



# Migration of Afro-Asian Monsoon Fringe Since Last Glacial Maximum

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### Specialty section:

This article was submitted to  
Quaternary Science, Geomorphology  
and Paleoenvironment,  
a section of the journal  
Frontiers in Earth Science

**Received:** 01 June 2020

**Accepted:** 10 July 2020

**Published:** 07 August 2020

### Citation:

Cheng J, Ma Y, Wu H, Long H and  
Liu Z (2020) Migration of Afro-Asian  
Monsoon Fringe Since Last Glacial  
Maximum. *Front. Earth Sci.* 8:322.  
doi: 10.3389/feart.2020.00322

Geological records indicated the termination of the Holocene Thermal Maximum (dramatic drying) occurred progressively later at lower latitudes in both North Africa and East Asia, along with the coherent weakening of local summer monsoon. Here we show that this time-transgressive evolution was dominated by the southward migration of monsoon fringe (shrinking monsoon domain) under monsoon weakening, as illustrated in a transient climate-terrestrial ecosystem model simulation. The monsoon fringe retreating southward during the Holocene, as well as expanding northward during the last deglaciation, occurred synchronously in a belt extending from North Africa to East Asia, which induced a locally humid-arid transition and the subsequent dramatic environment impact. The migration of Afro-Asia monsoon fringe since the Last Glacial Maximum was modulated by the orbital forcing through its impact on land-ocean thermal contrast, aiding by the variation of CO<sub>2</sub> concentration.

**Keywords:** Afro-Asian monsoon, fringe, hydrological evolution, land-ocean thermal contrast, external forcing, vegetation

## INTRODUCTION

Since the Last Glacial Maximum (LGM), the Afro-Asian monsoon system, including East Asian monsoon, South Asian monsoon and North African monsoon, has experienced a coherent strengthening during the last deglaciation and weakening during the Holocene (Fleitmann et al., 2003; Dykoski et al., 2005; Weldeab et al., 2007; Wang et al., 2008; Shi and Yan, 2019) with the maximum at the Holocene Thermal Maximum (HTM, around 8 ka, kilo years ago before 1950; Haug et al., 2001). Synthesis analysis of monsoon records in North Africa and East Asia illustrated a common asynchronous termination of the HTM, which occurred later in lower latitudes (An et al., 2000; Shanahan et al., 2015). The eco-environmental response to this time-transgressive termination of the HTM is much robust in the northern part of Afro-Asian monsoon domains,

as illustrated by the dramatic variation of paleo-lake and vegetation (Street and Grove, 1976; Yu and Harrison, 1996; Lézine et al., 1998; Enzel et al., 1999; Armitage et al., 2015; Goldsmith et al., 2017).

The time-transgressive evolution of paleo-hydrology during the period of the Holocene in North Africa and East Asia was previously attributed to the southward migration of monsoon rainbelt, which was forced by reduced summer insolation (Shanahan et al., 2015), or/and seasonality (An et al., 2000). The mechanism of rainbelt migration may work for East Asia, presented as the anti-phase changes of precipitation within large meridional range of the monsoon (Zhang et al., 2018), but it may not be so robust in North Africa (Doherty et al., 2000). For the uniform time-transgressive evolution of paleo-hydrology occurred in both North Africa and East Asia, is there a common mechanism? The southward shift of the Intertropical Convergence Zone (ITCZ) during this period (Haug et al., 2001) may have contributed to this time-transgressive evolution in the monsoon region, but its physical connection with the environment variation occurred at higher latitudes is not obvious. In addition, why is the environmental response in the northern part of the Afro-Asian monsoon domain so large? Meanwhile, is there any internal relationship between the time-transgressive evolutions of North Africa and East Asia?

To address these questions, the change of monsoon fringe, the limit of the monsoon domain, may be the critical factor. Besides the general monsoon precipitation which widely used to represent the intensity of monsoon (Shi and Yan, 2019), the fringe of Afro-Asian monsoon varied largely as documented in geological records (Winkler and Wang, 1993; Yan and Petit-Maire, 1994; Adams, 1997; Jiang and Liu, 2007; Schneider et al., 2014; Skonieczny et al., 2015; Yang et al., 2015; Goldsmith et al., 2017; Tierney et al., 2017; Sha et al., 2019), and simulated in climate models (Doherty et al., 2000; Jiang et al., 2015a,b). Reconstructions and simulations consistently indicated monsoon fringe swung northward during the last deglaciation, afterward swung southward during the Holocene. On the other hand, the Afro-Asian monsoon is accompanied by an abroad arid region on its northern side (**Figure 1A**), which is forced by atmospheric meridional circulation and favored by the Tibetan Plateau (Broccoli and Manabe, 1992). Therefore, the migration of northern Afro-Asian monsoon fringe, which corresponds to the expansion or shrink of the monsoon domain, may induce the time-transgressive evolution of local precipitation and the subsequent dramatic response of environment for reasons of possible humid-arid transition. Thus, we hypothesize the recorded time-transgressive evolution of paleo-hydrology in the Afro-Asian monsoon regions and the dramatic environment variation may be dominated by the migration of monsoon fringe.

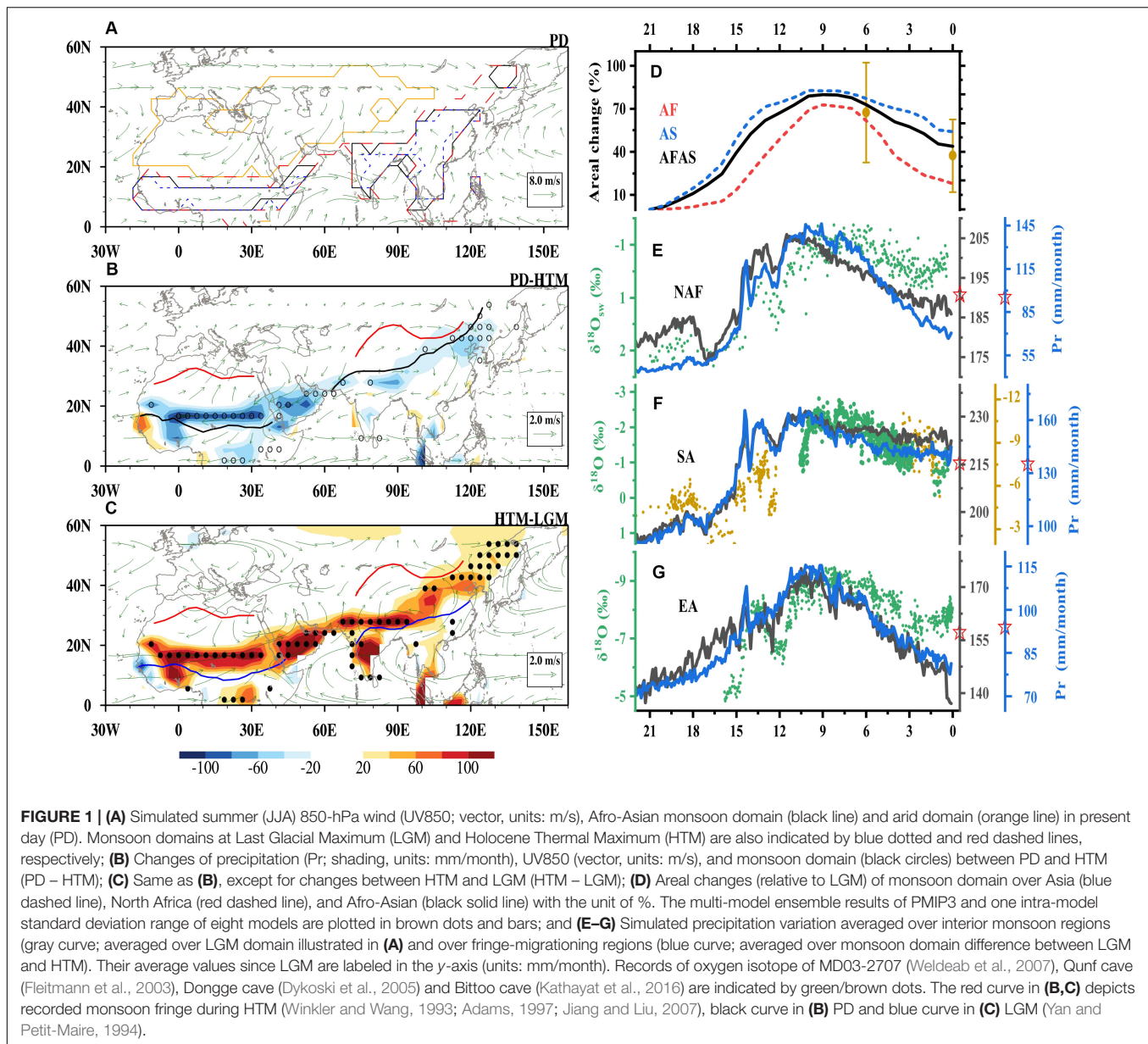
To test this hypothesis, we investigate the fringe change of the Afro-Asian monsoon and the possible subsequent environment response in a transient climate-terrestrial ecosystem model simulation since the LGM, aided by some other snapshot simulations at the LGM and mid-Holocene. Furthermore, the potential contributions of external forcing to the possible change of monsoon fringe are investigated.

## DATA AND METHOD

The transient climate-terrestrial ecosystem simulation starting from the LGM used here is TraCE21 (Liu et al., 2009). This simulation was performed using the fully coupled NCAR CCSM3 at a spatial resolution of T31 ( $3.75^\circ \times 3.75^\circ$ ; Collins et al., 2006), and forced by the realistic climatic forcing that consisted of orbital insolation (Orb; Berger, 1978), atmospheric  $\text{CO}_2$  (Joos and Spahni, 2008), meltwater discharge (McManus et al., 2004), and continental ice sheets (ICE-5G; Peltier, 2004). TraCE21 involved the land processes with a dynamic vegetation component, whose outputs could be used to directly compare with the corresponding proxy records. Four sets of solo-forcing experiments are also performed to investigate their individual contributions to the total climate variation since the LGM (He et al., 2013). In this paper, we employ the full-forcing and two solo-forcing experiments (Orb and  $\text{CO}_2$ ) of TraCE21 to study the variations of Afro-Asian monsoon fringe, the subsequent environmental impact and the underlying mechanism. The monsoon fringe in model simulation is defined as the edge of monsoon domain, whose general migration represents the expansion or the shrink of monsoon domain. To focus on the long-term evolution of monsoon fringe and local environment, our analyses are all based on the centennial mean data. Aiding to this transient climate simulation, a series of Paleoclimate Modeling Intercomparison Project Phase 3 (PMIP3) simulations during the LGM and mid-Holocene (**Supplementary Table 1**) are also included to improve the reliability of the results derived from TraCE21.

Comparing to the paleoclimate records, the full-forcing simulation of TraCE21 reasonably reproduced the general evolution of the Afro-Asian monsoon (Otto-Bliesner et al., 2014; Liu et al., 2014; Shanahan et al., 2015; Wen et al., 2016; Cheng et al., 2019; Shi and Yan, 2019). The spatial distribution of the Afro-Asian monsoon and adjacent arid regions are all well simulated (**Figure 1A**), compared to those derived from observations (**Supplementary Figure 1**). The simulated variation of monsoon intensity (black curves in **Figures 1E–G**, averaged precipitation in the monsoon regions) is roughly consistent with the proxies (green dots in **Figures 1E–G**), strengthening during the last deglaciation and weakening during the Holocene. The migration of northern Afro-Asian monsoon fringe indicated by geological records (Winkler and Wang, 1993; Yan and Petit-Maire, 1994; Adams, 1997; Jiang and Liu, 2007; Yang et al., 2015; Goldsmith et al., 2017) is also qualitatively reproduced by TraCE21, even though the varying magnitude in the simulation is smaller than that of the reconstructions (**Figures 1B,C**). The reasonable reproduction of TraCE21 for the variation of the Afro-Asian monsoon since the LGM provides the basis to test our hypothesis.

The monsoon domain is the region where the annual precipitation range (local summer minus winter) exceeds 300 mm (2 mm/day) and where summer precipitation exceeds 50% of the annual precipitation. Here, local summer and winter are defined as May through September (MJJAS) and November through next March (NDJFM), respectively, following Wang and Ding (2008). Arid regions are where the local



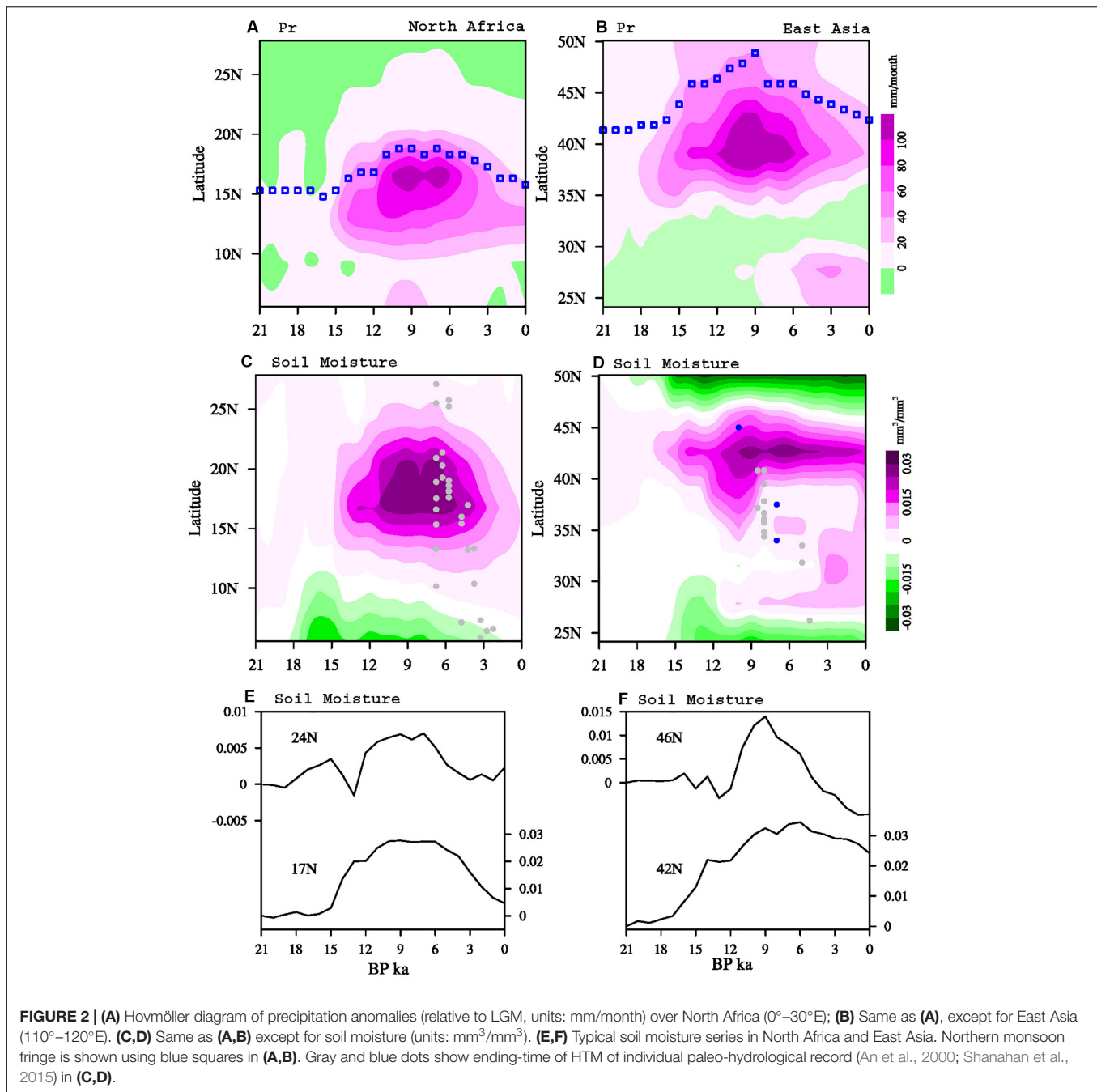
summer precipitation rate is below 1 mm/day (Liu et al., 2012). Here, we focus on the monsoon fringe (the limit of monsoon domain) close to the arid region, whose migration was robust and the subsequent environmental impact was dramatic as illustrated below.

## RESULTS

### Variation of Afro-Asian Monsoon Domain/Fringe

Since the LGM, Afro-Asian monsoon domains robustly co-varied in TraCE21. Along with the weakening of Afro-Asian monsoon during the Holocene (black curves in **Figures 1E–G**), the shrink of its domain (**Figure 1D**) was derived by the southward

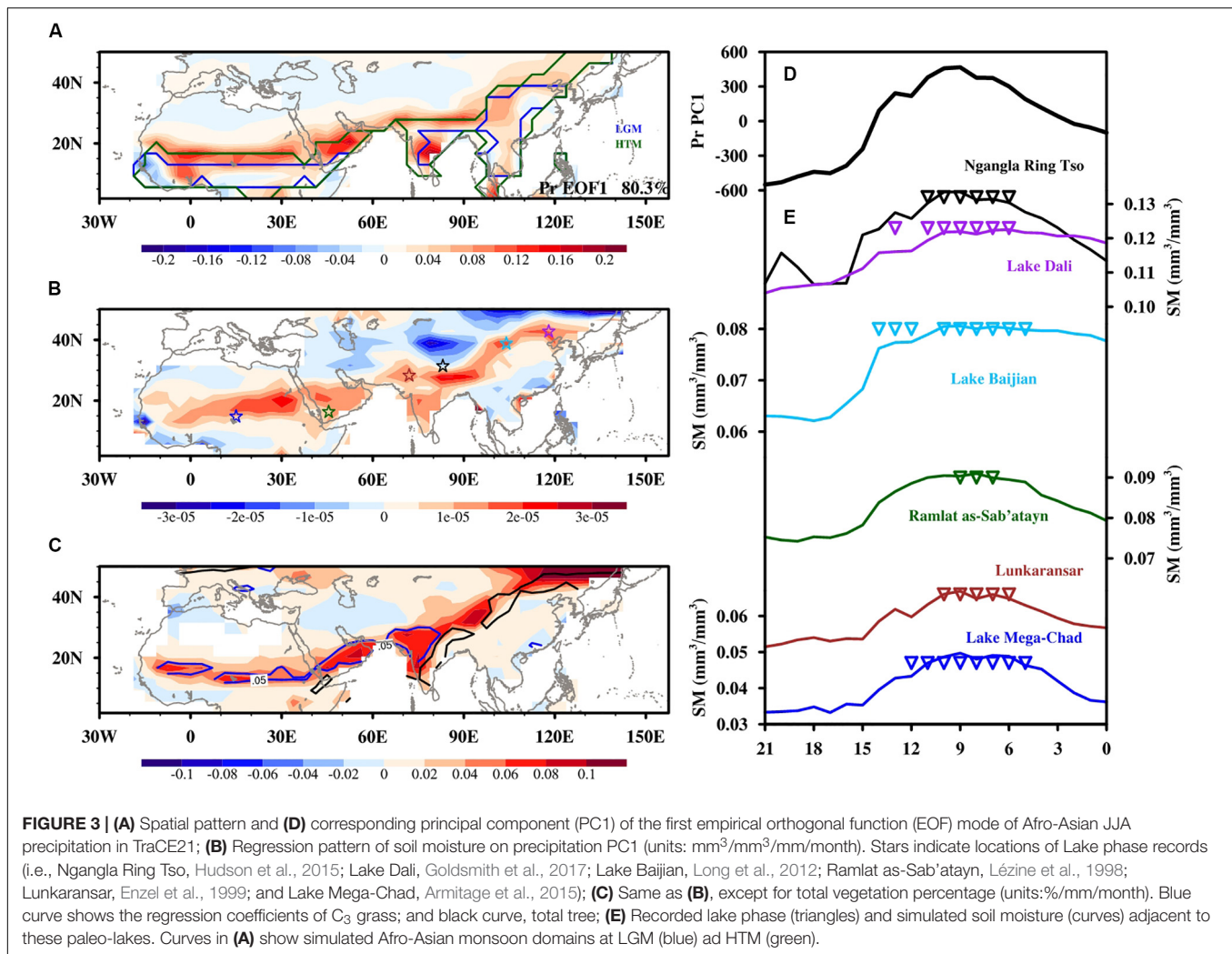
migration of northern monsoon fringe, with the amplitude of about 4 degrees in latitude (**Figure 1B**). Similar but reversed processes occurred during the last deglaciation (**Figure 1C**). Notably, referring to the state at the LGM, the varying magnitude of simulated Afro-Asian monsoon domain reached about 80% with the maximum at the HTM period (**Figure 1D**). In addition, the domain of Afro-Asian monsoon at present day (PD) is large by about 40% than that at the LGM (**Figure 1D**), expanded in the north, too (see **Supplementary Figure 2**). The multi-model mean results of PMIP3 indicated similar variation of the Afro-Asian monsoon domain (vertical bars in **Figure 1D**) and the migration of monsoon fringe (**Supplementary Figure 3**), with a slight difference in the varying magnitude. Therefore, the gradual variation of the monsoon domain, as indicated in the simulations, could induce the progressively meridional migration



of the northern monsoon fringe, and this simulated fluctuation of northern monsoon fringe is consistent with that reconstructed by geological records (Figures 1B,C).

According to the spatial configuration of Afro-Asian monsoon and arid regions (Figure 1A), the southward migration of northern monsoon fringe during the Holocene induced the transition from monsoonal humid climate to arid climate, which was accompanied by the dramatic decline of local precipitation (shading in Figure 1B). A reversed process occurred during the last deglaciation with a larger varying magnitude, which was due to mean state difference between LGM and PD

(shading in Figure 1C). Whether the fringe migrated during the last deglaciation or Holocene, the associated precipitation changes all occurred in a belt crossing North Africa to East Asia. Further analysis indicated that the precipitation variation in the fringe-migrating region (blue curves in Figures 1E–G) is synchronous with that of the interior monsoon (black curves in Figures 1E–G). Climatological precipitation in fringe-migrating regions was just about half of that in the interior monsoon regions; however, their varying magnitude was nearly twice of that in the interior monsoon regions (Figures 1E–G).



Along with the progressively meridional migration of the northern fringe since the LGM, the associated dramatic precipitation changes are time-transgressive (**Figures 2A,B**). The southward migration of northern fringe during the Holocene, whether in North Africa or East Asia, induced the decline of precipitation occurred on the north side of the fringe first and then occurred on the interior side later with a larger amplitude. Similar to the precipitation changes, simulated soil moisture indicated a clearer time-transgressive feature (**Figures 2C–F**), which are roughly consistent to the recorded paleo-hydrological evolution (gray and blue dots in **Figure 2**; An et al., 2000; Shanahan et al., 2015). Similar but reversed processes occurred during the last deglaciation.

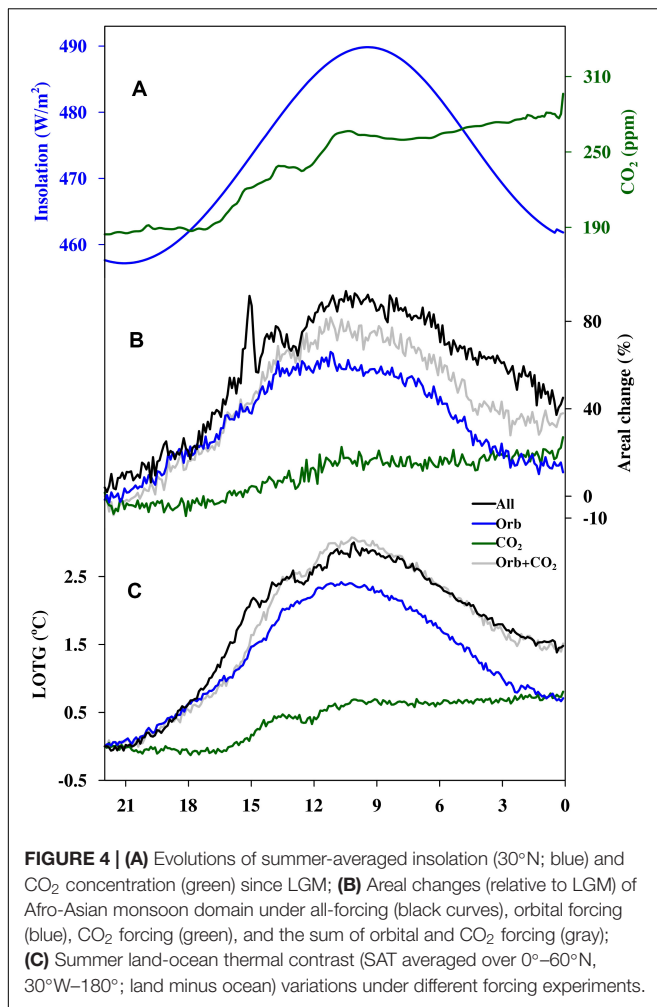
Different from the previous explanations which focusing on the migration of monsoon rainbelt (An et al., 2000; Shanahan et al., 2015), here we clearly show that in the model simulation, the Holocene time-transgressive evolution of hydrology in the Afro-Asian monsoon region was caused by the southward migration of the northern monsoon fringe because of shrinking monsoon domain. Along with the migration of

the northern monsoon fringe, intensive precipitation changes occurred locally for the reason of humid-arid transition. Furthermore, the model simulation indicated there was a reversed process during the last deglaciation, which is consistent with the finding of previous studies in records and simulations (COHMAP Members, 1988).

The model simulation also clarified the high sensitivity region of climate change associated with the monsoon, which was located around its northern fringe. Our results highlight the integrated changes of the Afro-Asian monsoon, which involved not only monsoon intensity but also the monsoon fringe. Neglecting the changes of monsoon fringe and just focusing on monsoon intensity, the time-transgressive feature and unequal magnitude of climate variation in a broad Afro-Asian monsoon region cannot be well understood.

## Eco-Environmental Impact of Monsoon Fringe Migration

As shown above, the intensive precipitation changes, associated with the migration of the northern monsoon fringe, occurred



over the humid-arid boundary region. However, in this semi-arid region, the spatial gradient of precipitation is usually large, which induces high sensitivity of local eco-environment to precipitation changes (Huang et al., 2017). Therefore, a dramatic eco-environmental response to the intensive precipitation change in this fringe-migrating region is expected, and the simulation confirms it.

The intensive precipitation change along the northern fringe of the Afro-Asian monsoon, the dominant variation mode of precipitation over this area (Figure 3A), induced robust variations of local soil moisture (Figure 3B), and vegetation (Figure 3C). With the northward migration of northern monsoon fringe during the last deglaciation, the intensive increasing precipitation over the newly-formed monsoon region increased local soil moisture and then improved local vegetation. After that, a decreasing precipitation in the region monsoon retreated during the Holocene reduced the local moisture and destroyed the local vegetation intensively. The records of paleo-lakes along the northern fringe of Afro-Asian monsoon confirmed the robust change of local soil moisture simulated in TraCE21 (curves in Figure 3E). These lakes only existed during the period of the HTM (triangles in Figure 3E) and disappeared

during the LGM and PD, indicating the dramatic variation of local hydrological condition and implying a reasonable simulation of local soil moisture variation in TraCE21. This dramatic hydrological variation around the northern fringe of Afro-Asian monsoon significantly controlled the abundance of local vegetation, grasses in low-latitude North Africa and trees in mid-latitude East Asia, as indicated by TraCE21 (Figure 3C).

Combined the geological records and model simulation, although the simulation is not validated for every process by limited records, we propose the recorded dramatic eco-environmental variation along northern fringe of Afro-Asian monsoon was caused by the migration of the northern monsoon fringe through the associated intensive variation of precipitation since the LGM. Owing to the intensive migration of monsoon fringe since the LGM, the sensitivities of both climate and eco-environment in the abroad region along northern fringe of Afro-Asian monsoon are all high, which provided the insight for the projection of future changes of climate and eco-environment under ongoing global warming.

### Cause for Varying Monsoon Domain

The monsoon is a complex climate system. The monsoon circulation is an extension of the cross equatorial Hadley Cell (Bordoni and Schneider, 2008; Merlis et al., 2013; Schneider et al., 2014) in the monsoon season, it is shaped in further by the local large-scale land-ocean thermal contrast (Webster et al., 1998). The moisture transported by the monsoon circulation converges over the monsoon domain, which induces the formation of monsoon precipitation. Thus, the past recorded and the future projected changes of monsoon (Biasutti, 2013; Boos and Korty, 2016; Bischoff et al., 2017; Seth et al., 2019), involving that in the circulation, the precipitation and the domain, could be dominated by the land-ocean thermal contrast (Chou et al., 2001; Bordoni and Schneider, 2008), the meridional temperature gradient (Wang et al., 2001; D'Agostino et al., 2019; Seth et al., 2019), the large scale circulation (Bordoni and Schneider, 2008), the local moist static energy (Neelin and Held, 1987), and the net energy input (Texier et al., 2000; Schneider et al., 2014; Boos and Korty, 2016; D'Agostino et al., 2019). Among all these potential mechanisms, our transient simulations indicate that the changes of land-ocean thermal contrast coincided with the changes of the Afro-Asian monsoon under long-term climate changes since the LGM, which were mainly forced by orbital and  $CO_2$  forcing (Cheng et al., 2019).

The solo-forcing experiments of TraCE21 of orbital and  $CO_2$  clearly indicate the dominance of land-ocean thermal contrast on the Afro-Asian monsoon domain (Figure 4). Precession-dominated orbital forcing modulates the deglacial expansion and the Holocene shrink of the Afro-Asian monsoon domain through the in-phase change of land-ocean thermal contrast. The increasing  $CO_2$  concentration, especially for the period of the last deglaciation, also could expand the domain of the Afro-Asian monsoon through enlarged land-ocean thermal contrast, which basically established the climatological difference between LGM and PD. Similar to the full-forcing experiment of TraCE21 (Figures 1B,C), the migration of the northern monsoon fringe is all dominant for the change of monsoon domain, and could

induce the intensive environment impact in the belt shown above (see **Supplementary Figure 4**). The sum of these two solo-forcing experiments (gray curve in **Figures 4B,C**) is roughly equal to the full-forcing experiment of TraCE21 (black curve in **Figures 4B,C**), which illustrates the dominance of these two external forcing during the long-term change of the Afro-Asian monsoon since the LGM. Comparing to the forcing of CO<sub>2</sub>, orbital forcing is the dominated factor in the simulated migration of monsoon fringe.

## CONCLUSION AND DISCUSSION

Combining model simulation with geological records, we proposed the recorded time-transgressive hydrological evolution around the northern fringe of the Afro-Asian monsoon and the recorded dramatic eco-environmental variation in the same region were caused by the gradual migration of the northern monsoon fringe since the LGM. The migration of the northern monsoon fringe could induce intensive variation of precipitation locally due to the humid-arid transition. Our results clarified the sensitive response of climate and eco-environment of monsoon located around its northern fringe, not the interior. We also propose the LGM-PD difference of climate and eco-environment was mainly attributed to the increasing CO<sub>2</sub> concentration, but their intensive long-term fluctuation was caused by orbital forcing through the impact on the land-ocean thermal contrast.

Our analyses clearly illustrated, besides monsoon intensity, we should pay more attention to the accompanying change of monsoon domain (migration of monsoon fringe) under long-term climate change. The clarification about the subsequence of monsoon fringe migration, as illustrated here, is important to understand the diverse evolution of individual geological record in the regions of the Afro-Asian monsoon, which was usually asynchronous in time and unequal in amplitude. The insight about the monsoon fringe, which was derived from its past changes, is important for the projection of future changes of monsoon-related climate and eco-environment under global warming.

Coherent long-term evolution of the Afro-Asian monsoon, as indicated by geological records and model simulation, illustrated the integrity of the Afro-Asian monsoon again, which is consistent with the analyses using the observations. For the long-term variation of the Afro-Asian monsoon, our analyses highlighted the importance of large-scale land-ocean thermal contrast (Webster et al., 1998). Comparing to the meridional scales of North Africa monsoon, it's large for the East Asia monsoon, which leads to an opposite rainfall changes over the

East Asia during the Holocene era as indicated in geological records (An et al., 2000; Xu et al., 2020) and model simulation (Liu et al., 2014). This asynchronous rainfall changes over interior regions of East Asia monsoon was caused by the migration of monsoon rainbelt, which is clearly different to the asynchronous rainfall changes around norther monsoon fringe caused by the migration of monsoon fringe.

Another point should be noticed is that the amplitude of northward migration of the Afro-Asian monsoon fringe and associated environment impact may be small under future warming, even the warming amplitude may be larger than that in the past. As illustrated in Cheng et al. (2019), the varying amplitude of land-ocean thermal contrast relies on the external forcing of temperature change, high under the orbital forcing and small under CO<sub>2</sub> forcing. Comparing to the past changes of Afro-Asian monsoon fringe which dominated by orbital forcing, its future changes dominated by CO<sub>2</sub> will be relative small.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: <https://www.earthsystemgrid.org/dataset/ucar.cgd.cesm3.trace.html>.

## AUTHOR CONTRIBUTIONS

JC: conceptualization and writing—original draft preparation. JC and YM: methodology and investigation. YM: formal analysis. HW, HL, and ZL: resources. HW and ZL: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

## FUNDING

This research was supported by the Program of Global Change and Mitigation, Ministry of Science and Technology of the People's Republic of China (2016YFA0600504), and by the National Natural Science Foundation of China (41776017, 41630527, and 41977381).

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2020.00322/full#supplementary-material>

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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