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Two decadal resolved records from north-west European peat bogs show rapid climate changes associated with solar variability during the mid–late Holocene

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ABSTRACT: Two ¹⁴C accelerator mass spectrometry (AMS) wiggle-match dated peat sequences from Denmark and northern England record changes in mire surface wetness reconstructed using plant macrofossil and testate amoebae analyses. A number of significant mid–late Holocene climatic deteriorations (wet shifts) associated with declines in solar activity were recorded (at ca. 2150 cal. yr BC, 740 cal. yr BC, cal. yr AD 930, cal. yr AD 1020, cal. yr AD 1280–1300, cal. yr AD 1640 and cal. yr AD 1790–1830). The wet shifts identified from ca. cal. yr AD 930 are concurrent with or lag decreases in solar activity by 10–50 years. These changes are replicated by previous records from these and other sites in the region and the new records provide improved precision for the ages of these changes. The rapidly accumulating (up to 2–3 yr cm⁻¹, ~1310 yr old, 34 ¹⁴C dates) Danish profile offers an unprecedented high-resolution record of climate change from a peat bog, and has effectively recorded a number of significant but short-lived climate change events since ca. cal. yr AD 690. The longer time intervals between samples and the greater length of time resolved by each sample in the British site due to slower peat accumulation rates (up to 11 yr cm⁻¹, ~5250 yr old, 42 ¹⁴C dates) acted as a natural smoothing filter preventing the clear registration of some of the rapid climate change events. Not all the significant rises in water table registered in the peat bog archives of the British and Danish sites have been caused by solar forcing, and may be the result of other processes such as changes in other external forcing factors, the internal variability of the climate system or raised bog ecosystem. Copyright © 2008 John Wiley & Sons, Ltd.

KEYWORDS: climate change; *Sphagnum* mires; ¹⁴C wiggle-match dating; solar forcing; Holocene.

Introduction

In 1991, the problem of constructing accurate and precise calibrated ¹⁴C chronologies was highlighted by Baillie (1991). Even if it were published today, its message would be equally relevant, since inaccurate and imprecise ¹⁴C-based chronologies are often the Achilles heel of palaeoecological research. Inaccurate/imprecise and simplistic age–depth models (sometimes all three) frequently reduce the value of even the most detailed datasets. This problem has become the focus of attention in papers by Bennett and Fuller (2002), Telford *et al.*

(2004) and Heegaard *et al.* (2005), which address some of the problems in generating ¹⁴C-based age–depth models. ¹⁴C wiggle-match dating of sequences of uncalibrated radiocarbon dates (van Geel and Mook, 1989; Kilian *et al.*, 1995) circumvents the problem of ¹⁴C chronologies based on a limited number of calibrated dates and can offer decadal precision (Blaauw *et al.*, 2007; Yeloff *et al.*, 2006). High-precision timescales are necessary to resolve the nature of regional climate change and its timing (Charman *et al.*, 2006; Kaplan and Wolfe, 2006), in addition to potential intra/interhemispheric leads and lags as a response to climate change (van Geel *et al.*, 2000). Investigating the role of changing solar activity driving Holocene climate change is increasingly becoming the focus of palaeoclimate research (Bard and Frank, 2006; Mauquoy *et al.*, 2004). Detecting evidence for a possible sun/climate relationship is highly dependent on

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precisely dated profiles, in peat (van Geel *et al.*, 1998; Blaauw *et al.*, 2004; Mauquoy *et al.*, 2004), lake (Hu *et al.*, 2003; Magny, 2004) and speleothem deposits (Wang *et al.*, 2005). In this paper we report peat bog proxy climate data from Butterburn Flow, UK, and Lille Vildmose, Denmark, with ^{14}C chronologies generated using the latest generation of ^{14}C age–depth models (Blaauw and Christen, 2005), with two aims: (1) to study regional north-west European climate change and test for evidence of solar forcing; (2) to test the replicability of the peat bog archive record from the two sites which have been subject to previous research and dated using ^{14}C wiggle-matching (Mauquoy *et al.*, 2002a,b) and less precise ^{14}C calibration of bulk dates (Hendon *et al.*, 2001) and tuning approaches (Charman *et al.*, 2006). The tuning approach adopted by Charman *et al.* (2006) calculates an ‘average’ age for key periods of hydrological change registered in multiple peat bog records within a region, in this case northern Britain. Replication of regional climate reconstructions are important given the potential for internal variability within rain-fed peat bogs (Belyea and Malmer, 2004; Couwenberg and Joosten, 2005).

Methods

Fieldwork

Site descriptions for Lille Vildmose (a lowland raised peat bog in north-east Jutland, Denmark) and Butterburn Flow (an intermediate ombrotrophic bog in northern England, both shown in Fig. 1) are available in Mauquoy *et al.* (2002b) and Hendon *et al.* (2001), respectively. For both sites a 1 m Wardenaar corer (Wardenaar, 1987) was used to recover peat samples from the surface of the bog to 1 m depth, overlapping with a Russian corer (7 cm $\times$ 50 cm) for the depth intervals 1 to 3 m (Lille Vildmose) and 1–4 m depth (Butterburn Flow). Coring sites for each of the peat bogs were chosen by first establishing the depth and nature of the peat stratigraphy by sinking a series of six test boreholes on two intersecting transects (see the sampling protocols detailed in Barber *et al.*, 1998). The co-ordinates for the DK and GB cores are $56^{\circ} 50' 89'' \text{ N}$, $10^{\circ} 11' 03'' \text{ E}$ and $55^{\circ} 05' 19'' \text{ N}$, $02^{\circ} 30' 31'' \text{ W}$, respectively.

Laboratory work

Contiguous 1 cm subsamples were taken from each peat monolith. Samples for dating by ^{14}C accelerator mass spectrometry (AMS) were cleaned to remove roots of Ericaceae, Cyperaceae, fungal mycelium and charcoal fragments, transferred to a Petri dish containing deionised water and then pretreated for radiocarbon analysis (Speranza *et al.*, 2000). An open-ended metal tube of 2.6 cm diameter was pressed into each 1 cm thick slice for the selection of plant macrofossil samples. Plant macrofossil samples were boiled with 5% KOH and sieved (mesh diameter 125 μm). Macrofossils were scanned using a binocular microscope ($\times 10$ – $\times 50$), and identified using an extensive reference collection of type material (Mauquoy and van Geel, 2007). Volume percentages were estimated for all components with the exception of seeds, *Eriophorum vaginatum* spindles, *Sphagnum* spore capsules, *Cenococcum sclerotia*, *Meliola ellisii* (Type 14) fruit-bodies and charcoal particles, which were counted and expressed as the number (*n*) present in each subsample. Zonation of the macrofossil diagrams was made using psimpoll 4.25 (optimal

Figure 1 Site locations: (a) Butterburn Flow (GB) and Lille Vildmose (DK); (b) position of the coring site on Butterburn Flow (located at X); (c) Lille Vildmose showing position of the coring site (located at X)

Table 1 DK ^{14}C AMS

Sample composition notes	Depth (cm)	$\delta^{13}\text{C}$ (‰)	Age BP	Sample code	Bpeat wiggle-match date, 2 sections, rounded to the nearest decade
<i>Sphagnum</i> stems	35.5	-25.31	100 ± 40	GrA-28770	cal. yr AD 1760
<i>Sphagnum magellanicum</i> stems, leaves and branches	37.5	-23.81	160 ± 35	GrA-28772	cal. yr AD 1740
<i>Sphagnum</i> section <i>Cuspidata</i> leaves and stems	39.5	-23.12	115 ± 35	GrA-25948	cal. yr AD 1720
<i>Sphagnum</i> stems	41.5	-22.43	155 ± 35	GrA-28773	cal. yr AD 1710
<i>Sphagnum</i> stems	43.5	-24.38	155 ± 35	GrA-28893	cal. yr AD 1690
<i>Andromeda polifolia</i> leaves, <i>Rhynchospora alba</i> seeds and <i>Sphagnum</i> stems	45.5	-25.34	220 ± 50	GrA-27663	cal. yr AD 1670
<i>Sphagnum</i> section <i>Acutifolia</i> leaves	53.5	-24.25	375 ± 35	GrA-28894	cal. yr AD 1600
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	57.5	-25.17	305 ± 35	GrA-25500	cal. yr AD 1560
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	61.5	-25.69	325 ± 30	GrA-28896	cal. yr AD 1520
<i>Sphagnum</i> section <i>Acutifolia</i> leaves	63.5	-25.6	325 ± 35	GrA-28897	cal. yr AD 1500
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	65.5	-26.3	455 ± 35	GrA-27521	cal. yr AD 1490
<i>Sphagnum</i> section <i>Acutifolia</i> leaves, branches and stems	71.5	-27.54	440 ± 60	GrA-28842	cal. yr AD 1430
<i>Sphagnum</i> section <i>Acutifolia</i> leaves, branches and stems	73.5	-27.48	620 ± 35	GrA-28898	cal. yr AD 1410
<i>Sphagnum</i> section <i>Acutifolia</i> leaves	77.5	-26.73	610 ± 35	GrA-28901	cal. yr AD 1380
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	79.5	-25.23	630 ± 35	GrA-27522	cal. yr AD 1360
<i>Sphagnum</i> section <i>Acutifolia</i> leaves, branches and stems	87.5	-24.34	640 ± 35	GrA-28902	cal. yr AD 1280
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	95.5	-24.26	780 ± 50	GrA-27664	cal. yr AD 1250
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	109.5	-24.41	850 ± 50	GrA-27666	cal. yr AD 1210
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	123.5	-26.32	850 ± 50	GrA-27667	cal. yr AD 1170
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	141.5	-26.52	920 ± 50	GrA-27668	cal. yr AD 1120
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	155.5	-24.97	790 ± 50	GrA-27671	cal. yr AD 1080
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	159.5	-25.86	905 ± 35	GrA-25501	cal. yr AD 1070
<i>Sphagnum</i> section <i>Acutifolia</i> leaves, branches and stems	169.5	-25.71	890 ± 60	GrA-27672	cal. yr AD 1040
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	177.5	-25.81	1015 ± 35	GrA-28903	cal. yr AD 1020
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	185.5	-25.29	1085 ± 40	GrA-27524	cal. yr AD 1000
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	199.5	-24.77	1165 ± 35	GrA-27526	cal. yr AD 960
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	215.5	-26.9	1150 ± 35	GrA-27528	cal. yr AD 920
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	229.5	-26.25	1185 ± 35	GrA-27523	cal. yr AD 880
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	245.5	-25.06	1165 ± 35	GrA-27529	cal. yr AD 830
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	259.5	-27.11	1280 ± 50	GrA-27673	cal. yr AD 795
<i>Sphagnum</i> section <i>Acutifolia</i> leaves, branches and stems	263.5	-26.78	1170 ± 35	GrA-28904	cal. yr AD 780
<i>Sphagnum</i> stems	273.5	-27.32	1215 ± 35	GrA-28906	cal. yr AD 760
<i>Sphagnum</i> section <i>Acutifolia</i> leaves and stems	281.5	-26.19	1175 ± 35	GrA-25502	cal. yr AD 730
<i>Sphagnum</i> section <i>Cuspidata</i> leaves and stems	299.5	-25.92	1265 ± 35	GrA-25505	cal. yr AD 690

splitting by information content). Testate amoebae samples were processed using standard techniques (Hendon and Charman, 1997), except that safaranin stain was not used and samples were counted in water rather than glycerol as this provided better visibility of some features. Counts were all in excess of 150 tests and identifications were made using the criteria in Charman *et al.* (2000). Sample resolution for the testate amoebae analyses varied and was generally lower than for plant macrofossils, especially for the GB site. This was due to the longer count times required for these analyses, especially in Butterburn Flow, where concentrations were very low.

Higher-resolution sampling and dating were concentrated on three 'focus intervals': (I) 2550–2050 cal. yr BC; (II) 1000–500 cal. yr BC; (III) cal. yr AD 800–1800. These time periods formed part of the climate change focus intervals for the ACCROTELM project ('Abrupt Climate Change Recorded Over The European Land Mass', www.glos.ac.uk/accrotelm), since wet shift dates from European raised and blanket peat bogs have been frequently registered during these time intervals (e.g. Barber *et al.*, 2003).

Data transformation and statistical analyses

The ^{14}C ages of the samples have been converted to calendar years using the program Bpeat for ^{14}C wiggle-match dating (Blaauw and Christen, 2005). Full details of the DK and GB

^{14}C wiggle-match dating procedure and a comparison with age/depth models generated using Bcal Bayesian calibration are presented in Yeloff *et al.* (2006). Both DCA and PCA ordinations failed to detect the presence of a mire surface wetness gradient in the plant macrofossil data from both the GB and the DK peat profiles; therefore Dupont's indices (Dupont, 1986) were applied to the plant macrofossil data to provide a qualitative indication of changes in water table. The indices used were: *Aulacomnium palustre* 8, *Polytrichum* spp. 8, Ericales rootlets 8, *Calluna vulgaris* macrofossils 8, *Erica tetralix* macrofossils 8, Ericaceae wood undifferentiated 8, monocots undifferentiated 6, *Eriophorum vaginatum* macrofossils 6, *Sphagnum imbricatum* 5, *Sphagnum* section *Acutifolia* 4, *Sphagnum magellanicum* 4, *Sphagnum papillosum* 3, *Andromeda polifolia* leaves 3, *Oxycoccus palustris* leaves 3, *Oxycoccus palustris* stems 3, *Eriophorum angustifolium* epidermis 2, *Rhynchospora alba* epidermis 2, *Sphagnum tenellum* 2, *Sphagnum* section *Cuspidata* 1, *Sphagnum cuspidatum* 1. Quantitative reconstruction of water table at both sites was conducted by applying a European-wide testate amoebae transfer function (full details given in Charman *et al.*, 2007). Solar activity changes are indicated by estimates of past ^{14}C production, derived from a Siegenthaler–Oeschger box diffusion carbon cycle model (Jürg Beer and Raimund Muscheler, pers. comm.). For comparison of climate and solar proxies, data were normalised by expressing values as the difference from the mean, measured in standard deviations.

Results and interpretation

¹⁴C Chronology

AMS radiocarbon dates of 34 samples for Lille Vildmose (site code DK) and 42 samples for the Butterburn Flow site (site code GB) are presented in Tables 1 and 2, respectively. The results of ¹⁴C wiggle-match dating using the Bpeat program for the DK and GB sites are presented in Fig. 2. The percentage of determinations used by the model is expressed as the *F* statistic (Blaauw and Christen, 2005). For the DK and GB sites, these values of *F* are 99% and 85%, which suggests a good fit of the dates to the INTCAL04 calibration curve (Reimer *et al.*, 2004). One outlier sample was identified in the DK site (GrA-27671, 155.5 cm) and two outliers were identified in the GB site (samples GrA-28276, 226.5 cm, and GrA-28272, 220.5 cm); these were statistically downweighted. The two section age/depth model for the 3 m DK peat profile shows accumulation rate values of ca. 2–3 yr cm⁻¹ between ca. cal. yr AD 690 and 1270, followed by a period of lower accumulation of ca.

9–10 yr cm⁻¹ between ca. cal. yr AD 1270 and 1760 (the top of the wiggle-match model). The three section age/depth model for the 4 m GB profile records lower values, which vary from ca. 14–15 yr cm⁻¹ between ca. cal. 3230 and 190 BC, then slow down to ca. 19–20 yr cm⁻¹ between ca. cal. yr 170 BC and ca. cal. yr AD 410, before increasing again to ca. 11–12 yr cm⁻¹ between ca. cal. yr AD 420 and 1910. All dates quoted are the *maximum a posteriori* estimate. Chronological precision of the date is indicated by the 95% confidence intervals shown in Fig. 2. As no ¹⁴C wiggle-match age estimate is exact, all ages are rounded to the nearest decade. Comparison of the Bpeat wiggle-match age models featured in this paper with BCal calibrated dates by Yeloff *et al.* (2006) suggests that outside of the intervals of closely spaced ¹⁴C dates (particularly the focus intervals), accuracy and precision of the Bpeat models will be relatively poor; and the apparently high chronological precision (as shown by the 95% confidence intervals in Fig. 2) is most likely spurious. Dates younger than the range of the ¹⁴C wiggle-match models are based on linear interpolation between the most recent age estimate of the wiggle-match age model and the oldest age estimate from an age model based on

Table 2 GB ¹⁴C AMS

Sample composition notes	Depth (cm)	δ ¹³ C (‰)	Age BP	Sample code	Bpeat wiggle-match date, 3 sections, rounded to the nearest decade
<i>Sphagnum</i> stems	19.5	-28.54	100 ± 40	GrA-29858	cal. yr AD 1910
<i>Sphagnum magellanicum</i> stems, leaves and branches	24.5	-27.22	220 ± 35	GrA-29896	cal. yr AD 1850
<i>Sphagnum magellanicum</i> leaves and stems	31.5	-24.33	170 ± 30	GrA-28659	cal. yr AD 1780
<i>Sphagnum magellanicum</i> leaves	33.5	-26.74	130 ± 30	GrA-28660	cal. yr AD 1750
<i>Sphagnum magellanicum</i> stems	41.5	-26.04	220 ± 30	GrA-28662	cal. yr AD 1660
<i>Sphagnum magellanicum</i> stems	43.5	-22.86	235 ± 35	GrA-28680	cal. yr AD 1640
<i>Sphagnum magellanicum</i> leaves	49.5	-24.99	305 ± 35	GrA-28681	cal. yr AD 1570
<i>Sphagnum magellanicum</i> leaves	53.5	-26.41	260 ± 35	GrA-28682	cal. yr AD 1530
<i>Sphagnum</i> stems	59.5	-29.07	485 ± 35	GrA-26857	cal. yr AD 1460
<i>Sphagnum</i> stems and charred <i>Calluna vulgaris</i> leaves	61.5	-27.98	710 ± 40	GrA-26858	cal. yr AD 1440
<i>Sphagnum magellanicum</i> and <i>S. section Acutifolia</i> leaves	63.5	-26.51	455 ± 30	GrA-26814	cal. yr AD 1420
<i>Sphagnum</i> stems	67.5	-28.02	735 ± 40	GrA-26859	cal. yr AD 1370
<i>Sphagnum magellanicum</i> leaves and stems	69.5	-25.14	505 ± 40	GrA-24777	cal. yr AD 1350
<i>Sphagnum imbricatum</i> stems, leaves and branches	75.5	-28.13	920 ± 35	GrA-26860	cal. yr AD 1280
<i>Sphagnum imbricatum</i> stems, leaves and branches	77.5	-28.35	860 ± 35	GrA-26815	cal. yr AD 1260
<i>Sphagnum imbricatum</i> stems, leaves and branches	79.5	-25.59	1080 ± 60	GrA-26862	cal. yr AD 1240
<i>Sphagnum imbricatum</i> stems and leaves	91.5	-27.82	830 ± 35	GrA-26883	cal. yr AD 1110
<i>Sphagnum imbricatum</i> stems and leaves + <i>S. s. Acutifolia</i> leaves	107.5	-25.99	1140 ± 40	GrA-24778	cal. yr AD 930
<i>Sphagnum tenellum</i> leaves, stems and <i>Calluna</i> leaves/stems	127.5	-26.67	1270 ± 45	GrA-24779	cal. yr AD 700
Charred <i>Calluna vulgaris</i> and charcoal fragments	158.5	-28.76	1715 ± 35	GrA-29922	cal. yr AD 310
Charred <i>Calluna vulgaris</i> and charcoal fragments	161.5	-25.82	1770 ± 35	GrA-29924	cal. yr AD 250
<i>Sphagnum imbricatum</i> stems and leaves, charred <i>Calluna vulgaris</i>	167.5	-25.36	1860 ± 35	GrA-28685	cal. yr AD 130
Charred <i>Calluna vulgaris</i> and charcoal fragments	177.5	-26.13	2070 ± 40	GrA-29921	cal. yr 70 BC
<i>Sphagnum section Acutifolia</i> leaves	182.5	-25.47	2210 ± 40	GrA-29925	cal. yr 170 BC
<i>Sphagnum imbricatum</i> leaves	187.5	-24.49	2300 ± 35	GrA-26816	cal. yr 240 BC
<i>Sphagnum section Acutifolia</i> leaves	192.5	-25.86	2215 ± 35	GrA-29926	cal. yr 300 BC
<i>Sphagnum imbricatum</i> stems, leaves and branches	203.5	-26.64	2410 ± 40	GrA-28686	cal. yr 470 BC
<i>Sphagnum imbricatum</i> stems and leaves	205.5	-27.10	2395 ± 40	GrA-28687	cal. yr 500 BC
<i>Sphagnum imbricatum</i> stems and leaves	209.5	-26.33	2375 ± 45	GrA-24782	cal. yr 550 BC
<i>Sphagnum imbricatum</i> leaves and <i>Calluna vulgaris</i> leaves	220.5	-27.20	1390 ± 40	GrA-28272	cal. yr 710 BC
Charred <i>Erica tetralix</i> leaves	226.5	-25.90	3050 ± 60	GrA-28276	cal. yr 790 BC
<i>Sphagnum section Acutifolia</i> leaves	228.5	-27.25	2690 ± 35	GrA-28690	cal. yr 820 BC
<i>Sphagnum papillosum</i> branches, stems and leaves	271.5	-26.68	3105 ± 45	GrA-24783	cal. yr 1430 BC
Charred <i>Calluna vulgaris</i> stems and leaves	301.5	-23.58	3435 ± 40	GrA-28691	cal. yr 1850 BC
<i>Sphagnum</i> stems and charred <i>Calluna vulgaris</i> leaves	312.5	-28.27	3790 ± 45	GrA-26863	cal. yr 2000 BC
<i>Sphagnum</i> stems, <i>Calluna vulgaris</i> stems and leaves	318.5	-26.63	3575 ± 40	GrA-28692	cal. yr 2090 BC
<i>Sphagnum section Acutifolia</i> leaves	322.5	-27.10	3740 ± 40	GrA-28693	cal. yr 2150 BC
Charred <i>Calluna vulgaris</i> leaves/stems	330.5	-29.30	3870 ± 45	GrA-28278	cal. yr 2260 BC
<i>Sphagnum</i> stems, sporangia and <i>Calluna vulgaris</i> stems	340.5	-27.50	3960 ± 60	GrA-28279	cal. yr 2400 BC
Charred <i>Calluna vulgaris</i> leaves/stems and flowers	345.5	-28.00	3945 ± 45	GrA-28269	cal. yr 2470 BC
Charred <i>Calluna vulgaris</i> leaves/stems and flowers	369.5	-28.97	4370 ± 80	GrA-28832	cal. yr 2810 BC
<i>Sphagnum section Cuspidata</i> leaves and stems	399.5	-25.26	4495 ± 45	GrA-24784	cal. yr 3230 BC

Figure 2 Chronology of Butterburn Flow (GB) and Lille Vildmose (DK) sites: (a) The *maximum a posteriori* fit of ^{14}C dates to the Intcal04 calibration curve (Reimer *et al.*, 2004) by Bpeat; (b) age–depth model based on the Bpeat wiggle-match; dark solid line indicates the *maximum a posteriori* estimate; grey bars indicate 95% confidence interval. Dashed lines indicate boundaries of focus intervals (numbered with roman numerals)

^{14}C ‘bomb peak’ dates (unpublished data). For the GB core, the youngest age of the Bpeat wiggle-match model is ca. cal. yr AD 1910 (19 cm), and the oldest date of the ^{14}C ‘bomb peak’ model is ca. cal. yr AD 1955 (17 cm). For the DK core, the youngest age of the Bpeat wiggle-match model is ca. cal. yr AD 1760 (35 cm), and the oldest date of the ^{14}C ‘bomb peak’ model is ca. cal. yr AD 1963 (21 cm).

Plant macrofossils and testate amoebae

The three major macrofossil components in the DK peat profile (Fig. 3, Table 3) are *Sphagnum* section *Acutifolia* leaves,

Eriophorum vaginatum epidermis and *Sphagnum magellanicum*. Leaves of *Sphagnum* section *Acutifolia* comprise the bulk of the peat profile, especially in zones DKM2–DKM4. Periods of high mire surface wetness are detectable using the macrofossil data in zones DKM1, 2, 4, 5 and 6 given the presence of *Sphagnum* section *Cuspidata*, *Sphagnum cuspidatum* and *S. tenellum* leaves. The accumulation rates of the 3 m DK peak profile (basal date, ca. cal. yr AD 690) are high, with values up to 2–3 yr cm⁻¹ between ca. cal. yr AD 690 and 1270. Given the number of dates used to construct the age/depth model and the good wiggle-match fit, this rapid accumulation is highly likely to have occurred. The peat stratigraphy largely comprises *Sphagnum* section *Acutifolia* leaves, especially in zones DKM2 and DKM4 (Fig. 3, 222 cm of

Figure 3 DK macrofossil diagram. Zonations made using information content in psimpoll 4.25

Table 3 Macrofossil zonation for the DK core

Macrofossil zone	Depth (cm)	Main features
DKM6	39–2	Abundant <i>Sphagnum magellanicum</i> interspersed with a peak of <i>Sphagnum</i> section <i>Cuspidata</i> leaves at 28 cm. High values of <i>Ericales</i> rootlets (up to 15%) at 16 cm
DKM5	53–39	High values of <i>Eriophorum vaginatum</i> are succeeded by abundant <i>Sphagnum</i> section <i>Cuspidata</i> leaves. Some <i>Sphagnum tenellum</i> leaves (up to 10%). Increase of <i>Sphagnum magellanicum</i> leaves (up to 5%)
DKM4	161–53	Abundant <i>Sphagnum</i> section <i>Acutifolia</i> leaves throughout. Sporadic charcoal. <i>Sphagnum</i> section <i>Cuspidata</i> leaves and <i>Sphagnum tenellum</i> leaves present between 68–54 cm. High values of <i>Ericales</i> rootlets at 156–154, 136 and 76 cm
DKM3	171–161	<i>Eriophorum vaginatum</i> alternates with <i>Sphagnum</i> section <i>Acutifolia</i> leaves. Peak of <i>Ericales</i> rootlets at 168 cm
DKM2	285–171	Abundant <i>Sphagnum</i> section <i>Acutifolia</i> leaves throughout. Sporadic charcoal. Four peaks of <i>Ericales</i> rootlets at 272, 248, 240 and 214 cm
DKM1	300–285	High <i>Sphagnum</i> section <i>Cuspidata</i> leaves at the base of the profile, followed by abundant <i>Eriophorum vaginatum</i> and <i>Sphagnum</i> section <i>Acutifolia</i> leaves

the entire profile depth). The predominance of these mosses may partly explain the rapid accumulation of the deposit, since these mosses are more decay resistant than those in *Sphagnum* section *Cuspidata* (Johnson and Damman, 1991). The latter only consistently occur in abundance in zone DKM5.

The considerably older GB peat profile (basal date, ca. 3230 cal. yr BC) is predominantly composed of monocots undifferentiated, *Eriophorum vaginatum* epidermis, *Sphagnum imbricatum*, *S. magellanicum* and *S. papillosum* (Fig. 4, Table 4). Periods of higher mire surface wetness are apparent in macrofossil zones GBM1, GBM3, GBM8 and GBM10, due to the increased presence of *Sphagnum* section *Cuspidata* leaves. The GB site differs from the DK peat sequence, in that multiple peat surface fires are recorded (charred leaves/stems of *Calluna vulgaris* were frequently identified). Frequent burning events were detected throughout the profile, particularly in zones GBM5 and GBM7 at ca. cal. yr 1140–580 BC and ca. cal. yr 150 BC–AD 660. Generally low values of *Sphagnum* mosses were recorded in these zones in addition to high values of *Ericales* rootlets. Some of the charcoal registered in the GB peat profile may have originated from fires started on the dry soils surrounding the bog by Bronze and Iron Age farmers, since changes in the regional pollen spectra from Butterburn Flow indicate increased agricultural activity during the intervals ca. cal. yr 1020–790 BC and ca. cal. yr 300 BC to cal. yr AD 50 (Yeloff *et al.*, 2007), although there is also the possibility that natural ignition was responsible (lightning strikes). It has been shown that burning, in combination with recent climate change and drainage, has caused marked reductions in water table depth in Canadian peatlands (Pellerin and Lavoie, 2003). Conversely, charcoal fragments have also been found together with mosses, which indicate high mire surface wetness (*Sphagnum balticum*) in an Estonian peat bog core (Sillasoo *et al.*, 2007). Disturbance by burning of the local peat-forming vegetation may have caused changes in mire surface wetness, potentially masking any changes in mire hydrology caused by increases in effective precipitation. Given this, the palaeoclimate indicator value of the GB peat profile may be compromised when frequent peat bog fires occurred (ca. cal. yr 1140–580 BC and ca. cal. yr 150 BC to ca. cal. yr AD 660, Fig. 4).

Both profiles record high abundances of *Sphagnum magellanicum* within the upper metre of each peat deposit. In the DK site this occurs across the zone DKM4/5 boundary and is dated to ca. cal. yr AD 1600. The replacement of abundant *Sphagnum imbricatum* by *S. magellanicum* in the GB peat core occurs earlier, at ca. cal. yr AD 1310 (72 cm) (zone GBM9/10 boundary). The local extinction of the former species and the

appearance of abundant *Sphagnum magellanicum* at Butterburn Flow are discussed in detail by McClymont *et al.* (submitted), and may be related to nutrient enrichment resulting from agricultural intensification on the farmland adjacent to the site.

The testate amoebae assemblages of the DK profile (Fig. 5, Table 5) record more variability than the macrofossils with alternations of the three principal taxa: *Arcella discoides* type, *Amphitrema flavum* and *Nebela militaris*; these taxa record periods of relatively high, intermediate and lower local water table depths, respectively (Charman *et al.*, 2007). The three major testate amoebae taxa in the GB profile (Fig. 6, Table 6) are *Arcella discoides* type, *Amphitrema flavum* and *Hyalosphenia subflava*, with a major change recorded from *Hyalosphenia subflava* abundance to *Arcella discoides* type at the zone GBT2–GBT3 boundary. This indicates a change from low local water tables to high local water table depths. The testate amoebae water table reconstructions (Figs 5 and 6) are based on a European training set of surface samples from eight peat bogs (Charman *et al.*, 2007), which has resolved some of the problems of no-analogues in previous training datasets (Blundell and Barber, 2005). Knowledge regarding the ecology of the testate amoebae species *Diffugia pulex* has been considerably improved by the findings of Charman *et al.* (2007), where it occurs at intermediate water table depths and slightly drier (moisture) positions in the hydrological gradient from hummock to hollow microforms. This type was previously only identified in fossil samples and was not present in surface samples used to create earlier testate amoebae transfer functions (Woodland *et al.*, 1998). Modern analogues in the new European-wide dataset have also confirmed *Hyalosphenia subflava* as a good indicator of low mire surface wetness and moisture levels. The testate amoebae water table reconstructions presented here therefore offer refined quantitative estimates of changes in mire surface wetness through time. Despite this, changes in mire surface wetness identified using the testate amoebae do not always match the macrofossil data. This may be partially explained by the low resolution of the testate amoebae record in some segments of both cores, particularly outside of the focus intervals (Figs 5 and 6).

The dominance of monocotyledonous remains, *Sphagnum imbricatum* (see Mauquoy and Barber, 1999, for a review of the palaeoecology of this species) and *Eriophorum vaginatum* epidermis in the GB profile prevent the identification of clear increases in mire surface wetness using the macrofossil data alone. Hammond *et al.* (1990) found that *Eriophorum vaginatum* occurs over a water table depth range spanning 0 to 28 cm in two Irish raised peat bogs, which demonstrates its

Table 4 Macrofossil zonation for the GB core

Macrofossil zone	Depth (cm)	Main features
GBM11	19–2	Abundant <i>Sphagnum papillosum</i> , zero charcoal fragments
GBM10	73–19	Leaves of <i>Sphagnum imbricatum</i> disappear and are replaced by abundant <i>Sphagnum magellanicum</i> . Two small peaks (c. 10–17%) of <i>Sphagnum</i> section <i>Cuspidata</i> occur between 68–66 cm and 56–54 cm. Three peaks of <i>Eriophorum vaginatum</i> occur between 52–48 cm, 42–40 cm and 32–28 cm. Decrease in charcoal fragments between 54–20 cm
GBM9	109–73	Decrease in Ericales rootlets. Abundant <i>Sphagnum imbricatum</i> leaves alternate with <i>Sphagnum</i> section <i>Acutifolia</i> leaves between 100–94 cm. Charcoal fragments consistently present
GBM8	131–109	Two peaks of Ericales rootlets occur between 130–128 cm and 120–112 cm. High values of <i>Sphagnum tenellum</i> and <i>Sphagnum</i> section <i>Cuspidata</i> between 128 and 122 cm are followed by abundant values of <i>Sphagnum</i> section <i>Acutifolia</i> leaves. Marked reduction of charcoal fragments
GBM7	181–131	High values of Ericales rootlets (c. 10–25%) between 168 and 154 cm. Abundant monocots undifferentiated throughout, except at 170–168 cm and 136 cm, where relatively high values of <i>Sphagnum imbricatum</i> leaves occur (c. 71–79%). Charcoal consistently present, with high values recorded between 178–172 cm
GBM6	211–181	Decrease in Ericales rootlets with abundant <i>Sphagnum imbricatum</i> leaves. Decrease in charcoal fragments
GBM5	251–211	Increase in Ericales rootlets with the highest value of c. 30% recorded at 240 cm. A second high value of Ericales rootlets (~25%) occurs at 214 cm. Marked decline in <i>Sphagnum</i> with abundant monocots undifferentiated. High numbers of charcoal fragments are frequently recorded between 246 and 230 cm
GBM4	275–251	Less Ericales rootlets and abundant <i>Sphagnum imbricatum</i> leaves preceded by a short interval (274–272 cm) with abundant <i>Sphagnum papillosum</i> . Charcoal fragments fluctuate, with relatively high numbers at 260 and 252 cm
GBM3	343–275	Overall increase in Ericales rootlets, with relatively high values of ~15% between 330 and 326 cm, ~10–25% between 304 and 292 cm and ~10–20% between 286 and 280 cm. Relatively high unidentifiable organic material (up to ~30%) between 290 and 284 cm. Monocots undifferentiated are the dominant peat component and alternate with <i>Sphagnum</i> section <i>Acutifolia</i> . Increased charcoal present
GBM2	371–343	Increase in Ericales rootlets. Abundant <i>Sphagnum</i> section <i>Acutifolia</i> leaves, with two bands of high <i>Eriophorum vaginatum</i> epidermis at 360 and 348 cm. Some charcoal fragments present
GBM1	400–371	High values of <i>Eriophorum vaginatum</i> epidermis (up to ~82%) alternate with high values of <i>Sphagnum</i> section <i>Acutifolia</i> and <i>Sphagnum</i> section <i>Cuspidata</i> leaves (peak values of ~55% and 51% respectively)

wide tolerance to water table depth. Økland (1990) also concluded that it was 'ubiquitous and omnipresent', although it was less common in carpets and low lawn microforms of the Kisselbergmosen mire complex in southeastern Norway. The presence of taxa with broad hydrological ranges such as *S. imbricatum* and *E. vaginatum*, considered together with the influence of fire and nutrient enrichment on the vegetation composition of the GB site, suggests plant macrofossils have a very limited potential to track past mire surface wetness changes on Butterburn Flow, and are not considered further.

The local vegetation composition of the DK site was dominated by *S. section Acutifolia* from 292 cm to 54 cm depth (ca. cal. yr AD 710 to cal. yr AD 1600). The plant macrofossil record (Dupont index) was therefore not sensitive to changes in water table up to this point, and the testate amoebae water table reconstruction is only considered up to ca. cal. yr AD 1600. Above 54 cm, testate amoebae counts have low resolution, and the higher-resolution macrofossil record shows evidence of significant changes in mire surface wetness – in particular, transitions between *S. section Acutifolia*, *S. cuspidatum*, *S. tenellum* and *S. magellanicum* (Fig. 3).

Discussion: evidence for solar forcing of north-west European climate during the mid-late Holocene

Figure 7 compares normalised reconstructions of mire surface wetness at the GB and DK sites with regional climate proxies, including the record of North Atlantic drift ice from Bond *et al.*

(2001), and lake level changes in mid Europe (Magny, 2004). These regional proxies both point to a strong link between past climate variability and solar activity. However, the chronologies of these regional studies are imprecise, as the Bond *et al.* (2001) ice-raft record is based on calibrated ^{14}C dates (with 2σ errors typically between ± 100 and ± 150 yr), and the Magny (2004) lake level reconstruction is a regional synthesis with a time resolution deliberately restricted to 50 yr. Comparison with solar minima lasting a few decades such as the Oort, Wolf, Spörer, Maunder and Dalton minima of the last millennium is therefore difficult. The combination of precise wiggle-matched ^{14}C chronologies with high-resolution climate records in our study offers the opportunity to evaluate the relationship between past climate change and solar activity at decadal timescales. This is particularly so for the focus intervals I, II, III, where ^{14}C dates and testate amoebae counts are most concentrated. Figures 8–12 show in detail solar activity and local hydrological changes interpreted as climate variability. Figures 8 and 9 are the hydrological changes identified for the GB site during focus intervals I and II, respectively. Figure 10 is the DK focus interval III results, while Fig. 11 focuses on the time period cal. AD 1000–1200 for the DK site. Figure 12 records hydrological changes for the GB site during focus interval III.

In Figs 8–12, changes of water table or Dupont index >2 SD units, and covering >2 samples, are regarded as significant. Focus intervals I and II were not recorded in the DK core owing to its young age. In the GB core, focus interval I (2550–2050 cal. yr BC) showed relatively little variability in water table, except for a moderate change at 2150 cal. BC of a little less than 2 SD units (Fig. 8). More distinct shifts have been recorded at a range of sites in other areas of north-west Europe, including the north of England (Hughes *et al.*, 2000; Barber *et al.*, 2003). Although data are fewer for this period, the

Figure 5 DK testate amoebae diagram. All counts exceed 150 tests. Reconstructed water table is shown on the right side of the diagram. Error bars show estimated errors of prediction based on bootstrapping (Charman *et al.*, 2007)

Table 5 Testate amoebae zonation for the DK core

Macrofossil zone	Depth (cm)	Main features
DKT9	16–3	Decrease of <i>Arcella discoides</i> type and <i>Euglypha tuberculata</i> . Increased abundances of <i>Corythion/Trinema</i> type, <i>Euglypha ciliata/strigosa</i> , <i>Hyalosphenia papilio</i> and <i>Nebela griseola</i>
DKT8	34.5–16	High values of <i>Arcella discoides</i> type (~44–58%) between 34 and 27 cm. Increase in <i>Assulina muscorum</i> between 25 and 22 cm. Relatively high values of <i>Euglypha tuberculata</i> and <i>Heleopera petricola</i> throughout the zone. Increase in <i>Heleopera sylvatica</i> between 25 and 17 cm. Relatively high species abundance
DKT7	68.5–34.5	Initial increases in <i>Amphitrema flavum</i> , <i>Assulina muscorum/seminulum</i> and a decrease in <i>Arcella discoides</i> type between 67 and 55 cm. Between 55 and 35 cm, as <i>Arcella discoides</i> type increases in abundance and both <i>Assulina muscorum/seminulum</i> record lower values
DKT6	86–68.5	Decrease in <i>Amphitrema flavum</i> and a large increase in <i>Arcella discoides</i> type, which forms the dominant taxon
DKT5	121–86	Large increase in <i>Amphitrema flavum</i> , which is the dominant species recorded (up to ~85% of the testate amoebae sum). Increase in <i>Hyalosphenia papilio</i> and decreases of both <i>Hyalosphenia elegans</i> and <i>Nebela militaris</i>
DKT4	166–121	Increased <i>Amphitrema flavum</i> between 162 and 147 cm. Three peak values of <i>Arcella discoides</i> type at 165, 155 and 135 cm. Increased <i>Hyalosphenia elegans</i> between 132 and 125 cm. Relatively constant <i>Nebela militaris</i>
DKT3	238–166	The major taxa are <i>Arcella discoides</i> type, <i>Assulina muscorum</i> and <i>Nebela militaris</i> . The latter species records high values (~31–51%) between 220 and 197 cm
DKT2	291–238	A large increase of <i>Arcella discoides</i> type occurs and <i>Nebela militaris</i> tests record relatively high abundances
DKT1	300–291	<i>Diffugia pulex</i> is the major species (highest abundances recorded in this zone) and <i>Nebela militaris</i> tests increase towards the top of the zone

stacked record for northern England also shows a major shift at 2300 cal. yr BC. Dates for the changes across Europe vary, but fall in the period 2550–2050 cal. yr BC (Barber *et al.*, 2003). A review of globally distributed palaeoclimate records by Mayewski *et al.* (2004) has also highlighted the period 2250–1850 cal. yr BC as being characterised by significant rapid climate change, with reduced temperatures in Eurasia and North America. Although the evidence for the change in the GB core analysed here is not as pronounced as for some other profiles, the Bpeat age–depth model estimates a date of 2150 cal. yr BC for the increased wetness in north-west Europe. Although there appears to be widespread evidence for a shift to cooler and/or wetter conditions at this time in northwest Europe, there is no significant anomaly in solar variability. This thus appears to be a period of significant climate change that cannot be explained by solar variability (Mayewski *et al.*, 2004).

A rise in water table at 740 cal. yr BC during focus interval II (1000–500 cal. yr BC) may correspond to an earlier decrease in solar activity at 850 BC, albeit with a ~110 yr lag (Fig. 9, Table 7). Climatic change relating to the rise in ^{14}C production at ca. 850 BC has been reported in numerous studies from around the globe (e.g. van der Putten *et al.*, 2004). It also emerges as one of the strongest signals in a composite record from northern Britain based on 12 profiles, including four from sites nearby the GB core, where the beginning of the change dates to 810 cal. yr BC (Charman *et al.*, 2006). However, most of these studies use calibrated ^{14}C dates, and in many cases employed conventional measurements of bulk material instead of AMS measurements of macrofossils, resulting in the establishment of imprecise chronologies with uncertainties often of the order of 10^2 yr. Changes in solar activity occur on decadal timescales; therefore the assessment of the timing of climate change in relation to the preceding decrease in solar activity is impossible with these studies. Wiggle-match dating of several raised bog profiles from Engbertsdijksveen in the Netherlands by Kilian *et al.* (1995) and Blaauw *et al.* (2004) showed responses to climate change (the transition to wetter-growing *Sphagnum* species) occurring over the interval

862–748 cal. yr BC. The timing of the rise in water table at Butterburn Flow (ca. 740 cal. yr BC) falls within the latest estimate of this range (given the 95% confidence intervals of the Bpeat ^{14}C wiggle-match model). Studies of nine Irish bogs by Plunkett (2006) and Swindles *et al.* (2007) using testate amoebae and peat humification also indicated a considerable gap between the decline in solar activity at ca. 850 yr BC and wet shifts in raised bogs, registered at ca. 740 cal. yr BC. This wet shift was constrained by two tephra layers, which were dated by wiggle-matching five conventional radiocarbon measurements of fulvic acid extracts (Plunkett *et al.*, 2004). Despite the improved precision of these age estimates, there are still likely to be errors of ± 30 years given the age range covered by samples as well as the remaining imprecision in the age estimates themselves. However, there is consistently a time lag between solar changes and increased surface wetness, suggesting this is a real phenomenon. The time lag between the decline in solar activity and climate change supports the idea of a regionally complex response to the forcing of the climate system at ca. 850 BC. This may be a delayed response of the oceanic British and Irish peatlands to solar-mediated changes in ocean circulation patterns, or may reflect nonlinear autogenic variability in European regional climate (Versteegh, 2005). An alternative explanation may be that the wet shift(s) of ca. 740 cal. yr BC identified in this study and by Plunkett (2006) and Swindles *et al.* (2007) is unrelated to solar activity.

During focus interval III, a significant drop in water table occurred on Lille Vildmose at ca. cal. yr AD 890; this was then followed by a rise in water table at ca. cal. yr AD 930, which is concurrent with the rise in ^{14}C production (Fig. 10, Table 7). During the dry period, the local vegetation was temporarily composed of *Eriophorum vaginatum*, before *S.* section *Acutifolia* became dominant again. The testate amoebae counts in GB profile lack enough resolution during this interval to register these higher frequency changes, but the northern Britain composite record suggests very similar changes here to Denmark. Water tables decline at 860 cal. yr AD and rise at 920 cal. yr AD (Charman *et al.*, 2006). A review by Barber *et al.* (2003) also indicates that a number of northern European peat

Butterburn Flow (GB) testate amoebae percentage diagram

Figure 6 GB testate amoebae diagram. All counts exceed 150 tests. Reconstructed water table is shown on the right side of the diagram. Error bars show estimated errors of prediction based on bootstrapping (Charman *et al.*, 2007)

Table 6 Testate amoebae zonation for the GB core

Macrofossil zone	Depth (cm)	Main features
GBT8	15–2	Highest values of <i>Corythion/Trinema</i> type with increases of <i>Euglypha strigosa</i> , <i>Heleopera sylvatica</i> and <i>Nebela tinctoria</i>
GBT7	37–15	<i>Cyclopyxis arcelloides</i> type and <i>Nebela militaris</i> are the dominant taxa. Increased tests of <i>Heleopera sylvatica</i> . Final peak of <i>Arcella discoides</i> type at 22 cm
GBT6	53–37	Relatively high values of <i>Amphitrema wrightianum</i> throughout. The other major taxa are <i>Amphitrema flavum</i> , <i>Assulina muscorum/seminulum</i> , <i>Cyclopyxis arcelloides</i> type and <i>Nebela parvula</i>
GBT5	135–53	Mix of taxa. Three peaks of <i>Arcella discoides</i> type at 110, 90 and 64 cm. Overall increase of <i>Cyclopyxis arcelloides</i> type and <i>Nebela militaris</i> throughout. Relatively high values (up to ~39%) of <i>Hyalosphenia subflava</i> between 100 and 96 cm
GBT4	196–135	Replacement of <i>Arcella discoides</i> type by <i>Hyalosphenia subflava</i> as the major species. Relatively high values of <i>Amphitrema wrightianum</i> at 190 cm. Relatively high values of <i>Trigonopyxis arcula</i> at 180 cm
GBT3	221–196	Abrupt decrease (almost complete absence) of <i>Hyalosphenia subflava</i> , and replacement by <i>Arcella discoides</i> type as the dominant taxon. Increased abundances of <i>Diffugia pulex</i> and <i>Nebela militaris</i> . High values of <i>Amphitrema flavum</i> between 208 and 206 cm
GBT2	305–221	A major change with increased abundances of <i>Hyalosphenia subflava</i> occurs between 300–280 cm and 260–222 cm. Between these peak values of <i>Hyalosphenia subflava</i> , an increase of <i>Amphitrema flavum</i> occurs at 270 cm in addition to the first record of <i>Arcella discoides</i> type
GBT1	400–305	<i>Amphitrema flavum</i> , <i>Assulina muscorum</i> and <i>Cyclopyxis arcelloides</i> type are the major taxa. High values of <i>Amphitrema wrightianum</i> (~11–26%) occur between 318 and 310 cm.

bogs showed dry periods preceding wet shifts which clustered within the interval ca. cal. yr AD 800–950. A rise in the water table at the DK site (testate amoebae) at ca. cal. yr AD 1020 lags the beginning of the Oort solar activity minimum (maximum in the ^{14}C production record) by ~10 yr. The GB site also records a smaller rise in water table at ca. cal. yr AD 1050, and a similar change is dated to 1090 cal. yr AD in the northern Britain record (Charman *et al.*, 2006). The combination of the high resolution of the testate amoebae counts with the rapid rate of peat accumulation at the DK site reveal a period of high-amplitude oscillations in the testate amoebae-derived water table after this time, which ends when the water table stabilises at ca. cal. yr AD 1170 (illustrated in detail in Fig. 11). Noticeably, the macrofossil (Dupont index) record of water table is in antiphase with the testate amoebae record, suggesting that the plant community took longer to respond to changes in water table than the testate amoebae. The water table at the GB site does not show such pronounced variation during this time interval, partly due to the considerably lower sampling resolution (Fig. 12). Testate amoebae counts in the DK core had a time resolution in the range of 5–14 yr, with each sample resolving 2–3 yr of peat accumulation. In contrast, testate amoebae counts in the GB core had a time resolution of 22–44 yr, with each sample resolving 11–12 yr of peat accumulation. The changes in water table at Lille Vildmose between the late 9th and late 12th centuries span the interval often labelled as the 'Medieval Warm Period', though there is some debate as to whether this was a truly global phenomenon (e.g. Broecker, 2001). Water temperature reconstructions from Chesapeake Bay on the Atlantic coast of North America by Cronin *et al.* (2003) suggest the 'Medieval Warm Period' had temporal structure, with a warm 'MWP-1' phase dated using ^{14}C measurements of mollusc shells ($2\sigma \sim 160$ yr) to ca. cal. yr AD 450–900; this was then followed by a significant cooling event at ca. cal. yr AD 1000–1100, followed by the warm 'MWP-II' lasting until ca. cal. yr AD 1300. The DK record also shows a warm/dry phase (beginning ca. cal. yr AD 890), followed by climate deterioration (beginning ca. cal. yr AD 930). However, the time interval in the DK core corresponding to 'MWP-II' (Fig. 11) is a period of climatic oscillation and cannot be broadly defined as either 'warm/dry' or 'cold/wet'.

At both the GB and DK sites, a significant wet shift occurs in the late 13th/early 14th century, lagging behind the Wolf solar minimum by 50 and 30 yr, respectively (Table 7 and Figs 10 and 12). This change is registered across northern Britain (estimated at cal. yr AD 1350) and Barber *et al.* (2003, 2004) noted a number of northern European bogs showing wet shifts during the interval ca. cal. yr AD 1230–1350. A synthesis of globally distributed palaeoclimate records by Mayewski *et al.* (2004) highlighted a period of significant rapid climate change beginning ca. cal. yr AD 1350, with cooling at higher latitudes.

The DK core records an increase of *S. cuspidatum* macrofossils at ca. cal. yr AD 1640 (the significant increase in the Dupont index shows a wet shift, Fig. 10), ~30 yr after the beginning of the Maunder solar minimum (Table 7). Wet shifts are also recorded around this time in a number of bogs around northern Europe (e.g. Blundell and Barber, 2005), and the rise in water table in the DK core replicates a previous core LVM-1 taken from Lille Vildmose by Mauquoy *et al.* (2002a,b). The LVM-1 core showed a wet shift (increase of *S. cuspidatum*) dated by ^{14}C wiggle-match to ca. cal. yr AD 1604, which fits well within the age estimate from the DK core. The same study also showed an apparently synchronous wet shift on Walton Moss in northern England, dated to ca. cal. yr AD 1601.

In the GB core, a significant wet shift starts at ca. cal. yr AD 1790 (Fig. 12, Table 7), concurrent with the beginning of the Dalton solar minimum. This replicates well the testate amoebae water table reconstructions of two cores BFA and BFB taken previously from Butterburn Flow by Hendon and Charman (2004), showing increasing dryness from the late 17th century followed by a wet shift beginning in the late 18th/early 19th century (Fig. 1 in Charman, 2007). Water table variability in the BFA and BFB cores was shown to be highly correlated with estimates of total seasonal moisture deficit (precipitation – evapotranspiration, $P - E$), based on long meteorological records from Carlisle and 'Central England' (Charman, 2007). The DK core also shows an increase in water table (Dupont index increases due to change to *S. cuspidatum*, Fig. 10) at a later date of ca. cal. yr AD 1830. However, this wet shift is not securely dated, as it is based on linear interpolation between the most recent age estimate of the wiggle-match age model (35 cm, ca. cal. yr AD 1760) and the oldest age estimate from an

Figure 7 Climate change in north-west Europe during the mid-late Holocene: (1) normalised testate amoebae water table reconstruction for the GB site (inverted); (2) normalised testate amoebae water table reconstruction for the DK site (inverted); (3) normalised and inverted plant macrofossil water table reconstruction for the DK site using the Dupont index (Dupont, 1986); (4) lake level fluctuations in mid Europe (Jura Mountains, northern French Pre-Alps and the Swiss Plateau) from Magny (2004); (5) stacked drift ice records from the north Atlantic (Bond *et al.*, 2001); (6) ^{14}C relative production rate (q), estimated by Jürg Beer and Raymond Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004). Shaded time intervals indicate ACCROTELM focus intervals, denoted by roman numerals (see Figs 8–12)

Figure 8 Focus interval I (2550–2050 cal. yr BC) at the GB site: thick grey line indicates normalised testate amoebae water table reconstruction (inverted); thin black line indicates normalised ^{14}C relative production rate (q), estimated by Jürg Beer and Raimund Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004)

Figure 9 Focus interval II (1000–500 cal. yr BC) at the GB site: thick grey line indicates normalised testate amoebae water table reconstruction (inverted); thin black line indicates normalised ^{14}C relative production rate (q), estimated by Jürg Beer and Raimund Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004). Arrow indicates start of significant rise in water table

age model based on ^{14}C 'bomb peak' dates (21 cm, ca. cal. yr AD 1963, unpublished data).

Conclusions

The lower-resolution Butterburn Flow record covers a longer period of the mid-late Holocene than the considerably younger Lille Vildmose profile, and the larger time intervals between samples and the greater length of time resolved by each sample

(as a result of the slower peat accumulation rate) in the GB profile may have acted as a natural smoothing filter preventing the clear registration of rapid climate change events. The changes during the intervals 2500–2000 cal. yr BC and 1000–500 cal. yr BC show similar wet shifts to those previously reported from profiles in the region with lower-precision chronologies, but provide improved estimates of the ages of these climate shifts. For the last 1500 years, the rapidly accumulating ($2\text{--}3\text{ yr cm}^{-1}$) DK profile offers an unprecedented high-resolution record of climate change from a peat bog, and has recorded a number of wet shifts, interpreted as significant

Figure 10 Focus interval III (cal. yr AD 800–1800) at the DK site: thick grey line indicates normalised testate amoebae water table reconstruction (inverted); thin black line indicates normalised ^{14}C relative production rate (q), estimated by Jürg Beer and Raimund Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004). Arrow indicates start of significant rise in water table. Historical solar minima are indicated

Figure 11 Cal. yr AD 1000–1200 at the DK site: dashed thick dark grey line indicates normalised plant macrofossil water table reconstruction using the Dupont index (Dupont, 1986) (inverted); thick grey line indicates normalised testate amoebae water table reconstruction (inverted); thin black line indicates normalised ^{14}C relative production rate (q), estimated by Jürg Beer and Raimund Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004)

but short-lived climate change events since ca. cal. yr AD 690. These high-frequency changes are not visible in lower-resolution records such as that from Butterburn Flow. Decadally resolved records such as the Danish record have the potential to revolutionise the understanding of the processes responsible for past climate change, and the replication of cores within climate regions shows that these significant changes in water table are likely to be due to climate change, and not to

local factors such as mire expansion, vegetation dynamics and microtopography.

The results show that not all large scale variations in solar activity during the mid-late Holocene have been responsible for the registration of climate change by the two northwest European peat bogs featured in this study, owing to the insensitivity of the climate system and/or the peat bog archive. Conversely, not all the significant rises in water table registered

Figure 12 Focus interval III (cal. yr AD 800–1800) at the GB site: dashed thick dark grey line indicates normalised plant macrofossil water table reconstruction using the Dupont index (Dupont, 1986) (inverted); thick grey line indicates normalised testate amoebae water table reconstruction (inverted); thin black line indicates normalised ^{14}C relative production rate (q), estimated by Jürg Beer and Raimund Muscheler (pers. comm.) using a Siegenthaler–Oeschger type box diffusion carbon cycle model, with input from the INTCAL04 ^{14}C calibration curve (Reimer *et al.*, 2004). Arrow indicates start of significant rise in water table. Historical solar minima are indicated

in the peat bog archives of the GB and DK sites have clearly been caused by solar forcing, and may be the result of other processes such as other external forcing factors, the internal variability of the climate system or raised bog ecosystem. However, a number of significant climate changes (wet shifts)

Table 7 Significant wet shifts during focus interval III (cal. yr AD 800–1800) at the GB and DK sites, in relation to declines of solar activity (rising ^{14}C production)

Solar activity		Start of rise in water table (cal. yr AD, unless stated)			
Historical solar minimum	Start of rise in ^{14}C production (year AD)	GB	Lag yr	DK	Lag yr
—	930	—	—	930	0
Oort	1010	1050	40	1020	10
Wolf	1250	1300 ^a	50	1280	30
Spörer	1370	—	—	—	—
Maunder	1610	—	—	1640 ^b	30
Dalton	1790	1790	0	1830 ^{b,c}	40

The start of the rise in water table was dated using the Bpeat ^{14}C wiggle-match models described in the text. All dates are rounded to the nearest decade. Changes of testate amoebae-derived water table or Dupont index >2 SD units, and covering >2 samples, are regarded as significant.

^aWet shift had an amplitude of 1.67 SD units.

^bWet shift based on Dupont index alone. The rise in water table is indicated by increase of *Sphagnum cuspidatum* macrofossils.

^cDate based on linear interpolation between most recent age estimate of wiggle-match age model (35 cm, ca. cal. yr AD 1760) and oldest age estimate from age model based on ^{14}C 'bomb peak' dates (21 cm, ca. cal. yr AD 1963, unpublished data). See Figs 8–12 and text for further details.

are recorded during the mid-late Holocene at Butterburn Flow and Lille Vildmose which are concurrent, or lag a few decades behind declines in solar activity (Table 7). Our research confirms two key points raised in previous work: (1) there is now an established pattern of mid-late Holocene climate change in north-west Europe (e.g. Charman *et al.*, 2006); (2) solar variability has possibly been the most likely important forcing factor for rapid climate changes during the mid-late Holocene, with the exception of the change to cooler, wetter conditions around 4.2 ka BP (Mayewski *et al.*, 2004).

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References

- Baillie MGL. 1991. Suck in and smear: two related chronological problems for the 1990s. *Journal of Theoretical Archaeology* 2: 12–16.
- Barber KE, Dumayne-Peaty L, Hughes PDM, Mauquoy D, Scaife RG. 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: 515–528.
- Barber KE, Chambers FM, Maddy D. 2003. Holocene palaeoclimates from peat stratigraphy: macrofossil proxy climate records from three oceanic raised bogs in England and Ireland. *Quaternary Science Reviews* 22: 521–539.
- Barber KE, Chambers FM, Maddy D. 2004. Late Holocene climatic history of northern Germany and Denmark: peat macrofossil inves-

- tigations at Dosenmoor, Schleswig-Holstein, and Svanemose, Jutland. *Boreas* **33**: 132–144.
- Bard E, Frank M. 2006. Climate change and solar variability: what's new under the sun? *Earth and Planetary Science Letters* **248**: 1–14.
- Bennett KD, Fuller JL. 2002. Determining the age of the mid-Holocene *Tsuga canadensis* (hemlock) decline, eastern North America. *Holocene* **12**: 421–429.
- Belyea LR, Malmer N. 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. *Global Change Biology* **10**: 1043–1052.
- Blaauw M, Christen JA. 2005. Radiocarbon peat chronologies and environmental change. *Applied Statistics* **54**: 806–816.
- Blaauw M, van Geel B, van der Plicht J. 2004. Solar forcing of climate change during the mid-Holocene: indications from raised bogs in The Netherlands. *The Holocene* **14**: 35–44.
- Blaauw M, Christen JA, Mauquoy D, van der Plicht J, Bennett KD. 2007. Testing the timing of radiocarbon-dated events between proxy archives. *The Holocene* **17**: 283–288.
- Blundell A, Barber KE. 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. *Quaternary Science Reviews* **24**: 1261–1277.
- Bond G, Kramer B, Beer J, Muscheler R, Evans MN, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I, Bonani G. 2001. Persistent solar influence on north Atlantic climate during the Holocene. *Science* **294**: 2130–2136.
- Broecker WS. 2001. Was the Medieval Warm Period global? *Science* **291**: 1497–1499.
- Charman DJ. 2007. Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions. *The Holocene* **17**: 217–227.
- Charman DJ, Hendon D, Woodland WA. 2000. *The Identification of Peatland Testate Amoebae*. Quaternary Research Association Technical Guide: London.
- Charman DJ, Blundell A, Chiverrell RC, Hendon D, Langdon PG. 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. *Quaternary Science Reviews* **25**: 336–350.
- Charman DJ, Blundell A, ACCROTELM Members. 2007. A pan-European testate amoebae transfer function for palaeohydrological reconstruction on ombrotrophic peatlands. *Journal of Quaternary Science* **22**: 209–221.
- Couwenberg J, Joosten H. 2005. Self-organisation in raised bog patterning: the origin of microtopo zonation and mesotopo diversity. *Journal of Ecology* **93**: 1238–1248.
- Cronin TM, Dwyer GS, Kamiya T, Schwede S, Willard DA. 2003. Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay. *Global and Planetary Change* **36**: 17–29.
- Dupont LM. 1986. Temperature and rainfall variation in the Holocene based on a comparative palaeoecology and isotope geology of a hummock and a hollow (Boutangerveen, The Netherlands). *Review of Palaeobotany and Palynology* **48**: 71–159.
- Hammond RF, van der Krogt G, Osinga T. 1990. Vegetation and water tables on two raised bog remnants in county Kildare. In *Ecology and Conservation of Irish Peatlands*, Doyle GJ (ed.). Royal Irish Academy: Dublin; 121–134.
- Heegaard E, Birks HJB, Telford RJ. 2005. Relationships between calibrated ages and depth in stratigraphical sequences: an estimation procedure by mixed-effect regression. *The Holocene* **15**: 612–618.
- Hendon D, Charman DJ. 1997. The preparation of testate amoebae (Protozoa: Rhizopoda) samples from peat. *The Holocene* **7**: 199–205.
- Hendon D, Charman DJ. 2004. High-resolution peatland water-table changes for the past 200 years: the influence of climate and implications for management. *The Holocene* **14**: 125–134.
- Hendon D, Charman DJ, Kent M. 2001. Palaeohydrological records derived from testate amoebae analysis from peatlands in northern England: within-site variability, between-site comparability and palaeoclimatic implications. *The Holocene* **11**: 127–148.
- Hu FS, Kaufman D, Yoneji S, Nelson D, Shemesh A, Huang Y, Tian J, Bond G, Clegg B, Brown T. 2003. Cyclic variation and solar forcing of Holocene climate in the Alaskan Subarctic. *Science* **301**: 1890–1893.
- Hughes PDM, Mauquoy D, Barber KE, Langdon PG. 2000. Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. *The Holocene* **10**: 465–479.
- Johnson LC, Damman AWH. 1991. Species controlled *Sphagnum* decay on a south Swedish raised bog. *Oikos* **61**: 234–242.
- Kaplan MR, Wolfe AP. 2006. Spatial and temporal variability of Holocene temperature in the North Atlantic region. *Quaternary Research* **65**: 223–231.
- Kilian MR, van der Plicht J, 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**: 959–966.
- Magny M. 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International* **113**: 65–79.
- Mauquoy D, Barber KE. 1999. Evidence for climatic deteriorations associated with the decline of *Sphagnum imbricatum* Hornsch. Ex Russ. in six ombrotrophic mires from Northern England and the Scottish Borders. *The Holocene* **9**: 423–437.
- Mauquoy D, van Geel B. 2007. Mire and peat macros. In *Encyclopedia of Quaternary Science*, Vol. 3, Elias SA (ed.). Elsevier: Amsterdam; 2315–2336.
- Mauquoy D, van Geel B, Blaauw M, van der Plicht J. 2002a. Evidence from North-West European bogs shows 'Little Ice Age' climatic changes driven by variations in solar activity. *The Holocene* **12**: 1–6.
- Mauquoy D, Engelkes T, Groot MHM, Markesteijn F, Oudejans MG, van der Plicht J, van Geel B. 2002b. High-resolution records of late Holocene climate change and carbon accumulation in two north-west European ombrotrophic peat bogs. *Palaeogeography, Palaeoclimatology, Palaeoecology* **186**: 275–310.
- Mauquoy D, van Geel B, Blaauw M, Speranza A, van der Plicht J. 2004. Changes in solar activity and Holocene climate shifts derived from ^{14}C wiggle-match dated peat deposits. *The Holocene* **14**: 45–52.
- Mayewski PA, Rohling EE, Stager JC, Karlén W, Maasch KA, Meeker LD, Meyerson EA, Gasse F, van Kreveland S, Holmgren K, Lee-Thorp J, Rosqvist G, Rack F, Staubwasser M, Schneider RR, Steig EJ. 2004. Holocene climate variability. *Quaternary Research* **62**: 243–255.
- McClymont EL, Mauquoy D, Yeloff D, Broekens P, van Geel B, Pancost RD, Evershed RP. Submitted. Changing nutrient supplies and the disappearance of *Sphagnum imbricatum* from Butterburn Flow, British Isles. *The Holocene*.
- Økland RH. 1990. A phytoecological study of the mire Northern Kiselbergmosen, SE Norway. III. Diversity and habitat niche relationships. *Nordic Journal of Botany* **10**: 191–220.
- Pellerin S, Lavoie C. 2003. Reconstructing the recent dynamics of mires using a multitechnique approach. *Journal of Ecology* **91**: 1008–1021.
- Plunkett GM. 2006. Tephra-linked peat humification records from Irish ombrotrophic bogs question nature of solar forcing at 850 cal. yr BC. *Journal of Quaternary Science* **21**: 9–16.
- Plunkett GM, Pilcher JR, McCormac FG, Hall VA. 2004. New dates for first millennium BC tephra isochrones in Ireland. *The Holocene* **14**: 780–786.
- Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac FG, Manning SW, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE. 2004. IntCal04 terrestrial radiocarbon age calibration, 26–0 ka BP. *Radiocarbon* **46**: 1029–1058.
- Sillasoo U, Mauquoy D, Blundell A, Charman D, Blaauw M, Daniell JGR, Toms P, Newberry J, Chambers FM, Karofeld E. 2007. Peat multi-proxy data from Männikjärve bog as indicators of Late Holocene climate changes in Estonia. *Boreas* **36**: 20–37.
- Speranza A, van der Plicht J, 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**: 1589–1604.
- Swindles GT, Plunkett G, Roe HM. 2007. A delayed climatic response to solar forcing at 2800 cal. BP: multiproxy evidence from three Irish peatlands. *The Holocene* **17**: 177–182.

- Telford RJ, Heegaard E, Birks HJB. 2004. All age-depth models are wrong: but how badly? *Quaternary Science Reviews* **23**: 1–5.
- van der Putten N, Stieperaere H, Verbruggen C, Ochyra R. 2004. Holocene palaeoecology and climate history of South Georgia (sub-Antarctica) based on a macrofossil record of bryophytes and seeds. *The Holocene* **14**: 382–392.
- van Geel B, Mook WG. 1989. High-resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations. *Radiocarbon* **31**: 151–156.
- van Geel B, van der Plicht J, Kilian MR, Klaver ER, Kouwenberg JHM, Renssen H, Reynaud-Farrera I, Waterbolk HT. 1998. The sharp rise of $\Delta^{14}\text{C}$ ca. 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* **40**: 535–550.
- van Geel B, Heusser C, Renssen H, Schuurmans CJE. 2000. Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis. *The Holocene* **10**: 659–664.
- Versteegh GJM. 2005. Solar forcing of climate 2: Evidence from the past. *Space Science Reviews* **120**: 243–286.
- Wang Y, Cheng H, Edwards RL, He Y, Kong X, An Z, Wu J, Kelly MJ, Dykoski CA, Li X. 2005. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science* **308**: 854–857.
- Wardenaar ECP. 1987. A new handtool for cutting soil monoliths. *Canadian Journal of Soil Science* **67**: 405–407.
- Woodland WA, Charman DJ, Sims PC. 1998. Quantitative estimates of water tables and soil moisture in Holocene peatlands from testate amoebae. *The Holocene* **8**: 261–273.
- Yeloff DE, Blaauw M, Mauquoy D, Bennett KD, van der Plicht H, van Geel B. 2006. The high precision ^{14}C dating of Holocene peat deposits: a comparison of Bayesian calibration and wiggle-matching approaches. *Quaternary Geochronology* **1**: 222–235.
- Yeloff DE, van Geel B, Broekens P, Bakker J, Mauquoy D. 2007. Mid-late Holocene vegetation and land-use history in the Hadrian's Wall region of northern England: the record from Butterburn Flow. *The Holocene* **17**: 527–538.