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Communication

# A Paleoclimate Prognosis of the Future Asian Summer Monsoon Variability

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**Abstract:** In recent years, more and more record-breaking extreme weather/climate events have been reported from the Asian monsoon region, which have caused tremendous loss of property and lives. In this paper, we analyzed the Asian summer monsoon (ASM) variability during the Holocene and evaluated future climate extremes in monsoonal China from a paleoclimatic view. We found a significant regime transition to more chaotic fluctuations, with enhanced decadal variability of the ASM since 6.6 ka BP. We suggested the gradual intensification of ENSO was responsible for enhancing the ASM variability since the late mid-Holocene. If the observed relationship of monsoon mean intensity, ENSO and decadal variability of the ASM in the past 11.2 ka continue to exist, enhanced decadal variability of ASM in the future warming world will be expected. As a result, the intensification of daily precipitation extremes, superimposed on enhanced decadal variability of ASM, might make the record-breaking extremes more frequent in the future, increasing the risk of climate-related disasters in China.

**Keywords:** Asian summer monsoon; decadal variability; Holocene; ENSO; future change



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As one of the most vigorous ocean-atmosphere coupled systems on the planet, the Asian summer monsoon (ASM) brings water vapor from the tropical oceans to south and east Asia, and the adjacent marginal seas, affecting more than 60% of the world's population. While the monsoon rainfall is crucial for supporting livelihoods and human well-being in the region, anomalous spatio-temporal distributions of precipitation can bring massive floods and droughts, causing severe disruptions to the monsoon societies [1,2]. In recent years, more and more record-breaking extreme weather/climate events have been reported from the Asian monsoon region, which have caused tremendous loss of property and lives. For example, the "7.21 storm event" in Beijing, China in 2012 brought 460 mm rainfall within 18 h, resulting in 79 deaths. More recently, the "7.20 storm event" in Zhengzhou, China this July brought 553 mm rainfall within just 24 h, resulting in 292 deaths and 47 persons were reported missing. The catastrophic flooding in the middle and lower Yangtze River during the summer of 2020 caused 142 deaths and direct economic losses of 116 billion Yuan (Chinese Currency). On the other hand, a severe drought from the autumn of 2009 to the spring of 2010 in southwest China resulted in water shortages to more than 16 million residents and direct economic losses of 19 billion Yuan.

It has been suggested that the frequency and amplitude of precipitation extremes have increased in China during the past 60 years [3]. Most climatologists ascribed the increasing climate extremes to global warming [4,5]. However, short instrumental records (observational data from most meteorological stations in China are less than 100 years) limit our understanding of monsoon variability on decadal- to centennial and even longer timescales. Consequently, it is vital to reconstruct the changes in ASM beyond the instrumental period by using accurate-dated, high resolution geological and biological archives such as stalagmite, ice core, coral and tree ring.

Recently, we reported a five-year resolved stalagmite $\delta^{18}O$ record from Wuya cave from the southwest margin of the Chinese Loess Plateau [6] which provided a good opportunity to put the instrumental ASM variations into the context of the past 11,200 years (Figure 1A). The average U-Th dating errors of the stalagmites are around 1% (2σ), and the precision of the $\delta^{18}O$ analyses is <0.1‰ (2σ), making it one of the best Holocene climates records from the Chinese Loess Plateau. Located close to the northern limit of the ASM, the stalagmite $\delta^{18}O$ from the Wuya cave is sensitive to changes in the ASM intensity, in such that stronger monsoon and higher precipitation amounts result in more depleted $\delta^{18}O$ values, and vice versa. The Wuya record reveals a long-term weakening of ASM in tandem with the declining trend in the Northern Hemisphere summer insolation during the Holocene. Superimposed on this long-term trend are notable millennial- to centennial- and- decadal-scale variations (Figure 1A). The abrupt weak ASM variations on the millennial- to centennial-scale correspond well with the ice-rafted debris events in the North Atlantic, indicating a fast response of ASM to cooling at high northern latitudes via the westerlies-mediated teleconnections [6].

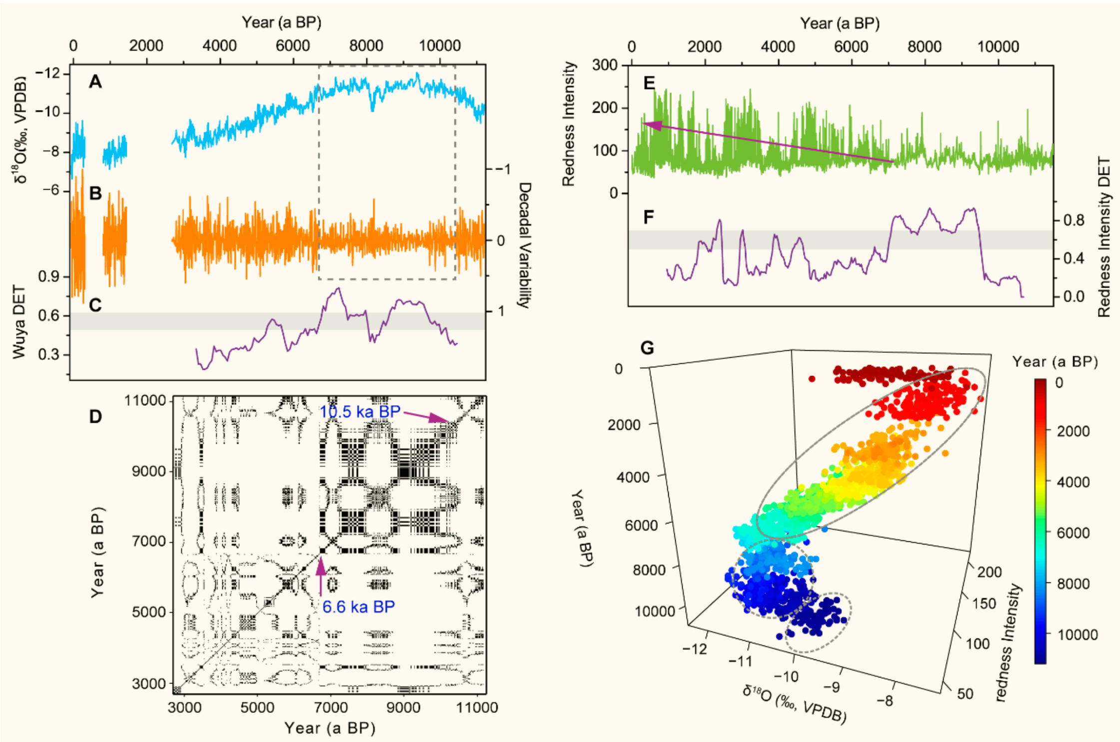


**Figure 1.** Stalagmite $\delta^{18}O$ record from Wuya cave in China and ENSO record from South American coast during the Holocene. (**A**) ASM variations indicated by Wuya $\delta^{18}O$ record [6], (**B**) Decadal scale variability of the Wuya $\delta^{18}O$ record decomposed by EEMD method [6]. The dotted box marks the strongest ASM period during the Holocene with less decadal variability. (**C**) DET measurement for the Wuya $\delta^{18}O$ record, (**D**) RP results for Wuya $\delta^{18}O$ record. The arrows indicate two regime transitions occurred at ~6.6 ka BP and 10.5 ka BP. (**E**) ENSO variations recorded by the red color intensity of lake sediment from South American coast [7], (**F**) DET measure for the red color intensity. Two gray bars in panels C and F denote 95% confidence levels. (**G**) Scatterplot of the Wuya $\delta^{18}O$ record [6] versus the red color intensity [7].

Understanding the evolution of past decadal-scale ASM variability and its future expression is extremely important from a societal point of view. The decadal timescale is also the bridge to linking short instrumental records and paleoclimatic reconstructions. We decomposed the Wuya record on different timescales by using the ensemble empirical mode decomposition (EEMD) method [6]. The results reveal a progressive increase in decadal-scale ASM variability since the late mid-Holocene (Figure 1B). Interestingly, the decadal-scale monsoon variability was also large during the weak monsoon period in the early Holocene. It is worth noting that the amplitude of ASM decadal variability during the past hundred years is the largest over the entire Holocene.

In order to detect the nonlinear dynamical transitions of the ASM and investigate the relationship between the monsoon mean state and decadal variability during the past 11,200 years, we applied recurrence plots (RP) and performed the recurrence quantification analysis of the system determinism (DET) for the Wuya $\delta^{18}O$ record. The low and high DET values indicate states with unpredictable and higher predictable (or stable) dynamics of the climate system, respectively [8,9]. A sharp change in DET values indicates a transition between different climate regimes. The RP results from the Wuya cave record show two distinct system transitions at ~10.5 and ~6.6 ka BP (Figure 1D). The DET result of the ASM shifted from low values to high ones from 10.5 ka BP and remained high for the next 5 ka, except for a short break during the 8.2 ka event. From 7.2 ka BP, the DET values continued to decrease and remained lower than the 95% confidence interval after 6.6 ka BP (Figure 1C), indicating a significant regime transition to more chaotic fluctuations, consistent with the enhanced decadal variability of the ASM since the late mid-Holocene (Figure 1B). The high DET values between 10.5 and 6.6 ka BP correspond well with the strongest monsoon period during the Holocene indicating stable climate conditions during this period with smaller decadal variability. A recently synthesized study also suggested more stable climate conditions during the middle Holocene in the EASM region of China [10], although the timing is slightly different from the Wuya record because of the relative larger dating uncertainties of the synthesized records and regional climate differences.

Considering the close relationship between the El Niño Southern Oscillation (ENSO) and ASM, the gradual intensification of ENSO has been suggested to be responsible for enhancing the ASM variability since the late mid-Holocene [6]. Indeed, proxy reconstructions [7,11] and modelling results [12] suggest that the ENSO variance reached a minimum around the mid-Holocene and increased thereafter. For example, the red color intensity measurements of lake sediments from the South American coast [7] reveal enhanced precipitation variability caused by strengthened ENSO activities since the late mid-Holocene (Figure 1E). The DET measurement for this record (Figure 1F) also indicates a regime transition to more chaotic conditions of ENSO after ~6.9 ka BP (lower than the 95% confidence interval), generally consistent with the Wuya record. The scatterplots of the Wuya $\delta^{18}O$ record and redness data also confirm the relationship dynamics of the ASM and ENSO. A generally significant positive correlation (r = 0.124, $p < 0.01$, 30 years smoothing) between the series has been observed in the past 11,200 years, with the correlations decreasing from the beginning of the Holocene and remaining low during ~10 ka and 7 ka. After that, gradually increased correlations can be observed (Figure 1G).

On a processional cycle, the Northern Hemisphere summer insolation will continue to decline in the next millennium [13], implying a further reduction in ASM intensity on an orbital timescale. Model simulations suggest the orbitally induced strengthening of ENSO since the middle Holocene was probably caused by increasing positive ocean–atmosphere feedbacks of tropical warming [12]. Some model projections of future greenhouse warming scenarios suggest a weaker gradient between the western and eastern Pacific Sea surface temperatures, which resemble more El Nino-like conditions [14]. If the observed relationship of the monsoon mean intensity, ENSO, and decadal variability of the ASM in the past 11,200 years continue to exist, one can expect enhanced decadal variability of ASM in the future. Nevertheless, the ASM could also be affected by other atmosphere and ocean circulation systems, such as the Intertropical Convergence Zone, Atlantic meridional overturning circulation, Western Pacific subtropical high, Atlantic Multidecadal Oscillation, land-sea pressure gradients, etc. In addition, debates and significant uncertainties have existed in ENSO amplitude projects in the 21st century in response to global warming in different models [15]. As a result, improved models, more accurately dated paleoclimate and ENSO records are needed in the future.

Considering the increase in moisture convergence due to increased sea surface evaporation and water vapor in the air column in a warming world [4], the intensification of daily precipitation extremes [16] superimposed on enhanced decadal variability of ASM might make the record-breaking extremes more frequent in the future, increasing the risk of climate-related disasters in monsoonal China. Adaptive strategies of urban and agriculture planning for the future ASM variability should be considered.

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**Data Availability Statement:** The raw data in this paper can be obtained from East Asian Paleoenvironmental Science Database online (http://paleodata.ieecas.cn/FrmDataInfo.aspx?id=86de4c11-dced-4944-a752-bfc2d2409b12 accessed on 16 October 2021).

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**Conflicts of Interest:** The authors declare no conflict of interest.

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