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# A three thousand year record of North Atlantic climate

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**Abstract** Annual band counting on three radiometrically dated stalagmites from NW Scotland, provides a record of growth rate variations for the last 3000 years. Over the period of instrumental meteorological records we have a good historical calibration with local climate (mean annual temperature/mean annual precipitation), regional climate (North Atlantic Oscillation) and sea surface temperature (SST; strongest at 65–70°N, 15–20°W), although the correlation with the latter breaks down prior to the instrumental record. This suggests that the climatic factors that force NW Scottish climate and therefore our stalagmite growth varied through time, and include winter NAO strength, the strength of the thermohaline circulation and possibly solar output. Spectral analysis was performed on the stalagmite growth rate time series. A spectral frequency of 50–70 years is predominant in two stalagmites that were deposited from 1000 to 3000 BP; a slightly longer frequency of 72–94 years is dominant from 1000 BP to present. These are the same as that observed in ocean GCM output for the North Atlantic region SSTs. Our stalagmites provide high resolution, precisely dated evidence of a similar periodicity predominating over the last 3000 years in a climate proxy record known to be sensitive to changes in forcing functions relevant to the North Atlantic sector.

## 1 Introduction

Annually banded stalagmites have recently been recognised as a potential source of high resolution proxy climate data covering the Holocene period (Genty and Quinif, 1996, Ming et al. 1997, Baker et al. 1999a). Luminescent annual growth bands in a stalagmite from the Uamh an Tartair cave in NW Scotland was first demonstrated by Baker et al. (1993). Another stalagmite from the same cave has more recently been used to obtain a thousand year record of precipitation (Proctor et al. 2000). Annual growth band width in this stalagmite shows a high negative correlation with precipitation and a weaker positive correlation with temperature over the period of instrumental meteorological records (1879–1993). The stalagmite's high sensitivity to precipitation is due to the presence of a thin cover of peat overlying the cave. The peat becomes saturated in wet periods, leading to reduced soil respiration and low $PCO_2$ in the soil water, and in turn a reduced stalagmite growth rate in the cave below. This high sensitivity to precipitation, coupled with the fact that temperature has varied little over the last thousand years, has allowed a long-term record of precipitation to be obtained from it. The precipitation record from the site is of particular significance as NW Scotland precipitation is tightly linked to the North Atlantic Oscillation (Hurrell 1995). The stalagmite precipitation record shows a high negative correlation with the historical NAO record and spectral analysis gives spectral frequencies of 6–9 years and 72–94 years.

This stalagmite has demonstrated the potential for the site to produce long records of precipitation and hence long-term behaviour of the North Atlantic climate system, however more stalagmites are needed to extend the record further back in time. The site's potential to provide a long precipitation record is limited by the time scale of development of the peat cover that is critical to the hydrological conditions resulting in the development of annually banded stalagmites in Uamh an Tartair. Baker et al. (1999b) and Charman et al. (2001) have demonstrated that the peat cover began to accumulate at least 3000 years ago so the site has the potential to provide a precipitation record three time as long as the

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existing one. A long record is needed to undertake spectral analysis on a longer time series and provide a longer term interpretation in terms of North Atlantic climate. Here we present results of annual band counting on two further radiometrically dated stalagmites that extend the record back a further 2500 years.

## 2 Sample and site description

The Uamh an Tartair cave lies in the Traligill valley in NW Scotland, at an altitude of 300 m: a fuller description is given in Proctor et al. (2000). The study used three minimum diameter stalagmites from the Grotto, a small chamber lying less than 10 m below the surface (Fig. 1). SU-96-7 was a small (32 mm high) in situ stalagmite that was actively growing when collected. The other two stalagmites (SU-96-1 and SU-96-2) were ex situ specimens, for conservation reasons collected from a loose block in the Grotto, a few metres from the collection site for the previous samples. Previous visitors had moved this from its original site so its exact original position is unknown, though it is highly unlikely that the block had been moved more than a few metres.

SU96-7 comprises clean stalagmite containing virtually no clastic detritus. There is no sign of any hiatuses suggesting it grew continuously (Fig. 1). It was under an active drip when collected and bomb carbon produced by nuclear weapons tests in the top layers confirms it was actively growing when collected (Genty et al. 2001). A TIMS uranium series date from the base of 1262 (1002–1349) years (before 2000 AD) gives an estimate of the start of growth (Proctor et al. 2000). SU-96-1 and SU-96-2 grew side-by side about 8 cm apart, and are joined such that sectioning reveals continuous visible calcite comprising alternating white porous calcite (WPC) and dark compact calcite (DCC; Genty et al. 1997) which can be traced from one to the other via the flowstone connecting them, allowing an approximate correlation between growth laminae in the stalagmites and confirming that they grew simultaneously (Fig. 1). Through most of their length the stalagmites comprise non-porous stalagmite containing very little clastic detritus. This suggests growth was continuous as significant breaks in deposition characteristically result in the build up of a layer of clastic and organic debris, and a vuggy horizon marking the start of new growth as discrete calcite crystals on top of the detritus layer. Such vuggy horizons with associated detrital particles occur in the lower half of one (SU-96-2) stalagmite suggesting growth hiatuses did occur early in the formation of this stalagmite. Three TIMS uranium series dates from the stalagmites have produced ages of 2073 ± 48, 2533 ± 60 and 3342 ± 82 years (Genty et al. 2001). None of these dates are from the top or base of either stalagmite, so the actual period of growth is actually rather longer.

Annual luminescent laminae are visible throughout all the stalagmites (Fig. 2). Luminescent laminae were counted and their widths measured using techniques detailed in Proctor et al. (2000), to compile a record of annual growth rate for each stalagmite. Results of laminae counting for SU-96-7 are described by Proctor et al. (2000). This stalagmite extends up into the period of instrumental meteorological records which allows correlation between growth rate and climate. For this study the five counts on different profiles were made of the top 150 bands, in order to obtain a mean growth rate curve for the period covering the meteorological records. In addition further counts on a thin section which had been embedded in resin before it was cut were used to determine the exact position of the top of the stalagmite and allow precise dating of the luminescent band chronology (it had previously been found that the top of the stalagmite was damaged in sectioning, resulting in the loss of the topmost few bands).

For SU-96-1 a continuous lamina count was obtained for the whole thickness of the stalagmite except for a few mm at the base which shows discontinuous lamination. The count for SU-96-2 was discontinued somewhat higher than the base due to presence near the base of frequent growth hiatuses, visible both in hand section and under the microscope as vuggy horizons with detritus and euhedral crystal growth immediately above.

For correlation with local climate 130 year records of monthly temperature and precipitation derived from nearby meteorological stations were used: details are given in Proctor et al. (2000).

## 3 Results

SU-96-7 contains a sequence of 1089 annual luminescent bands (Fig. 3). No hiatuses are visible either in hand section or under the microscope suggesting that this is a continuous sequence. The five duplicate counts on the top 160 bands show some lateral variability in growth rate in different parts of the stalagmite, probably resulting in slight shifts in impact point of the drip (Fig 3). A mean growth rate curve for the top 160 bands was constructed by taking the mean of these five counts. The use of resin embedded sections of the top of the stalagmite allowed the topmost band to be identified, providing an exact chronology. This implies the stalagmite

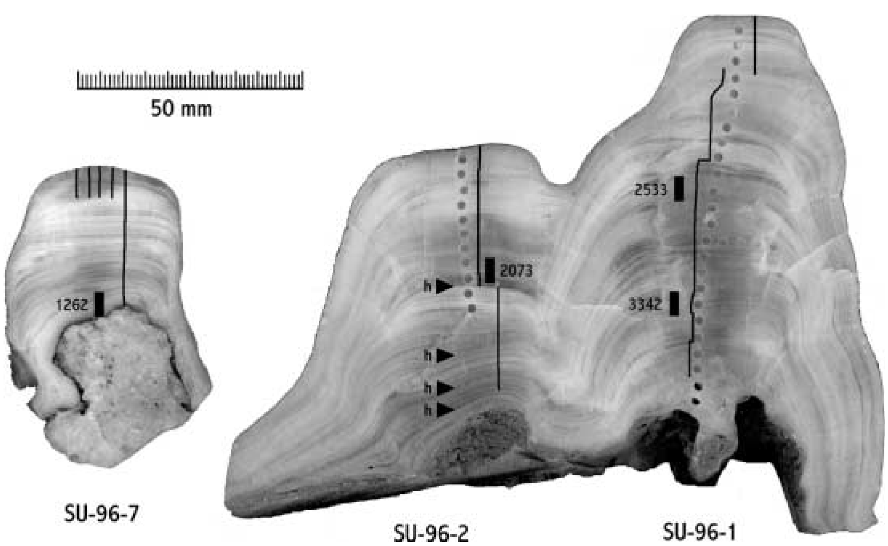



**Fig. 1.** Stalagmites SU-96-1, 2, and 7, showing locations of growth rate transects and TIMS U-Th analyses. *Arrows* mark major hiatuses in SU-96-2

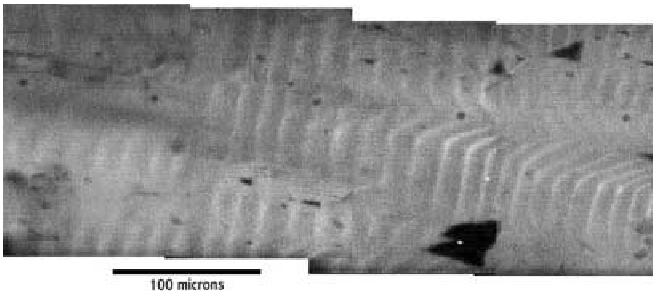



**Fig. 2.** Annual luminescent banding in stalagmite SU-96-7 from laminae 31–58 from top (1964–1937 AD). Scale bar is 100 microns

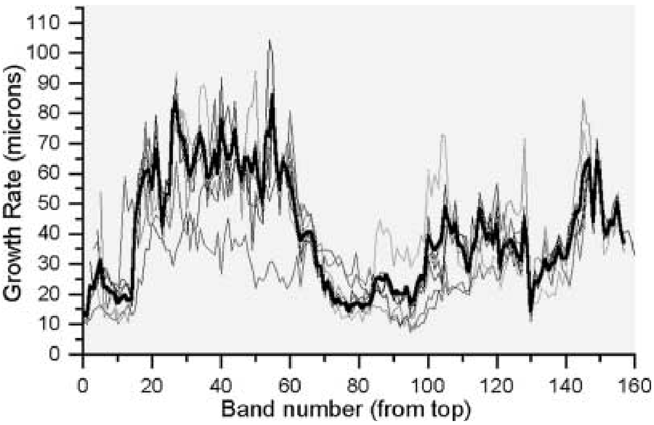



**Fig. 3.** Five replicate growth rate profiles on the top 160 laminae of SU-96-7. The *bold line* is the average of the five profiles used in our correlation with instrumental climate data

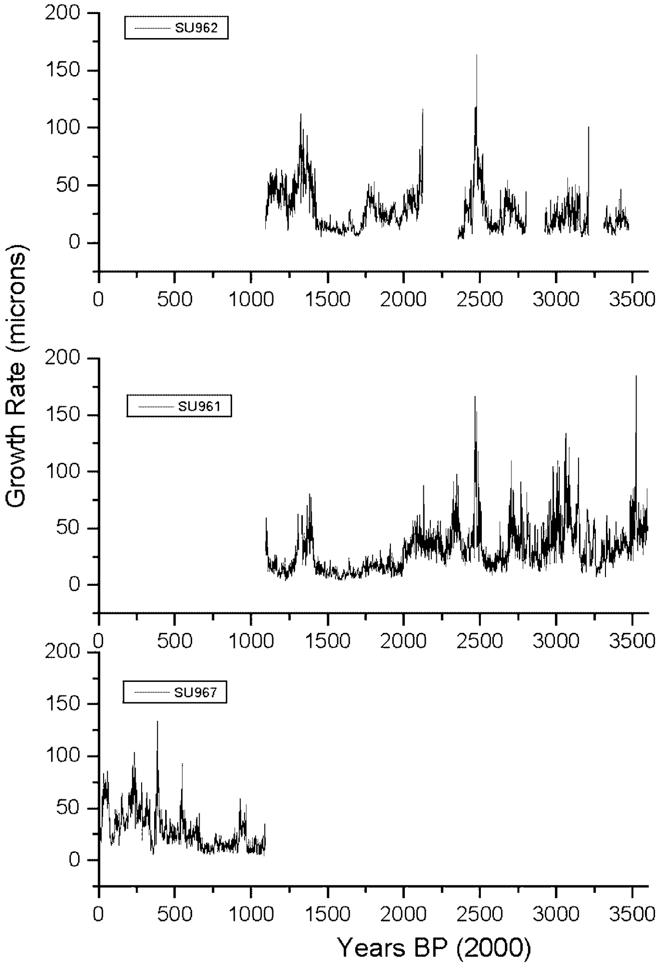



**Fig. 4.** Growth rate time series for stalagmites SU-96-1,2, and 7; see text for details

grew between 1094 to 5 years BP, in good agreement with the basal date of 1262 (1002–1349) years (Proctor et al. 2000).

SU-96-1 and SU-96-2 provided sequences of 2563 and 1920 luminescent bands respectively. These stalagmites demonstrably grew simultaneously (visible laminae can be followed from one stalagmite into the other via the flowstone joining them) and for much of their thickness variations in their growth rates are closely comparable allowing annual scale correlation between them. This confirms the presence of major hiatuses in SU-96-2 in positions corresponding to the hiatuses visible in hand section and under the microscope. The upper part of the SU-96-2 sequence can be securely correlated with SU-96-1 using a combination of visible laminae and correlation of the growth rate curves provided by the luminescent band counts (Fig. 4). This correlation shows that over the last 20 years of growth, growth in SU-96-1 rapidly increased while growth of SU-96-2 slowed down, probably due to a switching of water supply from one stalagmite to another as one drip pirated water from the other shortly before both dried up. This is something that might also have occurred during dry conditions in earlier growth periods, although this is not obvious in Fig. 4. Towards the base the growth rate curves are less similar than in the upper parts of the stalagmites and correlation becomes more difficult: two short sequences between hiatuses at the base of the SU-96-2 count cannot be securely correlated with SU-96-1 although their general location can be inferred using visible laminae. The decrease in correlation between samples is probably due to the thin or discontinuous peat cover at this time, as peat accumulates the peat hydrology will change and therefore so will the stalagmites' response to surface climate. Therefore we have most confidence in the data between 3000 BP and present when we know that peat overlay the site (Charman et al. 2001). The good correlation between the upper part of SU-96-2 and SU-96-1 also shows that a hiatus of 20 years is present in the SU-96-1 sequence 220 bands below the top. This brief hiatus is visible under the microscope as a highly luminescent horizon with detritus, and is the only discontinuity that has been identified in the SU-96-1 sequence. These two stalagmites thus provide a continuous chronology extending for more than 2500 years. This chronology has been dated using two TIMS ages from SU-96-1 and another from SU-96-2. The precisely known positions of the TIMS ages allows them to be used to constrain the luminescent band chronology, suggesting it extends from 1092 to 3673 years BP. Given the analytical uncertainty associated with the TIMS U-Th analyses of $\sim$50 years, it is difficult to be certain that the chronology overlaps the record provided by SU-96-7; however the three stalagmites provide a continuous or near continuous record of variations in growth rate extending from the present to around 3673 years BP.

Proctor et al. (2000) showed that growth rate at the top of SU-96-7 showed a positive correlation with annual temperature and a negative correlation with precipitation. Using the raw mean growth curve for the top 150 bands of SU-96-7, and decadally smoothed bandwidth and temperature/precipitation data, we obtain a similar result giving the following empirical formula:

$$\text{Annual band width} = -206 + 68200(T/P) \quad (r = 0.77)$$

Annual band width (microns), $T$ mean annual temperature (°C) and $P$ = mean annual precipitation (mm).

This differs from Proctor et al. (2000) in that this relates band width (in microns) directly to mean annual temperature and precipitation whereas the previous study correlated a normalised growth rate. Temperature is known to have varied relatively little over the period of stalagmite growth implying that major variations in growth rate must be driven predominantly by changes in precipitation (Proctor et al. 2000). This confirms that growth is climatically determined, with precipitation providing the main forcing factor, probably via changes in saturation of the peat overlying the cave. The link between climate and growth rate is inferred to be production of $CO_2$ by soil respiration, which will increase with increased temperature or decreased precipitation (Proctor et al. 2000). Over the calibration period the relationship is approximately linear but the longer dataset used in this study suggests that the stalagmites show a minimum growth rate of around 10–20 micrometres/year with extended periods showing this minimum growth rate (Fig. 3). This suggests that for periods of very high precipitation, growth rate may not have continued to respond linearly to changes in precipitation. Probably this is because once the peat is completely saturated any further increase in precipitation would merely cause increased surface runoff with no changes in hydrology of the peat or underlying limestone which could affect stalagmite growth rate.

## 5 Spectral analysis of the growth rate series

Spectral analysis was performed on the stalagmite growth rate time series. Given that there is a little uncertainty in the correlations between individual stalagmite time series, and that hiatuses are present in SU-96-1 and 2, rather than constructing a mean growth rate curve for the last 3600 years we perform spectral analyses on individual series. Table 1 shows that given these constraints we only consider SU-96-1 below the hiatus and we divide SU-96-2 into four separate series. For the uppermost section of SU-96-2, we omit the last 100 years to avoid any flow-switching effects as detailed earlier. Given the considerable length of each of these (290–2342 years), spectral periods of between 10 and 150 years are detectable. We utilised a combination of Hanning, Triangular and Blackman-Harris 3-point spectral windows using detrending and variable number of segments (1 to 8) depending on time series length. Results are presented in Table 1, and show that a spectral frequency of 50–70 years is predominant in all series in stalagmites SU-96-1/2, a slightly longer frequency of 72–94 years is dominant in SU-96-7. Other periodicities also occur but not in all time-series and so are not considered to be reliable, many are harmonics of the longer 50–70 year period. Wavelet analysis on the longest continuous time series (SU-96-1 and 7; not shown) demonstrate that the 50–70 year period has variations in periodicity within this range.

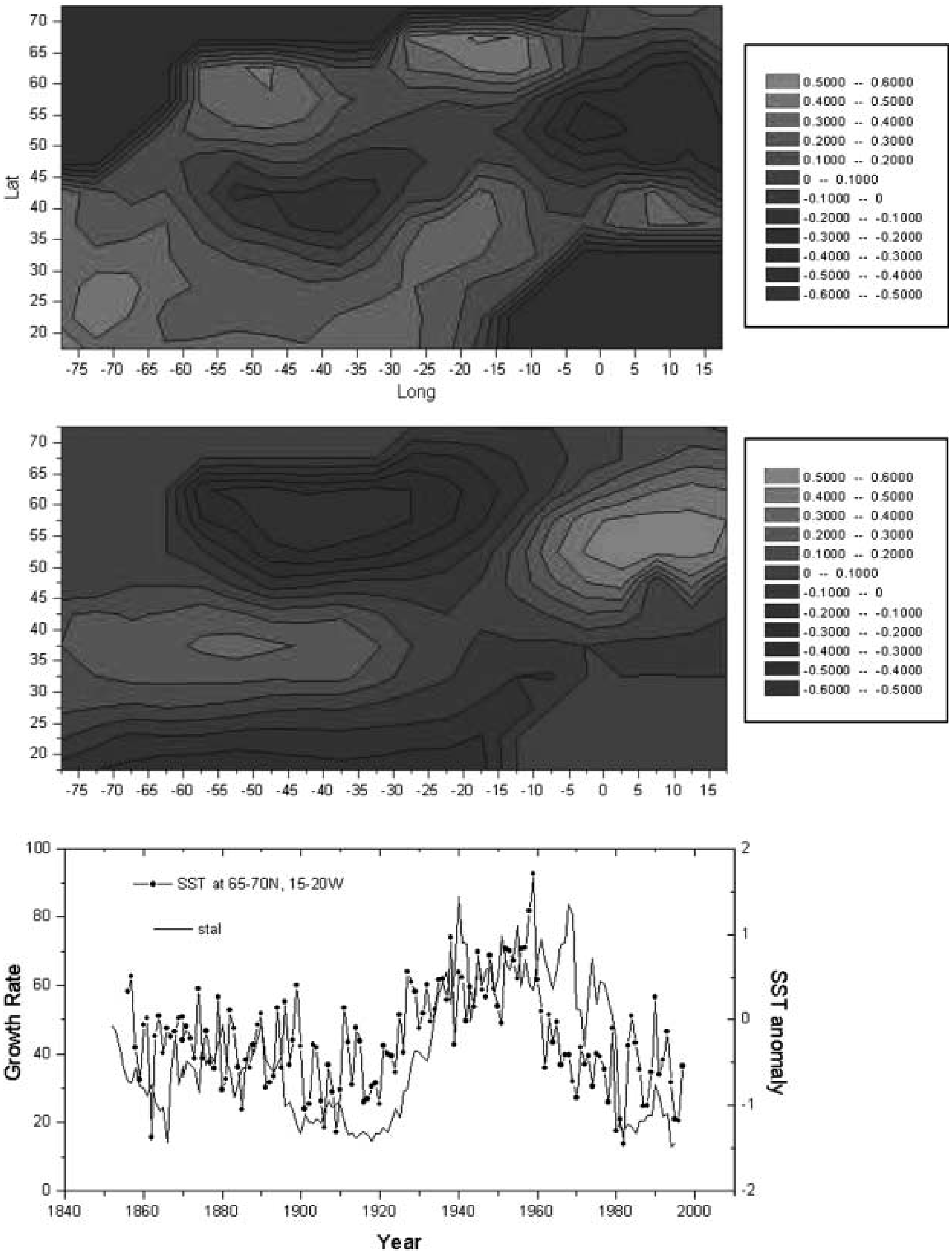
## 6 North Atlantic climatic interpretation

As stated already and in Proctor et al. (2000) we have a good historical calibration with local climate ($T/P$) and regional climate (NAO) over the period of historical meteorological records. Additionally over this period we observe a good correlation with sea surface temperatures. The best correlation between stalagmite growth rate and SST is for the 65–70°N, 15–20°W grid square (north of Iceland; decadal average, $r$ = 0.74). Figure 5 shows correlation between stalagmite growth rate versus SST (Kaplan reconstruction; Kaplan et al. 1998) at 5 × 5° for the whole North Atlantic region; an identical spatial pattern is observed with alternative SST reconstructions. The correlation between Kaplan SST reconstruction and winter NAO (using data in Hurrell 1995) is

**Table 1.** Results of spectral analyses. SU-96-2 is analysed in separate growth sections that are divided by hiatuses; the uppermost 100 years of the top growth section is also removed from the analysis due to possible flow-switching effects. For the same reason, only the basal growth section of SU-96-1 is analysed

| Stalagmite | Length of time-series | Spectral frequencies always present (years) | Other spectral frequencies (years) |
|---|---|---|---|
| SU-96-1 | | | |
| Base | 2342 years | 116–150, 59–81, 37–40, 20–21 | 46–49, 31, 26–27, 18 |
| SU-96-2 | | | |
| Top | 631 years | 48–60 | 81–97, 27–32, 22–25 |
| Mid | 289 years | 55–64 | 30–36, 15, 12, 9 |
| Mid | 448 years | 49–71 | 48–52, 39–41, 32–35, 22–23, 8 |
| Basal | 289 years | 44–81, 32–40 | 22–25, 16–17, 10 |
| SU-96-7 | 1087 years | 72–94, 49–59, 39–42, 25–27 | 15, 12, 7 |

**Fig. 5.** (*Top*) correlation between stalagmite growth rate and SST for 5 × 5° grids. (*Middle*) correlation between winter NAO and Kaplan SST over historical period. (*Base*) correlation between stalagmite growth rate and SST for the grid square with highest correlation coefficient




also shown for comparison. This shows a strong dipole pattern; a similar (negatively correlated) but weaker pattern is present in our stalagmite growth rate – SST correlation confirming that the NAO–SST relationship as observed elsewhere (Rodwell et al. 1999; D'Arrigo et al. 1997) is at least in part determining stalagmite growth in NW Scotland, through links with local temperature and precipitation. However, the strongest correlation between stalagmite growth rate is at 65–70°N, 15–20°W, north of Iceland and in a region of the North Atlantic that had considerable sea-ice cover before the period of instrumental meteorological records (Ogilvie and Jonsson 2001). Documentary reconstruction of Iceland sea ice shows that throughout the "Little Ice Age" period sea-ice cover was increased, SSTs are lower, and yet stalagmite growth rate increases at this time due to drier conditions. This is probably due to the stalagmite growth being predominantly driven by NAO strength at this time; our correlation with SST will break down before the period of instrumental meteorological records.

The precise relationship between precipitation, temperature and stalagmite growth rate found for the last 130 years cannot therefore be extended over the whole record, although we are certain that fast growth occurred in dry and warm conditions, slow growth in wet and cold. The climatic factors that force NW Scottish climate and therefore our stalagmite growth have varied through time, and include winter NAO strength, thermohaline circulation strength affecting SSTs and possibly solar output. However, we do have a 50–94 year spectral period in our stalagmite records, the same as that observed in the North Atlantic region SSTs by Schlesinger and Ramankutty (1994). Delworth et al. (1993) and Delworth and Mann (2000) amongst others have modelled this multidecadal variability as being due to variations in ocean-atmosphere circulation (NAO and thermohaline circulation interactions). Most previous studies have been limited to historical/instrumental periods, and although they demonstrate overwhelming evidence for multidecadal variation over this time period centred on the N Atlantic, the short nature of the records meant that it was not certain whether a true multidecadal oscillation actually occurs. Our stalagmites provide high resolution, precisely dated evidence of a similar periodicity predominating over the last 3000 years in a climate proxy record known to be sensitive to changes in forcing functions relevant to the North Atlantic sector.

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