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REPORT

Early warning signals for Asian summer monsoon tipping and implications for future monsoon changes

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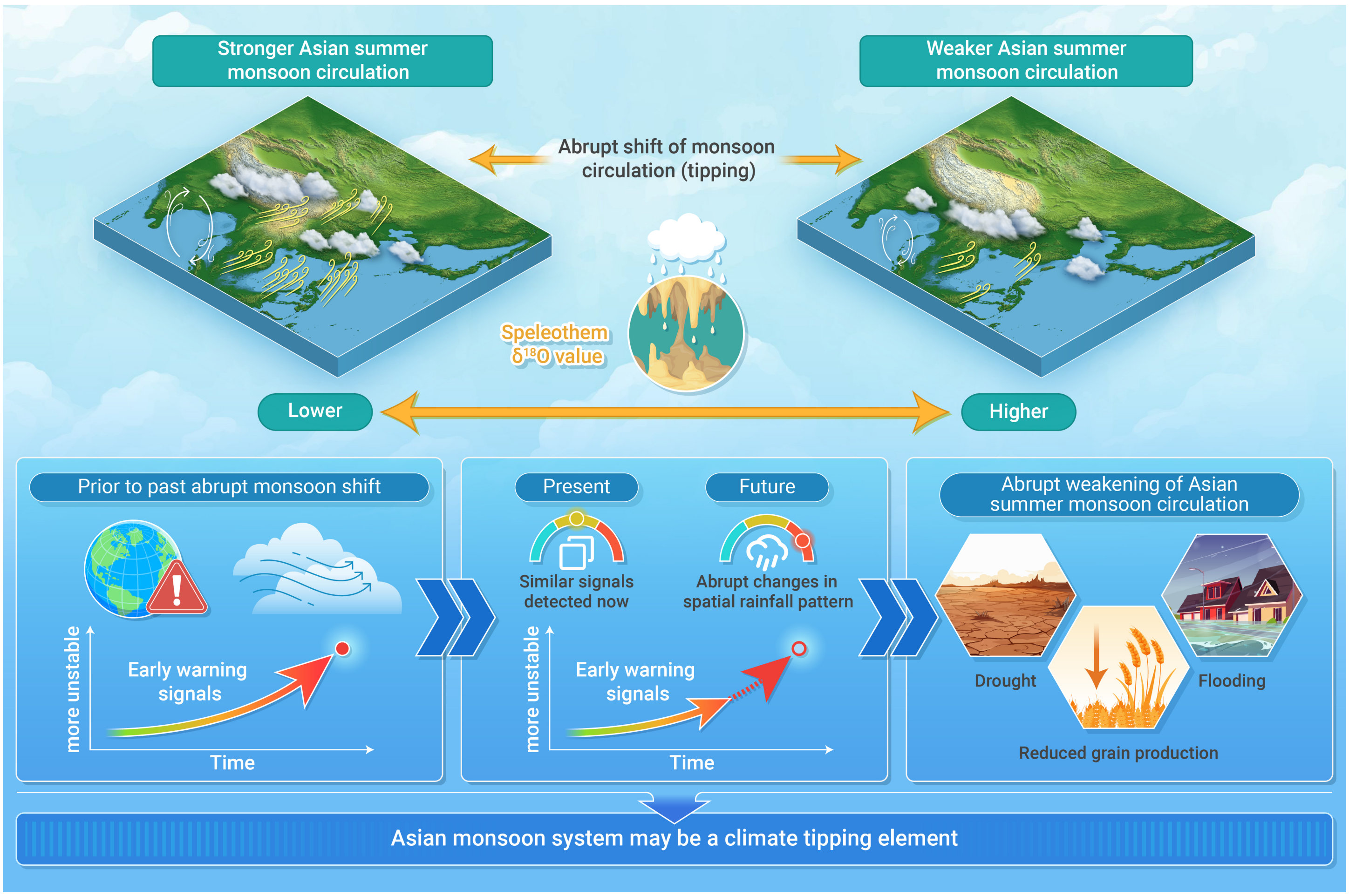
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- We conducted analyses of early warning signals in paleo- and recent speleothem proxy records.
- Our analyses reveal strong early warning signals for past abrupt Asian summer monsoon shifts.
- The current Asian summer monsoon circulation also shows strong early warning signals.
- The Asian summer monsoon circulation may be approaching an abrupt weakening in coming decades.
- The Asian summer monsoon system may be considered an important climate tipping element.

Early warning signals for Asian summer monsoon tipping and implications for future monsoon changes

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As shown by paleoclimate data and climate models, many climate systems on Earth undergo abrupt shifts when they cross tipping points (TPs), and these abrupt shifts are sometimes preceded by early warning signals (EWS). As a vital component of Earth's climate system, the Asian Summer Monsoon (ASM) system sustains the survival of billions of people. However, it remains unclear whether paleo-ASM abrupt events were preceded by EWS and whether the abrupt shifts in the ASM may ensue in the near future. In this study, we identified EWS preceding abrupt shifts in the ASM circulation using high-resolution speleothem $\delta^{18}O$ records, including rising variance and autocorrelation, and weakening resilience. Our analyses reveal akin EWS both in periods preceding historical ASM abrupt events (e.g., Heinrich events) and in modern records over the last 200 years, suggesting a plausibility that the ASM is approaching a TP by the mid-21st century. The dynamic coupling of the ASM circulation with the Atlantic meridional overturning circulation provides a possible mechanism behind the persistent reoccurrence of abrupt ASM transitions. These findings position the ASM system as a potential climate tipping element, and the potential tipping of its circulation can profoundly change spatiotemporal rainfall patterns over the ASM domain, thus necessitating urgent research.

INTRODUCTION

Many nonlinear dynamical systems have critical thresholds,[1] so-called tipping points (TPs), beyond which a system reorganizes to another state via self-propagating processes, often abruptly and/or irreversibly.[2] TPs occur in various systems, including the climate,[3] ecosystems,[4] finance,[5] medicine[6] and so on. They can be classified into three main categories according to the mechanisms by which TPs are crossed: (1) noise-induced tipping (N-tipping) driven by internal variabilities within the system; (2) bifurcation-induced tipping (B-tipping) caused by approaching a bifurcation due to slow changes in a forcing parameter; and (3) rate-induced tipping (R-tipping) due to rapid changes in a forcing parameter.[7,8] It should be noted that due to the complexity of real dynamical systems, e.g., the Earth's climate system, discrepancies remain among different studies regarding mechanisms of abrupt changes and their dynamical structures.[9-14]

Multiple studies on TPs focus on idealized fold bifurcations, treating B-tipping as the dominant mechanism of abrupt transition while accounting for the influence of noise.[9,15,16] In B-tipping scenarios, a system can exhibit critical slowing down (CSD) before reaching the TP, manifested as reduced stability, increased variability (increasing variance), enhanced memory (lag-1 autocorrelation approaching 1) and weakened resilience (restoring rate approaching 0).[9,17-20] Consequently, significant increasing trends in variance and autocorrelation may be detected, and used commonly as early warning signals (EWS) for impending abrupt transitions.[21,22] However, in real dynamical systems, noise and other processes can trigger abrupt transitions even before the bifurcation point is reached, potentially leading to false positives (Type I error) or false negatives (Type II error) in EWS analyses.[15,17] Presently, false positives are of greater concern, and cross-validation using multiple EWS indicators can help alleviate this issue.[15]

As for the Earth's climate systems, the chance of detecting abrupt transitions and TPs increases with the length of observations.[23] Paleoclimatic records provide the only information we have on the diversified abrupt transitions that have persistently reoccurred beyond the instrumental period.[23,24] An exemplary case of such past abrupt climate changes is the Dansgaard-Oeschger (DO) events, characterized by millennial-scale episodic climate oscillations between two states, cold intervals (stadials) and milder intervals (interstadials) in Greenland, which occurred repeatedly throughout the last glacial period (~11–70 thousand years before present, ka BP, where present is 1950 CE).[25,26] Oxygen isotope ($\delta^{18}O$) records from Greenland ice cores document decadal-scale transitions between stadials and interstadials and provide an exemplary case of paleoclimatic TPs.[23] Analyses of Greenland ice-core $\delta^{18}O$ records have revealed significant EWS prior to some DO cooling and warming transitions,[15,27] indicating possible B-tipping scenarios. Nevertheless, other studies[19] found no significant EWS for DO events. Further, it has been shown that adjustments in EWS calculations of ref.[15] lead to substantially fewer EWS, which were found to be inconsistent across Greenland ice core records, where temporal resolution appeared to be influential.[16]

Paleoclimatic studies have demonstrated a one-to-one coupling for the DO oscillations between Asian summer monsoon (ASM) waxing/waning and Greenland warming/cooling.[28-30] Particularly, some of the DO stadials show accorded extreme North Atlantic cooling and ASM weakening, known as Heinrich (H) events— robust evidence of past abrupt climate changes that have become a focal point in recent research.[31-33] While a conceptual model characterized ASM variations by involving tipping thresholds,[34] studies examining the predictability of past ASM abrupt transitions and/or their EWS remain scarce.[35] It is currently not clear whether the ASM system, which sustains the livelihoods of billions of people, can be considered a tipping element in contemporary climate change.[36] Nonetheless, addressing these questions is critical for understanding ASM dynamics and in turn assessing future risks and mitigation strategies. Yet, previous EWS studies at the forefront of climate change either focus solely on paleoclimate records[15] or on modern reconstruction datasets,[9,37] lacking a combined "past-present" analysis, partly due to limitations in both data resolution and chronology precision. Although quantitative projections of future TPs are still subject to high uncertainty,[38] the use of modern climatic proxy data in the context of past records could potentially provide a more realistic and sensible approach for the qualitative assessment of future TPs. This is because the statistical EWS indicators, such as the ones applied here, are theoretically independent of the background climate state and forcing mechanism detail.[13,22]

Speleothem records, one of the cornerstones in paleoclimate research,[39] excel on high temporal resolution and chronological precision over the past 690 thousand years (ka), which is essentially unparalleled in paleoclimate research due to persistent developments in high-precision U-Th/U-Pb dating and annual laminae detection techniques.[40-44] Particularly, ASM speleothem $\delta^{18}O$ records exhibit broad spatial coherence, characterizing large-scale monsoon circulation/convection dynamics in detail.[39,45-48] Of note are recent advances in a new generation of high-resolution and annually laminated speleothem records from the ASM domain that have further eliminated previ-

Table 1. Speleothem records used for Early Warning Signal (EWS) analyses

Speleothem	Latitude (N)	Longitude (E)	Considered time interval	Average resolution (years)	Age model uncertainty (years)	Data points	Filtering bandwidth (%)	Rolling window size (%)	Reference
Past tipping of the ASM									
Cherrapunji-2017-1	25°11'59"	92°27'11"	**Prior to H2** (24.7–24.4 ka BP)	2	~40	116	37	52	Dong et al. [31]
Cherrapunji-2	25°11'59"	92°27'11"	**Prior to H2b** (26.3–26 ka BP)	2	~20	141	55	62	Dong et al. [31]
Cherrapunji-2	25°11'59"	92°27'11"	23.6–22.6 ka BP	8	~20	121	79	63	Dong et al. [31]
Zhangjia-ZJD171A	32°35'	105°58'	**Prior to DO-8** (39.1–38.35 ka BP)	2.5	~60	115	82	73	Chen et al. [51]
Huangyuan-BH-2	39°42'	115°54'	**Prior to 8.2 ka event** (8.34–8.19 ka BP)	1.5	~30	157	89	72	Duan et al. [52]
Modern ASM									
Heshang-HS4	30°27'	110°25'	1850–2000 CE	1	—	151	17	74	Wang et al. [49]
Dongshiya-DSY-1201	33°46'	111°34'	1850–2014 CE	0.1	~30	325	5	75	Zhao et al. [57]

ous limitations in both data resolution and dating uncertainty,[35] allowing us to pursue combined past-present EWS analyses.

In practice, four assumptions are foundational in our EWS analysis: (1) the ASM circulation system can be approximated by a one-dimensional normal form of a fold-bifurcation model, which captures the essential system dynamics near a TP; (2) the noise perturbations are assumed to exhibit approximately stationary statistical properties across the studied timescales. These properties include a near-zero mean, constant variance, and stable short-range autocorrelation; (3) the underlying control parameter evolves approximately linearly near the TP; and (4) the system dynamics remain close to equilibrium on the timescales considered. We fully acknowledge that these are simplifying assumptions, as the real Earth's system is likely to be more complex and multi-dimensional.[38] Nevertheless, these assumptions are necessary in order to develop a tractable framework for a qualitative ASM tipping assessment, the outcomes of which will ultimately be testified by real-world tipping scenarios that have persistently reoccurred in the past.

In this study, we first analyzed four high-resolution ASM speleothem $\delta^{18}O$ records on precise chronologies constrained by both U-Th dating and annual-lamina counting, which span at least one of ASM abrupt shifts in the past. Our analysis revealed significant EWS preceding abrupt ASM weakening/strengthening events (or TPs) in the past. We further analyzed two high-resolution and annually laminated ASM speleothem $\delta^{18}O$ records over the last 200 years, which also show significant EWS similar to those observed in history. In the context of the past EWS-tipping analyses, the EWS detected from the last 200-year records appear to hint that the ASM may potentially undergo another abrupt transition near the mid-21st century. This tentative projection, combined with a comparison between the behavior of the ASM system and the criteria for a climate tipping element, suggests that the ASM system may represents a climate tipping element.

MATERIALS AND METHODS

Speleothem $\delta^{18}O$ records

Speleothem $\delta^{18}O$ records from the ASM domain primarily inherit the signal of precipitation $\delta^{18}O$, which to first order reflects the intensity of large-scale monsoonal circulation/convection and the north-south shifts of tropical rain belts. As such, they mainly indicate the dynamical aspect of the ASM system, whereas a small portion of their variability may be explained by local rainfall amount.[29,31,39,46,49] $\delta^{18}O$ values are reported in per mil (‰) deviations, relative to the Vienna Pee Dee Belemnite (VPDB) standard, $\delta^{18}O=[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VPDB}-1]\times1{,}000$‰. Higher values of speleothem $\delta^{18}O$ generally indicate a weaker ASM circulation/convection and more southward shifted tropical rain belts, while lower values correspond to a stronger circulation/convection with tropical rain belts shifted further northwards. This is consistent with results from a large body of theoretical and empirical studies.[29,31,39,45-4850]

Proxy records with high-resolution and precise age control are not only critical for accurately characterizing past abrupt climate transitions, but are also a key prerequisite for EWS analyses.[15,35] In this regard, we selected four well-dated high-resolution speleothem $\delta^{18}O$ records (i.e., Cherrapunji-2017-1, Cherrapunji-2, ZJD171A and BH-2) from the ASM domain for our study (Table 1). All these speleothems have clear annual banding (lamina), providing robust constraints on the relative chronologies that are critical for the EWS analyses.[31,51,52] Speleothem Cherrapunji-2017-1 was collected from Cherrapunji Cave (25°11'59" N, 92°27'11' E) in northeastern India (Figure 1),[31] and the Cherrapunji-2017-1 $\delta^{18}O$ record has an average resolution of 2 years, spanning the Heinrich event 2 (H2) (ca. 24.4 ka BP).[31] Speleothem Cherrapunji-2 is also collected from Cherrapunji Cave[31] and spans the Heinrich event 2b (H2b) (ca. 26.0 ka BP).[53] Heinrich events, which typically last about 250 years, correspond to large armadas of icebergs that spurred the North Atlantic.[32,54,55] These events were accompanied by a series of abrupt hydroclimatic changes worldwide, including changes in the Atlantic Meridional Overturning Circulation (AMOC), Northern Hemisphere cooling, substantial weakening of the ASM circulation/convection and southward shift of the tropical rain belts.[31,33] During the last glacial period, at least six Heinrich events occurred[32] at the middle or latter part of the corresponding DO stadials,[53,56] manifesting typical and important abrupt climate changes in the past. Speleothem ZJD171A was collected from Zhangjia Cave (32°35' N, 105°58'E) in central China (Figure 1), spanning the abrupt warming during DO-8.[51] Speleothem BH-2 was collected from Huangyuan Cave (39°42' N, 115°54' E) in Beijing, northern China (Figure 1),[52] spanning the 8.2 ka event, which occurred approximately 8,200 years ago with a smaller amplitude than Heinrich events. Overall, the Cherrapunji-2017-1, Cherrapunji-2, ZJD171A and BH-2 records have high temporal resolution and precise chronology, which allows us to evaluate whether there exist significant EWS prior to past abrupt monsoon transitions.

In order to assess whether the ASM circulation may potentially cross a TP in the future, we also selected two high-resolution speleothem $\delta^{18}O$ records (HS4 and DSY-1201) with very precise chronologies (Table 1; Figure 1). Speleothem HS4 is from Heshang Cave (30°27' N, 110°25' E), central China, and the analyzed portion of the record spans the time interval between 1,850 and 2,000 CE with an average resolution of 1 year.[49] Speleothem DSY-1201 is from Dongshiya Cave (33°46' N, 111°34' E), central China, covering the period from 1,850 to 2,014 CE with an average resolution of 0.1 year.[57]

Methods

We applied two established methods for EWS analyses: the commonly used "traditional" CSD indicators variance (σ^2) and lag-1 autocorrelation (α_1) metrics,[18] as well as the restoring rate (λ).[9]

The raw time series were linearly interpolated to their average resolution (Table 1) and smoothed using Gaussian kernel smoothing with bandwidth parameters calibrated based on sensitivity analyses to preserve critical transition-related variability (see Table 1 for bandwidth values). The detrended signal $\Delta x(t)$, or residual, was calculated as

$$\Delta x(t) = x(t) - K(x, b)(t),$$

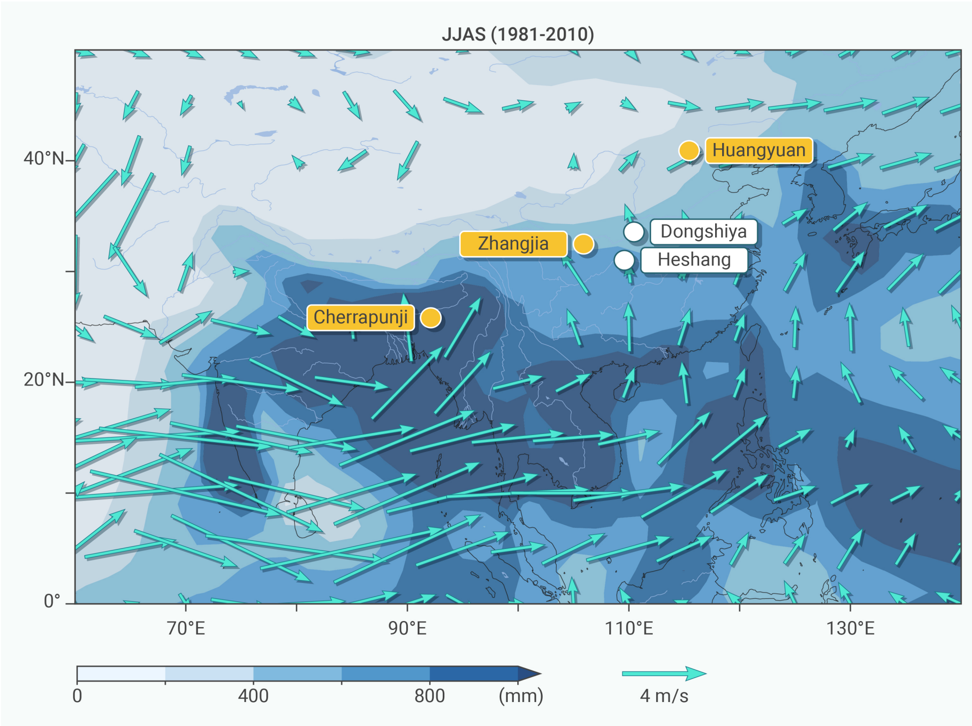

Figure 1. Cave locations Yellow dots show the locations of the cave records during the early Holocene and the last glacial period. White dots indicate the locations of the cave records spanning recent centuries. The background is the June–September (JJAS) rainfall (shaded) averaged over 1981–2010 CE from the Global Precipitation Climatology Project (GPCP)[81] and the JJAS low-level wind (arrows) from National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis.[82]

where $x(t)$ denotes the interpolated time series, b is the filtering bandwidth, and $K(x,b)(t)$ represents the discrete Gaussian smoothing operator. The kernel operation is defined as:

$$K(x,b)(t) = \frac{1}{b\sqrt{2\pi}} \sum_{\tau=-\infty}^{\infty} x(\tau) \cdot e^{-\frac{(t-\tau)^2}{2b^2}}.$$

Consequently, the EWS indicators, σ^2, α_1 and λ, were calculated in rolling window of length w (see Table 1 for the corresponding window lengths), which were shifted over detrended signal $\Delta x(t)$. While variance (σ^2) and the lag-1 autocorrelation coefficient (α_1) can be estimated directly, we followed the methods[9] for the calculation of the restoring rate (λ), where further details can be found. We only considered time periods prior to abrupt transitions. For all metrics, temporal trends were evaluated using Kendall's tau (τ) rank correlation coefficient, a nonparametric measure detecting monotonic increases. It allows us to identify systematic growth patterns indicative of CSD, where higher τ values indicate strengthened monotonic trends.

Sensitivity tests were conducted using different combinations of filtering bandwidths (b) and rolling window sizes (w), systematically calculating Kendall's τ for each combination to assess their influence on the EWS indicators. The resulting heatmaps are shown in Figures S1-S2. They revealed robust operational domains where indicator trends remained stable against parameter variations, distinguishing true transition signatures from methodological artifacts.

To assess statistical significance and mitigate false positives, we compared the true τ value with those derived from 1,000 surrogate time series preserving the autocorrelation structure of the detrended residuals. Statistical significance of trends was evaluated against a null distribution of Kendall's τ values, derived from 1,000 phase-randomized surrogates generated via Fourier transform and phase scrambling of the detrended time series.[9] The significance probability $1-P=P(\tau^* \leq \tau)$ was calculated as the proportion of surrogate τ values (τ^*) smaller than the observed τ. Their distributions for the EWS indicators are visualized in Figures S3-S4. We adopted $P<0.1$ as the significance threshold, consistent with methodologies established in prior research.[18,35,58]

RESULTS AND DISCUSSION

Analysis of EWS prior to past abrupt monsoon shifts (tippings)

Analysis results of the Cherrapunji-2017-1 record show significant increases in α_1 and σ^2 prior to the abrupt monsoon shift at H2 (about 24.4 ka BP), with a confidence level over 90% (Figure 2A), signaling enhanced instability of monsoon dynamics before H2. H2 is characterized by an approximately 2 ‰ increase in the $\delta^{18}O$ in the Cherrapunji-2017-1 record (Figure 2A), which took place within 76 ±5 years,[31] indicating a rather abrupt tipping in the ASM dynamic. It is worth mentioning that α_1 increases merely to a maximum value of approximately 0.7 (Figure 2A), which is considerably lower than the theoretically expected value (i.e., α_1=1). Generally, it is the increasing trends of the lag-1 autocorrelation coefficient (α_1) and the variance (σ^2), rather than their absolute values, that serve as key indicators of the CSD.[22,35] As such, even if the values of α_1 are likely influenced by external or site-specific factors (e.g., the epikarst processes here), their increasing trends are still diagnostically meaningful. Nevertheless, its value shortly before abrupt transitions can provide a reference for EWS analyses of modern speleothems from the same cave, through which one might get further, at least qualitatively, insight on how close we might be to a potential TP in the future.

Analysis results of the Cherrapunji-2 record also show significant EWS before the monsoon abrupt weakening at H2b (about 26 ka BP) (Figure 2B). The amplitude of speleothem $\delta^{18}O$ changes during H2 (ca. 2‰) is approximately twice as large as that during H2b (ca. 1‰) (Figures 2A-B). Intriguingly, the amplitude of EWS changes prior to H2 is also significantly larger than that before H2b (Figures 2A-B).

To further examine the reliability of EWS in these speleothem records prior to H2 and H2b, we also calculated α_1 and σ^2 for a period without abrupt monsoon shifts (Figure 2C). The results show no signs of EWS, with α_1 remaining within a small range below 0.5 (Figure 2C), and no significant increasing trends of the EWS indicators are observed either (Figures 2C & S3C). This suggests that the EWS analyses on these speleothem $\delta^{18}O$ records may not be particularly affected by the "false positive" problem. Additionally, we searched for EWS prior to the abrupt shift during the 8.2 ka event in the speleothem BH-2 record from northern China (Figure 2D). The 8.2 ka event is a Northern Hemisphere cooling event, which occurred approximately 8,200 years ago and was accompanied by a significant weakening of the ASM and the AMOC.[59] Our analysis also revealed significant increases of traditional EWS before the abrupt monsoon weakening associated with this event (Figure 2D), reinforcing the feasibility of deriving EWS from interglacial speleothem records. In addition to the aforementioned abrupt weakening events, we also analyzed EWS for the sudden ASM intensification associated with the abrupt warming of DO-8 (Figure 2E). The results also show significant increasing trends of the traditional EWS indicators prior to the abrupt ASM intensification around 38.34 ka BP (Figure 2E).

In addition to the traditional EWS, we further calculated the restoring rate (λ) of the speleothem records. Prior to the sudden monsoon changes at H2, H2b and DO-8, all λ values exhibit an increasing trend, continuously approaching to 0, indicating a loss of the resilience in the ASM system prior to these TPs (Figure 2). It should be noted that the change in λ before the abrupt shift during the 8.2 ka event was not significant (P > 0.1). However, it is important that the λ value was already very close to 0, and α_1 was also approaching 1 (Figure 2D). Therefore, the multifactorial analysis still supports the presence of EWS signatures prior to the 8.2 ka abrupt event.

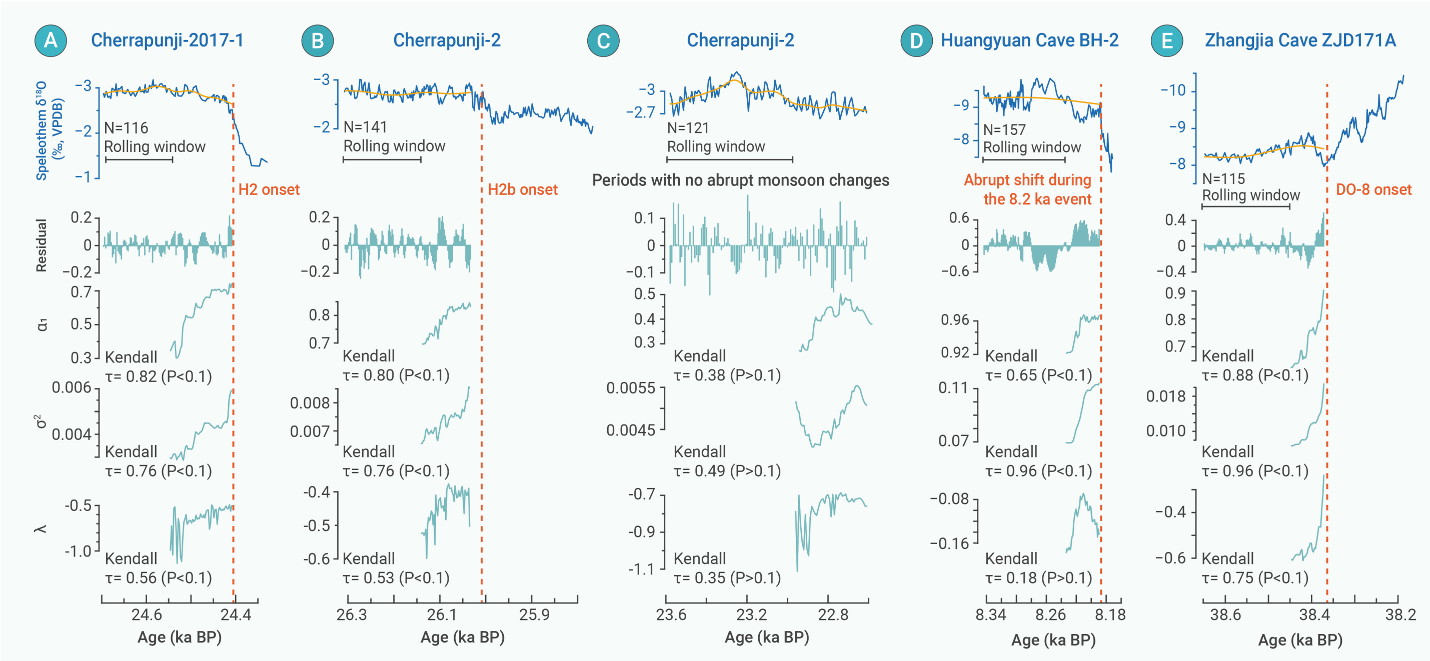

Figure 2. Early warning signals preceding past tipping points in the ASM circulation (A) Speleothem Cherrapunji-2017-1 δ18O record from Cherrapunji Cave,[31] along with early warning signals (lag-1 autocorrelation: α_1; variance: σ^2; restoring rate: λ) based on 116 data points prior to the tipping. The yellow curve represents the Gaussian-smoothed trend, with the residuals shown below. The vertical dashed line marks the onset of Heinrich 2 (H2) event (the identified tipping point). (B), (D), (E) are the same as in (A), but for speleothem Cherrapunji-2 from Cherrapunji Cave,[31] BH-2 from Huangyuan Cave,[52] and ZJD171A from Zhangjia Cave,[51] respectively. The tipping points correspond to the onset of H2b, the 8.2 ka cold event, and the Dansgaard-Oeschger (DO)-8 warm event. (C) A reference scenario showing no abrupt monsoon shifts, based on speleothem Cherrapunji-2 from Cherrapunji Cave.[31] Cave locations refer to Figure 1. Note that the early warning signals are statistically significant (P<0.1) in (A), (B) and (E), while they are not significant (P>0.1) in (C). In (D), only λ is not significant.

Overall, our analyses demonstrate that significant EWS is detectable prior at least to some of the abrupt ASM weakening and strengthening shifts recorded in speleothem δ18O records, which correspond to North Atlantic cooling and warming events, respectively. However, further analysis remains critical to answer whether EWS consistently precede other or even all the abrupt climate events that have occurred in past. This largely depends on the development of a series of new-generation paleoclimate records with much improved temporal resolution and chronology precision.

EWS over recent centuries and implications for future ASM changes

EWS analyses on the past abrupt ASM shifts (or tippings) may help shed light on the modern scenario, although climate conditions are quite different. As such, besides analyses of EWS in past ASM records, we further analyzed two speleothem records over recent two centuries. Albeit obtained from different caves, these two δ18O records reveal a consistent long-term ASM weakening trend that has persisted since the mid- 20th century (Figure 3).[46]

Remarkably, all EWS indicators derived from the two recent speleothem time series show a statistically significant increase in recent decades at 90% confidence, suggesting that the ASM might be approaching a TP (Figure 3). Sensitivity tests demonstrate the robustness of our EWS results derived from modern speleothem records (Figure S2). Importantly, and especially for natural systems, there are no strict prerequisites for the EWS indicators to reach their theoretical limits of $\alpha_1 = 1$ and $\lambda = 0$ at TPs due to the influence of noise (e.g., epikarst processes) and/or external processes. In fact, the observed α_1 values were between approximately 0.7 and 0.96 prior to the analyzed ASM tippings that occurred in the history (Figure 2). These results have important implications for evaluating EWS derived based on modern speleothems. Notably, the latest α_1 values (~0.86–0.88, Figure 3) are quite close to the values observed prior to abrupt ASM events (or TPs) in the past (Figure 2). This similarity, together with the observed significant increases in all EWS indicators, suggests that the ASM may now be approaching a potential TP, mirroring the scenarios that preceded past ASM abrupt shifts.

Although our study provides a projection of a future ASM TP, estimating its precise timing remains challenging due to the qualitative nature our approach. Nevertheless, analogous to the past scenarios (Figure 4A), the recent significant increases observed in α_1 (Figure 4B) can be viewed as causal precursors to a possible tipping in the future, or in other words, the recent EWS may be comparable to those seen in the past (the dashed boxes in Figures 4A-B). If so, it seems likely that the ASM might reach a TP and undergo a dynamic tipping in a few decades (as marked by the blue shaded "projected" region in Figure 4B).

Potential drivers of abrupt ASM shifts

It has long been recognized both empirically and theoretically that the ASM circulation/convection is tightly coupled with AMOC changes on multiple timescales. Mechanistically, the AMOC variability can alter interhemispheric meridional temperature gradients, which subsequently modulate the differential heating between land and oceanic atmospheric columns over the Asian monsoon region, further changing the ASM circulation/convection.[39,46,60] The ASM weakening trend over the past several decades, as inferred from the speleothem δ18O records, seems to be able to link to the AMOC change (weakening in the last decades) to some extent as well.[46,61] Nevertheless, there is an ongoing debate about whether the AMOC has yet significantly weakened over the past several decades.[62-65] Even so, the ongoing ASM weakening is very likely to continue in the future (Figure 4D).[2,46] This appears to be consistent with the projected AMOC weakening (with high confidence) in the 21st century.[2] Of note is that recent studies have further suggested that a possible TP of the AMOC might be forthcoming[13] and could occur at ~2,057 CE, with a 95% confidence interval spanning 2,025–2,095 CE (Figure S5).[37] These timing estimations for an AMOC tipping are broadly consistent with our qualitative approximation for an ASM tipping in the future (Figure 4). From a broader perspective, abrupt ASM changes, such as those associated with DO, Heinrich and 8.2 ka events, have also been primarily attributed to AMOC variations.[31,39,66-68] We thus speculate that the AMOC and ASM are still causally linked, both manifesting EWS in recent proxy data and hence likely to tipping in tandem in the near future. Indeed, Zhao[46] demonstrated a similarity between AMOC records and ASM speleothem records (represented by the first principal component of six records, Figure 4C), although this similarity remains an empirical observation rather than a causal assertion.

It is important to note that the response of the AMOC to warming scenarios varies substantially among models from the Climate Model Intercomparison Project Phase 6 (CMIP6), so confidence in assessments of future tipping

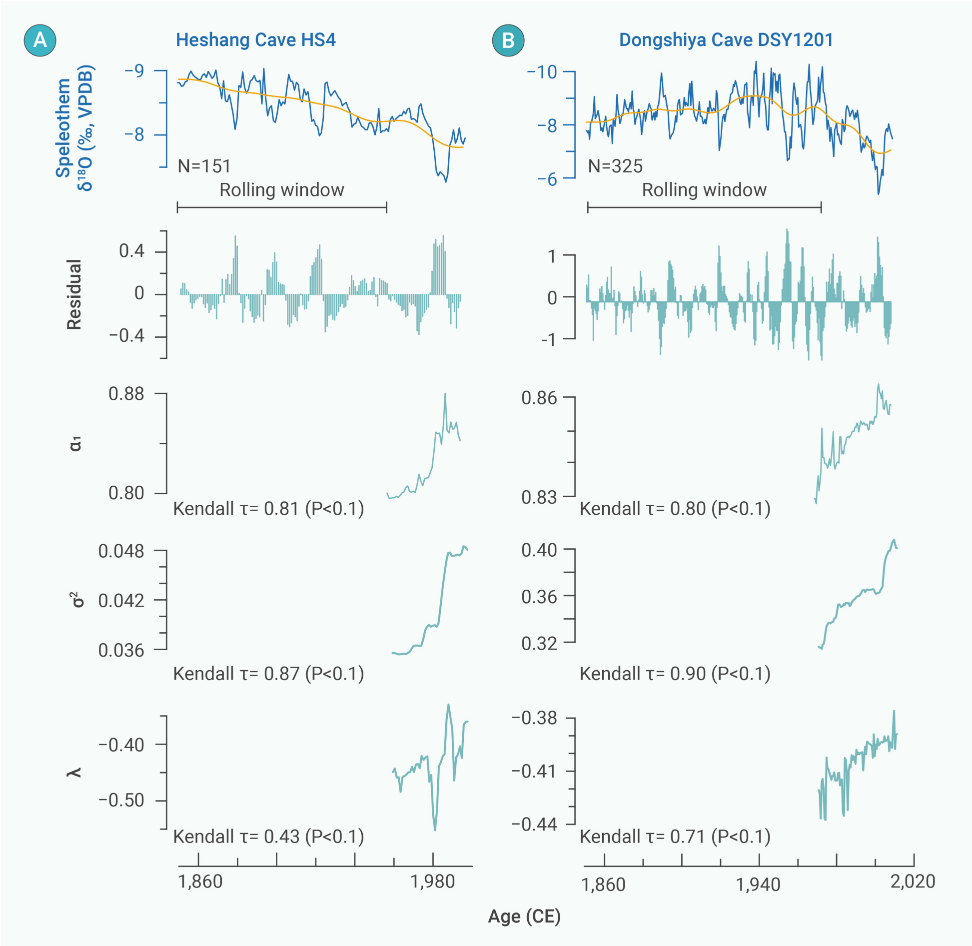

Figure 3. Analyses of early warning signals for the modern ASM circulation (A) Speleothem HS4 δ[18]O record from Heshang Cave[49] and the analyses for early warning signals (lag-1 autocorrelation: α_1; variance: σ^2; restoring rate: λ). The yellow curve represents the Gaussian-smoothed trend, with the residuals shown below. (B) is the same as in (A), but for speleothem DSY-1201 from Dongshiya Cave.[57] Cave locations refer to Figure 1. Note that all early warning signals are significant (P<0.1).

remains low.[2,69] Besides, other factors, such as dust aerosols, may also play important roles.[70,71] Nevertheless, how these mechanisms operate requires further investigation, which is beyond the scope of this study. Importantly, our EWS analysis does not depend on a specific AMOC-ASM coupling mechanism. The statistical indicators used here (lag-1 autocorrelation coefficient, variance, and restoring rate) are derived from the speleothem δ[18]O time series themselves, and indicate changes in the system's stability, which are, at least theoretically, independent of the underlying drivers in effect.[13,22]

Future rainfall variabilities across China

We note that the dynamical weakening of the ASM differs from the changes in rainfall amount, or the thermodynamic nature of the ASM (Figures 4D-E). In the context of the ongoing global warming, the moisture content of the atmosphere is expected to increase due to its enhanced water-vapor holding capacity.[72] Therefore, an abrupt weakening of the ASM dynamic may substantially enhance rainfall and/or flooding in southern China in this century, similar to the situation during Heinrich stadial 1.[73] Future changes in the amount of rainfall in northern China may likely be determined by a "tug of war" between the decreased monsoonal moisture transport caused by a weakened ASM circulation and the enhanced moisture content of the atmosphere due to global warming.

The ASM system as a potential climate tipping element

Currently recognized climate tipping elements (such as the AMOC or the Greenland Ice Sheet) are primarily identified based on three core criteria:[36,74] (1) self-perpetuating threshold response: once crossing a critical threshold, the system's evolution continues even if external forcing ceases; (2) irreversibility: the state change resulting from abrupt transition cannot be reversed within human lifespan (typically one century); and (3) macroscopic spatial scale: the impact must reach subcontinental scale, covering regions larger than 1 million square kilometers.

We argue that the ASM may also be a tipping element due to the following evidence. Firstly, on the basis of our qualitative EWS assessments, we suggest that the ASM may be approaching a TP within this century. Although a quantitative evaluation remains challenging and the ASM system is far more complex than one-dimensional speleothem δ[18]O timeseries, our EWS analysis suggests for the first time, that the ASM might undergo an abrupt change in the near future. Secondly, previous paleoclimatic studies indicate that the large-scale abrupt changes in the ASM require centuries to millennia to recover,[50,75] thus they behave irreversibly within the human lifespan. Thirdly, abrupt changes in the ASM circulation would have widespread impacts, with significant consequences affecting billions of people.[76,77] However, current model-based evidence remains inconclusive regarding whether the Asian monsoon can maintain self-perpetuating behavior (e.g., through moisture-advection feedback) under future climate conditions— particularly in the context of interactions with abrupt system transitions. This critical knowledge gap necessitates further research.

In short, as long as our EWS analysis is plausible, the ASM system may be considered to be a climate tipping element — a proposition requiring urgent validation, especially with respect to its self-perpetuating behavior.

Future outlook

Recent studies have introduced novel types of EWS, such as wavelet-based EWS, to analyze specific time series.[15,16,78] However, the application of these indicators to speleothem δ[18]O records requires further inquiry. To date, studies of abrupt climate events in speleothem records have primarily focused on their internal structures and underlying mechanisms, with much less attention paid to the equally critical periods preceding the abrupt shifts (or TPs).[79] Therefore, we advocate for more new generation climate reconstructions, targeting greatly improved age precision and temporal resolution of paleoclimate timeseries prior to abrupt climate shifts. Given the potentially complex influence of karst processes on cave systems, it would be ideal to reconstruct both paleo- and modern speleothem records from nearby samples within the same cave. This would allow to put recent ASM EWS into a more precise context with EWS detected prior to "real-world" tippings that happened in the past, thereby improving our ability to pinpoint whether the current ASM is approaching a TP, and if so, when this might occur. Furthermore, as subsystems of the ASM, the East Asian monsoon and Indian monsoon may likely exhibit distinct tipping behaviors due to subtle differences in their driving factors and response mechanisms. Future studies should prioritize reconstructions of additional climate records that facilitate scrutiny of regional differences, if any indeed.

Along with speleothem δ[18]O records, tree-ring δ[18]O records from the ASM domain[80] also hold a potential for analyses of ASM EWS. Moreover, speleothems contain a great variety of other climatic and environmental indicators, such as trace elements and carbon isotopes.[29] Analyses of these alternative proxies could help assess the effectiveness of using EWS to evaluate regional climate change, as they are essentially thermodynamic in

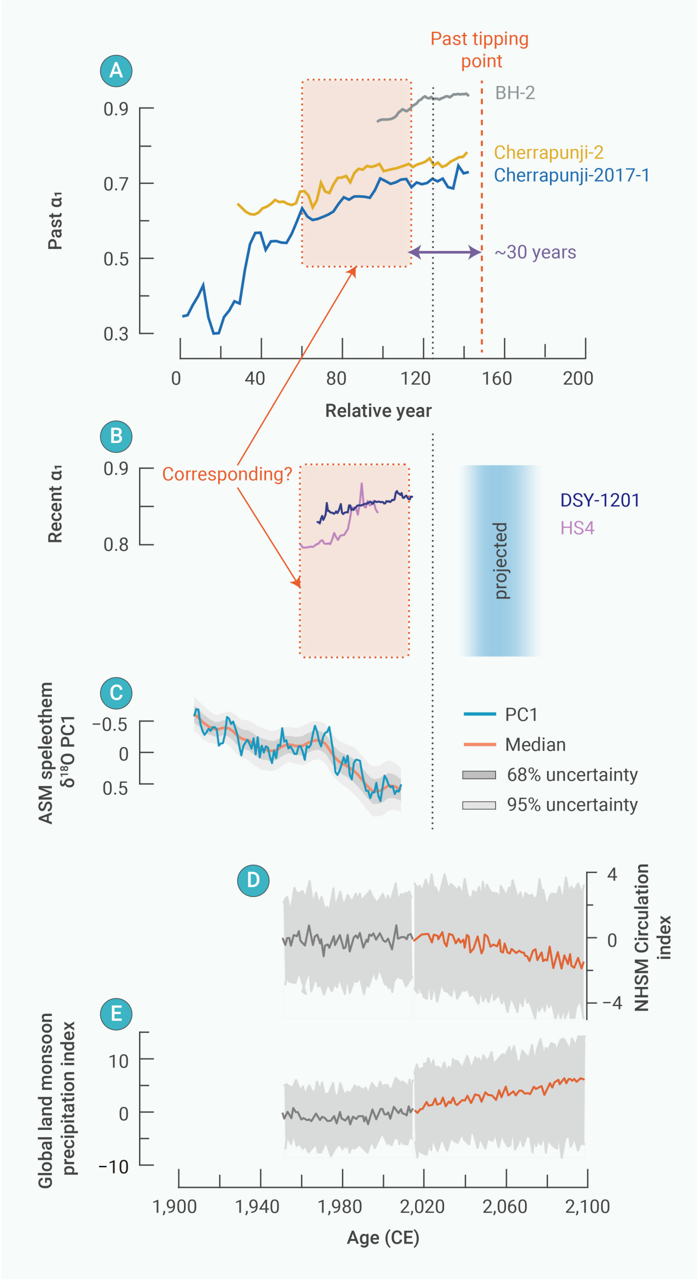

Figure 4. Qualitatively forecasting a potential tipping point in the ASM circulation: historical insights from early-warning signals (A) Lag-1 autocorrelation (α_1) preceding past abrupt ASM weakening events, consistent with Figure 2. The vertical red dashed line depicts the timing of past ASM abrupt transitions (TPs). (B) α_1 of recent ASM speleothem time series, consistent with Figure 3. The shaded "projected" region represents a qualitative projection of a future tipping point. The shaded dashed boxes in (A) and (B) highlight a tentative comparison between recent and past EWS trends. (C) The first principal Component (PC1) of six ASM speleothem $\delta^{18}O$ records.[46] (D) Anomalies of the Northern Hemisphere summer monsoon (NHSM) circulation index, defined as the vertical shear of zonal winds between 850 and 200 hPa averaged in a zone stretching from Mexico eastward to the Philippines (0°–20°N, 120°W–120°E) in Coupled Model Intercomparison Project Phase 6 (CMIP6) historical and projected simulations.[2] Anomalies are shown relative to the present-day (1,995–2,014 CE) mean. The black line shows the mean of CMIP6 historical simulations and the orange line indicates the SSP5-8.5 scenario. (E) Global land monsoon precipitation index anomalies (Unit: %), defined as the area-weighted mean precipitation rate in the global land monsoon domain for the CMIP6 historical simulation for 1,950–2,014 CE (black line, model mean) and SSP5-8.5 scenario 2,015–2,100 CE (orange line, model mean).[2] In both (D) and (E), shadings illustrate the 5–95% confidence interval. Note that the x-axis in (A) represents relative years, with year 0 tentatively aligned with 1,900 CE in the other panels.

nature, and further research is urgently needed to explore their full potential.

It should be noted that under the current assessment framework, EWS represents an insufficient condition for estimating potential TPs in the future. Future research should additionally consider the influence of noise perturbations and rate-dependent effects on early warning indicators.[8,38] Therefore, comprehensive studies, including precise data from proxies or observations, numerical modeling experiments and data-model comparisons would be crucial for advancing our ability to foresee future climate change, particularly abrupt shifts. These lines of research may help us better differentiate the impacts of the AMOC, aerosol feedbacks and other human activities on the ASM system in the context of global warming.

The ASM serves as a vital source of water for the world's most densely populated regions, the potential tipping of it clearly carries far-reaching consequences for billions of people. While the current evidence remains inconclusive regarding a possible tipping of the ASM, recognizing its possible behavior as a climate tipping element and advancing research into its mechanisms, monitoring systems, and adaptive governance strategies represent an essential response to global warming uncertainties. Continued investigation by the scientific community is indispensable to provide humanity with crucial preparation time and response capabilities.

CONCLUSION

Based on high-resolution and precisely dated speleothem $\delta^{18}O$ records, our study demonstrated for the first time that abrupt ASM changes were often preceded by significant EWS in the past. This finding opens up the possibility of foreseeing abrupt ASM changes via the analysis of EWS in ASM speleothem records. Importantly, our analyses based on high quality speleothem $\delta^{18}O$ records over the recent centuries also reveal significant increases in EWS indicators during the last few decades, suggesting that the ASM might be approaching a TP leading to an abrupt weakening. From this perspective, the ASM system can also be seen as an important tipping element in addition to many others identified already in the Earth's climate system. At present, it remains challenging to foretell when such an ASM tipping may happen. However, in the context of past abrupt ASM changes, the EWS detected in the last century appear to imply that a potential ASM tipping might take place in the next few decades. In reaching our conclusion, the key observation is not our EWS analysis of the speleothem records over the past two centuries, which may be also attainable in instrumental or other proxy records, but rather the real-world ASM tippings and their preceding EWS at earlier times. Analyses of these earlier scenarios establish the character of natural abrupt ASM changes, from which we argue that the modern comparable EWS may foreshadow a plausible ASM tipping in the near future.

REFERENCES

1. Gladwell M. (2000). The tipping point: How little things can make a big difference. (Little, Brown and Company), pp: 1–304.
2. IPCC. (2021). Climate change 2021: The physical science basis. (eds Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S.Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy,J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou) (Cambridge University Press). DOI:10.1017/9781009157896.
3. Möller T., Högner A.E., Schleussner C.-F., et al. (2024). Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nat. Commun.* **15**:6192. DOI:10.1038/s41467-024-49863-0
4. Flores B.M., Montoya E., Sakschewski B., et al. (2024). Critical transitions in the Amazon forest system. *Nature* **626**:555–564. DOI:10.1038/s41586-023-06970-0
5. Faranda D., Pons F.M.E., Giachino E., et al. (2015). Early warnings indicators of financial crises via auto regressive moving average models. *Commun. Nonlinear Sci. Numer. Simul.* **29**:233–239. DOI:10.1016/j.cnsns.2015.05.002
6. Helmich M.A., Schreuder M.J., Bringmann L.F., et al. (2024). Slow down and be critical before using early warning signals in psychopathology. *Nat. Rev. Psychol.* **3**:767–780. DOI:10.1038/s44159-024-00369-y
7. Ashwin P., Wieczorek S., Vitolo R., et al. (2012). Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. *Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci.* **370**:1166–1184. DOI:10.1098/rsta.2011.0306
8. Lohmann J., Dijkstra H.A., Jochum M., et al. (2024). Multistability and intermediate tipping of the Atlantic Ocean circulation. *Sci. Adv.* **10**:eadi4253. DOI:10.1126/sciadv.adi4253
9. Boers N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Change* **11**:680–688. DOI:10.1038/s41558-021-01097-4
10. Lohmann J., Castellana D., Ditlevsen P.D., et al. (2021). Abrupt climate change as a rate-dependent cascading tipping point. *Earth Syst. Dynam.* **12**:819–835. DOI:10.5194

/esd-12-819-2021
11. Riechers K., Gottwald G., and Boers N. (2024). Glacial abrupt climate change as a multiscale phenomenon resulting from monostable excitable dynamics. *J. Clim.* 37:2741–2763. DOI:10.1175/JCLI-D-23-0308.1
12. Riechers K., Rydin Gorjão L., Hassanibesheli F., et al. (2023). Stable stadial and interstadial states of the last glacial's climate identified in a combined stable water isotope and dust record from Greenland. *Earth Syst. Dynam.* 14:593–607. DOI:10.5194/esd-14-593-2023
13. van Westen R.M., Kliphuis M., and Dijkstra H.A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. *Sci. Adv.* 10:eadk1189. DOI:10.1126/sciadv.adk1189
14. Sinet S., Ashwin P., von der Heydt A.S., et al. (2024). AMOC stability amid tipping ice sheets: the crucial role of rate and noise. *Earth Syst. Dynam.* 15:859–873. DOI:10.5194/esd-15-859-2024
15. Boers N. (2018). Early-warning signals for Dansgaard-Oeschger events in a high-resolution ice core record. *Nat. Commun.* 9:2556. DOI:10.1038/s41467-018-04881-7
16. Hummel C., Boers N., and Rypdal M. (2024). Inconclusive Early warning signals for Dansgaard-Oeschger events across Greenland ice cores. *EGUsphere*[preprint]. DOI:10.5194/egusphere-2024-3567.
17. Dakos V., Carpenter S.R., Brock W.A., et al. (2012). Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. *PLoS One* 7:e41010. DOI:10.1371/journal.pone.0041010
18. Dakos V., Scheffer M., van Nes E.H., et al. (2008). Slowing down as an early warning signal for abrupt climate change. *Proc. Natl. Acad. Sci. U. S. A.* 105:14308–14312. DOI:10.1073/pnas.0802430105
19. Ditlevsen P.D., and Johnsen S.J. (2010). Tipping points: Early warning and wishful thinking. *Geophys. Res. Lett.* 37:L19703. DOI:10.1029/2010GL044486
20. Held H., and Kleinen T. (2004). Detection of climate system bifurcations by degenerate fingerprinting. *Geophys. Res. Lett.* 31:L23207. DOI:10.1029/2004GL020972
21. Lenton T.M. (2011). Early warning of climate tipping points. *Nature Clim Change* 1:201–209. DOI:10.1038/nclimate1143
22. Scheffer M., Bascompte J., Brock W.A., et al. (2009). Early-warning signals for critical transitions. *Nature* 461:53–59. DOI:10.1038/nature08227
23. Brovkin V., Brook E., Williams J.W., et al. (2021). Past abrupt changes, tipping points and cascading impacts in the Earth system. *Nat. Geosci.* 14:550–558. DOI:10.1038/s41561-021-00790-5
24. Boers N., Ghil M., and Stocker T.F. (2022). Theoretical and paleoclimatic evidence for abrupt transitions in the Earth system. *Environ. Res. Lett.* 17:093006. DOI:10.1088/1748-9326/ac8944
25. Dansgaard W., Johnsen S.J., Clausen H.B., et al. (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364:218–220. DOI:10.1038/364218a0
26. Rasmussen S.O., Bigler M., Blockley S.P., et al. (2014). A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* 106:14–28. DOI:10.1016/j.quascirev.2014.09.007
27. Mitsui T., and Boers N. (2024). Statistical precursor signals for Dansgaard–Oeschger cooling transitions. *Clim. Past* 20:683–699. DOI:10.5194/cp-20-683-2024
28. Cheng H., Edwards R.L., Southon J., et al. (2018). Atmospheric $^{14}C/^{12}C$ changes during the last glacial period from Hulu Cave. *Science* 362:1293–1297. DOI:10.1126/science.aau0747
29. Cheng H., Zhang H., Zhao J., et al. (2019). Chinese stalagmite paleoclimate researches: A review and perspective. *Sci. China Earth Sci.* 62:1489–1513. DOI:10.1007/s11430-019-9478-3
30. Wang Y.J., Cheng H., Edwards R.L., et al. (2001). A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* 294:2345–2348. DOI:10.1126/science.1064618
31. Dong X., Kathayat G., Rasmussen S.O., et al. (2022). Coupled atmosphere-ice-ocean dynamics during Heinrich Stadial 2. *Nat. Commun.* 13:5867. DOI:10.1038/s41467-022-33583-4
32. Hemming S.R. (2004). Heinrich events: Massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint. *Rev. Geophys.* 42. DOI:10.1029/2003RG000128
33. Menviel L.C., Skinner L.C., Tarasov L., et al. (2020). An ice–climate oscillatory framework for Dansgaard–Oeschger cycles. *Nat. Rev. Earth Environ.* 1:677–693. DOI:10.1038/s43017-020-00106-y
34. Schewe J., Levermann A., and Cheng H. (2012). A critical humidity threshold for monsoon transitions. *Clim. Past* 8:535–544. DOI:10.5194/cp-8-535-2012
35. Thomas Z.A., Kwasniok F., Boulton C.A., et al. (2015). Early warnings and missed alarms for abrupt monsoon transitions. *Clim. Past* 11:1621–1633. DOI:10.5194/cp-11-1621-2015
36. Lenton T.M., Armstrong McKay D.I., Loriani S., et al. (2023). The global tipping points report 2023. Lenton T. M., Armstrong McKay D. I., Loriani S., et al. (eds). The Global Tipping Points Report 2023 (University of Exeter), pp: 1–121. DOI: 10.5281/zenodo.15188118.
37. Ditlevsen P., and Ditlevsen S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat. Commun.* 14:4254. DOI:10.1038/s41467-023-39810-w
38. Ben-Yami M., Morr A., Bathiany S., and Boers N. (2024). Uncertainties too large to predict tipping times of major Earth system components from historical data. *Sci. Adv.* 10:eadl4841. DOI:10.1126/sciadv.adl4841
39. Cheng H., Li H., Sha L., et al. (2022). Milankovitch theory and monsoon. *The Innovation* 3:100338. DOI:10.1016/j.xinn.2022.100338
40. Cheng H., Edwards R.L., Sinha A., et al. (2016). The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* 534:640–646. DOI:10.1038/nature18591
41. Cheng H., Lawrence Edwards R., Shen C.-C., et al. (2013). Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth Planet. Sci. Lett.* 371-372:82-91. DOI: 10.1016/j.epsl.2013.04.006.
42. Niu X., Wang J., Kang L., et al. (2025). Millennial-scale climate variability of the Asian summer monsoon over the last 690,000 years: insights from cave records. *Sci. Bull.* 70:1513–1522. DOI:10.1016/j.scib.2025.02.011
43. Wang J., Niu X., Kang L., and Cheng H. (2025). U-Th and U-Pb geochronology of Quaternary carbonates. *Natl. Sci. Rev.* nwaf078. DOI: 10.1093/nsr/nwaf078.
44. Zhao J., and Cheng H. (2017). Applications of laser scanning confocal microscope to paleoclimate research: Characterizing and counting laminae[in Chinese]. *Quaternary Sciences* 37:1472–1474. DOI:10.11928/j.issn.1001-7410.2017.06.28
45. Liu X. et al. (2020) New insights on Chinese cave $\delta^{18}O$ records and their paleoclimatic significance. *Earth-Sci. Rev.* 207:103216. DOI: 10.1016/j.earscirev.2020.103216.
46. Zhao J., Cheng H., Cao J., et al. (2023). Orchestrated decline of Asian summer monsoon and Atlantic meridional overturning circulation in global warming period. *The Innovation Geosci.* 1:1–9. DOI:10.59717/j.xinn-geo.2023.100011
47. Hu J., Emile-Geay J., Tabor C., et al. (2019). Deciphering oxygen isotope records from Chinese speleothems with an isotope-enabled climate model. *Paleoceanogr. Paleoclimatology* 34:2098–2112. DOI:10.1029/2019PA003741
48. Tabor C.R., Otto-Bliesner B.L., Brady E.C., et al. (2018). Interpreting precession-driven $\delta^{18}O$ variability in the South Asian Monsoon region. *J. Geophys. Res.-Atmos.* 123:5927–5946. DOI:10.1029/2018JD028424
49. Wang M., Hu C., Liu Y., et al. (2022). Precipitation in eastern China over the past millennium varied with large-scale climate patterns. *Commun. Earth Environ.* 3:1–8. DOI:10.1038/s43247-022-00664-7
50. Cheng H., Zhang H., Spötl C., et al. (2020). Timing and structure of the Younger Dryas event and its underlying climate dynamics. *Proc. Natl. Acad. Sci. U. S. A.* 117:23408–23417. DOI:10.1073/pnas.2007869117
51. Chen X., Zhao J., Wang K., et al. (2025). Nonlinear feedback of Asian summer monsoon to abrupt events in North Atlantic: Evidence from a precisely dated speleothem record during late MIS3. *Glob. Planet. Change* 247:104733. DOI:10.1016/j.gloplacha.2025.104733
52. Duan P., Li H., Ma Z., et al. (2023). Interdecadal to centennial climate variability surrounding the 8.2 ka event in north China revealed through an annually resolved speleothem record from Beijing. *Geophys. Res. Lett.* 50:e2022GL101182. DOI: 10.1029/2022GL101182.
53. Martin K.C., Buizert C., Edwards J.S., et al. (2023). Bipolar impact and phasing of Heinrich-type climate variability. *Nature* 617:100–104. DOI:10.1038/s41586-023-05875-2
54. Zhou Y., and McManus J.F. (2024). Heinrich event ice discharge and the fate of the Atlantic Meridional Overturning Circulation. *Science* 384:983–986. DOI:10.1126/science.adh8369
55. Heinrich H. (1988). Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years. *Quat. Res.* 29:142–152. DOI:10.1016/0033-5894(88)90057-9
56. Rhodes R.H., Brook E.J., Chiang J.C.H., et al. (2015). Enhanced tropical methane production in response to iceberg discharge in the North Atlantic. *Science* 348:1016–1019. DOI:10.1126/science.1262005
57. Zhao J., Cheng H., Yang Y., et al. (2019). Reconstructing the western boundary variability of the Western Pacific Subtropical High over the past 200 years via Chinese cave oxygen isotope records. *Clim. Dyn.* 52:3741–3757. DOI:10.1007/s00382-018-4456-0
58. Boulton C.A., and Lenton T.M. (2015). Slowing down of North Pacific climate variability and its implications for abrupt ecosystem change. *Proc. Natl. Acad. Sci. U. S. A.* 112:11496–11501. DOI:10.1073/pnas.1501781112
59. Cheng H., Edwards R.L., Broecker W.S., et al. (2009). Ice Age Terminations. *Science* 326:248–252. DOI:10.1126/science.1177840
60. Sandeep N., Swapna P., Krishnan R., et al. (2020). South Asian monsoon response to weakening of Atlantic meridional overturning circulation in a warming climate. *Clim. Dyn.* 54:3507–3524. DOI:10.1007/s00382-020-05180-y
61. Caesar L., Rahmstorf S., Robinson A., et al. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* 556:191–196. DOI:10.1038/s41586-018-0006-5
62. Fraser N.J., and Cunningham S.A. (2021). 120 years of AMOC variability reconstructed from observations using the Bernoulli inverse. *Geophys. Res. Lett.* 48:e2021GL093893. DOI:10.1029/2021GL093893
63. Latif M., Sun J., Visbeck M., and Hadi Bordbar M. (2022). Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900. *Nat. Clim. Change*

12:455–460. DOI:10.1038/s41558-022-01342-4
64. Rossby T., Palter J., and Donohue K. (2022). What Can Hydrography Between the New England Slope, Bermuda and Africa Tell us About the Strength of the AMOC Over the Last 90 years. *Geophys. Res. Lett.* 49:e2022GL099173. DOI:10.1029/2022GL099173
65. Terhaar J., Vogt L., and Foukal N.P. (2025). Atlantic overturning inferred from air-sea heat fluxes indicates no decline since the 1960s. *Nat. Commun.* 16:222. DOI:10.1038/s41467-024-55297-5
66. He C., Liu Z., Otto-Bliesner B.L., et al. (2021). Hydroclimate footprint of pan-Asian monsoon water isotope during the last deglaciation. *Sci. Adv.* 7:eabe2611. DOI:10.1126/sciadv.abe2611
67. Yu T., Cheng J., Lin P., et al. (2018). Responses and mechanisms of East Asian winter and summer monsoons to weakened Atlantic meridional overturning circulation using the FGOALS-g2 model. *Int. J. Climatol.* 38:2618–2626. DOI:10.1002/joc.5373
68. Zhang R., and Delworth T.L. (2005). Simulated tropical sesponse to a substantial weakening of the Atlantic thermohaline circulation. *J. Clim.* 18:1853–1860. DOI:10.1175/JCLI3460.1
69. Baker J.A., Bell M.J., Jackson L.C., et al. (2025). Continued Atlantic overturning circulation even under climate extremes. *Nature* 638:987–994. DOI:10.1038/s41586-024-08544-0
70. Menary M.B., Robson J., Allan R.P., et al. (2020). Aerosol-forced AMOC changes in CMIP6 historical simulations. *Geophys. Res. Lett.* 47:e2020GL088166. DOI:10.1029/2020GL088166
71. Liu F., Li X., Luo Y., et al. (2024). Increased Asian aerosols drive a slowdown of Atlantic Meridional Overturning Circulation. *Nat. Commun.* 15:18. DOI:10.1038/s41467-023-44597-x
72. Trenberth K.E. (1998). Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Clim. Change* 39:667–694. DOI:10.1023/A:1005319109110
73. Zhang H., Griffiths M.L., Chiang J.C.H., et al. (2018). East Asian hydroclimate modulated by the position of the westerlies during Termination I. *Science* 362:580–583. DOI:10.1126/science.aat9393
74. Armstrong McKay D.I., Staal A., Abrams J.F., et al. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377:eabn7950. DOI: 10.1126/science.abn7950.
75. Cheng H., Xu Y., Dong X., et al. (2021). Onset and termination of Heinrich Stadial 4 and the underlying climate dynamics. *Commun. Earth Environ.* 2:1-11. DOI:10.1038/s43247-021-00304-6
76. Wang P., Wang B., Cheng H., et al. (2017). The global monsoon across time scales: Mechanisms and outstanding issues. *Earth Sci. Rev.* 174:84–121. DOI:10.1016/j.earscirev.2017.07.006
77. An Z., Wu G., Li J., et al. (2015). Global monsoon dynamics and climate change. *Annu. Rev. Earth Planet. Sci.* 43:29–77. DOI:10.1146/annurev-earth-060313-054623
78. Rypdal M. (2016). Early-warning signals for the onsets of Greenland interstadials and the Younger Dryas–preboreal transition. *J. Clim.* 29:4047–4056. DOI:10.1175/JCLI-D-15-0828.1
79. Kaushal N., Lechleitner F.A., Wilhelm M., et al. (2024). SISALv3: a global speleothem stable isotope and trace element database. *Earth Syst. Sci. Data.* 16:1933–1963. DOI:10.5194/essd-16-1933-2024
80. Xu C., Zhao Q., An W., et al. (2021). Tree-ring oxygen isotope across monsoon Asia: Common signal and local influence. *Quat. Sci. Rev.* 269:107156. DOI:10.1016/j.quascirev.2021.107156
81. Adler R., Sapiano M., Huffman G., et al. (2018). The Global Precipitation Climatology Project (GPCP) monthly analysis (New Version 2.3) and a review of 2017 global precipitation. *Atmosphere* 9: 138. DOI: 10.3390/atmos9040138.
82. Kanamitsu M., Ebisuzaki W., Woollen J., et al. (2002). NCEP–DOE AMIP-II reanalysis (R-2). *Bull. Amer. Meteor. Soc.* 83:1631–1644. DOI:10.1175/BAMS-83-11-1631

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AUTHOR CONTRIBUTIONS

Conceptualization: H.C., X.D; Analysis: X.D., R.C., X.N; Writing - original draft: X.D. Writing - review & editing: X.D., R.C., X.N., C.H., H.C; All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

Hai Cheng is an Editorial Board member of The Innovation Geoscience and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.

DATA AND CODE AVAILABILITY

No new speleothem $\delta^{18}O$ data was created in this study, all data can be found in the original references.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-geo.2025.100158

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Supplemental Information

Early warning signals for Asian summer monsoon tipping and implications for future monsoon changes

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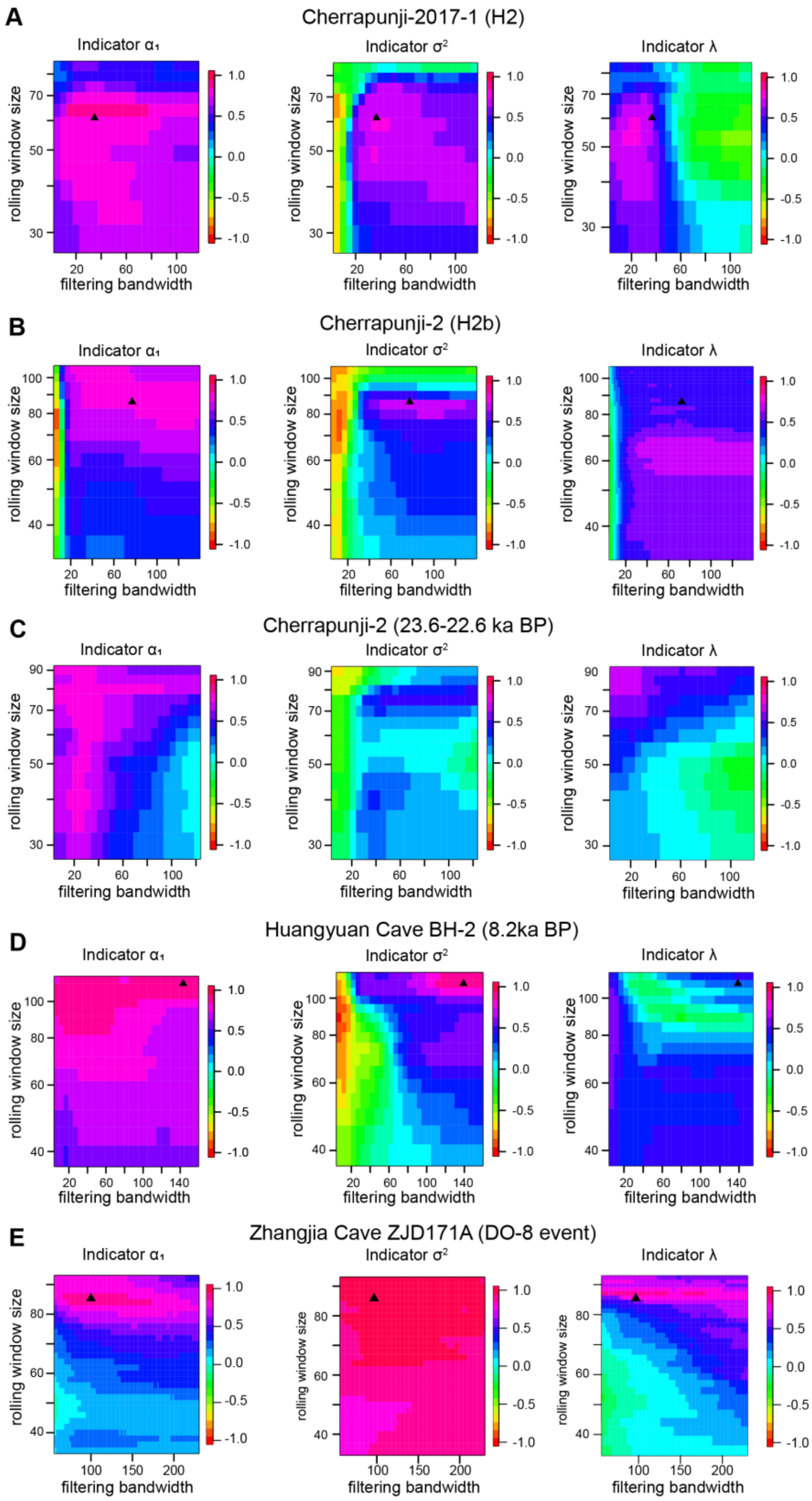

Figure S1 Sensitivity analysis for lag-1 autocorrelation coefficient, variance and restoring rate of paleoclimatic speleothem records. (A) Sensitivity analysis for the lag-1 autocorrelation coefficient (α_1) (left panel), variance (σ^2) (middle panel) and restoring rate (λ) (right panel) of the speleothem Cherrapunji-2017-1 $\delta^{18}O$ record from Cherrapunji Cave.[1] For each indicator, the heat map illustrates Kendall's τ calculated using different combinations of rolling window sizes (w) and filtering bandwidths (b).

The black triangle in heat map indicates the parameters chose for the Early warning signals (EWS) analysis. (B)–(E) are as same as in (A), but for speleothem Cherrapunji-2 (H2b and 23.6-22.6 ka BP) from Cherrapunji Cave,[1] BH-2 from Huangyuan Cave[2] and ZJD171A from Zhangjia Cave,[3] respectively.

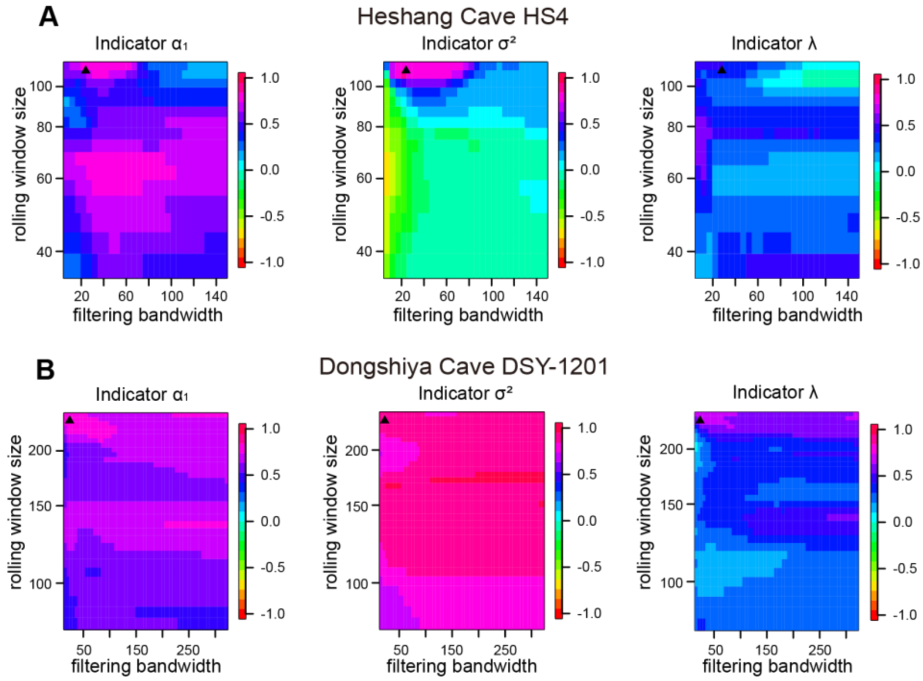

Figure S2 Sensitivity analysis for lag-1 autocorrelation coefficient, variance and restoring rate of modern speleothem records. (A) and (B) are as same as in Figure S1, but for speleothem HS4 from Heshang Cave[4] and DSY-1201 from Dongshiya Cave,[5] respectively.

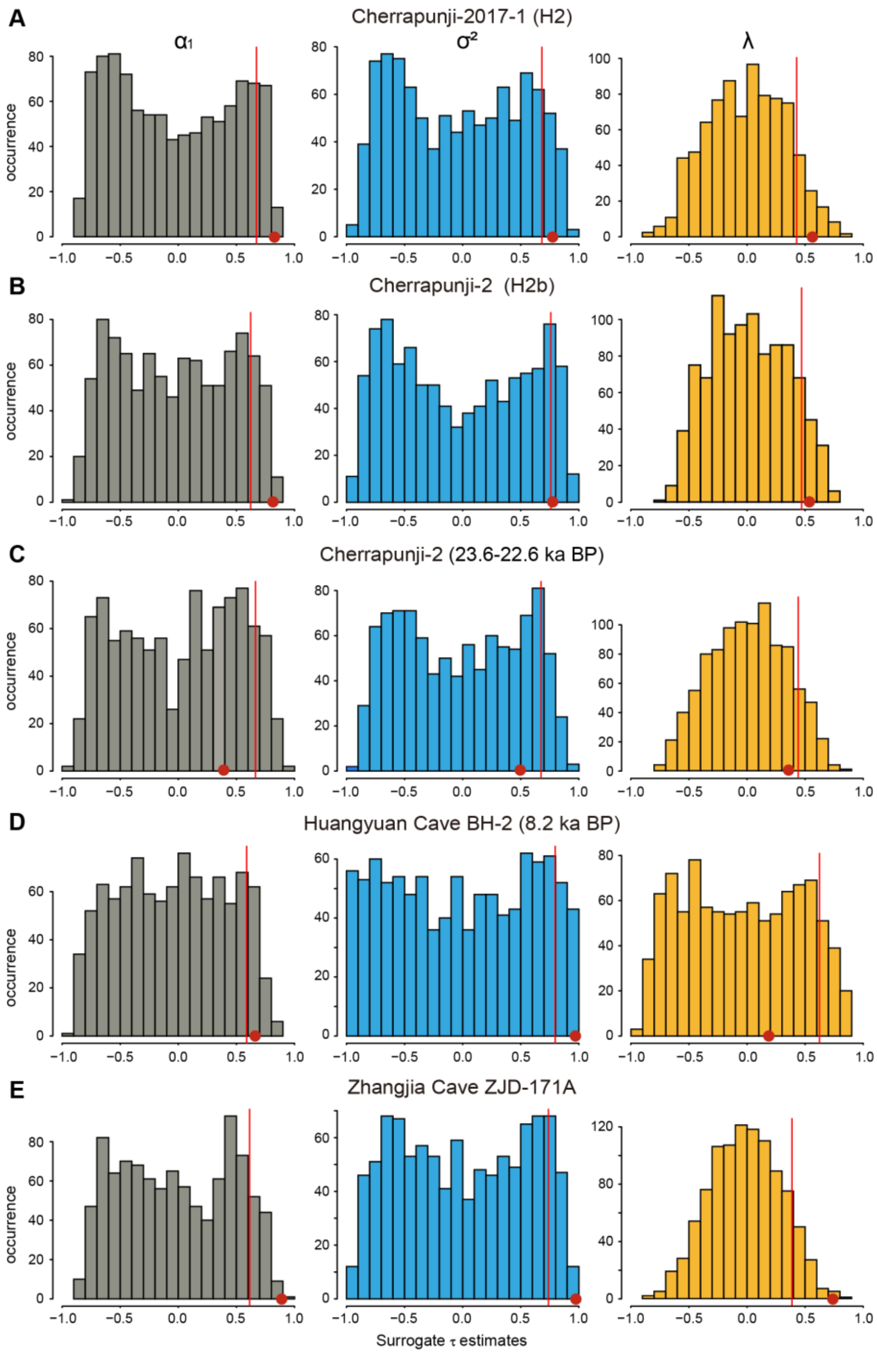

Figure S3 Significance test for the lag-1 autocorrelation coefficient, variance and restoring rate of paleoclimatic speleothem records. (A) Distribution of Kendall's τ of the lag-1 autocorrelation coefficient (left) and variance (middle) and restoring rate (right) from 1,000 surrogates of the residuals of speleothem Cherrapunji-2017-1 prior to Heinrich 2 (H2), using the selected rolling window size (w) and Gaussian filtering bandwidth (b). The red vertical line represents the significance level at $P = 0.1$. The red dot on the x-axis denotes the actual Kendall's τ estimated from the original residuals of speleothem using the same parameters. (B)–(E) are as same as in (A), but for speleothem Cherrapunji-2 (prior to H2b and spanning 23.6-22.6 ka BP, respectively) from Cherrapunji Cave,[1] BH-2 from Huangyuan Cave,[2] and ZJD-171A from Zhangjia Cave,[3] respectively.

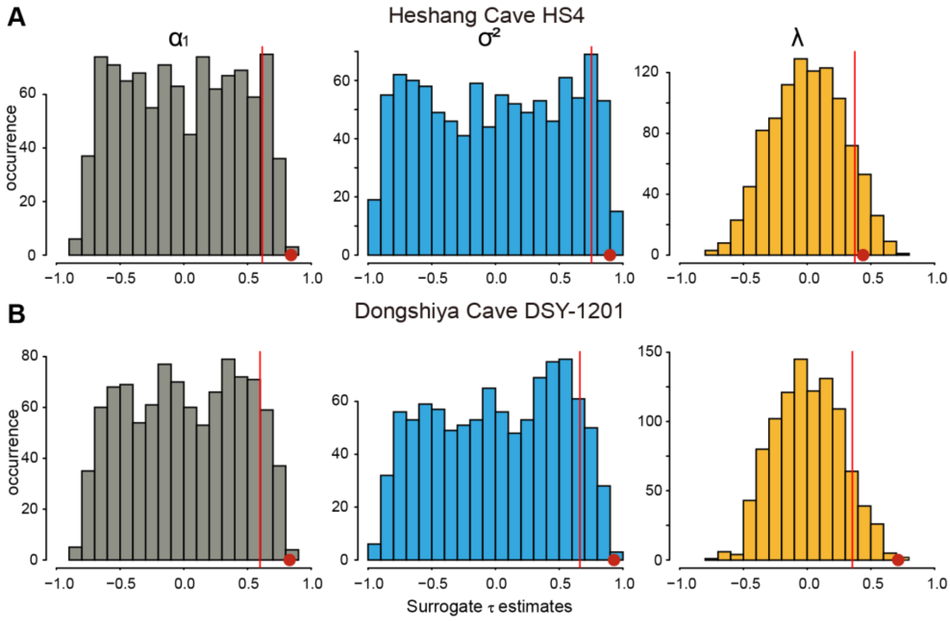

Figure S4 Significance test for the lag-1 autocorrelation coefficient, variance and restoring rate of modern speleothem records. (A) and (B) are as same as in Figure S3, but for speleothem HS4 from Heshang Cave[4] and DSY-1201 from Dongshiya Cave,[5] respectively.

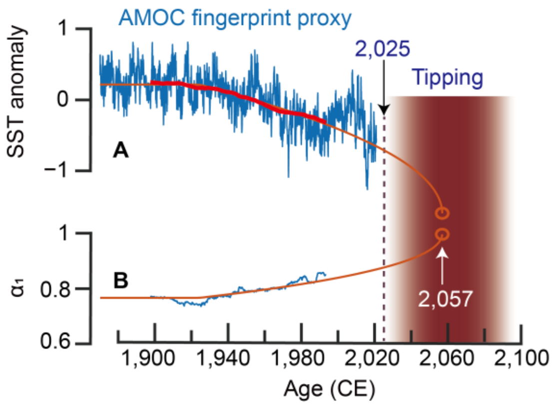

Figure S5 Projected tipping of the AMOC based on the analysis of early warning signals using AMOC fingerprint proxy. (A) The AMOC fingerprint, derived from the sea surface temperature (SST) anomaly in the subpolar gyre minus twice the global mean SST anomaly, compensating for the polar amplified global warming.[6] Also shown is the trend (red line) estimated through a linear fit between the mean level and the noise characteristics. (B) Lag-1 autocorrelation (α_1) of the SST anomaly (blue), with the estimated tipping time around 2,057 CE (white arrow).[6] The red shaded area indicates the 95% confidence range of the tipping estimate. This figure is adapted from Ditlevsen. P & Ditlevsen. S,[6] displays only the α_1 result from their more comprehensive analysis.

References

1. Dong X., Kathayat G., Rasmussen S.O., et al. (2022). Coupled atmosphere-ice-ocean dynamics during Heinrich Stadial 2. *Nat Commun* **13**:5867. DOI: 10.1038/s41467-022-33583-4.
2. Duan P., Li H., Ma Z., et al. (2023). Interdecadal to centennial climate variability surrounding the 8.2 ka event in north China revealed through an annually resolved speleothem record from Beijing. *Geophys. Res. Lett.* **50**: e2022GL101182. DOI: 10.1029/2022GL101182.
3. Chen X., Zhao J., Wang K., et al. (2025). Nonlinear feedback of Asian summer monsoon to abrupt events in North Atlantic: Evidence from a precisely dated speleothem record during late MIS3. *Glob. Planet. Change* **247**:104733. DOI: 10.1016/j.gloplacha.2025.104733.
4. Wang M., Hu C., Liu Y., et al. (2022). Precipitation in eastern China over the past millennium varied with large-scale climate patterns. *Commun Earth Environ* **3**:1-8. DOI: 10.1038/s43247-022-00664-7.
5. Zhao J., Cheng H., Yang Y., et al. (2019). Reconstructing the western boundary variability of the Western Pacific Subtropical High over the past 200 years via Chinese cave oxygen isotope records. *Clim. Dyn.* **52**:3741–3757. DOI: 10.1007/s00382-018-4456-0.
6. Ditlevsen P., and Ditlevsen S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat Commun* **14**(1):4254. DOI: 10.1038/s41467-023-39810-w.