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Sensitivity of Asian climate change to radiative forcing during the last millennium in a multi-model analysis

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ABSTRACT

The outputs of last millennium (A.D. 850–1850) experiments from seven climate models of the Paleoclimate Modeling Intercomparison Project 3, have been used to analyze decadal to centennial climatic variations over Asia, including the Indian monsoon, the East Asian monsoon and the westerly jet. In particular, the differences between the Medieval Warm Period (MWP, A.D. 901–1200) and the Little Ice Age (LIA, A.D. 1551–1850) are focused on. Statistically, significant temperature contrasts between the MWP and LIA are simulated by all of the models, and larger temperature deviations occur during colder periods. Although discrepancies exist, stronger Indian and East Asian summer monsoon circulations, as well as a stronger Asian westerly jet stream in winter, are found during the MWP compared to the LIA, in most of the models. These changes primarily originate from different atmospheric thermal structures over the two periods, which occur in response to the external radiative forcings. However, the monsoon-associated precipitation is quite complicated, with distinctly different patterns simulated among the models. There are phase differences in the multi-decadal variability of precipitation among the models, which consistently fail to detect a weakening in the precipitation at the minima of the radiative forcings. Only limited models are able to simulate the quasi-100-year solar cycles in the changes of precipitation over India and East Asia. Thus, although the climate system is certainly affected by external radiative forcings, our results imply that the natural forcings may not exert such a substantial influence on the Asian monsoon rainfall, or the models may underestimate the response.

1. Introduction

The Asian climate is characterized by a prominent coastal monsoon and inner aridity, and is an important component in the global climate system. The Asian monsoon, which includes the Indian and East Asian monsoons, provides fundamental water resources for the economic and social lives of a large proportion of the world's population. Over inland regions where the Asian monsoon hardly penetrates into, the precipitation is quite scarce and the westerly winds dominate nearly all year round.

The variation and evolution of the Asian monsoon and the westerly winds have basically controlled the patterns of climate change over Asia in modern- and paleo-times, and thus have attracted intensive studies (Gadgil, 2003; Ding and Chan, 2005; Wang, 2006; Zhang et al., 2006; Zhou et al., 2009; Lu et al., 2011; An et al., 2012, 2015; Shi et al., 2014). Among modern climate studies, the main focus has been on the variability of the Asian climate at relatively short timescales, from interseasonal to interdecadal, and their associated mechanisms, due to the limited time coverage of observational data. Further, in most cases, researches based on modern observations have only analyzed the internal oscillations of the climate system (e.g., Kumar et al. (1999); Chang et al. (2001); Goswami and Xavier (2005); Goswami et al. (2006); Sun et al. (2008); Wang et al. (2008); Ummenhofer et al. (2011); Rajagopalan and Molnar (2012) and Xu et al. (2015)) and has failed to consider the various changes in external forcings.

The external forcing that has been considered the most till now is the variation of greenhouse gases (GHG); GHG forcing has been proven to exert a significant role on the Asian climate change. Not only does the GHG forcing directly affect the interdecadal variations of the Asian monsoon (Ueda et al., 2006; Li et al., 2010; Sooraj et al., 2014), but it might also be responsible for changes in the internal monsoon dynamics (Krishnamurti and Goswami, 2000; Wu and Wang, 2002; Wang et al., 2008). Other external forcings, for example, solar irradiation and volcanic activities, may also have significant impacts. However, our knowledge on the decadal to centennial variations of the Asian climate and mechanisms associated with them are still limited. How the external forcings, especially natural ones, affect the climate and internal dynamics over Asia remain largely unclear.

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The last millennium is a good period to explore the decadal to centennial variations in the Asian climate. For this period, the climate variability over Asia has basically been reconstructed from various geological proxies, including tree rings, stalagmites, corals and lake deposits. Remarkable fluctuations have been shown in the proxy data, for both the Indian and East Asian monsoon regions, on the decadal to centennial time scales (e.g., Qian et al. (2003); Zheng et al. (2006); Zhang et al. (2008); Cook et al. (2010); Berkelhammer et al. (2010) and Sinha et al. (2011), 2015). In particular, severe droughts occurred in India and eastern China during solar minima, which indicates that the monsoons were simultaneously weakened during these periods (Agnihotri et al., 2002). However, reconstruction data from eastern Africa has shown the opposite behavior in that region (Verschuren et al., 2000). Nevertheless, from these data reconstructions, it is clear that some changes in the monsoons can be explained by manifestations of solar variability.

Two typical periods of the last millennium, the Medieval Warm Period (MWP) and the Little Ice Age (LIA), are documented within the climate proxies over Asia; in most proxies, distinct differences can be seen between the two periods. In large parts of northern China, warmer and wetter MWP climate anomalies can be seen in the proxies (Zhang et al., 2008). In southern China, these differences are not as distinct (Wang et al., 2005) and in certain areas, it appears that more precipitation occurred during the LIA (Zheng et al., 2006). Some proxies from India (von Rad et al., 1999; Sinha et al., 2007) indicate that the MWP was relatively wetter, while the driest period in the last millennium occurred during the transition into the early stages of the LIA. In addition, an apparently stronger upwelling occurred during the MWP in the Arabian Sea (Anderson et al., 2002), which might support an intensified Indian monsoon. In contrast, precipitation during the MWP decreased across the arid regions, from coastal Arabia to inland central Asia (Chen et al., 2008, 2010).

Although there have been intensive researches, through reconstructions, into Asian climate change over the past millennium, the proxy records used originated from specific sites, and so are unable to provide detailed climatological fields; thus, in this context, numerical experiments that cover the period provide a good supplementary tool, to explore the mechanisms of climate change. Using reconstructions of the boundary conditions, lots of climate models have been forced to simulate climate change over the past millennium, however, most of the studies have focused on global or hemispheric temperatures (e.g., Brovkin et al. (1999); Bertrand et al. (2002); Zorita et al. (2004); Goosse et al. (2005); Ammann et al. (2007) and Shi et al. (2007)). In terms of the Asian climate, most researches have concentrated on the long-term variability of the Asian monsoon, and in particular, precipitation over East Asia (Shen et al., 2008; Liu et al., 2011; Man et al., 2012).

Through analysis of the millennium model simulations, a significant centennial oscillation has been detected in the summer precipitation over eastern China, which is essentially a forced response, linked to the fluctuations of insolation and volcanic aerosols (Chen et al., 2008; Liu et al., 2011; Man et al., 2012). The response of the East Asian summer monsoon to external forcings, measured by the differences between the MWP and LIA, is also remarkable (Liu et al., 2011; Man et al., 2012). In addition, the spatial patterns observed are different from the interannual variability (Liu et al., 2011). Further, it has been found that the strength of the response may be latitude-dependent and precipitation over different latitudinal belts is sensitive to different forcings (Liu et al., 2011). Internally, ocean feedback also plays a role, and changes in the sea surface temperatures over the Pacific are of importance, in explaining the long-term variation of the Asian monsoon (Fan et al., 2009; Graham et al., 2011).

All the previous modeling studies have indicated that Asian climate change during the past millennium is a forced response, and that the response is significant; however, it is unknown whether the results of these studies are model-dependent. Thus, a multi-model analysis is conducted here, to examine the sensitivity of different models to the external forcings, during the last millennium. The main aims of this study are to identify: (1) how the Asian climate responds to external radiative forcings on the decadal to centennial timescale; (2) whether the remarkable temperature difference between the MWP and LIA could induce any differences in the Asian climate; (3) what the consistencies are among the modeling results and what the differences are. To answer these questions, the multi-decadal to centennial variability of Asian climate and its relation with the radiative forcing, as well as the differences between the MWP and LIA, are calculated and analyzed for all seven models. A short description of the last millennium experiments is presented in Section 2. The results are analyzed and discussed in Sections 3 and 4, respectively, and Section 5 provides a summary of this study.

Table 1
List of models used for the last millennium experiments in this study.

Model	Atmospheric resolution	Ensemble
CCSM4	288 × 192 × L26	r1i1p1
HadCM3	96 × 73 × L19	r1i1p1
BCC-CSM1-1	128 × 64 × L26	r1i1p1
CSIRO-Mk3L-1-2	64 × 56 × L18	r1i1p1
MPI-ESM-P	196 × 98 × L47	r1i1p1
GISS-E2-R	144 × 90 × L40	r1i1p124
IPSL-CM5A-LR	96 × 95 × L39	r1i1p1

2. Last millennium experiments

The modeling data used in this study are from the last millennium (LM) and the preindustrial control experiments, produced by seven different climate models. The data are available from the Paleoclimate Modeling Intercomparison Project 3 (PMIP3) and can be downloaded at the Earth System Grid Federation. All the models are coupled ocean–atmosphere models performed at various resolutions (Table 1). These models are integrated across the period A.D. 850–1850; so the models allow us to test the sensitivity of climate systems during the pre-industrial era. The simulations are performed with similar external forcings (Fig. 1), including solar irradiation, volcanic aerosols, land cover changes and greenhouse gases. The forcings used are discussed in detail by Schmidt et al. (2012), who demonstrate that, in general, there is similar variation in the forcings among the simulations. We note that all the experiments have used SBF and VSK reconstructions for solar changes (Steinhilber et al., 2009; Vieira et al., 2011); these data indicate that the solar irradiation varied by a range of 0.3 W/m^2 during the past millennium, which is a much smaller range than indicated by the SEA data (Shapiro et al., 2011). In addition, the radiative forcing of volcanic aerosols is larger, by about 9 and 7 W/m^2 for the 1250s and 1450s eruptions, respectively, in Indonesia and Vanuatu, in GRA data, than in CEA data

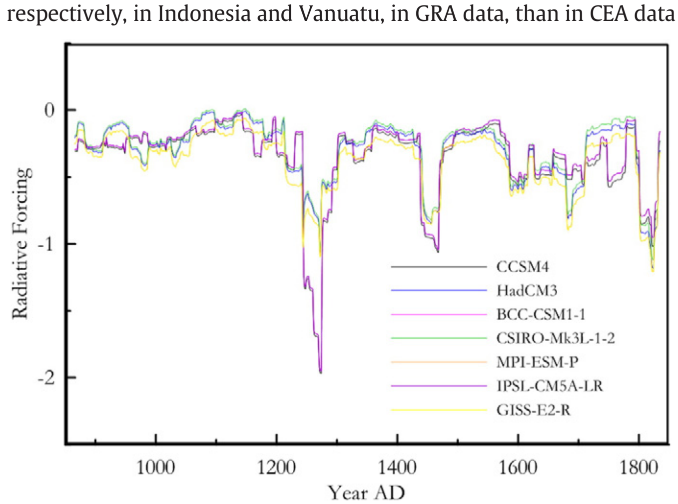

Fig. 1. Radiative forcings (W/m^2) used for the seven last millennium experiments. The curves are 31 year smoothed.