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Centennial-scale climate change in Ireland during the Holocene

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Abstract

We examine mid- to late Holocene centennial-scale climate variability in Ireland using proxy data from peatlands, lakes and a speleothem. A high degree of between-record variability is apparent in the proxy data and significant chronological uncertainties are present. However, tephra layers provide a robust tool for correlation and improve the chronological precision of the records. Although we can find no statistically significant coherence in the dataset as a whole, a selection of high-quality peatland water table reconstructions co-vary more than would be expected by chance alone. A locally weighted regression model with bootstrapping can be used to construct a 'best-estimate' palaeoclimatic reconstruction from these datasets. Visual comparison and cross-wavelet analysis of peatland water table compilations from Ireland and Northern Britain shows that there are some periods of coherence between these records. Some terrestrial palaeoclimatic changes in Ireland appear to coincide with changes in the North Atlantic thermohaline circulation and solar activity. However, these relationships are inconsistent and may be obscured by chronological uncertainties. We conclude by suggesting an agenda for future Holocene climate research in Ireland.

Keywords: Climate change; Holocene; Centennial-scale; Ireland; Palaeoclimate compilation; Statistical analysis

1. Introduction and Rationale

Until recent decades, the climate of the Holocene epoch was considered to be exceptionally stable compared to that of the Pleistocene (Denton and Karlen, 1973; Dansgaard et al., 1993; Mayewski et al., 2004). However, evidence from both marine and terrestrial proxy records suggests that the Holocene was characterised by marked climatic changes including cycles of millennial and centennial scales (e.g. Bond et al., 1997, 2001; Wanner et al., 2008), and abrupt events (e.g. Barber et al., 1999; Magny, 2004). As recent global mean temperatures are probably higher than they have been during the past millennium (Jones and Mann, 2004; Moberg et al., 2005; Osborn and Briffa, 2006), it is critical that natural climate change in the Holocene is fully understood, because this may either mask or enhance any human-influenced climate change of recent centuries. However, climate reconstructions from single sites tend to be heavily influenced by local factors, thus there is an urgent need to compile and scrutinise large proxy datasets from different climatic regions.

Ireland is a key location for the examination of Holocene climate dynamics as it is sensitive to any changes occurring in the North Atlantic Ocean (e.g. Lehman and Keigwin, 1992). Ireland's oceanic climate is strongly influenced by the North Atlantic Drift and thus does not have temperature extremes typical of many other countries at similar latitude (McElwain and Sweeney, 2003). Mean daily temperatures vary between 4-8°C in winter and 2-16°C in summer (http://www.met.ie/). The rainfall of Ireland mostly comes from Atlantic frontal systems, although there is marked spatial variation. Rainfall is highest in the west (~1000-1400 mm yr^{-1}) and in mountainous areas (often >2000 mm yr^{-1}), whereas typical rainfall in eastern Ireland is between 700-1000 mm yr^{-1}. December and January are usually the wettest months in Ireland (http://www.met.ie/). This spatial variation in temperature and precipitation leads to variation in annual water deficit (Mills, 2000; Figures 1 and 2).

The Armagh Observatory records, which began in 1838, represent the longest instrumental climate records for Ireland (Figure 2). The calibration of these records has provided data that are reliable, consistent and of high quality (Butler et al., 1998; 2005). In general, two main phases of change can be observed in the total annual rainfall data. Firstly, there is a phase of fluctuating but generally increasing rainfall from 1840 to the late 1960s. Secondly, a major decrease in rainfall occurs in the 1960-70s, followed by an apparent stabilisation at a lower level for the 1980-90s. The temperature data show three main phases. The first is a period of reasonably high temperatures from the 1840-1880s. Then, in 1880, a rapid fall in temperature is then followed by a period of fluctuating but generally increasing temperature until the 1960s. In the 1960s temperature appears to remain relatively stable until a rapid increase from the late 1980s. Despite these high-quality instrumental climate data, a compilation of Holocene palaeoclimate proxy data for Ireland is needed to examine the nature of climate changes in Ireland beyond recent centuries.

During the Holocene, multi-millennial-scale climatic changes should be relatively minor in Britain and Ireland as changes in insolation due to orbital forcing were much smaller than those experienced at high latitudes (Charman, 2010). Therefore, millennial and centennial-scale variability is likely to have been a more important factor for environmental change and human societal dynamics in Ireland. Over the last 20 years there has been a proliferation of Holocene climate studies in Ireland, including analysis of lacustrine (e.g. Schettler et al., 2006; Diefendorf et al., 2006; Holmes et al., 2010; Ghilardi and O'Connell, 2013), peatland (e.g. Plunkett 2006; Blundell et al., 2008; Swindles et al., 2010) and speleothem (McDermott et al., 1999; 2001) archives. Several Holocene tephra layers (microscopic 'cryptotephras') have been found in Irish peat bogs and lakes and have been used for dating and precise correlation of the profiles. The tephra layers and are mostly from Icelandic sources (Hall and Pilcher, 2002; Chambers et al., 2004).

In addition, much work has focused on records of climate change from North Atlantic marine sediments west of Ireland (e.g. Bianchi and McCave, 1999; Bond et al., 2001; Thornalley et al., 2009). Despite some attempts to compare marine records to individual terrestrial palaeoclimate records in Ireland (e.g. Swindles et al., 2007a; Blundell et al., 2008), further work is needed to examine these links using a comprehensive synthesis of terrestrial records. Although a general review of centennial-scale climate variability in the British Isles has been undertaken (Charman, 2010), there has been no similar study focussing on Ireland alone. The abundance of data from Ireland presents a unique opportunity to consolidate, analyse and interpret the Holocene proxy record at an island-wide scale. This will be valuable for further studies that seek to i) examine key periods of climate change within Ireland and put these into a wider spatio-temporal context (e.g. Diefendorf et al. 2006; Blundell et al., 2008; Swindles et al., 2010); ii) investigate climate forcing parameters (e.g. Swindles et al., 2007a); and iii) use archaeological data and historic records to examine human-environment relations in the past (e.g. Kerr et al., 2009; Stolze et al., 2012; Plunkett et al., 2013).

The aims of this paper are fourfold:

1. To review evidence for mid-late Holocene climate change in Ireland over centennial timescales and assess the coherence between records. We focus on the last 5,000 years as there are abundant data spanning this period. There are only a limited number of

early Holocene records from Ireland (e.g. McDermott et al., 2001; Schettler et al., 2006; Langdon et al., 2012; Figure 3a and b).

2. To decipher climatic signals from autogenic processes and statistical noise in a compilation of peat-based proxy climate records.
3. To determine whether the patterns observed at the centennial scale in Irish palaeoclimatic records could be explained as the result of chance alone. Blaauw et al. (2010) suggested that ecosystem changes claimed as significant features of many palaeoenvironmental records can in fact be produced by random-walk simulations. Thus a cautious approach to recognising palaeoclimatic features such as abrupt events, long-term trends, quasi-cyclic behaviour, immigrations and extinctions, is required.
4. To evaluate the role of climate-forcing parameters (including oceanic circulation and temperature changes, and solar radiance) in driving changes in Irish climate over the last 5,000 years.

2. Data compilation

A compilation was made of all available Holocene palaeoclimate proxy data from Ireland. The data comprised palaeoclimate proxy records from peatlands, lakes and a speleothem (Table 1, Figures 1 and 3a). A precisely dated palaeoclimatic index inferred from bog oak population dynamics in Northern Ireland (Turney et al., 2005) has been shown to be problematic and has therefore been excluded from this analysis. It has been illustrated that there is not a simple relationship between the frequencies of oaks and bog surface wetness (see Swindles and Plunkett, 2010).

2.1. Speleothem record

A high-resolution U-series dated oxygen isotope record from a speleothem in Crag Cave (County Kerry) represents one of the few temperature-sensitive Holocene proxy climate records in the British Isles (McDermott et al., 1999, 2001; Charman, 2010). This record is based on isotopic analysis of drilled sub-samples of calcite (every 2-2.5 mm) along the central growth axis of the speleothem (McDermott et al., 1999). Crag Cave itself is relatively shallow (~20m deep), situated 20 km inland of the SW coast of Ireland and contained within Lower Carboniferous limestone (McDermott et al., 1999). Speleothem CC3 was taken from the cave interior where the relative humidity is high (98-99%) and where modern measurements indicate a constant internal temperature (McDermott et al., 1999; 2001). Accordingly, the record from CC3 reflects variations in drip water $\delta^{18}O$ that are largely derived from changes in the $\delta^{18}O$ value in precipitation source water ($\delta^{18}Op$) (McDermott, 2004). In terms of Holocene palaeoclimate, this record has been interpreted as reflecting changes in air temperature as well as changes in the isotopic signature of the moisture source and total precipitation amount (McDermott et al., 2001).

2.2 Lake-based records

The brackish karst lake An Loch Mór fills a collapsed sinkhole on the small island Inis Oírr (Galway Bay, western Ireland). The geological setting makes the sediments of the lake a sensitive natural monitor for dissolved element influx via freshwater and seawater inflow, and for siliciclastic aeolian input. Dissolved influx of Ca and inorganic carbon (DIC) largely originate from chemical limestone dissolution in the lake's catchment (delivered through freshwater discharge), whereas the influx of algae and Mg is predominantly from seawater. A major component of the lake sediments is chemically precipitated as biogenic autochthonous calcite, which fluctuates in response to climatic conditions and well as human activity in the catchment (Molloy and O'Connell, 2004; Schettler et al., 2006; Holmes et al., 2007). It has been proposed that the proportion of sedimentary $CaCO_3$ in the record from An Loch Mór reflects precipitation (P) or Precipitation minus evapotranspiration (P-E), as a decrease in $CaCO_3$ with a coinciding increase in total organic carbon (TOC) and Mg/Ca documents periods of lowered rainfall or freshwater inflow, respectively. This signal is complicated by sea-level change and hydrological effects of human impacts on vegetation (Molloy and O'Connell, 2004; Schettler et al., 2006). The geochemical record from An Loch Mór is dated using a combination of ^{14}C, tephrochronology and pollen-based biostratigraphic markers (Chambers et al., 2004).

A ~1 kyr lacustrine carbonate oxygen-isotope time series from Lough-na-shade, a small (0.3 ha surface area) shallow lake (maximum depth ~3.5 m) in Co. Armagh, N. Ireland, is included (Holmes et al., 2010). The record from Lough-na-shade is based on isotopic analysis of the carbonate in contiguous 1-cm samples of isolated valves of the ostracod genus *Candona* from a two-metre core (NSH92) (Holmes et al., 2010). Lake water $\delta^{18}O$ composition is ultimately linked to that of precipitation source water. The extent to which this signal is modified once the water arrives in the lake depends on whether it is a closed or open system, and on the evaporation/precipitation balance. The $\delta^{18}O$ values of lacustrine carbonates are not only controlled by the $\delta^{18}O$ value and temperature of lake water, but also by kinetic and biochemical/vital effects in the precipitation of calcite. The Lough-na-shade record is dated by pollen and geochemical age-equivalent markers as i) short-lived radioisotopes are in low concentration owing to recent rapid sedimentation and ii) ^{14}C dating was not possible owing to the calcareous sediment and lack of terrestrial macrofossils (Holmes et al., 2010).

2.3 Interpretation of oxygen isotope records

It would be a misconception to suggest that oxygen isotope records reflect solely past changes in surface air temperature (Schmidt et al., 2007; Holmes et al., 2010; Daley et al., 2011), not least because the controls on the isotopic composition of the source precipitation are notoriously complex in the mid-latitudes (Cole et al., 1999; Araguás-Araguás et al., 2000). The sections of these records spanning the last 1000 years in the lake and speleothem records (CC3 and NSH92) were compared in a recent paper by Holmes et al. (2010). The authors demonstrated that the covariance between (and magnitude of) the respective isotope signals in the two archives was best explained by changes in past atmospheric circulation. Variations in the estimated $\delta^{18}Op$ therefore reflected changes in the origin and trajectory of the moisture sources for precipitation over Ireland. Lower $\delta^{18}Op$ values were interpreted to reflect the sourcing of moisture from either higher latitude or more continental source air masses. This interpretation is justified on the basis of instrumental evidence linking large (~4‰) variations in the isotopic composition of precipitation in the British Isles to the trajectories of air masses (Heathcote and Lloyd, 1986).

2.4 Peatland records

Peat-derived records represent the most abundant Holocene palaeoclimate data in Ireland. These records are based on testate amoebae (with transfer function-based water table reconstructions), plant macrofossils (with associated 1-dimensional statistical wetness summaries) and humification data from ombrotrophic raised bogs and blanket peatlands. These are well-established climate proxies in peatlands, although multiproxy approaches have revealed discrepancies between individual proxies (e.g. Blundell and Barber, 2005; Swindles et al., 2007b; Chambers et al., 2012). It has been suggested that peat-based records should be considered as proxies of effective precipitation (P-E), especially reflecting the summer deficit period (Charman, 2007; Charman et al., 2009; Booth, 2010). However, peatlands are dynamic ecohydrological systems and climatic signals may be modified by feedbacks inherent in peat formation, decomposition and hydrology (Belyea and Baird, 2006; Frolking et al., 2010; Morris et al., 2011; Swindles et al., 2012a).

In Ireland, there is also some evidence that bog bursts may have influenced the hydrology of peatlands, such as in Derryville (Lisheen) bog (Caseldine and Gearey, 2005; Caseldine et al., 2005; Gearey and Caseldine, 2006). Detailed stratigraphic survey and independent radiocarbon dating of the growth and development of Derryville Bog by Casparie (2005) produced evidence of several catastrophic failures of the hydrological integrity of the mire system attributed to 'bog bursts' at dates of c. 3200 cal. BP, 2770 cal. BP and 2550 cal. BP, with tentative evidence for a further burst at c. 2350 cal. BP. These events tend to be evidenced by erosion gullies, re-deposited peat and anomalous age-depth correlations. The precise causes of 'bog bursts' are unclear but seem to be related to an excess of water within the bog system leading to the crossing of a hydrological 'threshold' and the subsequent rupture of the mire. Study of recent bog bursts indicates that they may occur during periods of extreme weather, such as heavy rains or periods of prolonged dry weather followed by flash flooding (e.g. Feldmeyer-Christe et al., 2011).

Peat records in Ireland have been dated using ^{14}C (e.g. Barber et al., 2003), ^{14}C wiggle-matching (Plunkett and Swindles, 2008), spheroidal carbonaceous particles ('SCPs' - e.g. Swindles, 2006), tephra (e.g. Plunkett, 2006; Table 2), or a combination of these (Swindles et al., 2010). Peat humification data were detrended using linear regression and presented as % transmission residuals (Blackford and Chambers, 1991, 1993). Testate amoebae water table reconstructions are based on the ACCROTELM transfer function (Charman et al., 2007), except Glen West, which is based on the Northern Ireland transfer function (Swindles et al., 2009) and Ardkill and Cloonoolish which are based on the British transfer function (Woodland et al., 1998). However, the output of these transfer functions show markedly similar trends (Charman et al., 2007; Swindles et al., 2009; Turner et al., 2013).

3. Data analysis

The chronologies of four key high-resolution records (Derragh, Dead Island, Slieveanorra and Crag Cave) were firstly analysed through Bayesian methods to assess the typical chronological resolution of the proxy data. The chronological information was modelled using OxCal v4.2 with the IntCal09 calibration set (Bronk Ramsey, 2008, 2009a; Reimer et al., 2009). Each sequence was modelled independently using the procedures outlined in Blockley et al. (2007) with the following refinement: model averaged outlier detection was used to identify and down-weight proportionally the influence of possible outliers in the final model (a 'general outlier model' as specified in Bronk Ramsey, 2009b). The final age model for each data set including estimates of the total uncertainty between dated intervals was calculated by interpolating between points within OxCal. For Dead Island and Slieveanorra interpolation was carried out at 2.5cm intervals while at Derragh Bog 5cm interpolation was used. For Crag Cave, an interpolation interval of 2 mm was employed. When finalised the total chronological uncertainty (mean average and standard deviation) for each record was recorded and used as a guide for comparing the proxy data.

Statistical analysis of the data was carried out using R 2.14.1 (R Development Core Team, 2011). The time series were first detrended by fitting a linear regression line through each dataset and extracting the residuals. As all of the time series are several thousand years in length, this effectively acts as a high-pass filter, so that the focus of subsequent analysis is century-scale variation in climate. The detrending is necessary because the proxy climate data may contain long-term patterns related to (i) gradual changes in climate over millennia, for example tracking insolation changes, and (ii) gradual changes in the response of the proxy to climate at each site, for example the slow growth of ombrotrophic mires and the consequent slow variation in hydrological behaviour. The detrended time series were standardized to produce series with means of zero and one standard deviation. To facilitate comparisons, the irregular time series were converted to regular time series by calculating the weighted average of the data points within contiguous 100 and 250-yr-long 'bins'. An analysis of the direction of change (i.e. wetter/cooler - drier/warmer) from one bin to the next was carried out. The data were mapped with a separate map for each bin.

A null hypothesis that the data show no climatic coherence was tested using a Monte Carlo approach. A test statistic was constructed by finding, for each bin, the difference between the number of data points with positive values and the number of data points with negative values. In a fully random dataset this difference should be close to zero. These differences were summed across all time bins to give a single test statistic representing the overall coherence of the data. The significance of this value was assessed by randomly reordering each time series, 999 times, and calculating the test statistic for each permutation. The 95th percentile of the resulting set of statistics was used as the critical value for the hypothesis test. Full details of statistical testing are provided in section 4.3.1.

4. Results and discussion

4.1 Chronological uncertainties

While it is tempting to align records based around existing age models, frequently these do not fully quantify their chronological uncertainties. This may lead to the miscorrelation of unrelated events or conversely the failure to identify related climatic events, ultimately leading comparative records to appear to diverge and hence leading to the impression of 'noisy' regional reconstructions. This is especially important in Holocene records where subtle and short-lived climatic changes may have differing expressions across a region and may be masked at individual sites and sampling spots by autogenically-driven variation in proxy data. Extracting a climatic signal from this noise is fundamental to understanding the impacts of past climatic change, but may only be achieved when meaningful reconstructions of regional climatic trends can be identified. One approach advocated for dealing with these problems has been to align several records using common 'climatic events' and produce a single master curve for a region (Charman et al., 2006). This approach termed "tuning and stacking" has the potential to alleviate some of the problems outlined above. However, Swindles et al. (2012b) highlight that defining common climatic events and using these to constrain chronologies, potentially introduces further errors into a reconstruction. Ultimately, this approach removes the independence of individual sequence chronologies and makes it difficult to quantify the associated uncertainties of each record (see Blaauw, 2012). This may have the effect of masking the noise in the data and leading to mis-/missed correlations. Here we reconsider the chronology of four key records, Crag Cave, Derragh Bog, Dead Island Bog, and Slieveanorra, which were selected as they have high quality chronologies (McDermott et al., 2001; Brown et al., 2005; Swindles et al., 2007a; Langdon et al., 2012). The age-depth relationships of each site were remodelled in order to examine the maximum likely uncertainties encountered within records, and the most robust way of refining these uncertainties. The total uncertainty can be used as a guide of the robustness of correlation between proxy data and the potential of each record to recognise short-lived decadal-scale events.

The least-well constrained record (at least in the middle and later Holocene) is Crag Cave, which has a low density of dates during this period, indeed total uncertainties are greater than 1000 years between c. 2700-5000 cal. BP. For the entire record, the mean average uncertainty is 438 ±292 years, suggesting this record can only provide centennial-scale information at best. The best-constrained chronologies are found in the peat sites where either tephra or SCP data are available. In the case of the last 1000 years, tephras have calendar ages associated with them and these provide very precise tie points for correlation. However, uncertainties quickly increase away from these intervals. In the Derragh Bog chronology, no tephra or SCP data are available, but this site represents one of the best radiocarbon dated mid- to late Holocene peatland records for Ireland (Langdon et al., 2012). In this instance, the age model provides relatively consistent total uncertainties with the mean average uncertainty of 231 ±62 years (Figure 4). Dead Island and Slieveanorra have mean average uncertainties of 164 ±55 and 167 ±77 years respectively, indicating all three records can potentially be correlated at the centennial-scale. However, if the last c.1000 years are assessed (where annually dated tephras and SCP data are available) both Dead Island and Slieveanorra perform markedly better than Derragh Bog (Figure 4). In this time period, Derragh Bog has mean average uncertainty of 146 ±47 years while Dead Island and Slieveanorra have uncertainties of 72 ±70 and 65 ±47 years respectively. In this later period the tephra and SCP information potentially allow the assessment and correlation of proxy data at decadal scales.

Consequently, reconstructions based on radiocarbon dating alone have relatively consistent uncertainties in the order of 100s of years. However, where tephra and SCP data are available alongside radiocarbon information very precise reconstructions over the last c. 1000 years are achievable. This is also likely to be the case during the period 3000-2500 cal. BP where the widespread GB4-150, OMH-185 (Microlite) and BMR-190 tephra layers have been identified. Currently, these tephra layers constrain the Dead Island and Slieveanorra age models so that they have decadal-scale uncertainties between c. 2800-2600 years ago. Future improvements to these estimates alongside the recognition of other regional tephra marker layers are likely to provide significant reductions in the total chronological uncertainties over this time period where large-scale shifts in climate and environment have been proposed (van Geel et al., 1996; 1998; Plunkett and Swindles, 2008). Even tephra horizons that are less-well chronologically constrained can provide useful stratigraphic tie points. These independent marker layers alongside SCP counts may be used to make direct comparisons between sites, thus removing the need to undertake tuning and stacking approaches (Figure 3).

4.2 Spatial patterns

Figure 5 shows the directional changes across each 100-year bin for the last 5,000 years. It is evident that there is much variability in the data and there is much non-coherence at centennial timescales (also see section 4.3.1). However, two periods of shift to much wetter/colder conditions are apparent, one centred on 250 cal. BP and the other around 2.7 ka cal. BP. The first of these occurs during the 'Little Ice Age', which is well documented in NW Europe, and the second also coincides with a well-established period of climatic change in the early Iron Age transition (Plunkett, 2006; Swindles et al., 2007a). In the datasets analysed here, the first pulse of the Little Ice Age occurs at 550 cal. BP, there is recovery by

450 cal. BP, and only at 250 cal. BP is there strong evidence for a widespread deterioration. The 2.7 ka cal. BP event in Ireland appears to be a more northern phenomenon with quite widespread drying/warming (2750 cal. BP) preceding the shift at 2650 cal. BP. There seems to be a gradual shift to wetter/colder conditions peaking after 1650 cal. BP at 1450 cal. BP, which may reflect a climatic deterioration thought to have occurred in NW Europe during the Dark Ages (e.g. Blackford and Chambers, 1991). There is no unambiguous evidence for a widespread Medieval Warm Period, Roman Warm Period or 4.2 ka cal. BP event (e.g. Booth et al., 2005; Roland, 2012) in Ireland.

4.3 Peatland water table compilation (PWTC)

To refine the peatland proxy climate dataset, the following records were removed:

1. The peatland records from Lisheen (Derryville) as they are confounded by bog bursts (Caseldine and Gearey, 2005);

2. The peatland records from Cloonshannagh, Killeen, Longford Pass and Littleton as they have poor chronological control and low-resolution sampling;

3. All peatland humification and plant macrofossil records. Analysis of plant macrofossils and measurement of the degree of humification are semi-quantitative, and a number of complexities are associated with these proxies. Evaluating causal factors of hydrological change through plant macrofossils can be complicated, as ecological response thresholds may vary between sites (e.g. Moore, 1986; Barber, 1994). Differential preservation and representation of bog surface vegetation is apparent (Yeloff and Mauquoy, 2006), and taxonomical difficulties are exacerbated where peat decomposition increases (Grosse-Brauckmann, 1986). The records can also become 'complacent' where a single eurytypic *Sphagnum* species dominates the profile (Barber et al., 1994; Barber et al., 2003). In addition, different approaches have been used to generate 1-dimensional summaries, which leads to

inconsistency between records (for example, weighted averaging index values or ordination axis scores) (e.g. Daley and Barber, 2012).

Humification can be particularly useful in situations, for example in many blanket peatlands where little or no stratigraphy is apparent owing to the high level of decomposition (e.g. Blackford and Chambers, 1991; Langdon and Barber, 2005; Swindles et al., 2012c). However, there are potential problems with the extraction of humic acids from peat (Caseldine et al., 2000) and changes in botanical composition may have a significant influence on results because of differential decay rates of plant species (Blackford and Chambers, 1993; Yeloff and Mauquoy, 2006; Hughes et al., 2012). However, there are also problems with testate-amoebae based reconstructions. Differential preservation of tests (Mitchell et al., 2008; Swindles and Roe, 2007), particularly in highly humified peats (e.g. Payne and Blackford, 2008) and potential 'no analogue' situations may necessitate careful interpretation of results. While the ecology of these organisms is generally well understood, there remains a high level of complexity to their position in the microbial network (Sullivan and Booth, 2011; Turner and Swindles, 2012), and site-specific factors may influence community composition. Nevertheless, directional changes (i.e. wet/dry shifts) inferred by testate amoebae-based transfer functions are highly consistent when independently tested (Turner et al., 2013), however, the magnitudes of change should be viewed with some caution.

Peat-based water table reconstructions contain signals from autogenic processes (see Swindles et al., 2012a). We present a flexible statistical method in an attempt to decipher climate signals from a large compilation of noisy data from multiple sites. Water table reconstructions were carried out on eight high-quality testate amoebae records from Ireland using the European transfer function (Charman et al., 2007) (Ardkill, Ballyduff, Cloonoolish, Dead Island, Derragh, Glen West (high-resolution section only), Slieveanorra, Sluggan).

The chronologies and associated errors for each sequence were modelled using Bacon, an age-depth model based on piece-wise linear accumulation (Blaauw and Christen, 2011; Supplementary material 2), where the accumulation rate of sections depends to a degree on that of neighbouring sections. In Bacon, accumulation rates are constrained by a prior distribution (a gamma distribution with parameters acc.mean and acc.shape), as is the variability in accumulation rate between neighbouring depths ("memory", a beta distribution with parameters mem.mean and mem.strength). The age-modelling procedure is similar to that described in Blaauw and Christen (2005), although many more, shorter sections are used (default 5 cm thickness), resulting in more flexible and robust chronologies. The prior information was combined with the radiocarbon and tephra dates using millions of Markov Chain Monte Carlo iterations (Blaauw and Christen, 2011). The total chronological error (difference between maximum and minimum probability ages at 95%) associated with each depth (in all the above sites) was calculated from the model (Figure 6). Samples with chronological errors >500 years were removed from the compilation process.

The water table data were standardised to z-scores, combined and ranked in chronological order (i.e. by maximum age probability as modelled by Bacon). A Lowess (Locally weighted scatterplot smoothing; Cleveland 1979, 1981) (smooth = 0.02) was calculated. Polynomial regressions in a neighbourhood of x were fitted following:

$$n-1\sum_{i=1}^{n} W_{ki}(x)\left(y_i-\sum_{j=0}^{p}\beta_j x^j\right)^2$$

where $W_{ki}(x)$ denoted k-NN weights (Cleveland, 1979). Bootstrapping was used (999 random replicates) to calculate 95% bootstrap ranges on the Lowess function. In order to retain the structure of the interpolation, the procedure uses resampling of residuals rather than resampling of original data points. It was found that interpolation to annual interval made little difference to the overall shape of the Lowess function. This represents a statistical compilation of the peatland water table records (PWTC) and models the common inter-site trends (Figure 7).

4.3.1 Statistical testing

It is obvious that there is a lot of variability in the data and it is not immediately apparent by inspection that the water table reconstructions show a common pattern. This may be due to i) differences in regional climate; ii). chronological uncertainties; iii) response of proxies to factors other than climate and iv) internal peatland processes (Figures 8 and 9). Ideally it would be possible to test the null hypothesis "the sequences do not co-vary more than if they were drawn from an appropriate distribution at random". A conclusive test of this hypothesis is difficult for several reasons:

1. The interval between observations in any given water-table reconstruction time-series is irregular;
2. The observations in the different time-series do not represent the same years;
3. The age of each observation is uncertain (cf. Haam and Huybers, 2010);

4. Even after detrending, some of the time-series appear to be autocorrelated, which means that the effective degrees of freedom are reduced (Yule, 1926). However, because of the irregular nature of the time-series, standard approaches to treating autocorrelation (e.g. ARMA modelling) cannot readily be applied.

Nonetheless, useful insights can be made by comparing simulated datasets to the actual data. In order to compare the sequences, the detrended, standardized datasets were transformed into regular time-series by binning the data, with bins of 0-100, 100-200, ... 4900-5000 cal. BP (following the same approach used in mapping the data in Figures 5 and 7).

We then calculated a statistic w_{actual}:

$$w_{actual} = \sum_{b=1}^{n} \sum_{d=1}^{m} x_{b,d}$$

where b is the bin, n is the total number of bins, d is the (binned) dataset, m is the number of datasets, and $x_{b,d}$ represents each data point. Missing data points were ignored. This statistic will be close to zero if the datasets do not co-vary systematically (note that this statistic is less sensitive to large values than the more usual coefficient of co-variance, based on products rather than sums, commonly used for comparing two datasets).

We then generated 999 simulations of the dataset by randomly re-ordering the detrended, standardized observations. The statistic w was calculated for each simulated dataset and the 95^{th} percentile was recorded as w_{95}. The probability of attaining a higher value of w than w_{actual} by chance was estimated from the ranking of the simulations. We performed the same procedure for the datasets without first detrending. The statistics were calculated for the complete set of water-table reconstructions available, and then for the smaller set of eight records in the PWTC. The results are shown in Table 3. To check the effect of the choice of bin size or starting point, in each case we ran the test using 19 additional, random combinations of bin size (between 25 and 150 years) and starting point (between 0 and 150 cal. BP). The results are shown in Table 4. There was no obvious relationship between bin size, starting position, and the ratio of w_{actual} to w_{95}.

This approach to testing the hypothesis does not take into account the effect of autocorrelation in the time series. We measured the autocorrelation of the longest continuous series in the binned data (bin size 100 years, starting point 0 years cal. BP). On this basis, only four of the twelve records (Ballyduff, Dead Island, Derragh, Littleton) were found to be significantly autocorrelated (always at lag 1) at the 95% level; overall, the effect of autocorrelation on the data is therefore weak. Thus, while we stress that a perfect test of the hypothesis is not technically feasible, this analysis strongly suggests that the records co-vary more than we would be expected by chance alone. This is particularly true of the eight records that were selected on the basis of quality. This provides confidence that the PWTC shown in Figure 9 reflects, at least in part, genuine changes in regional climate.

All the raw lake, speleothem and peatland data in Figure 3a were subjected to the same permutation test and the following results were obtained: $w_{actual} = 219$, $w_{95} = 281$. Even with possible effects of autocorrelation making the data appear more coherent than they really are, there is no statistically significant co-variance in the unscreened data.

4.3.2. Comparison with the British compiled water table record

There is variable correspondence between the PWTC and the British 'tuned and stacked' water table reconstruction of Charman et al. (2006) (Figure 10). However, there are some potential periods of coherence including a clear shift to wetter conditions at c. 2700 cal. BP, 1400 cal. BP and a wet phase from c. 500-100 cal. BP. These correspond temporally with the Subboreal-Subatlantic transition (e.g. van Geel et al., 1996; Swindles et al., 2007a), the Dark Ages climatic deterioration (e.g. Blackford and Chambers, 1991) and the Little Ice Age (e.g. Lamb, 1995). Dry phases are present from 3200-2750 cal. BP and 2250-1550 cal. BP and a major swing to drier conditions occurred in the last ~100 years. The latter two episodes correspond temporally with the Roman Warm Period and 20th century (e.g. Wang et al., 2012; IPCC, 2007). Cross-wavelet analysis (Figure 10) suggests there are similar significant centennial-scale periodicities in the two records. This is most apparent from c. 3500-1400 cal. BP, suggesting a degree of structural coherence between the two records at this time despite some leads and lags.

4.4. Wider climate variability and forcing

A synthesis dataset comprising the PWTC, the isotope record from Crag Cave and the Inis Oírr $CaCO_3$ record is compared with other proxy data and climate forcing parameters. However, we note that the Crag Cave record has much poorer chronological precision than the water table data (see section 4.1). In addition, the Inis Oírr $CaCO_3$ record is complicated by the hydrological effects of human impacts on vegetation and sea-level change (Schettler et al., 2006).

We examine these proxy records alongside other climate proxy records including the $\delta^{18}O$ record from the NGRIP ice core (NGRIP members, 2004), indicators of changes of temperature and salinity in the Atlantic meridional overturning circulation which maintains the warm climate of NW Europe (Thornalley et al., 2009), the N. Atlantic IRD record (Bond et al., 2001) and the Na^+ content of the GISP2 ice core as a proxy of sea salt aerosol loading of the atmosphere over Greenland, related to expansion of the polar vortex (O'Brien et al., 1995; Mayewski et al., 1997) (Figure 11). Climate forcing was investigated using volcanic sulphate data from the GISP2 ice core (Zielinkski and Mershon, 1997), a combined CO2 record from Mauna Loa, the Law Dome ice cores and EPICA Dome C (Keeling et al., 1976; Etheridge et al., 1996; Monnin et al., 2004) and total solar irradiance data (Steinhilber et al., 2009) (Figure 11, Table 5).

It is clearly evident that there are differences and a high degree of variability between the climate proxy data. Although the proxies are ultimately driven to some degree by climatic variables, those variables may differ in importance depending on the individual proxy. Furthermore, some of the mechanisms by which climate changes are recorded in the proxy variables are rather poorly understood. This, along with chronological error, explains much of the apparent non-coherence between proxies. However, there are also some visible similarities between proxies. We present some tentative correlations in Table 5.

Apart from a rapid, but short-lived isotopic excursion in the Crag Cave speleothem record, there is no clear evidence for a '4.2 kyr event' (cf. Booth et al., 2005) in Ireland based on the terrestrial data. This supports the broader assertion of Roland (2012) that the manifestation of the event in Britain and Ireland is unclear. The '4.2 kyr event' has been correlated with ice-rafted debris (IRD)/Bond event 3, a cold event which took place in the North Atlantic c. 4200 cal. BP and is postulated to have been the result of a reduction in solar activity (Bond et al., 2001). Indeed, based on the global distribution of evidence for the '4.2 kyr event' (e.g.

Walker et al., 2012), from North America (Booth et al., 2005), South America (Marchant and Hooghiemstra, 2004), Africa (Thompson et al., 2002), western Asia (Cullen et al., 2000), eastern Asia (Liu and Feng, 2012), Continental Europe (Drysdale et al., 2006), it would be reasonable to suggest that it was driven by complex, albeit currently ambiguous, changes in Earth's ocean-atmospheric circulation systems, making its apparent absence in oceanic Britain and Ireland all the more interesting (Roland, 2012).

A wet/cold phase from 2700-2400 cal. BP is present in the PWTC, the NGRIP $\delta^{18}O$ and RAPiD-12-1K records, coincident with a decrease in TSI. This suggests that this climate event was widespread in the North Atlantic region. This event has previously been considered to be the product of solar forcing or related to solar-influenced changes in ocean circulation (e.g. Van Geel et al., 1996; Bond et al., 2001) and may be a global phenomenon (Chambers et al., 2007) with possible regional variation in its expression (Plunkett 2006; Plunkett and Swindles, 2008). The ice core records confirm that the start of the event was generally coincident with a decrease in TSI.

A Roman Warm Period (e.g. Wang et al., 2012) is suggested by the PWTC and tentatively by some of the other terrestrial, ice core and marine records. It occurs at a time of relatively high solar activity. A climatic deterioration in the Dark Ages (early medieval period) is supported by the terrestrial and ice core proxy data, although there are differences in timing. It is not manifest in the marine records. The Dark Ages deterioration (Blackford and Chambers, 1991) occurs at the same time as a major downturn in solar irradiance suggesting it was driven by solar forcing (e.g. Jiang et al., 2005). In contrast, the Atlantic records suggest a minor warming event at this time.

A potential Medieval Warm Period (e.g. Lamb, 1965) signal is much stronger in the Inis Oírr and Crag Cave data than the PWTC. It is coincident with a period of relatively high solar activity. The MWP is not clearly evident in the ice core and marine data. Increased GISP2 volcanic sulphate at this time illustrates the complex relationship between volcanic activity and climate. In comparison, a Little Ice Age signal is present in all proxy climate records, although with slightly different expressions of magnitude and timing. The climate forcing data suggest that this was also the product of solar and/or ocean mechanisms (e.g. Broecker, 2000; Mauquoy et al., 2002). The volcanic sulphate record suggests that volcanism was not the primary driver of the Little Ice Age. However, it has been suggested that the initial trigger for the Little Ice Age may have been due to increased volcanicity between c. AD 1275 and 1300 (Miller et al., 2012).

The major recent swing to drier/warmer conditions in the PWTC is also reflected in the marine and ice core proxies (but not in the Inis Oírr or Crag Cave records from Ireland) and is coherent with the global rise in CO_2 (e.g. IPCC, 2007). However, the PWTC may be influenced by the effects of peat cutting or drainage at this time which would complicate the peatland hydroclimatic signal. Further work is needed to investigate the nature of the rapid recent change in peatland hydrology that is present in many sites across Northern Europe (Rea, 2011; Turner, 2012).

5. Conclusions and future studies

We analysed Holocene climate proxy records from Ireland including isotope data from lakes and a speleothem, a $CaCO_3$ record from a karst lake, and palaeohydrological proxy data from peatlands. As only three records span the early Holocene to present day, we focused our analysis on the last 5,000 years, for which there is an abundance of records. We draw the following conclusions:

1. There is marked variability of the palaeoclimate proxy data from Ireland associated with proxy complexities and chronological uncertainties.
2. Bayesian modelling illustrates that there is significant centennial, multi-centennial scale associated with the climate proxies (and even millennial-scale chronological uncertainty in the case of the Crag Cave record). However, multi-decadal scale uncertainties are achieved when the record is constrained using historically dated tephra layers.
3. There is no statistically significant co-variance in the unscreened data.
4. Screened high-quality peatland water-table reconstructions co-vary more than would be expected by chance alone.
5. Although the peat-based palaeoclimate records are highly variable, a flexible statistical approach (using a Lowess model with bootstrapping and Bayesian age modelling) can be used to decipher the climatic signal from the noisy data. Data from specific peatlands are variable owing to autogenic factors, chronological uncertainties and potentially responses of testate amoebae to non-climatic factors.
6. There is variable correspondence between the PWTC and the British 'tuned and stacked' water table reconstruction of Charman et al. (2006). However, both reconstructions contain a shift to wetter conditions at c. 2700 cal. BP (Subboreal-Subatlantic transition), 1400 cal. BP (Dark Ages climatic deterioration) and a wet phase from c. 500-100 BP (the Little Ice Age). Dry phases are present from 3200-2750 cal. BP and 2250-1550 cal. BP (Roman Warm Period), and a major swing to drier conditions occurred in the last ~100 years.
7. There are some similarities between the terrestrial palaeoclimate records from Ireland and marine records from the North Atlantic and Greenland ice core data.

8. There is clear evidence that the terrestrial climate changes in Ireland are related to changes in the North Atlantic thermohaline circulation. Some (but not all) of these phases of climate change appear to be related to changing solar activity.

Future studies may lead to an improved understanding of Holocene climate change in Ireland within a wider NW European and even global context. Depending on funding availability and time, researchers planning Holocene climate research in Ireland should consider:

1. Using a combination of dating techniques, e.g. tephrochronology, SCP stratigraphies, short-lived radioisotopes (e.g. ^{137}Cs, ^{210}Pb), ^{14}C (potentially including wiggle-matching) and age-equivalent pollen markers, modelled using Bayesian methods (e.g. OxCal, Bacon), to achieve excellent chronological control and precise inter-record correlations.
2. Generating paired lake and peatland proxy records precisely correlated through tephrochronology.
3. Deciphering autogenic and allogenic factors in peat-based climate proxy records using a combination of multiple profiles from each site and peatland development models (e.g. Blaauw and Mauquoy, 2012; Swindles et al., 2012a).
4. Isotope and biomarker analysis in peatlands (e.g. McClymont et al., 2010; Daley et al., 2010; Nichols and Huang, 2012).
5. Analysis of other biological proxies in Irish lake records (e.g. diatoms, chironomids, cladocera). Chironomid-based temperature reconstruction should be investigated.
6. Analysis of speleothems in other Irish cave systems.
7. Focussing on early Holocene records, as there are still relatively few from Ireland covering this timeframe.
8. Analysis of Holocene tephras in North Atlantic marine records so that the marine and terrestrial data can be linked precisely.

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