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The 5.2 ka climate event: Evidence from stable isotope and multi-proxy palaeoecological peatland records in Ireland

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ABSTRACT

Evidence for a major climate event at 5.2 ka has been reported globally and is associated with considerable societal disruption, but is poorly characterised in northwest Europe. This event forms part of a broader period of re-organisation in the Earth's ocean-atmosphere circulation system between 6 and 5 ka. This study tests the nature and timing of the event in northwest Europe, a region highly sensitive to change in meridional overturning circulation and mid-latitude westerly airflow. Here we report three high-resolution Irish multi-proxy records obtained from ombrotrophic peatlands that have robust chronological frameworks. We identify the 5.2 ka event by a sustained decrease in $\delta^{18}O_{cellulose}$ at all three sites, with additional and parallel changes in $\delta^{13}C_{cellulose}$ and palaeoecological (testate amoebae, plant macrofossil and humification) data from two sites in northern Ireland. Data from Sluggan Moss demonstrate a particularly coherent shift towards wetter conditions. These data support the hypothesis that the event was caused by a prolonged period of positive North Atlantic Oscillation conditions, resulting in pervasive cyclonic weather patterns across northwest Europe, increasing precipitation over Ireland.

1. Introduction

1.1. A mid-Holocene climatic transition

The occurrence of a substantial transition in the global climate system during the period 6–5 ka is widely acknowledged (Steig, 1999; Mayewski et al., 2004; Wanner et al., 2008; Brooks, 2012). This transition marked the termination of the Holocene thermal maximum (HTM), a relatively warm period with temperatures markedly higher than those of the pre-industrial era, as recorded in a range of palaeoclimate archives (e.g. Davis et al., 2003; Kaufman et al., 2004; Jansen et al., 2009; Seppä et al., 2009; Bartlein et al., 2011). Forcing of the HTM is commonly attributed to the orbitally-driven summer insolation maximum in the Northern Hemisphere (NH) (Wanner et al., 2008; Bartlein et al., 2011), with its complex spatio-temporal structure explained by the influence of additional forcing mechanisms and feedbacks, including the decay of the remnant Laurentide ice sheet (LIS) (Renssen et al., 2009, 2012).

Whilst NH summer insolation decreased gradually from the early Holocene onwards, the steepest decline occurred c. 6 ka (Steig, 1999) associated with a decrease in ^{14}C and ^{10}Be residuals, indicating reduced solar activity, which continued until c. 5.1 ka (Finkel and Nishiizumi, 1997; Stuiver et al., 1998). These changes coincided with a global trend of glacial advance (Denton and Karlén, 1973; Hodell et al., 2001; Nesje et al., 2001; Mayewski et al., 2004; Kilian and Lamy, 2012), a major increase in ice-rafted debris in the North Atlantic (Bond event 4) (Bond et al., 2001; Oppo et al., 2003) and South Atlantic (Hodell et al., 2001) and register a strong signal in the glaciochemical proxies of the GISP2 ice core (Mayewski et al., 1997), all of which have been linked with a more positive North Atlantic Oscillation (NAO), and enhanced westerlies across the North Atlantic (Mayewski et al., 2004).

An extensive review of potentially correlative short-lived, multi-centennial climatic event signals recorded in palaeoclimate records from both hemispheres found that the majority occurred 5.6–5 ka

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(Magny et al., 2006 and references therein). Thirty-four of the records examined by Magny et al. (2006) have ages defining the onset of the event, of which the average was 5.23 ka and so the event will be referred henceforth as the '5.2 ka event'. Many of these signals are consistent with the 'cool poles, dry tropics' pattern typical of a number of climate episodes which punctuate the mid-to late-Holocene, including the 4.2 ka, 2.8 ka and Little Ice Age events (Mayewski et al., 2004). During the 5.2 ka event, widespread cooling was accompanied by drier conditions in central and eastern Asia, Africa, the Mediterranean and parts of North America, with wetter conditions in northern Europe and southern South America (Magny et al., 2006), demonstrating that the dynamic processes associated with the event extend beyond the influence of the NAO.

The abrupt termination of the African humid period c. 5.5 ka, following a weakening of the African monsoonal system, was rapid, occurring within several decades to centuries and provides a striking example of a non-linear response to gradual insolation forcing (Demenocal et al., 2000; Kröpelin et al., 2008). A trend towards drier conditions in South America, as recorded in the Cariaco Basin marine sediments, also began c. 5.4 ka (Haug et al., 2001), consistent with numerous other low-latitude records which show a similar drying trend at this time (Magny et al., 2006). This trend suggests a southward migration of the Intertropical Convergence Zone (ITCZ) and is consistent with many other low-latitude records which show a drying trend at this time (Magny et al., 2006).

The period 6–5 ka also witnessed the onset of the 'modern' El Niño Southern Oscillation (ENSO) (Sandweiss et al., 1996, 2001, 2007; Moy et al., 2002) and, importantly, the emergence of environmental boundary conditions similar to those of the present day following the final deglaciation of the LIS (Renssen et al., 2012), which played a significant role in early-Holocene climatic events, particularly in the North Atlantic region (Clark et al., 2001). Whilst the precise nature of the mechanisms that drove this ocean-atmosphere variability remains uncertain, it was likely to have been a complex response to variations in solar activity and orbitally-driven insolation changes (Hodell et al., 2001; Magny and Haas, 2004; Mayewski et al., 2004; Magny et al., 2006; Wanner et al., 2008), further complicated by non-linear feedback processes, teleconnections between and thresholds within the climate system components (e.g. NAO, ITCZ, ENSO) discussed here (e.g. Schneider, 2004; Broecker, 2006; Wunsch, 2006; Holmes et al., 2011). As a result, the 5.2 ka and subsequent late-Holocene events have considerable potential for providing 'process analogues' to understand future change (Alley et al., 2003; Broecker, 2006).

Wide scale mid-Holocene aridity across the (sub)tropics, particularly during the 5.2 ka event, has been linked with the abandonment of nomadic lifestyles and the rapid development of the world's first civilizations of large, complex, highly-urbanised, hierarchical and organised societies forming in response to drought and over-population in Egypt, north–central China, northern coastal Peru, the Indus valley, Mesopotamia and more broadly across western Asia (Sirocko et al., 1993; Sandweiss et al., 2001; Brooks, 2006, 2012; Staubwasser and Weiss, 2006). In Europe, cultural development and changes in settlement patterns have also been linked to the event (Berglund, 2003; Magny, 2004; Arbogast et al., 2006). In particular, considerable disruption to marginal Neolithic communities is recorded across Ireland, potentially owing to climatic deterioration, increased storm frequency and a subsequent abandonment of agricultural land (O'Connell and Molloy, 2001; Baillie and Brown, 2002; Caseldine et al., 2005; Turney et al., 2006; Verrill and Tipping, 2010; Ghilardi and O'Connell, 2013). However, despite being an historical focus for palaeoclimatic research, the 5.2 ka event is poorly characterised in northwest Europe. Regional climatic evidence for the Little Ice Age (Mauquoy et al., 2002), 2.8–2.6 ka event (Plunkett and Swindles, 2008) and 4.2 ka (Roland et al., 2014) events has been evaluated but an equivalent study for the 5.2 ka event has not been undertaken.

1.2. Stable isotope analysis in peatlands

Stable isotopic analysis of Holocene peat sequences provide a technique for palaeoclimatic and palaeohydrological reconstruction (e.g. Daley et al., 2009, 2010; Loisel et al., 2010). Peatland vascular and non-vascular plants possess significantly different isotopic ratios (Ménot and Burns, 2001; Ménot-Combes et al., 2002; Pancost et al., 2003; Loader et al., 2007; Moschen et al., 2009; Nichols et al., 2010; Stebich et al., 2011) and stable isotopic analysis of bulk peat (e.g. Cristea et al., 2014; Jones et al., 2014) and cellulose extracted from bulk peat (e.g. Aucour et al., 1996; El Bilali and Patterson, 2012; Hong et al., 2000; Jędrysek and Skrzypek, 2005) therefore risk being affected by botanical variation. *Sphagnum* mosses are more suited to stable isotopic analysis as they have relatively simple biomechanical pathways leading to cellulose synthesis, compared to vascular plants (Ménot-Combes et al., 2002; Zanazzi and Mora, 2005; Loader et al., 2007; Daley et al., 2010).

Sphagna have no stomata and are unable to physiologically regulate uptake of atmospheric CO_2 with varying saturation of the hyaline cells providing the only barrier to CO_2 assimilation (Ménot and Burns, 2001). Consequently, stable carbon isotope fractionation in *Sphagnum*, and therefore the ratio of cellulose stable carbon isotopes ($\delta^{13}C_{cellulose}$), is heavily dependent on water availability with lower $\delta^{13}C_{cellulose}$ values associated with drier conditions and *vice versa*. Correlations between *Sphagnum* $\delta^{13}C_{cellulose}$ and modern surface moisture gradients (Price et al., 1997; Ménot and Burns, 2001; Ménot-Combes et al., 2004; Loisel et al., 2009) and independent palaeohydrological proxy records (Lamentowicz et al., 2008; Loisel et al., 2010; Van der Knaap et al., 2011) support this, although discrepancies exist (e.g. Markel et al., 2010) and a small number of studies have found a relationship between *Sphagnum* $\delta^{13}C_{cellulose}$ and temperature (Skrzypek et al., 2007; Kaislahti Tillman et al., 2010; Holzkämper et al., 2012).

In the absence of stomata and vascular tissue Sphagna also possess a comparatively simple water use strategy. Although recently challenged (see Sternberg and Ellsworth, 2011), it is generally accepted that a temperature-insensitive, constant enrichment factor between source water and *Sphagnum* cellulose of 27 ± 3‰ for oxygen isotopes exists (Zanazzi and Mora, 2005), meaning that $\delta^{18}O_{cellulose}$ in *Sphagnum* should accurately reflect changes in the source water oxygen isotopic composition (Daley et al., 2010), which is entirely meteoric in an ombrotrophic context.

Isotopic offsets between the different *Sphagnum* components (e.g. leaves, stems, branches) can lead to systematic errors during analysis and so the isolation of stem material is considered preferable (Loader et al., 2007; Moschen et al., 2009; Kaislahti Tillman et al., 2010, 2013). It is also important to isolate a single chemical compound, with α-cellulose favoured owing to the greater level of homogeneity achievable during the purification process (McCarroll and Loader, 2004; Loader et al., 2007). Advances in the extraction and purification of α-cellulose (Loader et al., 1997; Rinne et al., 2005; Daley et al., 2010), developments in stable isotope ratio mass spectrometry (IRMS) (McCarroll and Loader, 2004; Filot and Leuenberger, 2006; Loader et al., 2007; Young et al., 2011; Woodley et al., 2012), including the simultaneous measurement of stable carbon and oxygen isotopes (Woodley et al., 2012; Loader et al., 2015), have also significantly increased the efficiency of the technique.

Studies have also shown that isotopic signals can vary with *Sphagnum* species (Ménot and Burns, 2001; Ménot-Combes et al.,