Responses of Global and East Asian Monsoon to the External Forcing over the Last Millennium

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Abstract

The climate variations related to Global Monsoon (GM) and East Asian summer monsoon (EASM) rainfall over the past 1000 years were investigated by analysis of a pair of millennium simulations with the coupled climate model named ECHO-G. The free run was generated using fixed external (annual cycle) forcing, while the forced run was obtained using time-varying solar irradiance variability, greenhouse gases (CO_2 and CH_4) concentration and estimated radiative effect of volcanic aerosols. The model results indicate that the centennial-millennial variation of the GM and EASM is essentially a forced response to the external radiative forcing (insolation, volcanic aerosols, and greenhouse gases).

The simulated GM precipitation (GMP) was weak during the Little Ice Age (1450–1850) and strong during the model Medieval Warm Period (1030–1240). The GMP exhibits a significant quasi-bi-centennial oscillation. The five periods with the weakest GMP coincide with the minimum periods of solar activity: the Oort, Wolf, Spörer, Maunders, and Dalton minimum. The effective solar forcing reinforces the hemispheric thermal contrast, resulting in the centennial-millennium variation. The unprecedented strengthening of the GMP in the last century is due in part to the increase of atmospheric greenhouse gas concentration. Noteworthy is that the GMP strength responds more sensitively to the effective solar forcing (r=0.78) than global-mean surface air temperature (r=0.69).

The EASM provides a unique opportunity for understanding the latitudinal differences in monsoonal responses to external forcing as it has the largest meridional extent (5^oN-55^oN) among all the regional monsoons. In the last millennium, the extratropical and subtropical rainfall variations tend to follow the effective solar radiation forcing closely; whereas the tropical rainfall is less sensitive to the radiation forcing but responds significantly to the modern anthropogenic CO_2 forcing. The spatial structure of the forced response differs from that of interannual variability which arises primarily from the internal feedback processes within the climate system. The behavior of the interannual variability is significantly modulated by the mean state change on the centennial-millennial time scales. These findings have important ramification in understanding the differences and linkages between the forced and internal modes of variability as well as in promoting communication between scientists studying modern- and paleo-monsoon variations.

Key words: Global monsoon, East Asian summer monsoon, precipitation, millennium, simulation

1. Introduction

The last millennium is the key period for bridging the proxy records and modern instrumental data, during which the earth environment and ecological system have become increasingly changeable due to the increasing influence of human activities and mixture of the anthropogenic and natural climate variability. Based on the reconstructed proxy data, such as stalagmite, tree ring, lake sediment etc., scientists have made great progress in climate variability in the last millennium (Soon et al., 2003). However little is known about the variability and mechanism of the global monsoon (GM) and East Asian summer monsoon (EASM) in the last millennium.

In contrast to numerous studies on the monsoon circulation and sea level pressure, we focus on monsoon precipitation in this study. Why we are particularly concerned with the global monsoon precipitation? Precipitation is of great scientific importance as it is the key variable of the global water cycle and it provides a critical heat source for driving atmospheric circulation. Also the monsoon rainfall provides water resources to about two-thirds of the world’s population, it is far more relevant for food production and water supply than other climatic variables, so that any improved knowledge on its variation will be of great societal importance. Moreover, for paleoclimatologists, it is easier to reconstructed precipitation than either circulation or sea level pressure.

One of the major roadblocks for studying GM and EASM variability on centennial- millennial scale is the lack of direct observations. To make progress, we consider numerical simulations with atmosphere-ocean coupled climate models for this research. These simulations may provide useful surrogate datasets for analyzing and understanding any changes of GM and EASM precipitation on multi-decadal to centennial time scales. These kinds of simulations have been constructed using a wide range of climate models with different levels of complexity, including the HadCM2 model (Johns et al., 1997), GFDL model (Manabe and Stouffer, 1993; Stouffer et al., 2000), CSIRO model (Vimont et al., 2002), ECHO-G model (Rodgers et al., 2004; Min et al.; 2005a and 2005b; Wagner et al.,2005), MRI-CGCM2.2 model (Kitoh, 2006) for control simulations; and the CLIMBER-2 model (Bauer et al., 2003), ECHO-G model (Zorita et al, 2003; Gonzalez-Rouco et al., 2003; Zorita et al., 2005; Gouirand et al., 2007a and 2007b), ECBILT–CLIO model (Goosse et al., 2005), MAGICC model (Osborn et al.,2006), ECHAM4-OPYC3 model (Stendel et al., 2006), HadCM3 model (Tett et al., 2007), NCAR-CSM (Mann et al., 2005a; Ammann et al., 2007) for forced simulations of the past millennium or past half millennium.

Based on these model results, the internal variability of temperature, precipitation, mean sea level pressure and major modes of climate variation, such as NAO, ENSO and Indian monsoon have been discussed (Min et al., 2005a and 2005b; Zorita et al., 2003; Kitoh, 2006). Variabilities on interannual, decadal, multi-decadal and centennial time scales under natural and anthropogenic forcing have also been examined in terms of surface and subsurface temperatures (Stouffer et al., 2000; Beltrami et al., 2006; Gonzalez-Rouco et al., 2003; Zorita et al., 2005; Wagner et al., 2005; Osborn et al., 2006). Both model-model comparison (Goosse et al., 2005; Osborn et al., 2006) and model-data comparison (Liu et al., 2005; Beltrami et al., 2006) among convenient indices like SST, ENSO, NAO and AO (Vimont et al., 2002; Rodgers et al., 2004; Goosse et al., 2005; Gouirand et al., 2007a and 2007b) have been performed in order to assess the reality and robustness of models' simulations. Roles of centennial-scale variations in solar activity (Wagner et al., 2001; Fleitmann et al., 2003; Weber et al., 2004; Wiles et al.,2004; Holzkämper et al., 2004; Delmonte et al., 2005; Lim et al., 2005; Wang et al., 2005; Haltia-Hovi et al., 2007) and changes between volcanic pulse-forcing (Crowley, 2000; Goosse and Renssen, 2004; Mann et al., 2005b) have also been recently investigated and argued through a combination of paleo proxy data analyses and climate modelings.

But how does the GM and EASM rainfall respond to the external forcing in the last millennium? How do the changes of GM rainfall relate to the changes of global temperature and inter-hemispheric temperature difference? Is there any modulation of external forcing to spatial mode of precipitation interannual variation? These questions will be addressed here.

2. Model and simulation

The ECHO-G climate model (*Legutke and Voss*, 1999) consists of the spectral atmospheric model ECHAM4 (*Roeckner et al.,* 1996) and the global ocean circulation model HOPE-G (*Wolff et al.,* 1997), both developed at the Max-Planck-Institute for Meteorology in Hamburg. The ECHAM4 is based on primitive equations with a mixed p-σ coordinate system. The model configuration used for these simulations has 19 vertical levels in the atmosphere and 20 levels in the ocean, and horizontal resolutions are approximately 3.75° (atmosphere) and 2.8° (ocean) in both latitudes and longitudes. The ocean model HOPE-G has a grid refinement in the tropical regions, where the meridional grid point separation reaches 0.5°. To enable the coupled model to sustain a simulated climate near to the real present day climate with minimal drift, both heat and fresh-water fluxes between atmosphere and ocean are modified by adding a constant (in time) field of adjustment with net-zero spatial average (*Roeckner et al.,* 1996; *Wolff et al.,* 1997).

Two millennial integrations with the ECHO-G model will be analyzed here. One is the 1000-year control simulation (CTL) which was generated using fixed external (annually cycling) forcing set to the present-day values (*Zorita et al.*, 2003). This CTL experiment can simulate annual to decadal climate oscillations through the internal dynamics of the coupled climate system (Min et al., 2005a and 2005b). The second simulation, named ERIK, covering the period 1000-1990 is forced by three external forcing factors (*Gonzalez-Rouco et al.*, 2003; *von Storch et al.*, 2004; *Zorita et al.*, 2005): solar variability (*Crowley,* 2000; *von Storch et al.*, 2004), greenhouse gas concentrations in the atmosphere including CO_2 and CH_4 (*Blunier et al.,* 1995; *Etheridge et al.,* 1996) and the effective radiative effects from stratospheric volcanic aerosols (*Crowley,* 2000) for the period 1000 to 1990 AD. The volcanic forcing is parameterized in this simulation as a simple reduction of the annual mean solar constant, starting in the year with a volcanic eruption and usually lasting a couple of years, according to the reconstructions of volcanic aerosol forcing (*Crowley*, 2000). This second experiment includes the major natural and anthropogenic forcings in the past millennium, but a number of other potentially important forcings (i.e., anthropogenic tropospheric sulphate aerosols, the effect of land-use and vegetation changes, and some other greenhouse gases, such as halocarbons and ozone) were excluded in the ERIK experiment.

The performance of ECHO-G in modeling precipitation climatology have been analyzed by Liu et al. (2009).

3. Responses of global and East Asian monsoon to external forcing

The global monsoon (GM) is the dominant mode of the annual cycle of the global tropical circulation (Wang and Ding, 2008). Following Wang and Ding (2008), the GM precipitation domain, the Global Monsoon Index (GMI), the Northern Hemisphere Monsoon Index (NHMI) and the Southern Hemisphere Monsoon Index (SHMI) could be defined (Liu et al., 2009). Figure 1 shows the time series of the 7-year and 31-year running means of the monsoon indices (NHMI, SHMI, GMI) for both the CTL and ERIK runs.

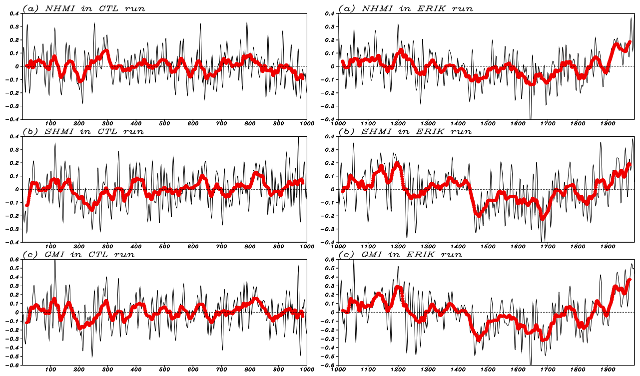

Fig. 1 Time series of the 7-year running mean monsoon indices for CTL (left panels) and ERIK (right panels) runs for NHMI (a), SHMI (b) and GMI (c), respectively. The red lines represent the 31-year running means, which highlight centennial variations.

The control run provides an opportunity to examine the internal variability due to feedback processes in the coupled system. In the control run, there is no trend in NHMI, SHMI, and GMI. Further the NHMI and SHMI are not related, as evidenced by the correlation coefficients between them valued at about zero for both the 7-year and 31-year running mean series. This result suggests a lack of coherency of the monsoon intensity between the two Hemispheres without external forcing. In the ERIK run, on the other hand, the simulated forced responses are quite different. Significant centennial variation can be seen. These variations correspond to the evolution of the global mean temperature, where a model MWP, LIA and PWP can be recognized (*Zorita et al.,* 2005).

According to the result of ERIK run (Fig. 2a), the GMP exhibits clear millennium-scale variation and quasi-bicentennial oscillation in response to the effective solar radiation (Fig. 2d, solar radiation plus effect of volcanic aerosol). The simulated GMP was weak during the Little Ice Age (1450–1850) and strong during the Medieval Warm Period (1030–1240) (Fig. 2c). The GMP has five weakest periods concurring with the minimum periods of solar activity (Fig. 2d). The effective solar forcing reinforces the hemispheric thermal contrasts (Fig. 2c), resulting in the centennial-millennium variation. The unprecedented strengthening of the GMP in the 20th century is due in part to the increase of atmospheric greenhouse gases concentration. Note that the GMP strength responds more directly to the effective solar forcing ($r=0.78$) than the global-mean surface temperature (r=0.69).

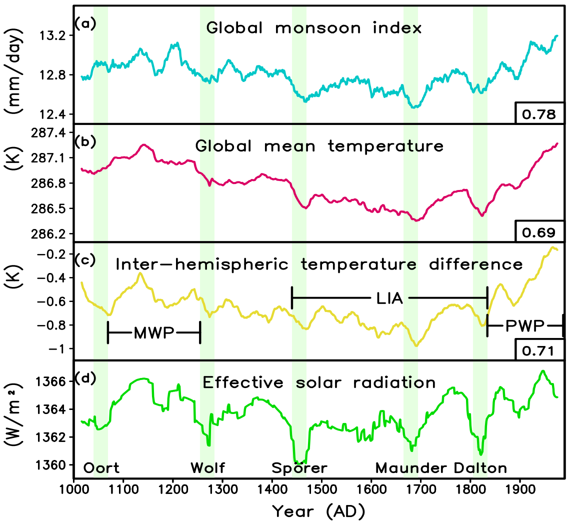

Fig. 2 The 31-year running mean time series of the global monsoon precipitation index (a, mm/day), global mean temperature (b, K), inter-hemispheric temperature difference (c, K, NH minus SH) and effective solar radiation (d, W/m^2).

Since the EASM comes across tropics, subtropics and extratropics, the first question of interest is how the EASM precipitations in the three sub-regions respond to the millennial variations of external forcings. Fig. 3a, b, c present time series of MJJA mean precipitation rate simulated in the ERIK run for the EA including the intertropical convergence zone (ITCZ) (8-17^{o}N), subtropical frontal rain belt (Meiyu) (23-32^{o}N), and extratropical (36-45^{o}N) regions. All three time series were subject to a 21-year moving average in order to underline the multi-decadal to millennial variability. In order to see the periodicity of the forced response, the corresponding power spectra for each region are shown in Fig. 3d, e, f, respectively. It shows there are significant centennial-millennial variations in all three regions, but the behavior of the forced variations depend on latitude. The extratropical EA responds to external forcing more sensitive than the subtropics and tropics. The subtropical EASM precipitation shows a significant quasi bi-centennial variation in accord with the effective solar forcing at 95% confidence level. The tropical East Asia ITCZ has least response to the external forcing, suggesting that the ITCZ is more stable and hard to be perturbed by moderate external forcing change in ERIK simulation.

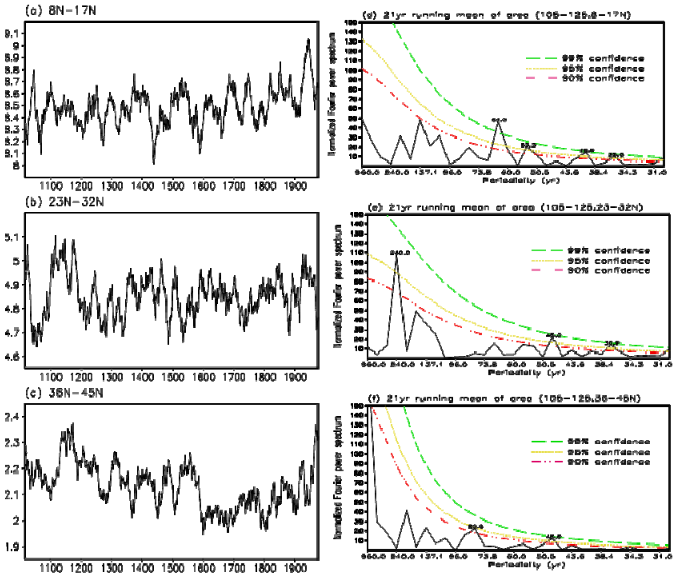

Fig. 3 21-year moving average time series of MJJA ERIK precipitation (left panels) and corresponding spectrum analysis (right panels) for (a) tropical (8°N -17°N, 105°E -125°E) (b) subtropical (23°N -32°N, 105°E -125°E) , and (c) extratropical (36°N -45°N, 105°E -125°E) EA regions

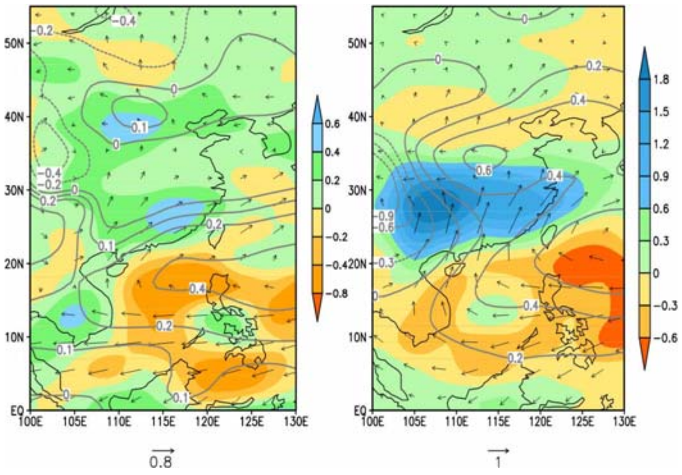

Fig. 4 Comparison of the spatial structures of the (a) forced and (b) internal mode. The structure of the forced mode is described by the differences between the MWP and LIA (MWP minus LIA). The structure of the internal mode is depicted by the composite strong minus weak subtropical (21-35^{o}N, 100-120^{o}E) rainfall of the interannual-decadal variation. The color shading represents the MJJA mean precipitation rate (mm day^{-1}), contours denote the sea-level pressure (hPa), and arrows represent the 850 hPa winds (m/s)

Figure 4 compares the spatial structures of the forced mode (Fig. 4a) and internal mode (Fig. 4b) of EASM. With regard to the relationship between the subtropical and extratropical rainfall, there is a difference between the forced and internal modes. For the forced mode, the subtropical and extratropical rainfall increases simultaneously (Fig. 4a). This feature implies that the forced mode is characterized by an in-phase relationship between the subtropical and extratropical rainfall. On the other hand, the internal mode features an out-of-phase relationship between the subtropics and extratropics (Fig. 4b). Note that the model simulated internal mode structure agrees well with the observed structure on interannual-decadal time scale: When Meiyu is abundant, the rainfall in northern China tends to be deficient or vice versa (e.g., Ding 1992).

4. Conclusion

From this study we found that:

(1) The GMP was weak during the Little Ice Age (1450–1850) and strong during the model Medieval Warm Period (1030–1240) (namely millennium variation). It also exhibits a significant quasi-bi-centennial oscillation.

(2) There are significant centennial-millennial precipitation variations in EA region, but the extratropical EA responds to external forcing more sensitive than the subtropics and tropics.

(3) The GMP strength responds more directly to the effective solar forcing (r=0.78) than the global-mean surface temperature (r=0.69).

(4) The forced mode has a different structure in comparison to the internal mode of EASM in the extratropical regions, inducing that the extratropical and subtropical monsoons vary in tandem on the centennial time scale.

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