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A thousand year speleothem proxy record of North Atlantic climate from Scotland

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Abstract Luminescent organic matter in stalagmites may form annual bands, allowing growth rate to be precisely determined. Stalagmite growth rate is controlled by precipitation, so annual bands can be used to derive long precipitation records. A continuously banded stalagmite from a cave in NW Scotland was used to provide a 1100 year high-resolution record of precipitation. The location of the cave means that precipitation is closely linked to the North Atlantic Oscillation, for which a record is also derived. This suggests that changes in the North Atlantic Oscillation state was an important control on European climate over the past millennium.

1 Introduction

In recent years investigations into speleothem luminescence variations Shopov et al. (1989, 1994) have shown that they contain a potential climate signal. Speleothem luminescence derives from organic material trapped within the speleothem calcite. In shallow limestone caves in the UK, luminescence intensity has been demonstrated to vary seasonally, with a winter luminescence peak caused by flushing of dissolved organic matter from the soil zone by high winter rainfall (Baker et al. 1993, 1997; Genty et al. 1997). These annual variations in luminescence intensity permit the identification of annual growth bands within the speleothem, providing a means to precisely measure variations in growth rate over time. Variations in growth rate result from hydrological factors (calcium concentration in the seepage water and drip rate) that are in turn dependent on climate, in particular precipitation (Dreybrodt 1988; Genty and Quinif 1996; Baker et al. 1998b). It has also become possible to measure variations in speleothem luminescence wavelength (Baker et al. 1998a), which varies with organic acid molecular weight and structure (Senesi et al. 1991), which in turn is partly determined by climate and vegetation changes (Christ and David 1996; Martin-Neto et al. 1998). Ming et al. (1997) have obtained a long record of monsoon precipitation from a laminated stalagmite in China, but speleothems from European sites have so far provided only short climatic records (Genty and Quinif 1996; Baker et al. 1999a). Here we describe the first thousand year long European precipitation record, provided by a stalagmite from the Uamh an Tartair cave in Northwest Scotland.

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2 Site description and methodology

Uamh an Tartair is part of the Cnoc nan Uamh cave system, about 3 km east of Inchnadamph in Assynt, northwest Scotland (National Grid Reference NC 276 206) (Lawson 1988). It lies at an altitude of 220 m OD, and is overlain by moorland with thin peat between 0.1 and 0.6 m thick. This area of moorland has remained undisturbed within historical times and analysis of cores from the peat has provided a dated 2000 year record of humification and vegetation from the site (Baker et al. 1999b). A small (35 mm high) stalagmite, SU-96-7, was collected from the Grotto, a chamber which lies < 10 m below the moorland surface above and has previously yielded annually banded stalagmites (Baker et al. 1993, 1999b). The stalagmite was actively growing when collected in June 1996. Other stalagmites collected from the Grotto all proved to be inactive and further collection to attempt to obtain a duplicate sample was not undertaken for conservation reasons.

A polished section of the stalagmite was examined for annual luminescent bands using standard UV microscopy techniques (Baker et al. 1993). It was found to be continuously banded and a total of 1087 bands were counted in the sample, varying in width from ~5 to 135 μm (Fig. 1). No evidence of any hiatus in deposition was found in the stalagmite, suggesting growth was continuous: hiatuses in other stalagmites from the site have been found to

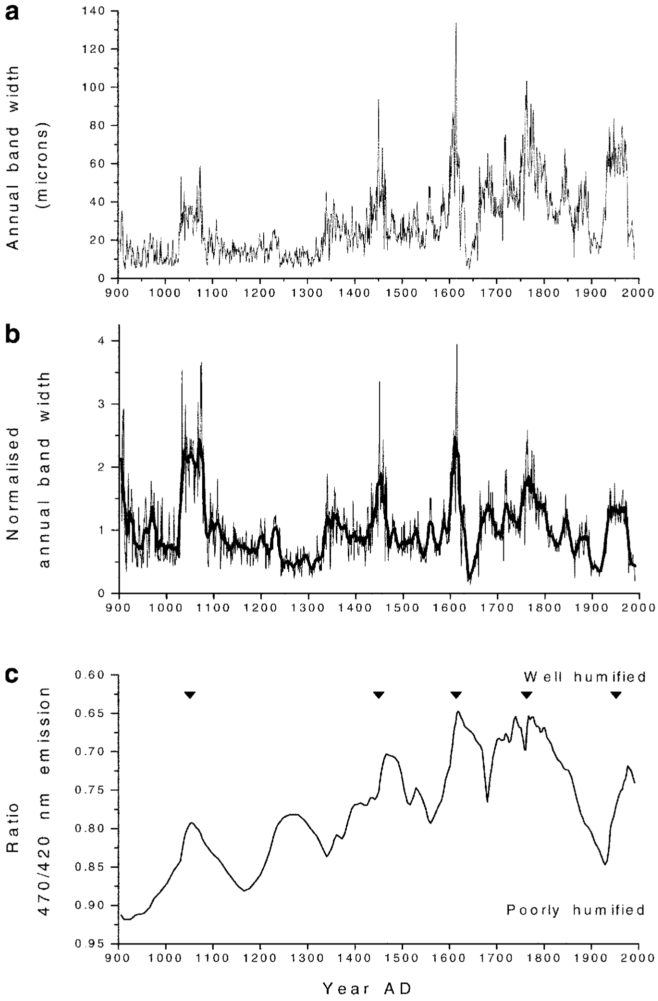

Fig. 1 **a** Full SU-96-7 band width record. Band widths were measured using a Zeiss Axiotech reflected light microscope with mercury vapour light source, black and white CCD camera and Image Pro Plus image analysis software. The *topmost counted band* is taken to date from 1990: see text for details. **b** Detrended band width record for SU-96-7. The stalagmite shows a gradual increase in band width from the base to the top, indicating that growth rate increased as it grew. The band width signal was normalised and this trend removed by fitting an order 2 polynomial trend line to the band width data. **c** Luminescence wavelength record for SU-96-7. Luminescence wavelength was measured by scanning the sample with a Perkin-Elmer UV spectrophotometer at a spatial resolution of 0.5 mm at two excitation/emission wavelength pairs (excitation 390 nm, emission 470 nm; and excitation 350 nm, emission 420 nm). The ratio of the two scans was then used to provide an index of variations in peak luminescence wavelength. Positions of growth rate peaks are indicated by *arrows*

be marked by a layer of detrital inclusions, and euhedral crystal growth and voids immediately above the hiatus. However a small uncertainty in counting was introduced by the presence of occasional double bands which might be attributable either to two closely spaced annual bands, or to two major periods of groundwater flushing in one year producing a double annual band. About 17 such bands were encountered, implying a counting error of < 20 years. The counted annual bands thus suggest the stalagmite was deposited over a period of 1087 ± 20 years, from about 900 AD to the present. This is supported by ^{14}C and TIMS uranium series analyses from the stalagmite. There is a marked increase in ^{14}C concentration at the top attributable to nuclear weapons tests in the 1950s, confirming that the stalagmite was actively growing when collected (D. Genty personal communication). A TIMS uranium series analysis from the base of the stalagmite provides an age of 1262 (1002–1349) years (Table 1), in excellent agreement with the age of 1087 ± 20 years obtained by counting luminescent annual bands.

In order to interpret the growth rate record provided by these variations in annual band width, correlation with historical United Kingdom Meteorological Office (UKMO) weather records was carried out. Raw meteorological data was supplied by the UKMO Edinburgh office. The data were tested for homogeneity against other long Scottish temperature and precipitation series using methods adapted from Alexandersson, (1986). Large inhomogeneities were found in the UKMO Stornoway precipitation series prior to AD 1900, so this was replaced with data from the Stornoway Board of Northern Lights (BNL) station for AD 1879–1900, applying a factor of 1.26 to the BNL data to correct for systematic differences between the UKMO and BNL. Continuous records for the Assynt study region extend back for less than 40 years so a longer climate record was constructed using long monthly series of temperature and rainfall from other stations. Correlation with recent data from Knockanrock (16 km south of the cave and similar in altitude and topographic position) indicated that of the available long homogeneous records, temperature from Abbotsinch (Glasgow) and precipitation from Stornoway provided the highest correlation, yielding correlation coefficients of $r = 0.99$ for Abbotsinch temperature and $r = 0.83$ for Stornoway precipitation (both statistically significant at the 99.9% CI). The temperature and precipitation datasets were trained to Knockanrock equivalent values to construct a 114 year weather record for Assynt extending from AD 1879 to AD 1993 (Fig. 2).

3 Comparison of stalagmite growth rate with historical climate

Comparison of variations in annual band width with the annual temperature and precipitation records shows a strong link between weather and band width (Figs. 2, 3). The correlation of normalised band width against mean annual temperature and precipitation is relatively poor using raw data, but results are much improved using 10 year smoothed data. In addition, regression results are highest if the topmost band corresponds to 1990.

Table 1 TIMS U-Th analytical data for the basal 4 mm of stalagmite SU-96-7

	^{238}U conc ppm	[^{234}U/^{238}U] act	^{234}U conc (ppm)	^{230}Th conc (ppb)	^{232}Th conc (ppb)	[^{230}Th/^{232}Th] act	[^{230}/Th/^{234}U] act	Age (years BP)	Corrected age[a] (years BP)
Mean	0.23026	1.21903	1.5E-05	6.4E-05	2.48163	7.34677	0.01390	1522	1262
Error	0.00018	0.00260	3.3E-08	1.4E-06	0.00506	0.16105	0.00030	33	+90, −260

[a] The corrected age was calculated using an initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$, the value for material at secular equilibrium with a crustal ^{232}Th/^{238}U value of 3.8. The error is arbitrarily assumed to be 50% and this is included in the corrected age error

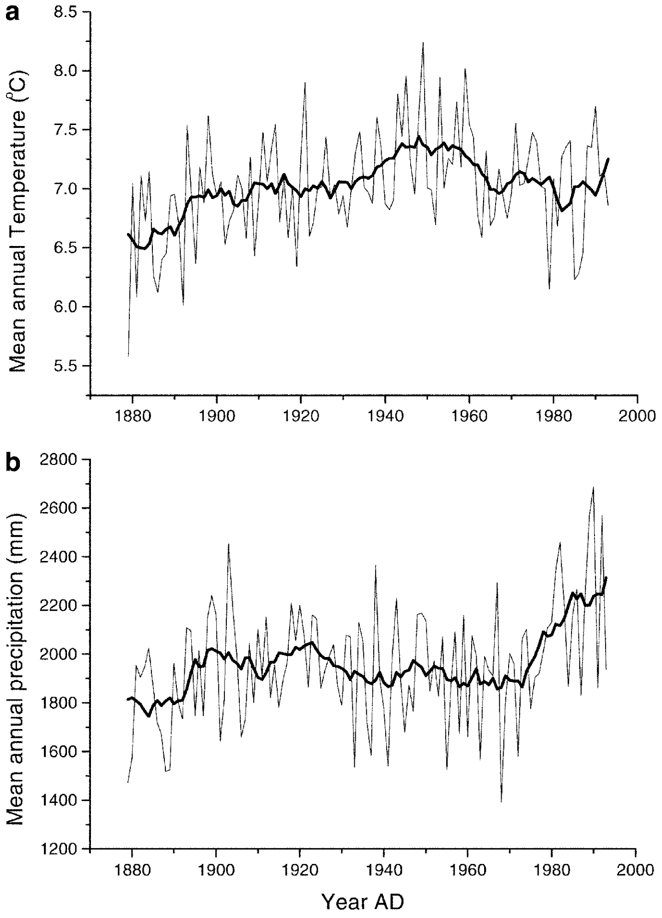

Fig. 2a, b Historical climate records for Assynt, 1879–1993. **a** Temperature, record constructed using Abbotsinch (Glasgow) data. **b** Precipitation, record constructed using Stornoway data. See text for further details. The *thick line* in each case shows decadal smoothed data

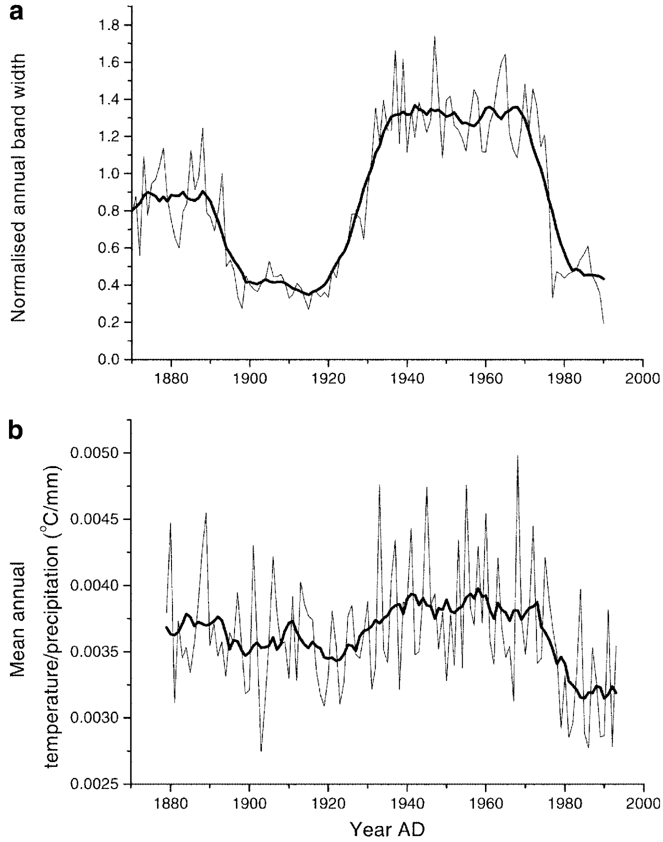

Fig. 3 a Detrended SU-96-7 band width record for 1870-present compared to **b** Assynt temperature/precipitation for the same period. The *thick line* in each case shows decadal smoothed data

This is supported by examination of the top of the counted section that indicates that approximately 50–100 μm was lost from the edge of the cut section during polishing. With a band width of around 15–20 μm near the top, this suggests 2–8 bands had been lost from the top, implying a date of AD 1988–1994 for the topmost counted band. Using decadal smoothed data and a top date of AD 1990, there is a clear positive correlation with temperature ($r = 0.49$) and negative correlation with precipitation ($r = -0.53$; both significant at the 99.9% CI). Further regression analyses using parabolic functions of temperature and precipitation, and using water excess (precipitation-evapotranspiration) did not result in an increased correlation. Combining these results, a linear regression of band width against temperature/precipitation (T/P) using decadal smoothed data yields the following empirical formula:

$$\text{Annual band width} = -4.637 + 1508\ (T/P), \quad (r = 0.80)\ .$$

This relationship implies that growth rate increased in warmer and/or drier conditions, which can be explained by the presence of wet peat overlying the cave. CO_2 production in peat (mostly by aerobic respiration by soil micro-organisms) is most rapid in warmer drier conditions, with production dropping to low levels in very cold or wet conditions (Silvola et al. 1996). This determines the partial pressure of CO_2 (PCO_2) and hence Ca^{2+} concentration in the cave water, controlling the growth rate of the speleothem with a high PCO_2 producing an increased growth rate. The sampled stalagmite is associated with a slow drip that shows little variability with changes in precipitation, hence changes in PCO_2 (and hence Ca^{2+}) are probably the major constraint on growth in this stalagmite (Dreybrodt 1988; Baker et al. 1998b). The negative correlation between precipitation and growth rate confirms this as an increase in drip rate due to increased precipitation would result in a higher growth rate, positively correlated with precipitation.

A more detailed comparison between mean annual temperature, precipitation and annual band width shows that the stalagmite shows changes in growth rate in response to notably warm/dry or cold/wet years, but at other times shows a much reduced response to annual variations in temperature and precipitation (Fig. 3) with several periods where growth rate shows relatively little change (e.g. 1897–1922, 1932–1975). This is probably due to the response of the peat cover to periodic drying out. Peat responds to desiccation by irreversible shrinkage which opens up cracks in the soil (Gilman and Newson 1980). The cracks do not close on rewetting of the peat so cracking may have a long-term effect, increasing drainage of the peat and increasing its susceptibility to desiccation in future years. The peat may remain well drained with increased CO_2 production for several years, until a prolonged wet period causes healing of the cracks by mushing. Thus the hydrological system has an in-built inertia which leads to its responding to major (decadal) climatic changes while tending to smooth over annual variations. Clear evidence for this is provided by the correlation between growth rate and T/P, which is relatively poor ($r = 0.36$; although this is statistically significant at the 99.9% CI) at annual time scales but increases to ($r = 0.80$) using decadal smoothed data.

Water excess is conventionally used in place of precipitation when examining climatic control on speleothem growth rates, as it better describes recharge to limestone aquifers. There are two probable reasons why water excess provides no better correlation with growth rate than precipitation. Firstly, the high rainfall of the study area means that there is substantial year-round water excess, which closely follows precipitation. In addition, the correlation results suggest that precipitation affects speleothem growth not via changes in recharge to the limestone but via changes in soil moisture, which is poorly described by water excess.

4 Comparison with peat humification and a 1100 year climate reconstruction

Confirmation of the role of peat hydrology in controlling the growth rate of SU-96-7 is provided by luminescence wavelength data from the stalagmite (Fig. 1). This shows that at times of higher growth rate, peak luminescence wavelength decreased. A decrease in luminescence wavelength indicates a decrease in the molecular weight of the organic acids in the stalagmite, resulting from increased humification of the peat above the cave, suggesting that it had a reduced moisture content (Baker et al. 1998a; Senesi et al. 1991; Christ and David 1996). There is a slight lag between the two signals, since humification of the peat (and hence change in peak emission wavelength) would have increased throughout a dry period, reaching a maximum just before it ended. Humification data is also available from the peat itself, though at lower resolution (Baker et al. 1999b). The comparatively low resolution of the peat humification data when compared to the stalagmite makes comparison difficult but provides additional support for higher humification at times of faster speleothem growth.

The instrumental weather records show that annual and longer scale variations in precipitation are much greater than for temperature, suggesting that precipitation is likely to be the major control on growth rate. The instrumental temperature records from AD 1879 to the present span the end of the Little Ice Age through to the current warm period, so probably samples most of the range of late Holocene temperature variability (Mann et al. 1998), allowing the contribution of temperature to the band width record to be assessed. This relationship was used to construct a precipitation record for the last millennium from the band width data (Fig. 4), using mean and ±2 standard deviation values for annual temperature of 7.02 ± 0.43 °C for decadal smoothed data. The reconstructed record shows good agreement with instrumental records over the calibration period (Fig. 5), although there is a trend in the reconstructed record due to the general increase in temperatures from 1879 to the present with precipitation at the low end of the reconstructed range early on, and tending towards the high end towards the present. In addition, the precipitation record thus constructed is liable to be affected by long-term non-climatic variations in growth rate. As a result, for the early part of the record the reconstructed curve should provide a good record of the timing and magnitude of changes in precipitation, but the absolute values are likely to be less reliable.

Precipitation in NW Scotland is strongly influenced by the winter North Atlantic Oscillation with higher precipitation in high NAO winters, due to stronger westerly flow and cyclonic rainfall (Hurrell 1995; Rodwell et al. 1999). This suggests that the SU-96-7 band width record may also provide a long-term record

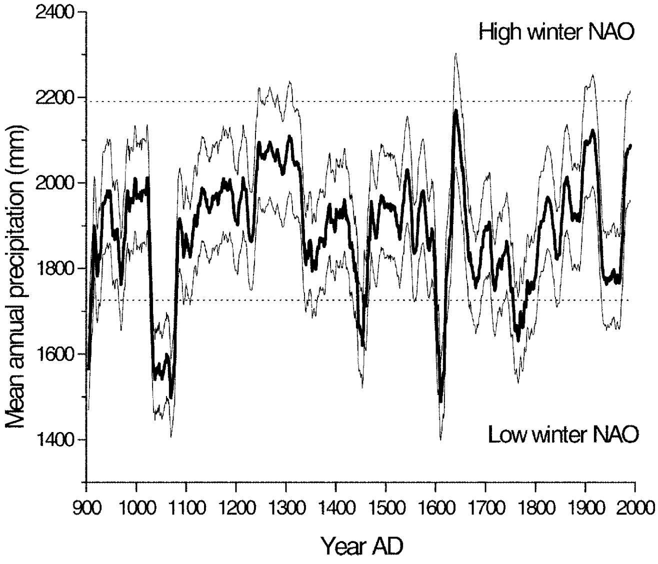

Fig. 4 Reconstructed Assynt mean annual precipitation record from SU-96-7. Mean and ±2 standard deviation values for annual temperature of 7.02 ± 0.43 °C for decadal smoothed data were used to construct the precipitation record by using the mean annual temperature to provide a mean precipitation curve (*thick line*), and the ±2 standard deviation limits of temperature to derive upper and lower limits for the possible range of precipitation. *Horizontal dotted lines* show the 2 standard deviation range of mean annual precipitation recorded in the period of instrumental observations (1879–1993), for decadal smoothed data

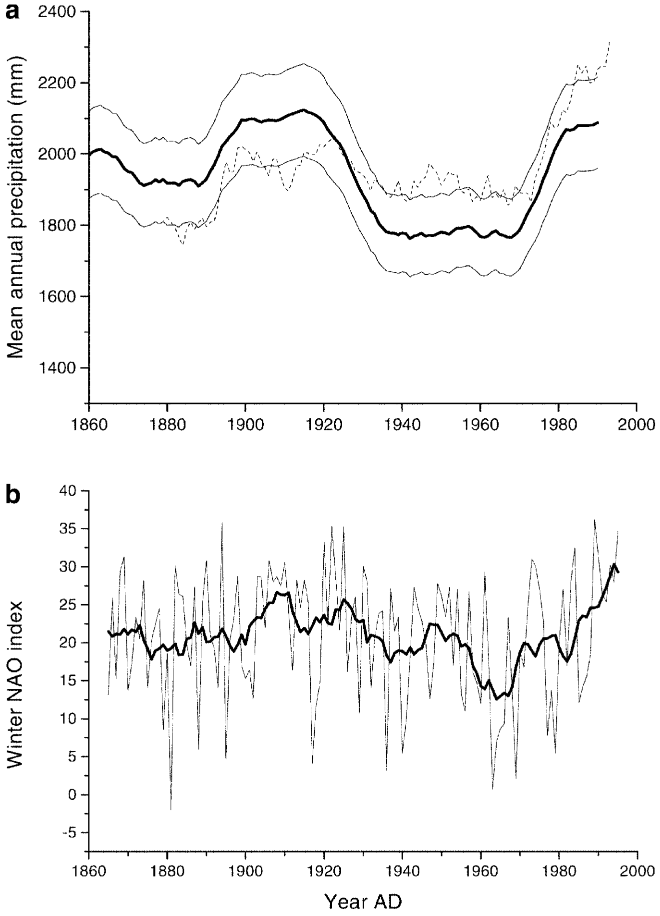

Fig. 5 **a** Comparison between historically recorded precipitation from 1879–1993 (*dotted line*) and precipitation reconstructed from speleothem growth rate over the same period (see Fig. 4 for details of the reconstruction). The two show generally good agreement, but note that recorded precipitation at the low end of the reconstructed range early on, and tending towards the high end towards the present. This is due to a trend in the reconstructed record caused by the general increase in temperatures from 1879 to the present. **b** Winter NAO index values over the same period for comparison. Data from Jones et al. (1997)

of the NAO. Correlation of decadal smoothed band width data against the winter NAO index for AD 1865 to AD 1990 yields a high negative and statistically significant correlation ($r = -0.70$), suggesting that approximately 50% of the growth rate signal is attributable directly to the winter NAO (Fig. 5). In addition, spectral analysis of the growth rate series has demonstrated statistically significant peaks within the range 6–9 years, similar to that observed in the NAO, as well as for 82 and 178 years which may be related to long term solar output variations.

5 Conclusions

SU-96-7 thus provides a 1087 year regional record of precipitation reflecting variations in the strength of the winter North Atlantic Oscillation (Fig. 4). The speleothem record provides a longer proxy of NAO than those reconstructed from tree-rings and ice cores (Cook et al. 1998; Appenzeller et al. 1998). It also has a slightly greater percentage of explained variance (50% against ice core 41%, on 5-point triangular filtered data and tree ring 33%, on decadal smoothed data). All three proxies suggests that the character of the NAO may have changed with time. Periods of relatively high and low NAO strength in our stalagmite record agree with those observed for the last 350 years in the Greenland ice cores, although less well with the tree-ring reconstruction. Our observed dominant spectral frequency of 6–9 years is also similar to the ice-core maximum power at 5–7 and 9–11 years and the tree-ring spectral frequency of 2 and 8 years. Reconstructed high precipitation amounts through much of the Medieval period (about 1080–1330) from our stalagmite record implies that the NAO index was persistently high over this period. In contrast, the next few hundred years is characterised by several periods of low precipitation, implying a much lower NAO index. This period spans the Little Ice Age, and the frequent low NAO index conditions were probably a factor in producing the cold winters recorded through the period. This supports recent work which suggests that long-term climate change can largely be explained as changes in the relative frequency of oscillating climate states such as the NAO (Corti et al. 1999; Hasselmann 1999).

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