

1
2
3
4
5
6
7
8
9
10
11
12
13

Methane, Monsoons, and Modulation of Millennial-scale Climate

Kaustubh Thirumalai¹, Steven C. Clemens², Judson W. Partin³

¹Department of Geosciences, University of Arizona, Tucson, AZ, USA
²Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI, USA
³Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA

Key Points:

- We assess the extent to which orbital forcing modulates millennial-scale climate variability.
- Millennial variations in atmospheric methane are directly modulated by precession whereas those in Chinese speleothem $\delta^{18}\text{O}$ are not.
- We propose that this decoupling has important consequences for understanding drivers and feedbacks in the climate system.

Corresponding author: Kaustubh Thirumalai, kaustubh@email.arizona.edu

Abstract

Earth's orbital geometry exerts a profound influence on climate by regulating changes in incoming solar radiation. Superimposed on orbitally-paced climate change, Pleistocene records reveal substantial millennial-scale variability characterized by trends, tipping points, and rapid swings. However, the extent to which orbital forcing modulates the amplitude and timing of these millennial variations is unclear. Here we isolate the magnitude of millennial-scale variability (MMV) in two well-dated records, both linked to precession cycles (19,000-23,000-year periodicity): atmospheric methane and Chinese speleothem $\delta^{18}\text{O}$, where the latter is commonly interpreted as a proxy for Asian monsoon intensity. At the millennial timescale (1,000-10,000 years), we find a fundamental decoupling wherein precession directly modulates the MMV of methane but not that of speleothem- $\delta^{18}\text{O}$. We hypothesize that mid-to-high latitude insolation modulates the MMV of atmospheric methane, but feedbacks internal to the Earth-climate system modulate the strength of millennial-scale monsoonal circulation.

1 Introduction

Well-known variations in Earth's orbital parameters have pronounced effects on its insolation (i.e. incoming solar radiation) and climate system. Also known as Milankovitch cycles, imprints of oscillatory changes in orbital precession, obliquity, and/or eccentricity of the Earth's orbit are found in virtually all sufficiently-resolved paleoclimatic records during and beyond the Cenozoic Era. Despite disagreement regarding causal mechanisms [Abe-Ouchi *et al.*, 2013], it is well-established that orbital forcing paced the glacial-interglacial cycles of the late Pleistocene [Imbrie *et al.*, 1992], with a periodicity approximating 100,000 years (hereafter 100-kyr). Regional records of temperature and hydroclimate change also indicate shorter-term variability [Caley *et al.*, 2011] tied to precession (19-kyr and 23-kyr periodicities) and obliquity (41-kyr periodicity). On even shorter timescales, arguably more pertinent to human and societal relevance [Castañeda *et al.*, 2009], high-resolution records reveal abrupt and substantial millennial-scale climate variability (1 to 10-kyr periodicity) superimposed on the more gradual, orbitally-induced changes [Brook and Buizert, 2018]. However, the relationship between millennial-scale climate variability and orbital variations of insolation remains elusive.

Previously, orbitally-paced changes in insolation have been hypothesized to modulate millennial-scale activity in both atmospheric methane [Brook *et al.*, 1996] and the Asian monsoons [Cheng *et al.*, 2016]. Studies have also postulated a strong coupling between monsoon intensity and methane at both precessional and millennial timescales, wherein increased monsoon rainfall is associated with increased methane production via wetland expansion in low-latitude regions [Guo *et al.*, 2011; Ruddiman and Raymo, 2003]. Clarifying their relationship under changing background conditions is important for constraining extreme future scenarios as uncertainties in monsoon hydrology and resultant wetland changes feedback onto the future trajectory of methane [O'Connor *et al.*, 2010; Kirschke *et al.*, 2013; Brook and Buizert, 2018]. However, the proposed mechanisms of how orbital forcing modulates millennial-scale variability are inconsistent: whereas Brook *et al.* [1996] posit increased millennial-scale methane activity with increased insolation, Cheng *et al.* [2016] find an anti-phased modulation relationship where high insolation values correspond to weakened monsoon intervals.

Does orbital forcing modulate the magnitude of millennial-scale variability? We define the term 'modulate' following signal-processing literature [Roder, 1931; Rial, 2000] wherein a higher-frequency carrier signal (millennial oscillations of the climate system) is modulated by a lower-frequency input signal (orbital variations) to yield a resultant modulated signal (observed paleoclimate record). Thus, modulation implies a significant control of a longer-timescale signal on shorter-event amplitude or frequency. Here, we isolate the magnitude of millennial-scale variability (MMV) of atmospheric methane and that of

monsoon intensity over the past 640 kyrs and quantitatively assess the extent to which primary orbital frequencies modulate the millennial band of climate variance. We stress that co-variability and coupling over millennial timescales between atmospheric methane and Chinese speleothem $\delta^{18}\text{O}$ (e.g. both records contain responses to Heinrich events [Marcott *et al.*, 2014; Rhodes *et al.*, 2015]) does not preclude that the amplitude of these two parameters are differently modulated by external factors [Extier *et al.*, 2018]. We show that there is a clear imprint of precession cycles in the MMV of methane whereas we cannot find any signature of insolation directly modulating the MMV of speleothem $\delta^{18}\text{O}$. Finally, we also find a long-term trend in the MMV of speleothem $\delta^{18}\text{O}$ coinciding approximately with the Mid-Brunhes Event (~ 430 ka) whereas no secular trend exists in the MMV of methane.

2 Methods

We focus on quantifying the magnitude of millennial-scale variability (MMV) in the EPICA Dome Concordia (EDC) CH_4 record [Louergue *et al.*, 2008] (Fig. 1a) and the Chinese speleothem composite $\delta^{18}\text{O}$ record [Cheng *et al.*, 2016] (Fig. 2a). At first, we assume that the composite purely reflects variations in East Asian monsoon rainfall intensity – the published interpretation [Cheng *et al.*, 2016] – although there is ongoing debate regarding the details of this interpretation [Chiang *et al.*, 2015; Clemens *et al.*, 2018; Beck *et al.*, 2018] which we address in our discussion below. Both records are extremely well-dated and represent state-of-the-art climate reconstructions in terms of their resolution over the past 640 kyrs, spanning multiple realizations of Milankovitch cycles. We evaluate the MMV in these records by first filtering them to isolate their millennial components (Figs. 1b and 2b). Next, we separate their positive and negative amplitude envelopes (Fig. 1c and 2c) to independently assess the modulation of high-value (e.g., Dansgaard-Oeschger interstadials) versus low-value (e.g., Dansgaard-Oeschger stadials, Heinrich Events) millennial-scale variability. We then calculate a continuous record of the MMV (Figs. 1d and 2d), which reflects a combined metric of both positive- and negative-amplitude variability, derived from the variance in the filtered records (Figs. 1b and 2b). Finally, we utilize spectral analysis to determine periodicities where variance is concentrated (Figs. 1e-h and 2e-h) and to identify the power of primary orbital frequencies in the MMV of atmospheric methane ($\text{MMV}_{\text{methane}}$) and the purported record of East Asian monsoon intensity ($\text{MMV}_{\text{China}}$). Although the methane and Chinese $\delta^{18}\text{O}$ records are variable in their timestep resolution as well as in their age-model uncertainties, we show that these effects have little impact on our results (Fig. S1 and Fig. S2). Furthermore, our analysis is insensitive to the various ice-core age models (Fig. S1) and for this work, we use the updated AICC timescale [Bazin *et al.*, 2013].

The MMV in each record was calculated using the following steps. The original time series was filtered using a Butterworth filter at a cutoff threshold of 10 kyrs. Prior to filtering, we interpolated the original time series to a common step of 100 years (changing this value to 50 years or 1000 years did not impact our interpretations; see Fig. S1). The MMV was calculated using a centered rolling standard deviation applied to the high-pass filtered time series with a window of 2 kyrs and a 100-year step (i.e., essentially a continuous window). The outcomes of our study remain unchanged if we reduced our cutoff threshold to 6 kyrs or increased it to 12 kyrs; we justify our choice of 10 so as to include the millennial band frequencies and exclude leakage from hemi-precession frequencies [Hagelberg *et al.*, 1994].

We also calculated the MMV in the following records: ice-volume over the past 640 kyrs (Fig. S3) from a recently compiled probabilistic stack [Spratt and Lisiecki, 2016], the EDC δD record from Antarctica [Jouzel *et al.*, 2007] (Fig. 4c; Fig. S4), the molybdenum XRF composite record from Cariaco Basin, Venezuela [Gibson and Peterson, 2014] (Fig. S5), and the composite Borneo speleothem $\delta^{18}\text{O}$ record [Carolin *et al.*, 2016] from Malaysia (Fig. S6). We normalized orbital eccentricity, tilt, and precession (ETP) param-

eters over the past 640 kyrs for use in the wavelet coherence calculations (Figs. 3b, 3d) to extract maximal phase and amplitude correlations with orbital forcing. Finally, all analyses evaluating the spectral characteristics of the time series in this study were performed using the Lomb-Scargle periodogram, a method chosen so as to not generate spurious spectral characteristics [VanderPlas, 2017]. Wavelet coherence between time series was performed in a Monte Carlo framework (n=1000) using published MATLAB codes [Grinsted *et al.*, 2004] wherein each time series was linearly detrended.

3 Results

Spectral analysis reveals the dominant influence of orbital forcing in atmospheric methane variability over the past 640 kyrs. In the original (“raw”) methane record, the variance is mainly concentrated in the obliquity and eccentricity bands [Chappellaz *et al.*, 1990; Loulergue *et al.*, 2008], to nearly the same magnitude (Fig. 1e). Peaks in the precessional bands are also present, although their magnitudes are comparatively small. Power in the millennial band becomes prominent in the filtered record, which, by construction, does not contain variance in periodicities beyond 10 kyrs (Fig. 1f; note change of scale in axis). Spectra of both high-value and low-value excursions contain separate and distinct peaks in the millennial bands (Fig. 1g), potentially pointing to separate and distinct controls on uptake and release of CH₄ during individual events [Siddall *et al.*, 2010]. However, over modulating timescales (>10-kyr), we find that the spectral peaks for both high-value and low-value CH₄ are identical. These peaks are also very similar to those observed in the MMV_{methane} record (Fig. 1h). Most notably, we find strong spectral power in both precessional bands as well as power in the obliquity band for the high-value and low-value records as well as in the MMV of methane (Figs. 1g and h).

On closer inspection, we find that precession minima (i.e., Northern Hemisphere summer insolation maxima) correspond to large increases in the MMV_{methane} (Fig. 3a). Many of these increases are associated with the release and subsequent drawdown of atmospheric methane coinciding with precession minima, nearing the culmination of deglaciation (Fig. 3a & Fig. S3; e.g., over the Bølling-Allerød and Younger Dryas sequence). Conversely, precessional maxima (i.e., Northern Hemisphere summer insolation minima) correspond to reduced MMV_{methane} (Fig. 3a). This relationship is insensitive to glacial or interglacial background state (Fig. S3). The amplitude of these swings in MMV often follow the amplitude of precession changes, e.g., a lull in MMV_{methane} is observed at ~400 ka, when variability in precession is subdued. Wavelets analysis reveals strong coherence and near-zero phase with the 19 kyr and 23 kyr bands over the last two glacial cycles, with varying but persistent power over the past 640 kyrs (Fig. 3b). Comparatively weak coherence and out-of-phase relationships are found at the 41 kyr and 101 kyr bands (Fig. 3b), despite the peaks in the periodograms (Fig. 1g and 1h), suggesting that MMV_{methane} is not directly modulated by either obliquity or eccentricity. Thus, we conclude that precession directly modulates millennial-scale variability in atmospheric methane, supporting the assertion of higher insolation facilitating increased variability [Brook *et al.*, 1996].

In stark contrast, we find no trace of precessional forcing in the modulation of millennial-scale speleothem $\delta^{18}\text{O}$ variability (Fig. 2). Variance in the original (“raw”) $\delta^{18}\text{O}$ record is dominated by precession (Figs. 2a and 2e), yet, power is absent in the precessional bands of both the high-value and low-value records (Figs. 2c and 2g), as well as in the MMV record (Figs. 2d and 2h). Instead, we observe power at a spectral peak near the obliquity band (~43 kyr). A time series comparison of MMV_{China} and obliquity demonstrates that 1) the correspondence between them is not consistent over the past 640 kyrs (Fig. 3c) and 2) MMV_{China} peaks *lead* obliquity from 350-640 ka (Fig. 3d). Hence, MMV in Chinese $\delta^{18}\text{O}$ is not modulated by precession and moreover, its relationship with obliquity is complex, as it *leads* obliquity-driven insolation changes.

Our analysis shows that the modulating agents of millennial-scale variability in atmospheric methane and in Chinese stalagmite $\delta^{18}\text{O}$ are disparate. Orbitally-paced insolation, via precession, modulates $\text{MMV}_{\text{methane}}$ but does not modulate $\text{MMV}_{\text{China}}$. The MMV timeseries are not correlated and also show limited coherence in the primary orbital bands (Figs. 4a and 4b). On the other hand, we find a striking correspondence between $\text{MMV}_{\text{China}}$ and the MMV in Antarctic δD ($\text{MMV}_{\text{Antarctica}}$ – see Fig. S4). Significant and in-phase coherence (Fig. 4c and 4d) between these records indicates a persistent and robust coupling over the past 640 kyrs, with trends towards higher magnitude millennial-scale variability in both records (particularly pronounced in $\text{MMV}_{\text{Antarctica}}$; Fig. S4d) starting around ~ 430 ka (Fig. 4c). Ultimately, the MMV in Chinese $\delta^{18}\text{O}$ and Antarctic δD share more commonalities in their modes of temporal variability than that of atmospheric methane – where the latter is modulated by precession.

4 Discussion

What does the decoupling of orbital modulation of millennial-scale variability in methane and monsoon intensity imply? Over the past three decades, low-latitude precipitation, via its influence on tropical wetlands, has been proposed to be a major driver of long-term variability in atmospheric methane over glacial cycles [Chappellaz *et al.*, 1990]. Although this interpretation has been challenged [Schmidt *et al.*, 2004; Crowley, 1991], it has also been used to tune ice-core age models to precession cycles [Ruddiman and Raymo, 2003]. Shifts in the intertropical convergence zone (ITCZ) and monsoon rainfall variability have been inferred as causes for orbital and millennial-scale variability in methane [Guo *et al.*, 2011; Brook and Buizert, 2018], with a secondary role for boreal sources [Chappellaz *et al.*, 1997] and a minimal role for “geological” emissions including marine clathrates, seeps, and mud volcanoes [Bock *et al.*, 2017; Petrenko *et al.*, 2017]. Yet the relative contributions of various sources to past methane changes and subsequent significance for future ramifications remains hotly debated [Baumgartner *et al.*, 2012; Kirschke *et al.*, 2013; Schuur *et al.*, 2015; Bock *et al.*, 2017].

Taken at face value, given that precession modulates $\text{MMV}_{\text{methane}}$ and not monsoon intensity (as recorded in Chinese speleothem $\delta^{18}\text{O}$), our results point to midlatitude and high-latitude sources as potentially important drivers of the amplitude of methane variability on millennial timescales. Several mechanisms involving boreal sources as major contributors to methane variations have been proposed, including variability in midlatitude wetlands and peatlands from changes in sea-level and hydroclimate [Baumgartner *et al.*, 2012; Bock *et al.*, 2017; Ridgwell *et al.*, 2012], high-latitude permafrost thawing [O’Connor *et al.*, 2010], and emissions from temperature-sensitive thermokarst lakes [Lewkowicz and Way, 2019]. We contend that precession-triggered changes in local summer temperatures and associated hydrological anomalies in extratropical northern latitudes could generate shifts in methane sources through a combination of these mechanisms, and thus explain the modulation of millennial-scale variability in atmospheric methane.

Uncertainty exists in strictly interpreting Chinese speleothem $\delta^{18}\text{O}$ as monsoon rainfall amount. However, even if the speleothem $\delta^{18}\text{O}$ were not a representative metric of the global paleomonsoons [Cheng *et al.*, 2016; Caley *et al.*, 2011] and instead reflected changes in the position of westerlies, or downstream vapor changes in the Indian monsoon domain over millennial timescales [Pausata *et al.*, 2011; Chiang *et al.*, 2015], the remarkable similarity between $\text{MMV}_{\text{China}}$ and $\text{MMV}_{\text{Antarctica}}$ indicates that disparate and distant regional ocean-atmosphere features of the climate system are modulated in the same manner (Fig. 4c-d). The lack of precession in these MMV records suggests that endogenous processes modulate the magnitude of millennial-scale climate variability.

Given these uncertainties in interpreting Chinese speleothem $\delta^{18}\text{O}$, another explanation for our findings is that $\text{MMV}_{\text{China}}$ is modulated purely by high-latitude and internal sources, thus explaining its similarity with $\text{MMV}_{\text{Antarctica}}$. In this case, the modula-

218 tion of $\text{MMV}_{\text{methane}}$ by precession and lack thereof in the speleothems would imply that
 219 $\text{MMV}_{\text{China}}$ is decoupled from tropical rainfall [Clemens *et al.*, 2018; Beck *et al.*, 2018] and
 220 that the MMV calculated in records of precipitation from the monsoon and ITCZ domain
 221 would contain precessional peaks. Such long, well-resolved and absolutely-dated records
 222 of tropical rainfall do not yet exist to refute this hypothesis and moreover, such a sce-
 223 nario would also argue for the decoupling of ITCZ and low-latitude rainfall shifts from
 224 the MMV in Chinese speleothem $\delta^{18}\text{O}$. As a preliminary investigation, we found that the
 225 MMV in a record of ITCZ changes from the Cariaco Basin [Gibson and Peterson, 2014],
 226 off Venezuela (shorter in length compared to the Chinese composite speleothem record),
 227 does not contain power in the precessional band as a modulator (Fig. S5). Speleothem
 228 $\delta^{18}\text{O}$ from Borneo (Fig. S6), although spanning only ~ 150 kyrs, also does not contain
 229 such a peak. These further point to an extratropical origin for the precessional modulation
 230 of $\text{MMV}_{\text{methane}}$.

231 The bipolar seesaw paradigm links millennial-scale climate change between Antarc-
 232 tica and Greenland [Barker *et al.*, 2011; Brook and Buizert, 2018; Siddall *et al.*, 2010].
 233 Barker and colleagues generated a synthetic record of millennial-scale Greenland tem-
 234 perature variability (“ GL_T_{syn} ”), beyond the past glacial cycle derived from Antarctic
 235 ice-core δD , assuming stationarity in this paradigm [Barker *et al.*, 2011]. Accordingly,
 236 $\text{MMV}_{\text{Antarctica}}$ is virtually identical to the MMV in the synthetic series (Fig. S7), which
 237 leads to the need for reconciliation: if $\text{MMV}_{\text{methane}}$ is modulated by high-latitude pre-
 238 cession via changes in local temperature and hydroclimate, why is this not reflected in
 239 $\text{MMV}_{GL_T_{\text{syn}}}$, by extension from $\text{MMV}_{\text{Antarctica}}$? One possibility is that the bipolar-seesaw
 240 is not stationary [Siddall *et al.*, 2010] over the past 640 kyrs, although more highly re-
 241 solved records are needed to explore this hypothesis. However, another reconciling ex-
 242 planation is offered by the delayed response of ice-sheets to external forcing. Whereas
 243 boreal sources of methane respond rapidly to direct insolation forcing [Lewkowicz and
 244 Way, 2019], the waxing and waning of ice-sheets offer more inertia [Abe-Ouchi *et al.*,
 245 2013], thus leading to different variability in the high-latitude isotopic records [Vimeux
 246 *et al.*, 2001]. Abrupt changes in far-field, regional climates can be linked through per-
 247 turbations of the Atlantic meridional overturning circulation [Siddall *et al.*, 2010; Barker
 248 *et al.*, 2011], and resultant impacts on hydroclimate – processes often invoked alongside
 249 the bipolar seesaw mechanism. Such teleconnections internal to the climate-system can
 250 also explain why $\text{MMV}_{\text{China}}$ and $\text{MMV}_{\text{Antarctica}}$ share many common traits. Considering
 251 that these records are coherent and in-phase at the obliquity band (Fig. 4d), despite not
 252 being in-phase with obliquity-forced changes in insolation (Fig. 3d) nor having power
 253 at the precessional bands (Fig. 2h and Fig. S4h), strongly suggests that internal ocean-
 254 ice-atmosphere interactions set the timing and magnitude of their millennial-scale climate
 255 variability.

256 Finally, we note the occurrence of a trend towards higher-amplitude millennial-scale
 257 variability in the latter half of the MMV in the Chinese and Antarctic records (Fig. 4c).
 258 This trend of increasing MMV in both records is independent of the timestep of the raw
 259 datasets (see Fig. S2). The onset of this trend coincides with the Mid-Brunhes Event
 260 (~ 430 ka), when ice-sheets increased in size and the 100-kyr cycle became more promi-
 261 nent [Wang *et al.*, 2003]. Changes in the carbon reservoir as well as the effect of insola-
 262 tion on the Southern Hemisphere have been invoked to explain this event [Yin and Berger,
 263 2010; Wang *et al.*, 2003]. According to our analysis, stronger glacial-interglacial cycles co-
 264 incide with stronger-magnitude millennial-scale climate variability. As insolation does not
 265 trend over the last 400 kyr, this observation provides an independent line of evidence that
 266 insolation does not modulate $\text{MMV}_{\text{China}}$ nor $\text{MMV}_{\text{Antarctica}}$. Curiously, we find that there is
 267 no trend in the millennial-scale activity of methane before or after this event, which reaf-
 268 firms our hypothesis that $\text{MMV}_{\text{methane}}$ is modulated by changes in Northern Hemisphere
 269 summer insolation linked to precession cycles.

5 Conclusions

We provide a new framework to isolate millennial-scale variability and address its modulation in well-dated late Pleistocene records. We find that precession directly modulates the amplitude and timing of atmospheric methane variations over millennial timescales but not of purported monsoon intensity. At face value, this decoupling implies that fluctuations in midlatitude and high-latitude sources of methane, forced by precession, are important for modulating millennial-scale variability. Conversely, we find a strong link between the MMV in Antarctic δD and Chinese composite speleothem $\delta^{18}O$, reinforcing a role for Earth-cryosphere-system feedbacks in modulating millennial-scale climate variability in the ice-core and monsoon-sensitive records.

Acknowledgments

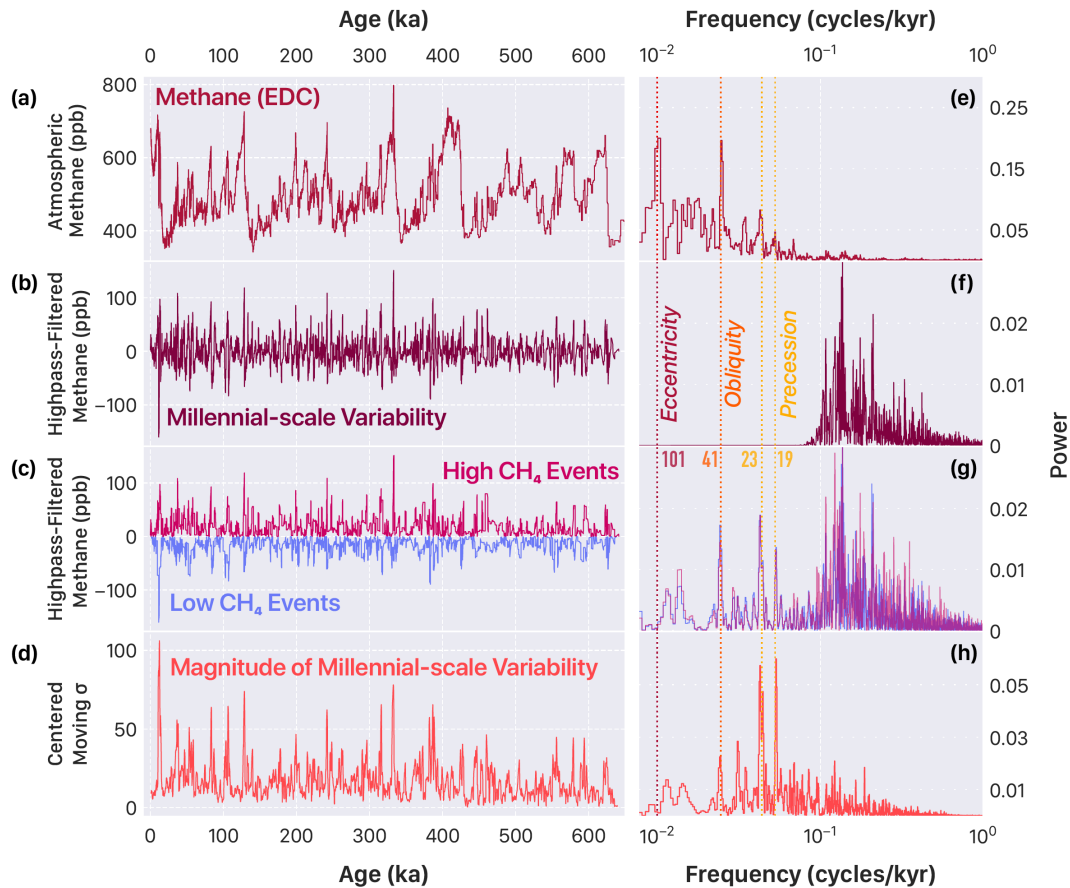
We are grateful to Warren Prell for commenting on a previous version of this manuscript and to Baylor Fox-Kemper who provided input on the statistical analysis. We thank Yoshimi Kubota and Joseph Orchardo for fruitful discussion. KT acknowledges the Brown University Presidential Fellowship and the Department of Geosciences at the University of Arizona. This research was supported by NSF grant AGS-1703123 to KT and JWP. The MMV datasets calculated by the authors are attached as a supplemental spreadsheet and will be archived in publicly available repository upon completion of peer-review.

References

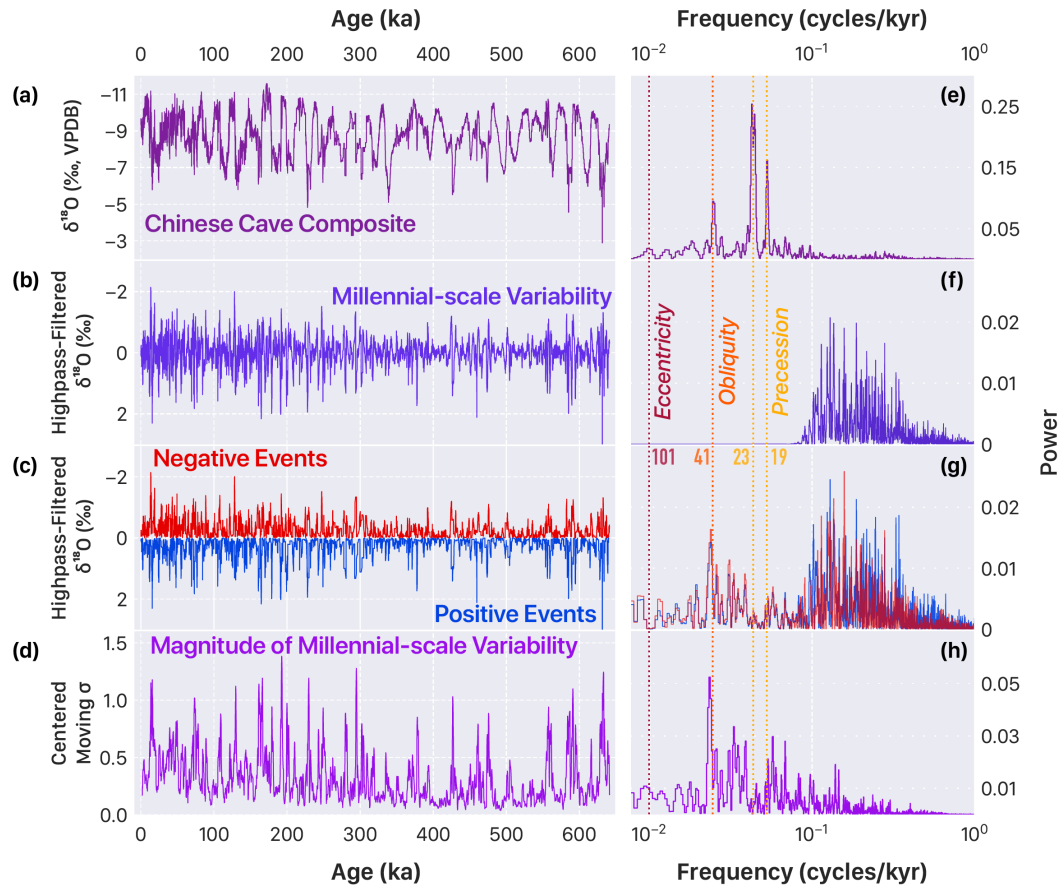
- Abe-Ouchi, A., F. Saito, K. Kawamura, M. E. Raymo, J. Okuno, K. Takahashi, and H. Blatter (2013), Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume, *Nature*, *500*(7461), 190–193.
- Barker, S., G. Knorr, R. L. Edwards, F. Parrenin, A. E. Putnam, L. C. Skinner, E. Wolff, and M. Ziegler (2011), 800,000 years of abrupt climate variability, *Science*, *334*(6054), 347–351.
- Baumgartner, M., A. Schilt, O. Eicher, J. Schmitt, J. Schwander, R. Spahni, H. Fischer, and T. F. Stocker (2012), High-resolution inter-polar difference of atmospheric methane around the last glacial maximum, *Biogeosciences*, *9*(10), 3961–3977.
- Bazin, L., A. Landais, B. Lemieux-Dudon, H. Toyé Mahamadou Kele, D. Veres, F. Parrenin, P. Martinerie, C. Ritz, E. Capron, V. Lipenkov, M.-F. Loutre, D. Raynaud, B. Vinther, A. Svensson, S. O. Rasmussen, M. Severi, T. Blunier, M. Leuenberger, H. Fischer, V. Masson-Delmotte, J. Chappellaz, and E. Wolff (2013), An optimized multi-proxy, multi-site antarctic ice and gas orbital chronology (aicc2012): 120–800 ka, *Climate of the Past*, *9*(4), 1715–1731.
- Beck, W. J., W. Zhou, C. Li, Z. Wu, L. White, F. Xian, X. Kong, and A. Zhisheng (2018), A 550,000-year record of east asian monsoon rainfall from 10be in loess, *Science*, *360*(6391), 877–881.
- Bock, M., J. Schmitt, J. Beck, B. Seth, J. Chappellaz, and H. Fischer (2017), Glacial/interglacial wetland, biomass burning, and geologic methane emissions constrained by dual stable isotopic ch_4 ice core records., *Proceedings of the National Academy of Sciences*, *114*(29), E5778–E5786.
- Brook, E. J., and C. Buizert (2018), Antarctic and global climate history viewed from ice cores, *Nature*, *558*(7709), 200–208.
- Brook, E. J., T. Sowers, and J. Orchardo (1996), Rapid variations in atmospheric methane concentration during the past 110,000 years, *Science*, *273*(5278), 1087–1091.
- Caley, T., B. Malaizé, M. Revel, E. Ducassou, K. Wainer, M. Ibrahim, D. Shoeaib, S. Migeon, and V. Marieu (2011), Orbital timing of the indian, east asian and african boreal monsoons and the concept of a ‘global monsoon’, *Quaternary Science Reviews*, *30*(25–26), 3705–3715.

- 319 Carolin, S. A., K. M. Cobb, J. Lynch-Stieglitz, J. W. Moerman, J. W. Partin, S. Lejau,
320 J. Malang, B. Clark, A. A. Tuen, and J. F. Adkins (2016), Northern borneo stalag-
321 mite records reveal west pacific hydroclimate across mis 5 and 6, *Earth Planet Sci Lett*,
322 *439(C)*, 182–193.
- 323 Castañeda, I. S., S. Mulitza, E. Schefuß, R. A. L. dos Santos, J. S. S. Damsté, and
324 S. Schouten (2009), Wet phases in the sahara/sahel region and human migration pat-
325 terns in north africa, *Proceedings of the National Academy of Sciences*, *106(48)*, 20,159–
326 20,163.
- 327 Chappellaz, J., J. M. Barnola, D. Raynaud, Y. S. Korotkevich, and C. Lorius (1990), Ice-
328 core record of atmospheric methane over the past 160,000 years, *Nature*, *345(6271)*,
329 127–131.
- 330 Chappellaz, J., T. Blunier, S. Kints, A. Dällenbach, J.-M. Barnola, J. Schwander, D. Ray-
331 naud, and B. Stauffer (1997), Changes in the atmospheric ch₄ gradient between green-
332 land and antarctica during the holocene, *Journal of Geophysical Research: Atmospheres*,
333 *102(D13)*, 15,987–15,997.
- 334 Cheng, H., R. L. Edwards, A. Sinha, C. Spötl, L. Yi, S. Chen, M. Kelly, G. Kathayat,
335 X. Wang, X. Li, X. Kong, Y. Wang, Y. Ning, and H. Zhang (2016), The asian monsoon
336 over the past 640,000 years and ice age terminations, *Nature*, *534(7609)*, 640–646.
- 337 Chiang, J. C. H., I. Y. Fung, C.-H. Wu, Y. Cai, J. P. Edman, Y. Liu, J. A. Day, T. Bhat-
338 tacharya, Y. Mondal, and C. A. Labrousse (2015), Role of seasonal transitions and west-
339 erly jets in east asian paleoclimate, *Quaternary Science Reviews*, *108(C)*, 111–129.
- 340 Clemens, S. C., A. Holbourn, Y. Kubota, K. E. Lee, Z. Liu, G. Chen, A. Nelson, and
341 B. Fox-Kemper (2018), Precession-band variance missing from east asian monsoon
342 runoff, *Nature Communications*, *9(1)*, 1–12.
- 343 Crowley, T. J. (1991), Ice-age methane variations, *Nature*, *353(6340)*, 122.
- 344 Extier, T., A. Landais, C. Bréant, F. Prié, L. Bazin, G. Dreyfus, D. M. Roche, and
345 M. Leuenberger (2018), On the use of $\delta^{18}O_{atm}$ for ice core dating, *Quaternary Science*
346 *Reviews*, *185*, 244–257.
- 347 Gibson, K. A., and L. C. Peterson (2014), A 0.6 million year record of millennial-scale
348 climate variability in the tropics, *Geophysical Research Letters*, *41(3)*, 969–975.
- 349 Grinsted, A., J. C. Moore, and S. Jevrejeva (2004), Application of the cross wavelet trans-
350 form and wavelet coherence to geophysical time series, *Nonlinear Processes in Geo-*
351 *physics*, *11(5-6)*, 561–566.
- 352 Guo, Z., X. Zhou, and H. Wu (2011), Glacial-interglacial water cycle, global monsoon and
353 atmospheric methane changes, *Climate Dynamics*, *39(5)*, 1073–1092.
- 354 Hagemberg, T. K., G. Bond, and P. Demenocal (1994), Milankovitch band forcing of sub-
355 milankovitch climate variability during the pleistocene, *Paleoceanography and Paleocli-*
356 *matology*, *9(4)*, 545–558.
- 357 Imbrie, J., E. A. Boyle, S. C. Clemens, W. R. Howard, G. J. Kukla, J. E. Kutzbach, D. G.
358 Martinson, A. McIntyre, A. C. Mix, B. Molfino, J. J. Morley, L. C. Peterson, N. G.
359 Pisias, W. L. Prell, M. E. Raymo, N. J. Shackleton, and J. R. Toggweiler (1992), On
360 the structure and origin of major glaciation cycles 1. linear responses to milankovitch
361 forcing, *Paleoceanography*, *7(6)*, 701–738.
- 362 Jouzel, J., V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Min-
363 ster, J. Nouet, J.-M. Barnola, and J. Chappellaz (2007), Orbital and millennial antarctic
364 climate variability over the past 800,000 years, *Science*, *317(5839)*, 793–796.
- 365 Kirschke, S., P. Bousquet, P. Ciais, M. Saunois, J. G. Canadell, E. J. Dlugokencky,
366 P. Bergamaschi, D. Bergmann, D. R. Blake, L. Bruhwiler, P. Cameron-Smith,
367 S. Castaldi, F. Chevallier, L. Feng, A. Fraser, M. Heimann, E. L. Hodson, S. Houwel-
368 ing, B. Josse, P. J. Fraser, P. B. Krummel, J.-F. Lamarque, R. L. Langenfelds,
369 C. Le Quéré, V. Naik, S. O’Doherty, P. I. Palmer, I. Pison, D. Plummer, B. Poulter,
370 R. G. Prinn, M. Rigby, B. Ringeval, M. Santini, M. Schmidt, D. T. Shindell, I. J. Simp-
371 son, R. Spahni, L. P. Steele, S. A. Strode, K. Sudo, S. Szopa, G. R. van der Werf,
372 A. Voulgarakis, M. van Weele, R. F. Weiss, J. E. Williams, and G. Zeng (2013), Three

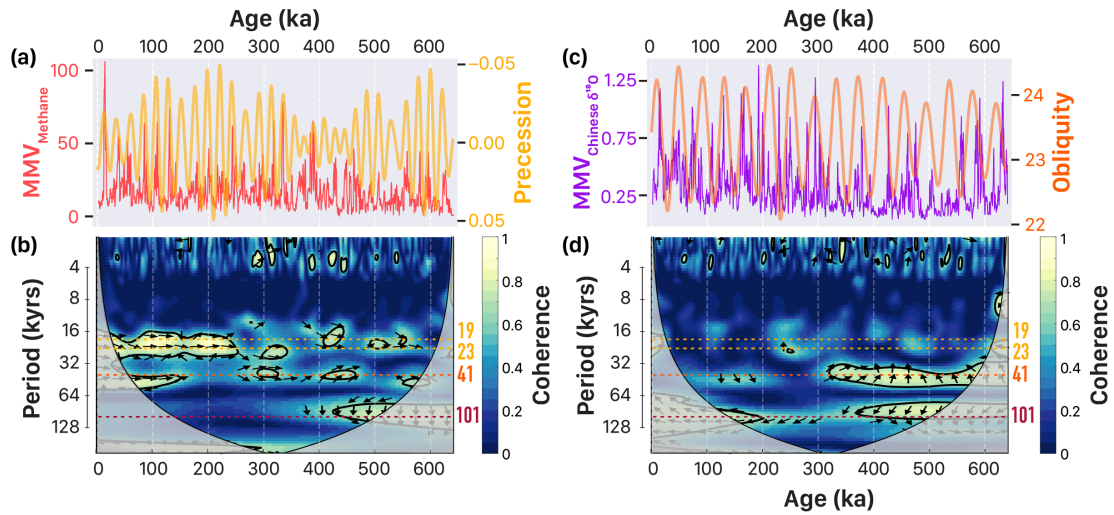
- 373 decades of global methane sources and sinks, *Nature Geoscience*, 6(10), 813–823.
- 374 Lewkowicz, A., and R. Way (2019), Extremes of summer climate trigger thousands of
375 thermokarst landslides in a high arctic environment., *Nat Commun*, 10(1), 1329.
- 376 Loulergue, L., A. Schilt, R. Spahni, V. Masson-Delmotte, T. Blunier, B. Lemieux, J.-M.
377 Barnola, D. Raynaud, T. F. Stocker, and J. Chappellaz (2008), Orbital and millennial-
378 scale features of atmospheric ch₄ over the past 800,000 years, *Nature*, 453(7193), 383–
379 386.
- 380 Marcott, S. A., T. K. Bauska, C. Buizert, E. J. Steig, J. L. Rosen, K. M. Cuffey, T. J.
381 Fudge, J. P. Severinghaus, J. Ahn, M. L. Kalk, J. R. McConnell, T. Sowers, K. C. Tay-
382 lor, J. W. C. White, and E. J. Brook (2014), Centennial-scale changes in the global car-
383 bon cycle during the last deglaciation, *Nature*, 514(7524), 616–619.
- 384 O’Connor, F. M., O. Boucher, N. Gedney, C. D. Jones, G. A. Folberth, R. Coppel,
385 P. Friedlingstein, W. J. Collins, J. Chappellaz, J. Ridley, and C. E. Johnson (2010), Pos-
386 sible role of wetlands, permafrost, and methane hydrates in the methane cycle under
387 future climate change: A review, *Reviews of Geophysics*, 48(4).
- 388 Pausata, F. S. R., D. S. Battisti, K. H. Nisancioglu, and C. M. Bitz (2011), Chinese sta-
389 lagmite $\delta^{18}\text{o}$ controlled by changes in the indian monsoon during a simulated heinrich
390 event, *Nature Geoscience*, 4(7), 474–480.
- 391 Petrenko, V. V., A. M. Smith, H. Schaefer, K. Riedel, E. Brook, D. Baggenstos, C. Harth,
392 Q. Hua, C. Buizert, A. Schilt, X. Fain, L. Mitchell, T. Bauska, A. Orsi, R. F. Weiss, and
393 J. P. Severinghaus (2017), Minimal geological methane emissions during the younger
394 dryas–preboreal abrupt warming event, *Nature*, 548(7668), 443–446.
- 395 Rhodes, R., E. Brook, J. Chiang, T. Blunier, O. Maselli, J. McConnell, D. Romanini, and
396 J. Severinghaus (2015), Enhanced tropical methane production in response to iceberg
397 discharge in the north atlantic., *Science*, 348(6238), 1016–1019.
- 398 Rial, J. (2000), Understanding nonlinear responses of the climate system to orbital forcing,
399 *Quaternary Science Reviews*, 19(17-18), 1709–1722.
- 400 Ridgwell, A., M. Maslin, and J. O. Kaplan (2012), Flooding of the continental shelves as
401 a contributor to deglacial ch₄rise, *Journal of Quaternary Science*, 27(8), 800–806.
- 402 Roder, H. (1931), Amplitude, phase, and frequency modulation, *Proceedings of the Insti-
403 tute of Radio Engineers*, 19, 2145–2176.
- 404 Ruddiman, W. F., and M. E. Raymo (2003), A methane-based time scale for vostok ice,
405 *Quaternary Science Reviews*, 22(2-4), 141–155.
- 406 Schmidt, G. A., D. T. Shindell, and S. Harder (2004), A note on the relationship between
407 ice core methane concentrations and insolation, *Geophysical Research Letters*, 31(23),
408 2362–2364.
- 409 Schuur, E. A. G., A. D. McGuire, C. Schädel, G. Grosse, J. W. Harden, D. J. Hayes,
410 G. Hugelius, C. D. Koven, P. Kuhry, D. M. Lawrence, S. M. Natali, D. Olefeldt, V. E.
411 Romanovsky, K. Schaefer, M. R. Turetsky, C. C. Treat, and J. E. Vonk (2015), Climate
412 change and the permafrost carbon feedback, *Nature*, 520(7546), 171–179.
- 413 Siddall, M., E. J. Rohling, T. Blunier, and R. Spahni (2010), Patterns of millennial vari-
414 ability over the last 500 ka, *Climate of the Past*, 6(3), 295–303.
- 415 Spratt, R. M., and L. E. Lisiecki (2016), A late pleistocene sea level stack, *Climate of the
416 Past*, 12(4), 1079–1092.
- 417 VanderPlas, J. T. (2017), Understanding the lomb-scargle periodogram, *arXiv.org, astro-
418 ph.IM*(1), 16.
- 419 Vimeux, F., V. Masson, G. Delaygue, J. Jouzel, J. R. Petit, and M. Stievenard (2001), A
420 420,000 year deuterium excess record from east antarctica: Information on past changes
421 in the origin of precipitation at vostok, *Journal of Geophysical Research: Atmospheres*,
422 106(D23), 31,863–31,873.
- 423 Wang, P., J. Tian, X. Cheng, C. Liu, and J. Xu (2003), Carbon reservoir changes preceded
424 major ice-sheet expansion at the mid-brunhes event, *Geology*, 31(3), 239–242.
- 425 Yin, Q. Z., and A. Berger (2010), Insolation and co₂ contribution to the interglacials be-
426 fore and after the mid-brunhes event, *Nature Geoscience*, 3(4), 243–246.



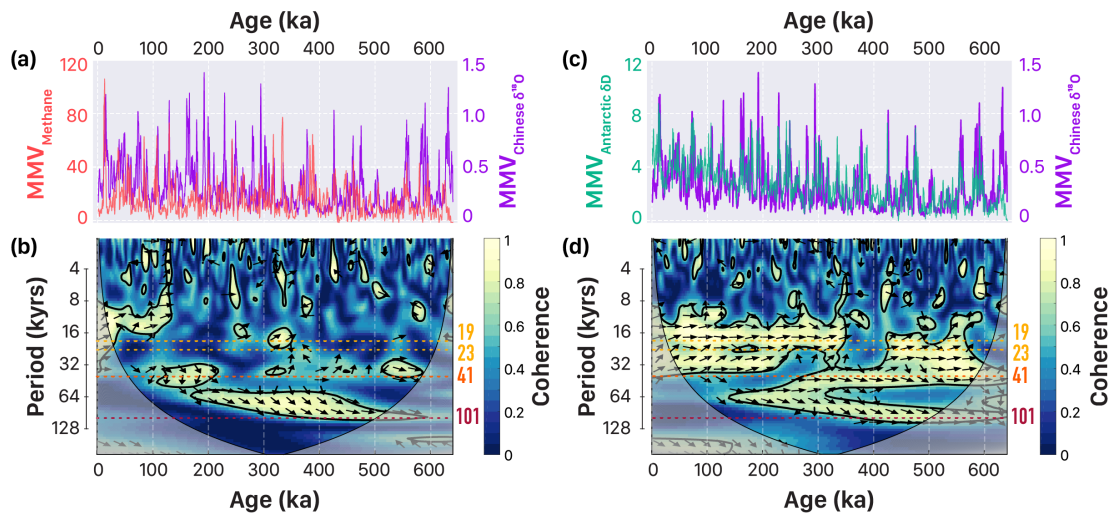
427 **Figure 1. Orbital and millennial-scale atmospheric methane variability over the past 640 kyr.** (a)
 428 EPICA Dome C record of CH₄, (b) its millennial-scale variability calculated as the 10-kyr high-pass filtered
 429 record of the original time series, (c) high-value and low-value CH₄ in the high-pass filtered record, and (d)
 430 the magnitude of millennial-scale variability calculated as the centered rolling standard deviation of the high-
 431 pass filtered record using 2-kyr sliding windows (100-yr step). (e-h) Periodograms of corresponding time
 432 series using the Lomb-Scargle methodology. Primary orbital frequencies are marked with dashed lines (19 &
 433 23 - precession; 41 - obliquity; 101 - eccentricity). Note different scaling for power spectral density.



434 **Figure 2. Orbital and millennial-scale variability in the composite Chinese speleothem record over**
 435 **the past 640 kyr.** (a) Chinese speleothem $\delta^{18}\text{O}$ composite, (b) its millennial-scale variability calculated as
 436 the 10-kyr high-pass filtered record of the original time series, (c) negative-value and positive-value $\delta^{18}\text{O}$ in
 437 the high-pass filtered record, and (d) the magnitude of millennial-scale variability calculated as the centered
 438 rolling standard deviation of the high-pass filtered record using 2-kyr sliding windows (100-yr step). (e-h)
 439 Periodograms of corresponding time series using the Lomb-Scargle methodology. Primary orbital frequencies
 440 are marked with dashed lines (19 & 23 - precession; 41 - obliquity; 101 - eccentricity). Note different scaling
 441 for power spectral density.



442 **Figure 3. Comparison of orbital forcing and MMV in atmospheric methane and Chinese $\delta^{18}\text{O}$.** (a)
 443 MMV_{methane} (red) compared with precession (yellow), the predominant peak in the MMV_{methane} spectra
 444 (Fig. 2h) and (b) wavelet coherence between MMV_{methane} and normalized eccentricity-tilt-precession (ETP)
 445 over the past 640 kyrs. (c) MMV_{China} (violet) compared with obliquity (orange), the predominant peak in the
 446 MMV_{China} spectra (Fig. 2h) and (d) wavelet coherence between MMV_{China} and ETP over the past 640 kyrs.
 447 Primary orbital frequencies are marked with dashed lines (19 & 23 - precession; 41 - obliquity; 101 - eccen-
 448 tricity) and lighter colors correspond to stronger coherence. The cone of influence, where edge effects could
 449 prevail, has been shaded. Black lines depict significance at the 10% level (number of Monte Carlo simulations
 450 = 1000) and black arrows indicate phase, where those pointing to the right depict zero-phase (upward arrows
 451 indicate that the phase of MMV leads ETP). Note that axis for precession is inverted to show higher Northern
 452 Hemisphere summer insolation upward and also note that the timeseries comparisons are with (a) precession
 453 and (c) obliquity, whereas the wavelet analyses use ETP to test sensitivity with all three aspects of primary
 454 orbital forcing.



455 **Figure 4. Comparison of MMV in atmospheric methane, Chinese $\delta^{18}\text{O}$, and Antarctic δD .** (a)
 456 $\text{MMV}_{\text{methane}}$ (red) compared with $\text{MMV}_{\text{China}}$ (violet) compared with obliquity (orange) and (b) wavelet co-
 457 herence between the two records over the past 640 kyrs. (c) $\text{MMV}_{\text{China}}$ (violet) compared with $\text{MMV}_{\text{Antarctica}}$
 458 (green) and (d) wavelet coherence between the two records over the past 640 kyrs. Primary orbital frequen-
 459 cies are marked with dashed lines (19 & 23 - precession; 41 - obliquity; 101 - eccentricity) and lighter colors
 460 correspond to stronger coherence. The cone of influence, where edge effects could prevail, has been shaded.
 461 Black lines depict significance at the 10% level (number of Monte Carlo simulations = 1000) and black arrows
 462 indicate phase, where those pointing to the right depict zero-phase (upward arrows indicate that the phase of
 463 MMV leads ETP).

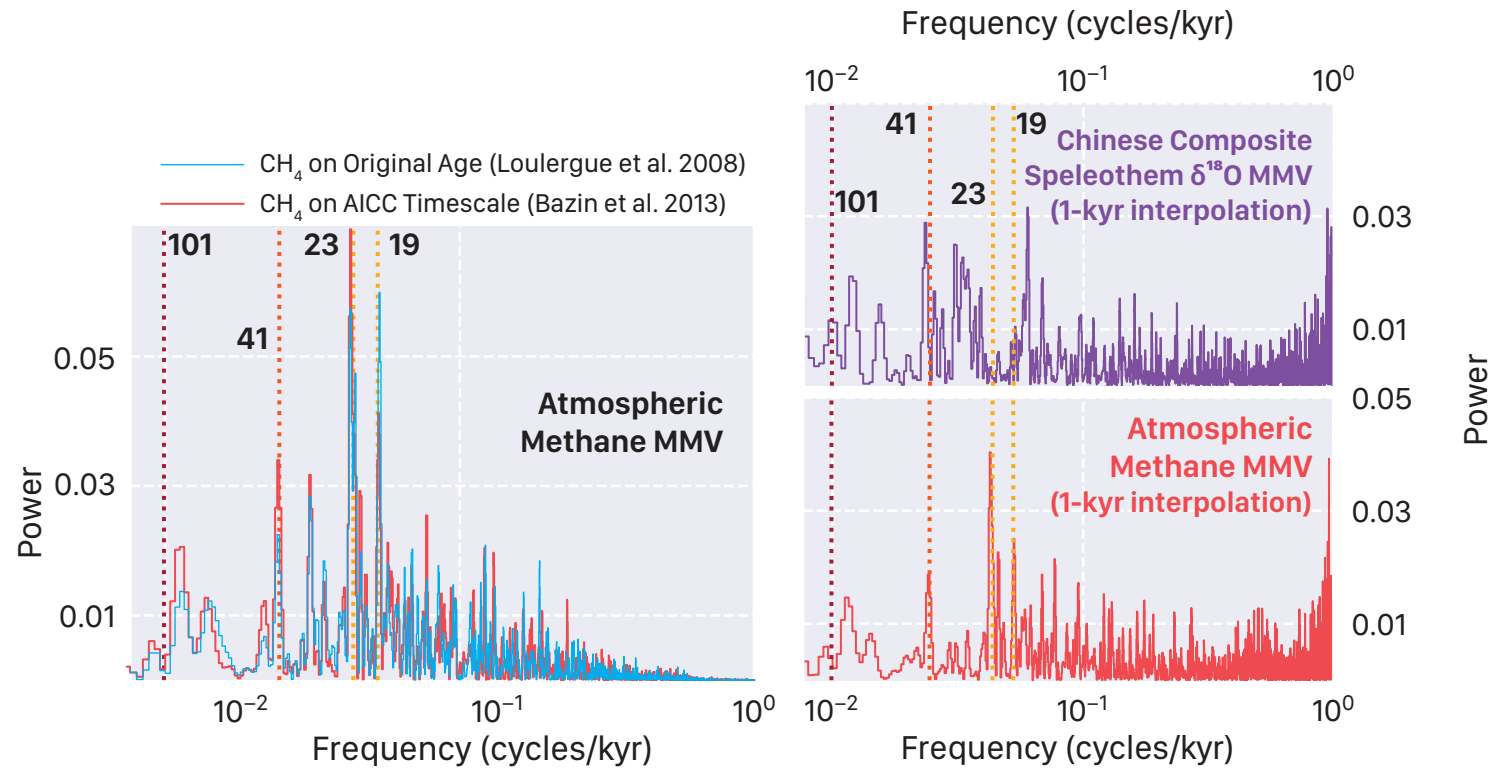


Figure S1. Sensitivity of the magnitude of millennial-scale variability (MMV) in methane and Chinese composite speleothem $\delta^{18}\text{O}$. (a) Comparison of MMV methane on originally published Louergue et al. 2008 age-model (light blue) versus that on the updated AICC timescale (Bazin et al. 2013) show virtually indistinguishable spectra with both indicating strong precessional power. (b-c) Comparison of MMV in Chinese speleothem $\delta^{18}\text{O}$ and atmospheric methane using a flat 1000-yr interpolation as the time-step of resolution. Although degraded, MMV of atmospheric methane yet shows power in the precessional band whereas the Chinese speleothem $\delta^{18}\text{O}$ do not.

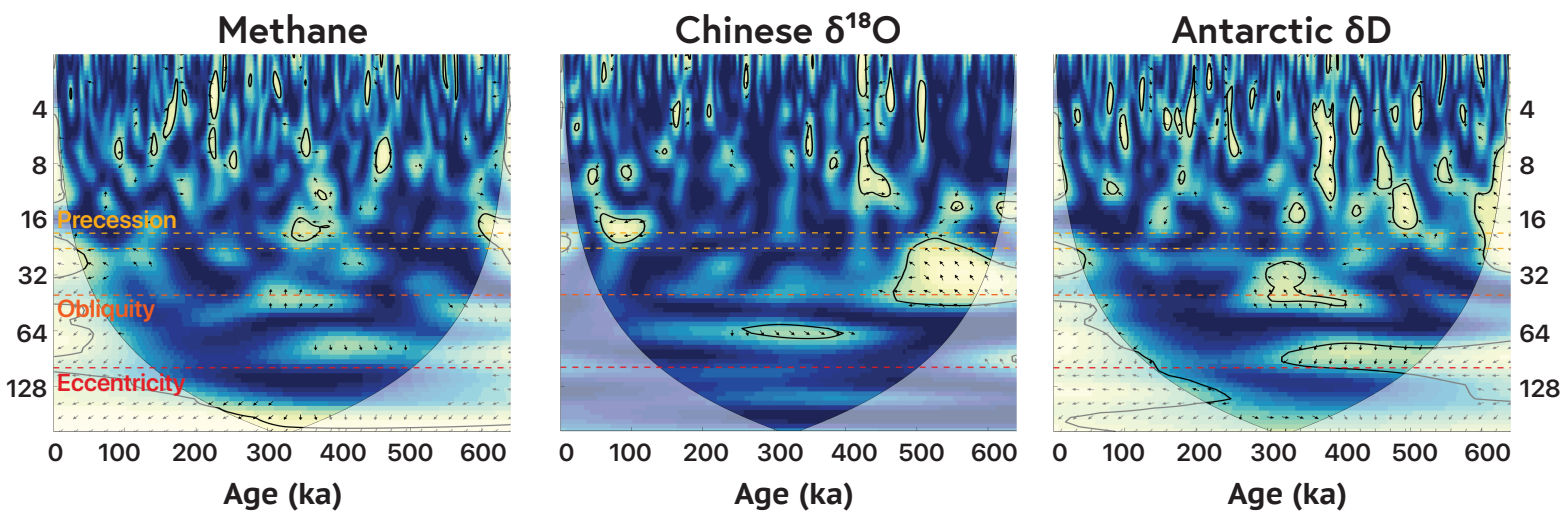


Figure S2. Cross-wavelet analysis of MMV versus the time-step resolution of the raw records themselves. We find no systematic or secular trends in the transferral of variance from one band to another in any of the records, thus indicating that the long-term trends are not sensitive to changes in the resolution of the records.

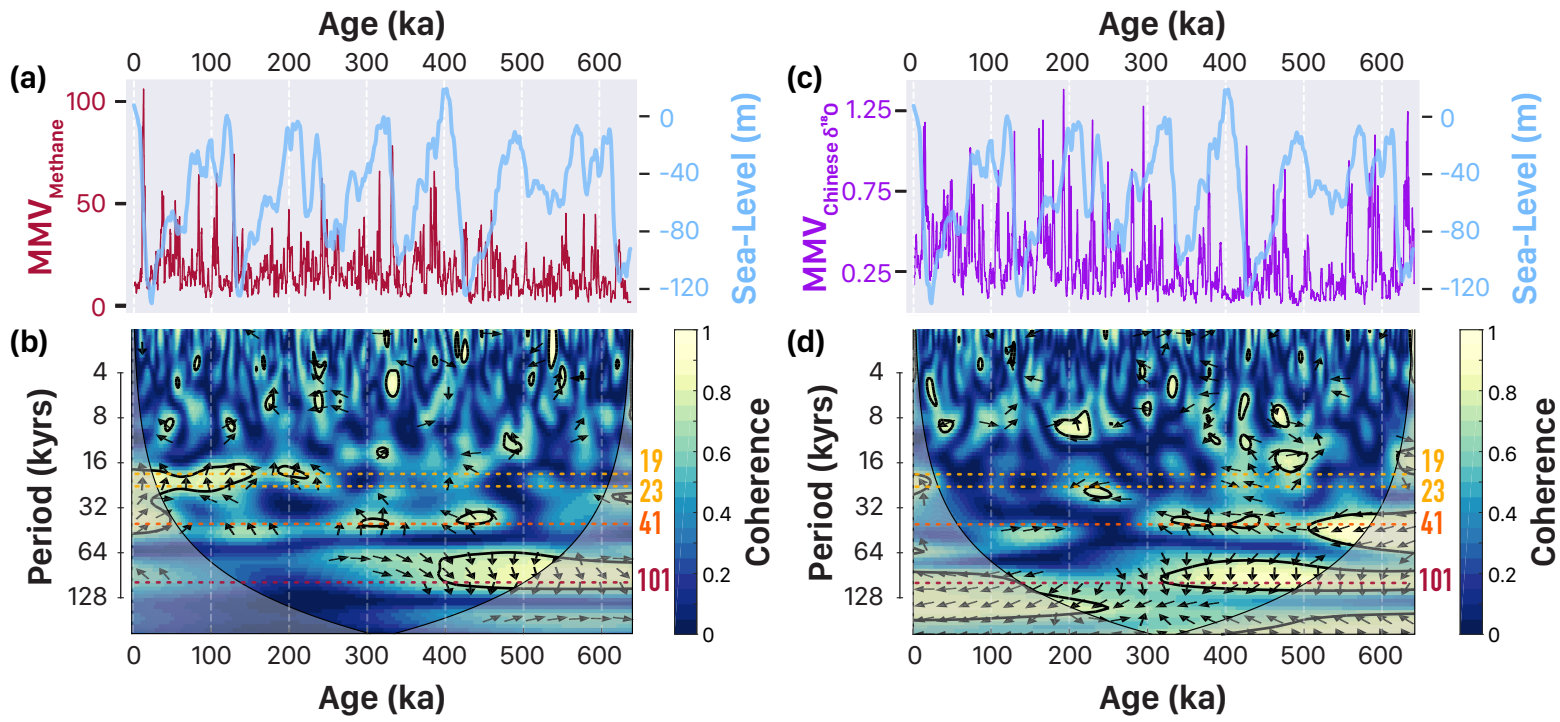


Figure S3. Comparison of sea-level and MMV in atmospheric methane and Chinese stalagmite $\delta^{18}\text{O}$. (a) $\text{MMV}_{\text{methane}}$ (red) compared with sea-level/ice-volume (blue) and (b) wavelet coherence between the two records over the past 640 kyrs. (c) $\text{MMV}_{\text{China}}$ (violet) compared with sea-level/ice-volume (blue) and (d) wavelet coherence between the two records over the past 640 kyrs. Primary orbital frequencies are marked with dashed lines (19, 23 - precession; 41 - obliquity; 101 - eccentricity) and lighter colors correspond to stronger coherence. The cone of influence, where edge effects could prevail, has been shaded. Black lines depict significance at the 5% level (number of Monte Carlo simulations = 1000) and black arrows indicate phase, where those pointing to the right depict zero-phase (upward arrows indicate that the phase of MMV leads ETP).

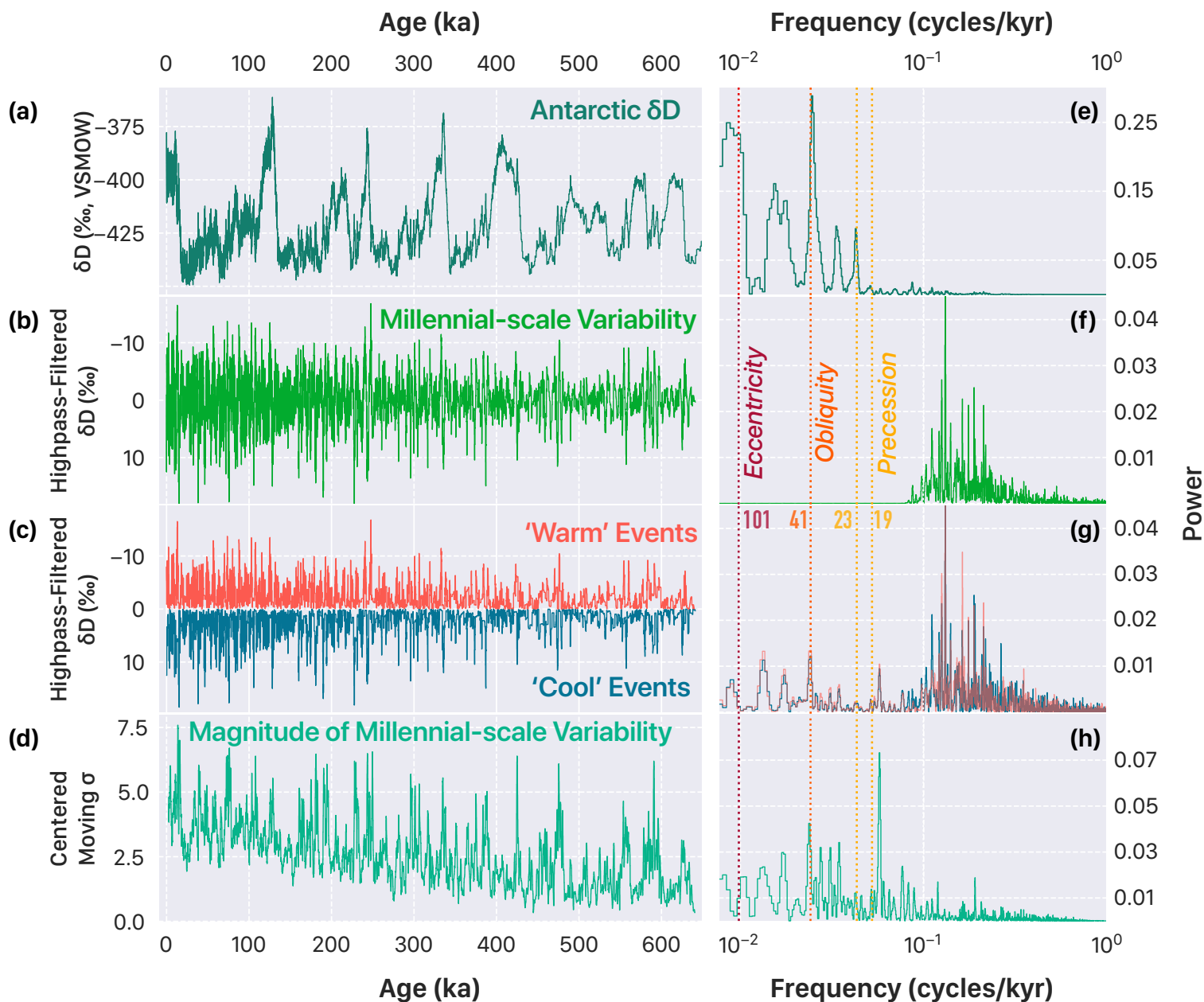


Figure S4. Orbital and millennial-scale variability in Antarctic δD over the past 640 kyrs. (a) Epica Dome C record of δD , (b) its millennial-scale variability calculated as the 10-kyr high-pass filtered record of the original time series, (c) high-value and low-value δD in the high-pass filtered record, and (d) the magnitude of millennial-scale variability calculated as the centered rolling standard deviation of the high-pass filtered record using 2-kyr sliding windows (100-yr step). (e-h) Periodograms of corresponding time series using the Lomb-Scargle methodology. Primary orbital frequencies are marked with dashed lines (19,23 - precession; 41 - obliquity; 101 - eccentricity). Note different scaling for power spectral density.

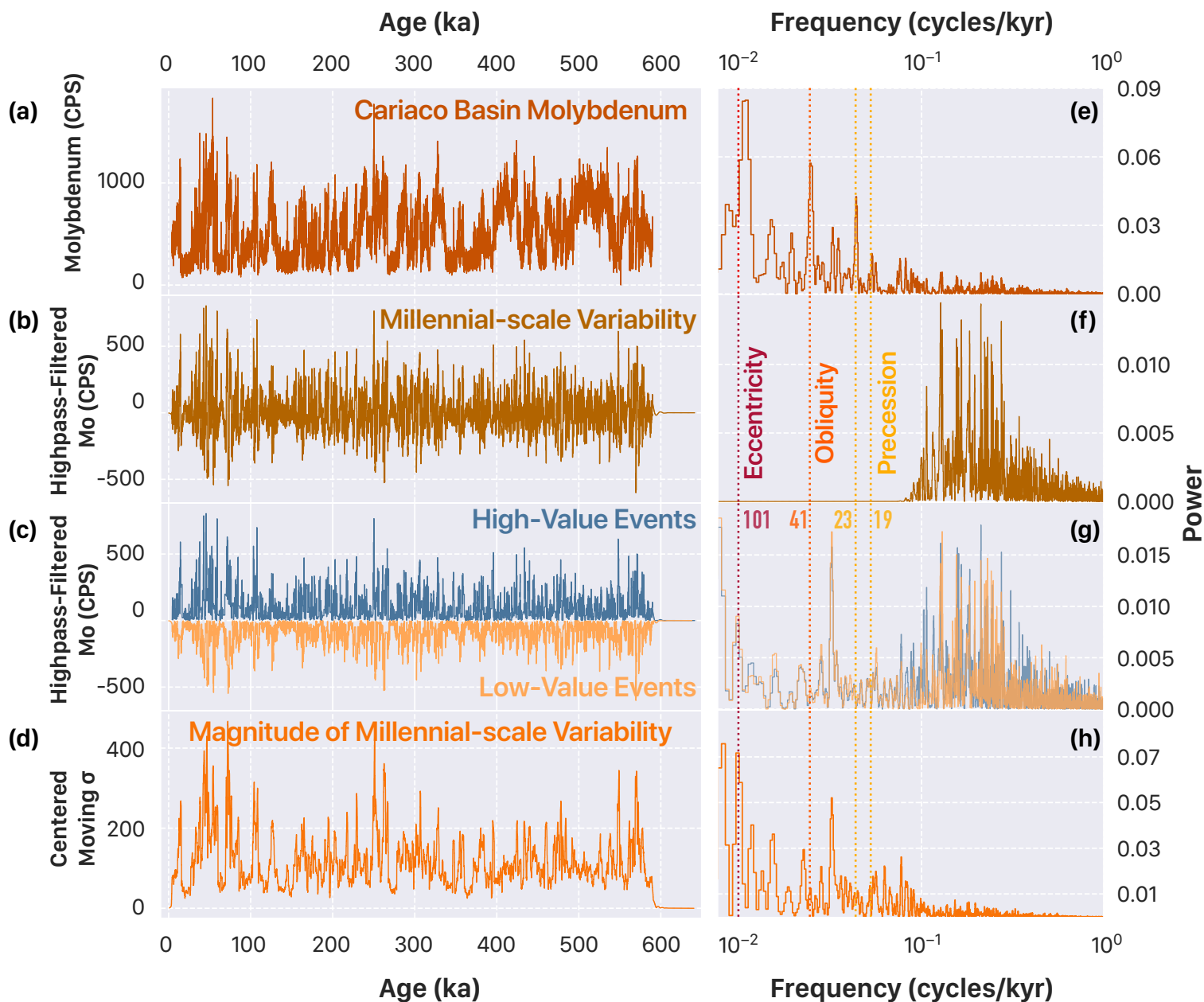


Figure S5. Orbital and millennial-scale variability in molybdenum (Mo) counts in Cariaco Basin over the past 600 kyrs. (a) Composite record of Mo (cps) from MD03-2622 and Site 1002, Cariaco Basin (b) its millennial-scale variability calculated as the 10-kyr high-pass filtered record of the original time series, (c) high-value and low-value Mo in the high-pass filtered record, and (d) the magnitude of millennial-scale variability calculated as the centered rolling standard deviation of the high-pass filtered record using 2-kyr sliding windows (100-yr step). (e-h) Periodograms of corresponding time series using the Lomb-Scargle methodology. Primary orbital frequencies are marked with dashed lines (19,23 - precession; 41 - obliquity; 101 - eccentricity). Note different scaling for power spectral density.

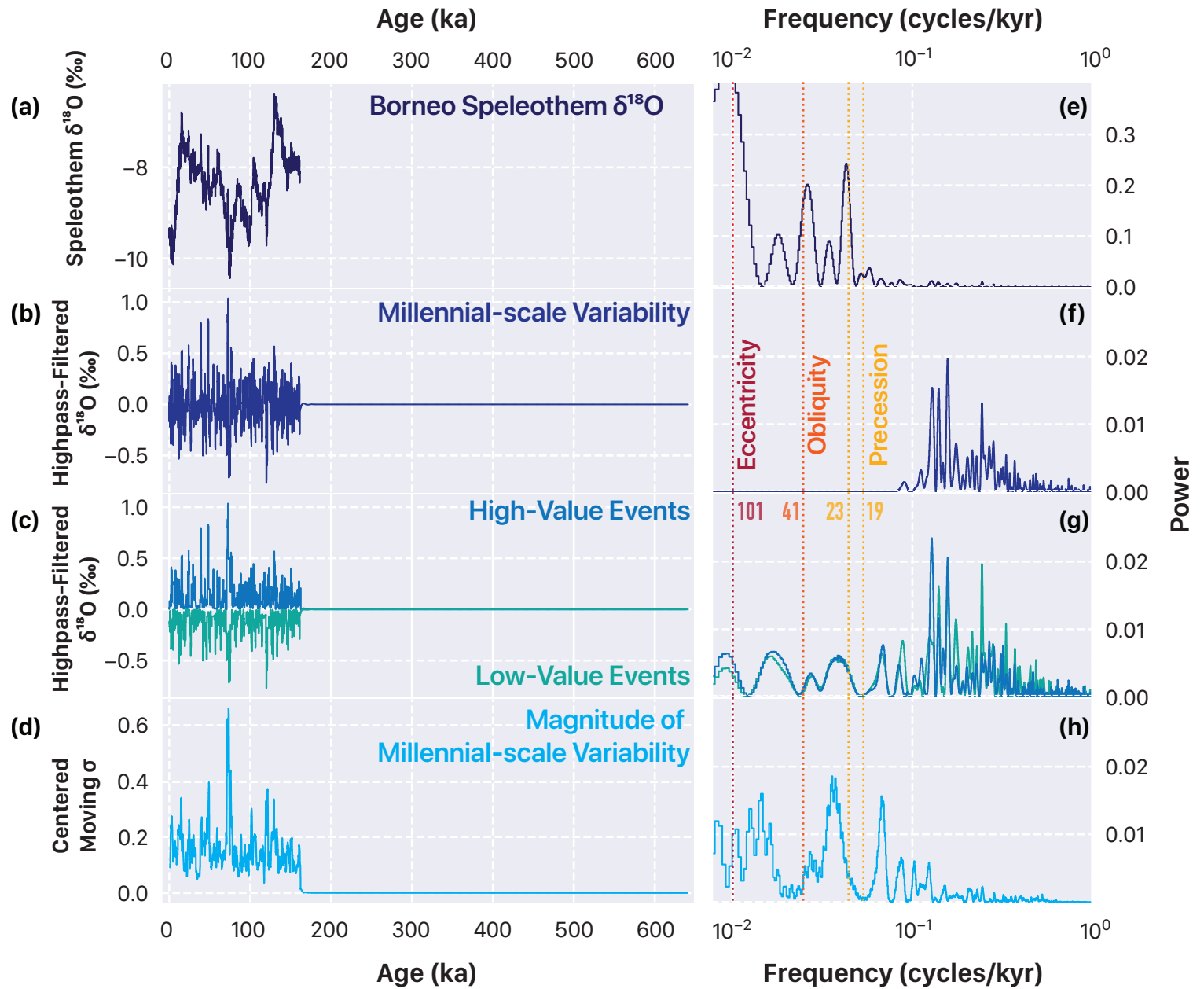


Figure S6. Orbital and millennial-scale variability in stalagmite $\delta^{18}\text{O}$ (‰) in Borneo Cave speleothems over the past 150 kyrs. (a) Composite record of Northern Borneo stalagmite $\delta^{18}\text{O}$ (‰) from Carolin et al. (2015) (b) its millennial-scale variability calculated as the 10-kyr high-pass filtered record of the original time series, (c) high-value and low-value $\delta^{18}\text{O}$ in the high-pass filtered record, and (d) the magnitude of millennial-scale variability calculated as the centered rolling standard deviation of the high-pass filtered record using 2-kyr sliding windows (100-yr step). (e-h) Periodograms of corresponding time series using the Lomb-Scargle methodology. Primary orbital frequencies are marked with dashed lines (19,23 - precession; 41 - obliquity; 101 - eccentricity). Note different scaling for power spectral density and also note that Y-axes for the $\delta^{18}\text{O}$ are lower to the bottom.

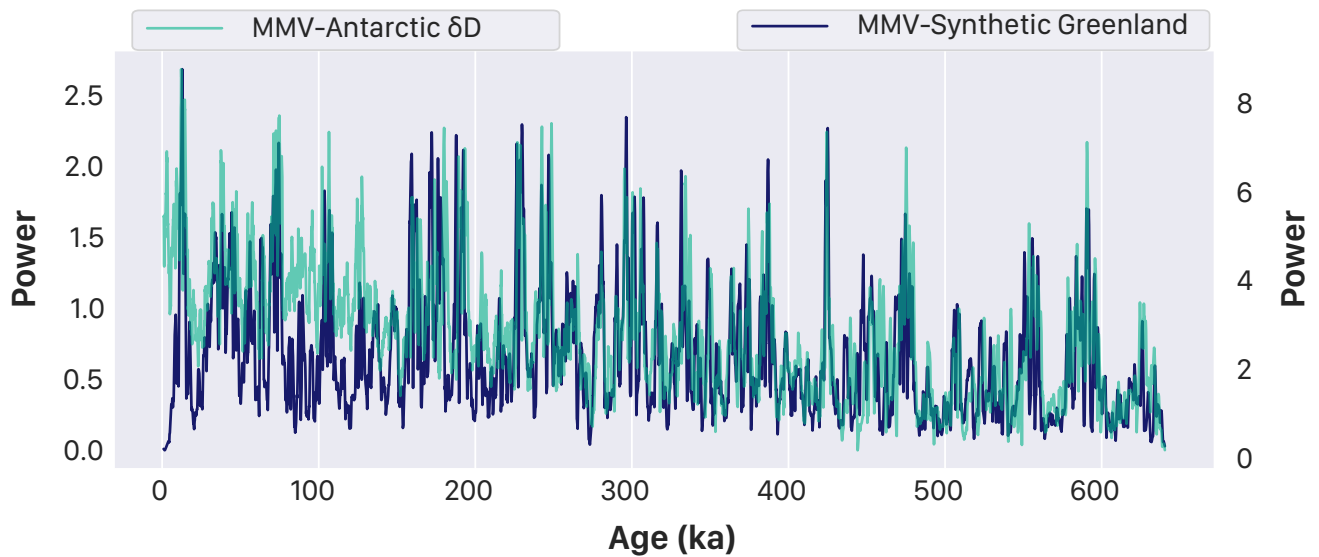


Figure S7. Comparison between the MMV in Antarctic δD and the MMV in synthetic Greenland $\delta^{18}O$. Note that the only discrepancies between the records occur over the past glacial cycle, i.e. over the span of when data exists from the Greenland ice cores.