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Correspondence and requests for materials should be addressed to Y.J.W. (yjwang@njnu.edu.cn)

* Current address: College of Geography Science, Nanjing Normal University, No. 1 Wenyuan Road, Nanjing 210023, China.

Evidence for solar cycles in a late Holocene speleothem record from Dongge Cave, China

Fucai Duan[1], Yongjin Wang[1]*, Chuan-Chou Shen[2], Yi Wang[3], Hai Cheng[4,5], Chung-Che Wu[2], Hsun-Ming Hu[2], Xinggong Kong[1], Dianbing Liu[1] & Kan Zhao[1]

[1]College of Geography Science, Nanjing Normal University, Nanjing 210023, China, [2]High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, [3]Department of Geography, School of Global Studies, University of Sussex, Brighton BN1 9QJ, UK, [4]Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an 710049, China, [5]Department of Geology and Geophysics, University of Minnesota, Minneapolis MN 55455, USA.

The association between solar activity and Asian monsoon (AM) remains unclear. Here we evaluate the possible connection between them based on a precisely-dated, high-resolution speleothem oxygen isotope record from Dongge Cave, southwest China during the past 4.2 thousand years (ka). Without being adjusted chronologically to the solar signal, our record shows a distinct peak-to-peak correlation with cosmogenic nuclide ^{14}C, total solar irradiance (TSI), and sunspot number (SN) at multi-decadal to centennial timescales. Further cross-wavelet analyses between our calcite $\delta^{18}O$ and atmospheric ^{14}C show statistically strong coherence at three typical periodicities of ~80, 200 and 340 years, suggesting important roles of solar activities in modulating AM changes at those timescales. Our result has further indicated a better correlation between our calcite $\delta^{18}O$ record and atmospheric ^{14}C than between our record and TSI. This better correlation may imply that the Sun–monsoon connection is dominated most likely by cosmic rays and oceanic circulation (both associated to atmospheric ^{14}C), instead of the direct solar heating (TSI).

The decadal to centennial changes in AM during the Holocene are considered to be influenced by a wide range of factors, such as global surface temperature[1], ENSO[2], ice-rafted events[3,4], snow cover[5] and solar activity[6,7]. Among those factors, the solar influence has been intensively studied because of its relative importance as compared with other forcing mechanisms. Previous studies have shown that at decadal to centennial timescales, monsoon changes could be sensitive to relatively weak solar signals (e.g., 0.1–0.3% variations in solar output)[3,6,7]. This conclusion was also supported by modeling results[8].

The evidence for solar–monsoon connection, however, remains a subject of debate, primarily due to the following uncertainties and limitations. First of all, dating uncertainties for proxy monsoon records usually prevent a precise correlation with tracers of solar activities. A good correlation between the monsoon and solar activity was often obtained by adjusting the chronologies of monsoon proxies to solar signals (e.g., cosmogenic nuclides) at decadal to centennial timescales[3,6,7]. However, this approach was claimed not to produce effective evidence for the solar forcing hypothesis, partly because of the dependence of a statistic assessment on the chronology adjustment[9]. Secondly, noises in monsoon reconstructions likely conceal the record of solar signals. For example, different stalagmite $\delta^{18}O$ data from the same cave[10] may contain different signals. Different caves[3,11], although locating on the same moisture transportation pathway[11], may produce different stalagmite $\delta^{18}O$ data. The inconsistence among the cave records may be due to different flow-through times, mixing-up conditions in the epi-karst, and other contingent factors. Thirdly, the strength of correlation may be dependent on selections of timescales and/or the proxy data for solar activity. For example, at millennial scales, the similarity between our Dongge Cave record and TSI[12] is better than that between our record and atmospheric ^{14}C (ref. 3), at centennial scales. Finally, other competing forcing factors may dampen solar signals. As suggested in a speleothem record from Oman[7], the influence of the solar forcing on the monsoon did not begin to surpass the influence of the glacial boundary conditions until after the middle Holocene.

Previously-published records from Dongge Cave, southwest China, have provided some clues to the Sun–monsoon connection over the period of the Holocene[3,13]. The wiggled match of those records indicates that some, but not all, of the monsoon changes at decadal-to-centennial timescales were associated with solar forcing

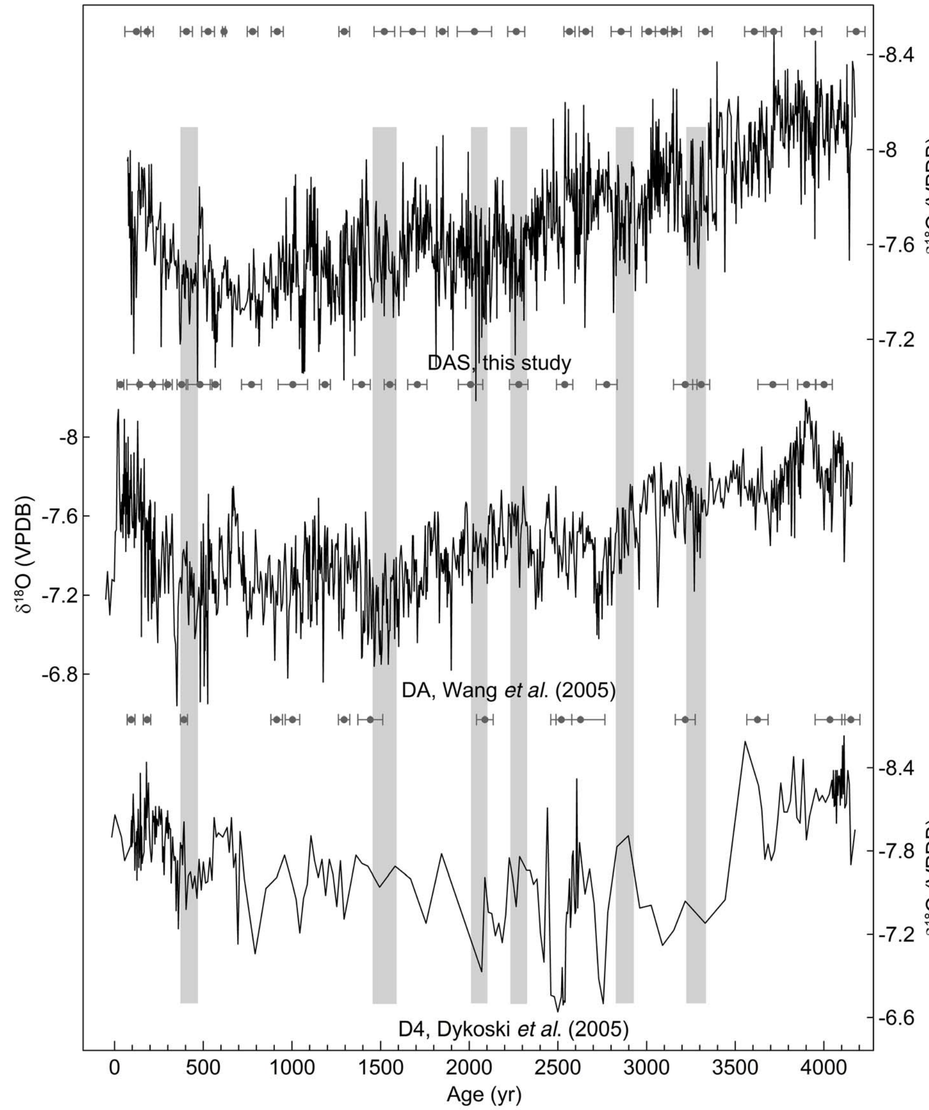

Figure 1 | Inter-comparison of stalagmite $\delta^{18}O$ records from Dongge Cave, China during the late Holocene. The DA record is from ref. 3, while the D4 record is from ref. 13. Black dots with horizontal error bars are MC-ICPMS U-Th ages (Table S1). Vertical gray bars denote the periods of weak monsoon events.

changes. Given the uncertainties in the chronology adjustment of the calcite data to the solar signal[9] and other non-climatic signals associated with site-specific karstic processes, it is therefore necessary to use a new speleothem record from the same cave to further study the Sun–monsoon connection. Here we focus on monsoon changes of the late Holocene at centennial timescale, which could be an ideal time window for testing the Sun–monsoon connection. This is mainly because of the dominated centennial-scale solar cycles in both the tree-ring ^{14}C (ref. 14) and most of published monsoon records[15]. In addition, at the centennial timescale, age uncertainties in speleothem records are usually on the order of a few decades, which have less significant influences on the wiggled match. Finally, during the late Holocene, the glacial boundary condition was relatively stable[16], which also imposed some minimum influences on the Sun-monsoon connection.

Results

Dongge Cave (25°17′N, 108°5′E, Elevation 680 M; Supplementary Fig. S1), as previously reported by Wang *et al.* (2005)[3], is climatically influenced by the AM system, featuring warm and humid summer, and cold and dry winter. The average annual precipitation is 1753 mm, 80% of which occurs during the rainy season (May–October). The annual mean temperature and relative humidity inside the cave are 15.6°C and >90%, respectively. Our new stalagmite (marked as DAS), growing close to previous stalagmite DA[3], is 590 mm long, and consists of less contaminated calcite.

Twenty-four ^{230}Th dates are established in a stratigraphic order within uncertainties (2σ) ranging from 8–97 yr (Supplementary Table S1). The age model is determined using the StalAge algorithm[17], which has a mean systematic uncertainty of ~40 yr (Supplementary Fig. S2). As shown in Figure 1, the stalagmite grew from 4,200 to 70 yr before present (before AD 1950). A total of 1,178 oxygen isotope analyses were carried out, with an average temporal resolution of 3.5 yr. Chinese stalagmite $\delta^{18}O$ time series was suggested to be either related to the strength of summer monsoon circulation[3], or to indicate changes in the area-averaged monsoon precipitation[18]. Normally, the smaller stalagmite $\delta^{18}O$ values correspond to stronger monsoon, and vice versa. Although recently being argued widely[19,20], this interpretation was supported strongly by a recent modeling study[21].

The DAS $\delta^{18}O$ record varies from −8.51‰ to −6.94‰, with an average value of −7.69‰ (Fig. 1). The $\delta^{18}O$ time-series shows a long-term increasing trend, broadly following the Northern Hemisphere summer insolation (Supplementary Fig. S2). The monsoon indicated by the DAS record has intensified significantly during the last 0.5 ka, which is also in good agreement with other records from the same cave[3] and from caves located in southwestern China and southern Oman[22]. Superimposed on the long-term trend are a series of multi-decadal to centennial timescale monsoon events that are reflected by a substantial variation of $\delta^{18}O$ of more than 0.5‰. However, all these events do not show a strong correlation with those among the DA[3] and D4[13] records from the same cave (Fig. 1). Based on a combination of our high resolution DA and DAS records, we have identified six joint major intervals of the weakest summer monsoon at ~0.4, 1.5, 2.1, 2.3, 2.9 and 3.3 ka, considering their age uncertainties (gray bars in Fig. 1). For example, the events at 2.1 and 2.9 ka in the DA are ~100 yr younger than those in the DAS, while the event at 2.3 ka is ~100 yr older in the DA than in the DAS. This discrepancy may be due to two potential factors: 1) different age constraints and dating uncertainties between the two records, and 2) different noise levels, which may be caused by a wide range of hydrological processes (e.g., different moisture transport pathways, residence times of seepage water). For the D4 record, substantially varying growth rates and generally low temporal resolution may be the most important factors responsible for its significant mismatch from the DA and DAS records. Currently, there are few completely identical speleothem $\delta^{18}O$ time series varying at multi-decadal to centennial timescales during the Holocene. Therefore, it is necessary for us to understand to what extent the two high-resolution $\delta^{18}O$ records vary in the same manner at those timescales. This evaluation is of great importance to our following study of the Sun–monsoon connection.

We have employed three solar parameters: atmospheric ^{14}C (ref. 14), SN[23], and TSI[12], to evaluate the Sun–monsoon connection. The SN and TSI data were derived, respectively, from ^{14}C reconstruction from tree rings, and a combination of the tree-ring ^{14}C and ^{10}Be data from ice cores. Nevertheless, the time series of atmospheric ^{14}C, SN and TSI differ significantly at centennial timescales, representing different aspects of solar activities[24]. The variations in TSI are regulated by the combined effect of dark sunspots and bright faculae, accounting for the bulk of the Sun's total magnetic flux. On the other hand, the variations in atmospheric ^{14}C are produced by terrestrial fluxes of cosmic rays that are governed by a relatively small fraction of the Sun's total magnetic flux extending into the heliosphere. Using these inherently different solar proxies, we can examine how the Sun exerts its influences on the monsoon changes.

In order to compare centennial-scale changes between time series of our monsoonal proxies and solar activities, all data were detrended using singular spectrum analysis. The detrended and 11-point smoothed DAS $\delta^{18}O$ anomaly ($\Delta^{18}O$) shows strong correlations to the time series of the detrended atmospheric ^{14}C anomaly ($\Delta^{14}C$)[14], ΔSN[23] and ΔTSI[12] at centennial timescales (Fig. 2). The Pearson correlation coefficients between them are 0.41, −0.36 and −0.28 (n = 153), respectively. Compared with previous studies for the Holocene solar–monsoon connection[3,4,7,12], our new data provide additional and robust evidence for the solar forcing. Firstly, without any chronological tuning, the majority of $\Delta^{18}O$ variations show a peak-to-peak correspondence with those in the solar data. Secondly, there is a striking similarity in both pattern and transition of major events between the monsoon and the Sun, indicating a dominated control of solar forcing in centennial-scale monsoon changes. Thirdly, our $\Delta^{18}O$ record mirrors the $\Delta^{14}C$ record generally over the whole time series, suggesting a broadly linear response of monsoons to changes in the solar forcing.

A further wavelet analysis of our $\Delta^{18}O$ data produces three statistically significant periodicities (>95% confidence level) at ~80 yr (Gleissberg cycle[14]), ~200 yr (Suess or deVries cycle[14]), and ~340 yr (unnamed[12]) (Fig. 3a). The Gleissberg cycle is persistent in the entire record. The Suess cycle is pronounced over the episode from 1.8 to 2.8 ka, while the periodicity of ~340 yr is dominated over the episodes from 2.9 to 3.5 ka and from 1.2 to 1.5 ka. These cycles correspond to those well-known from ^{14}C (ref. 25, Fig. 3b), ^{10}Be (ref. 25), and TSI[12]. The feature of these three common cycles is demonstrated also by a cross-wavelet spectrum analysis between our $\Delta^{18}O$ data and $\Delta^{14}C$ records (Fig. 3c). However, the distribution of these periodicities is not completely identical to that of the $\Delta^{14}C$ (Fig. 3b). We suggest that this discrepancy could be mainly due to the different age models, and other factors that may influence the AM changes.

Generally, our new and previous[3] Dongge Cave records show pronounced correlations to solar tracers at multi-decadal to centennial scales during the late Holocene. However, some minor mismatches are found between each of the two calcite records and the solar tracers in a few episodes. Given the high temporal resolution and intensive age constraint of our two records, we could afford to make some detailed inter-comparison between them during those mismatching periods. This inter-comparison may help us confirm the Sun-monsoon connection. Figure 2a shows the discrepancies between our two $\Delta^{18}O$ time series (marked by gray bars). Our DAS $\Delta^{18}O$ shows two substantially downward shifts relative to the previous DA record at 2.55 and 1.10 ka. Also, a lead-lag relationship is observed over the periods centered at 3.36, 1.60, 1.36 and 0.60 ka (Fig. 2a). However, at those periods of discrepancy, either the DAS or DA record shows a good correspondence to three solar tracers. For example, a good resemblance to solar records is observed in the DA, but not in the DAS record during the aforementioned four periods. In contrast, at 2.55 and 1.10 ka, a good resemblance to solar records is observed in the DAS, but not in the DA. Therefore, a combination of our DA and DAS records could compensate the discrepancy and support our study of Sun-monsoon connection. On the other hand, the uncertainties in solar parameters should be considered for evaluating the Sun–monsoon connection. The uncertainties in ^{14}C (ref. 14) and SN[23] are so small that their records of solar activities are quite reliable. Notable are the substantial uncertainties in the TSI[12]. However, its good overall resemblance to the DA record reveals its potential to measure the solar radiation confidentially[12]. Taken together, a combination of the reliable solar tracer and repeatedly-calibrated Dongge record provides convincing evidence for the Sun–monsoon connection.

Discussion

Processes for the solar–monsoon connection could be inferred from the spatial and temporal features of worldwide geological data recording solar activities. The three centennial-scale solar cycles (80, 200 and 340 yr) derived from our DAS record were also observed in many other monsoon proxies, such as two other stalagmites from the Dongge Cave[3,13], and other paleoclimatic records far away from our cave[4,7,15,22,26,27]. Therefore we may consider these solar cycles to be ubiquitous[28–30]. On the other hand, these solar cycles were also found during the last deglaciation, including the Ållerød interstadial[31] and Younger Dryas stadial[32], the marine isotope stage 3 (ref. 33), and earlier epochs up to hundreds of millions years ago[34]. The persistent presence of these solar cycles and their connections with monsoon records over a wide range of regions highlight the dominated solar control of the monsoon at centennial timescales. The persistence of these different periodicities also indicates that the influence of the low-frequency solar activity on the AM is independent of other climate backgrounds, such as ice volumes, orbital configurations, and concentrations of major greenhouse gases. The pronounced influence of the centennial-scale solar activities may, therefore, be amplified by some mechanism that has a global influence. The centennial-scale cycles have been suggested to be related to changes in the ocean component of the Earth's climate system[35–37]. The small solar variations could be amplified by ocean salinity

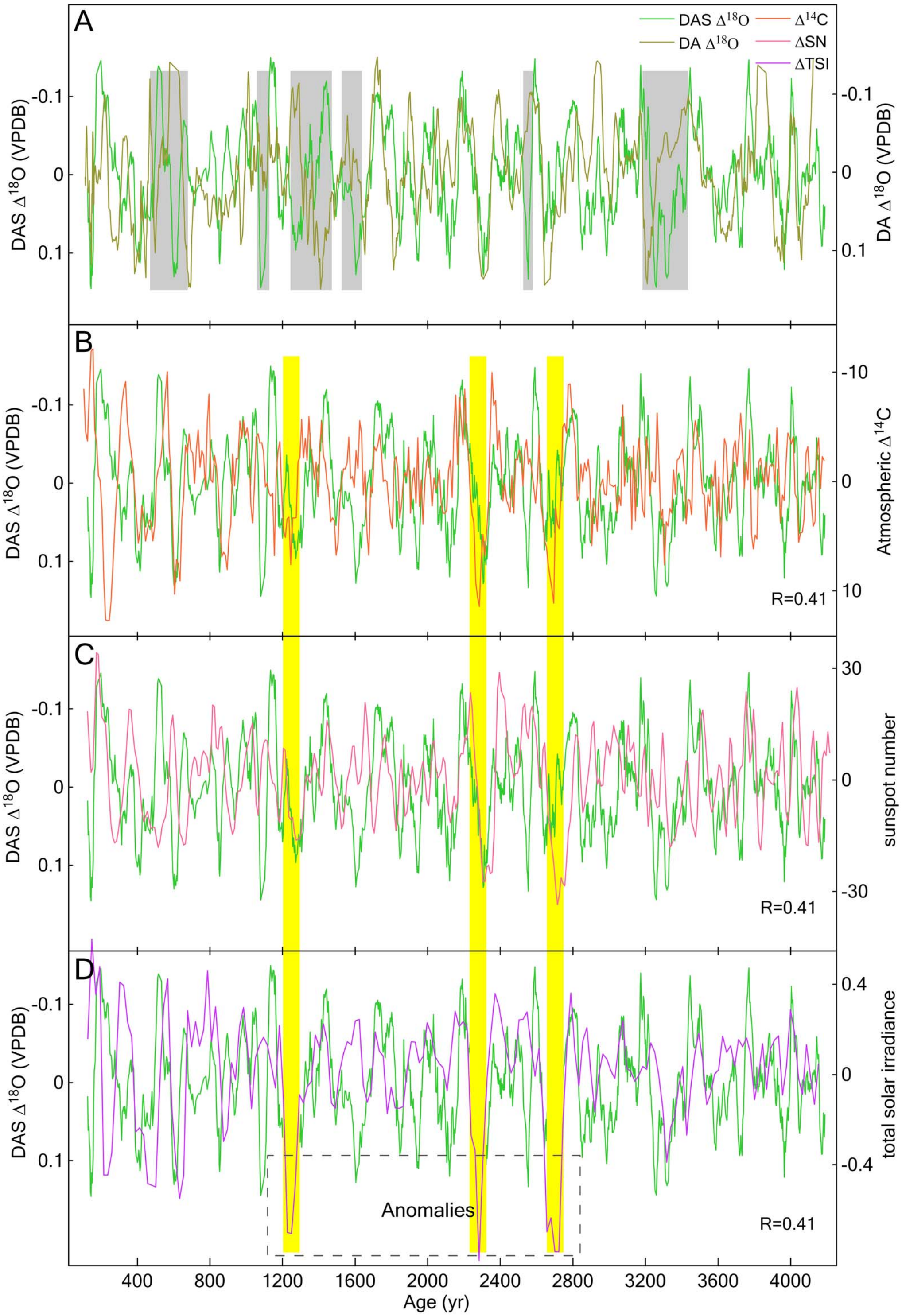

Figure 2 | Inter-comparison between Dongge Cave $\Delta^{18}O$ isotopic data and solar activity proxies. The DAS $\Delta^{18}O$ record (green) is plotted against the records of DA $\Delta^{18}O$ (grey, A), $\Delta^{14}C$ (orange, B), ΔSN (pink, C) and ΔTSI (purple, D). For the best correlation of two datasets, the chronology for the DAS record has been shifted older by 40 years and the one for the DA record younger by 47 years. Intensive solar activity (smaller $\Delta^{14}C$, larger ΔSN and ΔTSI) corresponds to a strong AM (smaller $\Delta^{18}O$). Vertical yellow bars indicate the weakest solar activity.

changes in the North Atlantic, which then transmit the signals globally through the North Atlantic deep water formation and thermohaline circulation. The importance of centennial solar cycles in the North Atlantic is supported by a close correlation between ^{14}C and ^{10}Be, and the amount of ice-rafted debris in deep-sea sediment cores[38]. Additional evidence for the solar influence on ocean circulations is that a quasi-periodicity of 1,470 yr for the successive Dansgaard–Oeschger events may result from the superposition of the two cycles of 87 and 210 yr (ref. 39). In our DAS record (Fig. 1), the three weak monsoon events (at 0.4, 1.5 and 2.8 ka) are, within dating errors, in phase with the ice-rafting events in the North Atlantic. This suggests that these monsoon failures may be related to the cold episodes in the northern high latitude. Other weak monsoon events, not strongly correlated to

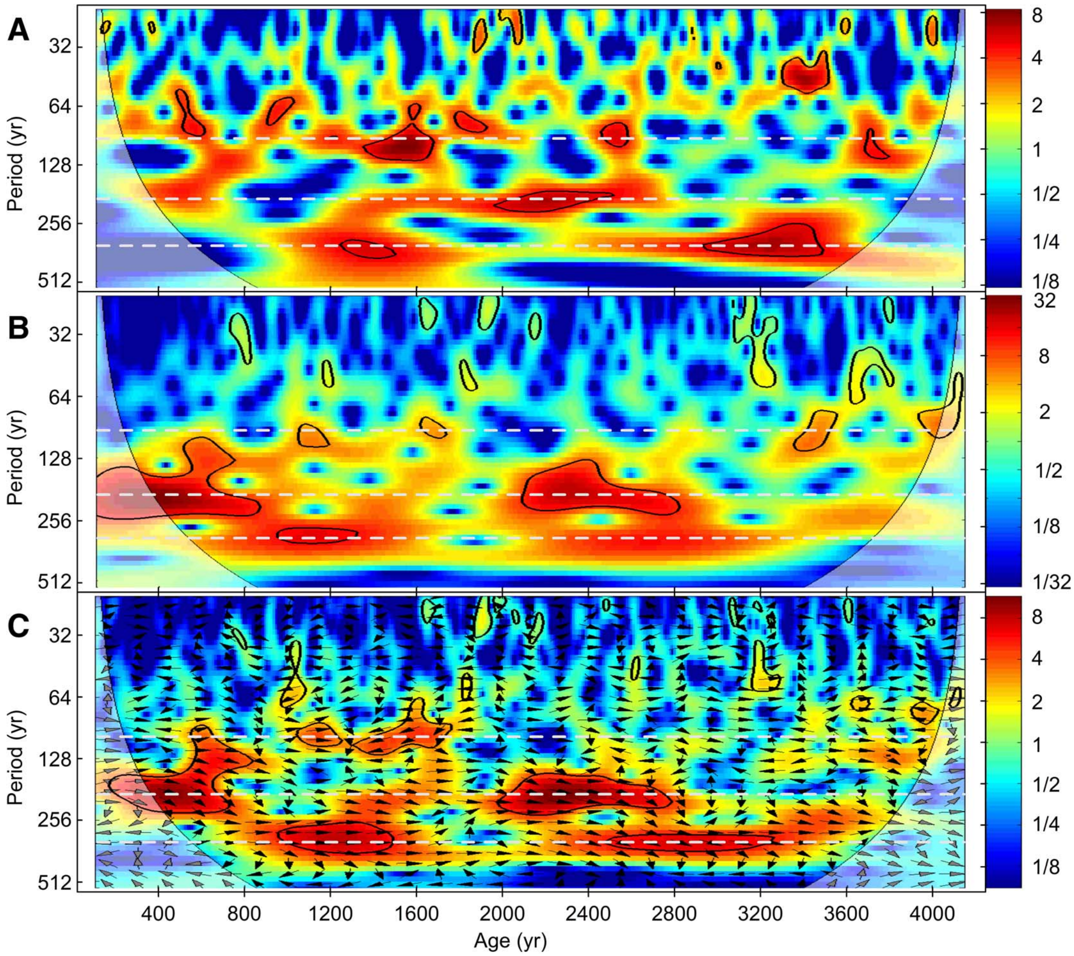

Figure 3 | Continuous transform wavelet spectra for the DAS Δ¹⁸O (A) and Δ¹⁴C (B) data, and cross-wavelet spectrum between them (C). Spectral power (variance) is shown by colors ranging from deep blue (weak) to deep red (strong). Gleissberg cycle at ~80 yr, Suess cycle at ~200 yr and unnamed cycle at ~340 yr are marked using horizontal, gray dashed lines. Black boundaries mark 95% significance level.

the ice-rafting events, are probably produced by other internal feedbacks of the climate system.

Physical mechanisms of solar forcing on the Earth's climate involve: 1) direct heating of the Earth by the TSI[40], 2) solar ultraviolet radiation mechanism through stratosphere–troposphere interaction[8], and 3) galactic cosmic rays mechanism via feedbacks of cloud formation[41–43]. Despite the general resemblance between the $\Delta^{18}O$ and ΔTSI records, large downward shifts in the ΔTSI record, relative to the $\Delta^{14}C$ and ΔSN records, appear significantly incoherent with the calcite $\Delta^{18}O$ record at ~1.2, 2.3 and 2.7 ka (Fig. 2d). At the three mismatches, the $\Delta^{14}C$ shifts by ~10‰ at 1.2 ka and 20‰ at 2.3 and 2.7 ka, much larger than the data uncertainties of 1.3–2.3‰ (1.2 and 2.3 ka) and 1.6–2.7‰ (2.7 ka) (ref. 14). However, the ΔTSI shifts by ~0.9 W/m^2 (1.2 ka) and 1.2 W/m^2 (2.3 and 2.7 ka) (ref. 12), only two to three times larger than the uncertainties of 0.38–0.41, 0.40–0.50 and 0.38–0.48 W/m^2. If the TSI shifts with an amplitude of ~0.4 at ~1.2, 2.3 and 2.7 ka (the box in Fig. 2) are not induced by the uncertainties, solar influence on the monsoon may be not through the direct heating but the other processes. The better correlation between the $\Delta^{18}O$ and the atmospheric $\Delta^{14}C$ than between the $\Delta^{18}O$ and the ΔTSI record supports the forcing mechanism of cosmic rays. Generally, an increase of cosmic ray flux could increase the global low cloud amount and therefore decrease atmospheric temperature and moisture[44], and the monsoon intensity. Alternatively, if the variation in cloud cover is greater at higher latitudes[44], the cloud influence on the AM is likely also associated with the ocean circulation, because the high sensitivity of the sea ice at high latitudes to the Earth's radiation budget is influenced by the cloud cover[45]. The link between cosmic rays, cloud and climate in East Asia is further supported by a tree-ring $\delta^{18}O$ record in Japan during the Maunder Minimum[46], which shows that minima of decadal solar cycles correlate to increase in relative humidity in East Asia, rapid cooling in Greenland and decrease in Northern Hemisphere mean temperature.

In conclusion, without chronological tuning, our newly obtained Dongge data confirm the importance of the solar influence on the AM, and provide direct and robust evidence for the Sun–monsoon connection at centennial timescales. The strong connection highlights the importance of solar forcing in predicting future AM changes, which will affect almost two thirds of the world population. Despite the pronounced correlation between the AM changes and global warming since the 1600s (refs. 47, 48), it is still unclear whether the greenhouse gas forcing has taken over the solar forcing as the major driver of AM changes, especially since AD 1950. We must wait for more sophisticated climate models, involving the ocean circulation[49] and cloud feedbacks[50].

Methods

U-Th dating was carried out at the Minnesota Isotope Laboratory, University of Minnesota, and at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University. A total of twenty-four sub-samples were collected for the dating. About 0.1–0.2 g samples of powder were taken by milling along the growth axis with a hand-held carbide dental drill. Procedures for chemical separation and purification of uranium and thorium are similar to those described in refs. 51 and 52. Measurements were made on a Finnigan ELEMENT inductively coupled plasma mass spectrometer (ICP-MS) equipped with a double-focusing sector magnet and energy filter in reversed Nier-Johnson geometry and a single MasCom multiplier in Minnesota, following procedures modified from ref. 53. In Taiwan, U-Th isotopic compositions and concentrations were determined on a Thermo-Fisher NEPTUNE multi-collection inductively coupled plasma mass spectrometer (MC-ICP-MS) (ref. 54).

For $\delta^{18}O$ analyses, a total of 1178 sub-samples of 50–100 μg powder were obtained. The sub-samples were collected with a dental drill bit of 0.3 mm in diameter from the polished surface at an interval of 0.5 mm. All of the measurements were performed in the Isotope Laboratory of Nanjing Normal University on a Finnigan MAT-253 mass spectrometer. The precision of $\delta^{18}O$ is 0.06‰ at the 1-sigma level.

Programs for continuous wavelet transform and cross wavelet transform are downloaded from Grinsted *et al.* (2004)[55] (available at http://noc.ac.uk/using-science/crosswavelet- wavelet-coherence).

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Author contributions

Y.J.W. designed the study. F.C.D. and Y.J.W. interpreted the results and wrote the manuscript. C.-C.S., Y.W., H.C., X.G.K., D.B.L. and K.Z. contributed to discussion of the results and manuscript refinement. C.-C.W. and H.-M.H. determined some ^{230}Th dates in the National Taiwan University and the others were measured by X.G.K. in the University of Minnesota.

Additional information

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