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

Maarten Blaauw,1* Bas van Geel1 and Johannes van der Plicht2

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

Abstract: Two cores of mid-Holocene raised-bog deposits from the Netherlands were 14C 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 Δ14C archive (probably caused by major declines in solar activity). The use of Δ14C 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, 14C wiggle-match dating, mid-Holocene, wet-shifts, The Netherlands.

Introduction

Changes in solar activity during the Holocene can be reconstructed using the proxy Δ14C (Stuiver and Braziunas, 1993; 1998; Stuiver et al., 1998; Chambers et al., 1999; Beer, 2000; Goslar, 2002). A temporal link between changes in Δ14C and Holocene climatic changes has been documented by several studies (Blackford and Chambers, 1995; Karlén and Kuylenstierna, 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 14C wiggle-match dating, high-precision chronologies can be obtained of peat deposits (e.g., Killian et al., 1995; 2000; Blaauw et al., 2003). Wet-shifts in northwest and central European peat deposits dated with this method coincided with abrupt Δ14C 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 Engbertsdijksvenen; 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.

*Author for correspondence. Present address: Botany Department, Trinity College Dublin, Dublin 2, Ireland (e-mail: drieteenmeew@hotmail.com)
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(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 hygrofphilous 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).

- Eric tetralix is characteristic of wet heath and mire communities in oceanic western Europe (Bannister, 1966). It appears to grow in slowly 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 cespitosum) 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.

- Amphihterena 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 (Engbertsdijksvenen). However, a large hiatus (lasting from c. 4200 to 2500 cal. bc) was encountered in a core from Engbertsdijksvenen that was sampled to investigate the period of c. 4500 to 2500 cal. bc (Blauw, 2003). Therefore, an additional core was collected at a different site (Meerstalblok; core MSB-2K). Cores MSB-2K and Eng-XV were 14C wiggle-match dated (for explanation, see Blauw et al., 2003). The resulting chronologies are shown in Figure 3. The 14C sequences of both cores were divided into three subsets based upon changes in stratigraphy and most likely positions of 14C 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 σ 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 (Blauw 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 Δ14C (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 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.
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, 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**

**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 Δ¹⁴C 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). Δ¹⁴C is the relative ¹⁴C content (i.e., deviation of the activity from the standard), corrected for radioactive decay, and expressed in ‰. Here Δ¹⁴C is, in addition, detrended for the geomagnetic component and is called ‘residual Δ¹⁴C’.

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.

Δ¹⁴C rises and wet-shifts
As can be seen from Figures 4 and 5, and Table 1, most of the major rises in the residual Δ¹⁴C 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 Δ¹⁴C rise (core MSB-2K during the Δ¹⁴C rise of c. 4265–4215 cal. BC, and core Eng-XV during the Δ¹⁴C rise of c. 1535–1485 cal. BC). Even smaller increases in Δ¹⁴C at times appear to have been coeval with wet-shifts (wet-shifts Eng-1, 3 and 4), although this may be a coincidence.
Table 1 Major $\Delta^{14}C$ 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) $\Delta^{14}C$ record to be considered major here, it has to comply with two rules: its amplitude should be at least twice the 1σ error envelope of the $\Delta^{14}C$ record (which averages 5‰ during the period considered) and the $\Delta^{14}C$ record should show rising levels during more than two measurements (≥30 y).

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

Discussion

The local vegetation composition of two sequences from raised-bog deposits in The Netherlands has been reconstructed in detail and the sequences were $^{14}C$ 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 $\Delta^{14}C$ 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 $\Delta^{14}C$ 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 $^{14}C$ 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 $\Delta^{14}C$ record. Core Eng-XIV (Killian et al., 1995; 2000) was collected at a location within a few metres from core Eng-XV, and was $^{14}C$ wiggle-match dated at high resolution. This core showed a major wet-shift at the start of the rise of $\Delta^{14}C$ 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 Δ14C 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 14C 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 Δ14C rise of c. 850 cal. BC (Kilian et al., 2000). Owing to constraints in time and budget, it was not possible to 14C wiggle-match date duplicate cores from the period of c. 4500 to c. 1150 cal. BC.

The wet-shift at the major rise of Δ14C 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 (Armout et al., 2002) and across the continent of North America (Viau et al., 2002).

### Δ14C

Past variations in atmospheric 14C content (Δ14C) have been the result of changes in 14C production (depending on solar variability, galactic cosmic ray flux and geomagnetic field strength) and/or changes in the carbon cycle (in particular ocean ventilation changes). Radiocarbon and other cosmogenic isotopes such as 10Be 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).

### Δ14C and solar activity

Rapid major increases in Δ14C 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 10Be levels changed together with observed sunspot indices and climatic changes during recent centuries (e.g., Beer, 2000). Recently the 14C 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, 10Be 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).

### Δ14C 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 14C. 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).

### Δ14C and geomagnetic field

Fluctuating geomagnetic activity could influence atmospheric 14C 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 Δ14C 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 (<103 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 Δ14C 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).

### Δ14C and the ocean

When 14C is produced in the atmosphere, it oxidizes to 14CO2 and enters the global carbon cycle. As the ocean is the largest reservoir in the carbon cycle, changes in CO2 exchange between the ocean and the atmosphere could cause changes in atmospheric 14CO2 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 Δ14C rise. Such a rise could have been caused by increased ocean uptake of CO2 from the atmosphere and/or reduced ventilation of 14C-depleted ocean water, after which even a constant production of 14CO2 would cause rising atmospheric 14CO2 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 Δ14C 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 14C 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 $^{14}$C content during the Holocene (Stuiver et al., 1991).

**Solar forcing of climatic change**

A strong case that changes in $^{14}$C production rate (and not ocean circulation) were the cause of the rapid changes in atmospheric levels of $^{14}$C during the Holocene is that $^{14}$Be and $^{14}$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 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 $^{14}$C discussed in this paper were most probably caused by changes in solar activity. Moreover, nearly every major $^{14}$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 changes in the 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 $^{14}$C rises were coeval with wet-shifts (as inferred from changes in reconstructed vegetation composition) in two precisely $^{14}$C wiggle-match dated raised-bog deposits. By demonstrating the temporal link between major $^{14}$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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