Quaternary Science Reviews 27 (2008) 175–184

Determining the Sun's influence on Lateglacial and Holocene climates: a focus on climate response to centennial-scale solar forcing at 2800 cal. BP

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Received 14 February 2006; accepted 29 January 2007

Abstract

The influence of solar variability on the climate of the Lateglacial and Holocene periods has been the subject of increasing discussion during the last decade. In the Mid-Holocene, several studies have identified cold/wet events that occur at ca 2800 cal. BP and a link with a reduction in solar activity, inferred from the ^{14}C record, has been postulated. We present results from a multi-proxy study of peat humification, plant macrofossils and testate amoebae from a raised bog at Glen West, northwest Ireland, that indicate that dry bog surface conditions were experienced in the north of Ireland at the time of the solar anomaly starting at 2800 cal. BP. With the aid of ^{14}C wiggle-matching and tephrochronology, an abrupt shift to wetter conditions is dated to ca 2700 cal. BP, coinciding with a ^{14}C maximum but clearly post-dating the 2800 cal. BP event identified elsewhere in Europe. We explore the significance of this apparent lag in the Irish record, considering the possible role of the ocean in generating spatial and temporal complexities in the climate patterns of the North Atlantic region. We conclude that these complexities are likely to give rise to time-transgressive climate responses around the North Atlantic that will only be recognised by more critical chronological approaches.

1. Introduction

Although the highly complex relationships between solar variability, ocean circulation and climate change continue to be debated, the potential influence of centennial-scale solar forcing on climate during the Lateglacial and Holocene periods has been propounded by numerous investigations. For instance, GS-1 (Younger Dryas), the Preboreal Oscillation, cold events at 10 300 and 8200 cal. BP (the '8.2 ka event'), a wet/cold event at 2800 cal. BP and the Little Ice Age generally coincide temporally with periods of large excursions in atmospheric $\Delta^{14}C$ and ^{10}Be fluxes that possibly signify higher nuclide production rates as a result of reduced solar output at these times (Kilian et al., 1995; van Geel et al., 1996, 1998, 2003; Goślar et al., 2000; Renssen et al., 2000; Björck et al., 2001; Mauquoy et al., 2002, 2004a,b; van der Plicht et al., 2004). Furthermore, Blaauw et al. (2004) report up to nine wet shifts in Dutch bogs that coincide with $\Delta^{14}C$ excursions during the period ca 6500–2300 cal. BP, lending additional support to the suggestions of a solar influence on climate.

Freshwater impulses into the North Atlantic, on the other hand, are considered an alternative driving force for many of these climate events through their hypothesised impact on North Atlantic thermohaline circulation, most notably during the Lateglacial/Early Holocene transition (Barber et al., 1999; Hughen et al., 2000; Clark et al., 2001; Teller et al., 2002; Delaygue et al., 2003; Magny and Bégeot, 2004). The southwards and eastwards transport of drift ice in the North Atlantic attested by ice-rafting debris (IRD) in marine cores affirms that oceanic changes took place at these times (Bond and Lotti, 1995; Bond et al., 1997, 2001). The significance of IRD events has largely been interpreted in terms of iceberg discharges following air temperature decreases, as the events are accompanied by shifts to cold-tolerant foraminifera assemblages and, at GS-1, by a concomitant $\Delta^{18}O$ enrichment indicating ocean

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0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2007.01.015

surface coolings (Bond et al., 1997). Bond et al. (2001) propose that reduced solar irradiance (inferred from available ^{10}Be and ^{14}C records) may have increased drift ice, leading to cooler sea surface temperatures and impacting further on global climate patterns by causing disruptions to North Atlantic thermohaline circulation.

Changes in ocean ventilation could also account at least in part for the observed variability in the Δ^{14}C record (Stocker and Wright, 1996; Muscheler et al., 2000; Clark et al., 2001, 2002), however, and discrepancies between the timing of Δ^{14}C concentration increases and ^{10}Be fluxes have been noted (e.g. Hughen et al., 2000). Thus, mechanisms internal to the deglaciation and/or ocean system could be the driving factors behind climate reversals during the Lateglacial/Early Holocene transition at least. Comparable freshwater impulses into the Atlantic are not known during the Mid- to Late Holocene and it is perhaps during this time period that the effects of solar forcing can be more easily isolated.

An abrupt climate change concurrent with a Δ^{14}C maximum between 2800 and 2710 cal. BP reported from continental Europe (Kilian et al., 1995; van Geel et al., 1996, 1998; Speranza et al., 2002; Blaauw et al., 2004) is especially interesting. These climate reconstructions are based primarily on plant macrofossil data from ombrotrophic bogs, tightly dated through ^{14}C wiggle-matching, and supporting evidence has been advocated on the basis of diverse data from as far afield as the Siberian steppes (van Geel et al., 2004) and Chile (van Geel et al., 2000). Notwithstanding the rather wide chronological uncertainties of marine cores, the 2800 cal. BP event occurs around the time of IRD event 2 (Bond et al., 1997, 2001) and Hall et al. (2004) identified a deep water perturbation in the North Atlantic at ca 2700 cal. BP as the most widespread and pronounced weakening of Iceland–Scotland Overflow Waters (ISOW) during the Holocene.

In Ireland, in contrast, high-resolution peat humification studies across the centuries bracketing 2800 cal. BP point to a possibly more regionalised response to solar variability at this time (Plunkett, 2006). Here, a tendency towards *drier* bog surface conditions can be seen at ca 2800 cal. BP, and a shift to increased surface wetness is not observed until ca 2700 cal. BP. The latter event is replicated at five sites and the timing of its initiation is constrained by two bracketing tephra horizons dating to 2750–2708 cal. BP (GB4-150 tephra) and 2705–2630 cal. BC (Microlite tephra). These data imply that Ireland experienced either an opposite climate response to solar forcing at 2800 cal. BP, becoming warmer/drier as conditions became colder/wetter in other regions, or there was a lag in the onset of colder/wetter conditions due to the complexities of the forcing mechanism, the climate system and/or subsequent feedback factors.

As a proxy for past climate change, however, peat humification analysis has been criticised on a number of counts; for example, it can be influenced by the species composition of the peat (Aaby and Tauber, 1975; Blackford and Chambers, 1993; Yeloff and Mauquoy, 2006) and temporal comparisons are hindered by the non-uniform measurement scale of humification (Charman et al., 1999; Caseldine and Geary, 2005). Multi-proxy approaches are therefore needed to formulate meaningful palaeohydrological interpretations from peat profiles. The majority of recent peat-based palaeoclimate research has combined plant macrofossils, humification and testate amoebae analyses, which are probably the most complementary methods (cf. Chiverrell, 2001). Non-pollen palynomorphs have also been used as supplementary palaeohydrological indicators (e.g. Mauquoy et al., 2004b).

Here, we present data from plant macrofossil and testate amoebae analyses from one of the sites (Glen West) described by Plunkett (2006) in order to elucidate climate change between ca 2880 and 2500 cal. BP in Ireland. We examine the implications of the results for understanding the role of solar forcing at this time, as well as during other periods of apparently reduced solar activity in the Holocene and Lateglacial periods.

2. Regional setting

Glen West, County Fermanagh, is a raised bog that forms part of an extensive stretch of peatland in northwest Ireland (Fig. 1). The region is characterised by relatively

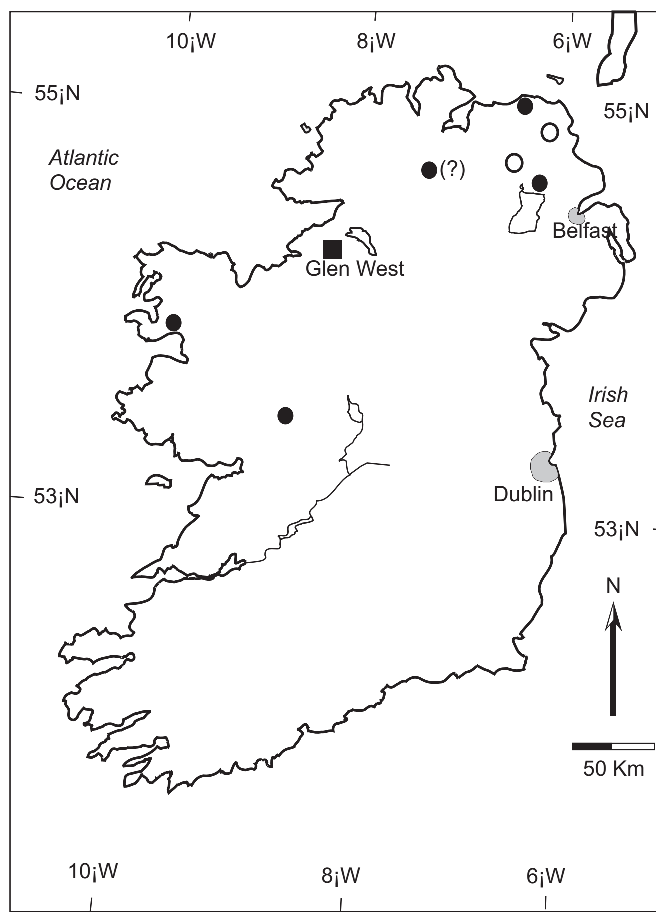

Fig. 1. Location of Glen West, Co. Fermanagh. Other Irish ombrotrophic bogs that register a wet shift at ca 2700 BP are also shown (solid circles—Plunkett, 2006; hollow circles—Swindles, 2006; Swindles et al., 2007).

high mean annual rainfall exceeding 1200 mm, and mild winter (4.0–4.5 °C) and summer (14.0–14.5 °C) temperatures (Sweeney, 1997). The western part of the bog supports a well-developed pool-and-hummock structure with a typical raised bog vegetation including *Sphagnum imbricatum*, *Narthecium ossifragum* and *Calluna vulgaris*. The eastern end of the bog slopes gently down to the Roogagh River and is characterised by a less pronounced surface topography featuring *N. ossifragum* lawns with *Molinia caerulea* and *Trichophorum cespitosum*, low-growing Ericaceae and occasional low hummocks.

3. Materials and methods

A 2.2 m-long peat sequence was extracted from an exposed peat face at Glen West using monolith tins. The chronology of the sequence was formerly established by high-precision ^{14}C wiggle-matching and tephrochronology, with the wiggle-match also providing refined age estimates for three previously undated tephra isochrons (Plunkett, 1999, 2006; Plunkett et al., 2004). This chronology has since been augmented by conventional ^{14}C determinations on two bulk peat samples at 49–51 and 148–150 cm. The results are calibrated using OxCal v3.10 (Bronk Ramsey, 1995, 2001) and the INTCAL04 calibration curve (Reimer et al., 2004). A time–depth curve for the sequence is based on linear interpolation between dated horizons. Peat humification levels measured at 1 cm intervals (approximating 11-year resolution) between the period 3450 and 2500 cal. BP, as well as the peat stratigraphy of this section, were reported by Plunkett (2006). The humification results between 2880 and 2500 cal. BP (91–121 cm) are reproduced here.

Plant macrofossil analysis of the peat profile was carried out on 1 cm-thick samples at 3 cm intervals using the 'Quadrat and Leaf Count' method (Barber, 1981, 1993; Haslam, 1987; Barber et al., 1994). Macrofossil identification was aided by reference to Grosse-Brauckmann (1972, 1974, 1992), Katz et al. (1977) and Smith (1980). Nomenclature follows Stace (1991) for vascular plants and Daniels and Eddy (1985) for *Sphagnum* species. Detrended correspondence analysis (DCA) was applied to the plant macrofossil data using CANOCO v4.5 (ter Braak and Šmilauer, 2002). DCA axis-1 scores provide a one-dimensional summary of the changes in the assemblage that can be used as a semi-quantitative palaeohydrological index (Barber et al., 1994, 2000, 2004; Chiverrell, 2001).

Samples were prepared for testate amoebae analysis following Hendon and Charman (1997) from the same levels as the plant macrofossil samples. Testate amoebae were analysed at $\times 200$ and $\times 400$ magnification and at least 150 specimens were counted when practical, but counts as low as 50 were accepted for statistical analysis where preservation was poor in three levels (108–109, 111–112 and 114–115 cm). The lower counts are considered statistically reliable in view of the low species diversity represented in these levels (cf. Woodland et al., 1998; Charman et al., 1999; Wilmshurst et al., 2003). Individual tests were identified using Charman et al. (2000). A water table depth transfer function based on contemporary testate amoebae assemblages has been developed for peatlands in Northern Ireland using weighted averaging (tolerance downweighted) regression (WA-Tol) (Swindles, 2006). This transfer function was improved through the removal of a small number of outlier samples and the tolerance and optima of individual taxa were quantified. The transfer function was applied to the fossil testate amoebae assemblage from Glen West to provide a quantitative reconstruction of palaeo-water table depths. Sample specific errors of prediction were generated using 1000 bootstrap cycles (Birks et al., 1990; Line et al., 1994) using the C2 software (Juggins, 2003).

Palynomorphs from 1 cm-thick samples were counted at 2 cm intervals during routine pollen analysis of the peat profile (Plunkett, 1999) with identifications and nomenclature following van Geel (1978). Some of the taxa are presented here, expressed as percentage of the total pollen sum. Principal components analysis (PCA) was conducted on the total palynomorph assemblage using CANOCO v4.5 (ter Braak and Šmilauer, 2002) and provides a one-dimensional summary of these data.

Results are plotted using the TILIA software group (Grimm, 1993, 2004) and zoned using CONISS (Grimm, 1987).

4. Results

The ^{14}C determinations obtained at 49–51 and 148–150 cm provide dates of 2041–1729 cal. BP (1950 $\pm$ 60 BP, Beta-200492) and 3608–3337 cal. BP (3220 $\pm$ 60 BP, Beta-200493), respectively, supplementing the chronology previously reported for the profile (Plunkett et al., 2004; Plunkett, 2006; Fig. 2). Fig. 3 presents the main palaeohydrological indicators identified by the various proxies and the diagram has been divided into two zones. Zone GW-a, spanning ca 2880–2700 cal. BP, is represented by relatively high humification (lower light transmission values), with peat dominated by identifiable monocotyledons and unidentifiable organic material (UOM). Preservation of tests is poor before 2850 cal. BP, possibly a product of dissolution or disaggregation in the well-humified peat (Swindles and Roe, 2007). Thereafter, the testate assemblage is dominated by varied abundances of *Assulina muscorum*, *Cyclopyxis arcelloides* type, *Hyalosphenia subflava* and *Trigonopyxis arcula* type. *H. subflava* and *T. arcula* type are both dry indicators, and overall GW-a seems to represent predominantly dry bog surface conditions.

The opening of GW-b is marked by decreasing peat humification (higher light transmission values) and a shift to *Sphagnum*-dominated peat, including *S.* section *Acutifolia*, *S. magellanicum*, *S. papillosum* and *S.* section *Cuspidata*. The testate amoebae assemblage registers a change to wet indicator taxa, including *Amphitrema flavum*, *A. wrightianum* and *Centropyxis aculeata* type. Slight

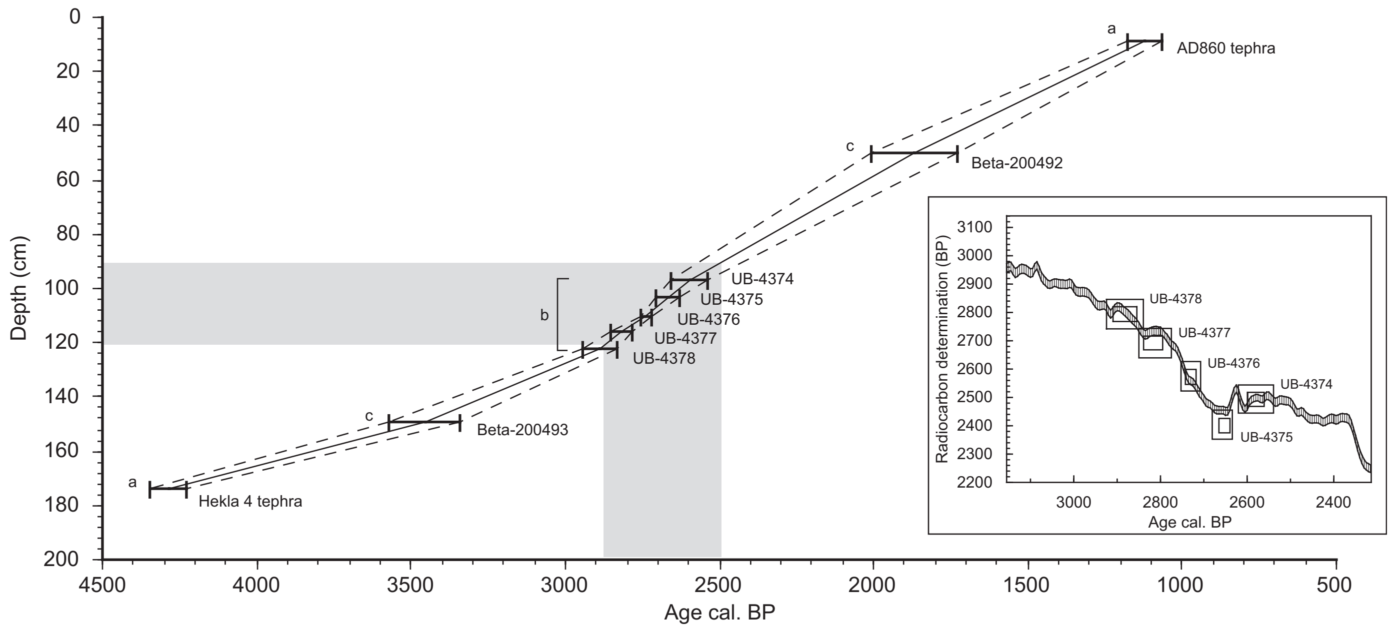

Fig. 2. Time–depth curve for Glen West profile showing calibrated date ranges (at 2σ) obtained by tephrochronology (dates for AD860 and Hekla 4 tephras based on Pilcher et al., 1995), (b) high-precision ^{14}C wiggle-matched determinations on bulk peat samples (Plunkett et al., 2004) and (c) conventional ^{14}C determinations on bulk peat samples (Swindles, 2006). The inset shows the position of the wiggle-matched age estimates in relation to the ^{14}C calibration curve (UB-4374 corresponds to the level of the BMR-190 tephra, UB-4375 corresponds to the level of the Microlite tephra, while the GB4-150 tephra is located 1 cm above UB-4376). The section of the profile examined in this paper is shown by grey shading.

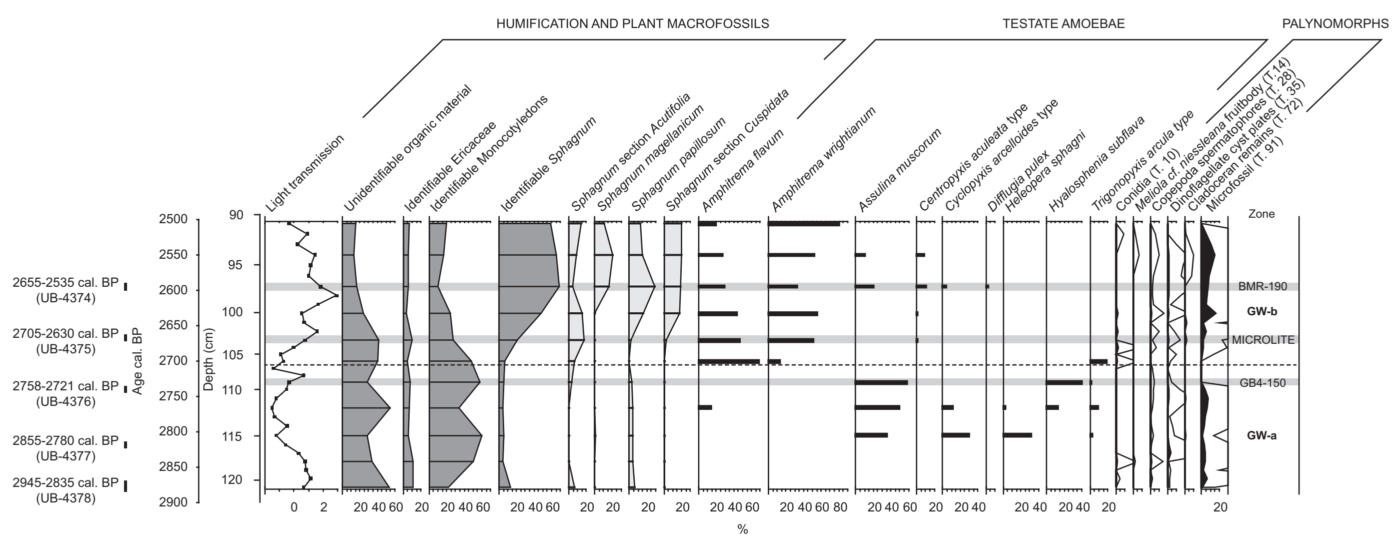

Fig. 3. Main palaeohydrological indicators identified by the various proxies at Glen West. Peat humification is expressed as standardised light transmission (Plunkett, 2006). Selected plant macrofossils include main peat components (dark grey curves) and % *Sphagnum* leaf counts (light grey curves). Testate amoebae are shown as % abundances. Palynomorph abundances are presented as % total pollen sum (Plunkett, 1999) (exaggeration $\times 10$). The positions of the ^{14}C wiggle-match dates (left of diagram) and GB4-150, Microlite and BMR-190 tephra layers (grey bands) (Plunkett et al., 2004) are illustrated.

increases in Copepoda spermatophores and dinoflagellate cyst plates and a rise in cladoceran remains can be seen in the palynomorph assemblage, reflecting standing water, and the results as a whole point to higher water levels after ca 2700 cal. BP.

Fig. 4 illustrates summary palaeohydrological indices derived from the proxies plotted alongside residual $\Delta^{14}C$. Water table depth reconstructed from the testate amoebae transfer function indicates a shift from deep (−20 cm) to surface water levels (+5 cm) after 2700 cal. BP. These data corroborate the relative measurements of bog surface wetness provided by humification and plant macrofossil analyses, and the change is also registered in the PCA axis-1 score on the palynomorph assemblage. Humification changes follow the water table rise quite rapidly, but the DCA axis-1 score derived from plant macrofossil data

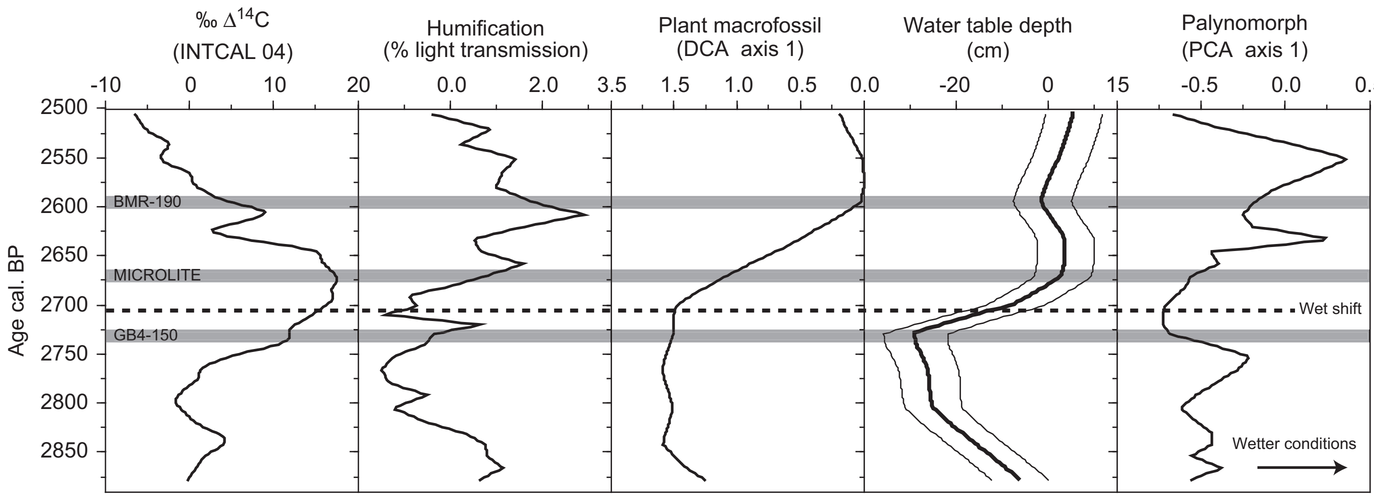

Fig. 4. A summary of the palaeohydrological indices derived from multiple proxies at Glen West plotted alongside residual $\Delta^{14}C$ (‰) (Reimer et al., 2004). DCA axis-1 scores carried out on the total plant macrofossil data set are shown. Water table depth reconstructions based on WA-Tol regression and calibration are shown with sample-specific errors generated from bootstrapping. PCA axis-1 scores are based on the total palynomorph assemblage (Plunkett, 1999).

suggests a slower response in bog vegetation. The combined results signify a major change in hydrology after 2700 cal. BP that represents a large increase in effective moisture on the bog surface. This change clearly begins between the levels of the GB4-150 and Microlite tephras, which provide convenient isochrons that delimit the start of the event. Maximum water levels of +5 cm are reached by ca 2650 cal. BP, and the testate amoebae data indicate a high water table that is sustained until at least 2500 cal. BP. The humification record, on the other hand, shows a tendency towards drier conditions (decreasing light transmission values) after ca 2600 cal. BP, which might in some part be explained by secondary decomposition within the peat (cf. Borgmark and Schoning, 2006).

5. Discussion

This multi-proxy investigation corroborates the findings of Plunkett (2006) that a shift to wetter conditions on Irish bogs post-dates the start of the ^{14}C anomaly of 2800 cal. BP, in contrast to evidence from peatlands in continental Europe (Kilian et al., 1995; van Geel et al., 1996, 1998; Speranza et al., 2002; Blaauw et al., 2004). At Glen West, effective moisture levels on the bog surface at 2800 cal. BP are relatively low, increasing only when $\Delta^{14}C$ levels are at their maximum, and by inference, when solar activity is at its lowest. At this point, an abrupt and considerable rise in water table implies a major shift to cooler and/or wetter conditions at Glen West. Similar hydrological changes are also suggested by humification records from at least four other Irish bogs (Plunkett, 2006) and by water table reconstructions derived from multi-proxy data at two additional sites in the north of Ireland (Swindles, 2006; Swindles et al., 2007) (see Fig. 1). Where the GB4-150 and Microlite tephras are present at these sites, the onset of the wet shift is constrained, as at Glen West, between the two isochrons. These wider findings demonstrate that the hydrological change was determined by factors external to any one bog, and a regional climate shift is almost certainly responsible.

The use of ^{14}C wiggle-match dating in the continental European investigations (Kilian et al., 1995; van Geel et al., 1996, 1998; Speranza et al., 2002; Blaauw et al., 2004) and at Glen West strengthens the chronological comparability of these palaeoclimate records. Thus, with age uncertainty minimised, it seems incontrovertible that the difference in the timing of wet shifts in the two areas is real. While a non-uniform response to climate change in bogs in continental and oceanic regions might arise as a result of their varying sensitivities to specific parameters, for example, seasonal temperature and/or precipitation changes (cf. Charman et al., 2004), this does not account adequately for the contrasting trends between the Irish and continental European records. Although it is possible that the observed climate events are ultimately unrelated to each other and/or to any specific forcing mechanism, we wish to explore the significance of the Irish evidence in terms of solar forcing, as discrepant environmental changes at times of solar variance have clear implications for understanding the mechanisms by which the Sun influences global climate (cf. Versteegh, 2005).

Two processes have been put forward to explain how relatively small changes in solar irradiance can have an impact on climate. The first, based on a converse interpretation of simulations by Haigh (1996), considers the effects of decreased UV radiation during periods of low solar irradiance on stratospheric ozone production, resulting in a realignment of atmospheric circulation patterns (van Geel and Renssen, 1998; van Geel et al., 1998, 1999). This theory suggests that an expansion of the polar cells and an equatorwards shift of the storm tracks would lead to wetter and colder conditions at mid-latitudes, while a contraction of the Hadley cell and a weakening of the monsoons would lead to drier conditions at the tropics. However, the data from Glen West and other Irish sites show that mid-latitudes at this time were not uniformly subject to wetter/colder conditions, and imply that any response to solar forcing must entail greater spatial complexity.

An alternative hypothesis invokes an extension of low-altitude cloud cover following an increase of cosmic ray intensity, leading to a greater reflection of incoming radiation and higher rainfall, and resulting in a global cooling effect (Svensmark and Friis-Christensen, 1997). This hypothesis has been the subject of intense debate (e.g. Gierens and Potter, 1999; Jørgensen and Hansen, 2000; Svensmark and Friis-Christensen, 2000; Sun and Bradley, 2002, 2004; Marsh and Svensmark, 2004). The results presented here suggest that widespread cooling arising from a rapid increase in low cloud cover is improbable at this time, as this would have been registered as a wet shift in the Irish bogs at or very soon after 2800 cal. BP. Spatial variations in the production of low- and high-altitude clouds over land and oceans, respectively, on the other hand, might account for the discrepancy, as high-altitude clouds could lead to warming (cf. Rind and Overpeck, 1993).

Both hypotheses currently fail to explain the regionalised discrepancy between Ireland and continental Europe. However, some global circulation models predict spatial variations in climate response to solar forcing. Rind and Overpeck (1993), for example, found that solar forcing might produce varied sea level pressure and advection patterns leading to warming over the mid-North Atlantic. This model also forecasts the occurrence of decreased effective moisture in the continental interior of North America, which seems to be reflected in palaeoenvironmental records in this region by drought frequencies that mirror periods of solar minima (Yu and Ito, 1999). Shindell et al. (2001) also simulate an increase in annual temperature over the North Atlantic and North Pacific oceans during a period of decreased solar activity in the Late Holocene (the Maunder Minimum). If similar patterns were experienced ca 2800 cal. BP, Ireland, with its marginal position on the northeastern Atlantic, may well have been sensitive to solar-forced oceanic warming. This could explain dry bog surface conditions at sites such as Glen West while more continental areas became wetter/colder.

This scenario of warming over the Atlantic is not consistent with the colder surface waters associated with the IRD event at ca 2800 cal. BP (Bond et al., 1997, 2001), nor with the suggested ISOW disruption at ca 2700 cal. BP (Hall et al., 2004), unless these latter events are not precisely synchronous with the Δ^{14}C anomaly. Indeed, the chronologies of the marine records have wide error margins and an exact correlation with the Δ^{14}C maximum has not been demonstrated. Furthermore, the wet shift observed in Irish bogs at 2700 cal. BP requires explanation, as it signals the onset of colder/wetter conditions in the north of Ireland approximately a century after the start of the solar anomaly.

We hypothesise that the disparity between Irish and continental European records is the result of non-uniform responses of oceanic and continental climate regimes to solar forcing and to a lag in the response of the North Atlantic. Indeed, Stuiver et al. (1997) attribute a 40-year phase lag between Δ^{14}C maximum and Δ^{18}O minimum in the GISP2 record over the last millennium to thermal inertia of the mixed layers of the ocean. One possibility is that increased run-off from continental areas that experienced wetter/colder conditions at ca 2800 cal. BP eventually had an impact on the thermohaline system, triggering colder conditions over the North Atlantic and leading to an expansion of sea ice evidenced by the IRD events. Alternatively, destabilisation of the polar ice masses could have been the primary impetus that disrupted ocean circulation and reversed any localised warming trends. In either case, we suggest that cooling in the North Atlantic may have been delayed by several decades following the initial reduction in solar activity and this would account for the lag in the onset of colder/wetter conditions in Irish bogs.

Our theory is not unlike that proposed by van Geel et al. (1998, 1999) and Bond et al. (2001) to explain the amplifying role of the North Atlantic during periods of solar variability, but we consider that the temporal and spatial impact of solar forcing on climate is much more complex than previously envisaged. Indeed, the absence of a temperature perturbation in the high-resolution, speleothem-derived Δ^{18}O record from Crag Cave, County Kerry, southwest Ireland (McDermott et al., 2001), and the existence of continuously wet bog surface conditions at the nearby bog of Moyreen, County Limerick (Plunkett, 2006), over this period may imply that, even within Ireland, certain areas were less sensitive to, or buffered from, regionalised climate change. The duration of the wet episode at Glen West is also notable, as water table reconstructions suggest that it was sustained until at least 2500 cal. BP. It is therefore more prolonged than the 2800 cal. BP event in continental Europe, where the effects of any delayed oceanic response do not appear to be registered. Clearly, this raises questions about the extent of any ocean-forced climate variability during the Mid- to Late Holocene.

Such subtle variations of climate change at ca 2800 cal. BP have not previously been reported. Most palaeoclimate studies of this period have insufficient chronological precision to resolve the exact timing of observed climate events. For example, pronounced wet shifts are registered in palaeohydrological records from peatlands in Northern Britain at ca 2800–2700 cal. BP (Stoneman, 1993; Chambers et al., 1997; Hendon et al., 2001; Langdon et al., 2003; Charman et al., 2006), in northern Germany and Denmark at ca 2700 BP (Barber et al., 2004) and in Newfoundland at 3200–2880 and ca 2500 cal. BP (Hughes et al., 2006), while increased flood events throughout Britain have been reported at ca 2730 cal. BP (Macklin et al., 2005). However, these investigations lack the temporal resolution needed to correlate them with, or distinguish them from, the start of the solar anomaly at 2800 cal. BP. A tendency to 'suck in' (*sensu* Baillie, 1991) environmental events as evidence of a single, widespread phenomenon continues to be a problem in palaeoclimate studies, and until addressed will inhibit a full understanding of climate change. While ^{14}C wiggle-matching provides an optimum means of comparing palaeoclimatic data to changes in the ^{14}C record, and by extrapolation to possible changes in solar activity, the identification of the GB4-150 and/or Microlite tephras in suitable deposits would also help elucidate the timing of climate shifts around this period.

We have focused on one interval of suspected solar variability in the Mid-Holocene but our results undoubtedly have implications for studies of other time periods when solar anomalies are suggested. For instance, many investigations have attempted to correlate solar minima with climate events during the Little Ice Age and Lateglacial/Early Holocene transition (see above). Both periods can make an enormous contribution to our understanding of the respective roles and interplay of the Sun, oceans, climate and ecosystems, but only if leads, lags and spatial variations in palaeoenvironmental responses can be teased out. The Little Ice Age is perhaps the ideal period in which to examine the impact of solar forcing, given the availability of empirical records from many areas and the limited effects of freshwater forcing over the last millennium. Some researchers have attempted to improve the chronological precision of their palaeoclimatic records using ^{14}C wiggle-matching (e.g. Mauquoy et al., 2002), but surprisingly few have incorporated tephrochronology (but see Hall and Mauquoy, 2005) despite the potential to identify a wide suite of distal tephras dating to the last millennium (e.g. Hall and Pilcher, 2002), some of which are historically dated (e.g. Oraefajøkull 1362, Hekla 1510, Askja 1875). There is clearly scope for achieving excellent chronological control in palaeoclimate studies over the last millennium to facilitate comparisons with instrumental and historical records of climate and solar activity.

The Lateglacial/Early Holocene transition presents a much greater challenge, as changes in ocean ventilation and the geomagnetic field further obscure the determination of solar variability at this time. The use of ^{14}C wiggle-matching in studies of this period provides better links between palaeoclimate and ^{14}C records (e.g. Goślar et al., 1995a, b; Hajdas et al., 1995; Gulliksen et al., 1998), but the synchroneity of climate patterns can only be scrutinised if similar precision can be obtained over wider areas. Recently, Lowe (2001) and Davies et al. (2002) have advocated tephrochronology as an invaluable aid to chronological refinement in Lateglacial/Early Holocene records, drawing attention to the increasing number of recognised tephras from Icelandic, German, French and Italian volcanic sources that date to this period. Indeed, spatial variations in climate conditions have already been illustrated using this approach: Eiríksson et al. (2000) identify warming along the North Atlantic shelf during GS-1 at a time when much of Europe was experiencing cold conditions, and the correlation is borne out by the identification of the Vedde ash in the marine and many terrestrial records (Lowe, 2001). In light of the current investigation, it is interesting to note that two Δ^{18}O records from lakes in western Ireland (O'Connell et al., 1999; Diefendorf et al., 2006) suggest a relatively late response to climate change during GS-1 in Ireland, perhaps reflecting spatially incoherent responses to solar and/or ocean forcing.

6. Conclusions

We have used a multi-proxy approach to reconstruct bog surface wetness at Glen West during the period 2880–2500 cal. BP. The start of the 2800 cal BP Δ^{14}C maximum corresponds to relatively dry conditions on the bog. A rapid and major shift to colder/wetter conditions is identified at ca 2700 cal. BP in all proxies. This wet episode is distinguished from the widely reported 2800 cal. BP event using a combination of high-precision ^{14}C wiggle-matching and tephrochronology, implying that the effects of solar forcing at this time were variable even within a small region of northwest Europe.

Our data lend support to GCM simulations that predict regional differences in warming and cooling between oceanic and continental areas as a result of solar variability. Furthermore, we propose that the response of the North Atlantic to such forcing is gradual, possibly prolonged over several decades, at least during the Mid- to Late Holocene when freshwater disturbances within the ocean are likely to have been comparatively small. We suggest therefore that regions around the North Atlantic may have been affected to varying degrees by either solar forcing at ca 2800 cal. BP or resultant ocean circulation perturbations, and that these effects are likely to be time-transgressive at different localities. Only by obtaining palaeoclimate records with high chronological precision at regional and sub-regional scale can researchers expect to identify subtle spatial and temporal patterns that may lead to a better understanding of the mechanisms that alter climate.

Acknowledgements

The research was carried out as a part of doctoral degrees funded by NIDevR/ESF (G.P.) and DEL(NI) (G.T.S.). Additional ^{14}C dates reported here were funded by a Quaternary Research Association New Workers Award. We wish to thank Dr. Paula Reimer for informative discussions relating to the ^{14}C record and Dr. Helen Roe, Yoma Megarry and John McAlister for technical assistance. We are grateful to Dr. Pierre J.H.

Richard and Dr. Dmitri Mauquoy for their useful comments that have helped improve this paper.

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