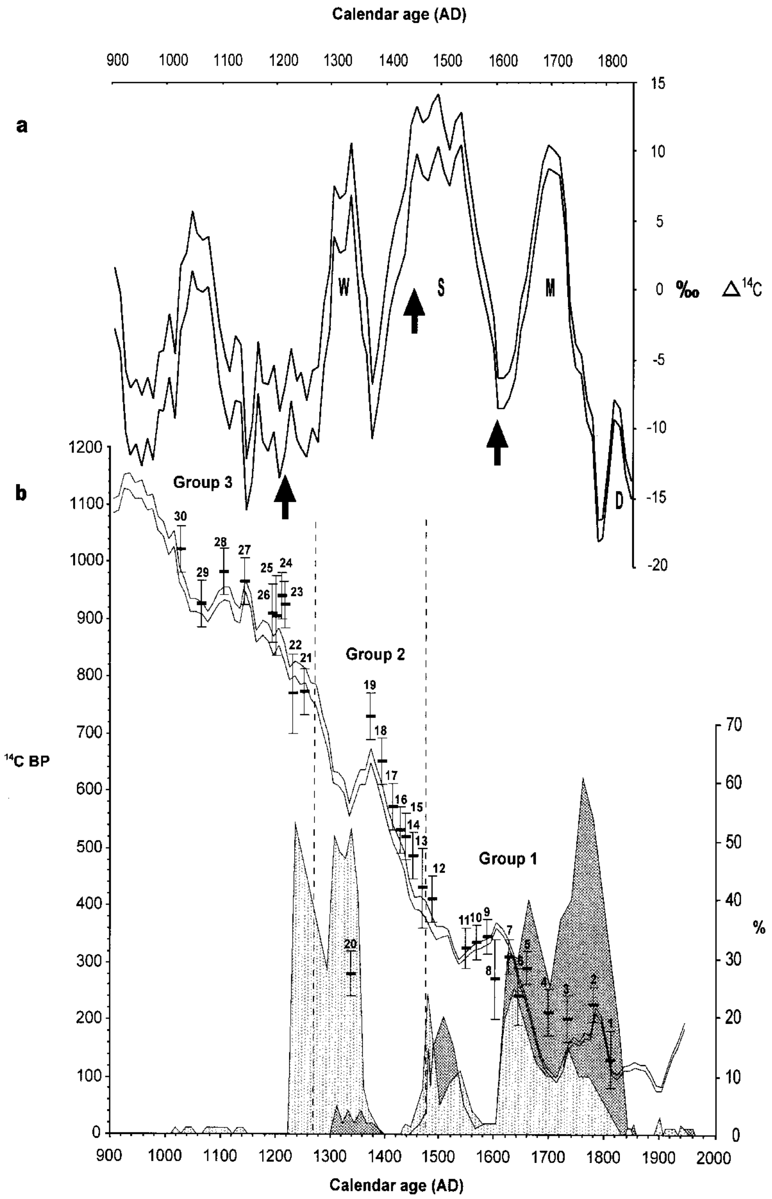


Figure 3 (a) Detrended $\Delta^{14}C$ presented with 1 σ error bars versus calendar age. W = Wolf, S = Spörer, M = Maunder and D = Dalton Minimum (periods of reduced solar activity). Black arrows on the $\Delta^{14}C$ curve indicate the initiation of climatic deteriorations as recorded by *Sphagnum tenellum* and *Sphagnum cuspidatum.* (b) Radiocarbon versus calendar ages of *Sphagnum* samples wiggle-match dated from Walton Moss 19 (WLM19). Both the ^{14}C dates and the INTCAL98 calibration curve (Stuiver *et al.,* 1998) are presented with 1 σ error bars. Three subgroups of the ^{14}C dated samples were independently wiggle-matched to the tree-ring calibration curve (van Geel and Mook, 1989; van der Plicht, 1993) on the basis of pronounced changes in peat bulk density (dry mass cm^{-3}), since these subgroups are likely to have accumulated at different rates. Abundances of *Sphagnum tenellum* (light shading) and *Sphagnum cuspidatum* (dark shading) are superimposed and register increases in mire surface wetness (cool, moist climatic conditions). Volume abundances of these vegetative macrofossils are expressed as percentages in the *c.* 5 cm^{3} samples investigated.

for much of the suggested natural preindustrial temperature variability in the Northern Hemisphere (Lean *et al.*, 1995). Solar activity is estimated to have varied by 0.24% from the Maunder Minimum to the present time (Lean and Rind, 1998). Given these possible small changes in solar radiative output, amplifying mechanisms may operate to effect climate forcing. The precise nature of these amplifying mechanisms is uncertain, however (van Geel *et al.,* 1998; 1999). Nevertheless, this increasing body of evidence for a link between changes in ^{14}C production and the occurrence of climate change signals in ombrotrophic peat bogs suggests that variations in solar activity may well have been an important factor driving Holocene climate change.

Acknowledgements

We thank the Dutch National Research Programme on Global Air Pollution and Climate Change for funding this research (Project No. 952275), and Bent Aaby for recommending Lille Vildmose as a study site. We also thank Anita Aerts-Bijma and Fsaha Ghebru, Centre for Isotope Research, University of Groningen, for help and support with ^{14}C sample preparation. We are grateful to Major Johnson for allowing access to and sampling of Walton Moss, UK. Comments made by Jürg Beer and an anonymous referee helped to improve the paper.

Table 1 Radiocarbon and wiggle-match date results for Lille Vildmose. The dates were calibrated using the INTCAL98 calibration curve (Stuiver *et al.*, 1998) within the Groningen program Cal25 (van der Plicht, 1993)

Date (no.)	GrA-number	$\delta^{13}C$ (‰)	Carbon content (%)	^{14}C age (BP)	Laboratory standard deviation (BP)	Mid-point sample depth (cm)	Wiggle-match date	Sample composition (*S.* = *Sphagnum*)
1	16578	−27.49	43.2	170	30	29.5	AD 1808	*S. capillifolium* leaves+branches+stems
2	16582	−26.52	38.1	165	30	37.5	AD 1765	*S. capillifolium* leaves+branches+stems
3	14110	−25.74	41.9	120	35	46.5	AD 1717	*S. capillifolium* leaves+branches+stems
4	16583	−27.98	44.1	245	30	56.5	AD 1663	*S. capillifolium* leaves+branches+stems
5	16586	−27.55	44.1	275	30	58.5	AD 1652	*S. capillifolium* leaves+branches+stems
6	16587	−25.36	43.9	310	30	61.5	AD 1636	*Sphagnum tenellum* leaves
7	16588	−24.3	43.4	330	30	63.5	AD 1625	Sphagnum tenellum+*S. cuspidatum* leaves+stems
8	12743	−25.8	43.8	330	70	64.5	AD 1620	*S. capillifolium* branches+stems+opercula
9	16589	−25.73	45.2	335	30	65.5	AD 1614	*S. capillifolium* branches+stems+opercula
10	12755	−26.58	43.5	350	70	66.5	AD 1609	*S. capillifolium* branches
11	16591	−26.89	44.8	340	30	67.5	AD 1604	*S. capillifolium* branches
12	16592	−24.97	44	305	30	70.5	AD 1588	*S. capillifolium* branches
13	16593	−25.82	44.6	290	30	72.5	AD 1577	*S. capillifolium*+*S. tenellum*
14	16623	−24.85	43.5	405	35	75.5	AD 1449	leaves
15	16599	−24.44	43.6	410	30	76.5	AD 1442	*Dicranum* leaves+*Sphagnum*
16	16625	−26.35	43.1	700	35	78.5	AD 1428	stems
17	16597	−27.24	44.2	570	30	81.5	AD 1408	*Dicranum* leaves
18	16627	−26.22	44.7	635	35	85.5	AD 1380	*S. capillifolium* leaves
19	14111	−27.21	40	550	40	91.5	AD 1340	*S. capillifolium* stems
								S. capillifolium leaves+branches
								S. capillifolium leaves+branches

Table 2 Radiocarbon and wiggle-match date results for Walton Moss Core 19. The dates were calibrated using the INTCAL98 calibration curve (Stuiver *et al.*, 1998) within the Groningen program Cal25 (van der Plicht, 1993)

Date (no.)	GrA-number	$\delta^{13}C$ (‰)	Carbon content (%)	^{14}C age (BP)	Laboratory standard deviation (BP)	Mid-point sample depth (cm)	Wiggle-match date	Sample composition (*S.* = *Sphagnum*)
1	16470	−24.09	52.6	130	50	35.5	AD 1815	*S. magellanicum* stems
2	16627	−23.99	43.1	225	30	37.5	AD 1776	*Sphagnum* stems
3	17511	−21.35	43.2	205	40	39.5	AD 1737	*Sphagnum* stems
4	17513	−20.54	43.5	215	40	41.5	AD 1699	*Sphagnum* stems
5	16598	−21.38	45.5	290	30	43.5	AD 1660	*S.* sect. *Cuspidata* leaves
6	16471	−20.74	46.3	240	50	44.5	AD 1640	*S.* sect. *Cuspidata* leaves
7	16596	−21.02	46	310	30	45.5	AD 1621	*Sphagnum* steps
8	12744	−23.58	46	270	70	46.5	AD 1601	*S. imbricatum*+*S. papillosum* branches+stems
9	16601	−25.48	46.1	345	30	47.5	AD 1582	*S. imbricatum* branches
10	16602	−24.96	46.4	335	30	48.5	AD 1563	*S. imbricatum* branches
11	16626	−26.85	45.2	325	35	49.5	AD 1543	*Sphagnum* stems+branches
12	16635	−26.01	45.8	410	40	52.5	AD 1485	*Sphagnum* stems
13	16636	−23.96	46.5	430	40	55.5	AD 1464	*S. imbricatum* branches
14	16637	−23.9	45.4	485	40	57.5	AD 1446	*S. imbricatum*
15	16472	−23.85	27.2	520	50	59.5	AD 1428	branches+stems
16	16639	−24.04	45	535	40	60.5	AD 1419	*S. imbricatum*
								branches+stems
								S. imbricatum branches

Table 2 Continued

Date (no.)	GrA-number	δ^{13}C (‰)	Carbon content (%)	^{14}C age (BP)	Laboratory standard deviation (BP)	Mid-point sample depth (cm)	Wiggle-match date	Sample composition (*S.* = *Sphagnum*)
17	17514	−23.67	46.2	575	40	61.5	AD 1410	*S. imbricatum* branches
18	17510	−23.14	46.3	650	40	63.5	AD 1392	*S. imbricatum* branches
19	16640	−20.51	46.4	730	40	65.5	AD 1374	*S. imbricatum* branches
20	16641	−26.22	45.8	280	40	69.5	AD 1338	*Sphagnum* stems+capsules
21	16634	−26.75	46.2	775	40	71.5	AD 1247	*Sphagnum* stems
22	12772	−26.07	47.1	770	70	73.5	AD 1231	*Sphagnum* stems
23	16644	−25.57	46.5	925	40	75.5	AD 1215	*S. imbricatum* branches
24	16645	−25.87	46.7	940	40	76.5	AD 1207	*S. imbricatum* branches
25	16646	−25.75	46.2	905	40	77.5	AD 1199	*S. imbricatum* branches
26	16473	−26.44	43.6	910	50	78.5	AD 1191	*S. imbricatum* branches
27	16647	−25.92	46.8	965	40	84.5	AD 1144	*S. imbricatum* branches
28	17515	−17.81	44.5	980	40	89.5	AD 1104	*S. imbricatum* branches
29	17509	−25.51	52	925	40	94.5	AD 1065	*S. imbricatum* branches
30	16649	−25.75	47.4	1020	40	99.5	AD 1025	*S. imbricatum* branches

References

Aaby, B. 1976: Cyclic climatic variations in climate over the past 5,500 years reflected in raised bogs. *Nature* 263, 281–84.

Barber, K.E. 1981: *Peat stratigraphy and climatic change: a palaeoecological test of the theory of cyclic peat bog regeneration.* Rotterdam: Balkema.

Barber, K.E., Chambers, F.M., Maddy, D., Stoneman, R. and **Brew, J.S.** 1994: A sensitive high-resolution record of late-Holocene climatic change from a raised bog in northern England. *The Holocene* 4, 198–205.

Barber, K.E., Dumayne-Peaty, L., Hughes, P.D.M., Mauquoy, D. and **Scaife, R.G.** 1998: Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria, England. *Journal of Quaternary Science* 13, 515–28.

Bard, E., Raisbeck, G.M., Yiou, F. and **Jouzel, J.** 1997: Solar modulation of cosmogenic nuclide production over the last millennium: comparison between ^{14}C and ^{10}Be records. *Earth and Planetary Science Letters* 150, 453–62.

Beer, J. 2000: Long-term indirect indices of solar variability. *Space Science Reviews* 94, 53–66.

Beer, J., Blinov A., Bonani, G., Finkel, R.C., Hofmann, H.J., Lehmann, B., Oeschger, H., Sigg, A., Schwander, J., Wander, J., Staffelbach, T., Stauffer, B., Suter, M. and **Wölfli, W.** 1990: Use of ^{10}Be in polar ice to trace the 11-year cycle of solar activity. *Nature* 347, 164–66.

Beer, J., Siegenthaler, U., Bonani, G., Finkel, R.C., Oeschger, H., Suter, M. and **Wölfli, W.** 1988: Information on past solar activity and geomagnetism from ^{10}Be in the Camp Century ice core. *Nature* 331, 675–79.

Cohen, T.J. and **Lintz, P.R.** 1974: Long term periodicities in the sunspot cycle. *Nature* 250, 398–99.

Crowley, C.J. and **Lowery, T.S.** 2000: How warm was the Medieval Warm Period? *Ambio* 29, 51–54.

Grove, J.M. 1988: *The Little Ice Age.* London: Routledge.

Hughes, P.D.M., Mauquoy, D., Barber, K.E. and **Langdon, P.G.** 2000: Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. *The Holocene* 10, 465–79.

Kilian, M.R., van der Plicht, J. and **van Geel, B.** 1995: Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* 14, 959–66.

Kilian, M.R., van Geel, B. and **van der Plicht, J.** 2000: ^{14}C AMS wiggle matching of raised bog deposits and models of peat accumulation. *Quaternary Science Reviews* 19, 1011–33.

Korhola, A., Weckström, J., Holmström, L. and **Erästö, P.** 2000: A quantitative Holocene climatic record from diatoms in northern Fennoscandia. *Quaternary Research* 54, 284–94.

Lean, J. and **Rind, D.** 1998: Climate forcing by changing solar radiation. *Journal of Climate* 11, 3069–94.

Lean, J., Beer, J. and **Bradley, R.** 1995: Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Research Letters* 22, 3195–98.

Leftus, V. 2000: Sunspot and auroral activity during Maunder Minimum. *Solar Physics* 197, 203–13.

Mauquoy, D. and **Barber, K.E.** 1999: A replicated 3000 yr proxy-climate record from Coom Rigg and Felecia Moss, the Border Mires, northern England. *Journal of Quaternary Science* 14, 263–75.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S. and **Whitlow, S.I.** 1995: Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* 270, 1962–64.

Ram, M., Stolz, M. and **Koenig, G.** 1997: Eleven year cycle of dust concentration variability observed in the dust profile of the GISP2 ice core from Central Greenland: Possible solar cycle connection. *Geophysical Research Letters* 24, 2359–62.

Speranza, A., van der Plicht, J. and **van Geel, B.** 2000: Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching. *Quaternary Science Reviews* 19, 1589–604.

Stuiver, M. and **Braziunas, T.F.** 1989: Atmospheric ^{14}C and century scale solar oscillations. *Nature* 338, 405–408.

—— 1993: Sun, ocean, climate and atmospheric $^{14}CO_2$: an evaluation of causal and spectral relationships. *The Holocene* 3, 289–305.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., van der Plicht, J. and **Spurk, M.** 1998: INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon* 40, 1041–83.

van der Plicht, J. 1993: The Groningen radiocarbon calibration program. *Radiocarbon* 35, 231–37.

van Geel, B. 1978: A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands, based on the analyses of pollen, spores and macro- and microscopic remains of fungi, algae, cormophytes and animals. *Review of Palaeobotany and Palynology* 25, 1–120.

van Geel, B. and **Mook, W.G.** 1989: High resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations. *Radiocarbon* 31, 151–55.

van Geel, B., Buurman, J. and **Waterbolk, H.T.** 1996: Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science* 11, 451–60.

van Geel, B., Raspopov, O.M., Renssen, H., van der Plicht, J., Dergachev, V.A. and **Meijer, H.A.J.** 1999: The role of solar forcing upon climate change. *Quaternary Science Reviews* 18, 331–38.

van Geel, B., van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M., Renssen, H., Reynaud-Farrera, I. and **Waterbolk, H.T.** 1998: The sharp rise of Δ^{14}C ca. 800 cal BC: Possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* 40, 535–50.

Wardenaar, E.C.P. 1987: A new handtool for cutting soil monoliths. *Canadian Journal of Soil Science* 67, 405–407.