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Natural and anthropogenic impacts on the Asian monsoon precipitation during the 20th century

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The increase in the global average temperature during the last century is considered an integrated result of anthropogenic and natural forcing, but different views remain about the anthropogenic impacts on the Asian monsoon precipitation. Based on the ~2000-year records of stalagmite $\delta^{18}O$ from the Dongge Cave (Guizhou Province) and Wanxiang Cave (Gansu Province), we address the possible anthropogenic impacts on the southwest and southeast Asian monsoon from 1900–2000 AD, using the method of Singular Spectrum Analysis (SSA). The results show that the monsoon precipitation trends in the last 100 years at both sites can be obtained through SSA prediction using the data prior to 1900 AD. These suggest that human activity has not significantly affected the trends of monsoon precipitation despite of its impact on the global temperature.

global warming, Asian monsoon, Singular Spectrum Analysis (SSA), stalagmite $\delta^{18}O$

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The increase in the global surface temperature during the 20th century has become a common concern for scientists and public alike [1]. Among the possible consequences of this global warming trend, the spatial variability of rainfall, particularly for the monsoon regions, received much attention [2] as ~60% of the world's population resides in the monsoon zones [3]. Discriminating the possible impacts of human activity and natural forcing on the monsoon precipitation is particularly important for understanding the future changes of monsoon rainfall.

Observation data showed that precipitation in the southwest [4, 5] and southeast Asian monsoon zones [6] decreased in the last several decades. However, controversies persist over the underlying causes. One view suggested that human activity would have increased the Asian monsoon rainfall due to increased water vapor supply and land-sea thermal contrasts along with the increased continental surface temperature [7]. Some other scientists considered that human activity would have weakened the monsoon precipitation through releasing sulfate and black carbon aerosols, which may offset the hydrological effects of greenhouse warming [8, 9]. A third view suggested that global warming in the last century had not significantly affected the monsoon precipitation in Asia [10, 11]. There is, thus, a need to explore this issue through examining relevant geological records as the available instrumental data are too short to capture the full range of monsoon variability.

In recent years, several high-resolution stalagmite records were recovered from the southwest and southeast monsoon zones in Asia, yielding the monsoon histories for the past 2000 years. Although the significance of stalagmite $\delta^{18}O$ is still a controversial issue [12], it is mostly inter-

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preted as a proxy of monsoon precipitation [13–15].

In this paper, the ~2000-year stalagmite $\delta^{18}O$ monsoon records from the Dongge [14] (southwest monsoon zone) and the Wanxiang caves [16] (southeast monsoon zone) are examined using the method of Singular Spectrum Analysis (SSA) [17] to explore the possible influences of human activity and natural forcing on the monsoon precipitation during the 20th century.

1 Materials and methods

The 2000-year stalagmite $\delta^{18}O$ record of Dongge Cave [14] from the southwest monsoon zone and the 1810-year record of Wanxiang Cave [16] from the southeast monsoon zone were analyzed. They were interpolated respectively into 5-year and 2-year spaced data before the time-series analyses, according to their original analytical resolutions.

Time-series analysis is one of the methods for climate prediction. The rationale is to predict the unknown future trends based on known datasets. SSA method [17] is a powerful tool for time-series prediction as it is able to identify the trends, oscillatory components, and noises within a time-series through orthogonal decomposition [18–20]. Selected components can then be used to reconstruct and predict future changes under the conditions that no major changes of climate cycles occurred over the time interval considered [21, 22]. Maximum entropy spectral analyses [23] were performed to check the possible changes in the main climate cycles.

The rationale of this study is as follows:

(1) We assume that the changes of monsoon precipitation prior to 1900 AD were mainly driven by natural forcing as significant human influences mainly occurred since the early 20th century, and intensified in the late 20th century [1].

(2) We use the time-series prior to 1900 AD to predict the trends for the 1900–2000 AD interval. The predicted results can be regarded as the natural trends of monsoon precipitation.

(3) We compare the predicted results with the stalagmite records to explore the possible human influences on the monsoon precipitation in the 20th century.

2 Results and discussion

Spectral analyses of the stalagmite $\delta^{18}O$ records are given in Figure 1. The results show significant ~36, ~19–14, and ~10-year cycles for the Dongge Cave, ~25, ~16, and ~12–10-year cycles for the Wanxiang Cave. The ~25 and ~12–10-year cycles in these monsoon records were already revealed in earlier studies and have been attributed to solar activity [25]. The lack of clear ~36-year cycles in the Wanxiang record may suggest a difference in the dynamics between the southeast and southwest Asian monsoons [26]. These results do not show any major changes in the dominant cycles of the monsoon precipitation close to the 20th century.

To test the validity of the SSA method for the used sta-

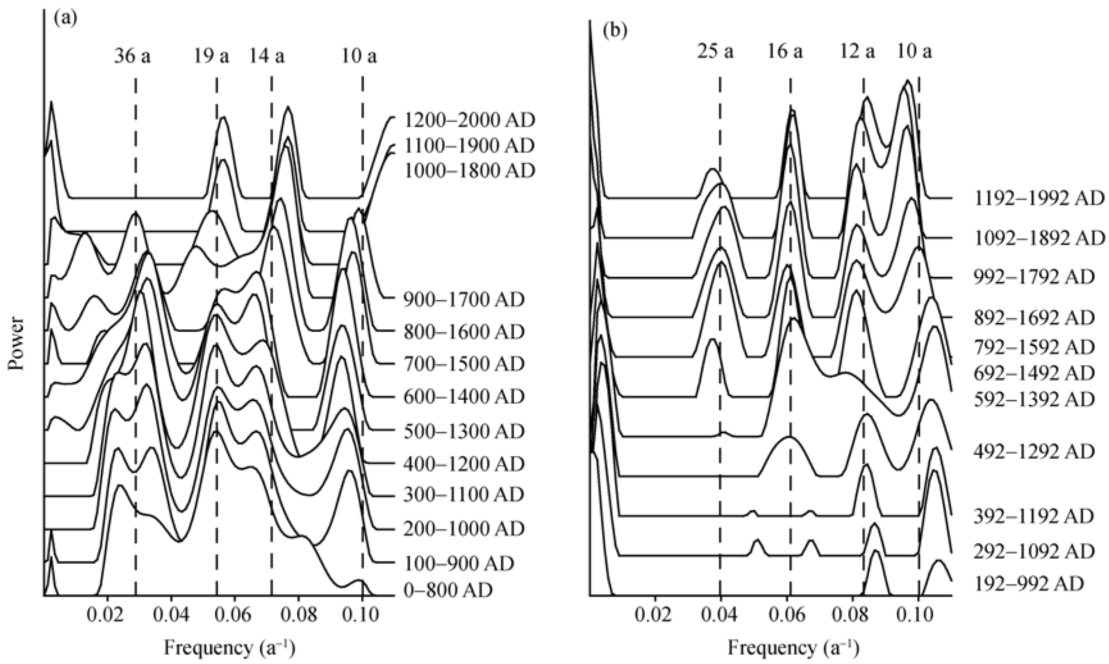

Figure 1 Spectral analyses of the stalagmite $\delta^{18}O$ records (evolutive spectra are made using a sliding window length of 800 years and a sliding step of 100 years). (a) Dongge Cave (data from ref. [14]), (b) Wanxiang Cave (data from ref. [16]). Only the spectral density over the 90% confidence limit is shown. Analyses were performed using the 3Pbase software [24].

lagmite δ^{18}O records, data prior to 1650 AD were used to predict the monsoon precipitation from 1650 to 1750 AD, an interval prior to the industrial era. The time-series were decomposed into 60 components using the SSA method. 56 components from the Dongge Cave and 49 components from the Wanxiang Cave were used for the reconstruction and prediction. The used components explain 98.35% of the variance for the Dongge Cave and 93.05% for the Wanxiang Cave. The predicted results for both records are consistent with the stalagmite records within the error ranges (Figure 2), suggesting that the SSA method is suitable for the used stalagmite records.

We then use the stalagmite δ^{18}O records prior to 1900 AD to predict monsoon precipitation trends from 1900 to 2000 AD. The time-series were also decomposed into 60 components. 56 components from the Dongge Cave and 48 components from the Wanxiang Cave were used for the reconstruction and prediction. The used components explain 98.63% of the variance for the Dongge Cave and 93.45% for the Wanxiang Cave.

Comparison between the predicted results and the stalagmite records reveals relatively larger inconsistencies for the 1930–1975 AD interval at Dongge, and for the 1975–2000 AD interval at Wanxiang (Figure 3(b), (c)). The causes are unclear. It might be attributable to temporary disturbances of the monsoon system by non-oscillatory and non-trending factors. However, the predicted trends (Figure 3) are mostly consistent with the stalagmite data with the uncertainties of predictions to the original records (−1.3%–4.1% for Dongge and −3.3%–3.6% for Wanxiang).

These results have three implications:

(1) With the assumption of an insignificant human intervention, natural forcing would have led to declining trends of the monsoon precipitation in the past century.

(2) The overall consistency between the stalagmite records and the predicted results suggests that human activity would have not significantly affected the monsoon precipitation trends in the past century despite of the influence on the global average temperature.

(3) These features are obvious for both southeast and southwest Asian monsoon zones.

Our discussions are based on an interpretation that stalagmite δ^{18}O signals are indicative of monsoon rainfall as many believed [13–15]. This interpretation is supported by

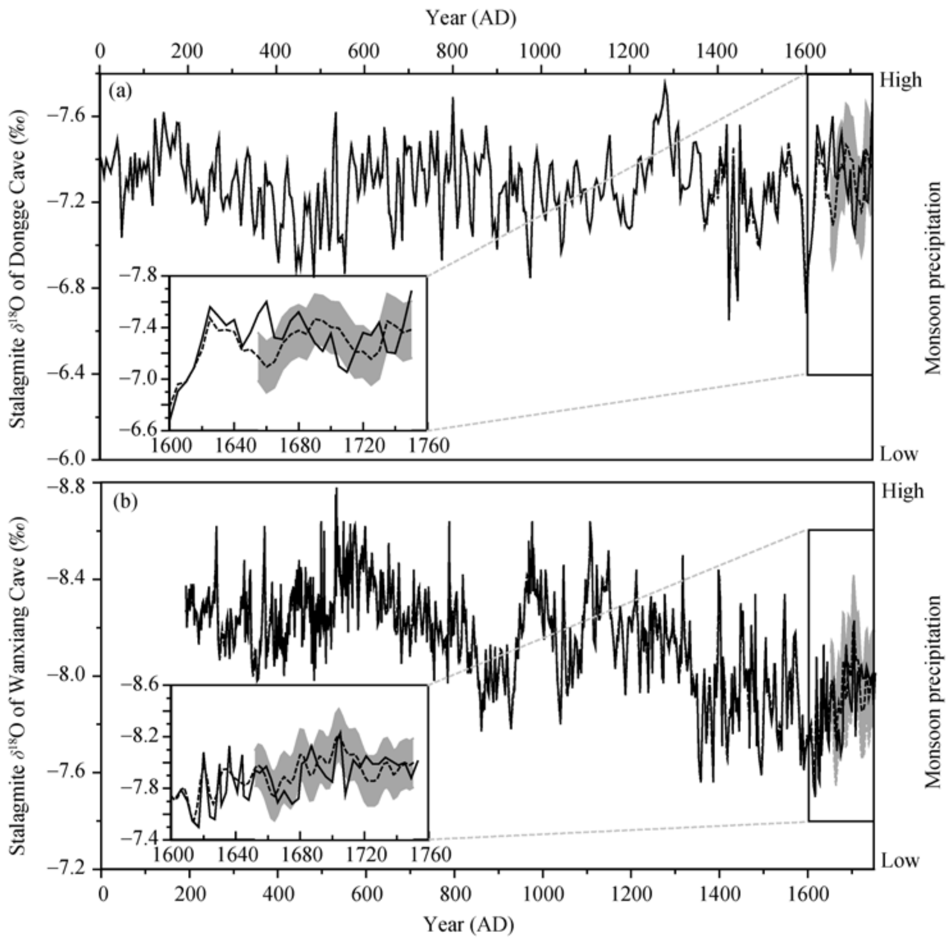

Figure 2 Comparisons between the predicted results by SSA and the stalagmite δ^{18}O records for the interval from 1650 to 1750 AD. (a) Dongge Cave [14], (b) Wanxiang Cave [16]. Stalagmite δ^{18}O records are shown in black solid line; reconstructed and predicted results are shown in black dashed line; grey shadows indicate error ranges obtained by a cross-validation model.

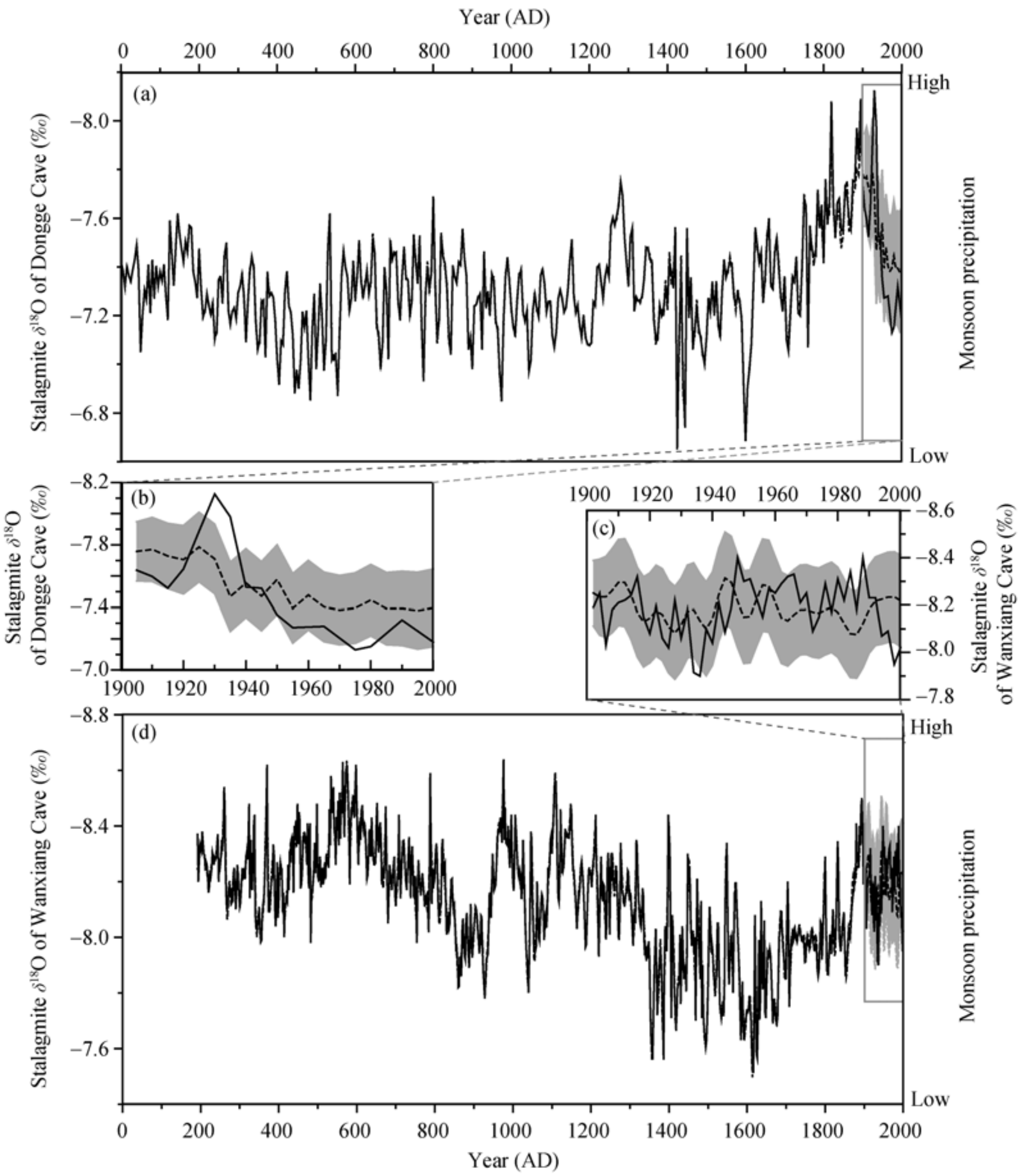

Figure 3 Comparisons between the predicted results by SSA and the stalagmite δ^{18}O records for the interval from 1900 to 2000 AD. (a), (b) Dongge Cave [14]; (c), (d) Wanxiang Cave [16]. Stalagmite δ^{18}O records are shown in black solid line; reconstructed and predicted results are shown in black dashed line; grey shadows indicate error ranges given by a cross-validation model.

the consistency between the stalagmite δ^{18}O signals and the 50-year instrumental rainfall records [27, 28]. The consistencies between the 150-year instrumental precipitation record from northwestern India [4] and the stalagmite δ^{18}O from the Dongge Cave, between the rainfall record of Beijing [29] and the stalagmite δ^{18}O signals at Wanxiang, also support this interpretation (Figure 4).

Other data also showed decreased precipitation on the northern subtropical continents and at least no increase was observed in East Asia during the 20th century [1]. These are consistent with the meteorological data of China that showed an overall drying trend in the monsoon zones for the past 50 years, with an obvious shift to drier conditions at the end of 1970s [31].

In summary, the above comparisons consistently support the validity of interpreting the stalagmite δ^{18}O signals as a proxy of monsoon rainfall for the past 2000 years, although other factors might have played some role at longer terms [12]. Accordingly, the consistency between the SSA-predicted results and the stalagmite δ^{18}O records from 1900 to 2000 AD implies that human activity has not played a significant role in modulating the monsoon precipitation trends. Our results support the view that that the decrease in the Asian monsoon precipitation since the late 20th century is a part of the natural trend [32].

The strength of Asian monsoon is generally positively correlative with the changes in land surface temperature as monsoon is strongly driven by the thermal contrast between

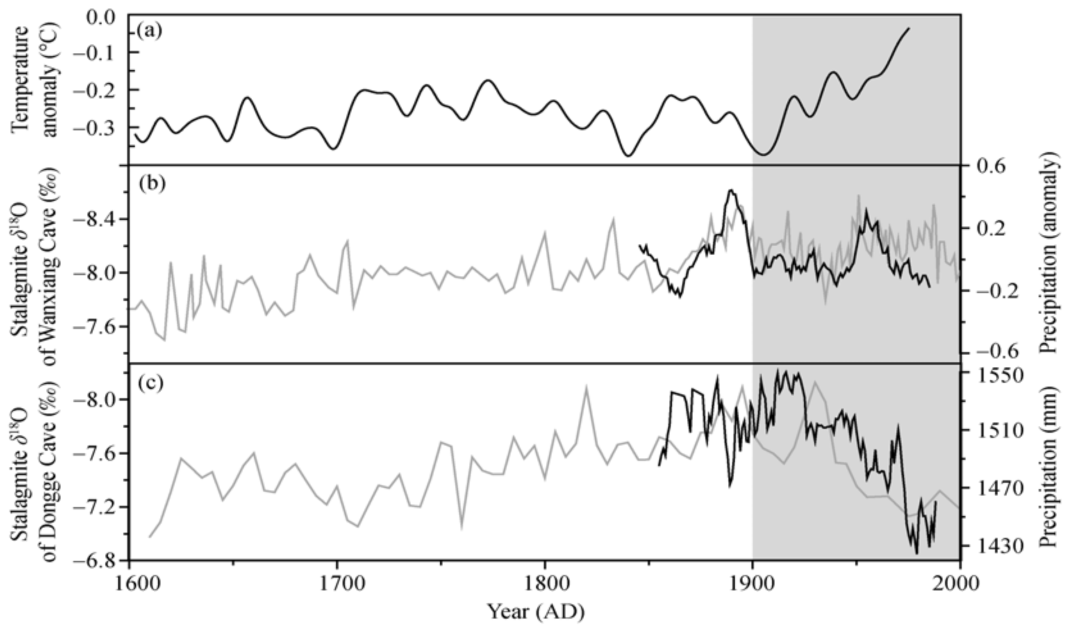

Figure 4 Comparison of monsoon precipitation with temperatures. (a) Northern Hemisphere temperature anomaly (relative to the 1961–1990 instrumental reference period mean) [30], (b) stalagmite $\delta^{18}O$ of Wanxiang Cave (grey) and instrumental precipitation record from Beijing (black, 15 points running average) during the 1840–1990 AD interval [28], (c) stalagmite $\delta^{18}O$ of Dongge Cave (grey) and instrumental precipitation record from northwest India (black, 11 points running average) for the 1848–1995 AD interval [4].

the Asian continent and the tropical Indo-Pacific Ocean [33]. This is likely supported by the longer-term trends of monsoon precipitation in the past 400 years along with the increased Northern Hemisphere temperature [34]. However, the fact that the Asian monsoon rainfall decreased in the last century under a global warming scenario has already drawn attentions [5, 16].

Increased release of aerosol due to human activity has been invoked to explain these monsoon trends [16], as sulfate aerosols [35] and black carbon [36] could decrease the land-sea thermal contrasts through reflecting solar radiation. These effects might have not only offset the effect of increased land temperature [37, 38], but also led to weaker land-sea thermal contrasts, and consequently, to decreased monsoon rainfall. Vegetation destruction and desertification might have also helped [39].

However, our study shows that the monsoon precipitation trends in the 20th century can mostly be predicted using the data prior to 1900 AD when the human influences on climate were rather weak. It is hard to believe that the positive and negative feedbacks of human activity to the monsoon climate rightly counterbalanced, leading to the monsoon precipitation to keep their natural trends. Moreover, climate modeling in considering both increase in the concentration of greenhouse gases and aerosol release cannot produce the decreasing trends of monsoon rainfall in Asia [32].

Here, we invoke the spatial variability of surface temperature to explain the monsoon precipitation trends during the 20th century. Although the average surface temperature in the Northern Hemisphere has increased during the last century, available data show that the temperatures in the Yangtze River Basin and Southwest China have significantly decreased [40]. This cooling trend in the low-latitude continents would have led to reduced land-sea thermal contrasts, and consequently, to less monsoon rainfall. Whatever the causes, our results suggest that human activity has had insignificant impacts on the Asian monsoon precipitation, such that the monsoon rainfall has mostly kept their natural trends during the 20th century.

3 Conclusions

Based on the time-series analyses of two stalagmite records of monsoon rainfall, we have studied the impacts of human activity on the monsoon precipitation in Asia during the 20th century. Our results suggest that (1) natural forcing should have driven the monsoon rainfall towards decreasing trends from 1900 to 2000 AD, and (2) the changes in the monsoon rainfall during the 20th century can be mostly predicted using the data prior to 1900 AD, suggesting an insignificant role of human activity in modulating the Asian monsoon precipitation. The decrease in the monsoon rainfall in the last century under a global warming scenario may be attributable to the cooling surface temperatures in the low-latitude Asian continents. These are helpful for understanding the future monsoon evolution in Asia.

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