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SHORT COMMUNICATION

RECONSTRUCTING HEMISPHERIC-SCALE CLIMATES FROM MULTIPLE STALAGMITE RECORDS

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ABSTRACT

The magnitude of recent warming, and the variability of climate on centennial-millennial time scales are compromised by questions concerning the ability of tree rings to capture low-frequency climate fluctuations. Annually laminated stalagmite records can potentially provide a low-frequency climate archive through variations in annual growth rate. Presented here is an initial attempt to demonstrate the applicability of annually laminated stalagmite series to a large-scale climate reconstruction, by producing a 500-year Northern Hemisphere temperature reconstruction. The reconstruction shows an overall warming trend with a magnitude of 0.65 K and several other low-frequency characteristics consistent with other independent Northern Hemisphere archives. The result is sufficiently encouraging to warrant significant future effort in characterising annual growth rate records from laminated speleothems. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: stalagmite; temperature reconstruction; Northern Hemisphere; low frequency

1. INTRODUCTION

The Northern Hemisphere temperature reconstruction for the past millennium of Mann *et al*. (1998) (MBH98) has sparked controversy among climate researchers. While providing a valuable benchmark for palaeoclimatological research (IPCC, 2001), the record does differ from other published reconstructions (Briffa and Osborn, 1999; Crowley and Lowery, 2000; Esper *et al*., 2002: ECS02). Of particular interest is the lesser amount of long-term variability present in the MBH98 reconstruction compared with that of ECS02. ECS02 reconstructed about twice the temperature amplitude than that of MBH98 around the 'Little Ice Age' period during the seventeenth century (Figure 1). Simulations from general circulation models are also indicative of greater low-frequency variability than is suggested by MBH98 (Tett *et al*., 1997; Jones and Mann, 2004), and reconstructed borehole temperatures reveal a cumulative warming of 1.1 K over the Northern Hemisphere during the last 500 years (Huang *et al*., 2000). This larger magnitude of variation is absent from the majority of other conventional proxy reconstructions (Jones *et al*., 1998; Briffa *et al*., 2001), which tend to lie somewhere between the extremities of MBH98 and ECS02 (Figure 1).

Since the amplitude of past low-frequency climate fluctuations is highly relevant for an assessment of modern and future climate change, it is important to understand these disparities. The seasonality of tree ring data, which are predominantly representative of the warm growing season, is recognised as playing an important role (Briffa, 2000) in the discrepancies between the data. However, a widely accepted view, cited

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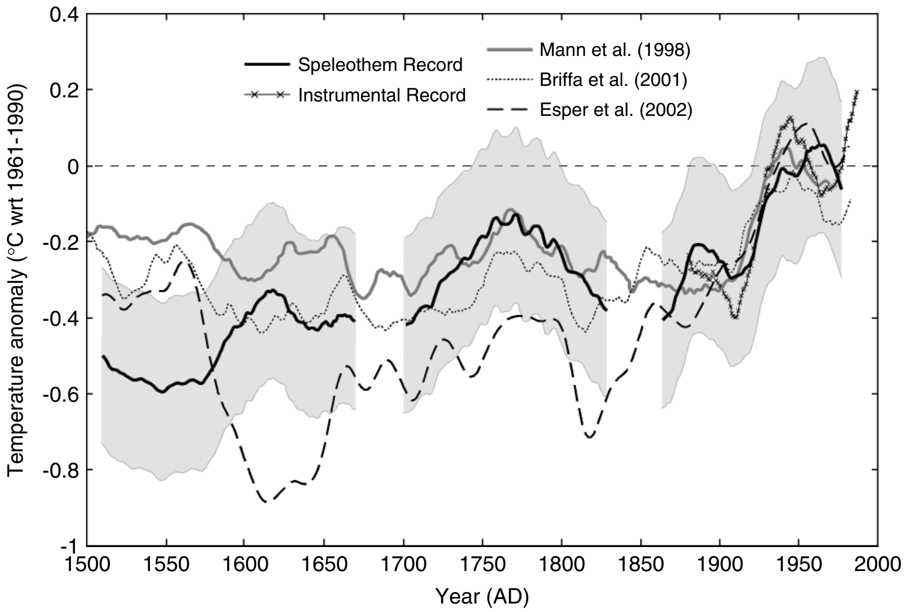

Figure 1. Northern Hemisphere mean annual temperature reconstructions, smoothed with a 20-year low-pass filter for the past 500 years with the speleothem reconstruction shown with 2 standard error intervals (shaded area)

by Esper *et al.* (2004), suggests that the various methods of processing tree ring data to retain low-frequency variability can subsequently lead to significant differences in the magnitude of centennial to millennial-scale temperature fluctuations. More recently, the lesser amplitude exhibited by the proxy reconstructions has been associated with the use of a regression-based method (Esper *et al.*, 2004; von Storch *et al.*, 2004), and to the lack of 'redness' in the proxy time series that have been used (Osborn and Briffa, 2004).

The robustness of the low-frequency signal within current multi-proxy reconstructions is therefore questionable; emphasising the need for the development of annually resolved series from additional proxy sources, which are capable of providing information complementary to that of tree rings and ice cores. Speleothems can go some way to resolving the low-frequency issues associated with tree-age related biases and segment length limitations (Cook *et al.*, 1995), as they grow under constant conditions on a centennial to multi-millennial time scale (Dorale *et al.*, 1998; Wang *et al.*, 2005).

The annual layering present in the stratigraphy of many speleothems is either defined by seasonal couplets differing in porosity or mineralogy (Railsback *et al.*, 1994; Genty and Quinif, 1996), or by seasonal infiltration events represented by luminescent laminae (Baker *et al.*, 1993; Shopov *et al.*, 1994), and/or geochemical (trace element) variations which can reflect aspects of both types of laminae (e.g. Fairchild *et al.*, 2001). More recently, oxygen isotope variability has been found to correlate with visible laminae thickness in monsoonal climates (Fleitmann *et al.*, 2004). The annual lamina thickness reflects a combination of driving factors affecting growth rate (dripwater Ca content, dripwater film thickness, cave PCO_2; Dreybrodt, 1988). Of these, variations in drip-water supersaturation due to variability in Ca content or drip water PCO_2 (as a function of degassing in the epikarst or in the cave) are the most likely to vary on a multi-year timescale. These factors controlling supersaturation primarily reflect changes in CO_2 production and storage in the soil and epikarst above the cave, which in turn are likely to be functions of temperature and rainfall. Hence, lamina thickness series can capture a smoothed low-frequency signal due to the inertial hydrological properties (mixing and storage) of the feeding system for the stalagmites (Proctor *et al.*, 2000).

The ability of speleothems to preserve low-frequency climate variability has been recognised by their inclusion in the multi-proxy reconstructions of Pauling *et al.* (2003) and Moberg *et al.* (2005). Traditionally, however, palaeoclimate reconstructions from speleothems have used a single speleothem growth rate record in isolation. This is commonplace in speleothem studies, where conservation issues limit the amount of

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available samples, thereby restricting the degree of sample replication possible. Although there are examples of correlation between speleothem isotope records within the same cave (Dorale *et al*., 1998; Wang *et al*., 2001), the strength of the captured climate signal within laminated speleothems has been difficult to establish due to the lack of replicability; and the extent to which the signal contained is representative of low-frequency climate fluctuations requires verification, independent of reconstructions which contain information from additional proxy sources. Here, information from three independent speleothem annual layer thickness chronologies is combined to produce an extra-tropical, mean annual, Northern Hemisphere temperature reconstruction for the past 500 years, derived solely from speleothem data. Since this is a pioneering development, the aim is not to derive a definitive reconstruction, but rather to examine the degree to which speleothems from spatially diverse environments contain a common low-frequency signal that can be interpreted as a climatic response, and whether this signal is comparable to the phase and amplitude of the low-frequency variability within dendroclimatological reconstructions.

2. DATA AND METHODS

The temperature reconstruction is derived using the annual stalagmite growth rate for three recently published stalagmite time series from northwest Scotland (Proctor *et al*., 2000), alpine Italy (Frisia *et al*., 2003) and eastern China (Tan *et al*., 2003). The raw data is archived at the World Data Center for Paleoclimatology (http://www.ngdc.noaa.gov/paleo/speleothem.html) and is displayed in Figure 2. Previous studies have confirmed that speleothem growth at these sites is influenced by local temperature. A logarithmic relationship between annual growth rate in the Chinese speleothem and Beijing summer (MJJA) temperature was found to be significant (Tan *et al*., 2003), while the Scottish sample was found to be responding to a combination of local mean annual temperature and precipitation (Proctor *et al*., 2000, 2002). Growth in the Italian sample was interpreted as reflecting the duration of frozen soil conditions during the cold season, which is modulated by winter temperature (Frisia *et al*., 2003). The impact of large-scale climate patterns upon speleothem growth was also addressed in the original studies, with particular reference to the Northern Hemispheric domain. All three series have previously been shown to display a significant relationship to hemispheric scale temperatures, but vary in the seasonal weighting of the relationship. The Chinese speleothem is representative of mean annual conditions (Tan *et al*., 2003), whereas the Scottish and Italian records have a stronger coupling with winter conditions. Here, they are independently found to be significantly related to the Northern Hemispheric mean annual temperature.

The raw data series were used in favour of a detrended series, such as that used by Tan *et al*. (2003) to remove sedimentary trends in early stalagmite growth. This is appropriate because the dataset used in this study only uses information concerning the later stages of speleothem growth, which would be unaffected by such a phenomenon (see the supplementary figure in Tan *et al*., 2003). Moreover, the removal of long-term trends can result in a loss of long-term climatic information, similar to that incurred by the traditional curve-fitting procedures used in dendroclimatology (Fritts, 1976). Prior processing of the annual layer thickness data, involved transforming the three time series so that the data were distributed with a mean of 0 and a variance of 1. Pre-whitening the data series, as is common in many dendroclimatology studies (Cook, 1992), was avoided as the persistence present in speleothem series is most likely attributed to climate processes in the preceding months or years (Proctor *et al*., 2000).

The time series were then transformed using eigenvector techniques, to extract the common mode of variability contained within the three records (von Storch and Zwiers, 1999). The principal empirical orthogonal function displays remarkably high, positive loadings with all three series and explains 55% of the total variance. The effect of this transformation is an improved signal-to-noise ratio, and increased confidence that although the datasets are spatially sparse, the established links with Northern Hemispheric climate suggest this to be the common mode of variability contained within the three records.

The reconstructed temperature series was derived using a simple ‘local calibration’ approach (Rutherford *et al*., 2005), which is based upon a linear regression method. The transformed dataset was calibrated to the instrumental temperature record (Jones *et al*., 1999; land areas north of 20°N) over the period 1870–1960 and

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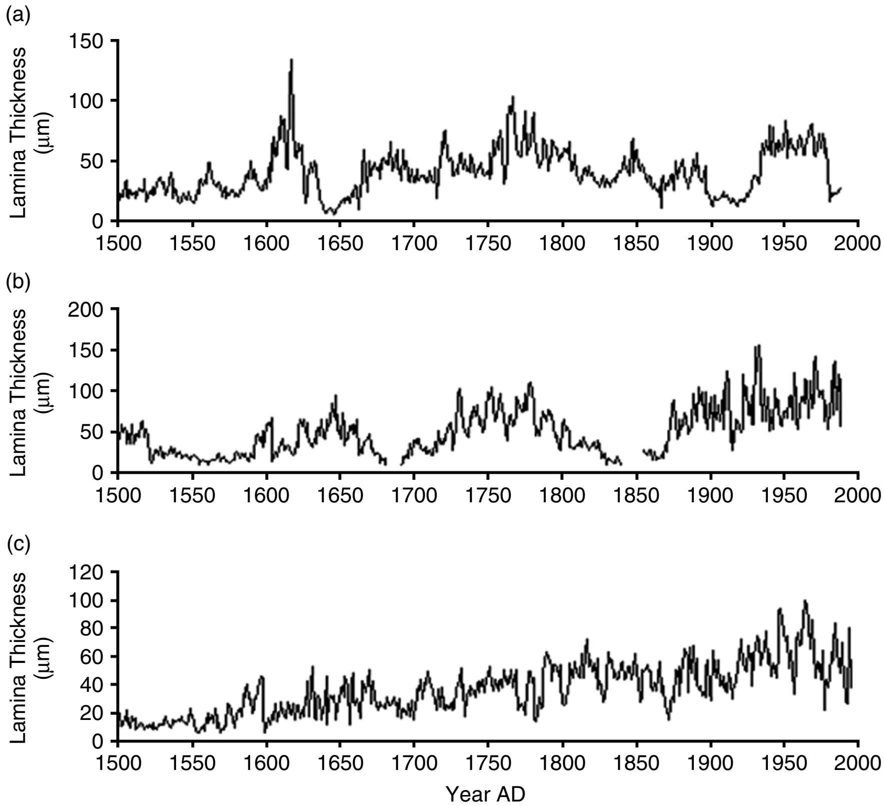

Figure 2. Time series of layer thickness chronologies for (a) Scotland, (b) Italy and (c) China

validated using the remaining overlapping instrumental record, before extending back in time to encompass the last 500 years (Figure 1).

3. RESULTS AND DISCUSSION

Although currently restricted by its length and the sparseness of available samples, the presented stalagmite temperature reconstruction provides strong evidence that speleothem growth rate is closely related to large-scale patterns of climate variability. Comparisons with a number of published Northern Hemisphere temperature reconstructions prove to be highly favourable (Table I). While each of these reconstructions differs in terms of the number and location of proxies, and the degree to which they are reflective of annual temperature, they are assumed to be adequately representative of annual temperature variability for comparison purposes (Cook *et al.*, 2004). A correlation of 0.9 exists between the speleothem reconstruction and the (non-calibrated; 1960 onwards) instrumental record of mean annual temperature, and significant correlations ($r > 0.43$; $p < 0.01$, after correction for autocorrelation) were found with all the reconstructions when smoothed with a 20-year low-pass filter over the past five centuries (Table I). Quantitative estimates of the uncertainty associated with the utilisation of a regression-based reconstruction, including the loss of temperature variance that such an approach can incur (von Storch *et al.*, 2004), were calculated using the method of Briffa *et al.* (2002). These are notionally 2 standard error estimates, but are subject to correction due to the autocorrelative structure of the merged stalagmite series. The dating errors associated with inaccuracies in annual laminae counts (∼2%; Proctor *et al.*, 2000) are considered negligible relative to the degree of smoothing.

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Table I. Comparison of climatic records and their correlation with the composite stalagmite series. All records have been smoothed with a 20-year low-pass filter. Correlations for the whole reconstruction and the more robustly dated 1700–2000 period

	Proxies Used	Stalagmite (1500–2000)	Stalagmite (1700–2000)
Instrumental record	N/A	N/A	0.90[a,b]
Jones *et al*. (1998)	Multiproxy:tree rings, ice cores, coral & historical records	0.72[a]	0.86[a]
Mann *et al*. (1998, 1999)	Multiproxy: tree rings, ice cores, historical records, coral & instrumental records	0.43[a]	0.85[a]
Crowley and Lowery (2000)	Multiproxy: tree rings, ice cores, pollen and historical records	0.58[a]	0.74[a]
Briffa *et al*. (2001)	Tree rings	0.58[a]	0.80[a]
Esper *et al*. (2002)	Tree rings	0.59[a]	0.82[a]

[a] $p < 0.01$ for all reconstructions accounting for the level of autocorrelation (The first order autocorrelation coefficient, $r_1 = 0.994$.
[b] For the uncalibrated period of the instrumental record (1960–2000).

The reconstruction is subject to two discontinuities, which correspond to hiatuses in the Italian stalagmite, from 1840 to 1855 and *ca* 1680 to 1690. Uncertainty in the earlier part of the reconstruction arises as a consequence of the ambiguous duration of the hiatus that occurred in the late seventeenth century (Frisia *et al*., 2003). This is in addition to the 2% lamina count error, as the laminae in the hiatus are unable to be resolved and is reflected by the lack of correspondence between the reconstructions prior to this time and by the improvement in correlations for the latter part of the reconstruction (Table I). Indeed, Baumgartner *et al*. (1989) found that chronological errors less than 3% could significantly degrade the relationship between a proxy variable and a climate signal. Dating uncertainty during the earlier part of the reconstruction could be greatly improved with the availability of more annually laminated samples, the incorporation of which provide a potential means of extending the reconstruction further back in time.

Discrepancies in the time series may be further exacerbated by the overly restrictive assumption of linearity that is integral to the method of reconstruction. The approach of calibrating the proxy by modern data is limited by the short timeframe of the instrumental record and its limited range of temperature variation (Bradley *et al*., 2003). It is debatable whether the stalagmite has responded linearly to climate before this time, in particular, when measurements fall out of the range of those present in the instrumental record. Thus, the exceptional negative anomaly during the mid-sixteenth century in the speleothem reconstruction may be no more than a consequence of a non-linear growth rate-climate response within the Chinese stalagmite, which shows a prominent departure from the mean around that time, as a particular threshold is reached. Again, the availability of more annually laminated stalagmites would decrease the emphasis on any non-linear climate responses in an individual stalagmite.

The speleothem temperature reconstruction closely resembles that of Briffa *et al*. (2002) for the time interval ∼1700 to the present. The overall magnitude of warming in the speleothem reconstruction is 0.65 K, compared with around 0.4 K displayed by the reconstruction of Briffa *et al*. (2002). The twentieth century, as with all the other reconstructions, is significantly warmer than the previous four centuries. The temperature is shown to increase by 0.35 K over the last century, compared with the 0.29 K increase that occurred between 1700 and 1780, and the 0.27 K amplitude change in temperature that occurred during the late sixteenth to early seventeenth centuries. With such a short dataset, it is difficult to assess whether the amplitude of the temperature increase during the twentieth century is truly anomalous relative to what occurred in the preceding centuries, but the recent warming does not appear as exceptional as that suggested by the borehole reconstruction of Huang *et al*. (2000), where the nineteenth and twentieth centuries are responsible for 80% of the net temperature increase over the last 500 years. The discrepancy between borehole and speleothem records may be due to the European weighting of the speleothem reconstruction, as the borehole reconstructions show

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greater warming in North America and Asia compared to Europe (Huang *et al.*, 2000). A recent temperature reconstruction for the past 2000 years, from an alpine speleothem oxygen isotope record suggests that there were periods in that region of Europe when temperatures were more comparable (or even warmer) than today (Mangini *et al.*, 2005), although this result is specifically dependent on the continuity of contribution of the same types of weather systems throughout this record.

Since the ECS02 reconstruction was derived using a methodology specifically tailored to preserve multi-centennial climate signals within ring width indices, a similar pattern of variability within the implied low-frequency speleothem reconstruction would be expected. Yet, although the speleothem reconstruction displays a greater negative anomaly than many of the reconstructions, the dramatic negative departure in ECS02 (1600–1800) remains unmatched by the speleothem series, particularly *ca* 1590–1650 where the ECS02 reconstruction falls well below the lower error bound of the speleothem reconstruction and shows an apparent antiphase relationship. However, it should be emphasised that this uncorrelated period falls within the uncertainly dated period, before the seventeenth century hiatus in the Italian speleothem record, and a better fit may be obtained allowing for error in the time axis. Consistent with the other reconstructions, the speleothem record does not show any positive temperature anomalies (with respect to 1961–1990) prior to the twentieth century. Other common low-frequency characteristics include a cool pre-1700, followed by a warming, which peaks toward the end of the eighteenth century. There is also apparent cooling that precedes the warming of the twentieth century.

A multitaper spectral analysis (Percival and Walden, 1993) of the unsmoothed temperature reconstruction displays a typical red noise structure, indicating the presence of a high component of significant low-frequency behaviour (Figure 3). Over 50% of the total reconstruction variance is contained at frequencies lower than 0.05 cycles per year (periodicities greater than 20 years), supporting the idea of a karstic smoothing filter that is capable of retaining low-frequency climate information.

The difference in amplitude of temperature variations within proxy reconstructions has been of recent concern (von Storch *et al.*, 2004; Esper *et al.*, 2005), with a number of factors in methodological procedures highlighted as being responsible for anomalies in the magnitude of temperature change within palaeoclimate records. The speleothem reconstruction displayed here has not been specifically manipulated to retain low-frequency temperature variations or to preserve higher amplitude behaviour, but it does show a greater amplitude change over the past 500 years than that displayed by reconstructions that have been derived using 'traditional' regression methods. Thus, the larger temperature range present within the speleothem reconstruction over the last 500 years provides further support for the capture of a more slowly evolving climate signal within the speleothem records.

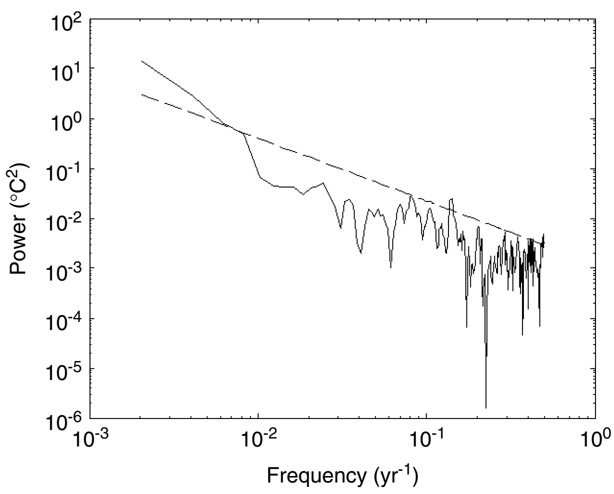

Figure 3. The multi-taper power spectrum of the speleothem reconstruction; dashed line shows 95% significance level

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4. CONCLUSION

Annually laminated stalagmites that have accumulated over the last 500 years from three Northern Hemisphere sites display a dependency of lamina width (i.e. growth rate) on Northern Hemispheric temperature, suggesting that stalagmites offer key annual resolution palaeoclimatic information. This paper has used a relatively simple methodology to reconstruct large-scale temperature anomalies from annually laminated speleothems. There exist some data limitations within the three stalagmite series as it stands, particularly with respect to the dating of the earlier part of the reconstruction and the small size of the dataset. The addition of further annually laminated stalagmites will help overcome these issues: continuous annual laminae series on various time periods are increasingly being published from other locations (e.g. Brook *et al*., 1999; Polyak and Asmerom, 2001; Burns *et al*., 2002), and are to be expected in shallow caves with a strongly seasonal climate (Tan *et al*., submitted). Here we emphasise the potential value of annual laminated speleothems and aim to encourage the collection of robustly dated, annual lamina width speleothem datasets, which will ameliorate our understanding of past, low-frequency climate variability.

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