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THE SHARP RISE OF $\Delta^{14}C$ *ca.* 800 cal BC: POSSIBLE CAUSES, RELATED CLIMATIC TELECONNECTIONS AND THE IMPACT ON HUMAN ENVIRONMENTS

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ABSTRACT. In this study we report on accelerator mass spectrometry (AMS) wiggle-match dating of selected macrofossils from organic deposits *ca.* 800 cal BC (*ca.* 2650 BP). Based on paleological, archaeological and geological evidence, we found that the sharp rise of atmospheric ^{14}C between 850 and 760 cal BC corresponds to the following related phenomena:

1. In European raised bog deposits, the changing spectrum of peat forming mosses and a sharp decline in decomposition of the peat indicate a sudden change from relatively dry and warm to cool, moist climatic conditions.
2. As a consequence of climate change, there was a fast and considerable rise of the groundwater table so that peat growth started in areas that were already marginal from a hydrological point of view.
3. The rise of the groundwater table in low-lying areas of the Netherlands resulted in the abandonment of settlement sites.
4. The contemporaneous earliest human colonization of newly emerged salt marshes in the northern Netherlands (after loss of cultivated land) may have been related to thermal contraction of ocean water, causing a temporary stagnation in the relative sea-level rise.

Furthermore, there is evidence for synchronous climatic change in Europe and on other continents (climatic teleconnections on both hemispheres) *ca.* 2650 BP. We discuss reduced solar activity and the related increase of cosmic rays as a cause for the observed climatological phenomena and the contemporaneous rise in the ^{14}C-content of the atmosphere. Cosmic rays may have been a factor in the formation of clouds and precipitation, and in that way changes in solar wind were amplified and the effects induced abrupt climate change.

INTRODUCTION

Natural variations in the atmospheric radiocarbon content, which are reflected as wiggles in the ^{14}C calibration curve, severely limit the possibilities for high-resolution dating of changes in vegetation and climate recorded in lake deposits and bogs. van Geel and Mook (1989) stressed the importance of the strategy of ^{14}C wiggle-match dating (WMD) of organic deposits, and the fact that WMD can reveal relationships between ^{14}C variations and short-term climatic fluctuations caused by solar and/or geomagnetic variations (Wigley and Kelly 1990; Davis, Jirikowic and Kalin 1992; Magny 1993a,b; Jirikowic, Kalin and Davis 1993; Stuiver and Braziunas 1993). Kilian, van der Plicht and van Geel (1995) have shown that by using the strategy of WMD, raised-bog deposits in particular can be dated more precisely. The technique of precise wiggle-matching is usually restricted to samples showing annual banding (trees, annually laminated lake sediments). The assumption of constant accumulation, or a linear time-depth relation (Kilian, van der Plicht and van Geel 1995), is evidently simplistic for complex peat sequences. However, it seems to suit brief stratigraphic intervals well, and can easily be adapted to fit a more complex picture (Kilian, van Geel and van der Plicht ms.).

With WMD, the raised-bog archive can be compared effectively with other proxy data archives, more so because WMD showed that an unexpected ^{14}C reservoir effect plays a role in raised-bog deposits (individual conventional ^{14}C dates appeared to be 100–250 yr too old). WMD is an elegant way of

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identifying this reservoir effect and of estimating its magnitude. Moreover, Kilian, van der Plicht and van Geel (1995) showed that the sharp rise of the former ^{14}C content of the atmosphere (Δ^{14}C, as it is calculated from the dendrochronologically dated ^{14}C-calibration curve) between *ca.* 2750 and 2450 BP (*ca.* 850–760 cal BC), appeared to be synchronous with the transition from the often highly decomposed, so-called "older *Sphagnum* peat", to the less decomposed "younger *Sphagnum* peat" at the Subboreal/Subatlantic transition in northwest European raised bogs. This change in decomposition and also in species composition of raised bogs represents one of the most clearly defined climate shifts during the Holocene, and was used by Blytt and Sernander (Sernander 1910) in their classical division of the Holocene. The Subboreal was interpreted as representing a relatively warm, dry period and the Subatlantic as a humid and, especially in the beginning, a cold episode.

Van Geel, Buurman and Waterbolk (1996) illustrated and interpreted the succession of peat-forming mosses in a core from the raised bog Engbertsdijksveen and described details of the correspondence between the changing moss composition, the fluctuations in the pollen curve of *Corylus avellana* (Hazel) and the rise in Δ^{14}C *ca.* 800 cal BC. Van Geel *et al.* (1996) combined paleoecological evidence with archaeological information for the impact of climate change *ca.* 800 cal BC on human populations in the Netherlands. They also considered evidence from elsewhere in Europe and other areas for a synchronous climate change. Here, we present new and more detailed evidence for the abovementioned climate change and we discuss the apparent link between trends in changes of solar activity and cosmic rays, cloudiness, precipitation and temperature changes. An example of that link is provided by Svensmark and Friis-Christensen (1997). We apply their discussion here, in addition to another possible mechanism, to the Subboreal/Subatlantic climate change.

Radiocarbon, Paleoecology and Archaeology of Investigated Sites

The End of the Bronze Age Habitation in West-Friesland and AMS Dating of the Rising Groundwater Table at the Site Enkhuizen-Dijk

Tidal activity ceased *ca.* 3500 BP in the northeast part of the province of Noord-Holland as a consequence of the closure of a tidal inlet. The area known as West-Friesland became attractive for Bronze Age farmers who colonized the area *ca.* 3350 BP. During the later habitation period, for which 13 ^{14}C dates are available (ranging from 2760 to 2620 BP; see Table 1), people adapted to increasing wetness

TABLE 1. ^{14}C Dates of the "Terpen" Phase (Extremely Wet Conditions) of Excavated Settlement Sites in West-Friesland, the Netherlands

^{14}C age (yr BP)	Lab no.	Material
2760 ± 35	GrN-7475	Wood
2745 ± 30	GrN-8561	Charcoal
2745 ± 30	GrN-7507	Charcoal
2740 ± 40	GrN-7508	Charcoal
2710 ± 35	GrN-7509	Charcoal
2700 ± 70	UtC-2355	Charred seeds
2690 ± 25	GrN-8563	Charcoal
2685 ± 30	GrN-8562	Charcoal
2680 ± 50	GrN-5051	Charcoal
2660 ± 60	UtC-2356	Charcoal
2650 ± 30	GrN-8334	Wood
2650 ± 45	GrN-5048	Charcoal
2620 ± 20	GrN-8564	Charcoal

of the area by building their houses on dwelling mounds ("terpen"). However, the settlement areas eventually became so wet that no further adaptations were possible and the area was abandoned shortly after 2620 BP, and was not reoccupied until medieval times. The ^{14}C dates of archaeological material for the period of accelerated rise of the water table range between *ca.* 850 and 800 cal BC. Apart from the archaeological evidence, van Geel, Buurman and Waterbolk (1996) also referred to ample paleoecological evidence for an accelerated water table rise in West-Friesland during this period and they realized that: 1) the period of the dwelling mound phase was contemporaneous with the beginning of a rapid increase in ^{14}C content of the atmosphere, and 2) indications for increasing wetness and the final abandonment of the area reflect the abrupt climatic change as recorded in raised-bog deposits (a shift from older, highly decomposed, to younger, fresh *Sphagnum* peat).

Enkhuizen-dijk is a site where the rise of the water table was recorded in sediments (van Geel, Hallewas and Pals 1983). The Bronze Age soil surface consisted of sandy clay (Fig. 1). The upper *ca.* 5 cm of the soil was a pitch-black horizon, containing numerous charcoal particles. On top of the black soil surface, a 14-cm-thick shallow water deposit and a 45-cm-thick peat deposit were present. In 1980 a bulk sediment sample of the shallow water deposit was conventionally dated at 2800 ± 50 BP (GrN-10993). However, the sediment contained many small charred particles, possibly eroded from the pitch-black soil horizon which had been exposed during the preceding habitation phase. In 1995, we realized that the original 2800 BP date for the recorded rise of the water table was probably too old. The metal box containing the original sediment core was still available, so we selected seeds and moss remains for AMS dating from the levels at 13, 14, 15 and 17 cm. Figure 1 shows the new

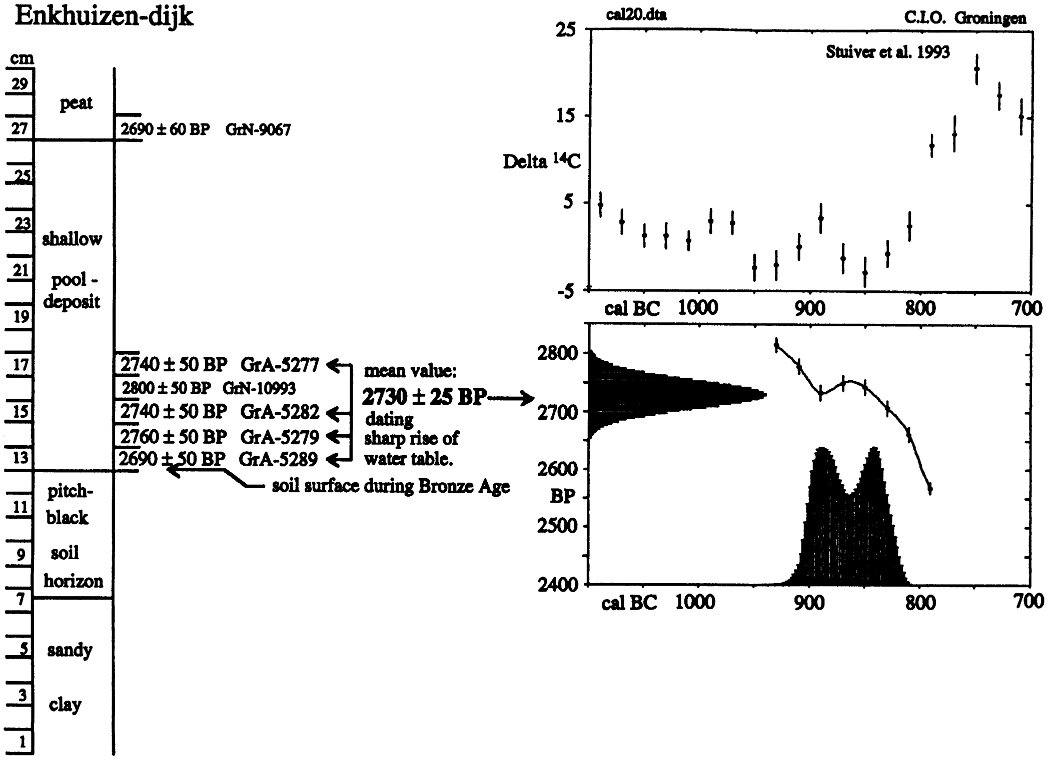

Fig. 1. Stratigraphic position of AMS samples dating a sudden rise of the water table at the site Enkhuizen-dijk (van Geel *et al.* 1983) and calibration of the mean value of these dates.

dating results (four GrA- dates ranging between 2760 and 2690 BP). The pool deposit showed characteristics of running water, and, after comparison with the calibration curve, we conclude that the sequence of the four AMS dates from bottom to top apparently does not represent a chronological order. Therefore, we calibrated the mean value of the four dates as shown at the right side of Figure 1. The calibration results in a probability distribution in calendar years, ranging from *ca.* 906 to *ca.* 820 cal BC (95% confidence level). This range includes the moment of the start of the sharp rise of $\Delta^{14}C$ (more cosmic rays, more clouds, more precipitation; see discussion and Fig. 2), which is the most probable calendar age for the suddenly rising water table. This also fits with the archaeological ^{14}C dates for the start of the period of extremely wet conditions (Table 1).

Rising Water Tables at Zwolle-Ittersumerbroek

At Zwolle-Ittersumerbroek (province of Overijssel), near the river IJssel, a Late Neolithic/Bronze Age/Early Iron Age settlement area was excavated on a relatively low coversand plateau (Waterbolk 1995a,b). The termination of local settlements was caused by a rise in the water table and related peat growth and deposition of clays and sands by the river IJssel. The youngest ^{14}C dates of the settlement (2670 ± 35 BP, 2600 ± 30 BP and 2540 ± 30 BP, GrN-18122, 18726 and 18123, respectively) indicate that the area became uninhabitable (apparently as a consequence of impeded drainage after abrupt climate change) during the period of sharp increase of $\Delta^{14}C$ (compare the above mentioned dates with the calibration curve and corresponding $\Delta^{14}C$ as illustrated in Fig. 3).

Start of Peat Growth in the Raised Bog Fochtelooër Veen

The former raised bog Fochtelooër Veen is situated in the eastern part of the province of Friesland, at a relatively low part of the sandy Pleistocene area. It is a remnant of the large bog complex of Smilde-Fochteloo-Haule, situated on a slightly northwest-sloping plateau that forms part of the watershed between two river systems (Vecht and Ems). The western part of the former bog complex has been removed in historical time (peat was used for fuel), and it is in this formerly peat-covered area that archaeological evidence for settlement sites is present. Klaver (1981) studied a peat column located <1 km from a prehistoric barrow excavated at "de Knolle" in 1926. The barrow was built in the Middle Bronze Age and contained a secondary urn burial dating from the Early Iron Age. Barrow and urn cemeteries are generally situated within or at the edge of a so-called Celtic field-system. Such Celtic (arable) fields have been identified at various places in and near the former bog area, but not so far near this particular spot. The local topography suggests that at least a part of the Celtic field to be expected here must have been lying between the sample site and the barrow. A detailed study of the occupation history of the area in relation to bog growth is in preparation by H. T. Waterbolk.

In the column studied by Klaver (1981), a bulk peat sample that had been taken *ca.* 3.5 cm above the sandy subsoil was conventionally ^{14}C dated at 2520 ± 55 BP (GrN-10130). The complete sample sequence had been taken, and stored in metal boxes, so in 1995, to address new questions, we took extra material from the column to apply ^{14}C AMS wiggle-match dating. The wiggle-matched dating results from a series of six contiguous charcoal and peat samples on top of the sandy subsoil show that peat growth started here *ca.* 2690 BP (Fig. 3; Table 2). As in the area of West-Friesland, a sharp rise of the water table as a consequence of climate change in the area of the Fochtelooër Veen will have caused the loss of formerly cultivated land in the beginning of the Early Iron Age. The horizontal line in Figure 3 *(p. 542)* shows that the evidence for climate change is at the start of a sharp rise of $\Delta^{14}C$. For our interpretation (more cosmic rays mean more clouds and precipitation) we refer to the discussion and to a simplified illustration of changes in the landscape of the northern Netherlands (Fig. 2).

According to Kilian, van der Plicht and van Geel (1995), conventionally dated bulk samples of raised-bog peat often show a reservoir effect (100–250 ^{14}C yr too old). The source of old carbon

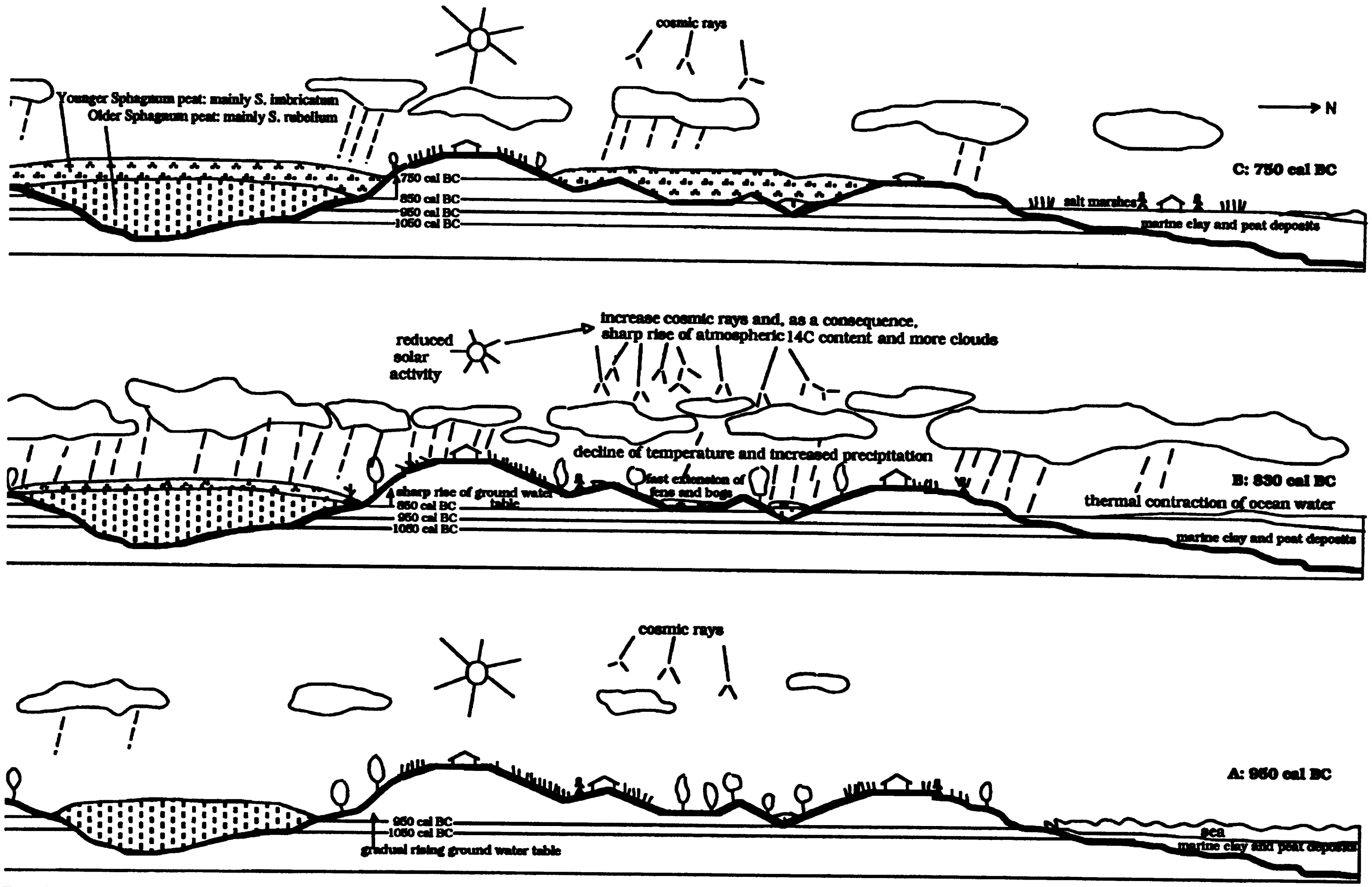

Fig. 2. Development of the landscape in the northern Netherlands during the older part of the first millennium BC under influence of climate change. Between phases A and B a decline of solar irradiance caused an increase in cosmic rays, resulting in a sharp increase in the atmospheric ^{14}C content and also in more clouds, more precipitation and lower temperatures (change of atmospheric circulation patterns). Consequently, there was a sharp increase of the groundwater level and enhanced bog growth. Farmers in hydrologically marginal areas had to move to drier sites. Salt marshes emerged, probably as a consequence of thermic contraction of ocean water, and these areas were colonized. When the solar irradiance changed again to the less extreme values, the atmospheric circulation patterns did not move to their earlier positions and, consequently, the relatively cool and wet climate persisted.

TABLE 2. ^{14}C Dates Fochtelooër Veen-I, the Netherlands

Sample (cm)	^{14}C age (yr BP)	Lab no.	Material
69	2190 ± 50	GrN-10132	Bulk sample of peat
45	2410 ± 55	GrN-10131	Bulk sample of peat
29	2520 ± 55	GrN-10130	Bulk sample of peat
28	2495 ± 40	GrA-5283	AMS-date of selected overground remains of *Calluna* and *Erica*
27	2500 ± 50	GrA-5284	AMS-date of selected overground remains of *Carex*, *Calluna* and *Erica*
26	2690 ± 50	GrA-5285	AMS-date of selected overground remains of *Carex* and charred stems and leaves of *Calluna* and *Erica*
25	2730 ± 50	GrA-5287	AMS-date of unidentified charred material
25	2750 ± 50	GrA-5286	Duplo of GrA-5287
24	2820 ± 50	GrA-5278	AMS-date of unidentified charred material

could not be directly detected yet, but based on circumstantial evidence they supposed that methane from deeper peat layers is taken up by methane-consuming bacteria, thus forming a source of old carbon in the root zone of especially ericaceous plants. Fungi associated with the living roots are likely to fix CO_2 and may transport CO_2 into the roots of their host plant. In the present study the peat cores do not show evidence of reservoir effects. The samples from the Fochtelooër Veen as shown in Figure 3 represent the start and early growth of the peat-forming vegetation (no raised bog yet). The samples were at low vertical distances from the sandy subsoil, so there was no thick peat layer that could be an important source of "old", carbon-containing gas. The AMS samples from Carbury Bog (see Table 3) consisted of carefully selected aboveground plant remains. Only sample GrA-976 consisted of *ca.* 1 volume percent rootlets of Ericales, but, fitting quite well in the sequence of the series of dates, this sample does not seem to show an apparent age.

TABLE 3. ^{14}C AMS dates from Carbury Bog, Ireland

Sample (cm)	^{14}C age (yr BP)	Lab no.	Material
100	2515 ± 50	GrA-2136	Seeds of *Rhynchospora alba*
99	2625 ± 30	GrA-976	*Sphagnum imbricatum*, *ca.* 1 vol.% rootlets of Ericales
98	2615 ± 35	GrA-975	*Sphagnum imbricatum*
97	2700 ± 35	GrA-979	*Sphagnum imbricatum*
96	2715 ± 35	GrA-980	*Sphagnum imbricatum*
95	2850 ± 35	GrA-981	Stems and opercula of *Sphagnum* species, seeds and stems of *Rhynchospora alba*, overground remains of Ericales and some elytra of Coleoptera

Colonization of the Salt Marshes in the Northern Netherlands

The loss of cultivated land in Pleistocene sandy areas in the northern Netherlands (areas that were already marginal from a hydrological point of view) caused depopulation. A causal relationship between this depopulation and the colonization of the salt marshes in the northern Netherlands during the Early to Middle Iron Age was already mentioned by Waterbolk (1959, 1966). Arguments for migration to the salt marsh areas were based on archaeological evidence: pottery of the so-called

Ruinen-Wommels type was found in both areas. ^{14}C dates from the earliest settlements in the salt marsh area are particularly important. The start of the settlement at Middelstum (Boersma 1983) is dated at 2555 ± 35 BP, which may indicate that the earliest colonization occurred during or shortly after the period of climate change, when Δ^{14}C showed a steep rise. The colonization of the salt marsh area was not only related to the abovementioned environmental changes in the adjacent Pleistocene areas. Earlier migration was not possible because salt marshes emerged for the first time *ca.* 2650 BP (Roeleveld 1976; Griede 1978). Van Geel, Buurman and Waterbolk (1996) postulated that a slowing in sea level rise, contemporaneous with climate change, was caused by thermal contraction (for the phenomenon of thermal expansion, see Mörner 1995; Wigley and Raper 1993) of the upper layer of the ocean (Fig. 2) and/or of reduced velocity and pressure on the coast by the Gulf Stream. Moreover, after this climate change in the temperate zones more water will have accumulated in glaciers, as ground water in soils, in fens and bogs, and in clouds.

Evidence for Climatic Change Elsewhere in Europe and on Other Continents ca. 800 cal BC

In a review paper, van Geel, Buurman and Waterbolk (1996) compiled evidence for a considerable and abrupt climate change *ca.* 850 cal BC. The evidence was based on studies of lake and peat deposits, pollen analysis, dendrochronology, geomorphology, glacier studies and archaeological information. It was concluded that a climate change to cooler, wetter conditions occurred in the temperate and boreal zones of Europe, North- and South America, Japan and New Zealand. In addition to the paleoclimatological-archaeological evidence as mentioned by van Geel, Buurman and Waterbolk, new ^{14}C dates from the earliest Scythian grave monuments in Europe may indicate that extreme climatological conditions in Central Asia triggered the migration of Scythians to southeast Europe and western Asia. The oldest dates of the Kelermess monuments (northwest Caucasus) are 2690 ± 150 and 2610 ± 60 BP (Zaitseva *et al.* 1998), and thus also may correspond to the period of the sharply rising ^{14}C content of the atmosphere.

A climate change to cooler, wetter conditions in the temperate and boreal zones is in contrast with evidence for contemporaneous climate change in the Caribbean and in tropical Africa, where a change to drier conditions occurred. For the present study the example of evidence for climate change in Cameroon (Reynaud-Farrera, Maley and Wirrmann 1996) was derived in more detail: extra pollen samples were studied and extra samples from the sediment core were AMS-dated. In the discussion of the present paper we will use the recently published evidence for the effect of changing solar activity, related changes in cosmic rays, and the effect of such changes on cloudiness in the tropical and non-tropical part of the world (Pudovkin and Raspopov 1992; Raspopov *et al.* 1997; Svensmark and Friis-Christensen 1997). Here we present our AMS data from the Carbury Bog (Ireland) and Lac Ossa.

The Start of *Sphagnum imbricatum* in Carbury Bog, Ireland

Kouwenberg (1985) studied pollen and macrofossils in a peat sequence from the raised bog Carbury Bog, 46 km west of Dublin. The abrupt appearance and dominance of the oceanic species *Sphagnum imbricatum* was dated in the first instance by extrapolation of two ^{14}C dates at *ca.* 2600 BP. The original samples had been taken in metal boxes and stored at the laboratory in Amsterdam. In 1994, with new questions in mind, we took six contiguous subsamples around the transition from the more decomposed ericaceous peat to the fresh *S. imbricatum* peat. From these subsamples we selected aboveground macrofossils for AMS-dating (Table 3). For the relevant interval the changing frequencies of a selection of peat forming plant taxa (according to Kouwenberg 1985) are shown in the diagram (Fig. 4), and the corresponding AMS dates are shown in relation to the calibration curve. Considering the pureness of the selected material (almost no rootlets; see Table 3) no reservoir effect

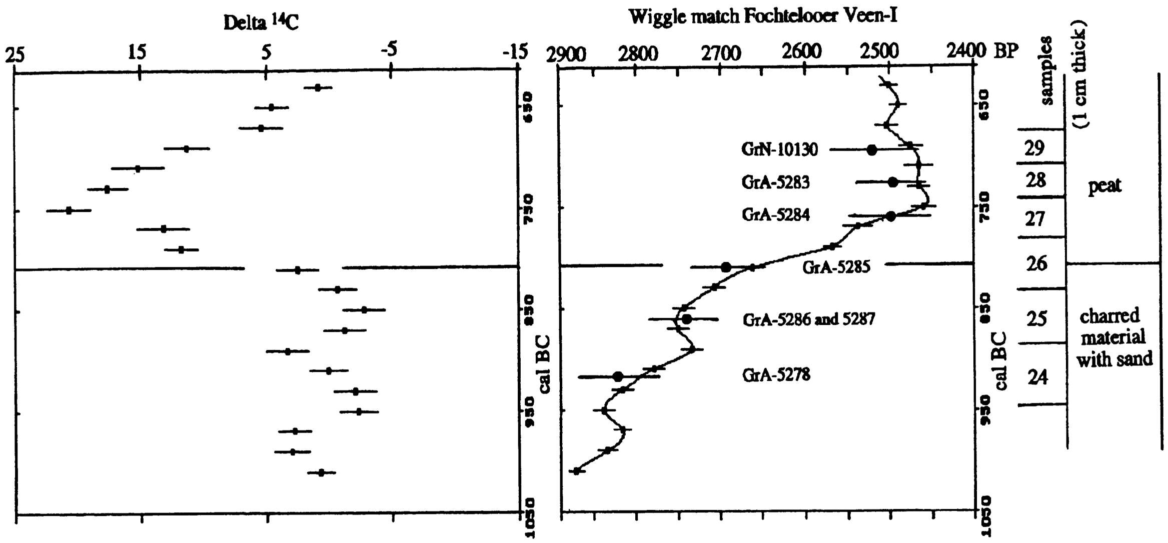

Fig. 3. ^{14}C wiggle-match of the base of the peat sequence Fochtelooër Veen-I, showing that a rise of the water table occurred when Δ^{14}C sharply rose *ca.* 800 cal BC (start of peat growth). Calibration curve and corresponding Δ values after Stuiver and Reimer (1993).

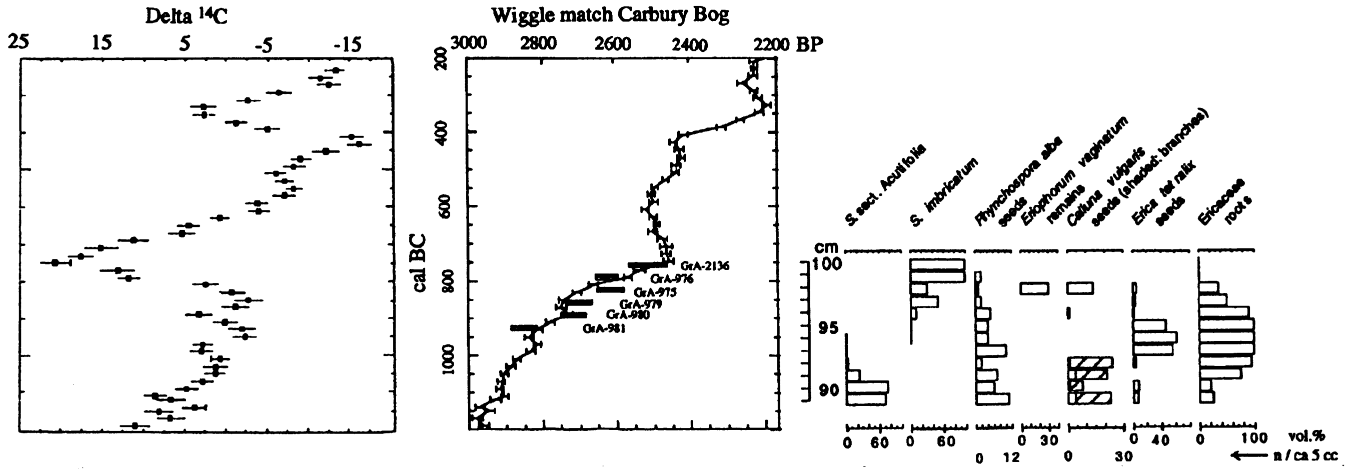

Fig. 4. ^{14}C wiggle-match of the start of ***Sphagnum imbricatum*** as a peat former in Carbury Bog, Ireland. Local conditions indicate that oceanic climate started when Δ^{14}C sharply rose at *ca.* 850 cal BC. Calibration curve and corresponding Δ values after Stuiver and Reimer (1993).

was expected (*cf.*, Kilian, van der Plicht and van Geel 1995). Figure 4 shows that the sharp increase of the oceanic species *S. imbricatum* is at the start of the sharp rise of Δ^{14}C *ca.* 850 cal BC.

Dating Climate Change as Recorded in the Sediments of Lac Ossa (Cameroon)

From palynological evidence in southwest Cameroon, Reynaud-Farrera, Maley and Wirrmann (1996) recorded a major change in vegetation at low and high altitudes after *ca.* 2730 BP and additional pollen analysis performed on the same core (Fig. 5) confirms this event. All the forest types present in this region since at least *ca.* 5000 BP were affected synchronously. A great extension of pioneer taxa such as *Alchornea, Macaranga,* an increase of Poaceae and the strong decrease of pollen taxa belonging to the Biafrean and montane forests were observed. This major change in the forest communities from southwest Cameroon is linked to a major climatic event, an arid crisis, previously recognized in the Congo and Cameroon *ca.* 3000 BP (Elenga and Vincens 1990; Elenga, Schwartz and Vincens 1992, 1994; Elenga *et al.* 1996; Maley 1992; Schwartz 1992; Giresse, Maley and Brenac 1994). This climatic event was also detected in East Africa between *ca.* 4000 BP and *ca.* 2500 BP (Vincens 1986, 1989; Hamilton 1987; Bonnefille and Riollet 1988; Roche, Bikwemu and Ntaganda 1988; Ssemmanda and Vincens 1993; Jolly, Bonneville and Roux 1994). The dry phase is responsible for the extension of disturbed and/or open types of vegetation. It leads to local fragmentation of the African forest, as it has been observed in some forested areas in the Congo with the occurrence of isolated enclosed savannas (De Foresta 1990; Schwartz, Guillet and Dechamps 1990), and to a complete drying up of some lakes such as lake Sinnda in the Niary valley (Congo) (Vincens *et al.* 1994). These local openings of the forests made the migration of Iron Age populations possible (Bantu immigration) as well as the spreading of metallurgic techniques which appeared at *ca.* 2400–2200 BP within a central African domain, which is now completely forested (Schwartz 1992).

The climate change originally recorded in Lac Ossa was only roughly dated by interpolation between two ^{14}C dates: 3330 ± 50 BP (244 cm; Beta-73084) and 2442 ± 43 BP (174 cm; Utc-3911). Bearing in mind the possibility that climate change here was also contemporaneous with the sharp rise of Δ^{14}C *ca.* 2650 BP, we AMS-dated extra samples from core OW4 of Lac Ossa (Fig. 5). Table 4 shows all the ^{14}C dates from core OW4. The pollen diagram shows the changes in the vegetation occurring from sample 200 cm onward. There are some irregularities in the sequence of ^{14}C dates that prevent the

TABLE 4. ^{14}C Dates (Bulk Sediment Samples) Lac Ossa, Cameroon

Depth	^{14}C age (yr BP)	Lab code
7.9 cm	90 ± 60	Beta 73082
63.7 cm	740 ± 50	Beta 86769
124 cm	1890 ± 60	Beta 73083
174 cm	2442 ± 43	Utc 3911
178 cm	2000 ± 70	GrA-4266
180 cm	2470 ± 60	GrA-4273
185 cm	2520 ± 50	GrA-6853
197 cm	2830 ± 50	GrA-5560
200 cm: sharp change in forest composition after climate change to drier conditions		
204 cm	2600 ± 50	GrA-6851
210 cm	2840 ± 50	GrA-5559
244 cm	3330 ± 50	Beta 73084
360 cm	3880 ± 60	Beta 73085
525 cm	4580 ± 60	Beta 73086
549 cm	4770 ± 60	Beta 73087

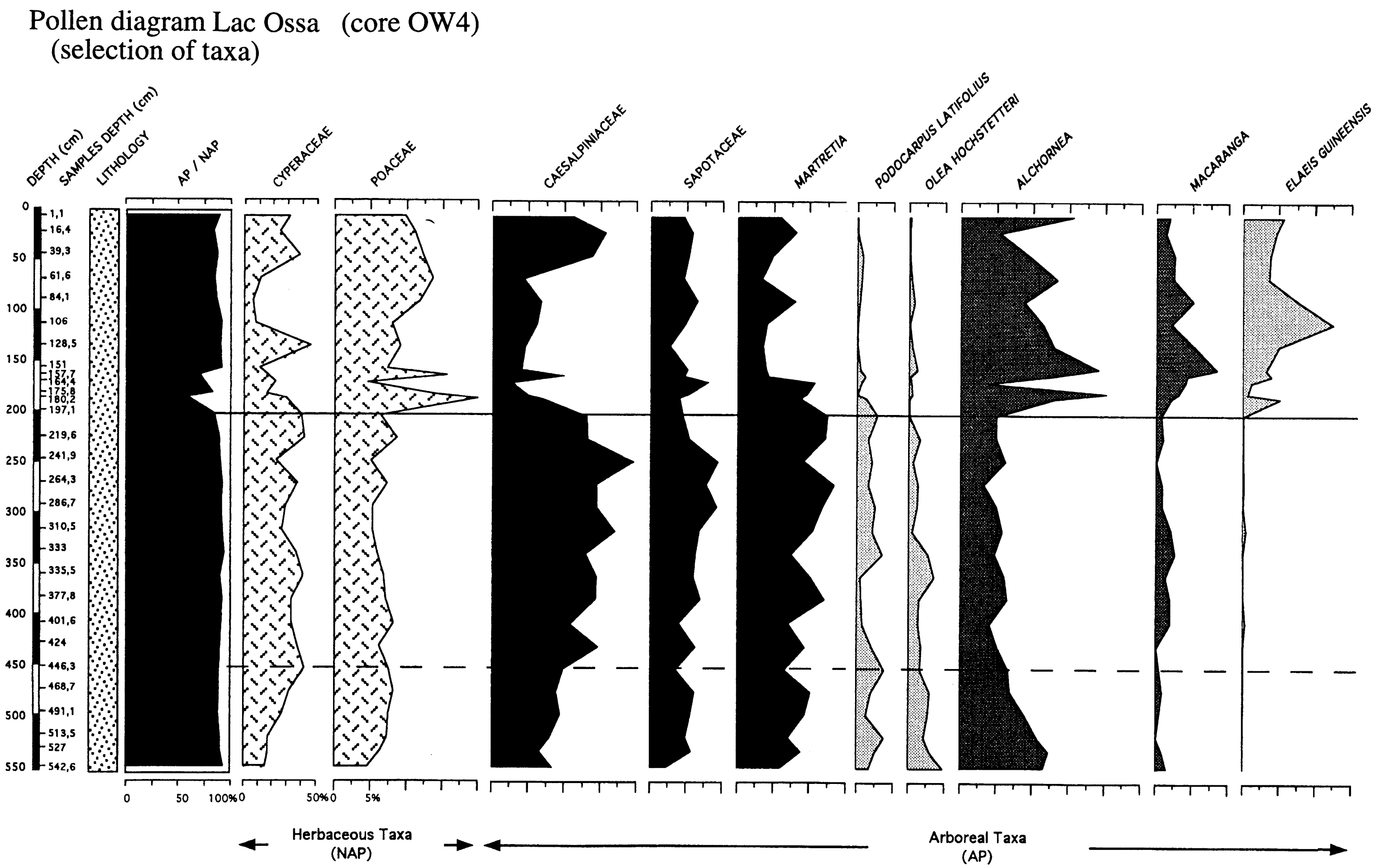

Fig. 5. Pollen diagram Lac Ossa (Cameroon) showing a major vegetational landscape change at the 200 cm level, which corresponds to *ca.* 2800 BP (*cf.* Table 4). A great extension of pioneer taxa such as *Alchornea, Macaranga,* an increase of Poaceae and the strong decrease of pollen taxa belonging to the Biafrean and montane forests indicate an arid crisis. Local openings of the forests stimulated the immigration of Neolithic populations.

application of WMD. Especially the date at 197 cm does not fit in the sequence. Nevertheless, the samples show that the change in the forest composition, as recorded at the 200-cm level, was contemporaneous with the rise in $\Delta^{14}C$ *ca.* 850 cal BC.

DISCUSSION

Climate Change *ca.* 800 cal BC and its Relation to $\Delta^{14}C$, Cosmic Rays and Solar Activity

The noted abrupt climate change *ca.* 2650 BP corresponds to one of a number of Holocene cold events identified by Harvey (1980). He analyzed the published proxy climate evidence and found indications for at least three Holocene phases with simultaneous cooling in Europe, North America and the Southern Hemisphere, *viz.*, *ca.* 4700–4500 BP, *ca.* 2700–2300 BP and the Little Ice Age.

Recently, O'Brien *et al.* (1995) inferred a direct correlation with the above periods in glaciochemical time series derived from the GISP2 Greenland Ice core. Based on changing concentrations of sea salt and terrestrial dusts, O'Brien *et al.* conclude that the cool phases are characterized in the North Atlantic region by an intensified polar atmospheric circulation, more often bringing winter-like, stormy weather to the region. Cooler climates reoccurred at intervals of *ca.* 2600 yr. Earlier, a similar oscillation was inferred by Dansgaard *et al.* (1984) using the Camp Century $\delta^{18}O$ Greenland ice core record. Moreover, as reported by Kerr (1995), Bond found evidence for small increases of ice-rafted debris in the Holocene part of North Atlantic Ocean cores at an interval of 1000–2400 yr, thus possibly coinciding with the quasi-cycle found by O'Brien *et al.* (1995). The discussed periods may correspond to so-called triple oscillation events during which the ^{14}C production rate changed, as reconstructed from tree rings (Stuiver and Braziunas 1989; Stuiver *et al.* 1991). The triple oscillations are defined as $\Delta^{14}C$ intervals during which at least two Spörer and Maunder type patterns occurred. The Spörer- and Maunder events were periods (1416–1534 AD and 1645–1715 AD, respectively) during which a minimum number of sunspots were present, thus coinciding with reduced solar activity (estimated 0.4% reduction) and with a corresponding increase in atmospheric ^{14}C. Stuiver and Braziunas (1989) argue that such century-scale $\Delta^{14}C$ variations during the Holocene are best explained by variations in the ^{14}C production rate induced by solar change. This conclusion is partly based on the similarity of the ^{10}Be and ^{14}C records (Beer *et al.* 1994). Stuiver and Braziunas (1989) note that there are no indications that changes in the ocean circulation caused the discussed ^{14}C variations (*viz.*, by a reduced CO_2 gas exchange at the air-sea interface or a reduced upwelling of ^{14}C deficient deep ocean water). It is now generally believed that the triple oscillations in $\Delta^{14}C$ are caused by a reduced solar activity. The triple oscillations were reconstructed at *ca.* 8500–7800 cal BP, *ca.* 5400–4700 cal BP, *ca.* 2680–2200 cal BP and 1100–400 cal BP. Accordingly, a *ca.* 2500-yr quasi-cycle of solar variability seems present in the ^{14}C record in tree rings. As changes in the magnetic-dipole moment follow a cycle of 8–10 ka (Harvey 1980), fluctuations in the geomagnetic field can be excluded as a cause for the triple $\Delta^{14}C$ variations. A possible correlation between the $\Delta^{14}C$ triple oscillation and the quasi-cycles of cold periods reported by Harvey (1980), O'Brien *et al.* (1995), Dansgaard *et al.* (1984) and others may indicate that the forcing mechanism behind the cool events is a variation in solar wind. Such a relation was already suggested in the 1960s by Bray (1968).

How could a relatively small reduction in solar activity induce the relatively large change in global climate inferred for 2650 BP? Answering this question involves a considerable degree of speculation, since the effect of solar variability on the Holocene climate is still controversial (*e.g.*, Wigley 1981; Roederer 1995). In any case, to provide an answer, it is necessary to look at the effect of solar variations on the atmosphere. An important effect of a reduced solar activity is an increase in the cosmic-ray flux. This increase in turn produces more ^{14}C in the stratosphere.

Two theories are available that explain how a relatively small reduction of solar radiation and an accompanying increase in cosmic-ray flux may affect the lower stratosphere. The first theory is based on the notion that a reduction of (ultraviolet) radiation may also lead to a decline in ozone production in the lower stratosphere (Harvey 1980). This could trigger the inferred climate changes. Such a mechanism may be deduced from recent climate modeling studies by Haigh (1994, 1996), who performed simulations with climate models to study the relation between the 11-yr solar activity cycles, ozone production and climate change. First, Haigh (1994) used a chemical model of the atmosphere and found that a 1% increase in UV radiation at the maximum of a solar activity cycle generated 1–2% more ozone in the stratosphere. Subsequently, Haigh (1996) used this increase in the stratospheric ozone content as input in a January climate model experiment. In the simulation results, this increase in stratospheric ozone produced a warming of the lower stratosphere by the absorption of more sunlight. In addition, the stratospheric winds were also strengthened and the tropospheric westerly jet streams were displaced poleward. The position of these jets determines the latitudinal extent of the Hadley cells and, therefore, the poleward shift of the jets resulted in a similar displacement of the descending parts of the Hadley Cells. This ultimately led to a poleward relocation of the mid-latitude storm tracks. Recently the results of Haigh (1996) are supported by an analysis of Christoforou and Hameed (1997), who found a close correlation between solar activity, as expressed by mean annual sunspot numbers, and the intensity and locations of low and high pressure centers in the North Pacific area.

The opposite effect to the one simulated by Haigh may have played a role in the discussed climate change *ca.* 2650 BP (800 cal BC). The observed strong increase of atmospheric ^{14}C during the period *ca.* 2650 BP may have been caused by reduced solar activity. Such a reduction in solar activity could also have resulted in a decrease in the stratospheric ozone content. If one assumes that this decrease in stratospheric ozone content leads to an opposite effect to the one simulated by Haigh (1996), a decrease of the latitudinal extent of the Hadley Cell circulation follows. Furthermore, an expansion of the Polar Cells and a repositioning of the main depression tracks at mid-latitudes towards the equator may be inferred.

A contraction of the Hadley Cell circulation and a possible weakening of monsoons would be consistent with the inferred drier conditions in the tropics *ca.* 2650 BP. Similarly, an expansion of the Polar Cells and a shift of storm tracks closer to the equator would possibly be compatible with the reconstructed cooler and wetter conditions at middle latitudes in both hemispheres.

The second theory is based on the idea that an increase in the cosmic ray flux may directly lead to an increase in global cloud cover. This relation may be explained by ionization in the atmosphere by cosmic rays, thus positively affecting aerosol formation and cloud nucleation (Pudovkin and Raspopov 1992; Raspopov *et al.* 1997; van Geel *et al.* ms.). Svensmark and Friis-Christensen (1997) found an excellent correlation between the variation in cosmic ray flux and the observed global cloud cover for the most recent solar cycle. An increase in the global cloud cover is believed to cause a cooling of the earth, especially when low altitude clouds are involved, because more incoming radiation is reflected (Svensmark and Friis-Christensen 1997). Earlier, Friis-Christensen and Lassen (1991) analyzed for the period 1861–1989 the similarity between the Northern Hemisphere temperature record and the length of the solar cycle (as an indicator of solar activity), and found a close match. Moreover, it is expected that the effect would be most marked at high latitudes, since the shielding effect of the geomagnetic field is larger near the equator. Indeed, the correlation between cosmic-ray flux and cloud cover increases going from the Equator towards the poles (Svensmark and Friis-Christensen 1997).

A direct increase in cloudiness and accompanying cooling would be in agreement with the reconstructed wetter and cooler conditions at middle latitudes *ca.* 2650 BP. The inferred drier conditions in the tropics are less easily explained by this second theory. One may speculate, however, that the proposed changes in cloud cover and temperature may invoke changes in the atmospheric circulation, possibly involving an increase in the number of El Niño events and drier conditions at several places in the tropics (Svensmark, personal communication 1997).

Possibly, the inferred decrease in solar activity triggered variations in the ocean circulation through the above-inferred changes in the atmosphere. An increase in precipitation at middle latitudes by a change in the position of the storm tracks or by the above inferred changes in the atmosphere could have disturbed the thermohaline circulation in the North Atlantic Ocean. This relationship was tentatively postulated by Stuiver and Braziunas (1993) for the Maunder minimum. Through its association with the Gulf stream, this thermohaline circulation releases significant amounts of heat to the atmosphere at mid-latitudes, contributing to the relatively mild climate of Europe today. The thermohaline circulation is driven by the formation of North Atlantic deep water (NADW). Modeling studies have shown that the thermohaline circulation may indeed be very sensitive to changes in the freshwater flux (*e.g.*, Rahmstorf 1994). A weakening of the thermohaline circulation would have two major effects. First, it would cause a relatively intense cooling of Europe. Second, the cooling could have caused an increase in the area covered by sea-ice and snow, generating further cooling through the positive ice-albedo feedback. In conclusion, *ca.* 2650 BP a weakening of the thermohaline circulation could have amplified the climate change originally initiated by the reduced solar activity. It should be noted, however, that the thermohaline circulation may change due to the internal variability of the atmosphere-ocean system, thus without a trigger mechanism like a reduced solar activity.

The above hypothesis—involving a weakening of the thermohaline circulation—agrees with the reconstruction of the surface salinity and density for an ocean core at the Rockall plateau (55°N, 14'W) by Duplessy *et al.* (1992). The reconstructed surface salinity and density of the ocean water show a clear minimum *ca.* 2500–3000 BP. This minimum is simultaneous with a small decrease (1°C) in the sea surface temperature.

CONCLUSION

A sudden and sharp rise in the atmospheric ^{14}C content *ca.* 2650 BP was found to be contemporaneous with abrupt climate change at middle latitudes of the Northern Hemisphere (Europe, North America, Japan) and Southern Hemisphere (New Zealand, South America), changing to a cooler and wetter climate, and, in the tropics (Africa, Caribbean), changing to a drier climate, as evidenced by archaeological and paleoecological data.

The inferred variations in atmospheric ^{14}C content and in climate may be tentatively explained by reduced solar activity. Two possible mechanisms are given. The first one is based on the idea that a reduced solar input could have reduced the stratospheric ozone content. The latter process may have been the trigger mechanism responsible for a decreased latitudinal extent of the Hadley Cells, an expansion of the Polar Cells and an Equator-ward displacement of the mid-latitudinal storm tracks. These inferred variations in the atmospheric circulation are consistent with the reconstructed climatic changes based on archaeological and paleoecological data.

The second theory is based on the notion that an increase in cosmic-ray flux, accompanying the reduction in solar activity, could have directly caused an increase in global cloud cover through the formation of cloud condensation nuclei. An increase in cloud cover would probably have led to more precipitation and cooler conditions at middle latitudes, again in agreement with the inferred climate changes.

A weakening of the thermohaline circulation in the Atlantic Ocean, as a result of the displacement of the mid-latitudinal storm tracks, could have played an additional role. Such a weakening could have caused a relatively strong cooling of Europe through the reduced release of heat by the Gulf Stream and through the positive ice-albedo feedback.

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REFERENCES

Beer, J., Joos, F., Lukasczyk, C., Mende, W., Rodriguez, J., Siegenthaler, U. and Stellmacher, R. 1994 ^{10}Be as an indicator of solar variability and climate. *In* Nesme-Ribes, E., ed, *The Solar Engine and Its Influence on Terrestrial Atmosphere and Climate*. NATO ASI series I 25. Berlin-Heidelberg, Springer Verlag: 221–233.

Boersma, J. W. 1983 De opgraving Middelstum-Boerdamsterweg in een notedop. *In* Kooi, P. B., ed., *Leven langs de Fivel: Van Helwerd tot Zwart Lap. In Middelstum-Kantens. Bijdragen tot de plattelandsgeschiedenis met een beschrijving van de boerderijen en hun bewoners*. Kantens: 31–35.

Bonnefille, R. and Riollet, G. 1988 The Kashiru pollen sequence (Burundi). Paleoclimatic implications for the last 40 000 yr BP in tropical Africa. *Quaternary Research* 30: 19–35.

Bray, J. R. 1968 Glaciation and solar activity since the fifth century BC and the solar cycle. *Nature* 220: 672–674.

Broecker, W. S. 1992 The strength of the nordic heat pump. *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation: Absolute and Radiocarbon Chronologies*. NATO ASI Series I2. Berlin, Springer Verlag: 173–180.

Christoforou, P. and Hameed, S. 1997 Solar cycles and the Pacific "centers of action". *Geophysical Research Letters* 24: 293–296.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. and Hammer, C. U. 1984 North Atlantic climatic oscillations revealed by deep Greenland ice cores. *In* Hansen, J. E. and Takahashi, T., eds., Climate Processes and Climate Sensitivity. *Geophysical Monograph* 29: 288–298.

Davis, O. K., Jirikowic, J. and Kalin, R. M. 1992 Radiocarbon record of solar variability and holocene climatic change in coastal southern California. *In* Redmond, K. T., ed., Proceedings of the Eighth Annual Pacific Climate (PACLIM) Workshop, March 10–13, 1991. *California Department of Water Resources Interagency Ecological Studies Program Technical Report* 31: 19–33.

De Foresta, H. 1990 Origine et évolution des savanes intramayombiennes (RP du Congo) II. Apports de la botanique forestière. *In* Lanfranchi, R. and Schwartz, D., eds., *Paysages Quaternaires de l'Afrique Centrale Atlantique*. Paris, ORSTOM: 236–355.

Duplessy, J. C., Labeyrie, L., Arnold, M., Paterne, M., Duprat, J. and van Weering, T. C. E. 1992 Changes in surface salinity of the North Atlantic Ocean during the last deglaciation: *Nature* 358: 485–488.

Elenga, H., Schwartz, D. and Vincens, A. 1992 Changements climatiques et action anthropique sur le littoral congolais au cours de l'Holocène. *Bulletin de la Société Géologique de France* 163(1): 83–90.

Elenga, H., Schwartz, D., Vincens, A., Bertaux, J., de Namur, C., Martin, L., Wirrmann, D. and Servant, M. 1996 Diagramme pollinique holocène du lac Kitina (Congo): Mise en évidence de changements paléobotaniques et paléoclimatiques dans le massif forestier du Mayombe. *Comptes Rendus de l'Academie des Sciences* 323(IIa): 403–410.

Elenga, H., Schwartz, D. and Vincens, A. 1994 Pollen evidence of late Quaternary vegetation and inferred climate changes in Congo. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109: 345–356.

Elenga, H. and Vincens, A. 1990 Paléoenvironnements quaternaires récents des Plateaux Batéké (Congo): Étude palynologique des dépôts de la dépression de Bilanko. *In* Lanfranchi, R. and Schwartz, D., eds., *Paysages Quaternaires de l'Afrique Centrale Atlantique*. Paris, ORSTOM: 271– 282.

Friis-Christensen, E. and Lassen, K. 1991 Length of the solar cycle: An indicator of solar activity closely associated with climate. *Science* 254: 698–700.

Giresse, P., Maley, J. and Brenac, P. 1994 Late Quaternary palaeoenvironments in the Lake Barombi Mbo (West Cameroon) deduced from pollen and carbon isotopes of organic matter. *Palaeogeography, Palaeoclimatology, Palaeoecology* 107: 65–78.

Griede, J. W. 1978 (ms.) Het ontstaan van Frieslands Noordhoek. Ph.D. thesis. Vrije Universiteit, Amsterdam.

Haigh, J. D. 1994 The role of stratospheric ozone in modulating the solar radiative forcing of climate. *Nature* 370: 544–546.

____1996 The impact of solar variability on climate. *Science* 272: 981–984.

Hamilton, A. C. 1987 Vegetation and climate of Mt. Elgon during the late Pleistocene and Holocene. *Palaeoecology of Africa* 18: 283–304.

Harvey, L. D. D. 1980 Solar variability as a contributing factor to Holocene climatic change. *Progress in Physical Geography* 4: 487–530.

Jirikowic, J. L., Kalin, R. M. and Davis, O. K. 1993 Tree-ring ^{14}C as a possible indicator of climate change. *In* Climate Change in Continental Isotopic Records. *Geophysical Monograph* 78: 353–366.

Jolly, D., Bonnefille, R. and Roux, M. 1994 Numerical interpretation of a high resolution Holocene pollen record from Burundi. *Palaeogeography, Palaeoclimatology, Palaeoecology* 109: 357–370.

Kerr, R. 1995 A fickle sun could be altering earth's climate after all. *Science* 269: 633.

Kilian, M. R., van der Plicht, J. and van Geel, B. 1995 Dating raised bogs: New aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* 14: 959–966.

Kilian, M. R., van Geel, B. and van der Plicht, J. (ms.) ^{14}C AMS wiggle matching of raised bog deposits and models of peat accumulation. In preparation.

Klaver, E. R. 1981 Een Holocene vegetatie successie in het Fochtelooerveen. *Internal Report, Hugo de Vries-Laboratorium* 101, University of Amsterdam.

Kouwenberg, J. 1985 Reconstructie van de vegetatie op en rond een Iers hoogveen uit de Midden en Late Bronstijd (ca 4600-2400 BP) te Carbury (Co. Kildare). *Internal Report, Hugo de Vries-Laboratorium* 187, University of Amsterdam.

Magny, M. 1993a Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* 40: 1–9.

Magny, M. 1993b Un cadre climatique pour les habitats lacustres préhistoriques? *Comptes Rendus de l'Académie des Sciences Paris* 316(II): 1619–1625.

Maley, J. 1992 Commentaires sur la note de D Schwartz. Mise en évidence d'une péjoration climatique entre ca 2500 et 2000 ans BP en Afrique tropicale humide. *Bulletin de la Société Géologique de France* 163(3): 363–365.

Mörner, N. A. 1995 Recorded sea level variability in the Holocene and expected future changes. *In* Eisma, D., ed., *Climate Change: Impact on Coastal Habitation.* London, Lewis Publishers: 17–28.

O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S. and Whitlow, S. I. 1995 Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science* 270: 1962–1964.

Pudovkin, M. I. and Raspopov, O. M. 1992 The mechanism of action of solar activity on the state of the lower atmosphere and meteorological parameters (a review). *Geomagnetism and Aeronomy* 32: 593–608.

Rahmstorf, S. 1994 Rapid climate transitions in a coupled ocean-atmosphere model. *Nature* 372: 82–85.

Raspopov, O. M., Shumilov, O. I., Kasatkina, E. A., Dergachev, V. A. and Creer, K. M. 1997 Impact of cosmic ray flux variations caused by changes in geomagnetic dipole moment on climate variability. Russian Academy of Sciences IOFFE Physical-Technical Institute, Preprint 1693: 1–41.

Reynaud-Farrera, I., Maley, J. and Wirrmann, D. 1996 Végétation et climat dans les forêts du Sud-Ouest Cameroun depuis 4770 ans BP: Analyse pollinique des sédiments du Lac Ossa. *Comptes Rendus de l'Académie des Sciences Paris* 322(IIa): 749–755.

Roche, E., Bikwemu, G. and Ntaganda, C. 1988 Evolution du paléoenvironnement quaternaire au Rwanda et au Burundi. Analyse des phénomènes morphotectoniques et des données sédimentologiques et palynologiques. *Travaux de la Section Scientifique et Technique Institut Français de Pondichéry* XXV: 105–123.

Roederer, J. G. 1995 Solar variability effects on climate. *In* Frenzel, B., Nanni, T., Galli, M. and Gläser, B., eds., Solar output and climate during the Holocene. *Paläoklimaforschung - Palaeoclimate Research* 16: 1–13.

Roeleveld, W. 1976 The Holocene evolution of the Groningen marine-clay district. *Berichten Rijksdienst voor het Oudheidkundig Bodemonderzoek* 24 (supplement): 1–133.

Schwartz, D. 1992 Assèchement climatique vers 3000 BP et expansion Bantu en Afrique centrale atlantique: Quelques réflexions. *Bulletin de la Société Géo-logique de France* 163(3): 353–361.

Schwartz, D., Guillet, B. and Dechamps, R. 1990 Etude de deux flores forestières mi-holocène (6000–3000 BP) et subactuelle (500 BP) conservées in situ sur le littoral pontenegrin (Congo). *In* Lanfranchi, R. and Schwartz, D., eds., *Paysages Quaternaires de l'Afrique Centrale Atlantique.* Paris, ORSTOM: 283–297.

Sernander, R. 1910 Die schwedischen Torfmoore als Zeugen postglazialer Klimaschwankungen. Die Veränderungen des Klimas seit dem Maximum der Letzten Eiszeit. *Herausgegeben von dem Exekutivkomitee des* 11. Stockholm, Internationalen Geologenkongresses: 197–246.

Ssemmanda, I. and Vincens, A. 1993 Végétation et climat dans le bassin du lac Albert (Ouganda, Zaïre) depuis 13 000 ans BP: Apport de la palynologie. *Comptes Rendus de l'Académie des Sciences Paris* 316(II): 561–567.

Stuiver, M., Braziunas, T. F., Becker, B. and Kromer, B. 1991 Climatic, solar, oceanic and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}C/^{12}C$ change. *Quaternary Research* 35: 1–24.

Stuiver, M. and Braziunas, T. F. 1989 Atmospheric ^{14}C

and century-scale solar oscillations. *Nature* 338: 405–408.

____1993 Sun, ocean, climate and atmospheric $^{14}CO_2$: An evaluation of causal and spectral relationships. *The Holocene* 3: 289–305.

Stuiver, M. and Reimer, P. J. 1993 Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *In* Stuiver, M., Long, A. and Kra, R. S., eds., Calibration 1993. *Radiocarbon* 35(1): 215–230.

Svensmark, H. and Friis-Christensen, E. 1997 Variation of cosmic ray flux and global cloud coverage: A missing link in solar-climate relationships. *Journal of Atmospheric and Solar-Terrestrial Physics* 59: 1225–1232.

van Geel, B., Buurman, J. and Waterbolk, H. T. 1996 Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science* 11: 451–460.

van Geel, B., Hallewas, D. P. and Pals, J. P. 1983 A Late Holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of N-Holland, the Netherlands): Palaeoecological and archaeological aspects. *Review of Palaeobotany and Palynology* 38: 269–335.

van Geel, B. and Mook, W. G. 1989 High-resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations. *Radiocarbon* 31(2): 151–156.

van Geel, B., Raspopov, O. M., van der Plicht, J. and Renssen, H. (ms.) Solar forcing of abrupt climate change around 850 BC. Submitted to *British Archaeological Reports*.

Vincens, A. 1986 Diagramme pollinique d'un sondage Pléistocène supérieur – Holocène du lac Bogoria (Kenya). *Review of Palaeobotany and Palynology* 47: 169–192.

Vincens, A. 1989 Les forêts claires zambéziennes du bassin Sud-Tanganyika. Evolution entre 25 000 et 6 000 ans BP. Comptes Rendus de l'Académie des Sciences Paris 308(II): 809–814.

Vincens, A., Buchet, G., Elenga, H., Fournier, M., Martin, L., de Namur, C., Schwartz, D., Servant, M. and Wirrmann, D. 1994 Changement majeur de la végétation du lac Sinnda (vallée du Niari, Sud-Congo) consécutif à l'assèchement climatique holocène supérieur: Apport de la palynologie. Comptes Rendus de l'Académie des Sciences Paris 318(II): 1521–1526.

Waterbolk, H. T. 1959 Nieuwe gegevens over de herkomst van de oudste bewoners der kleistreken. *Koninklijke Nederlandse Akademie van Wetenschappen, Akademiedagen* 11: 16–37.

____1966 The occupation of Friesland in the prehistoric period. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek* 15/16: 13–35.

____1995a The Bronze Age settlement of Zwolle-Ittersumerbroek: Some critical comments. *Palaeohistoria* 35/36: 73–87.

____1995b De prehistorische nederzetting van Zwolle-Ittersumerbroek. *Archeologie en Bouwhistorie in Zwolle* 3: 123–173.

Wigley, T. M. L. 1981 Climate and paleoclimate: What can we learn about solar luminosity variations? *Solar Physics* 74: 435–471.

Wigley, T. M. L. and Kelly, P. M. 1990 Holocene climatic change, ^{14}C wiggles and variations in solar irradiance. *Philosophical Transactions of the Royal Society, London* A330: 547–560.

Wigley, T. M. L. and Raper, S. C. B. 1993 Future changes in global mean temperature and sea level. *In* Warrick, R. A., Barrow, E. M. and Wigley, T. M. L., eds., *Climate and Sea Level Change.* Cambridge, Cambridge University Press: 111–133.

Zaitseva, G. I., Possnert, G., Alekseev, A. Y., Sementsov, A. A. and Dergachev, V. A. 1998 The first ^{14}C dating of monuments in European Scythia. *Radiocarbon,* this issue.