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**8000 years of North Atlantic storminess reconstructed from a Scottish peat record:
implications for Holocene atmospheric circulation patterns in Western Europe**

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ABSTRACT: North Atlantic storminess can affect human settlements, infrastructure and transport links, all of which strongly impact local, national and global economies. An increase in storm frequency and intensity is predicted over the North-East Atlantic in the 21st century because of a northward shift in storm tracks and a persistently positive North Atlantic Oscillation (NAO), driven by recent atmospheric warming. Although documentary records of North Atlantic storminess exist, these are generally limited to the last c. 1000 years. This paper presents a continuous high-resolution proxy record of storminess spanning the last 8000 years from a 6 m-long core taken from a peat bog in northern Scotland. Bromine concentrations in the peat, derived from sea spray, are used to reconstruct storm frequency and storm intensity, and mire surface wetness is used as an

indicator of longer-term climate shifts. The results suggest a relationship between positive phases of the NAO and increased North Atlantic storminess. However, subtle differences between bromine concentrations and mire surface wetness suggest that high intensity but perhaps less frequent periods of storminess are not necessarily associated with a wetter climate.

KEYWORDS: Holocene storminess; micro-XRF; mire surface wetness; NAO; Scotland.

Introduction

The location and intensity of mid-latitude storm tracks strongly influence the climate of Europe (Hanna *et al.*, 2008). The most intense and damaging storms affecting Europe originate in the North Atlantic, often causing extensive flooding and damage to infrastructure, and resulting in significant detrimental economic impacts. The highest magnitude storms occur most frequently during winter, when the storm tracks are most intense, and extend in a north-westerly direction from the east coast of North America, to Ireland, Great Britain and Norway (Cheng *et al.*, 2011). North Atlantic storminess has increased over recent decades in association with increasing air temperatures over the same period (Alexander and Tett, 2005; Allan *et al.*, 2009; Wang *et al.*, 2009). Predictions suggest that over the next 100 years North Atlantic storm tracks will shift northwards and storm frequency will increase in the British Isles due to an intensified jet stream (Pinto *et al.*, 2009; Orme *et al.*, 2015).

Records of past storminess have been reconstructed through both observational and sedimentary (or palaeoenvironmental) records. Observational records tend to span the past few hundred years and are based on air temperature (Dawson *et al.*, 2003), sea surface temperature (Hurrell, 1995) and wind speed (Clarke and Rendell, 2009; Dawson *et al.*, 2010). In Europe and the North East Atlantic, proxy measures for increased wind strength include aeolian sand influx (de la Vega-Leinert *et al.*, 2000; Clarke *et al.*, 2002; Sommerville *et al.*, 2003; de Jong *et al.*, 2006; Clarke and Rendell, 2009; Tisdall *et al.*, 2013), over-wash deposits in coastal lagoons (Sabatier *et al.*, 2012), cliff-top storm deposits left by extreme waves (Hansom and Hall, 2009), marine records reflecting windblown current strength and storm deposits (Hass, 1996; Andresen *et al.*, 2005) and Na⁺ from the Greenland ice cores (Dawson *et al.*, 2003). Palaeoenvironmental reconstructions of North Atlantic storminess tend to span from the mid-Holocene to the present and so high-resolution records on a millennial timescale (10³ a) are an important goal to gauge longer-term trends and better understand Holocene climate variability.

The position and strength of the polar front jet stream in the Northern Hemisphere strongly determines the process of cyclogenesis between ~40 and 65°N, and, therefore, the number and frequency of high-energy storms in the North Atlantic region (Fig. 1). The development of a vigorous jet stream in winter, enabled by strong temperature contrasts between mild moist mid-latitude and cold polar air, accounts for the strength and trajectory of dominant westerly winds as well as the frequency of extra-tropical storms and their tracks over NW Europe (Hurrell 1995, Hurrell *et al.*, 2003; Athanasiadis *et al.*, 2010). Secular changes in the North Atlantic Oscillation (NAO), defined as the sea-level pressure difference between the main North Atlantic pressure dipole measured in Iceland and the Azores, are strongly

associated with changes in the polarfront jet stream (Hurrell 1995; Woollings *et al.*, 2008, 2010). An enhanced NAO (positive) mode typically results from undisturbed strong zonal (east to west) jet stream flow between 50 and 60°N; while a negative NAO mode results from disturbed, meridional flow with a large north-south component leading to blocking highs and cut-low pressure systems. During a negative NAO, the dominant westerly winds often follow a more southern trajectory owing to the development of a large quasi-stationary high-pressure system over Greenland (Woollings *et al.*, 2008, 2010). Both strongly positive and strongly negative NAO modes represent end members and require relatively vigorous jet-stream-driven atmospheric circulation in the North Atlantic sector. These conditions are normally optimized during European winter, hence the strong positive correlation between NAO mode and winter precipitation in NW Britain and western Norway (Hurrell, 1995; Hurrell *et al.*, 2003). However, other more subdued long-term synoptic situations can occur. These include a neutral NAO phase, where the pressure index is neither strongly positive nor strongly negative, normally associated with a weakening of the main Iceland cyclonic and Azores anticyclonic pressure systems. In this situation, the development of large persistent Scandinavian high-pressure systems can block the path of westerly winds into NW Europe, further reducing cyclonic activity and dampening the NAO index into a more neutral state (Mauri *et al.*, 2014).

This paper presents chemical variability and palaeo-moisture indices from a 6 m-long peat core in maritime northern Scotland. Analyses of down-core variations in bromine concentrations as an indicator of storm intensity are coupled with mire surface wetness (MSW) as an indicator of longer-term storm-track position and climate shifts in the North-

East Atlantic. Finally, we compare our record to other proxies for shifts in the NAO during the Holocene.

Bromine as an indicator of storminess

The generation of sea-salt aerosol is the principal global source of atmospheric Br, producing $\sim 6.2 \text{ Tg a}^{-1}$ (Sanders *et al.*, 2003). The bursting of air bubbles and the direct formation of droplets by wave crests injects sea-salt aerosol into the atmosphere and so the flux of Br is dependent on wind speed (Moldanová and Ljungström, 2001). Marine aerosols may be transported long distances (tens to hundreds of kilometres) and be dry deposited or scavenged from the atmosphere by rainfall (Gustafsson and Franzén, 2000). Other sources of inorganic Br are dust, biomass-burning and fossil fuels but these are of an order of magnitude less than marine sources. Crustal sources are estimated to be 4% of the global Br flux and its deposition is geographically restricted to the equatorial Atlantic and North Pacific Oceans (Sander *et al.*, 2003). Ombrotrophic peat bogs receive only atmospheric inputs and so provide excellent archives of climatic change. It has been argued that Br concentrations are determined by climate-controlled biogenic processes (Biester *et al.*, 2004; Moreno *et al.*, 2015) and / or are not stratigraphically retained. However, Zaccone *et al.* (2008) argue that Br is stably conserved in the humic acid content of peat. Br concentrations in peat bogs around the maritime fringes of the North Atlantic, are very likely to be derived from sea spray; hence, higher Br levels suggest an increase in sea turbulence, accentuated wave action, and increased windiness during storms. Therefore, down-core variations in Br may be interpreted as an indicator of storminess (Orme *et al.*, 2015; Turner *et al.*, 2014). MSW, an additional measure, indicates longer-term changes in

precipitation patterns with increased MSW signalling a more persistent wetter climate (Charman *et al.*, 2006; Turner *et al.*, 2014).

Materials and methods

Site description and field sampling

A continuous high-resolution peat core (to 6.08 m depth) was obtained from the central part of a large mire at Shebster, northern Caithness (58°33′06.6″ N, 003°42′39.0″ W; 82 m asl; 4.8km from the North Atlantic coast) (Fig. 2). The mire surface is bordered by the Burn of Shebster that drains northwards. The bedrock underlying the site is Middle Devonian sandstone of the Bighouse Formation (Auton *et al.*, 2005). The core was sampled from within the deepest part of the Shebster peat bog using a 1 m-long (75 mm diameter) Russian D-section sampler (with 10 cm overlapping sections). Recovered cores were transferred into plastic guttering, sealed in lay-flat tubing, and stored at the University of Stirling at a constant temperature of 4°C.

Minerogenic analysis

The core was sub-sampled in contiguous 2 cm³ sections for acid digestion to remove organic matter (cf. Dugmore *et al.*, 1995a). The mineral residue was then scanned using light microscopy to identify tephra glass shards to supplement the radiocarbon chronology with tephrochronology.

Organic content

To provide a record of bio-productivity and organic content, contiguous samples of 2 cm depth were combusted in a muffle furnace at 550°C for 4 h to enable calculation of the percentage loss-on-ignition (LOI₅₅₀).

Mire surface wetness

The degree of peat humification, as a proxy of MSW, was estimated using the colorimetric alkali extract method modified from Blackford (1993). Under drier conditions peat is more oxidized, the accumulation rate is slower and there is an increase in humic material. The greater the humic content the darker the extract solution and the lower the transmitted light values. Therefore, lower percentage transmission (%T) values indicate drier peat accumulation conditions whereas higher percentage transmission values indicate wetter conditions. Contiguous sub-samples of 2 cm³ were taken from the 608 cm core. Samples were oven dried at 80°C for 24 h and then ground using a small rotating blade grinder. Sub-samples of 0.2 g were placed into 50 ml falcon centrifuge tubes and 50 ml of 8% (w/v) NaOH was added to each sample and the tubes placed in a boiling water bath for 60 minutes and intermittently stirred. The samples were then centrifuged at 3000 r.p.m. for 5 min and a 0.5 ml aliquot pipetted into a 10 mm cuvette and 2.5 ml of distilled water added. The cuvettes were analysed in a Thermo Scientific Genesys 20 spectrophotometer and the percentage transmitted light was measured at 540 nm. This method allowed for batches of 20 samples to be analysed in under 30 min from removal from the water bath and so minimize any fading of the solution (cf. Blackford, 1993).

Micro X-ray fluorescence geochemistry

The core was analysed using an Itrax X-ray fluorescence core scanner at Aberystwyth University. Non-destructive elemental analysis, including Br was performed at 2 mm intervals using a molybdenum (Mo) anode X-ray tube (settings: 30 kV, 50 mA, count time 10 s). The elemental peak area values were normalized to the total of the coherent and incoherent scatter to minimize the effects of downcore variations in organic matter and water content. Density and colour information was further obtained using X-radiography and digital RGB optical imagery.

Chronology

Five samples of wood material were radiocarbon dated by accelerator mass spectrometry (AMS) to enable the construction of a Bayesian age-depth model. All samples were pretreated with an acid/alkali/acid treatment. To augment the radiocarbon chronology, a cryptotephra layer (346 cm depth) was analysed through the geochemical fingerprinting of individual shards by the SX100 Cameca Electron microprobe at the University of Edinburgh using methods established by Hunt and Hill (1993) and Hayward (2012).

The cryptotephra at 346 cm is geochemically correlated to the eruption of Hekla 4 (TephraBase; Newton, 1996) and provides an isochronic marker dated to 3826 ± 12 ^{14}C a BP (Dugmore *et al.* 1995b). The AMS radiocarbon and tephra ages were calibrated using Calib ver.7.10 (Stuiver and Reimer, 1993) and IntCal13 (Reimer *et al.*, 2013)(Table 1). The Bayesian program, BACON v2.2 (Blaauw and Christen, 2011) was used to construct an age-depth model to constrain the stratigraphic results (Fig. 3). The age-depth model indicates a mean accumulation rate of 13 a cm^{-1} and a uniform rate of peat accumulation during the Holocene.

Results

From 612 to 608 cm depth greyish-brown organic mud grades to a dark brown moderately humified peat (with wood fragments at 404 – 406 cm depth) that continues to ~370 cm.

From ~370 to 271 cm, the core comprises very dark brown well-humified amorphous peat.

At 271 cm, there is a marked transition to a dark brown peat with abundant sedge fragments. The sedge-rich peat continues to 27 cm and is moderately well humified and with occasional wood fragments. From 27 cm to the surface root mat, the core comprises a dark brown fibrous sphagnum peat.

To aid the interpretation, the Shebster stratigraphic data are divided into eight major zones based on major changes in the MSW as this is a site-specific proxy (Fig. 3).

SH-1, 8210–7400 cal a BP: MSW was not measured in the lowest ~10 cm of the peat to avoid any potential influence from the underlying lake sediments; measurements commenced at 590 cm. In Zone SH-1 the MSW curve is characterized by two peaks at c. 7960 and 7610 cal a BP, separated by a nadir at c. 7740 cal a BP. The Br ratios appear to be in antiphase with the largest peak of the entire record occurring at c. 7800 cal a BP, before both MSW and bromine decline to a low at the upper zone boundary at c. 7400 cal a BP.

SH-2, 7400–5270 cal a BP: At the start of this zone there is a marked step up to higher MSW values that fluctuate (between ~20 and 30 %T) through the first half of the zone. Br values commence from a peak between c. 7400 and 7300 cal a BP and then decline to a broad low

also during the first half of the zone, between c. 7300 and 6200 cal a BP. At c. 6145 cal a BP there is a rapid increase in Br to a sustained peak until a fall at c. 5700 cal a BP to lower but fluctuating values and then increasing towards the upper zone boundary. The MSW values in the second half of the zone also continue to fluctuate (between ~25 and 35 %T) but at higher values than previously.

SH-3, 5200-4000 cal a BP: Br increases to a peak between c. 5200 and 4900 cal a BP followed by a sustained declining trend towards the upper zone boundary at c. 4000 cal a BP. The decline in Br is reflected in a similar profile in the MSW, except for a brief minor peak in MSW at c. 4540 cal a BP.

SH-4, 4000-3300 cal a BP: The Br ratios reach their minima at c. 3850 cal a BP and remain relatively stable before gradually increasing from c. 3400 cal a BP to a peak at the upper zone boundary. During this zone the stratigraphy changes to well-humified peat and this is reflected in the sharp fall of MSW values where they reach their lowest values of the entire record before rising again at the top of the zone.

SH-5, 3300-2400 cal a BP: MSW values rise to a peak at c. 3160 cal a BP (25.6 %T) and continue to rise to ~30%, punctuated by a brief decline to 17.5 %T at c. 3005 cal a BP. Br values remain relatively stable, with small fluctuations occurring throughout this period.

SH-6, 2400-1400 cal a BP: MSW values fluctuate between ~33 and 20 %T during this zone and Br values continue to be relatively stable.

SH-7, 1400–600 cal a BP: Br ratios peak between c. 1225 and 1130 cal a BP and between c. 855 and 750 cal a BP before declining to a low at c. 600 cal a BP. MSW values increase to a peak at c. 1365 cal a BP (39.1 %T) then decline to a low at c. 1115 cal a BP (18.0 %T) followed by peaks at c. 950 (34.1 %T) and 675 cal a BP (34.8 %T).

SH-8, 600–0 cal a BP: MSW values decline to a low at c. 300 cal a BP (18.8 %T) before rising to a peak of 43.3 %T at c. 140 cal a BP. In contrast, Br values rise rapidly to a sustained peak between c. 380 and 200 cal a BP.

Discussion

The down-core variations in Br and MSW indicate that changes in Br concentrations probably reflect longer-term changes in storminess in the North-East Atlantic rather than biogenic processes within the peat bog. Therefore, our ~8000 year palaeo-wetness and storminess record from Shebster, northern Scotland, can be interpreted alongside other key proxy records from around the North Atlantic to place the inferred palaeoenvironmental trends in a wider context of Holocene atmospheric circulation changes. These proxy records include: a 5000-year glacier record from Folgefanna in southern Norway (Bakke *et al.*, 2008); a reconstructed 5000-year NAO index based on a lake-sediment core in south-west Greenland (Olsen *et al.*, 2012); a Scottish speleothem record (Baker *et al.*, 2015); and an Iberian speleothem record (Walczak *et al.*, 2015) (Fig. 4). Variations in speleothem laminae thickness provide an annual growth-rate record that can be used as a proxy for past climate and environmental change. Growth rates are determined by changes in precipitation and higher growth rates suggest warmer and wetter conditions (positive NAO

state) whereas low growth rates are associated with colder and drier conditions (negative NAO state) (Baker *et al.*, 2015). The NAO index based on a south-west Greenland lake-sediment core is reconstructed from deep-water anoxia data (Olsen *et al.*, 2012). A negative NAO is associated with above average temperatures and below average winter precipitation, leading to earlier ice melt and allows stronger vertical mixing of the water column. This weakens thermal stratification and hence increases oxygen transfer into the deep-water zone, with associated implications for redox processes. A positive NAO, associated with colder conditions, leads to later ice melt, which coincides with maximum solar radiation and results in limited water column mixing. This leads to the rapid onset of thermal stratification, and hence maintenance of hypoxic conditions. Deep-water anoxia can alter cycling of redox-sensitive elements. The Mn/Fe ratio reflects the strength of seasonal thermal stratification and is therefore a proxy for dominant NAO circulation patterns. A higher Mn/Fe ratio and carbonate concentration reflects predominantly weaker stratification and is associated with negative NAO conditions, whereas a lower Mn/Fe ratio and carbonate concentration reflects stronger stratification and is associated with positive NAO conditions.

SH-1, 8210–7400 cal a BP: To avoid the influence of any mineral material from the underlying lacustrine sediments the degree of peat humification was not analysed at the base of the peat (608 cm). The lowest part of the available record is characterized by several high-magnitude fluctuations in wetness and storminess. Although the base of the analysed peat record starts at c. 8200 cal a BP, neither the Br record nor the MSW data completely capture the 8.2ka event, expressed as a marked rapid negative temperature anomaly across much of the Northern Hemisphere (Larsen *et al.*, 2012; Tipping *et al.*, 2012). However, SH-1 is dominated

by a large positive Br anomaly centred at c. 7800 cal a BP, suggesting a period of enhanced storminess lasting c. 300-400 years. By contrast, the humification record at this time suggests conditions of below-average wetness. This anti-phase relationship between MSW and Br appears paradoxical, but may suggest that these storms were cold, moisture-starved Polar vortex systems rather than moisture-bearing westerly winds. This is supported by the Iberian speleothem record, which shows a stable, positive record indicating warmer and wetter conditions. Rainfall in southern Iberia was more evenly distributed throughout the year, typical of a more temperate climate lacking a clear dry season (Walczak *et al.*, 2015) and may indicate a more southerly position of the jet stream and, therefore, a persistent negative NAO phase (phase B1, Fig. 1).

SH-2, 7400-5270 cal a BP: After c. 7400 cal a BP there was a marked increase in MSW at Shebster and although the values fluctuate during the period between c. 7400 and 6200 cal a BP, they remain high suggesting the persistence of wetter conditions. However, Br values decrease from the initial peak in zone SH-1 which may suggest that although this zone reflects wetter conditions storminess was less intense than in SH-1. This period probably indicates a northerly migration of the jet-stream-driven westerly winds accompanied by a movement of the North Atlantic storm tracks to a position located over northern Scotland. This atmospheric circulation pattern is best described by the positive mode of the NAO (phase A, Fig. 1).

In the second half of SH-2, from c. 6200 to 5270 cal a BP, MSW continues to reflect increased and more sustained wetter conditions. At the same time, Br values remain high indicating higher levels of storminess throughout this period. A pronounced peak in storminess occurs in zone SH-2 between c. 6145 and 5700 cal a BP. It is not certain what might have caused this

~400-year window of increased storminess, during a period of relatively wetter but more stable climatic conditions. The Iberian speleothem record is characterized by a decline in growth rates between 6100 and 5300 cal a BP suggesting decreased moisture availability (Walczak *et al.*, 2015) and this is consistent with a stronger polar-front jet stream bringing an increase in the number and intensity of storms tracking over northern Scotland (i.e. a strongly positive NAO mode).

SH-3, 5270-4000 cal a BP: Between c. 5300 and 4000 cal a BP, MSW and Br values reflect a synchronized period of gradual and near-continuous decline in both precipitation and storminess over northern Scotland. Several proxy records reflect a mixed climate signal at this time. The glacier-equilibrium line altitude-reconstructed winter precipitation record from Bakke *et al.* (2005) indicates a comparable near-continuous decrease in wetness over most of this period (c. 5000-4000 cal a BP) and is consistent with the Iberian speleothem record which also shows a shift to drier conditions with the exception of an increase in wetness at c. 4200 cal a BP. This climate period is also captured by the earliest part of the SW Greenland lake-sediment-reconstructed NAO index, which shows a sustained positive NAO phase between c. 5200 and 4400 cal a BP (Olsen *et al.*, 2012). These climatic conditions are all compatible with a period of geographically unstable jet stream position and/or declining jet stream strength bringing generally warmer, drier summer conditions to NW Europe accompanied by a decline in cyclogenesis with fewer storms tracking across northern Scotland. After c. 4400 cal a BP, the reconstructed NAO index (Olsen *et al.*, 2012) enters a relatively neutral phase consistent with a decrease in jet stream vigour, at a time when the Shebster peat record indicates steadily decreasing North Atlantic storm activity.

SH-4, 4000-3300 cal a BP: This period marks the most striking departure in the Shebster peat record when MSW and Br values are at their lowest for the entire ~ 8000-year record. We relate these values to a sustained period of relatively drier climate and greatly reduced storminess following on from the decline in storminess seen in the preceding millennium (c. 5300-4000 cal a BP; SH-3). A marked decrease in North Atlantic storminess in Northern Scotland could be associated with two different atmospheric circulation scenarios: (i) westerly wind and storm-track migration to a more southerly latitude (c. 40°N) equating to a strongly negative winter NAO phase; (ii) reduced jet stream strength and a low-value or neutral NAO phase. This period of unusual drier and calmer climate identified in the Shebster peat record is not restricted to Caithness, but is probably the expression of a pan-European/North Atlantic event seen widely in other Holocene palaeoclimate proxies. Peat surface-wetness records from a composite of 12 sites in northern Britain (Charman *et al.*, 2006) show a period of considerably decreased wetness from c. 3900 to 3400 cal a BP, the most pronounced in the mid to late Holocene (interrupted by a brief increase in wetness at c. 3750 cal a BP). In southern Europe, often in antiphase with the climate of northern Britain, Mediterranean records from south-eastern Italy to south-western France record a period of relatively drier conditions between c. 4000 and 3400 cal a BP (e.g. Di Rita and Magri, 2009; Genty *et al.*, 2006; Walczak *et al.*, 2015), and this can also be seen in the Iberian speleothem record. Further afield, in continental North America and Mexico declining monsoon strength is recorded in several geographically diverse proxies from c. 4200 to 3500 cal a BP (Booth *et al.*, 2005; Metcalfe *et al.*, 2015). This is also coincident with the marked southerly migration of the Intertropical Convergence Zone (c. 4000 cal a BP) seen in several low-latitude records, including the high-resolution Cariaco Basin (Haug *et al.*, 2001; Metcalfe *et al.*, 2015). Closer to Scotland, the same SH-3 time interval (c. 4000-3300 cal a BP) sees lower than present

precipitation in the Norwegian glacier record (Bakke *et al.*, 2005); by contrast temperatures in south-west Ireland inferred from speleothems show a broad thermal minimum *c.* 3800 to 3400 cal a BP (McDermott *et al.*, 2001). It is notable that this period is also characterized by a marked negative departure in chlorine in the GISP2 record, inferred as a weakening of the Icelandic low-pressure system between *c.* 4500 and 3600 cal a BP (O'Brien *et al.*, 1995; Mayewski *et al.*, 2004).

The collected multi-proxy evidence from both sides of the North Atlantic points towards jet stream weakening during SH-4, leading to a decrease in cyclonic activity which reaches a minimum at *c.* 3800 cal a BP. Negative NAO conditions normally result in increased rainfall and storminess over southern Europe (e.g. Hurrell *et al.*, 2003; Pinto *et al.*, 2009), something that is not seen in most of the proxy records between *c.* 4000 and 3300 cal a BP (see above). Secondly, negative NAO phases have been strongly linked with meridional airflow and strong temperature contrasts causing enhanced but intermittent cyclogenesis in north-west Europe (Trouet *et al.*, 2012; Van Vliet-Lanoë *et al.*, 2014). Again, this is not evident in the Shebster record during SH-4, with storm-driven Br values reaching their 8000-year minimum within this time window. However, these observations, in combination with a prolonged neutral phase of the reconstructed NAO index (Olsen *et al.*, 2012), are entirely consistent with a decrease in jet stream vigour during SH-4. We would expect that this period experienced considerably reduced westerly (zonal) airflow at 50-60°N, accompanied by a higher incidence of quasi-stationary high-pressure systems over northern Europe. There is evidence from the Shebster Br and MSW data that this *c.* 700-year period of subdued westerly winds (reduced jet stream vigour) and cyclogenesis over northern Scotland is the ultimate expression of a declining trend in storminess and wetness that started at *c.* 4500 cal a BP (in SH-3), coincident with the switch

from positive to low-value or neutral NAO values (<1.0) in the Greenland sediment record (Olsen *et al.*, 2012).

SH-5, 3300 – 2400 cal a BP: A marked broadly synchronous increase in MSW and Br values at c. 3200-3300 cal a BP indicates the return to wet and stormy conditions in northern Scotland. This period (SH-5) is characterized by generally increasing MSW levels throughout (c. 3300-2400 cal a BP) and a relatively high but fluctuating storminess index. Supporting proxy data suggest more vigorous cyclogenesis, increased precipitation and raised water tables in north-west Europe at this time (Hughes *et al.*, 2000; Swindles *et al.*, 2007; Charman, 2010; Oldfield *et al.*, 2010), although the reconstructed NAO index displays a strong fluctuation from initially positive (c. 3300-3000 cal BP) to strongly negative values (c. 3000-2400 cal a BP) (Olsen *et al.*, 2012). A marked concomitant rise in air temperatures and winter precipitation, seen in the Irish speleothem, Norwegian glacier and Iberian speleothem proxy-records (Fig 4) between c. 3300 and 2700 cal a BP would also suggest a return to more dynamic atmospheric circulation patterns over north-west Europe with strongly zonal moisture-bearing winds and more moderate levels of cyclogenesis.

The most sustained period of negative NAO in the Greenland lake-sediment record is synchronous with an increase in MSW at Shebster (c. 2800-2400 cal a BP). This probably relates to a strengthening of the westerly winds (after the quiescent SH-4 phase) and a mean storm track positioned to the south of Scotland, consistent with the relative decrease in storminess at this time. The annually resolved north-west Scotland speleothem record also starts during this time (Baker *et al.*, 2015). Although no overall trend in the composite speleothem climate-index is apparent during the first ~500 years, relatively high-magnitude

peaks in speleothem growth rates at c. 2900 and 2600 cal a BP probably reflect decadal to centennial periods of higher precipitation in northern Scotland (Baker *et al.*, 2015).

At c. 3000 cal a BP glaciers become permanently established at some marginal sites in Iceland, Norway and southern Greenland for the first time since their complete disappearance in the early Holocene (c. 8000-7000 cal a BP) (Andresen and Bjork, 2005; Larsen *et al.*, 2012; Balascio *et al.*, 2015). Numerous other studies have linked this renewed ice growth, or Neoglaciation, with a shift towards wetter and/or cooler climate in Northern Hemisphere higher latitudes after c. 4200 cal a BP (Blaauw *et al.*, 2004; Swindles *et al.*, 2007; Wang *et al.*, 2012).

SH-6, 2400-1400 cal a BP: During this period MSW at Shebster remains relatively high whilst Br levels are somewhat subdued (close to, but slightly below the 8000-year mean), continuing the long-term trend established in SH-5. The north-west Scotland speleothem record exhibits high growth rates suggesting moist but more stable climatic conditions. Elsewhere around Europe this millennium is synonymous with the 'Roman Warm Period' (2500-1600 cal a BP) (Wang *et al.*, 2012) and is characterized by a predominantly positive (>1.0) NAO index in Greenland (Olsen *et al.*, 2012). This strong pressure dipole, but relatively stable low-storm index state, suggests a poleward shift of the westerly storm tracks to a position between Iceland and Scotland, as seen during positive NAO summers. However, the low storm index suggests a more complex relationship, possibly with an increased polar front latitudinal range in winter with storms tracking to the south of northern Scotland. Support for this hypothesis comes from a peat record from Cors Fochno, mid Wales where sustained higher Br values between c. 2200 and 1600 cal a BP suggest that although the

Roman Warm Period was comparatively dry at Shebster in northern Scotland, North Atlantic storms still tracked across central and southern Britain with relatively high frequency (Orme *et al.*, 2015).

SH-7, 1400 – 600 cal a BP: This period includes the Medieval Climate Anomaly (MCA: 700-1100 cal a BP; Mann and Jones, 2003) and is characterized at Shebster by higher but variable MSW alongside relatively higher and variable Br levels in the peat record. Together they suggest a wetter and stormier period in northern Scotland than the previous millennium (SH-6) which is consistent with the unusually long and unbroken, strongly positive, NAO phase (Trouet *et al.*, 2009). This is seen in the Greenland lake-sediment record from c. 1400 to 600 cal a BP (Olsen *et al.*, 2012). A positive NAO mode is normally associated with a vigorous jet stream and a North Atlantic winter storm track focused between 55 and 60°N (at the latitude of northern mainland Scotland) (Hurrell *et al.*, 2003; Woollings *et al.*, 2008, 2010). This circulation pattern is supported by several other palaeoenvironmental proxies from the British Isles and adjacent areas. Firstly, the composite British peat-surface wetness record compiled by Charman (2010) shows a continuous phase of elevated water tables spanning the entire 800-year period with a peak c. 1100-1200 cal a BP. Secondly, the Irish speleothem record shows several centuries of increasing above-average (inferred) temperatures, with a peak c. 700-900 cal a BP (McDermott *et al.*, 2001). Thirdly, the winter moisture index from Norwegian glaciers shows well above-average precipitation (120-140% of present day) in this time interval (Bakke *et al.*, 2008). Fourthly, the occurrence of outsized wave-transported boulders (cliff-top storm deposits) 15-60 m above sea level in Shetland, northern Scotland, dated to between c. 1300 and 800 cal a BP (Hansom and Hall, 2009), indicates enhanced storminess at ~60°N. Finally, lower values of Br at Cors Fochno peat bog, relative to the

preceding period (Orme *et al.*, 2015), suggest that the main westerly storm tracks were not focused at the latitude of mid Wales (52°N) but further north over Scotland. However, more complexity is introduced when comparing these proxy records with growth rates from the north-west Scotland speleothem record. Baker *et al.* (2015) reconstruct strongly negative NAO-like conditions from c. 1400 to 1100 cal a BP, at which point the trend is reversed and their reconstruction shows a strongly positive phase throughout the MCA, similar to the Olsen *et al.* (2012) NAO record. Therefore, we interpret the MCA period to be one of a strong polar-front jet stream and enhanced cyclogenesis, bringing westerly storms tracking across northern Scotland (57-60°N). However, the variable antiphase relationship between MSW and Br records at Shebster perhaps suggests, at times, decreased storm frequency but higher storm intensity across the northern British Isles, consistent with the generation of high-energy storm deposits around northern Scotland's coasts (Hansom and Hall, 2009).

SH-8, 600-0 cal a BP: The most recent period captured in the Shebster peat record spans from c. 600 to 100 cal a BP and almost exactly corresponds to the Little Ice Age (LIA: c. 150-700 cal a BP; Mann and Jones, 2003). This period is characterized at Shebster by high but variable MSW and generally high Br values, indicating increased wetness and storminess for much of this 500-year window. A notable exception is the period between c. 100 and 200 cal a BP when Br (i.e. storminess) is subdued with levels equivalent to SH-6. However, the cause of the LIA cooling (and/or any associated storminess) has been the source of considerable research and debate (Lamb, 1995; Trouet *et al.*, 2012; Orme *et al.*, 2016). A clear LIA signal is seen in the proxy-reconstructed NAO indices of Olsen *et al.* (2012) and Baker *et al.* (2015), where an abrupt shift from strongly positive to negative NAO occurs at c. 600 cal a BP in both records. The shift is larger and more sustained in the reconstruction provided by Baker *et al.*

(2015). The record suggests that this dominantly negative NAO phase was associated with a vigorous jet stream, a higher incidence of moisture-bearing winds and a higher frequency of storms generally tracking across the latitude of northern Britain (55-60°N) for much of the LIA (c.100-600 cal a BP). The normal negative NAO configuration involves a significant southward shift in dominant westerly winds and storm tracks, to the latitude of southern France, northern Iberia and the western Alps (40-45°N) (Woollings *et al.*, 2008, 2010). However, other records from around Scotland show with a high level of certainty that the LIA period (esp. from 400-100 BP) was one of periodically enhanced storminess, increased sea state and wave activity, and generally disrupted weather patterns (Sommerville *et al.*, 2003; McIlvenny *et al.*, 2013; Orme *et al.*, 2016). These features are the hallmarks of an unusually turbulent period of atmospheric circulation, typically associated with disturbed jet stream strength and an unstable location (switching from zonal to meridional flow pattern), consistent with variable but high levels of Br-inferred storminess at Shebster (this study) and to a lesser degree at Cors Fochno (Orme *et al.*, 2015) during the second half of the LIA. However, the speleothem and MSW records reflect a shift to relatively drier although perhaps less stable conditions. Again the contrast between the records of storminess and local wetness is probably due to the LIA being dominated by overall colder and drier conditions but affected by lower-frequency higher-intensity storm events (supporting the findings of Trouet *et al.*, 2012).

Conclusions

The Shebster climate record provides insights into the timing and nature of North Atlantic climate changes and is a significant advance to the existing records in that it spans much of the Holocene. The combined Br and MSW records highlight the millennial to centennial scale changes in the position of the polar jet stream, a significant driver of environmental

change in northern Scotland and the wider North Atlantic region. The Shebster climate record is consistent with the Norwegian glacier record, Greenland sediment-inferred NAO index, Scottish speleothem record and Iberian speleothem record but most importantly advances our understanding of the development and fluctuations of the NAO from the early Holocene. We infer from the data that periods of high Br and MSW levels probably relate to a jet stream position over northern Scotland and, therefore, increased storminess and a positive NAO mode. Periods of reduced Br and mire wetness levels probably relate to a more southerly position of the jet stream and, therefore, a decline in storminess and a negative NAO. Between c. 4000 and 3300 cal a BP there are very low levels of Br and mire wetness consistent with a drier period across much of the northern hemisphere which may relate to a neutral NAO state and a weaker jet stream. However, subtle differences between these two proxies suggest that single indicators of storminess may not be sufficient to reconstruct changes in jet stream movement and NAO index. These differences also suggest that higher intensity but perhaps less frequent periods of storminess are not necessarily associated with a wetter climate, which may be exemplified during the LIA. This work shows that important high-resolution palaeoenvironmental information can be gleaned by X-ray fluorescence analysis of peat accumulations in cold-temperate climates. Furthermore, these analyses in combination with other established techniques offer a novel and under-used way to examine the climate record of the recent past on a decadal to millennial scale.

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Abbreviations. AMS, accelerator mass spectrometry; LIA, Little Ice Age; LOI, loss on ignition; MCA, Medieval Climate Anomaly; MSW, mire surface wetness; NAO, North Atlantic oscillation.

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Figure 1. The preferred positions of the Polar Front Jet Stream and the corresponding phases of the NAO. White lines – Polar Front (i.e. average southern winter limit of Polar air

masses). Grey long-dashed line – mean position of jet stream core between 1958 and 2006 (from Strong and Davis, 2008). Coloured arrows – approximate position of Polar vortex winds (colours match storms). Mode A dominates during strongly positive NAO phases; mode B1 or B2 dominates during strongly negative NAO. Neutral NAO phase (neither positive nor negative) equates to a weak jet stream, with much-reduced storm frequency probably along negative NAO tracks (B1, B2). Sites mentioned in text: 1) Shebster (this study); 2) Folgefanna, southern Norway (Bakke et al., 2008); 3) SW Greenland (Olsen et al., 2012); 4) Scottish speleothem record (Baker et al., 2015); 5) Iberian speleothem record (Walczak et al., 2015).

Figure 2: A) Location map showing the study site in northern Scotland. B) Detailed map of peat coring site near the Burn of Shebster. Grid ticks are in British National Grid. C) Average climatological conditions (1981-2010) at the nearest long-running weather station (Wick Airport; 58.454 N, 3.089 W; 36 m asl). Mean monthly air temperature (maximum and minimum) and normal wind speed envelope (at 10 m) plotted on the same axis. Mean monthly precipitation shown as blue bars. Data from metoffice.gov.uk. Note the marked seasonality in average wind strength, peaking in winter (December-March).

Figure 3: Shebster stratigraphy, LOI₅₅₀, mire surface wetness, bromine (ratio of Br / Incoherent+Coherent) and BACON age/depth model.

Figure 4: Shebster mire surface wetness, bromine, 5000-yr glacier record from Folgefanna in southern Norway (Bakke *et al.*, 2008), reconstructed 5000-yr NAO index based on a lake-sediment core in SW Greenland (Olsen *et al.*, 2012), Scottish speleothem record (Baker *et al.*,

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Table 1: Radiocarbon dates and ages for the Hekla 4 tephra layer correlated to the Shebster record. ^{14}C dates have been calibrated using CALIB rev. 7.10 (Stuiver and Reimer, 1993) and IntCal 13.14c. (Reimer *et al.*, 2013).

Figure 1

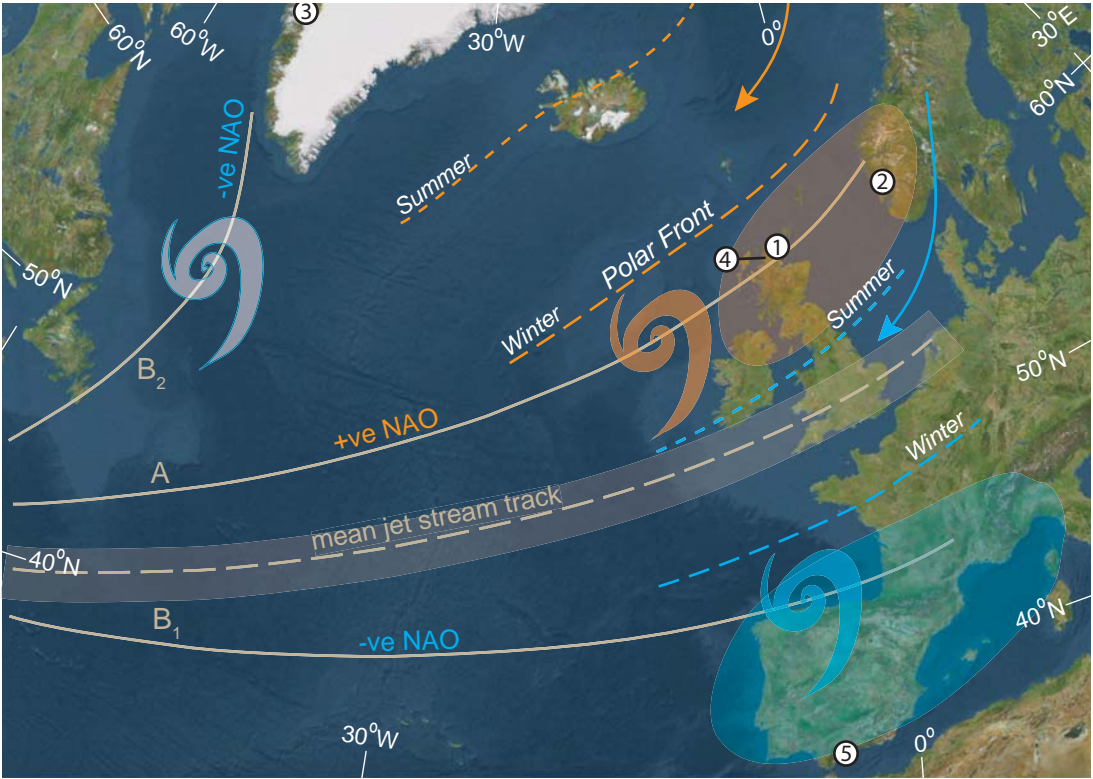


Figure 2

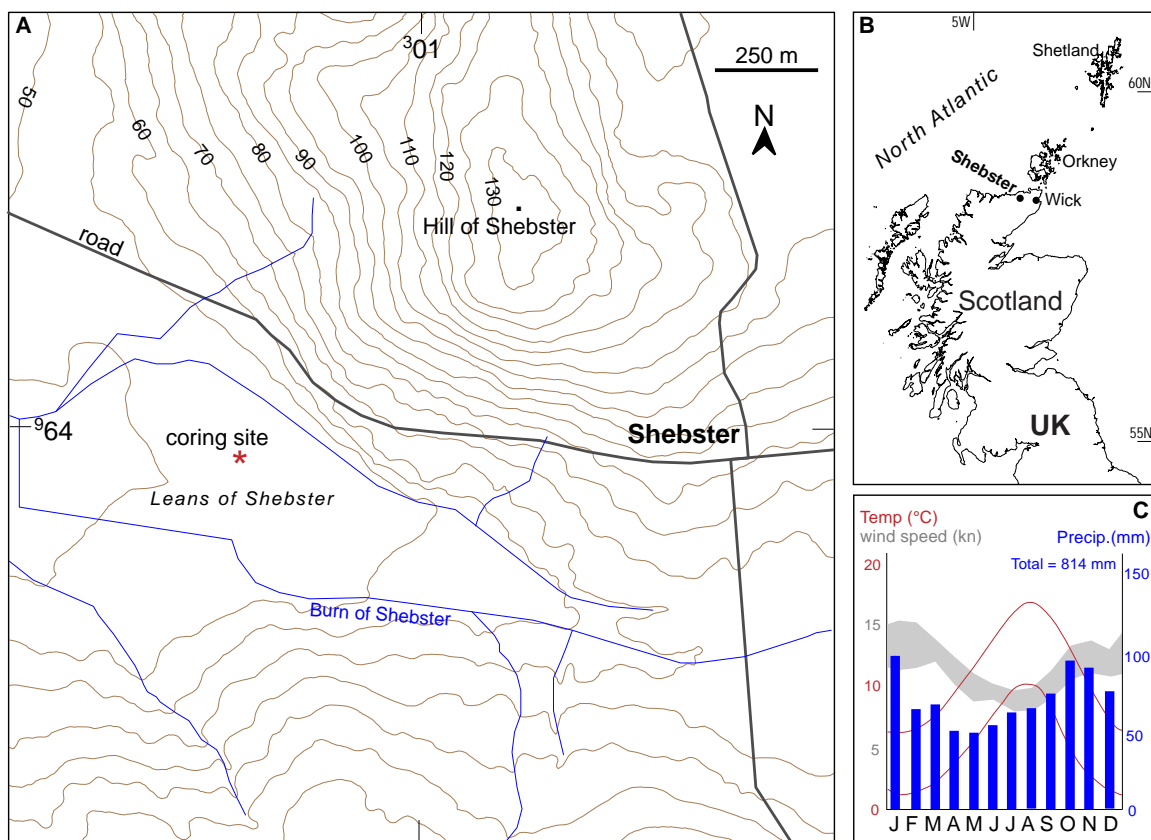


Figure 3

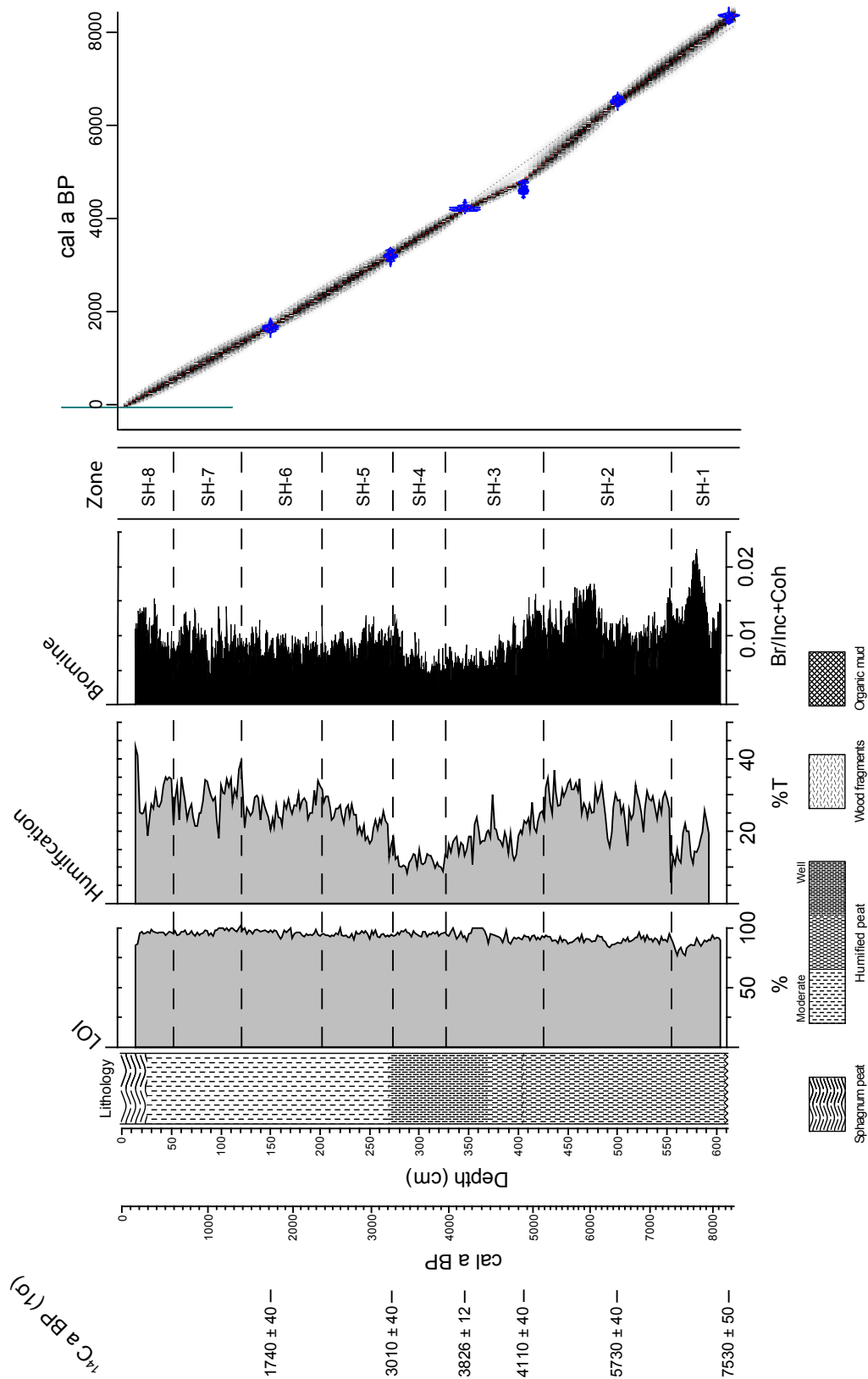


Figure 4

