Greenhouse gases modulate the strength of millennial-scale subtropical rainfall, consistent with future predictions

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Abstract

Millennial scale East Asian monsoon variability is closely associated with natural hazards through long-term variability in flood and drought cycles. Here we present a new East Asian summer monsoon (EASM) rainfall reconstruction from the northwest Chinese loess plateau spanning the past 650,000 years. The magnitude of millennial monsoon variability (MMV) in EASM rainfall is strongly linked to ice volume and greenhouse gas (GHG) at the 100,000-year earth-orbital eccentricity band and to GHG and summer insolation at the 23,000-year precession band. At the precession band, times of stronger insolation and increased atmospheric GHG lead to increases in the MMV of EASM rainfall. These findings indicate increased extreme precipitation events under future warming scenarios, consistent with model results.

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Key Points

The new precipitation-sensitive proxy (Ca/Ti) shows persistent millennial-scale East Asian summer monsoon changes over past 650 ka;

Greenhouse gases (GHG) and summer insolation modulate millennial fluctuations of loess Ca/Ti at the precession band but not that of δ^{18}Osp;

Increasing GHG and strong insolation lead to more frequently occurrence of extreme rainfall, consistent with model results.

Abstract: Millennial scale East Asian monsoon variability is closely associated with natural hazards through long-term variability in flood and drought cycles. Here we present a new East Asian summer monsoon (EASM) rainfall reconstruction from the northwest Chinese loess plateau spanning the past 650,000 years. The magnitude of millennial monsoon variability (MMV) in EASM rainfall is strongly linked to ice volume and greenhouse gas (GHG) at the 100,000-year earth-orbital eccentricity band and to GHG and summer insolation at the 23,000-year precession band. At the precession band, times of stronger insolation and increased atmospheric GHG lead to increases in the MMV of EASM rainfall. These findings indicate increased extreme precipitation events under future warming scenarios, consistent with model results.

Plain Language Summary

We present a new East Asian summer monsoon rainfall reconstruction from the northwest Chinese loess plateau over the last 650,000 years. This new precipitation proxy (Ca/Ti) and speleothem $\delta^{18}O$ ($\delta^{18}Osp$) are assessed to illustrate the modulating drivers of magnitude of millennial monsoon variability (MMV) in long-term trend. Wavelet analysis highlights the remarkable ice volume and GHG modulation at 100 kyr band as well as GHG and local insolation forcing at precession band for the MMV of Ca/Ti, but not that of MMV in $\delta^{18}Osp$. The MMV of loess Ca/Ti and $\delta^{18}Osp$ are modulated differently at orbital time scales, implying that these two proxies document different climatic response of millennial-scale monsoon circulations. At the precession band, increasing atmospheric GHG following with larger insolation results in further enhancement in MMV of EASM rainfall, which agrees with the model result and prediction in more frequently occurrence of extreme rainfall under future global warming conditions.

1. Introduction

The Chinese loess is a unique terrestrial archive that can well documents East Asian monsoon (EAM) variability at tectonic to millennial timescales (Porter and An, 1995; Liu and Ding, 1998; An, 2000; An et al., 2011). High-resolution loess have revealed persistent millennial-scale (1-10 kyr periodicity) EAM fluctuations spanning the last several glacial cycles (Guo et al., 1996; Ding et al., 1999; Sun et al., 2012, 2016, 2021a; Yang et al., 2014; Wang et al., 2020; Guo et al., 2021), which are dynamically linked with high-latitude abrupt changes in the north Atlantic including Heinrich (H) (Heinrich, 1988; Bond et al., 1992) and Dansgaard-Oeschger (DO) events (Dansgaard et al., 1982, 1993; Bond et al., 1993). This millennial-scale monsoon variability is superimposed on glacial-interglacial variations (Ding et al., 1999; Sun et al, 2016; Yang et al., 2014; Clemens et al., 2018). Abrupt summer monsoon changes are closely linked to natural hazards such as flood and drought events (Huang et al., 2007; Wu et al., 2017), since summer monsoon plays a leading role in transporting water vapor from low to middle/high latitudes of the northern hemispheres (Webster et al., 1998; Wang and Ding, 2008; Wang, 2009; Guo et al., 2012; Liu et al., 2013; An et al., 2015). Abrupt rainfall events associated with short-term summer monsoon variations have seriously influence on agriculture, food production, water supply and social economic development (Ding and Chan, 2005; Huang et al., 2007; Yancheva et al. 2007; Cook et al. 2010; Li et al., 2017; Wu et al., 2021). However, how these flood/drought events are affected by both natural and anthropogenic factors remains poorly constrained. Understanding the mechanisms that modulate the magnitude of millennial-scale variability (MMV) is of critical importance for the scientific community as well as policy makers.

A number of well-dated, high-resolution speleothem δ^{18}O records have been developed in recent years (Wang et al., 2001, 2008; Cheng et al., 2016), providing the opportunity to examine the underlying relationship(s) between East Asian monsoon MMV and potential longer-term (orbital-scale) modulators. Cheng et al., (2016) hypothesized, on the basis of an East Asian composite speleothem δ^{18}O record (δ^{18}Osp), that periods of maximum Northern Hemisphere summer insolation correspond to weaker millennial-scale variability. Subsequently, however, Thirumalai et al. (2020) showed that precession does not modulate the MMV of δ^{18}Osp and postulated that it is, instead, modulated by internal processes related to the cryosphere. This work also raised the possibility that δ^{18}Osp is decoupled from regional Asian monsoon rainfall over millennial timescales (Zhang et al., 2018). As such, two important outstanding questions remain; is there a reliable proxy for East Asian summer monsoon (EASM) rainfall at the millennial timescale and what modulate the MMV thereof?

To address these questions, we have generated a high-resolution summer monsoon proxy (Ca/Ti) from Linxia (LX, 103.63°E, 35.15°N, 2200 m a.s.l.) on the western Chinese loess plateau (CLP) (Fig. S1). The Ca/Ti ratio is a precipitation-sensitive proxy linked to summer monsoon rainfall (Guo et al., 2021). Low values of Ca/Ti indicate stronger Ca leaching associated with intensified summer rainfall. The new precipitation proxy (Ca/Ti) and δ^{18}Osp are evaluated to elucidate the modulating drivers of these two proxy records. As discussed in the Results section, we find that the MMV of Ca/Ti is mainly modulated by ice volume and greenhouse gases (GHG) at the eccentricity band. GHG and summer insolation modulate the MMV of Ca/Ti at the precession band but not that of δ^{18}Osp; δ^{18}Osp MMV is modulated by winter insolation at the eccentricity and obliquity bands. The interpretations of these results are presented in the Discussion section.

2. Materials and Methods

Here we present a high-resolution loess record (LX loess profile, 103.63°E, 35.15°N, 2,200 m a.s.l.) from the western edge of the CLP (Fig. S1). At present, mean annual temperature and precipitation in this region are about 8.1°C and 484 mm, respectively, with ~80% of the annual precipitation falling during the summer season (May to September). 203.8 m-long core A (LXA, consisting of 185 m of eolian loess-paleosol sequences, underlain by 17 m of fluvial loess and 1.8 m of sandy gravel layers), 72 m-long core B (LXB) and a 7 m pit were excavated in 2017. Powder samples were collected at 2 cm intervals for analyzing mean grain size (MGS). Meanwhile, each core was scanned at 2-cm resolution by XRF core scanning to obtain elemental intensities.

The upper 18 m is mapped to the OSL dated Yuanbao loess outcrop (~4 kilometers away) (Lai et al., 2006, 2007). The whole 180 m loess chronology has been generated using an independent loess chronology by synchronizing Chinese loess and speleothem δ^{18}O records back to 650 ka (Sun et al., 2021). The first set of control points delineate the loess/paleosol boundaries S_6 to S_0 matching well with the timing of the glacial terminations/inceptions of speleothem δ^{18}O (Cheng et al., 2009; 2016). The second and third sets of age control points delineate the timing of precessional transition boundaries and abrupt cooling events (Fig. 1), respectively, based on the assumption that the East Asian summer and winter monsoon co-vary with each other at orbital timescales, and millennial-scale abrupt events are synchronous in the northern hemisphere (Hemming et al., 2004; Sun et al., 2012; Rao et al., 2013; Barker et al., 2011; Clemens et al., 2018). The tie points are shown in Fig.1.

Due to weak pedogenesis and high sedimentation rates, millennial-scale oscillations are well preserved in the western and northwestern CLP over the past glacial cycles (Sun et al., 2012, 2016; Guo et al., 2021). Meanwhile, the LX profile is well-suited for reconstructing rapid monsoon changes because it is located in monsoon frontal zone and sensitive to high- and low-latitude climate variability. The MGS reflects grain-size sorting, an indicator sensitive to winter monsoon variations (An et al., 1990; Porter and An, 1995; Sun et al., 2006). The Ca/Ti ratio reflects precipitation-induced leaching intensity linked to summer monsoon rainfall (Guo et al., 2021). The high resolution $\delta^{18}O$ of Sanbao-Hulu speleothem is an indicator of East Asian monsoon changes at orbital to centennial timescales (Cheng et al., 2009, 2016). Beyond clear glacial-interglacial and precessional fluctuations, high pass filtering (10 ka) of Ca/Ti and MGS in the LX sections shows persistent millennial-scale variations similar to that of Chinese speleothem $\delta^{18}O$ (Fig. 2 and S2).

In order to estimate the MMV, all the raw datasets are linear interpolated at 0.1 kyr interval. The original time series are filtered using a Butterworth filter at a cutoff threshold of 10 kyr (XX-hi-10ka). The standard deviation of millennial-scale variability is applied to reflecting the orbitally evoked modulation and its association with internal and external forcing with 2 ka sliding window (calculation method following the paper from Thirumalai et al., 2020). The spectral result of all the proxies in this paper were conducted by using the Lomb-Scargle periodogram online (https://exoplanetarchive.ipac.caltech.edu/cgi-bin/Pgram/nph-pgram), which could analyze discontinuous time series and remove spurious spectral characteristics (VanderPlas, 2018). Normalized orbital parameters eccentricity, tilt, and precession (ETP), GHG, insolation and benthic $\delta^{18}O$ of LR04 over the past 650 kyr are applied in the wavelet coherence (WTC) calculations to extract maximal phase and amplitude correlations with astronomical, ice volume and greenhouse gases forcing. WTC between time series was performed in a Monte Carlo framework (n = 1, 000) using open source metlab codes (Grinsted et al., 2004).

In this paper, the parameter ΔRF_{GHG} is regarded as GHG radiative forcing factors and applied in WTC to evaluate the relationship between MMV of Ca/Ti and $\delta^{18}O$ sp. The ΔRFGHG is reconstructed by referencing the content of EPICA ice core greenhouse gases to the modern value. ΔRFGHG is defined as the difference between a certain past GHG level ($[CO_2]$ and $[CH_4]$) and the pre-industrial greenhouse gas level ($[CO_2]_0 = 280$ ppm, $[CH_4]_0 = 700$ ppb) (Ramaswamy et al., 2001). Although CH_4 contributes only <5%, we calculated the ΔRFGHG using both CO_2 and CH_4. The equation used to determine ΔRFGHG is as follows (Li et al., 2017):

$$\Delta RFGHG = \Delta RFCO_2 + \Delta RFCH_4$$

$$= 4.841\ln([CO_2]/[CO_2]_0) + 0.0906(\sqrt{[CO_2]} - -\sqrt{[CO2]})_0 + 0.036\ln(\sqrt{[CH_4]}) - (\sqrt{[CH_4]_0}).$$

3. Results

The Ca/Ti ratio exhibits distinct glacial-interglacial and precessional variations over the last 650 ka as seen in LR04 $\delta^{18}O$ (Lisiecki and Raymo, 2005) and speleothem $\delta^{18}O$ (Cheng et al., 2009, 2016), respectively (Fig. 1). Both Ca/Ti and $\delta^{18}O$sp show clear millennial-scale fluctuations overlaying orbital-scale variations. The high frequency millennial signals (isolated with a 10 kyr high pass filter) persist over the last 650 ka for the loess Ca/Ti and speleothem $\delta^{18}O$ records, but the amplitude varies proxy to proxy (Fig. 1a and S2a). Spectral analysis of the raw records and MMV for loess and speleothem records display variable associations with eccentricity- (~100 kyr), obliquity- (~41 kyr), and precession-scale (~23 and ~19 kyr) over the past 650 ka. Loess Ca/Ti variance is mainly concentrated in obliquity with lesser variance in the eccentricity and precession bands (Fig. 2b), indicating prominent ice volume (eccentricity and obliquity) and isolation (precession) forcing. The speleothem $\delta^{18}O$ shows predominant precession-scale variance (Fig. S2a) suggesting strong links to insolation forcing (Cheng et al., 2009, 2016). These results indicate ice volume and insolation play dominated roles in driving changes in loess Ca/Ti and speleothem $\delta^{18}O$, respectively. (Cheng et al., 2009, 2016; Clemens et al., 2010; An et al., 2011, 2015; Sun et al, 2015, 2019, 2021a).

Millennial-scale fluctuations co-exist with long-term orbital- and ice-volume variability; we seek to assess the potential linkages among them and in particular, the extent to which MMV is modulated by these longer-term orbital and internal climate parameters. The spectra of Ca/Ti MMV shows dominant eccentricity with less strong precession and weak obliquity variance (Fig. 2d). The spectrum of $\delta^{18}O$sp MMV has a small peak near 100 kyr and an offset 41 kyr peak with little to no variance at the 23 kyr period (Fig. S2d). Thus, while both proxies are similarly modulated at the 100-kyr period (such that the MMV is larger during glacial intervals relative to interglacial times) the MMV modulation is variable for the two proxies at other orbital bands. As with the spectral differences in the raw records, the MMV spectra also implies different MMV modulating drivers, potentially associated with insolation, ice volume, and/or GHG for the two different archives (Friedrich et al., 2009; Thirumalai et al., 2020). How do internal and external drivers interact with each other and modulate the MMV of these records at the orbital timescale? We performed wavelet coherence and phase analyses (WTC reference here) of both MMV records relative to ETP, ice volume, ΔRF_{GHG} (the GHG radiative forcing factor, more details refer to methods section. CO_2 is the main contributor and CH_4 contribution is less than 5%), summer insolation, and winter insolation to identify which variables might modulate the MMV of these EASM records.

The MMV in Ca/Ti is strongly coherent with ice volume and GHG at the 100,000-year earth-orbital eccentricity band and to GHG and summer insolation at the 23,000-year precession band (Figure 3c, d). δ^{18}Osp MMV is most strongly coherent with GHG and ice volume at the 100-kyr band and with winter insolation at the eccentricity and obliquity band (Figure S4c, d, g).

4. Discussion

Orbital-scale modulation factors for MMV of the EASM

Previous geological records and modeling indicate that high latitude ice volume or ice sheet topography plays an important role in triggering abrupt climate changes (MacAyeal, 1993; Broecker et al.,1994; Alley et al., 1999; Clark et al., 2001). In particular, abrupt climate changes are highly sensitive to ice volume variations and ice sheets are widely hypothesized to motivate and amplify these high frequency signals within a constrained benthic oxygen isotope-"ice volume threshold" between 3.5 and 4.5‰ (Wara et al., 2000; Shackleton et al., 2000; Bailey et al., 2010; Naffs et al., 2013; Zhang et al., 2014). Wavelet coherence between the MMV of loess Ca/Ti, speleothem δ^{18}O and the global benthic δ^{18}O stack show excellent coherence and near-zero phase with ice volume at the 100 kyr band (Fig. S3a, c and S4e, g); this demonstrates that EASM MMV primarily follows the glacial-interglacial rhythm of ice volume variations, enlarged during glacial times and dampened during interglacial times. However coherence of the MMV for these two proxies with the benthic δ^{18}O stack are relatively weak and variable at the 41 kyr band (δ^{18}Osp; Figure S4e,g) and 23-kyr band (Ca/Ti; Fig. S3a,c). These relationships demonstrate that ice volume directly modulates the MMV of the EASM, predominantly at the 100 kyr band, with high ice volume corresponding to larger MMV.

GHG concentration is another potential driver of abrupt climate changes (Ruddiman and Raymo, 2003; Alvarez-Solas et al., 2011; Hopcroft et al., 2014; Zhang et al., 2017).Wavelet coherence between the MMV of loess Ca/Ti, speleothem δ^{18}O and the record of GHG RF show excellent coherence and ~180° phase at the 100-kyr eccentricity band (Fig. 3b, d and Fig. S4b, d) indicating strong MMV at times of low GHG. Given the coupled nature of global ice-volume and atmospheric GHG, it is clear that over the late Pleistocene glacial-interglacial cycles, these two factors modulate the MMV of the EASM as recorded by Ca/Ti and speleothem $\delta^{18}O$ such that abrupt climate change is amplified during times of high ice volume and low GHG concentration. However, this is not the case for the precession band. MMV of loess Ca/Ti displays discrete intervals high coherence and near-zero phase with GHG RF at the precession band (Figure 3b, d), which is not the case for speleothem $\delta^{18}O$ (Figure S4b, d). Thus, GHG RF does play a role in modulating Ca/Ti MMV but not that of $\delta^{18}O$sp at the precession band, indicating a difference in the millennial-scale response of these two proxies at this time-scale. We investigate this further by assessing the response to local insolation forcing.

The MMV of Ca/Ti show discontinuous relatively weak coherence with 35°N summer insolation at the precession band with even weaker coherence at the 41-kyr band (Figure 3a, c); we note that the summer insolation modulation is less strong relative to that of GHG at the precession band (Figure 3b, d). In contrast, the MMV of $\delta^{18}O$sp displays high coherence and zero phase with 35°N winter insolation at 100 kyr period, relatively weaker coherence, with a lagging phase, at the 41 kyr band, and negligible coherence at the 23-ky band (Figure S4a, c). These results indicate that the MMV of speleothem $\delta^{18}O$ is modulated by local winter insolation, opposite to the Cheng et al., (2016) hypothesis calling on north hemisphere summer insolation.

Mechanism and implication for modulation of EASM MMV

At glacial-interglacial time scales, the MMV is amplified under the glacial boundary conditions. These millennial-scale variability recorded in loess and cave records is thought dynamic linked with high latitude North Atlantic Heinrich and DO events (Cheng et al., 2009, 2016; Sun et al., 2012, 2021a, b). They are thought to be controlled by ice volume and freshwater perturbation / Northern Hemisphere ice sheet changes, respectively and associated with Atlantic meridional overturning circulation (AMOC) changes (McManus et al., 1999; Hemming, 2004; Hodell et al., 2008; Naffs et al., 2013; Zhang et al., 2013; Menviel et al., 2014). At the intermediate heights (volume) of the ice sheets, minor changes in the height of Northern Hemisphere ice sheet and atmospheric CO_2 concentrations can trigger the rapid climate transitions (Zhang et al., 2014, 2017). Altering the height of Northern Hemisphere ice sheets (NHISs) lead to changes in the gyre circulation and sea-ice coverage by shifting the Northern westerlies (Zhang et al., 2014). The maximum westerly wind stress shifts northwards associated with gradual increase of the Northern

Hemisphere ice volume. This, in turn, encourages the EAM move northward and results in increases in the MMV of EASM rainfall (especially northern China). In addition, CO_2 is supposed to act as an internal feedback agent to AMOC changes (Baker et al., 2007, 2016). Under intermediate glacial condition, when the AMCO reaches a regime of bi-stability, rising CO_2 during Heinrich Stadial cold events can trigger abrupt transitions to warm conditions. Decreasing CO_2 during warm events leads to abrupt cooling transitions (Zhang et al., 2017). Therefore, CO_2 generally provides a negative feedback on MMV of EASM rainfall. During interglacial times, decreasing ice volume, accompanied by reduced sea ice and stronger freshwater perturbation, is correlated with lower frequency and smaller amplitude variability. The increasing GHG concentrations in atmosphere would further alter the sea surface temperature by greenhouse effect and then modulate the MMV sequentially.

At the precession band, higher GHG concentration and local insolation correspond to larger MMV of subtropical rainfall. Recent transient sensitivity experiments of δ^{18}Osp suggests that millennial-scale rainfall variability is driven primarily by meltwater and secondarily by insolation (He et al., 2021). During interglacial times under the combined influence of insolation and CO_2, model simulation shows that when insolation reaches the lower "threshold" value (358.2 and 352.1 W. m^{-2}), it triggers a strong abrupt weakening of the AMOC and results in abrupt cooling transitions over last 800ka (Yin et al., 2021). Increased insolation could warm sea surface temperature and accelerate freshwater input from high latitude ice sheet as well as altering GHG concentration in the atmosphere (Lewkowicz and Way, 2019; Zheng et al., 2020), which could, in turn, modulate MMV changes in the low latitude monsoon regions.

If both millennial-scale Ca/Ti and δ^{18}Osp represent subtropical rainfall amount, the modulation factors should be consistent. However, eccentricity, obliquity and precession bands MMV modulators differ for loess Ca/Ti and δ^{18}Osp, indicating they monitor different aspects of millennial-scale monsoon circulations. Modern observations and Lagrangian trajectories of air parcels in China during the summer monsoon indicate that moisture-induced precipitation doesn't derive from the strongest water vapor pathways (Sun et al., 2011; Jiang et al., 2017); local water vapor recycling contributes significantly to regional precipitation in East China (over 30%) and North China (exceeding 55%) (Shi et al., 2020). Hence, we speculate that δ^{18}Osp MMV monitors changes in the isotopic composition of rainfall, varying with changes in westerly transport paths associated with North Atlantic cooling events, consistent with the MMV of δ^{18}Osp being closely linkage to winter insolation at 100- and 41- kyr periods and the absence of MMV modulation at precession band. We further hypothesize that Ca/Ti mainly represents the MMV in local rainfall amount, consistent with the MMV of tropical rainfall being more dynamically related to GHG and summer insolation at precession band.

In recent decades atmospheric GHG concentration is accelerating due to anthropogenic contribution of fossil fuels suggesting that EASM (extreme) precipitation will increase as well. This inference is consistent with model simulations indicating that the number of extreme daily precipitation events and mean precipitation overall will increase significantly in response to higher GHG concentration (Dairaku and Emori, 2006; Li et al., 2015; Li and Ting, 2017). The anthropogenic GHG-evoked warming is projected to increase the lower-tropospheric water vapor content and enhance the thermal contrast between land and ocean (Kitoh et al., 1997; Hu et al., 2000; Ashrit et al., 2003). This will give rise to a northward shift of lower tropospheric monsoon circulation and an increase rainfall during the East Asian summer monsoon (Vecchi and Soden, 2007; Held and Soden 2006). Our results indicate that factors modulating EASM precipitation MMV in the past are consistent with those predicted to influence future changes in monsoonal precipitation, lending further confidence in those projections.

5. Summary

Our high-resolution loess Ca/Ti record displays millennial monsoon oscillations were persistent over the last 650 kyr. Wavelet results highlights the remarkable GHG modulation at both 100 kyr and precession band as well as ice volume at 100 kyr period and local insolation forcing at precession band. The MMV of loess Ca/Ti and speleothem δ^{18}O are modulated by different orbital factors, implying that these two proxies document different climatic response of millennial-scale monsoon circulations. The underlying dynamics on how these internal and external factors modulate the MMV still needs further model testing. In recent decades, atmospheric GHG concentration is dramatically increasing due to anthropogenic contribution of fossil fuels (Bousquet et al., 2006; Davis et al., 2010), resulting in accelerated melting of ice-sheets in bi-polar regions (Swingedouw et al., 2008; Pattyn et al., 2018; Golledge et al., 2019). Their combined effects lead to more frequently occurrence of extreme rainfall (Dairaku and Emori, 2006; Li et al., 2015; Li and Ting, 2017; IPCC, 2018). Our results indicate that the MMV EASM rainfall can be modulated by ice volume, GHG, and insolation factors, consistent with those predictions to influence future changes in monsoonal precipitation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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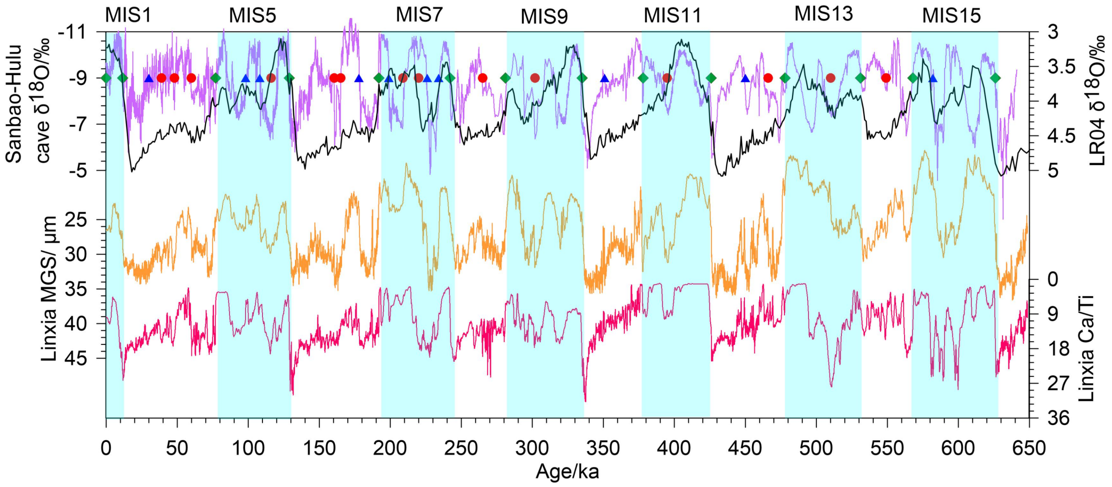

Fig. 1 Variations of mean grain size, Ca/Ti over last 650 ka and age model of Linxia loess section. Comparison of mean grain size and Ca/Ti in Linxia section with Sanbao-Hulu (Cheng et al., 2009, 2016) and benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). The dark brown squares, blue triangles and red dots represent the first (glacial-interglacial transition), second (precession cycles) and third (millennial-scale events) class age control points at the corresponding position of cave record, respectively (Sun et al., 2021). Light blue bands donate the interglacial times.

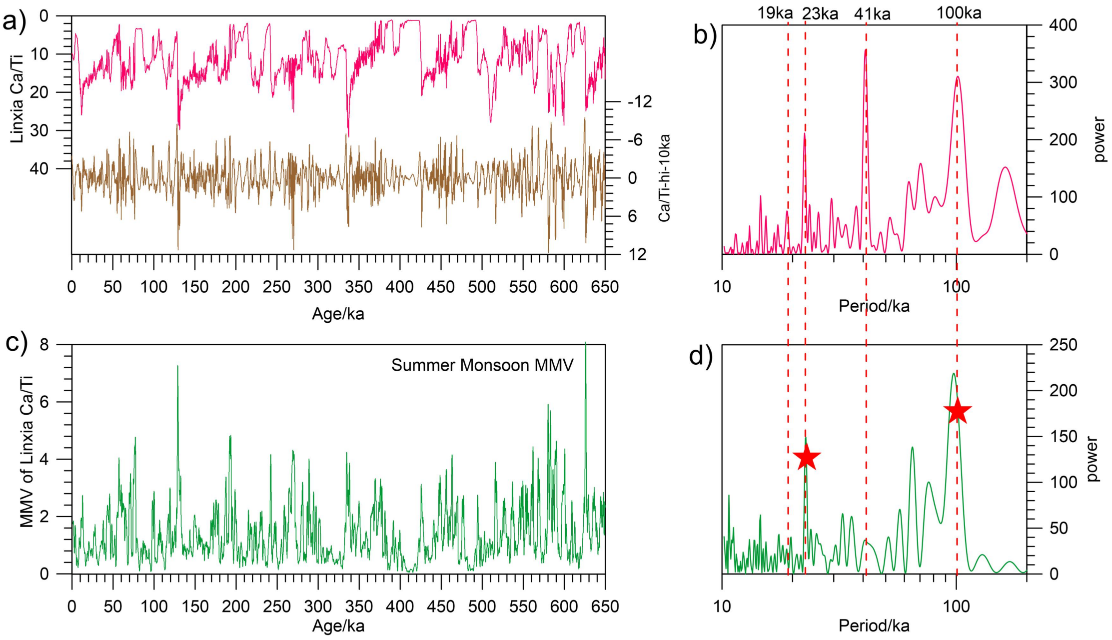

Fig.2 Raw datasets, millennial-scale components (10ka high pass filtering signals) and MMV of the Linxia loess Ca/Ti record over the past 650 ka with their corresponding spectra . The orbital bands are marked with red dashed lines (eccentricity-100 ka, obliquity-41 ka ,precession-23 ka and 19 ka). Clearly variable eccentricity, obliquity and precession variances as well as persistent millennial-scale components are observed for loess Ca/Ti.

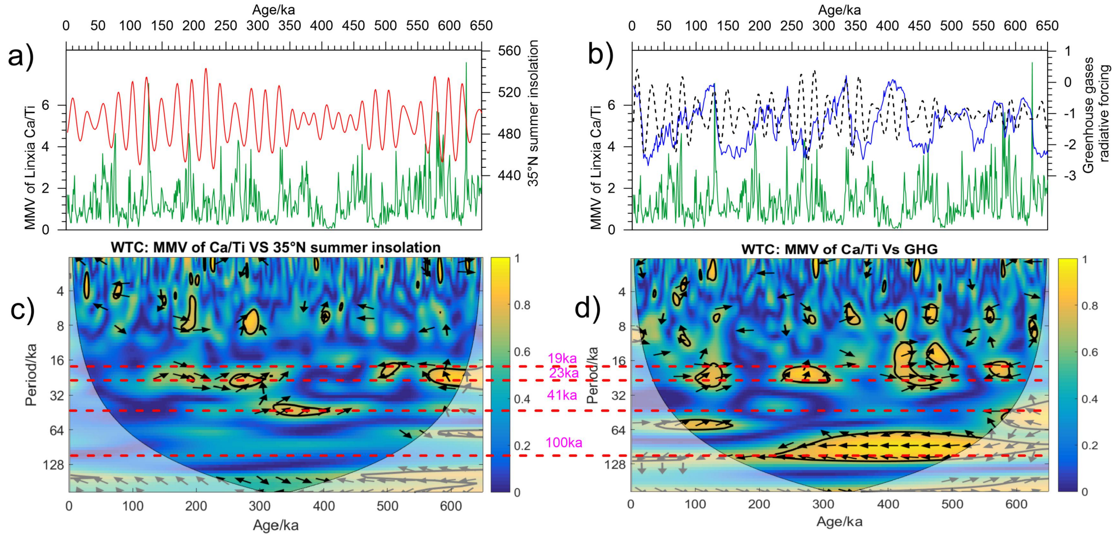

Fig. 3 Comparison of a) 35°N summer insolation and b) GHG radiative forcing (black dashed line donates the precession band-pass filtering results of GHG) for MMV of Linxia loess Ca/Ti; Wavelet coherence between c) 35°N summer insolation, d) GHG concentration and MMV of loess Ca/Ti over the past 650 ka. The orbital bands are marked with red dashed lines (eccentricity-100 kyr, obliquity-41 kyr , precession-23 kyr and 19 kyr). The black outlines indicate coefficients of determination greater than 0.76. The black arrows represent the phrase relationship with rightward, upward and downward arrows indicating in-phase, leading and lagging phase, respectively. Strong eccentricity- and precession-band GHG modulation as well as weak summer insolation forcing are observed for MMV of loess Ca/Ti.

Supporting Information for

Greenhouse gases modulate strength of millennial subtropical rainfall and future forecasts

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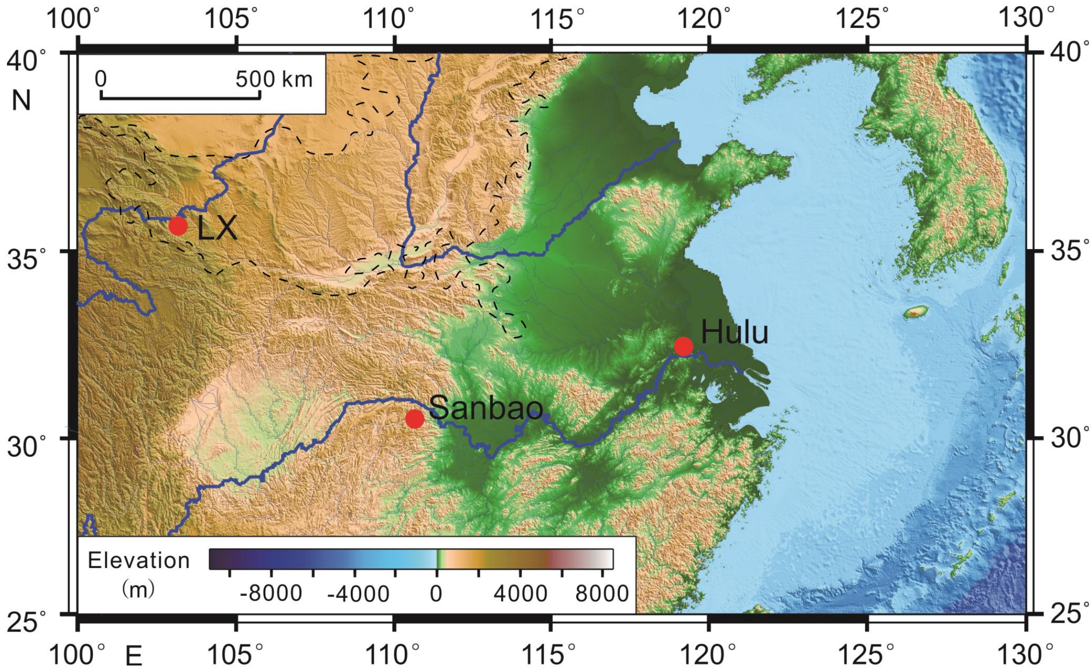

Fig. S1 The location of the Linxia (LX) loess profile and Hulu-Sanbao cave records. The Linxia profile, located on the edge of convergence zone for of alpine Qinghai-Tibet Plateau, northwest arid and the southeast monsoon area, is very sensitive to the migration of desert regions and monsoon rainfall. Sanbao-Hulu cave is located in monsoon-influenced Yangtze River Valley, sensitive to the monsoon-induced precipitation changes. Black dash line represents the scope of Chinese Loess Plateau.

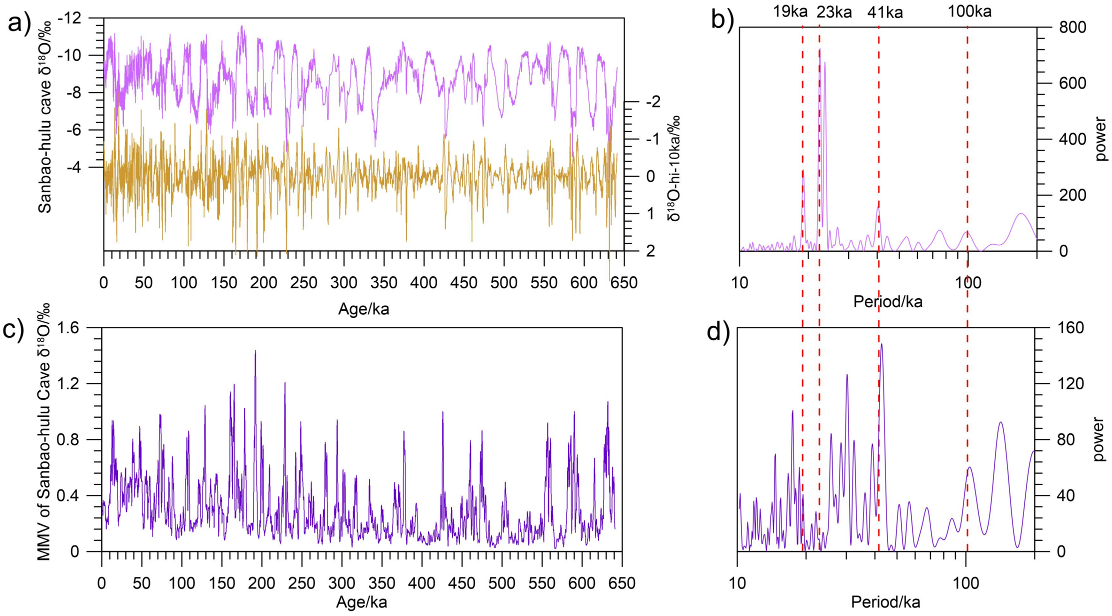

Fig. S2 Raw datasets, millennial-scale components (10ka high pass filtering signals) and MMV of the speleothem d18O record over the past 650 ka with their corresponding spectra. The orbital bands are marked with red dashed lines (eccentricity-100 ka, obliquity-41 ka ,precession-23 ka and 19 ka).

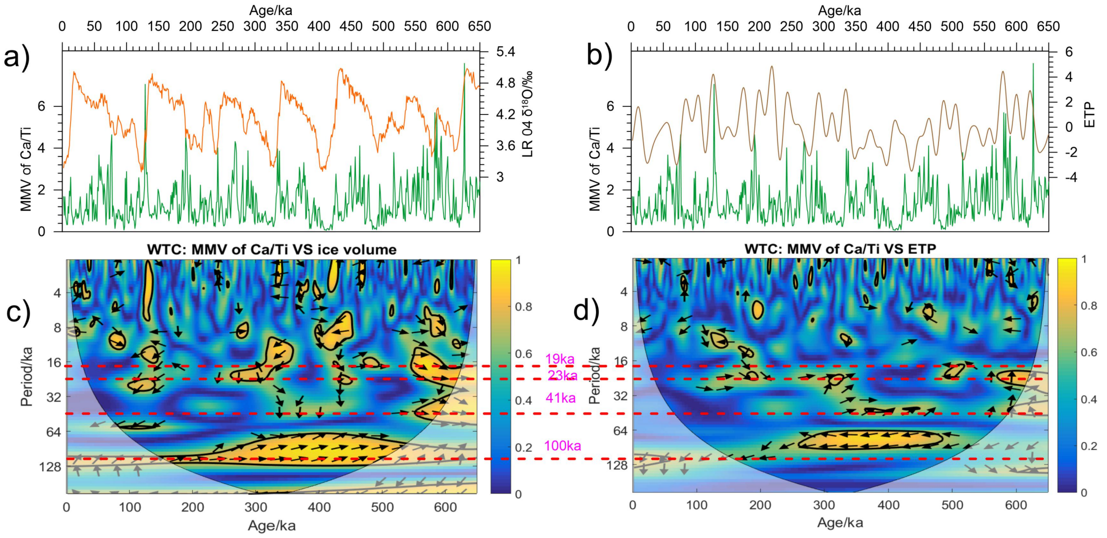

Fig. S3 Comparison of a) ice volume and b) ETP forcing for MMV of Linxia loess Ca/Ti; Wavelet coherence between c) ice volume, d) ETP and MMV of loess Ca/Ti over the past 650 ka. The orbital bands are marked with red dashed lines (eccentricity-100 kyr, obliquity-41 kyr , precession-23 kyr and 19 kyr). The black outlines denote coefficients of determination greater than 0.76. The black arrows represent the phase relationships with rightward, upward and downward arrows indicating in-phase, leading and lagging prase, respectively. Strong eccentricity, weak obliquity and precession bands ice volume modulation are observed for MMV of loess Ca/Ti.

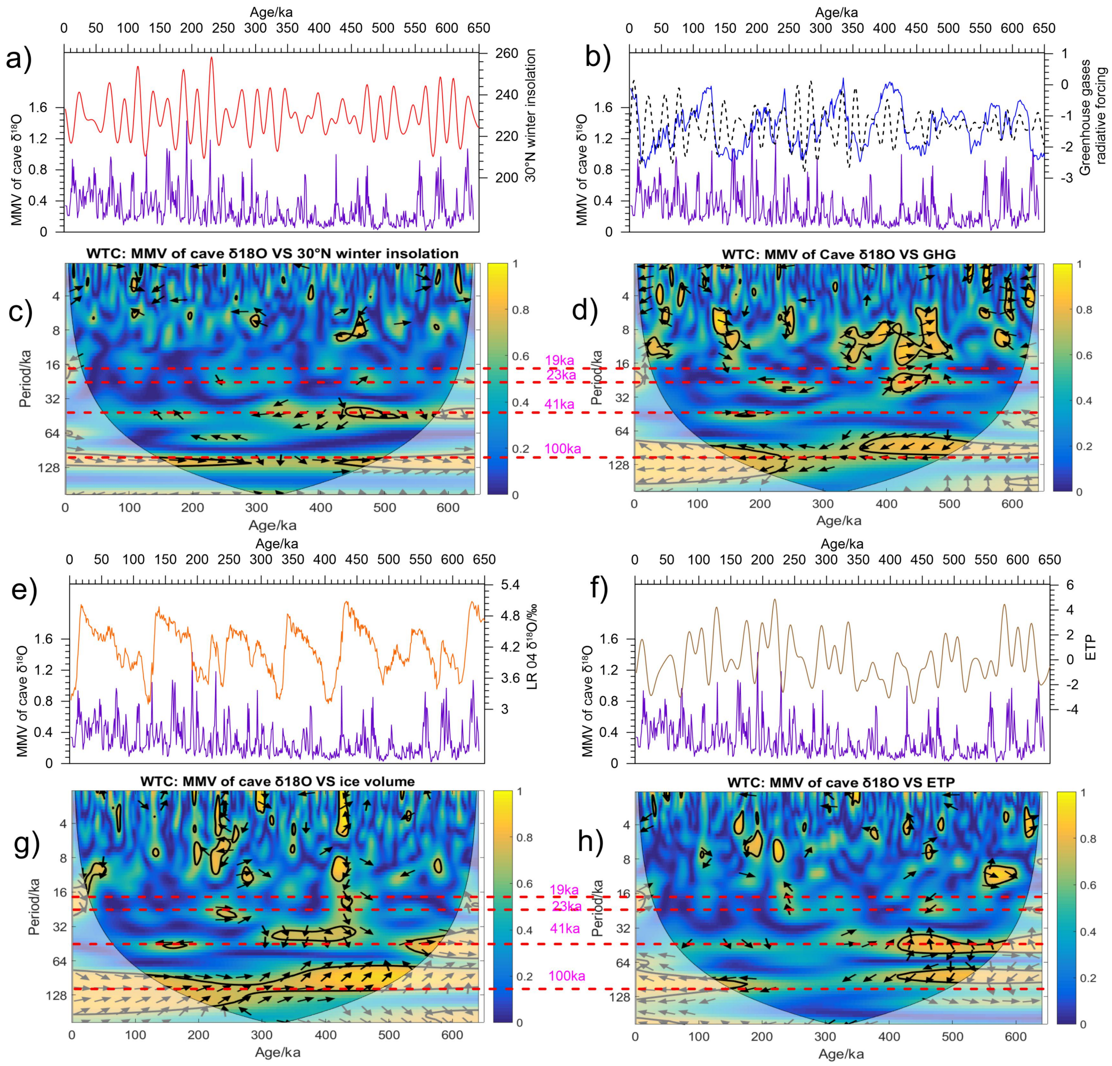

Fig. S4 Comparison of a) 30°N winter insolation, b) GHG radiative forcing (black dash line donates the precession band-pass filtering results of GHG), e) ice volume and f) ETP forcing for MMV of speleothem $\delta^{18}O$; Wavelet coherence between c) 30°N winter insolation, d) GHG, g) ice volume, h) ETP and MMV of speleothem $\delta^{18}O$ over the past 640 ka. The orbital bands are marked with red dashed lines (eccentricity-100 kyr, obliquity-41 kyr , precession-23 kyr and 19 kyr). The black outlines denote coefficients of determination greater than 0.76. The black arrows represent the phase relationship with rightward, upward and downward arrows indicating in-prase, leading and lagging phrase, respectively. Strong ice volume, GHG and winter insolation modulation at 100 kyr band, relative weak ice volume and winter insolation forcing as well as unclear precession band modulation are observed for MMV of speleothem $\delta^{18}O$.