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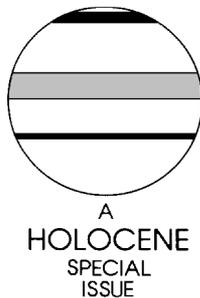
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# Solar forcing of climatic change during the mid-Holocene: indications from raised bogs in The Netherlands

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**Abstract:** Two cores of mid-Holocene raised-bog deposits from the Netherlands were <sup>14</sup>C wiggle-match dated at high precision. Changes in local moisture conditions were inferred from the changing species composition of consecutive series of macrofossil samples. Several wet-shifts were inferred, and these were often coeval with major rises in the  $\Delta^{14}\text{C}$  archive (probably caused by major declines in solar activity). The use of  $\Delta^{14}\text{C}$  as a proxy for changes in solar activity is validated. This paper adds to the increasing body of evidence that solar variability forced climatic changes during the Holocene.

**Key words:** Climatic change, solar forcing, raised bogs, <sup>14</sup>C wiggle-match dating, mid-Holocene, wet-shifts, The Netherlands.

## Introduction

Changes in solar activity during the Holocene can be reconstructed using the proxy  $\Delta^{14}\text{C}$  (Stuiver and Braziunas, 1993; 1998; Stuiver *et al.*, 1998; Chambers *et al.*, 1999; Beer, 2000; Goslar, 2002). A temporal link between changes in  $\Delta^{14}\text{C}$  and Holocene climatic changes has been documented by several studies (Blackford and Chambers, 1995; Karlén and Kuylenskierna, 1996; Chambers *et al.*, 1999; Hong *et al.*, 2000; Björck *et al.*, 2001; Bond *et al.*, 2001; Hodell *et al.*, 2001; Neff *et al.*, 2001; Magny, 2004), while other studies report climate cycles with periodicities close to those of solar variability (e.g., Wijmstra *et al.*, 1984; Chambers *et al.*, 1999; Ram and Stolz, 1999; Chambers and Blackford, 2001). However, the chronologies obtained in these studies often were rather imprecise. To establish securely whether a temporal correspondence exists between short-term (decadal to centennial) changes in solar activity and climatic changes, chronologies with much higher precision are needed.

Using <sup>14</sup>C wiggle-match dating, high-precision chronologies can be obtained of peat deposits (e.g., Kilian *et al.*, 1995; 2000; Blaauw *et al.*, 2003). Wet-shifts in northwest and central European peat deposits dated with this method coincided with abrupt  $\Delta^{14}\text{C}$  rises during periods of the Holocene (Subboreal/Subatlantic transition: van Geel *et al.*, 1996; Speranza *et al.*, 2000; 2002; 'Little Ice Age': Mauquoy *et al.*, 2002a; 2002b). In this paper, we

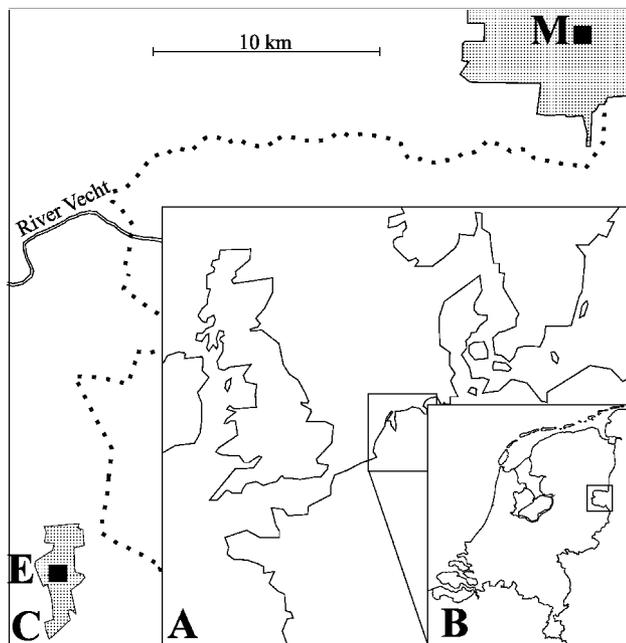
extend our investigations to the mid-Holocene. We present local vegetation reconstructions of two peat cores, together encompassing the period from c. 4500 to c. 340 cal. BC, and investigate the possible relation between changes in solar activity and changes in the peat records during this period.

Cores from raised bogs provide a well-known archive of climatic changes. Raised bogs are dependent on precipitation alone for water and nutrients. Because plant species found in raised bogs each have their own requirements concerning depth of the water table (Malmer, 1986; Hammond *et al.*, 1990; Økland, 1990; van der Molen, 1992; Wheeler and Proctor, 2000; Økland *et al.*, 2001), the macro- and microfossil composition of consecutive samples can inform us about past changes in local moisture conditions, and therefore about changes in effective precipitation (precipitation minus evapotranspiration).

## Material and methods

Two peat cores were taken from drained raised bogs in the eastern part of the Netherlands (Figure 1). Core Eng-XV (Blaauw *et al.*, 2003; 2004) was collected from Engbertsdijkswenen; core MSB-2K (Blaauw *et al.*, 2003) was collected from the location Meerstalblok in the Bargerveen nature reserve. The sequences were analysed at high resolution (mostly 1 cm; 0.5 cm at some intervals) for various proxies to reconstruct mire surface wetness.

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**Figure 1** (A) Part of Europe, with The Netherlands indicated by a rectangle (inset B). (C) Location of the cores MSB-2K (M) and Eng-XV (E). The dotted line indicates the Dutch-German border. Dotted areas indicate the present extent of the raised-bog deposits.

#### <sup>14</sup>C wiggle-match dating

The cores were <sup>14</sup>C wiggle-match dated in order to obtain high-precision chronologies. For details of the wiggle-match procedures and results we refer to Blaauw *et al.* (2003); here the method will be summarized. At first instance, a constant accumulation rate was assumed for the cores. The <sup>14</sup>C dates of the cores were matched with those of the <sup>14</sup>C calibration curve INTCAL98 (Stuiver *et al.*, 1998). At levels where <sup>14</sup>C dates started to deviate from the <sup>14</sup>C calibration curve and where at the same time lithology suggested either a hiatus or a change in accumulation rate, the sequences were divided into subsets. These subsets were then wiggle-match dated separately with the assumption of linear accumulation rate for every subset. Two measures of the goodness-of-fit were assessed: one based on minimalization of weighted least squares (cf. Pearson, 1986) and one on maximalization of the product of probability densities (Blaauw *et al.*, 2003). Confidence intervals were calculated.

#### Local vegetation reconstruction

From 0.5–1 cm slices of the peat cores, samples of 2.5 cc volume were boiled for *c.* 10 min in 5% KOH solution and, after rinsing and sieving over a 100 µm sieve using demineralized water, the >100 µm fraction (macrofossils; Birks, 2001) was analysed. Identification was based on literature (Grosse-Brauckmann, 1972; 1974; Grosse-Brauckmann and Streitz, 1992) and on a reference collection. Abundances of plant and other remains were recorded on the basis of estimated volume percentage (e.g., mosses), number (e.g., seeds) or absence/presence. Samples were stored in demineralized water containing some droplets of 5% HCl.

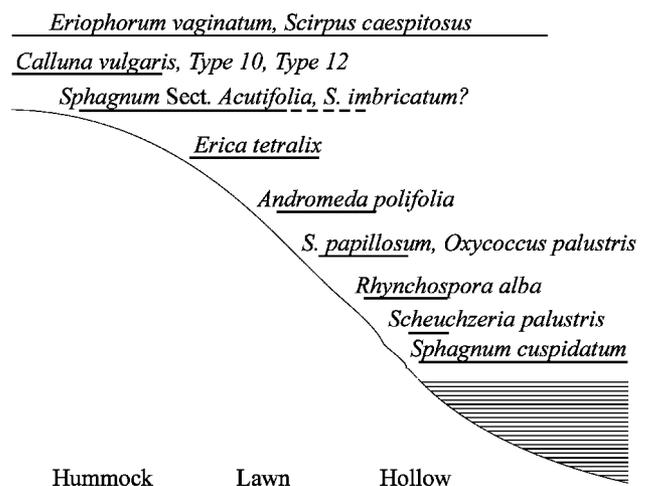
Core Eng-XV was also analysed for microfossils. Microfossil samples *c.* 1 cm<sup>3</sup> in volume were prepared as described by Fægri and Iversen (1989), with 1 tablet of *Lycopodium* spores added to estimate pollen concentration (Stockmarr, 1971). Identification of pollen grains was based on Moore *et al.* (1991) and on a reference collection, while non-pollen palynomorphs were identified based on van Geel (1978) and on a reference collection.

#### Ecology of raised-bog species

Changes in vegetation composition were interpreted based on the present ecology of species in raised bogs. The wetness-

preferences of the species most commonly found in the cores are reviewed below (see also Figure 2).

- *Scheuchzeria palustris* (hereafter abbreviated to *Scheuchzeria*) grows in places where the ground water table is very high or where there is permanent standing water; it is susceptible to drying out of the peat surface (Moore, 1955; Tallis and Birks, 1965). Ordination studies also showed that the occurrence of *Scheuchzeria* indicated very wet conditions (Økland, 1990). As *Scheuchzeria* was placed rather high on the second axis of DCA by Økland (1990), indicating a poor–rich gradient, the species can be considered to be slightly minerotrophic compared to other raised-bog plants. Other studies also mention its slight minerotrophy (e.g., Casparie, 1972).
- *Rhynchospora alba* is also indicative of pools or high water tables (Godwin and Conway, 1939; Mauquoy, 1997). *R. alba* appears to occur at poorer (more acid) locations than *Scheuchzeria* (Newbould, 1960; Økland, 1990). Compared with *Scheuchzeria*, *R. alba* perhaps grows in a wider range of mire surface water levels (Overbeck, 1975).
- *Sphagnum cuspidatum* is indicative of wet, oligotrophic conditions, i.e., floating or submerged in bog pools, along pool margins and in wet hollows and soaks (Godwin and Conway, 1939; Newbould, 1960; Boatman, 1977; Daniels and Eddy, 1985; Mauquoy, 1997). As *S. cuspidatum* is found floating in deep pools, we assume it can occur at even wetter conditions than *Scheuchzeria*. If *Sphagnum cuspidatum* (partly or entirely) replaces *Scheuchzeria* in the macrofossil record, we therefore interpret this as a possible shift to even wetter conditions.
- *S. papillosum* is an indicator of moist conditions as it is most common in low lawns, although it is occasionally found higher up on lawns or even in hummocks, and although it can resist drought (Godwin and Conway, 1939; Mauquoy, 1997). DCA by Økland (1990) placed the species at rather wet and relatively rich conditions.
- *S. imbricatum* is a highly oceanic species (Daniels and Eddy, 1985). Nowadays it often occurs in hummocks, but there are strong indications that in the past *S. imbricatum* grew mostly in rather wet ‘lawn’ conditions (Casparie, 1972; Barber, 1981; Green, 1968; Stoneman *et al.*, 1993; Mauquoy and Barber, 1999). As with most palaeoecological studies, we interpret its appearance as indicating a change to moister climate (higher air humidity and cooler conditions).
- *S. sect. Acutifolia* comprises a group of species that cannot be identified to species level during macrofossil analysis. Most species of the section grow at relatively dry conditions



**Figure 2** Interpreted range of occurrence (horizontal lines) of raised-bog plant species along a dry-wet (hummock-hollow) gradient, based on literature (e.g., Overbeck, 1975; see text). Thin horizontal lines indicate water.

(hummocks). DCA by Økland (1990) placed *S. rubellum*, according to Barber (1981) the most important peat-building species of the section *Acutifolia*, close to *Eriophorum vaginatum* and Ericaceae on the first axis.

- *Oxycoccus palustris* is characteristic of waterlogged ombrogenous peat (Jacquemart, 1997). Its growth optimum is found in moist hollows, and it is very sensitive to surface drying (Jacquemart, 1997). Økland's (1990) DCA placed the species at intermediate levels on the moisture gradient axis.
- *Andromeda polifolia* occurs at greatest shoot frequency in low hummocks and lawns of ombrotrophic bogs (Jacquemart, 1998). According to Jacquemart (1998), *A. polifolia* is not necessarily a hygrophilous species, and is not found at the wettest locations. DCA by Økland (1990) placed the species at intermediate levels on the moisture gradient axis. *A. polifolia* grows slightly higher at a lawn-hummock gradient than *Oxycoccus palustris* (Overbeck, 1975).
- *Erica tetralix* is characteristic of wet heath and mire communities in oceanic western Europe (Bannister, 1966). It appears to grow in slightly moister conditions than *Calluna vulgaris* (e.g., Overbeck, 1975). DCA confirms this (Økland, 1990).
- *Calluna vulgaris* (Gimingham, 1960; Wallén, 1987) is clearly a hummock species, restricted to drier microhabitats (Nordbakken, 2001) with a relatively deep water table because the roots need an aerated layer.
- *Eriophorum vaginatum* (Wein, 1973) can grow at a wide range of moisture conditions (e.g., Wallén, 1987), and is dominant where water tables are at surface level in spring and dry out during summer. It can survive drought, but is also able to invade pools. As a consequence of the wide ecological range of *E. vaginatum*, its use in reconstructing mire surface water levels is limited (Mauquoy, 1997).
- *Scirpus caespitosus* (*Trichophorum caespitosum*) can grow under a wide range of water tables, as is the case with *E. vaginatum* (Mauquoy, 1997). Its use for reconstruction of mire surface water level is therefore limited.
- Macroscopic charcoal particles indicate local fires.
- *Amphitrema flavum* is a testate amoeba indicating relatively wet local conditions (van Geel, 1978; Charman *et al.*, 2000).
- Type 10 is the spore of a fungus occurring on the roots of *Calluna vulgaris* (van Geel, 1978). Like its host plant, it indicates relatively dry conditions.
- Type 12 is a fungal spore indicating relatively dry local conditions (van Geel, 1978).

Summarizing, *Scheuchzeria palustris*, *Rhynchospora alba* and *Sphagnum cuspidatum* clearly indicate very wet conditions in raised bogs, while *Calluna vulgaris*, Type 10 and Type 12 are obvious indicators of relatively dry conditions. The wetness-preferences of other species are either intermediate (e.g., *Sphagnum papillosum*) or difficult to interpret (e.g., *Eriophorum vaginatum*). As the aim of this study was to identify wet-shifts, *Scheuchzeria*, *Rhynchospora alba* and *Sphagnum cuspidatum* are considered most relevant here.

## Results

Originally, it was planned to obtain a mid-Holocene record of climatic change from a single site (Engbertsdijkvenen). However, a large hiatus (lasting from *c.* 4200 to 2500 cal. BC) was encountered in a core from Engbertsdijkvenen that was sampled to investigate the period of *c.* 4500 to 2500 cal. BC (Blaauw, 2003). Therefore, an additional core was collected at a different site (Meerstablok; core MSB-2K). Cores MSB-2K and Eng-XV were <sup>14</sup>C wiggle-match dated (for explanation, see Blaauw *et al.*, 2003). The resulting chronologies are shown in Figure 3. The <sup>14</sup>C

sequences of both cores were divided into three subsets based upon changes in stratigraphy and most likely positions of <sup>14</sup>C dates on the calibration curve (Figure 3, a and b). The black dots in Figure 3, c and d, give the most probable wiggle-match dating derived calendar ages for every depth; sizes of the dots indicate probabilities of calendar age. Average 1  $\sigma$  confidence intervals for calendar ages are 52, 99 and 86 y for the lower, middle and upper subsets of core MSB-2K respectively, and 204, 114 and 36 y respectively for the lower, middle and upper subsets of core Eng-XV (Blaauw *et al.*, 2003). In the text, calendar ages are rounded to the nearest five years.

### Wet-shifts

Changes in vegetation composition through time are summarized in Figures 4 and 5, together with residual  $\Delta^{14}\text{C}$  (Stuiver *et al.*, 1998). Numbered hatched lines with arrows show wet-shifts as inferred from changes in the vegetation composition of the cores. According to Aaby (1976), wet-shifts in raised-bog sequences were most probably caused by changes in climate, while changes to drier conditions often should be attributed to local succession (peat accumulating away from the water table). Therefore, in this paper we focus on the wet-shifts as proxies of climatic change.

### Core MSB-2K

The record begins with the base of core MSB-2K (Figure 4), experiencing dry, hummock conditions: *Calluna vulgaris*, Ericaceae rootlets and *Eriophorum vaginatum* are dominant (although *Oxycoccus palustris* is also found).

#### MSB-1

Starting at *c.* 4390 cal. BC, *Sphagnum cuspidatum*, *Rhynchospora alba* and *Scheuchzeria* peak briefly, suggesting a wet-shift. Later (starting *c.* 4325 cal. BC), alternating dominances of *C. vulgaris*, Ericales rootlets, *Eriophorum vaginatum* and *Sphagnum* sect. *Acutifolia* indicate dry local conditions.

#### MSB-2

At *c.* 4115 cal. BC, surface wetness increases for a short period (*S. cuspidatum* peaks, and also *R. alba* shows a small peak).

#### MSB-3

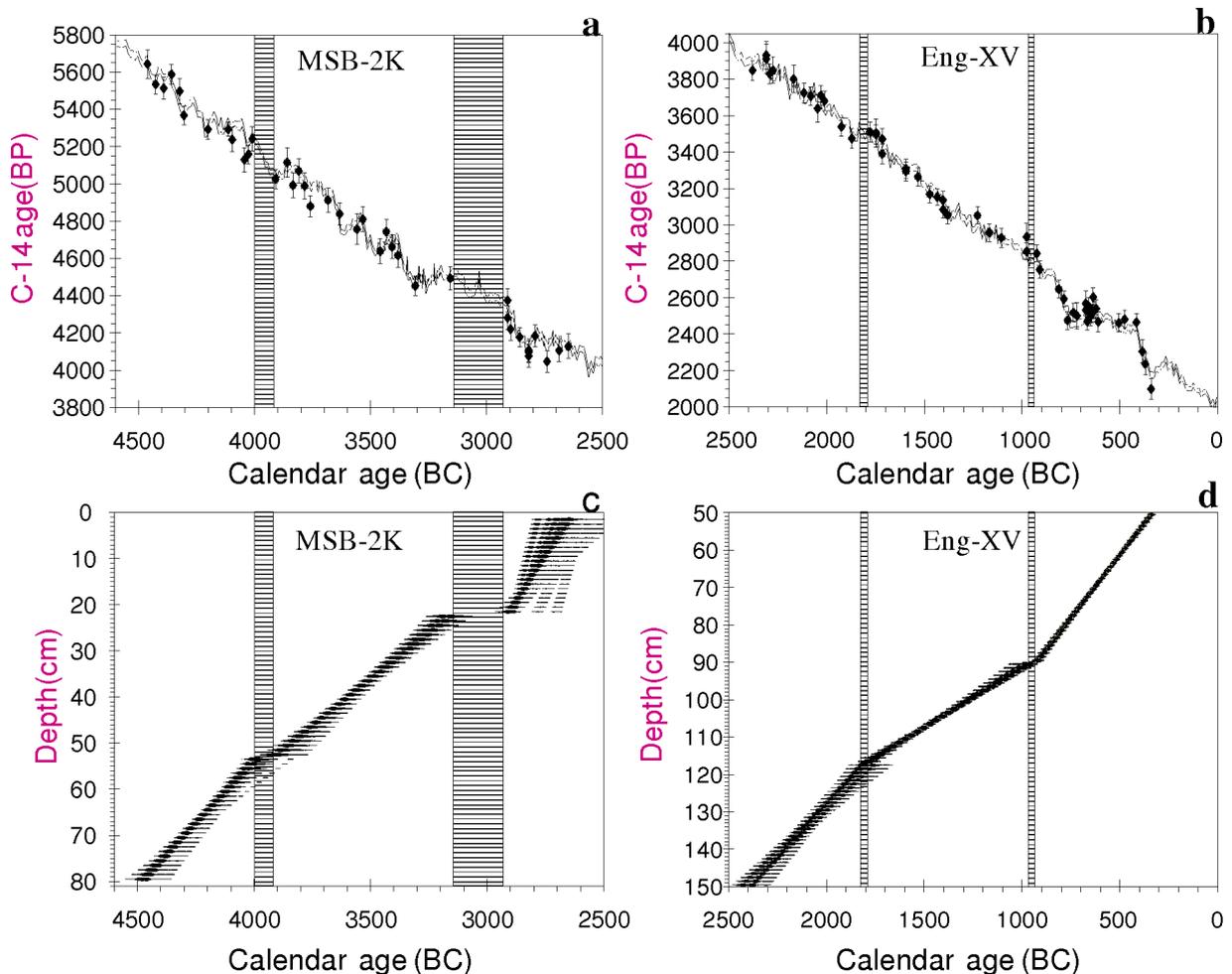
At *c.* 3910 cal. BC a major wet-shift occurs, as indicated by a hiatus (from *c.* 4010 to 3910 cal. BC) and subsequent dominance of *Scheuchzeria* with some *R. alba*. We interpret this as follows: at some stage of the wet period, streaming water at the surface of the bog may have eroded surficial material (cf. Casparie, 1972). Peat accumulation started again with *Scheuchzeria* and *R. alba*. Later (*c.* 3760 cal. BC), *Calluna vulgaris* and Ericales rootlets indicate drier local conditions. Other explanations could be found for the hiatus, but are considered less plausible. We have no evidence for local peat digging during the period considered. Excessive dryness as a cause of the hiatus is unlikely because the local macrofossil record clearly indicates very wet local conditions (dominance of *Scheuchzeria* and *R. alba*). Moreover, a local fire is not assumed to have caused the hiatus, as no significant charcoal peaks were present.

#### MSB-4

Around *c.* 3635 cal. BC, *C. vulgaris* is replaced by *Andromeda polifolia*, *Oxycoccus palustris* and some *Sphagnum cuspidatum*. Remains of *Scheuchzeria* increase in abundance. All these changes point to a wet-shift.

#### MSB-5

At *c.* 3535 cal. BC, *Sphagnum cuspidatum* becomes dominant over *Scheuchzeria* and *R. alba*, indicating a possible shift to even



**Figure 3**  $^{14}\text{C}$  wiggle-match dating chronologies of cores MSB-2K and Eng-XV. The  $^{14}\text{C}$  sequences of both cores were divided into three subsets based upon changes in stratigraphy and best fits of  $^{14}\text{C}$  dates on the calibration curve (a, b). Error bars of  $^{14}\text{C}$  dates indicate  $1\sigma$  confidence intervals. For the calibration curve, the  $1\sigma$  error envelope is depicted. The most probable calendar-year ages for every depth are plotted in (c, d), their shape indicating probabilities of calendar age. The vertical boxes with horizontal lines indicate hiatuses. See text.

wetter conditions. Around c. 3410 cal. BC conditions get drier again as *A. polifolia* and Ericales rootlets show small peaks.

#### MSB-6

At c. 3360 cal. BC, the abundance of remains of *Scheuchzeria* increases slightly. This might imply wetter conditions.

#### MSB-7

After a hiatus from c. 3160 to 2910 cal. BC, at c. 2895 cal. BC *Sphagnum cuspidatum* briefly gets dominant over *Scheuchzeria*. This indicates a shift to even wetter conditions. The hiatus can be explained by an erosion event caused by excess surface water; compare with wet-shift 3. Also in this case, other causes for the hiatus could be ruled out: there is no evidence for peat digging, the macrofossil record shows very wet local conditions, and no charcoal was found. Around c. 2755 cal. BC, conditions become drier again (*Calluna vulgaris* and Ericales rootlets get dominant over the hygrophilous species).

#### Core Eng-XV

Approximately 270 years (from c. 2650 to c. 2380 cal. BC) are not represented in the core intervals studied here. The base of core Eng-XV (Figure 5) represents relatively dry conditions as shown by dominance of *Eriophorum vaginatum*, *Scirpus caespitosus*, *Andromeda polifolia* and charcoal.

#### Eng-1

At c. 2310 cal. BC, *Scheuchzeria* replaces *E. vaginatum* and *A. polifolia* shows a decline, indicating a wet-shift. *Amphitrema flavum* enters. Subsequently around c. 2115 cal. BC conditions get drier as first *S. papillosum* and later *E. vaginatum* and Types 10 and 12 peak.

#### Eng-2

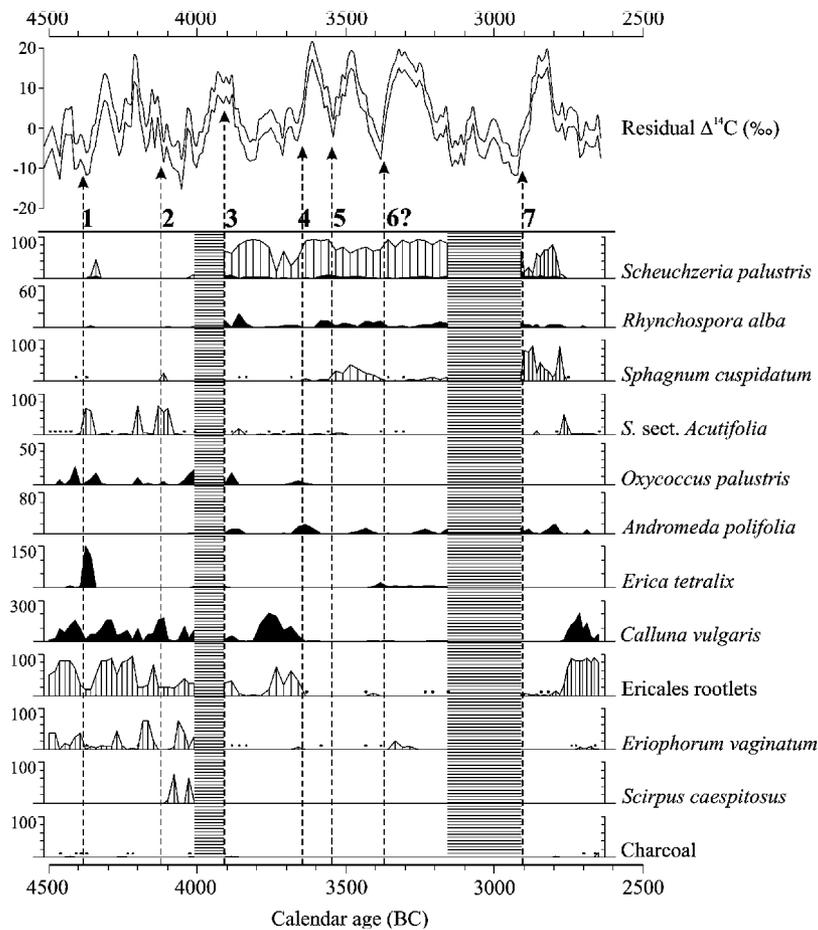
At c. 1960 cal. BC, *Scheuchzeria* replaces *E. vaginatum*, implying a wet-shift.

#### Eng-3

Around c. 1870 cal. BC, *Sphagnum cuspidatum* replaces *Scheuchzeria* after a large charcoal peak, indicating a wet-shift. *Amphitrema flavum* enters again and *O. palustris* shows a maximum.

#### Eng-4

After relatively dry conditions (dominance of *Sphagnum* sect. *Acutifolia*), at c. 1715 cal. BC *S. cuspidatum* takes over. *Amphitrema flavum* peaks. Later, around c. 1595 cal. BC, the sequence becomes drier again, indicating hummock conditions (*C. vulgaris*).



**Figure 4** Residual  $\Delta^{14}\text{C}$  and changes in local vegetation derived from core MSB-2K, with the chronology based on Figure 3. Vertical boxes with horizontal striping indicate hiatuses, numbered vertical lines with arrows indicate inferred wet-shifts (ambiguous wet-shifts are labelled with question marks), vertically hatched areas indicate occurrence of macrofossils in estimated volume percentage, black areas indicate macrofossils counted as numbers, dots indicate macrofossils counted as present at low amounts, lines indicate percentages of microfossils (expressed on a tree pollen sum).  $\Delta^{14}\text{C}$  is the relative  $^{14}\text{C}$  content (i.e., deviation of the activity from the standard), corrected for radioactive decay, and expressed in ‰. Here  $\Delta^{14}\text{C}$  is, in addition, detrended for the geomagnetic component and is called 'residual  $\Delta^{14}\text{C}$ '.

#### Eng-5

Hummock conditions change into lawn conditions as around c. 1435 cal. BC *Calluna vulgaris* and *S. sect. Acutifolia* are replaced by *S. papillosum*, through a distinctly wet phase of *S. cuspidatum*, *R. alba*, *Erica tetralix* and *O. palustris*. Types 10 and 12 show a decline.

#### Eng-6

At c. 1230 cal. BC, *S. cuspidatum* and *R. alba* indicate a wet-shift. Later (starting c. 1170 cal. BC), *S. papillosum* gradually replaces *S. cuspidatum*.

#### Eng-7

Around c. 1075 cal. BC, *R. alba* starts dominating *S. papillosum*, and some *S. cuspidatum* occurs. Although this could point to slightly wetter local conditions, at the same time *S. sect. Acutifolia*, *C. vulgaris* and Ericales rootlets reach rather high values.

#### Eng-8

During a phase of relatively very dry conditions (thick branches of *C. vulgaris* are found, together with Ericales rootlets and *S. sect. Acutifolia*), at c. 785 cal. BC a short but distinctive peak of *S. imbricatum* occurs, and also *Scheuchzeria* enters again with low values.

#### Eng-9

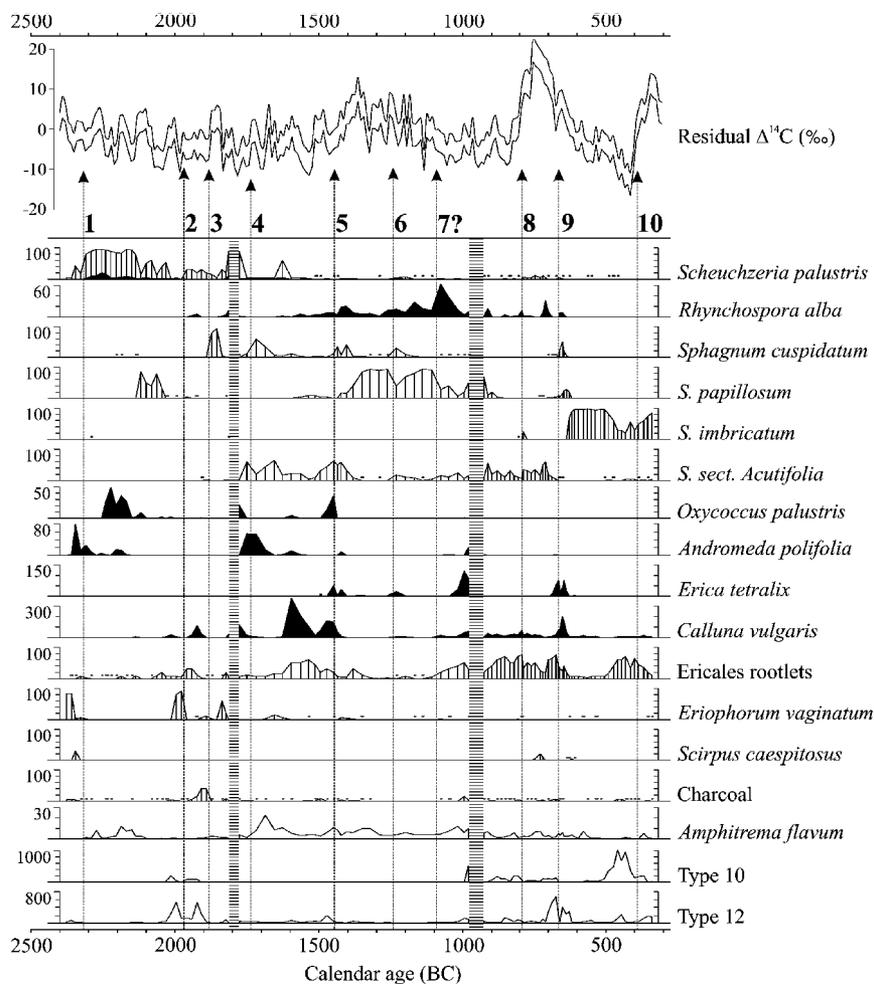
At c. 660 cal. BC, *Sphagnum sect. Acutifolia* and *Calluna vulgaris* are replaced by *S. imbricatum*, through a short phase of *S. cuspidatum* and *S. papillosum*. Numbers of Types 10 and 12 show a decline. All these changes clearly point to conditions getting wetter. Later (c. 475 cal. BC) an increase of Ericales rootlets and Type 10 show that conditions become drier again.

#### Eng-10

Around c. 385 cal. BC, *S. imbricatum* increases again with an associated decline of Ericales rootlets and Type 10, reflecting a wet-shift.

#### $\Delta^{14}\text{C}$ rises and wet-shifts

As can be seen from Figures 4 and 5, and Table 1, most of the major rises in the residual  $\Delta^{14}\text{C}$  record were coeval with wet-shifts in the studied raised-bog deposits (MSB-1, 3, 4, 5, 6, 7, Eng-5, 8, 10). Most of these wet-shifts were evident, whereas one of the wet-shifts (MSB-6) was less clear. On only two occasions, no wet-shift was recorded during a large  $\Delta^{14}\text{C}$  rise (core MSB-2K during the  $\Delta^{14}\text{C}$  rise of c. 4265–4215 cal. BC, and core Eng-XV during the  $\Delta^{14}\text{C}$  rise of c. 1535–1485 cal. BC). Even smaller increases in  $\Delta^{14}\text{C}$  at times appear to have been coeval with wet-shifts (wet-shifts Eng-1, 3 and 4), although this may be a coincidence.



**Figure 5** Residual  $\Delta^{14}\text{C}$  and changes in local vegetation derived from core Eng-XV, with the chronology based on Figure 3. For explanation, see Figure 4.

**Table 1** Major  $\Delta^{14}\text{C}$  rises during the mid-Holocene, their duration, amplitude and temporally corresponding wet-shifts in the studied raised-bog deposits (Figures 4 and 5). For a rise in the (residual)  $\Delta^{14}\text{C}$  record to be considered major here, it has to comply with two rules: its amplitude should be at least twice the  $1\sigma$  error envelope of the  $\Delta^{14}\text{C}$  record (which averages 5‰ during the period considered) and the  $\Delta^{14}\text{C}$  record should show rising levels during more than two measurements ( $\geq 30$  y)

Major $\Delta^{14}\text{C}$ rise (start–end; cal. BC)	Amplitude $\Delta^{14}\text{C}$ rise (in ‰)	Corresponding wet-shift (cal. BC)
c. 4375–4315	18.7	MSB-1 (c. 4390)
c. 4265–4215	18.6	(no wet-shift)
c. 4005–3935	18.2	MSB-3 (c. 3910)
c. 3665–3615	20.4	MSB-4 (c. 3635)
c. 3545–3485	17.1	MSB-5 (c. 3535)
c. 3385–3325	22.9	MSB-6 (c. 3360)?
c. 3105–3075	10.6	(hiatus)
c. 2925–2825	26.9	MSB-7 (c. 2895)
c. 2505–2455	14.8	(no record)
c. 1535–1485	11.2	(no wet-shift)
c. 1465–1365	13.4	Eng-5 (c. 1435)
c. 845–755	26.0	Eng-8 (c. 785)
c. 415–345	25.5	Eng-10 (c. 385)

## Discussion

The local vegetation composition of two sequences from raised-bog deposits in The Netherlands has been reconstructed in detail and the sequences were  $^{14}\text{C}$  wiggle-match dated at high resolution

(Figure 3), thereby forming a discontinuous, precisely dated record from c. 4500 to c. 340 cal. BC. From the local vegetation reconstruction, several wet-shifts were inferred (Figures 4 and 5).

Most of the major rises in the residual  $\Delta^{14}\text{C}$  record were coeval with wet-shifts in the cores (Figures 4 and 5; Table 1). As raised bogs depend entirely on precipitation for water and nutrients, the wet-shifts in the sequences are assumed to have been caused by increases in effective precipitation (precipitation minus evapotranspiration), and thus by changes into a wetter and/or cooler climate (e.g., Barber, 1981; Blackford, 2000; Mauquoy *et al.*, 2002a; 2002b). Some wet-shifts in the studied peat cores occurred without a corresponding  $\Delta^{14}\text{C}$  rise. This was not unexpected; several factors could cause climatic changes and, moreover, wet-shifts could also be caused by internal dynamics.

Temporal links between archives of climate change and changes in solar activity have been reported before (e.g., Wijmstra *et al.*, 1984; Blackford and Chambers, 1995; Hong *et al.*, 2000; Bond *et al.*, 2001; Chambers and Blackford, 2001; Magny, 2004), but the chronologies used in these studies often were rather imprecise. With our approach of  $^{14}\text{C}$  wiggle-match dating, peat chronologies become far more precise. Only with such high-precision chronologies can short-term (decadal to centennial) events in climate proxy records be securely compared with short-term events in independently dated archives, e.g., with rises in the  $\Delta^{14}\text{C}$  record.

Core Eng-XIV (Kilian *et al.*, 1995; 2000) was collected at a location within a few metres from core Eng-XV, and was  $^{14}\text{C}$  wiggle-match dated at high resolution. This core showed a major wet-shift at the start of the rise of  $\Delta^{14}\text{C}$  at c. 850 cal. BC. However, no such major wet-shift was identified in core Eng-XV at this time. Only for a short time did *Sphagnum imbricatum* enter,

accompanied by some *Scheuchzeria* (wet-shift Eng-8; *c.* 785 cal. BC). The site had grown into a dry hummock; from *c.* 1100 to *c.* 600 cal. BC, the core consisted almost completely of thick stems and branches of *Calluna vulgaris*. Hummocks are thought to be less responsive to climatic changes than hollows or intermediate sites; even large increases in surface water level would not be recorded in high hummocks (Aaby, 1976; Barber *et al.*, 1998). This could also explain the lack of wet-shifts at the time of the large  $\Delta^{14}\text{C}$  rises starting at *c.* 4265 cal. BC (core MSB-2K) and *c.* 1535 cal. BC (core Eng-XV); at these times, the cores experienced hummock conditions (large amounts of *C. vulgaris* and *Ericales* rootlets).

Multicore investigations of precisely  $^{14}\text{C}$  wiggle-match dated peat cores could help in assessing the representativity and replicability of climate records as derived from peat deposits (Barber *et al.*, 1998; Charman *et al.*, 1999; Mauquoy *et al.*, 2002a). The precisely dated core Eng-XIV (see above) forms a duplicate of core Eng-XV from *c.* 1150 cal. BC to *c.* 340 cal. BC. As opposed to core Eng-XV, core Eng-XIV did show a major wet-shift at the major  $\Delta^{14}\text{C}$  rise of *c.* 850 cal. BC (Kilian *et al.*, 2000). Owing to constraints in time and budget, it was not possible to  $^{14}\text{C}$  wiggle-match date duplicate cores from the period of *c.* 4500 to *c.* 1150 cal. BC.

The wet-shift at the major rise of  $\Delta^{14}\text{C}$  at *c.* 850 cal. BC mentioned above was coeval with a major climatic change in many parts of the world. An overview of the global climatic change during this period is given by van Geel *et al.* (1998); additional evidence of this change comes from the North Atlantic Ocean (Bond *et al.*, 2001), the Norwegian Sea (Calvo *et al.*, 2002), Northern Norway (Vorren, 2001), England (Waller *et al.*, 1999), the Czech Republic (Speranza *et al.*, 2000; 2002), central southern Europe (Magny, 2004), Chile (van Geel *et al.*, 2000), New Mexico (Armour *et al.*, 2002) and across the continent of North America (Viau *et al.*, 2002).

### $\Delta^{14}\text{C}$

Past variations in atmospheric  $^{14}\text{C}$  content ( $\Delta^{14}\text{C}$ ) have been the result of changes in  $^{14}\text{C}$  production (depending on solar variability, galactic cosmic ray flux and/or geomagnetic field strength) and/or changes in the carbon cycle (in particular ocean ventilation changes). Radiocarbon and other cosmogenic isotopes such as  $^{10}\text{Be}$  are produced by galactic cosmic rays entering the Earth's atmosphere. Solar wind (a low-density proton-electron gas, streaming from the sun) in combination with the Earth's magnetic field, provides a shield against a large amount of the galactic cosmic rays entering the Earth's atmosphere. A decreased solar activity leads to less solar wind, reduced shielding against cosmic rays, and thus to increased production of cosmogenic isotopes (e.g., Hoyt and Schatten, 1997; Beer, 2000).

### $\Delta^{14}\text{C}$ and solar activity

Rapid major increases in  $\Delta^{14}\text{C}$  during the Holocene, such as the one starting around 850 cal. BC and the increases during the 'Little Ice Age', are attributed to decreases in solar activity (e.g., Stuiver and Braziunas, 1993; 1998; Chambers *et al.*, 1999; Beer, 2000; Beer *et al.*, 2002; Goslar, 2002; R. Muscheler, personal communication). Radiocarbon and  $^{10}\text{Be}$  levels changed together with observed sunspot indices and climatic changes during recent centuries (e.g., Beer, 2000). Recently the  $^{14}\text{C}$  signal has been disturbed by nuclear bombs and by large-scale burning of fossil fuel. Moreover, changes in instrumental records (measured reliably only since the most recent decades) of cosmic rays,  $^{10}\text{Be}$  levels, solar irradiance and solar activity indices such as sunspot numbers showed highly comparable behaviour (e.g., Hoyt and Schatten, 1997; Beer, 2000; Goslar, 2002).

### $\Delta^{14}\text{C}$ and cosmic ray intensity

An increase in galactic cosmic ray flux, for example caused by a supernova, could lead to increased atmospheric levels of cosmogenic isotopes such as  $^{14}\text{C}$ . To our knowledge, such explanations of changes in cosmogenic isotope levels have only been reported for periods before the Holocene (e.g., Shaviv, 2002). Moreover, there are strong theoretical arguments in favour of a quite stable galactic cosmic ray flux (J. Beer, personal communication).

### $\Delta^{14}\text{C}$ and geomagnetic field

Fluctuating geomagnetic activity could influence atmospheric  $^{14}\text{C}$  levels as well. Most studies assume that only the long-term (>3 ka) changes in cosmogenic isotopes are forced by geomagnetic changes (e.g., Merrill *et al.*, 1996; Beer, 2000; Beer *et al.*, 2002). Holocene changes in geomagnetism have been reconstructed from several regions (e.g., Valet *et al.*, 1998; Ali *et al.*, 1999; Gogorza *et al.*, 2000; Yang *et al.*, 2000; Laj *et al.*, 2002; Ojala and Saarinen, 2002; Snowball and Sandgren, 2002). Although long-term geomagnetic trends appear to be more or less similar between these records, they differ at shorter timescales. Several of the records show intriguing short-term changes in intensity, declination and inclination. However, changes in geomagnetic field are complex and only partly understood, and it is not known to what extent the reported short-term changes were coeval globally or merely artifacts caused by chronological problems, changes in sedimentation, and/or local, non-dipolar changes in magnetic field (Merrill *et al.*, 1996). Local variations in magnetic field would not have a global effect and could thus not cause major changes in the production rate of cosmogenic isotopes (J. Beer, personal communication). Neither do the reported rapid changes in the geomagnetic records correspond well with the rapid fluctuations in the  $\Delta^{14}\text{C}$  record. Snowball and Sandgren (2002: 529) however, state that owing to 'the current lack of a high-resolution reconstruction of the geomagnetic field intensity (in terms of a dipole-moment), it cannot be assumed that short-term (<10<sup>3</sup> year) variations in solar activity are solely responsible for similar duration anomalies in the production rates of cosmogenic nuclides, as the internal dynamics of the Earth's geodynamo may promote similar features'. However, even if changes in geomagnetic field would cause major and rapid  $\Delta^{14}\text{C}$  changes, it has to be noted that changes in the Earth's magnetic field can be caused by changes in solar activity (Merrill *et al.*, 1996).

### $\Delta^{14}\text{C}$ and the ocean

When  $^{14}\text{C}$  is produced in the atmosphere, it oxidizes to  $^{14}\text{CO}_2$  and enters the global carbon cycle. As the ocean is the largest reservoir in the carbon cycle, changes in  $\text{CO}_2$  exchange between the ocean and the atmosphere could cause changes in atmospheric  $^{14}\text{CO}_2$  content. Several studies (Hughen *et al.*, 1998; 2000; Muscheler *et al.*, 2000; Marchal *et al.*, 2001) hold a supposed near-cessation of the thermohaline circulation in the North-Atlantic Ocean during the Younger Dryas at least partly responsible for the concurrent  $\Delta^{14}\text{C}$  rise. Such a rise could have been caused by increased oceanic uptake of  $\text{CO}_2$  from the atmosphere and/or reduced ventilation of  $^{14}\text{C}$ -depleted ocean water, after which even a constant production of  $^{14}\text{CO}_2$  would cause rising atmospheric  $^{14}\text{CO}_2$  levels. Goslar *et al.* (2000) and Renssen *et al.* (2000) propose 'non-oceanocentric' scenarios, where a decline in solar activity is argued to have caused the Younger Dryas  $\Delta^{14}\text{C}$  rise, and also the shift to cold climatic conditions (possibly in concert with ocean circulation changes). If the ocean should be held responsible for the major, rapid rises in atmospheric  $^{14}\text{C}$  content during the Holocene, major changes in ocean circulation would need to have occurred. During the Holocene, no such major ocean circulation changes have been detected (Chapman and Shackleton, 2000; Keigwin and Boyle, 2000; Bond *et al.*, 2001). Therefore, changes in ocean circulation cannot have caused the rapid and large

increases in atmospheric  $^{14}\text{C}$  content during the Holocene (Stuiver *et al.*, 1991).

### Solar forcing of climatic change

A strong case that changes in  $^{14}\text{C}$  production rate (and not ocean circulation) were the cause of the rapid changes in atmospheric levels of  $^{14}\text{C}$  during the Holocene is that  $^{10}\text{Be}$  and  $^{14}\text{C}$  showed highly similar changes (Bard *et al.*, 1997; R. Muscheler, personal communication). The fluctuations of these isotopes also corresponded with major changes in the sunspot cycle during the last c. 350 years, and with precise satellite measurements of solar irradiation during the last few decades (Hoyt and Schatten, 1997). Considering the evidence above, the major rises in  $\Delta^{14}\text{C}$  discussed in this paper were most probably caused by changes in solar activity. Moreover, nearly every major  $\Delta^{14}\text{C}$  rise was coeval with a wet-shift in the mid-Holocene peat cores reported here. Because these wet-shifts were most probably caused by a change to a wetter and/or cooler climate, the present study gives additional indications for solar forcing of climatic change.

### Forcing mechanisms

Most climate models cannot explain how relatively small changes in solar irradiance alone could force changes in climate. Possible amplifying factors for solar forcing of climatic change are discussed by van Geel *et al.* (1999). One likely forcing mechanism involves variations of solar UV irradiance, which cause changed production of ozone and related absorption of heat in the earth's atmosphere, resulting in shifts of the atmospheric circulation cells (Haigh, 1996; van Geel *et al.*, 1999; 2001; Schuurmans *et al.*, 2001; Rozema *et al.*, 2002). Carslaw *et al.* (2002) review a possible amplifying mechanism for solar forcing of climatic change through the connection between cosmic rays and cloud formation. Ocean circulation changes forced by solar variability could form an additional amplifying mechanism (Bond *et al.*, 2001).

### Conclusions

Nine out of 11 mid-Holocene major  $\Delta^{14}\text{C}$  rises were coeval with wet-shifts (as inferred from changes in reconstructed vegetation composition) in two precisely  $^{14}\text{C}$  wiggle-match dated raised-bog deposits. By demonstrating the temporal link between major  $\Delta^{14}\text{C}$  rises (probably caused by declines in solar activity) and wet-shifts in peat (probably caused by climate getting cooler and/or wetter), the present paper adds to the accumulating evidence that solar variability has played an important role in forcing climatic change during the Holocene. Knowledge about solar forcing of climatic change is important for evaluating causes of recent global warming (anthropogenic and natural), and for predicting future climatic changes.

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