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Synchronous or asynchronous Holocene Indian and East Asian summer monsoon evolution: A synthesis on Holocene Asian summer monsoon simulations, records and modern monsoon indices

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ABSTRACT

Holocene climate records obtained from the Asian summer monsoon domain suggest a regionally-delineated response to changing summer monsoon. The interaction between the East Asian summer monsoon (EASM) and the Indian summer monsoon (ISM), two subsystems of the Asian summer monsoon, has been considered as a factor that explains those inconsistent Holocene climate records. However, this assumption is not valid when the relationship between the two subsystems is not clear. This paper presents a literature review regarding climate simulation of the Asian summer monsoon for testing the long-term relationship. The absolutely-dated Holocene speleothem records in the EASM domain and the ISM domain were compared to verify the simulation results. In addition, a unified monsoon index, which has a unified solid dynamic basis and is appropriate for different monsoon regions, was used in order to identify the modern relationship between the two subsystems. The speleothem records show more synchronous than asynchronous on the Holocene millennial-scale monsoon evolution, furthermore the two subsystems respond to the Younger Dryas (YD) and 8.2 ka events in a similar way. However, these monsoon simulations roughly suggest that the two subsystems respond to Holocene climate change in different ways. While the simulations were mostly performed in a certain period of the Holocene, the speleothem records provided a relatively continuous Asian summer monsoon history. Therefore, time scales could affect the comparison between simulations and speleothem records. Then, we further discussed the interaction between the Asian monsoon subsystems according to simulations and modern monsoon indices. Overall, the relationship between the two subsystems is more complicated than synchronous or asynchronous, which is a dynamic relationship and related to the atmosphere–land–ocean–vegetation interaction. In addition, the relationship can vary over different time scales, and the links between time scales should be paid more attention to. Besides, the interaction between the westerly winds and the Asian summer monsoon in the mid-latitudes of East Asia will profoundly affect those areas in response to Holocene climate change. It is recommended that further research should be emphasized in dynamic mechanisms between the Asian summer monsoon subsystems and between the Asian monsoon and the westerly winds.

1. Introduction

The Asian monsoon climate system plays a significant role in the global energy and water cycle (Webster et al., 1998; Wang et al., 2005). Long-term trend and abrupt events of the Asian monsoon provide a context for recent Asian summer monsoon variability. Holocene Asian monsoon research is able to resolve the full spectrum of monsoon variability and to place the limited instrumental records in a long-term perspective. Holocene Asian monsoon history is complicated by inconsistent monsoon records from different parts of the Asian monsoon domain (An et al., 2000; He et al., 2004; Hong et al., 2005; An et al., 2006; Herzschuh, 2006; Chen et al., 2008; Y. Wang et al., 2010). The Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM) are two main subsystems of the Asian monsoon, while there is a relatively broad range of boundary between them that is roughly divided at 100º–110°E (Tao and Chen, 1987; Wang and Lin, 2002; Ding and Chan, 2005, Fig. 1). Responding to the strength of the continental high- and low-pressure cells, the two subsystems interact with each other; however, they also have significant differences dictated by the contrasting sea–land distributions. The annual cycle of rainfall exhibits a remarkable difference between the two monsoon subsystems that are also closely interlinked (Wang and Lin, 2002). Scientists have seen the interaction between the two monsoon subsystems as a factor causing asynchronous Holocene climate change over East Asia. For example, Hong et al. (2005) showed the inverse phase oscillations between the East Asian and Indian Ocean summer monsoons during the Holocene by comparing plant cellulose $\delta^{13}C$ time series of peat bogs from the

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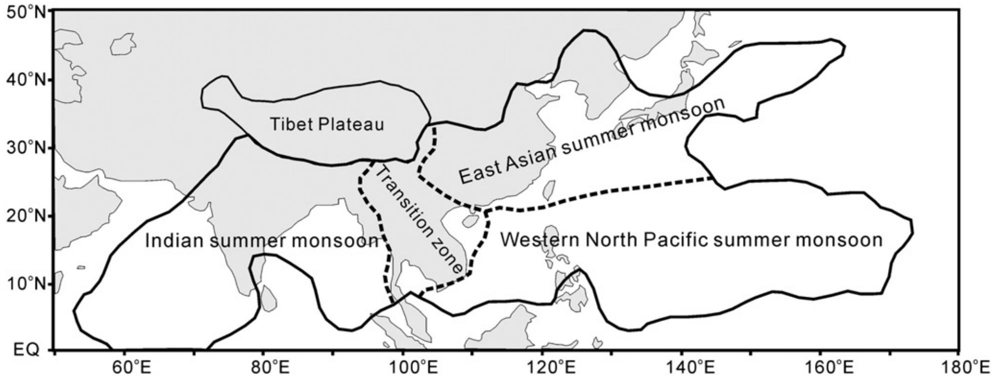

Fig. 1. Map showing that the Indian summer monsoon and the East Asian summer monsoon are two subsystems of the Asian summer monsoon (after Wang and Lin, 2002).

two subsystems. Y. Wang et al. (2010) synthesized 92 proxy records of moisture change in East and Central Asia, which reveal a strong spatial heterogeneity in Holocene moisture evolution between the EASM domain and the ISM domain, and proposed that the variability of Holocene Hadley Circulation could result in asynchronous millennial-scale climate change between the two Asian monsoon subsystems. Although this approach is interesting, it suffers from poor understanding of the interaction between the two subsystems, especially on the Holocene millennial-scale.

Numerical simulation of paleoclimate provides insights into why past climate changes have occurred, also helps in evaluating reliability of future climate predictions. Over the last two decades, there has been much progress in Holocene climate simulation (Joussaume and Braconnot, 1997; Kutzbach and Liu, 1997; Wang, 1999; Otto–Bliesner et al., 2006; T. Wang et al., 2010). Holocene Asian monsoon simulation provides information about the long-term driving mechanisms of the monsoon circulation (Kutzbach and Liu, 1997; Joussaume et al., 1999; Liu et al., 2003, 2004; T. Wang et al., 2010). In this review, we presented a synthesis on Holocene Asian monsoon simulations that largely focuses on the interaction between the EASM and the ISM. The absolutely-dated Holocene speleothem records in the domains of the two monsoon subsystems were used to verify those model results. In addition, a unified monsoon index (UMI), which has a solid dynamic basis and is appropriate for different monsoon regions, was used in calculating modern monsoon indices of the two subsystems that help explore the modern relationship between them. This combination of Holocene Asian monsoon simulations, monsoonal records and modern monsoon indices is helpful in evaluating the interaction between the two subsystems on different time scales.

2. Data and methods

2.1. Selection of Holocene Asian monsoon simulations

A large number of palaeoclimatic simulations from East and Central Asia has been published during the last two decades. While providing insights into the mechanisms of climate change, these simulations, however, have different focus, such as precipitation, temperature and evaporation. To ensure the simulations can be used to imply monsoon mechanisms, all of those included in our analyses were required to meet the following criteria:

1) Simulations should provide information for the Holocene epoch, at least some intervals in the Holocene.
2) Simulations should be indicative of monsoon intensity, monsoon water vapor transport, or monsoon rainfall.
3) Both the EASM domain and the ISM domain should be included in the simulations, so that we can detect the interaction between the two subsystems.

Totally, 13 simulations were selected for this study (see detailed information in Table 1). Eight simulations focus on the mid-Holocene (~6.0 ka) and the present-day or the pre-industry that can represent the late Holocene period. The other four simulations (CCSM 3.0, CLIMBER-2, FOAM-NCAR-CSM and FOAM-FSSTAM) compare the early Holocene simulations with the mid-to-late Holocene results. In these simulations, the monsoon status is usually shown by precipitation that is also complemented by pressure and wind fields. In order to further examine the relationship between the two monsoon subsystems, we

Table 1
Summary of Holocene climate simulations in the Asian monsoon domain.

Models	Periods	Duration of the model experiment (years)	Whether the difference between the two subsystems can be detected	References
AGCM + SSiB	Present-day and 6 ka	11	Yes	Chen et al. (2002), Liu et al. (2002)
ECHAM5/JSBACH-MPIOM	Present-day and 6 ka	600	Yes	Dallmeyer et al.(2009), Dallmeyer and Claussen (2011)
CCSM 3.0	Pre-Industrial, 6 ka, and 8.5 ka	100 and 50	Yes	Li and Morrill (2010), Jin et al. (2012)
CLIMBER-2	9.0 ka to present-day	9000	Yes	Jin et al. (2005, 2008)
FOAM-NCAR-CSM	Present-day, 3 ka, 6 ka, 8 ka and 11 ka	120	Yes	Liu et al. (2003, 2004)
FOAM-FSSTAM	Present-day, 6 ka, and 11 ka	260	Yes	Li and Harrison (2010)
PMIP 1*	6 ka	10	Yes	Joussaume et al. (1999)
PMIP 2**	6 ka	500	Yes	T. Wang et al. (2010)
IAP-AGCM	6 ka	5	Yes	Wang (1999)
AGCM-BIOME	6 ka	5	Yes	Wang (2002)
RegCM2	Present-day and 6 ka	5	Yes	Zheng et al. (2004)
FGOALS-g1.0	Present-day and 6 ka	/	Yes	Zheng and Yu (2009)
LMD AGCM	6 ka	15	Yes	Texier et al. (2000)

* PMIP 1 includes 18 models: BMRC, CCC2, CCM3, CCSR1, CNRM2, CSIRO, ECHAM3, GEN2, GFDL, GISS, LMD4, LMD5, MRI2, MSU, UGAMP, UIUCll, UKMO and YONU.
** PMIP 2 includes 12 models: CCSM, CSIRO-Mk3L-1.0, CSIRO-Mk3L-1.1, ECHAM5-MPIOM1, FGOALS-1.0 g, FOAM, GISSmodelE, IPSL-CM4-V1-MR, MIROC3.2, MRI-CGCM2.3.4fa, MRI-CGCM2.3.4nfa and UBRIS-HadCM3M2.