

# Evidence of Suess solar-cycle bursts in subtropical Holocene speleothem $\delta^{18}\text{O}$ records

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**SAGE**

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## Abstract

Several studies indicate that changes in solar activity may have driven Holocene subtropical monsoon variability on decadal and centennial timescales, but the strength and nature of this link remains debated. In this study, we combine a recent mapping of the Holocene solar-cycle activity with four subtropical speleothem  $\delta^{18}\text{O}$  records, which allows a strong test of the link between solar activity, monsoon activity (or intensity), and the hydrological cycle. This is possible because the speleothem  $\delta^{18}\text{O}$  records mainly reflect changes in local rainfall composition, which is controlled by changes in total moisture loss along the atmospheric transport path and monsoon intensity. We find that the spectral density distributions of the speleothem records exhibit particularly significant  $\sim 210$  yr cyclicities that tend to coincide in time with the three Suess solar-cycle bursts, i.e. intervals around 1850–3200 BP, 4500–5700 BP, and 7750–8850 BP when the  $\sim 210$  yr solar cycle was particularly strong. The speleothems from Dongge Cave (China) and Sofular Cave (Turkey) appear to have recorded all three Suess bursts, whereas the speleothems from Heshang Cave (China) and Pink Panther Cave (southwestern USA) only recorded the first and last Suess bursts, and the middle Suess burst, respectively. The temporal relationship between the Suess solar cycle and particularly significant 210 yr oscillations in the speleothem  $\delta^{18}\text{O}$  records therefore supports the notion that solar variability played a significant role in driving centennial-scale changes in the hydrological cycle in the subtropics during the Holocene.

## Keywords

hydrological cycle, monsoon variability, solar variability, speleothems, Suess solar cycle, Sun–climate link

## Introduction

Reconstructions of past hydrological change in the northern subtropics indicate a pronounced drying trend during the Holocene, which has been attributed to orbitally induced lowering of Northern Hemisphere summer insolation during this interval (e.g. Haug et al., 2001). The decline in summer insolation is believed to have led to a gradual southward migration of the Intertropical Convergence Zone (ITCZ), which dominated millennial-scale changes in hydrology and monsoon activity in large parts of the Northern Hemisphere low-latitude region (Wanner et al., 2008). The Sun, however, does not only affect variations in hydrology and monsoon activity via long-term, orbitally induced insolation changes. Several studies suggest that actual variations in solar output also play a significant role in driving Holocene climate and monsoon variability (e.g. Cosford et al., 2008; Marchitto et al., 2010; Neff et al., 2001), as indicated by the presence of oscillations with periods similar to well-known solar cycles in Holocene speleothem  $\delta^{18}\text{O}$  records from e.g. China (Wang et al., 2005), Oman (Fleitmann et al., 2003; Neff et al., 2001), and the southwestern USA (Asmerom et al., 2007). More specifically, these speleothem  $\delta^{18}\text{O}$  data, which are believed to primarily reflect variations in the isotopic composition of precipitation (e.g. Lachniet, 2009), indicate that centennial-scale changes in the hydrological cycle were linked to solar variability. The reported correlations between solar activity and speleothem  $\delta^{18}\text{O}$  records have been subject to debate, however, partly because the speleothem  $\delta^{18}\text{O}$  data in several of these studies were tuned to the  $\Delta^{14}\text{C}$  signal within the uncertainties of the speleothem age models (Muscheler et al., 2004). Furthermore, it is arguably problematic to uniquely link periodicities in speleothem  $\delta^{18}\text{O}$  data of single

spectra spanning the entire Holocene interval to solar variability, because non-solar climate-forcing factors, such as ocean circulation processes, could oscillate with periodicities similar to those of the Sun.

The present study aims to extend and complement some of the above-mentioned studies that have detected well-known solar-cycle oscillations in speleothem  $\delta^{18}\text{O}$  records (e.g. Asmerom et al., 2007; Fleitmann et al., 2003; Neff et al., 2001; Wang et al., 2005). Our study takes advantage of recent findings showing that solar cycles, including the Gleissberg ( $\sim 88$  yr) and Suess ( $\sim 210$  yr) cycles, have changed amplitude dramatically on millennial timescales, with particularly prominent cyclic variations during certain parts of the Holocene, whereas the Sun's periodicity faded during other intervals (Knudsen et al., 2009). In particular, we investigate whether these variations in solar-cycle amplitude are also reflected in the spectral patterns of subtropical monsoon activity as should be expected if the two parameters are closely linked. We

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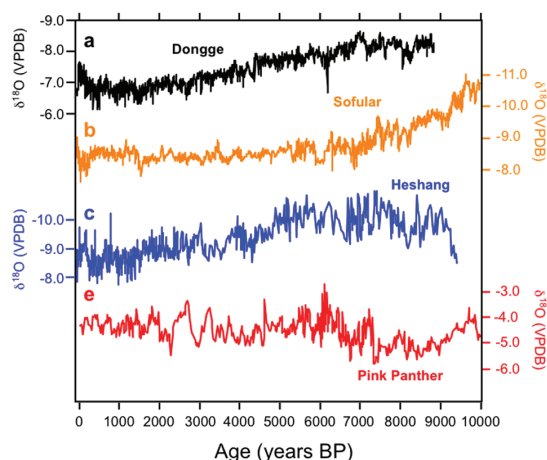
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**Figure 1.** Continuous, high-resolution speleothem  $\delta^{18}\text{O}$  records covering the last 8000 years or more. These include speleothem  $\delta^{18}\text{O}$  records from (a) Dongge Cave (China), (b) Sofular Cave (Turkey), (c) Heshang Cave (China), (d) Pink Panther Cave (southwestern USA). The records are ordered according to their average temporal resolution

focus mainly on the Suess  $\sim 210$  yr solar cycle, because this oscillation is commonly believed to be one of the most intense centennial-scale solar cycles (Raspopov et al., 2008), and because it has been identified in several subtropical monsoon records (e.g. Fleitmann et al., 2003; Wang et al., 2005). Particularly intense Suess solar-cycle bursts took place around 1850–3200 BP, 4500–5700 BP, and 7750–8850 BP (Knudsen et al., 2009). If the speleothem  $\delta^{18}\text{O}$  records show oscillations with comparable timing and frequency to the Suess solar-cycle bursts, these variations likely represent a solar fingerprint that is highly improbable to have been generated by other, non-solar processes.

## Holocene solar variability

Changes in the Holocene solar-cycle intensity have been reconstructed by combining  $^{14}\text{C}$  data from the IntCal04 radiocarbon calibration curve (Reimer et al., 2004) and  $^{10}\text{Be}$  data from the GRIP ice core (Vonnmoos et al., 2006) with a reconstruction of the geomagnetic dipole moment (Knudsen et al., 2008), and a quantitative model that links cosmogenic nuclide production rates to changes in the geomagnetic dipole moment and solar activity (Masarik and Beer, 1999). The two solar reconstructions show that the Suess solar cycle was particularly prominent during the following ‘burst’ intervals 1850–3200 BP, 4500–5700 BP, and 7750–8850 BP (Knudsen et al., 2009). The timing of the early Suess solar-cycle burst (7750–8850 BP) is primarily based on the

$^{14}\text{C}$  record, partly because the  $^{10}\text{Be}$  record from the GRIP ice core only extends back to 9315 BP. Further details are given in Knudsen et al. (2009).

## Holocene subtropical speleothem $\delta^{18}\text{O}$ records

Holocene changes in hydrology and monsoon activity in the subtropics can be reconstructed from measurements of  $\delta^{18}\text{O}$  in various geological archives. Speleothems in particular have proven to be excellent recorders of past monsoon variability (Overpeck and Cole, 2008), but speleothem  $\delta^{18}\text{O}$  records do not solely reflect changes in monsoon rainfall. Various factors, such as temperature, precipitation, seasonality, initial source composition, and transport pathways, all influence the final  $\delta^{18}\text{O}$  composition of speleothems (LeGrande and Schmidt, 2009). Variations in local environmental effects, such as evaporation and mixing in the cave environment (Lachniet, 2009), may also affect the  $\delta^{18}\text{O}$  signal during speleothem growth and thus introduce a varying degree of noise into the climate record (Lachniet, 2009; Overpeck and Cole, 2008). In this study, we focus on continuous speleothem records with no major growth hiatuses, that have an average temporal resolution better than 25 years (Figure 1). The selected records must additionally have been shown to be sensitive to variations in the hydrological cycle in subtropical regions over the past 8000 years or more (see Table 1 for further details).

The selected data include speleothem  $\delta^{18}\text{O}$  records from Dongge Cave in China (Wang et al., 2005), Sofular Cave in Turkey (Fleitmann et al., 2009), Heshang Cave in China (Hu et al., 2008) and Pink Panther Cave in the southwestern USA (Asmerom et al., 2007) (see Table 1). The  $\delta^{18}\text{O}$  record from Dongge Cave was originally interpreted to reflect changes in seasonality, i.e. summer-to-winter precipitation ratio, and amount of precipitation (Wang et al., 2005). Hu et al. (2008) subsequently used the proximity of Heshang Cave to Dongge Cave to quantify past changes in absolute rainfall by arguing that the difference between the two  $\delta^{18}\text{O}$  records must be due to moisture loss along the atmospheric transport pathway between the two cave systems. Overall, the two individual  $\delta^{18}\text{O}$  speleothem records from SE China are dominated by changes in the transport and loss of moisture associated with the Asian summer monsoon system, as less than 20% of the annual precipitation falls during the winter (Hu et al., 2008). A recent model study suggests that long-term changes in the  $\delta^{18}\text{O}$  composition of rainfall in SE China are actually not dominated by changes in local precipitation, but rather the transport of water vapour onto China from the Pacific, which strongly correlates with millennial-scale changes in  $\delta^{18}\text{O}$  in this region (LeGrande and Schmidt, 2009). The speleothem  $\delta^{18}\text{O}$  record from Pink Panther cave in New Mexico, USA, is believed to mainly reflect changes in the balance between summer and winter precipitation

**Table 1.** Overview of the four speleothem climate-proxy records included in this study

Record	Region	Latitude	Longitude	Proxy	Resolution <sup>a</sup> (yr/sample)	Radiometric ages <sup>b</sup>	Reference
Dongge Cave	E. China	25°17'N	108°05'E	$\delta^{18}\text{O}$	$\sim 4$	45 (U/Th)	Wang et al. (2005)
Sofular Cave	Turkey	41°25'N	31°56'E	$\delta^{18}\text{O}$	$\sim 5$	33 (U/Th) <sup>c</sup>	Fleitmann et al. (2009)
Heshang Cave	E. China	30°27'N	110°25'E	$\delta^{18}\text{O}$	$\sim 8$	21 (U/Th)	Hu et al. (2008)
Pink Panther Cave	New Mexico	33°53'N	104°51'W	$\delta^{18}\text{O}$	$\sim 19$	22 (U/Th)	Asmerom et al. (2007)

<sup>a</sup>Average sample resolution for the last 10 kyr.

<sup>b</sup>Number of radiometric dates and dating method type (in parentheses).

<sup>c</sup>The number quoted for Sofular Cave refers to the Holocene portion of the 50 kyr long record.

and, to a certain degree, changes in the amount of rainfall (Asmerom et al., 2007). From July to December, rainfall in this area is dominated by the North American monsoon, transporting moisture from the Gulf of Mexico into the southern USA, whereas winter precipitation is derived from westerly low-pressure systems from the Pacific Ocean. According to Fleitmann et al. (2009), centennial-scale changes in the  $\delta^{18}\text{O}$  record from Sofular cave most likely reflect variations in temperature and seasonality of precipitation, whereas millennial-scale changes are believed to reflect variations in the  $\delta^{18}\text{O}$  of Black Sea surface water.

The age models associated with two of the speleothem records (Dongge Cave and Pink Panther Cave) were tuned to the IntCal98  $\Delta^{14}\text{C}$  record (Stuiver et al., 1998) within the uncertainties of the  $^{230}\text{Th}$  ages used to construct the speleothem chronologies. For these two speleothems, we use the tuned age models that were also used in the original studies of monsoon variability (see supplementary material for detailed information on the age models, available online). Note that two separate Holocene  $\delta^{18}\text{O}$  records have been published from Dongge Cave in China (Dyskoski et al., 2005; Wang et al., 2005). The two records have a similar overall structure, but show some differences in detail. In this study, we focus on the record from stalagmite DA (Wang et al., 2005), which has a higher resolution and features a more uniform growth rate.

## Methods

The Holocene speleothem  $\delta^{18}\text{O}$  records were first detrended using a polynomial of degree 20 to suppress spectral leakage from low-frequency variations ( $\sim 1000$  yr and longer periods). Subsequently, the data were grouped in overlapping 2000 yr Welch-type windows, with a spacing of 50 years, before calculating the spectrum and associated red-noise false-alarm levels for all individual windows (Figure 2a). A window size of  $\sim 2000$  years was chosen to obtain optimal balance between spectral smoothing and temporal resolution, but the application of such a window renders it impossible to obtain estimates for the first and last  $\sim 1000$  years of the records. Since good spectral resolution is essential for this study, the method was optimized through various tests to provide the highest possible spectral resolution without significantly compromising the temporal resolution. The spectrum associated with each 2000 yr data window was estimated using the Lomb-Scargle Fourier transform (Lomb, 1976; Scargle, 1982) for unevenly spaced data combined with a Welch parabolic weight function. The univariate spectra were then bias-corrected using 1000 Monte-Carlo simulations. This was done by use of the publicly available program REDFIT (Schulz and Mudelsee, 2002), which was also used to calculate red-noise false-alarm levels based on a first-order auto-regressive (AR1) model. All the individual spectra were then aligned according to their age, given by the mid-point of the time window, and the frequencies for which the spectral power exceeded the red-noise false-alarm levels (90%, 95%, and 99%) were color-coded (Figure 2a). A schematic example of this approach is shown for the Heshang record, depicting how the periodogram (Figure 2a) is composed of individual spectra for data included in the 2000 yr time windows (Figure 2b and c). Finally, we ensured that the data could be adequately approximated by an AR1 model. This approach relies on the same methods used in numerous earlier paleoclimatological studies to evaluate the statistical significance of spectral peaks (e.g. Asmerom et al., 2007; Fleitmann et al., 2003; Knudsen et al., 2011). Other studies have employed wavelet transforms to extract time-varying spectra of climate proxy records (e.g. Cosford et al., 2008; Debret et al., 2009). We have compared time-varying spectra, based on overlapping Welch windows, to wavelet spectra

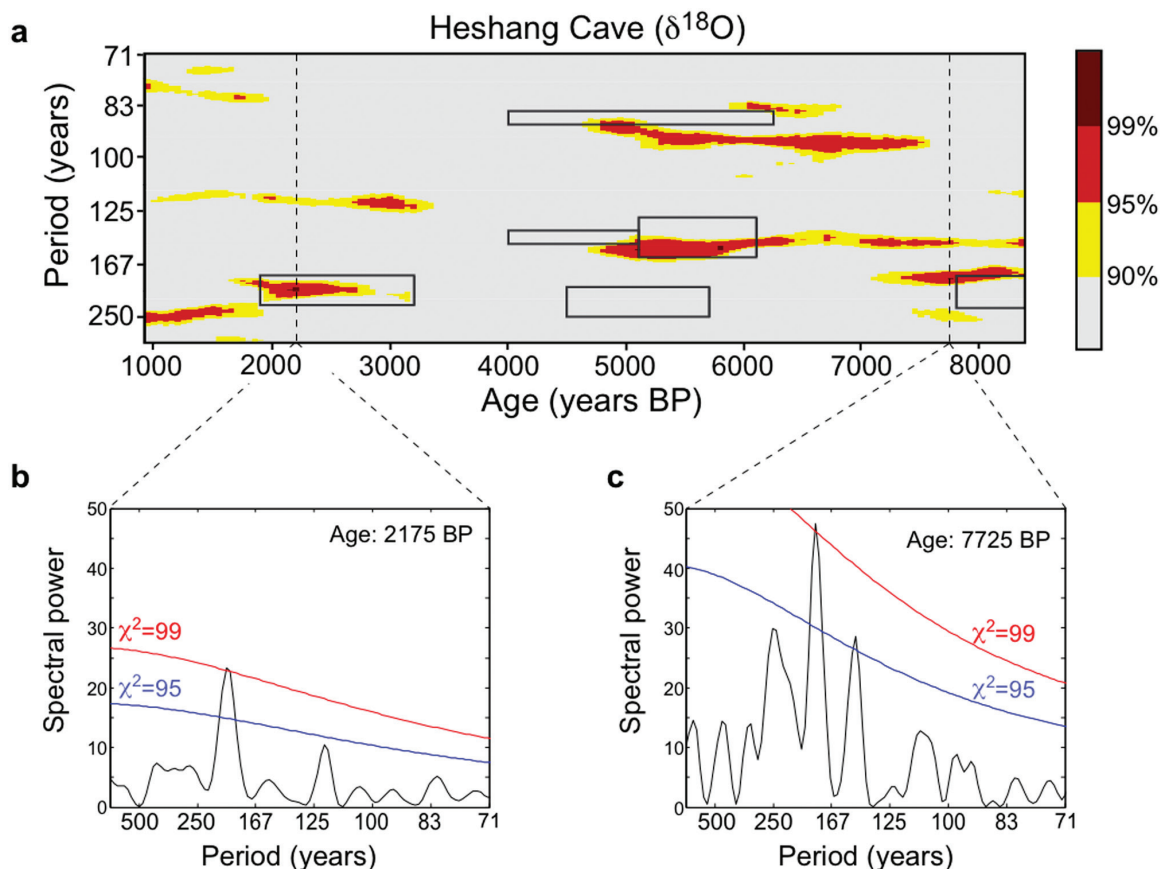
based on Morlet mother wavelets. The results (not shown here) demonstrate that different choices of Welch-window lengths and wavelet-duration parameters lead to very different appearances for both the Welch-window spectra and wavelet spectra, respectively, but for suitably chosen pairs of window length and duration parameter the two types of spectral estimates are almost indistinguishable. We are therefore quite confident that our results would also be reproduced under other approaches to spectral estimation.

## Results and discussion

The results of the spectral analysis of the four paleo-precipitation proxy records are presented in Figure 3. The tuned Dongge Cave record (Figure 3a), with a temporal resolution of  $\sim 4$  years, shows intervals characterized by highly significant  $\sim 210$  yr cycles that almost exactly coincide with the three Holocene Suess solar-cycle bursts (Figure 3e). Similarly, the untuned Sofular record (Figure 3b), characterized by a  $\sim 5$  year temporal resolution, appears to have recorded all three Suess solar-cycle bursts, although less clearly so for the most recent 1850–3200 BP burst. The two remaining records from Heshang Cave (untuned) and Pink Panther Cave (slightly tuned) (Figure 3c and d), which have temporal resolutions of  $\sim 8$  and  $\sim 19$  years, respectively, did not record all three Suess solar-cycle bursts. Nevertheless, significant spectral power with periods similar to  $\sim 210$  yr are present for the first and the third Suess solar-cycle bursts in the Heshang record (Figure 3c), and for the second Suess solar-cycle burst in the Pink Panther record (Figure 3d), whereas little or no spectral power is recorded outside the Suess solar-cycle burst intervals.

Spectral analyses of the untuned  $\delta^{18}\text{O}$  record from Dongge Cave reveal a pattern that resembles the pattern observed for Heshang Cave, with some additional evidence for significant oscillations overlapping the second Suess burst (see supplementary material). For Dongge Cave, tuning of the age model therefore results in more significant  $\sim 200$  yr oscillations overlapping the second Suess burst and frequencies that become perfectly aligned with the frequency of the Suess cycle. Although the  $\delta^{18}\text{O}$  record from Dongge Cave was not tuned specifically to the Suess solar cycle, the effect of tuning represents a kind of ‘best case’ scenario. Even so, it is remarkable how well the significant  $\sim 210$  yr oscillations in the tuned Dongge record match the Suess bursts after only subtle tuning of the age model within the  $^{230}\text{Th}$  age uncertainties (see supplementary material, available online). For any given solar influence, a speleothem  $\delta^{18}\text{O}$  age model based on linear interpolation between radiometric age constraints is likely to suppress the solar influence, because age model uncertainties, along with local cave processes during speleothem growth, are likely to obscure the recording of periodic climate signals. To a certain degree, the tuning process can be regarded as a recovery of the solar imprint on the  $\delta^{18}\text{O}$  record, but a recovery that potentially exaggerates the solar influence. The true solar influence on the Dongge  $\delta^{18}\text{O}$  record probably lies somewhere between that suggested by the untuned record (Figure S3a, available online) and that observed for the tuned age model (Figure 3a). It is impossible to evaluate the effect of age-model tuning for the Pink Panther  $\delta^{18}\text{O}$  record, because the tuning method and the untuned age model are unavailable.

Considering the potential problems related to age model uncertainties, as well as the list of factors that potentially could dominate or overshadow any inherent solar-induced centennial-scale variations, it is, in fact, remarkable that all four records have spectral density distributions with highly significant cyclicities that coincide with the Suess solar-cycle bursts (Figure 3). In particular, we note that all three Suess solar-cycle bursts appear to



**Figure 2.** An example of the method used to estimate distributions of spectral significance for the climate proxy records. (a) Temporal distribution of spectral power that exceeds the red-noise false-alarm levels for the  $\delta^{18}\text{O}$  record from Heshang Cave, China, between 1000 and 9000 yr BP. The colour coding indicates that the spectral power exceeds the 90%, 95%, and 99% false-alarm levels, respectively. (b) An example of the spectral power distribution calculated for a 2000 yr data window centred at 2175 BP, and (c) the spectral power distribution of a 2000 yr window centred at 7725 BP. The blue and red lines in (b) and (c) denote the 95% and 99% red-noise false-alarm levels. The black rectangles in (a) denote the timing and periodicity of the most pronounced solar-cycle activity during the Holocene (Knudsen et al., 2009). Note how the occurrence of statistically significant oscillations in the Heshang  $\delta^{18}\text{O}$  record tends to coincide with the most pronounced solar-cycle activity

have been recorded in the tuned speleothem  $\delta^{18}\text{O}$  record from Dongge Cave and the untuned speleothem  $\delta^{18}\text{O}$  record from Sofular Cave.

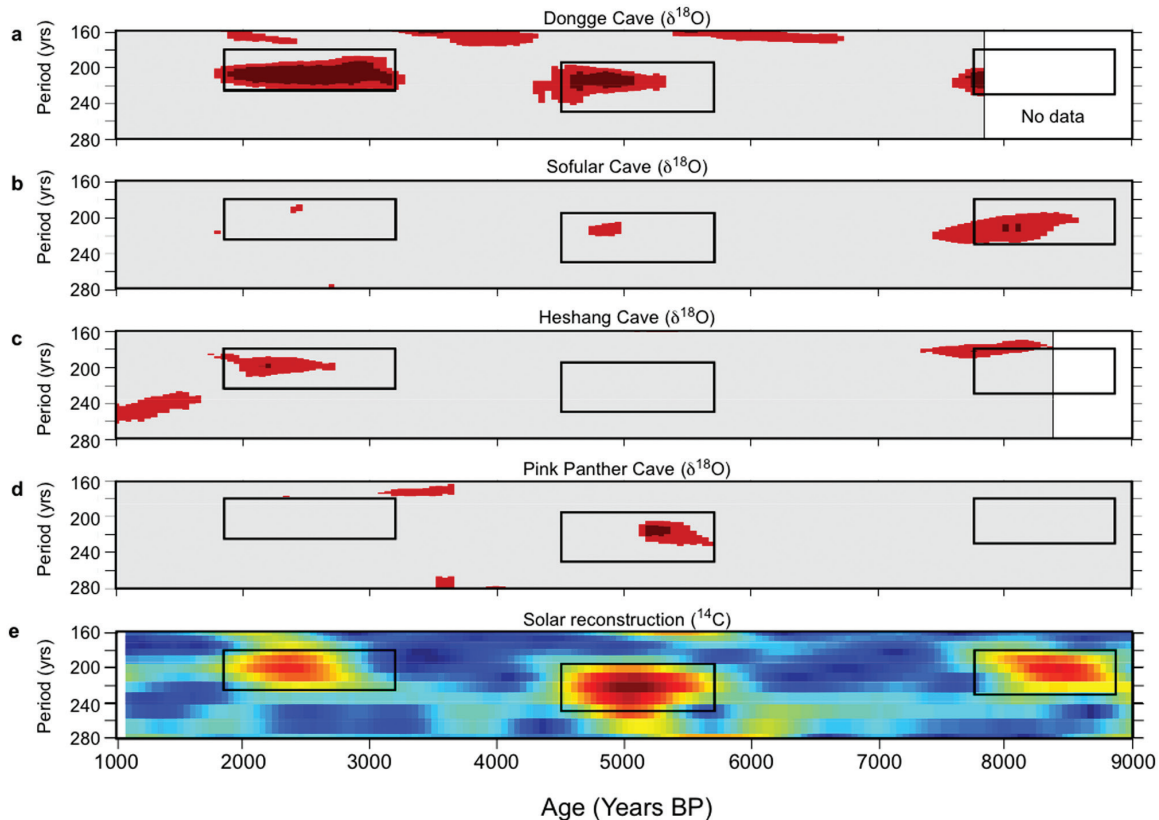
#### *Solar influence on subtropical speleothem $\delta^{18}\text{O}$ records*

Two of the proxy records included in this study have previously been used to discuss solar–climate links, namely the records from Dongge Cave (Figure 3a; Wang et al., 2005) and Pink Panther Cave (Figure 3d; Asmerom et al., 2007). Our study lends additional and independent support to the original claim that solar variability played a significant role in driving centennial-scale variations in monsoon variability recorded in these speleothem records. The two other proxy records have not previously been linked to solar variability, i.e. the Sofular record from Turkey (Figure 3b; Fleitmann et al., 2009) and the Heshang record from China (Figure 3c; Hu et al., 2008). Since neither of these two  $\delta^{18}\text{O}$  records has been tuned to IntCal98, good correlation with solar variability cannot represent an artefact of tuning the speleothem age models. Based on our results, it therefore seems highly plausible that the Holocene centennial-scale climate variability recorded by speleothems from both the Sofular and Heshang caves was influenced by the Suess solar cycle. It is notable that

the observed relationship with solar variability for the two Asian monsoon records from Dongge Cave and Heshang Cave was opposite to that observed in the southwestern USA.

Solar variability may influence climate through various direct and indirect processes. Although changes in the Total Solar Irradiance (TSI) are relatively small ( $\sim 0.07\%$  over the 11 yr cycle; Gray et al., 2010), they may influence climate via changes in large-scale circulation patterns, such as the strength of the Hadley and Walker circulation. Changes in the UV spectrum of solar irradiance, which may be more than an order of magnitude larger than changes in the TSI ( $\sim 6\%$  near 200 nm over the 11 yr solar cycle), significantly modify the ozone production through photolysis of molecular oxygen with considerable impact on temperature and circulation patterns in the stratosphere (Haigh, 1994). Solar heating of the stratosphere, termed the ‘top-down’ effect, is believed to result in strengthened tropical convection and a poleward-shifted Intertropical Convergence Zone (ITCZ) during solar maxima (Meehl et al., 2008). The ‘top-down’ effect (Lockwood et al., 2010) appears to add to the ‘bottom-up’ effect, based on solar heating of the sea surface, to produce an amplified SST, precipitation, and cloud response in the tropical Pacific to relatively small changes in solar activity (Gray et al., 2010; Meehl et al., 2009; Rind et al., 2008). The inertia and slow feedback





**Figure 3.** Evidence of Suess solar-cycle bursts in subtropical speleothem  $\delta^{18}\text{O}$  records between 1000 and 9000 yr BP. Spectrograms delineating the temporal distribution of highly significant (red:  $\chi^2 > 95\%$  and dark red:  $\chi^2 > 99\%$ ) spectral power of speleothem  $\delta^{18}\text{O}$  records from (a) Dongge Cave, China, (b) Sofular Cave, Turkey, (c) Heshang Cave, China, and (d) Pink Panther Cave, Southwestern USA. (e) Distribution of spectral power for a  $^{14}\text{C}$ -based solar reconstruction (Knudsen et al., 2009). The black rectangles delineate the prominent bursts in amplitude of the Suess (~210 yr) solar cycle, which, except for the burst around 7750–8850 BP, are based on both  $^{14}\text{C}$  and  $^{10}\text{Be}$ . The white zones at the old end of the Dongge and Heshang records denote intervals from which data are unavailable

mechanisms of the climate system generally imply that long-term changes in solar activity may have had a relatively large impact on climate compared to short-term changes (Gray et al., 2010).

Of particular relevance to this study, it has recently been shown that the Walker circulation strengthened during solar maxima with enhanced upward motion in the troposphere over the tropical western Pacific and stronger downward motion over the tropical eastern Pacific (Gleisner and Thejll, 2003). This is in accord with observations of high SSTs and El Niño-like (warm) conditions off the west coast of Baja California, Mexico, during millennial-scale solar minima (Marchitto et al., 2010). This seesaw pattern between the western and eastern parts of the Pacific may potentially explain the apparently opposite relationship between solar activity and speleothem  $\delta^{18}\text{O}$  in SE Asia and southwestern USA, respectively. Times of high solar activity may thus have been associated with a northwardly displaced ITCZ, a strengthened Walker circulation, increased precipitation over the western tropical Pacific, and a decrease in precipitation over the eastern Pacific. This, in turn, may also have influenced land-to-sea contrasts and the balance between summer and winter precipitation. We conjecture that the Suess solar cycle mainly influenced changes in monsoon activity through modulation of the ITCZ and the Walker circulation, and that this influence was particularly strong during the three Suess solar-cycle bursts. However, the influence of the Suess solar cycle was not equally strong, or detectable, throughout the three Suess bursts. We hypothesize that orbitally induced changes in solar insolation, which are known to

have shifted the location of the ITCZ southwards during the Holocene (Haug et al., 2001), may have influenced, or modified, the link between solar variability, Walker circulation, and changes in the hydrological cycle recorded in SE Asia and southwestern USA. This could potentially explain why no significant ~210 yr oscillations are observed in the Pink Panther record during the first burst in Suess solar cycle activity (7750–8850 BP).

## Conclusions

This study presents the first observation of Suess solar-cycle bursts recorded in Holocene paleoclimate proxy data. In particular, we demonstrate that subtropical changes in the hydrological cycle during the Holocene in some regions resembled the non-stationary Suess solar-cycle pattern with respect to the periodicity and timing of significant ~210 yr oscillations (Figure 3). The fact that the Suess solar-cycle bursts are observed in the four selected subtropical speleothem records strongly support the suggestion that parts of the centennial-scale changes in hydrology and monsoon activity in these regions have a solar origin. These observations may contribute to our understanding of the complex mechanisms through which solar variability modulates the climate system, a link that may be underestimated in current general circulation models (e.g. Marchitto et al., 2010).

Suess solar-cycle bursts represent an interesting fingerprint for further studies of the link between solar activity and past climate variability recorded in geological archives, given that spectral

patterns similar to the Suess solar-cycle bursts are highly unlikely to be generated by non-solar processes. The general approach outlined in the present study may therefore furnish a strong test of the Sun–climate link applicable to high-resolution Holocene climate proxy data.

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