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# Evaluating periodicities in peat-based climate proxy records

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## ABSTRACT

Proxy records derived from ombrotrophic peatlands provide important insights into climate change over decadal to millennial timescales. We present mid- to late- Holocene humification data and testate amoebae-derived water table records from two peatlands in Northern Ireland. We examine the replication of periodicities in these proxy climate records, which have been precisely linked through tephrochronology. Age-depth models are constructed using a Bayesian piece-wise linear accumulation model and chronological errors are calculated for each profile. A Lomb-Scargle Fourier transform-based spectral analysis is used to test for statistically significant periodicities in the data. Periodicities of c. 130, 180, 260, 540 and 1160 years are present in at least one proxy record at each site. The replication of these periodicities provides persuasive evidence that they are a product of allogenic climate controls, rather than internal peatland dynamics. A technique to estimate the possible level of red-noise in the data is applied and demonstrates that the observed periodicities cannot be explained by a first-order autoregressive model. We review the periodicities in the light of those reported previously from other marine and terrestrial climate proxy archives to consider climate forcing parameters.

## 1. Introduction

### 1.1. Background

The recognition and understanding of periodicities in Holocene climate records are amongst the most important challenges facing climate scientists. Numerous studies from the Northern Hemisphere now provide clear evidence for persistent climate periodicities operating on decadal to millennial timescales, some of which have been linked with recognised drivers, for example, celestial factors (e.g. Haigh, 1994; Yu and Ito, 1999; Chapman and Shackleton, 2000; Bond et al., 2001; Chambers and Blackford, 2001; Cumming et al., 2002; Hu et al., 2003; Patterson et al., 2007; Wanner et al., 2008; Gray et al., 2010). Understanding the timing, character and causes of these periodicities is fundamental for improving our knowledge of global climate system dynamics. In the terrestrial realm, a proliferation of studies have focused on peatlands as archives of Holocene climate change (Blackford, 2000; Chambers and Charman, 2004; Blundell and Barber, 2005; Mauquoy et al., 2008; Nichols and Huang, 2012). Ombrotrophic (water-shedding) peatlands are directly coupled to the atmosphere and can provide continuous palaeohydrological records spanning much of the Holocene (Barber, 1981; Hughes et al., 2000; Langdon et al., 2003; Chambers and Charman, 2004).

Palaeohydrological reconstructions from ombrotrophic peatlands agree well with other proxy climate data (Baker et al., 1999; Charman et al., 2001; Booth et al., 2004) and instrumental climate records (Charman et al., 2004; Hendon and Charman, 2004; Schoning et al., 2005). It has been suggested that estimates of bog surface wetness can be utilised as a proxy of summer water deficit, which is controlled by summer rainfall in oceanic locations, with summer temperature playing a greater, albeit subsidiary, role in higher-latitude, continental settings (Charman, 2007; Charman et al., 2009).

Well established peat-based palaeohydrological proxies include plant macrofossils (Barber et al., 1994), testate amoebae (Woodland et al., 1998) and colorimetric peat humification data (Blackford and Chambers, 1993). These methods have been used to generate mid to late Holocene palaeohydrological records from peatlands in NW Europe (e.g. Blundell and Barber, 2005; Mauquoy et al., 2008), North America (e.g. Booth and Jackson, 2003; van Bellen et al., 2011) and the Southern Hemisphere (e.g. Mauquoy et al., 2004).

Several authors have applied spectral analysis to such hydroclimate proxy data, which has revealed millennial, centennial and

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sub-centennial periodicities (Wijmstra et al., 1984; Barber et al., 1994; Chambers et al., 1997; Hughes et al., 2000; Chambers and Blackford, 2001; Langdon et al., 2003; Blundell and Barber, 2005; Borgmark, 2005; Swindles et al., 2007a). However, the precise inter-site replication of these periodicities has been limited by chronologies based on radiocarbon dates. Peatlands in Northern Ireland have an advantage over those in many other regions as they contain multiple cryptotephra layers enabling direct correlation of palaeoclimate records. This is necessary for testing the replicability of periodicities between sites.

### 1.2. Research aim

In this study we present new 4500-year peat humification records from two ombrotrophic peatlands in Northern Ireland, which are supplemented with published water table reconstructions from the same sites (Swindles et al., 2010). The aim of the study is to test the replicability of periodicities in these tephra-linked proxy climate records. If similar periodicities are found in both sites, it is reasonable to conclude that they have been driven by allogenic climatic controls rather than site-specific factors. We place this research into context by providing an overview of the climate periodicities documented in other key terrestrial and marine records from the Northern Hemisphere and consider potential forcing parameters.

## 2. Materials and methods

### 2.1. Field and laboratory methods

Two ombrotrophic peatlands were investigated: Dead Island (DI), a lowland raised bog in County Londonderry, and Slieveanorra (SA), an upland raised bog and blanket peat complex in County Antrim (Fig. 1). Both sites have an intact dome, although their margins/laggs have been damaged locally by peat cutting in recent centuries. Since these peripheral, cut-over areas are limited in relation to the total areas of the bogs, we assume that their impact on the hydrology of the cupola area has been minimal (Swindles, 2006).

A Russian peat corer was used to extract cores from lawn microforms on the main bog cupola at the two sites following the parallel-hole method (with 20 cm overlap). The cores were wrapped in aluminium foil, returned to the laboratory, and stored in refrigeration at 4 °C. The cores were sub-sampled at consecutive 1-cm intervals. The peat subsamples ($2\ \text{cm}^3$) were dried at 105 °C for approximately 16 h and then combusted in a muffle furnace at 450 °C for 8 h to calculate percentage loss-on-ignition (Schulte and Hopkins, 1996).

Peat humification analysis is based on alkali extraction of humic acids and spectrophotometry (Aaby, 1976). The principle behind humification analysis is that during periods of drier climate, bog water tables will be lower and it will take longer for litter to reach the anoxic catotelm, resulting in greater decomposition. During wetter periods, high water tables result in peat being less decomposed. Peat samples were prepared for colorimetric humification analysis following the methods of Roos-Barraclough et al. (2004), which uses smaller reagent volumes and is more efficient than the traditional method (cf. Aaby and Tauber, 1975; Blackford and Chambers, 1993). Percentage transmission data was corrected for fading and loss-on-ignition following standard procedures (Blackford and Chambers, 1993). The humification data were detrended using linear regression to remove the increase of humification with depth (Clymo, 1991; Mauquoy and Barber, 1999) and expressed as humification residuals (Chambers and Blackford, 2001; Supplementary material A).

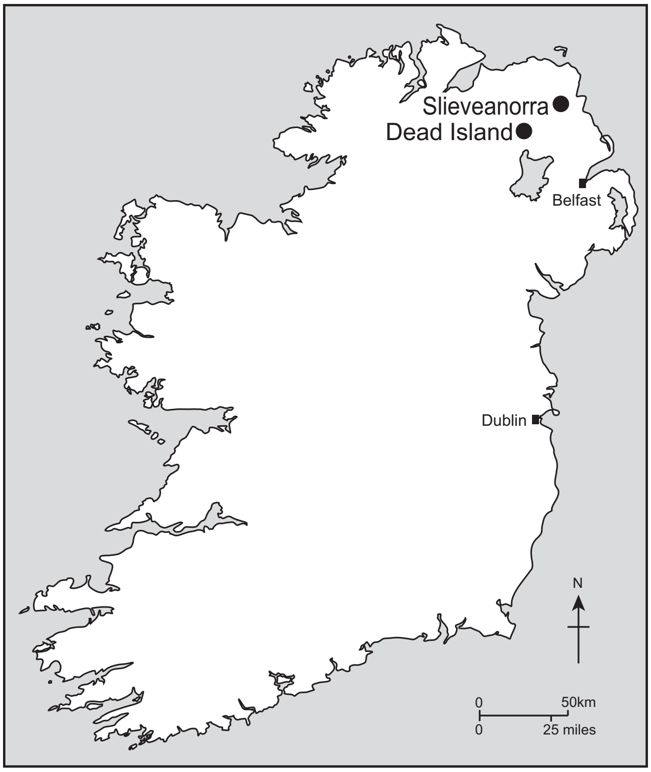
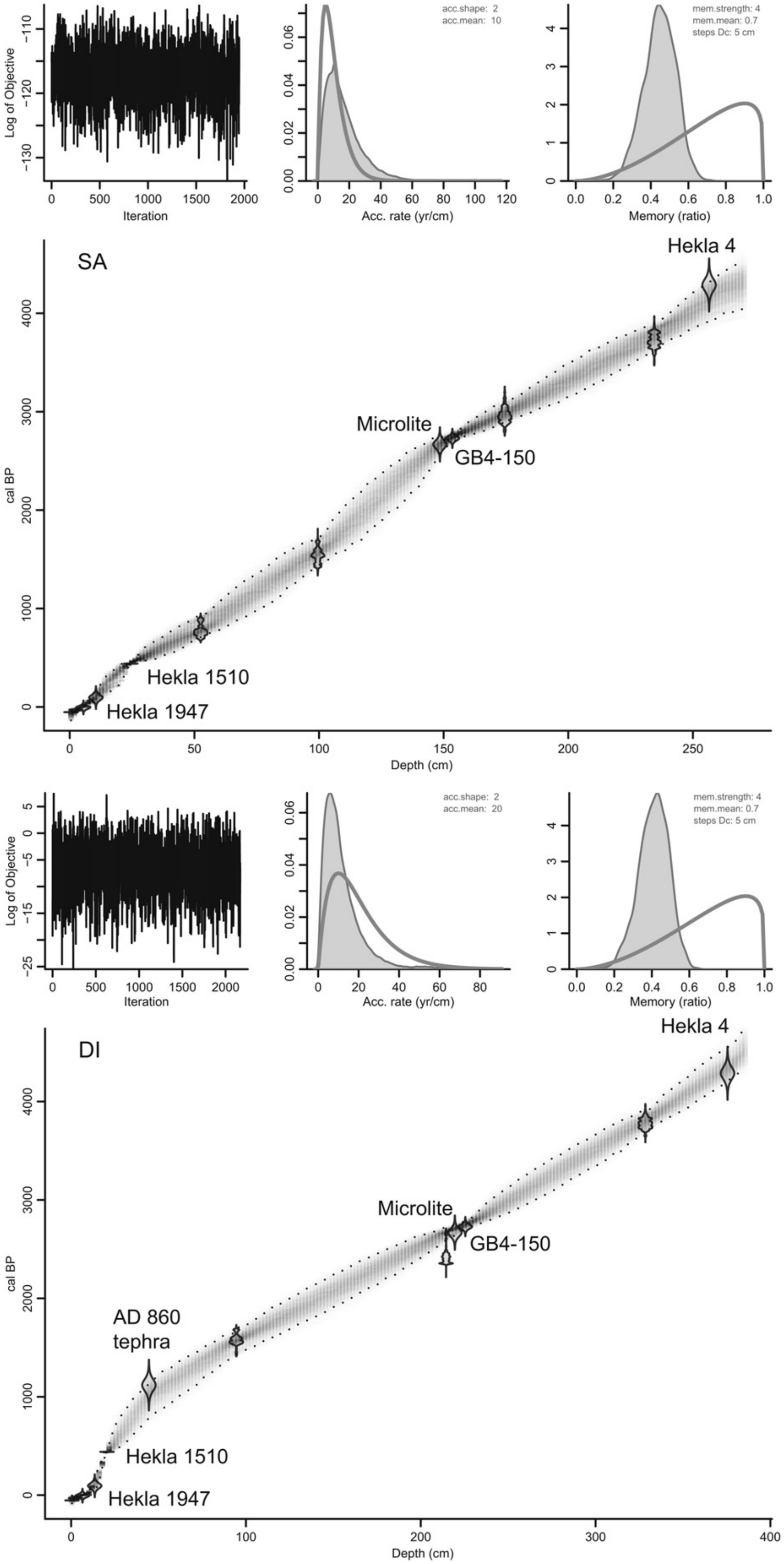


**Fig. 1.** Map showing the location of study sites: Slieveanorra (SA), County Antrim (55° 040′ 22″ N, 06° 13′ 39″ W) and Dead Island (DI), County Londonderry (54° 53′ 15″ N, 06° 32′ 51″ W).

Testate amoebae-derived water table reconstructions from each site have been published previously (Swindles et al., 2010). The reconstructions were carried out using the ACCROTELM pan-European transfer function, which is based on weighted averaging tolerance-downweighted regression with inverse deshrinking (Charman et al., 2007). Sample-specific reconstruction errors were calculated through 1000 bootstrap cycles (Line et al., 1994). Plant macrofossil data were not integrated as the analysis was only carried out at key intervals and is not a continuous dataset (Swindles, 2006; Swindles et al., 2007a).

Chronological control for the records of DI and SA is based on tephrochronology, AMS $^{14}$C dating and spheroidal carbonaceous particle (SCP) stratigraphies as described in Swindles et al. (2010). The tephrochronological framework enables precise correlation of the proxy climate records. Radiocarbon dates were calibrated with IntCal09 (Reimer et al., 2009) and expressed with $2\sigma$ ranges (Supplementary material B).

Probability distributions for calibrated radiocarbon dates were used for the estimation of the age-depth models along with the tephra and SCP determinations. The calendar year of AD 2003 was attributed to the top of the profile as this was the time of core collection. An age-depth model (Bacon), based on a piece-wise linear accumulation model (Blaauw and Christen, 2011), where the accumulation rate of sections depends to a degree on that of preceding sections was applied to the chronological data. The age-modelling procedure is akin to that described in Blaauw and Christen (2005), although more numerous and shorter sections are used (of 5 cm thickness) to generate more flexible and robust chronologies. A priori, accumulation rates were assumed to have been between 5 and 40 yr/cm (mean 20; Fig. 2). The degree of dependence of accumulation rates between neighbouring sections was believed to be low a priori. The prior information was


Log of Objective
−110
−120
−130
0
500
1000
1500
2000
Iteration
acc.shape: 2
acc.mean: 10
0.00
0.02
0.04
0.06
0
20
40
60
80
100
120
Acc. rate (yr/cm)
mem.strength: 4
mem.mean: 0.7
steps Dc: 5 cm
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0
Memory (ratio)
SA
Hekla 4
Microlite
GB4-150
Hekla 1510
Hekla 1947
cal BP
0
1000
2000
3000
4000
0
50
100
150
200
250
Depth (cm)
Log of Objective
5
0
−5
−15
−25
0
500
1000
1500
2000
Iteration
acc.shape: 2
acc.mean: 20
0.00
0.02
0.04
0.06
0
20
40
60
80
Acc. rate (yr/cm)
mem.strength: 4
mem.mean: 0.7
steps Dc: 5 cm
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0
Memory (ratio)
DI
Hekla 4
Microlite
GB4-150
AD 860
tephra
Hekla 1510
Hekla 1947
cal BP
0
1000
2000
3000
4000
0
100
200
300
400
Depth (cm)

combined with the radiocarbon and tephra dates using thousands of Markov Chain Monte Carlo iterations (Blaauw and Christen, 2005). Chronological errors for each profile were calculated from the Bacon models. We ensured that all data were treated in the same way to minimise methodological errors.

### 2.2. Spectral analysis

Spectral analysis was carried out on the proxy climate records to test the palaeoclimatic series in the frequency domain. The Lomb-Scargle Fourier transform method was used because unevenly spaced data points characterise the data. This method does not interpolate the data to an equal sample interval, which can bias results because data points become somewhat dependent after interpolation (Schulz and Stattegger, 1997). Harmonic analysis was used to detect periodic signal components in the presence of noise (Percival and Walden, 1993; Borgmark, 2005). A rectangular window was used with the significance set to $\alpha = 0.05$ and $\lambda = 0.4$ (99.6% false alarm level) for Siegel's test (Siegel, 1980) with 2–3 harmonic components. The analysis was carried out using the software package SPECTRUM (Schulz and Stattegger, 1997). All data were detrended by linear regression prior to analysis. The highest frequency that can be determined is termed the *Nyquist frequency* and is exactly twice the chronological distance between successive observations (Davis, 1986). The REDFIT program was used to estimate the red-noise spectra in the dataset (Schulz and Mudelsee, 2002), because red-noise backgrounds can pose a particular problem during the analysis of palaeoclimatic time series (Schwarzacher, 1993). A first-order autoregressive parameter was generated from the dataset and presented in the frequency domain to test if spectral peaks are significant against the red-noise background generated from a first-order autoregressive process (null hypothesis).

## 3. Results

Bayesian age-depth models and the palaeohydrological records from the two study sites, DI and SA bogs, are presented in Figs. 2 and 3. Multiple statistically significant periodicities (identified by Siegel's test) are recorded in both the testate amoebae-derived water table reconstructions and the peat humification data (Fig. 4). These periodicities were classified into 100-year bins to test inter-site replication and averages were calculated (Table 1). Statistically significant and replicated periodicities of c. 1160, 540, 260, 180 and 130 years are present in at least one proxy at both sites (Table 1). REDFIT analysis demonstrates that these periodicities cannot be explained by the first-order autoregressive process (AR1) (Supplementary material C) and thus, are not the product of red-noise. Replication of these periodicities suggests they are likely to be an expression of allogenic controls, i.e. climatic changes (Table 1).

## 4. Discussion

### 4.1. Review of periodicities

The replication of multiple periodicities in paleohydrological records from DI and SA bogs provides evidence that they are the product of allogenic climate-related controls rather than internal processes operating within individual peatlands. We discuss all periodicities in the two records and provide a review of similar periodicities reported in the literature.

### 4.2. Unambiguous periodicities

Numerous paleoclimate studies demonstrate correlation between total solar irradiance (TSI) and climate change at decadal to millennialscales through the Holocene (e.g. Bond et al., 2001; Neff et al., 2001; Steinhilber et al., 2010). The TSI is the amount of solar radiative energy incident on the Earth's upper atmosphere, which varies in phase with the ~9–12-year Schwabe sunspot cycle, with an amplitude of about 0.1% and an average value of about 1366 W/m$^2$ (Friis-Christensen and Lassen, 1991; Willson and Hudson, 1991). Variation in TSI through a sunspot cycle has small but detectable effects on the Earth's climate (Labitzke, 2003) due to the influence of atmosphere-ocean amplifiers (Labitzke and van Loon, 1988; Carslaw et al., 2002; Gray et al., 2010). The longer wavelength ~20–22-year Hale Cycle, and the ~72–90-year Gleissberg sunspot cycle (Gleissberg, 1958; Garcia and Mouradian, 1998), are part of a well-documented amplitude modulation of the shorter Schwabe cycle (Dean, 2000). On longer centennial and millennial time scales, the influence of TSI has varied by as much as a factor of 3–4 as a result of stochastic changes of solar magnetic activity and changes of the geomagnetic field (Carslaw et al., 2002). Fluctuations in production rates of the cosmogenic nuclides $^{14}$C and $^{10}$Be are coeval with annual to millennial timescale changes documented in globally distributed proxies of drift ice, suggesting that celestial forcing plays a dominant role in centennial (~200–500 years) and millennial-scale (~1000–1500 years) climate fluctuations (Bond et al., 2001). A suite of high- and low- latitude paleoclimate records provide evidence that intervals of reduced solar activity were associated with declines in global temperature (e.g. van Geel et al., 1996; Hu et al., 2003; Wiles et al., 2004; Mangini et al., 2005). However, it is important to note that while some regions cooled, others warmed due to modulation of effects of solar activity by global teleconnections and other secondary influences on climate. Changes in precipitation patterns influenced by solar activity show similar spatial variations in expression (van Geel et al., 1998; Fleitmann et al., 2003; Plunkett and Swindles, 2008).

Minor changes in solar irradiance (e.g. $<0.1\%$ over the 11-year sunspot cycle) appear to be amplified by the ocean-atmosphere system so that they affect large-scale components of climate, such as major stratospheric and tropospheric circulation patterns, including the position of the intertropical convergence zone, the South Pacific convergence zone, and atmospheric Rossby waves. This affects monsoons, the position of storm tracks, and ocean circulation patterns through, for example, by modification of sea level pressure (Clement et al., 1999; van Geel et al., 2000; Ding and Wang, 2005; Asmerom et al., 2007; Meehl et al., 2008).

The c. 1160-year periodicity documented in Northern Ireland peat bogs is coherent with the c. 1100-year periodicities found in two peatlands in Northern England (Hughes et al., 2000; Langdon et al., 2003), other millennial-scale periodicities identified in North Atlantic marine sediments (Chapman and Shackleton, 2000), cold water injections in the western Barents Shelf (Sarnthein et al., 2003) and Iceland-Scotland overflow water (Bianchi and McCave, 1999). This persistent cycle of Holocene climate change has also been recognised in ice rafting events in the North Atlantic, which

**Fig. 2.** Bayesian age-depth models for SA (top) and DI (bottom) (after Swindles et al., in press). On the top panels of both graphs, the leftmost plots show that both MCMC runs were stable (>2000 iterations), middle plots show the prior (curves) and posterior (filled histograms) distributions for the accumulation rate (yr/cm), and the rightmost plots show the prior (curves) and posterior (filled histograms) for the dependence of accumulation rate between sections. Major plots show the age distributions of calibrated $^{14}$C dates, tephras and SCP isochrons, and the age-depth model (grey-scale). The Hekla 4 (2395–2279 BC), GB4-150 (800–758 BC), Microlite (755–680 BC), AD 860 (AD 776–887), Hekla 1510 and Hekla 1947 tephras are present. Dark grey areas indicate precisely dated sections of the chronology, while lighter grey areas indicate less chronologically secure sections (Swindles et al., in press).

operates with a period of 1470 ± 500 years in the Late Quaternary (1374 ± 502 years for the Holocene period alone), and may be linked to changes in solar irradiance (Bond et al., 1997, 2001). A period of c. 1000 years has been identified in alkenone-based SST data from the North Atlantic (Rimbu et al., 2004), periods of ~1400 and c. 980 years were documented in glaciochemical records from Greenland (Witt and Schumann, 2005), and a period of c. 1450 years has also been identified in a German speleothem (Niggemann et al., 2003). Throughout North America, a c. 1150-year cycle in air temperature is documented by changes in the abundance of pollen (Viau et al., 2006) and millennial-scale climate cycles have been discovered in lacustrine, stalagmite and marine records (e.g. Cumming et al., 2002; Hu et al., 2003; Patterson et al., 2004a; Springer et al., 2008; Galloway et al., 2011).

A significant proportion of the evidence for a solar influence on climate is based on statistical associations to $^{10}$Be and $^{14}$C cosmogenic isotope records (e.g. Hu et al., 2003), and pan-hemisphere distribution of records that document correlative cyclic climate changes, which suggests links but do not provide evidence of causal mechanism(s). Assessing the role of solar forcing is also complicated by substantial internal variability in the climate system. However, there is evidence that millennial-scale periodicity in climate may result from rectification of solar forcing by the thermohaline circulation, through a threshold response (Debret et al., 2007; Dima and Lohmann, 2009) and sea surface temperature anomalies that affect air circulation patterns (Springer et al., 2008). The periodicity of these millennial-scale Holocene ‘Bond events’ closely match Dansgaard-Oeschger events that operated during glacial phases (Dansgaard et al., 1993). The c. 1050 and 1530-year periodicities recorded in the SA water table and DI humification records, respectively, are also within the envelope of the Holocene ‘Bond event’ cycle.

The c. 540-year periodicity recognized in this study is correlative to the c. 580-year periodicity recorded in County Fermanagh, Northern Ireland (Swindles et al., 2007b) and a c. 560 cycle previously identified in a testate amoebae-derived water table reconstruction from Tore Hill Moss, Scotland (Blundell and Barber, 2005). The c. 540-year cycle is similar to the c. 600-year cycle noted in palaeohydrological records from the Border Mires (Hughes et al., 2000) and the c. 500-year cycle registered in humification records from Draved Moss, Denmark (Aaby, 1976). Late Holocene climate cycles of ~500-years are also documented in marine, lacustrine and speleothem records from North America (Hu et al., 2003; Patterson et al., 2004a; Springer et al., 2008) and interpreted to be a harmonic of Bond events (Springer et al., 2008). Cycles of c. 512 and c. 550 years have been reported from tree ring and ocean core data (Stuiver and Braziunas, 1993a; Bianchi and McCave, 1999; Chapman and Shackleton, 2000) and a periodicity of ~550 years has been found in the Holocene solar reconstruction (Dima and Lohmann, 2009), providing evidence for a solar driver of climate change on this frequency.

The c. 260-year periodicity is coherent with the c. 260-year periodicity found in a peat humification record from County Fermanagh, Northern Ireland (Swindles et al., 2007b), the persistent c. 260-year periodicity identified in a Danish bog (Aaby, 1976) and the c. 250-year periodicity identified in two peat humification profiles from Sweden (Borgmark, 2005). This cycle also matches similar periodicities reported in glaciolacustrine sediments in northern Norway (Matthews et al., 2000), marine sediments in the Baltic Sea (Kunzendorf and Larsen, 2002) and laminated sediments of Loch Ness, Scotland (Cooper et al., 2000). A c. 250–300-year cycle has also been documented in sediment colour in laminated marine sediments from coastal British Columbia, Canada (Patterson et al., 2004a, 2007), and in late Holocene fish records in the same region (Patterson et al., 2004b). A cycle of c. 250 years has been reported in historical ‘naked-eye’ observations of sunspots between 165 BC and 1918 AD (Vaquero et al., 2002). This series may also contain climatic information because specific meteorological conditions are required for sunspots to be visible by eye. The c. 260-year periodicity identified here may reflect quasi-periodic signals of the Suess solar cycle or a combination of the Suess cycle and the Gleissberg cycle (72–90 years).

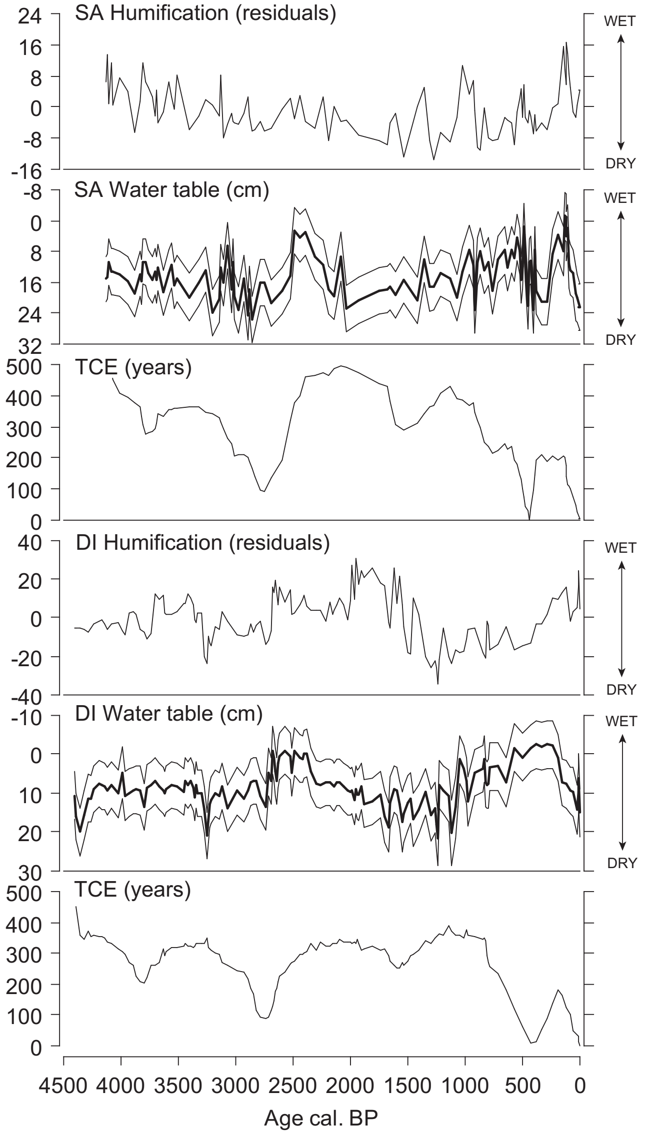


**Fig. 3.** Humification data and testate amoebae-derived water table reconstructions for SA and DI plotted against modelled age. The total chronological errors (TCE) for the records, as calculated from the Bayesian age-depth models (Fig. 2), are illustrated. The water table reconstruction errors, as derived from bootstrapping, are shown.

The periodicity at c. 180 years is coherent with ~200-year periodicities found in numerous humification profiles from peatlands in the UK and Ireland (Chambers et al., 1997; Chambers and Blackford, 2001; Plunkett, 2006) and sediments in the southern Baltic Sea (Yu, 2003). In North America, the ~200-year cycle is documented in a peatland biomarker and isotope record (Nichols and Huang, 2012), in Sr/Ca and $\delta^{13}$C preserved in the west-Virginian stalagmite record (Springer et al., 2008), in biogenic silica in an Alaskan lake (Hu et al., 2003), and as a c. 210-year cycle in charcoal accumulation rates at Dog Lake, British Columbia (Hallett et al., 2003). A c. 200-year cyclicity has also been correlated with glacial activity in Alaska: glaciers advanced during periods of lower solar activity associated with lower summer temperatures and/or

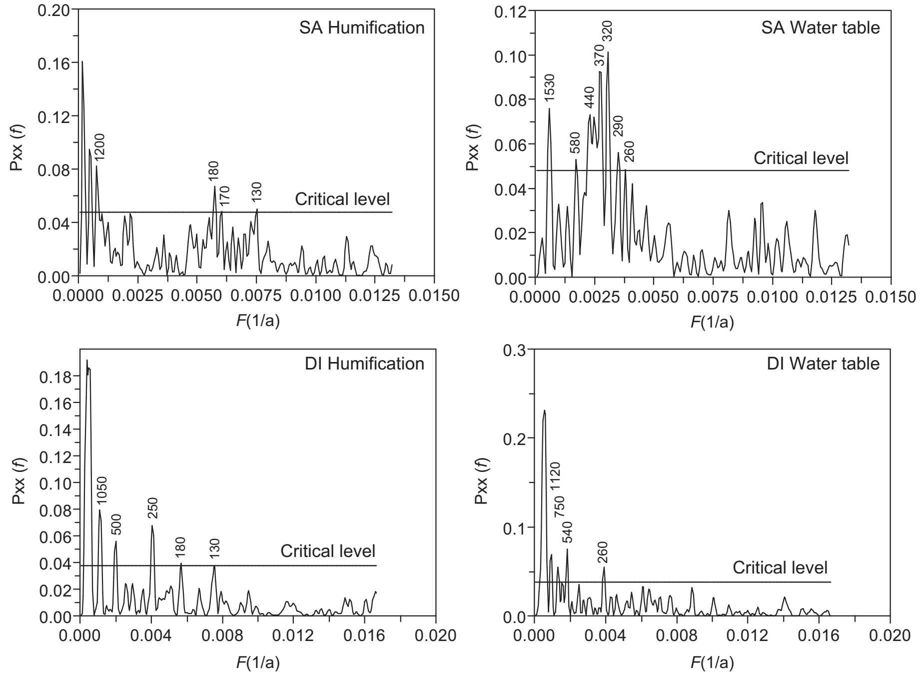


**Fig. 4.** Spectral analysis of humification data and testate amoebae-derived water table reconstructions from SA and DI. Critical level for Siegel's test is shown.

increased precipitation (Wiles et al., 2004). Ostracod-derived Mg/Ca ratios from Holocene lacustrine deposits on the northern Great Plains of North America are also characterized by a c. 200-year cyclicity, which correlate well with temporal changes in water temperature and levels of evaporation/precipitation (Yu and Ito, 1999). These results suggest that cyclic drought coincided with lower solar activity in central North America. Planktic foraminiferal assemblage changes in sediments from the Gulf of Mexico and Ti content from cores from Cariaco Basin off Venezuela are also characterized by a c. 200-year cyclicity (Haug et al., 2001; Poore et al., 2003, 2004). This record has been used to map a centennial-scale southward Holocene drift in the mean latitudinal position of the Intertropical Convergence Zone (ITCZ), a movement which has been linked to intervals of lower solar activity (Haug et al., 2001; Poore et al., 2003, 2004). Such periodicities may reflect quasi-periodic signals of the Suess (or De Vries) 180–211-year solar cycle.

Periodicities between 100 and 200 years (e.g. the c. 130-year periodicity identified here) may also represent sub-harmonics of the Hale frequency that have been found in annually laminated sediment colour records from the Northeast Pacific Ocean (Patterson et al., 2007), and records of $^{14}$C and historical aurorae (Pearson and Stuiver, 1986; Attolini et al., 1988, 1990; Stuiver and Braziunas (1993b)). An equivalent periodicity of c. 129 years was also found in biomarker and isotope data from a peatland in north-eastern USA (Nichols and Huang, 2012).

### 4.3. Other periodicities

The c. 750-year periodicity is most difficult to explain because it was only found in the DI water table record, and therefore could be a product of internal peatland dynamics. Periodicities of c. 750 years have not been found in peat-based proxy climate records to

**Table 1**
Inter-site correlation of the statistically significant periodicities (as determined through Siegel's test).

| Century band | SA Humification | SA Water table | DI Humification | DI Water table | Information |
|---|---|---|---|---|---|
| 1500–1600 | | 1530 | | | No replication |
| 1400–1500 | | | | | No periodicities |
| 1300–1400 | | | | | No periodicities |
| 1200–1300 | | | | | No periodicities |
| 1100–1200 | 1200 | | | 1120 | c. 1160 |
| 1000–1100 | | | 1050 | | No replication |
| 900–1000 | | | | | No periodicities |
| 800–900 | | | | | No periodicities |
| 700–800 | | | | 750 | No replication |
| 600–700 | | | | | No periodicities |
| 500–600 | | 580 | 500 | 540 | c. 540 |
| 400–500 | | 440 | | | No replication |
| 300–400 | | 370 | | | No replication |
| 300–400 | | 320 | | | No replication |
| 200–300 | | 290 | | | No replication |
| 200–300 | | 260 | 250 | 260 | c. 260 |
| 100–200 | 180 | | 180 | | c. 180 |
| 100–200 | 170 | | | | No replication |
| 100–200 | 130 | | 130 | | c. 130 |
| 0–100 | | | | | No periodicities |

date, although a c. 715–775-year cycle has been determined to represent a harmonic of the Bond event periodicity in other proxy records from the Northern Hemisphere (von Rad et al., 1999; Wang et al., 1999; Springer et al., 2008). Similar cycles have been found in North Atlantic alkenone-based SST data (Rimbu et al., 2004), Sr/Ca and $\delta^{13}$C values in Holocene stalagmite records in east-central United States (Springer et al., 2008) and a prominent c. 725-year drought cycle has been documented in a lake record from central Africa, which probably represents variations in Indian Ocean monsoons (Russell et al., 2003).

Periodicities at c. 290–440 years were found only in the SA water table record. We interpret the lack of replication of these cycles to mean that they may not be expressions of climate forcing. However, the c. 290–440 year cycles are coherent with periodicities of c. 300–400 years documented in a peat-based proxy record from County Fermanagh, Northern Ireland (Swindles et al., 2007b), humification records from two peatlands in Sweden (Borgmark, 2005), and planktic foraminiferal assemblage changes in sediments from the Gulf of Mexico (Poore et al., 2003). A quasi-400–650-year periodicity in sea-ice formation and storminess has been reported from the sedimentary record off the western Barents shelf (Sarnthein et al., 2003). Cycles of c. 400 years are also well-documented in lake sedimentary records from the Great Plains of North America (Laird et al., 1996; Dean, 1997; Yu and Ito, 1999; Dean and Schwalb, 2000; Fritz et al., 2000; Dean et al., 2002) and Alaska (Hu et al., 2003). A prominent 400-year wet-dry climate cycle has been found in a lacustrine record in NW China (Wu et al., 2009). The 400-year periodicity may relate to the oscillatory mode of the Sun's convective zone, and has been identified in $^{14}$C and $^{10}$Be records (Stuiver and Braziunas, 1989).

The non-replicated periodicities may represent the product of non-climatic factors (e.g. internal peatland dynamics), however, correlatives do appear to be expressed in other global palaeoclimate records. An alternative hypothesis is that these periodicities relate to climatic fluctuations but are weaker than those expressed in both sites. It is possible that these periodicities may have been diminished in one of the sites due to insensitivity related to factors such as internal peatland ecohydrological dynamics and regional climatic setting.

### 4.4. *Evaluation*

We have shown that testate amoebae-derived reconstructions of hydrological change and peat humification records from DI and SA are broadly coherent (Fig. 2; Swindles et al., 2010). Discrepancies between the records likely reflect i) internal peatland factors such as hydrological and ecological dynamics; ii) non-linear responses between proxies to allogenic controls or responses to factors other than climate; and iii) chronological errors. Outputs of spectral analysis should be treated with caution as they are limited by chronological accuracy and precision of the records. In this study, the chronological errors associated with the age-depth models are greater than several of the periodicity magnitudes (Fig. 2). However, the replication of these periodicities in our investigation and their coherence with multiple other studies from across the Northern Hemisphere suggests that they are not solely related to random variations. Nevertheless, the use of Bayesian age-depth modelling to determine and illustrate chronological errors is a useful step for contextualising the significance of periodicities in palaeoclimate records. The c. 1160 year periodicity should be interpreted tentatively due to the total chronological duration of the proxy records (~4500 years). It is also currently difficult to precisely match the timing of individual peaks and troughs with other palaeoclimate records as this would involve a thorough re-assessment of published chronologies. However, it is evident that many features in the records from DI and SA are broadly coherent with other proxy data from Northern Europe (see Swindles et al., 2010).

Several authors have suggested that the relationship between climate and peat humification is complex, although the directions of inferred climate changes are likely valid (e.g. Blackford and Chambers, 1993). For example, low-weight fulvic acids, polysaccharides and amino acids may also be contained in the humic acid fraction following alkali extraction (Caseldine et al., 2000). Secondary decomposition of peat through subsequent water table lowering may also affect the initial humification signal recorded in the peat profile (Tipping, 1995; Borgmark and Schoning, 2006). In addition, plant species effects are likely to have an influence on peat humification (Overbeck, 1947; Yeloff and Mauquoy, 2006). Problems associated with testate amoebae-derived water table reconstructions include selective preservation of tests (Swindles and Roe, 2007; Mitchell et al., 2008), lack of contemporary monitored hydrological data for transfer function development (Swindles et al., 2009), taxonomic issues (Swindles et al., 2009), spatial autocorrelation (Telford and Birks, 2009), and underestimation of reconstruction errors (Payne et al., submitted for publication).

Despite these limitations, the replicated periodicities presented here provide compelling evidence for common climate forcing of peat hydrology throughout the mid- to late Holocene. The c. 1160, 540, 260, 180 and 130-year periodicities identified here corroborate the findings of previous palaeoclimate studies in the UK (e.g. Hughes et al., 2000; Chambers and Blackford, 2001) and further-afield (e.g. Wanner et al., 2008). Although these results support the paradigm that peatlands are important archives of past climate change, future work should explore the nature and mechanisms of the peatland hydrological response to climate change in a truly process-based ecohydrological sense. A combination of high-resolution palaeoenvironmental data and peat development models (e.g. DigiBog – Baird et al., 2011) may provide much-needed insights into the spatio-temporal responses of peatland systems to initial climate forcings.

## 5. Conclusions

[1] Spectral analysis of tephra-linked humification data and testate amoebae-derived water table reconstructions from two peatlands in Northern Ireland define periodicities indicative of changes in effective moisture.

[2] Periodicities documented at both sites occur at c. 1160, 540 and 260, 180 and 130 years. A technique to estimate the possible level of red-noise illustrates that the periodicities cannot be explained by a first-order autoregressive model.

[3] The periodicities documented in the peat records are coherent with periods observed in a wide variety of proxy records elsewhere in Europe, the North Atlantic and North America, suggesting common allogenic climate drivers. The 1160-year periodicity may be linked to the solar forcing-driven millennial-scale periodicities identified in North Atlantic marine sediments. The 180–260-year periodicities may reflect quasi-periodic signals of the Suess solar cycle or a combination of the Suess cycle (180–211 years) and the Gleissberg cycle (72–90 years).

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## Appendix. Supplementary material

Supplementary material related to this article can be found online at doi:10.1016/j.quascirev.2012.03.003.

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