Review Article

Weihe Ren*, Quan Li, Feng Qin, and Guitian Yi

Potential CO₂ forcing and Asian summer monsoon precipitation trends during the last 2,000 years

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Abstract: Holocene records for the Asian Summer Monsoon (ASM) indicate that, apart for the last 2,000 years (“2 kyr shift”), solar insolation was the dominant factor controlling the monsoon climate. The aim of this review is to provide a synopsis of climate characteristics over the last 2 kyr, clarifying mechanisms for the diverse trend with Northern Hemisphere Summer Insolation (NHSI) records. Here, we initially review proxy-based climate reconstructions for the last 2 kyr, and then compare them with records from the last five interglacial periods. Finally, we examine potential physical mechanisms responsible for the “2 kyr shift.” Findings from this review indicate that the “2 kyr shift” is a representative pattern of Holocene climate change within the core area of the ASM, and the “2 kyr shift” could be mainly controlled by changes in atmospheric CO₂ concentration. In addition, suggestions to address a more humid condition dominating the Asian monsoonal margin zones are offered.

Keywords: Asian summer monsoon, 2 kyr shift, interglaciations, atmospheric CO₂ concentration

1 Introduction

Climate changes during the Holocene period in monsoonal Asia have been reconstructed using geological carriers such as stalagmites [1–10], lacustrine sediments [11–21], peat sediments [22–31], and loess sections [32,33]. Previous studies have indicated that the Asian Summer Monsoon (ASM) strengthened during the early-middle Holocene before recording a continuous trend of weakening during the middle-late Holocene, corresponding to changes recorded in the North Hemisphere Solar Insolation (NHSI) [15,25,34,35]. Interestingly, Cheng et al. [36] recorded an opposite trend over the past ~2 kyr (referred to as a “2 kyr shift”) from stalagmite records in Sanbao Cave, central China.

Although numerous Holocene records based on well-dating and reliable ASM proxies have been published since the year 2000, these studies [1,10,12,14,20,25,30,37] fail to fully discuss late Holocene ASM intensity trends. Recently, the “2 kyr shift” pattern has been identified from peat sediments [38], lacustrine sediments [39], and stalagmite data [10] in monsoonal Asia. The increasing interest in the “2 kyr shift” has resulted in an urgent need to systematically review and clarify possible physical mechanisms associated to this event.

Changes in the Atlantic Meridional Overturning Circulation (AMOC) have been suggested as a key factor accounting for the anomalous “2 kyr shift” [36]. Atmospheric CO₂ has also been believed to be a possible driving force for climate transformation by offsetting the effect of insolation forcing during the past 2 kyr [38]. In addition, high-latitude forcing [40], Antarctic ice sheet discharge [41], and volcanic forcing [42] have been suggested as having a contribution to the “2 kyr shift.” Although Yamada et al. [43] recorded solar insolation to have a dominant effect on the ASM variations throughout Asian monsoonal regions until 2 kyr BP (BP, before the year 1950), mechanisms accounting for the “2 kyr shift” still remain unclear.

* **Corresponding author: Weihe Ren**, College of Geography and Tourism, Hengyang Normal University, Hengyang, Hunan, 421002, China; Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China, e-mail: renweiheeee@outlook.com

Quan Li, Feng Qin: Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

Guitian Yi: Hengyang Normal University, Hengyang, Hunan, 421002, China

In this study, therefore, we examine two important issues: (1) the nature of the underlying physical mechanisms of the “2 kyr shift,” and (2) implications for forecasting the future trend of the ASM. We aim to address these research issues by presenting a comprehensive compilation of the available paleoclimate data and discussing the characteristics of the ASM on different interglacial periods and regions.

2 Overview of the “2 kyr shift” in monsoonal Asia

The modern ASM limit can be regarded as the approximate northern boundary of monsoonal Asia [44,45] (Figure 1). Precipitation changes of monsoonal Asia are overwhelmingly dominated by summer monsoon circulation. Abundant

rainfall is provided by the Indian and East Asian monsoon subsystems, resulting in a significantly wetter climate in the summer [46,47]. Although the modern Asian monsoonal margin (MAMM; Figure 1) is possibly influenced by both westerlies and monsoon systems [35], the spatial extents of the transitional MAMM and the ASM region may vary on different time periods depending on the changing intensities of the ASM.

In this study, we compile precipitation/moisture records spanning the last 2 kyr from 21 stalagmite and 59 peatland/lake investigations (Figure 1), having reliable chronologies and robust proxies. These records were classified into two groups: those with (i) increasing or (ii) decreasing linear trends. Results indicate that the ASM regions mainly experienced a wetting climate during the late Holocene, shown by an increase in tree pollen [19,23,25], the accumulation of organic carbon [39,48,49], and depleting speleothem oxygen isotopes [3,6,10,70,74]. Only some monsoonal records were not significant [72,73,75]. However, it is worth

Figure 1: Locations of proxy records of paleo-precipitation/moisture changes over the past 2 kyr, in which those with increasing trend are in red and the decreasing ones in white. The green solid line indicates the modern limit of the summer monsoon [45]. See supplementary material for details of these proxy records.

noting that the “2 kyr shift” pattern almost disappeared in MAMM records, which are distinctly different from the ASM regions (Figure 1). There is also a growing consensus that climate changes in the MAMM region are inconsistent with those in the ASM regions [40,50,71]; the mechanism of regional differentiation, however, is still unclear.

3 Physical mechanisms of the “2 kyr shift”

As the majority of the ASM intensity records significantly increased over the last 2 kyr, we therefore regard the “2 kyr shift” as a representative pattern of the Holocene within the core area of the ASM (Figure 1). $\delta^{18}\text{O}$ results by Yamada *et al.* [43] from ostracod shells indicated that solar insolation dominantly affected the ASM variations until ~2 kyr BP; after this date, other factors controlled ASM intensity. Currently, mechanisms driving the “2 kyr shift” in the ASM regions are disputed. Lu *et al.* [38], Li *et al.* [40], and Cheng *et al.* [36] proposed atmosphere CO_2 concentration and AMOC to be the dominant factors, controlling late Holocene ASM under decreasing summer solar insolation in the Northern Hemisphere. In addition, although anthropogenic activities and climate may have interacted with each other in the late Holocene [9,51,52], it is not clear if and to what extent anthropogenic activities influenced climatic trends.

Previous studies predominantly focused on reconstructing climate in the Holocene (or Marine Isotopic Stage 1; MIS 1), restricting separate anthropogenic influences. It is therefore important to solve this problem by analyzing past interglaciations (e.g., MIS 5e, MIS 7e, MIS 9e, MIS 11c, and MIS 13). Recently, a “Late-MIS 11c shift” climate pattern, similar to the “2 kyr shift,” has been identified based on a comparison between Holocene and MIS 11c paleo-monsoon intensity records [53]. Although no further analysis of physical mechanisms has been completed, these findings provide a seemingly feasible way to clarify the dominant drivers of climate. Oxygen isotope records from caves in China characterize the ASM changes over the past 640,000 years [36]. The length of the records and temporal precision enables us to discuss how the “2 kyr shift” mode behaved during other interglacial periods. Although the significance of $\delta^{18}\text{O}$ record of stalagmite to precipitation is disputed [47,76], it is undeniable that stalagmite can reliably reflect the variation of monsoon strength [36].

3.1 Indications of the ASM records during the past five interglaciations

A “2 kyr shift”-like pattern has been identified in the late periods of MIS 5e, MIS 11c, and MIS 13, but not identified in either MIS 7e or MIS 9e (Figure 2). Notably, $\delta^{18}\text{O}$ amplitude was higher in late MIS 11c and MIS 13, similar to records from the late Holocene, with only the duration differing in each period. Therefore, a common climate transition might occur during late interglacial periods, an event we term as a “Late Interglaciation Shift (LIS).” Excluding the composite $\delta^{18}\text{O}$ record [36], recent results from a new speleothem record from Yongxing Cave in central China indicate a LIS during late MIS 11c [53]. By using records of climatically sensitive arbor pollen in lacustrine sediments from the eastern Tibetan Plateau, we were able to reconstruct regional temperature and moisture evolution trends. The increase in arbor pollen and accumulation of highly organic-rich sediments from Zhao *et al.* (unpublished data) indicated that late MIS 5e experienced a warmer and wetter climatic trend, suggesting that LIS events also occurred in wider monsoonal areas.

Anthropogenic influences on climate were negligible during the past five interglaciations, and comparisons highlighted above show LISs to be common in interglacial periods. This finding suggests that the “2 kyr shift” could be mainly controlled by natural factors rather than anthropogenic [52] or solar activities [43].

3.2 Atmosphere CO_2 concentration could be the main mechanism for “2 kyr shift”

Comparison of ASM reconstructions with atmospheric CO_2 concentration and AMOC intensity records enabled the physical mechanisms of the “2 kyr shift” to be examined. Predominantly based on Antarctic ice cores, an 800,000-year atmospheric CO_2 concentration history was provided by Bereiter *et al.* [68]. The epibenthic foraminifera *Cibicides wuellerstorfi* $\delta^{13}\text{C}$ record possibly reflects changes in deep Atlantic ventilation patterns related to AMOC intensity [54]. Mean grain size of silt (10–63 μm) from North Atlantic sediment can also be a proxy of North Atlantic deep-water formation [55]. The chronology of CO_2 and AMOC intensity records have been corrected and are reliable, but errors are inevitable.

Comparison analysis (Figure 3) reveals a strong consistency between the ASM intensity and atmospheric CO_2 ; LIS and an increase in CO_2 concentration occurred almost simultaneously. The anomalous fashions (“2 ka-shift” or

Figure 2: Comparison among ASM records during the Holocene (MIS 1), MIS 5e, MIS 7e, MIS 9e, MIS 11c, and MIS 13 (a–f). The ASM composite $\delta^{18}\text{O}$ record (black-dotted line) [36], July insolation at 65°N (dark red line) [66], and the Yongxing Cave record (light green line) [53]. Vertical gray bars depict strong monsoon events. The arrows depict trend of the ASM.

“LIS”) of the ASM intensity occurred during the late periods of MIS 1, MIS 5e, and MIS 11c, while AMOC intensity and atmospheric CO₂ concentration increased. Although no significant changes in the ASM intensity were recorded in the late periods of MIS 7e or MIS 9e, AMOC intensity significantly increased and atmospheric CO₂ concentration was in line with the weakening the ASM trend. Therefore, we can preliminarily conclude that atmospheric CO₂ concentration may relate to the occurrence of LIS events. In addition, there was an obvious climate shift during late MIS 13 with a weakening AMOC intensity and an increase in atmospheric CO₂ concentration. These changes indicate that atmospheric CO₂ concentration may be a key driving factor for LISs (also the “2 kyr shift”). There is a certain time-lag for the ASM record in MIS 11c and MIS 13 (Figure 3k and l), possibly due to stalagmite dating errors [36].

Increases in atmospheric CO₂ concentration have been suggested as a key forcing driver of the ASM precipitation change on the Chinese Loess Plateau since the last glacial maximum [56]. Previous studies have shown that an increase of atmospheric CO₂ concentration (~100 ppm) can lead to the northward migration of the Intertropical Convergence Zone (ITCZ) by regulating temperature changes in the northern hemisphere [56–58]. It is also possible that monsoonal rainfall could respond to indirect greenhouse gas forcing through changes in latitudinal temperature gradients [59]. However, changes in CO₂ concentration during the Holocene were small (~20 ppm) and the extent of influence on the ASM remains unclear. During the early-middle Holocene, $\delta^{18}\text{O}$ in Chinese stalagmites was negative, and CO₂ concentration was low with a steady increase (Figure 3g), suggesting that CO₂ forcing might not be the major driving force during high insolation [69]. Maximum CO₂ values in the late Holocene may have contributed to the anomalous increase of summer precipitation over the past 2 kyr [38,56,69] as lowering summer insolation can weaken the ASM [60]. TraCE-21 ka transient simulation results also indicate that greenhouse gas forcing exceeded full forcing at ~2.3 kyr BP, before becoming the dominated contributor for late Holocene summer rainfall [38]. We therefore suggest that atmospheric CO₂ forcing may have offset the effects of insolation forcing over the past 2 kyr when summer insolation was in a trough.

4 Perspectives of the “2 kyr shift”

Our investigation has indicated that the “2 kyr shift” nearly disappeared in most paleoclimate records of the

Figure 3: Comparison among ASM, AMOC intensity, and atmosphere CO₂ records during the Holocene (MIS 1), MIS 5e, MIS 7e, MIS 9e, MIS 11c, and MIS 13. ASM records refer to Figure 2. Proxies for changes of AMOC intensity (a–f, dark blue lines, MIS 1 [55]; MIS 5e, 7e, 9e and 11c [54]; MIS 13 [67]). Atmosphere CO₂ concentration records (g–l, purple lines) [68]. The arrows indicate the overall trend.

Figure 4: Comparison of climatic records. $\delta^{18}\text{O}$ records of Dongge Cave stalagmite D4 (a) [3] and Buddha Cave stalagmite SF (c) [7]. Evergreen tree pollen percentage of the Dajiuahu Basin, the western Shennongjia Mountains (b) [24]. Tree pollen percentages of the Lake Qinghai (d) [37] and Lake Daihai (e) [11,12]. Blue bars indicate Holocene optimum, respectively. The arrows indicate the overall trend.

MAMM (Figure 1). Most records in the MAMM show the wettest period (also named the “Holocene optimum”) between ~7 and 5 kyr BP; comparisons of records (Figure 4) suggest this lagged ~2 kyr behind monsoonal records (~9–7 kyr BP). Previous studies indicate that climate changes in the MAMM may be influenced by both westerlies and the ASM [50,61]. A large decrease in summer insolation would lead to a southward migration of the summer westerly jet stream, thereby impeding the northward movement of the summer monsoon rain belt [62].

Thus, the near-absence of the “2 kyr shift” in the MAMM may have been influenced by westerlies. Further, the lag response of precipitation in the MAMM region to climatic records in the core area of the ASM and summer insolation could attribute to the remnant melting Laurentide ice sheet [71]. On the other hand, however, characteristics of the southeast-northwest time-transgressive of the ASM during the Holocene have been previously recorded [20,46,63]. This may explain the ~2–3 kyr delay in the ASM precipitation between the MAMM and monsoonal Asia. In a world experiencing greenhouse gas-induced warming, the thermal equator of the Earth and westerly jets will move northward, and the monsoon rain belt will be promoted to the northwest of China [56,64,65]. This study strongly supports that the “2 kyr shift” will occur and that climate will become wetter due to increasing global temperatures in the MAMM.

5 Conclusion

Understanding spatial and temporal patterns, as well as possible regional climatic responses to large-scale forcing, provides essential information to understand underlying mechanisms of the “2 kyr shift.” In this synthesis, we showed that the “2 kyr shift” is a representative pattern of late Holocene climate change within the core area of the ASM. Further comparisons suggest that anthropogenic activity could not be the dominate mechanism of the “2 kyr shift.” However, an increase in atmospheric CO₂ concentration may have shifted its relative role during the late Holocene by gradually changing the boundary conditions of waning insolation. It is worth noting that precipitation differences existed between monsoonal Asia and the MAMM during the late Holocene on a suborbital timescale. We propose that climate in the MAMM will become wetter with an increase in global temperatures.

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