Impact of the Atlantic Multidecadal Oscillation on the Asian summer monsoon

Riyu Lu,1,2 Buwen Dong,3 and Hui Ding2,4

Received 23 July 2006; revised 18 September 2006; accepted 19 October 2006; published 20 December 2006.

[1] The impact of the Atlantic Multidecadal Oscillation (AMO) on the Asian summer monsoon is investigated using a coupled atmosphere-ocean global general circulation model by imposing the AMO-associated sea surface temperature anomalies in the Atlantic as boundary forcing, and allowing atmosphere-ocean interactions outside the Atlantic. The positive AMO phase, characterized by anomalous warm North Atlantic and cold South Atlantic, leads to strong Southeast and east Asian summer monsoons, and late withdrawal of the Indian summer monsoon. These changes of monsoons are mainly through coupled atmosphere-ocean feedbacks in the western Pacific and Indian Oceans and tropospheric temperature changes over Eurasia in response to the imposed forcing in the Atlantic. The results are in agreement with the observed climate changes in China corresponded to the AMO phases. They suggest a non-local mechanism for the Asian summer monsoon variability and provide an alternative view to understanding its interdecadal variation during the twentieth century.


1. Introduction

[2] The sea surface temperatures (SSTs) in the Atlantic exhibit an oscillation with period of 65–80 years on the multidecadal timescale, which is referred to as the Atlantic Multidecadal Oscillation (AMO [Delworth and Mann, 2000; Kerr, 2000]), and is thought to be related to multidecadal fluctuations of the Atlantic thermohaline circulation (THC [Delworth and Mann, 2000]). The AMO appears to be the pacemaker of climate in the globe [e.g., Knight et al., 2005], especially in the Northern Hemisphere. It contributes to the multidecadal fluctuations of the global mean surface temperature [Schlesinger and Ramankutty, 1994], modulates the ENSO variability [Dong et al., 2006], affects North American and European summer climate [Enfield et al., 2001; Sutton and Hodson, 2005].

[3] The east Asian and Indian monsoons also vary on decadal-multidecadal time scales [Kripalani and Kulkarni, 2001; Zhu and Wang, 2001, 2002; Li et al., 2004; Goswami, 2005; Goswami et al., 2006; Li and Bates, 2006]. However, the space and time structure of the monsoon decadal-multidecadal variability is not well documented, and mechanisms responsible for it are not fully understood although it has been proposed that the low frequency change of ENSO [e.g., Krishnamurthy and Goswami, 2000; Huang, 2001] and aerosol [Menon et al., 2002] may play a role. Recent studies suggest that the multidecadal monsoon variability is related to the AMO [e.g., Goswami et al., 2006; Li and Bates, 2006]. Goswami et al. [2006] suggested a link between the AMO and the Indian summer monsoon rainfall by using observational data. Li and Bates [2006] indicated that the AMO has an impact on the east Asian winter monsoon. Zhang and Delworth [2005] showed that a substantially weakened Atlantic THC leads to weakened Indian and east Asian summer monsoons. All these studies suggest a possible role of the Atlantic Ocean in the low frequency fluctuation of the Asian climate. However, detailed mechanisms through which the Atlantic Ocean influences the Asian summer monsoon are still unclear and need to be elucidated. Understanding the relationship between the AMO and Asian monsoon would be great helpful for climate prediction and agricultural planning in Asian countries, because the AMO may be predictable [Griffies and Bryan, 1997].

[4] In this study, we investigate the impact of the AMO on the Asian summer monsoon by imposing the AMO-associated SST anomalies in the Atlantic as boundary forcing and allowing atmosphere-ocean interactions outside the Atlantic. This regional coupling allows monsoons to respond to not only the direct forcing imposed in the Atlantic, but also atmosphere-ocean interactions in the Indian Ocean and Pacific, which might play a role. Recent studies suggest that the multi-decadal monsoon variability is related to the AMO [e.g., Goswami et al., 2006; Li and Bates, 2006].

2. Model and Experiments

[5] The model used in this study is a coupled atmosphere-ocean general circulation model developed at the Hadley Centre (HadCM3). The atmospheric component of HadCM3 has 19 levels with a horizontal resolution of 2.5° of latitude by 3.75° of longitude [Pope et al., 2000], and the oceanic component has 20 levels with a horizontal resolution of 1.25 by 1.25° [Gordon et al., 2000]. The two components are coupled once a day. The model does not require flux corrections to maintain a stable climate. The mean climate and its stability in a 1000-yr control simulation are discussed by Gordon et al. [2000].
The JJA mean differences between positive and negative AMO experiments: (a) surface temperature (°C) and (b) precipitation (mm d⁻¹). Shading indicates significant differences at 95% confidence level using t-test. Contours are plotted at ±0.1, ±0.2, ±0.4, ±0.8, and ±1.2 for temperature, and plotted at ±0.1, ±0.3, ±0.6, ±1.0, ±2.0, and ±4.0 for precipitation.

Two regional coupled experiments, each 150 years long, corresponding to AMO warm and cold phases were performed by relaxing SSTs over the Atlantic Ocean to prescribed values with a time scale of 2.5 days [Dong et al., 2006]. The prescribed Atlantic SST consisted of the model climatology plus or minus 3 times the AMO pattern, i.e., the second empirical orthogonal function, characterized by warm North Atlantic and cold South Atlantic, of low-pass filtered SST variability [Dong et al., 2006, Figure 1]. The differences in the results between the warm and cold AMO experiments allow us to assess the response of the mean climate change in the Asian monsoon region to the anomalous Atlantic Ocean state. It should be noted that, however, without the higher frequency forcing, for example, the interannual variability of SST superimposed on the prescribed AMO pattern, the present modeling results exclude the possible contribution of the higher frequency forcing over the Atlantic on the low frequency response over the Asian monsoon region. We analyze the results of last 145 years, although any transient adjustment effects are small.

3. Results

Shown in Figure 1 are the differences in mean surface temperature and precipitation between the AMO positive and negative phase experiments for JJA season. Surface temperature anomalies (Figure 1a) show the expected dipolar pattern in the Atlantic and also warm anomalies about 0.25°–0.5°C over Africa and Eurasia, and about 0.25°C over the maritime continent and the Indian Ocean. In the western Pacific, the SST differences are zonally elongated, with alternative signs in the meridional direction.

Precipitation anomalies (Figure 1b) show significant enhanced precipitation (0.3–0.6 mm day⁻¹) over Southeast Asia and east Asia. These anomalies correspond to an increase about 5–10% relative to the negative AMO phase experiment and indicate a stronger Asian summer monsoon. In the tropical Pacific, the positive (negative) precipitation anomalies correspond to the warm (cold) SST anomalies. The positive precipitation anomalies (~0.6–1.0 mm day⁻¹) in the maritime continent and eastern Indian Ocean are also related to the underlying warmer SSTs. There are no significant precipitation anomalies over India and in the Philippine Sea. In fact, precipitation is reduced slightly over India in JJA (Figure 1b) and this reduction is associated with the enhanced convection over tropical southeastern Indian Ocean [e.g., Gadgil et al., 2004].

The positive AMO leads to significant 850-hPa westerly anomalies over the tropical Atlantic, America and eastern Pacific, and easterly anomalies in the tropical western Pacific (Figure 2a). In the western North and South Pacific, there are twin anticyclonic anomalies at lower troposphere (see also Figure 2b), which are likely to be induced by the warmer SSTs and enhanced precipitations in the southeast Indian Ocean and maritime continent shown in Figure 1b. The anticyclonic anomaly in the western North Pacific results in westward extension of the climatological subtropical anticyclone [Lu, 2001], enhances the east Asian monsoon circulation (Figure 2a) and leads to more precipitations in east Asia (Figure 1b). These circulation anomalies tend to exhibit a baroclinic vertical structure, but with weaker signals at upper troposphere (not shown).

The precipitation anomalies in the western Pacific and Indian Ocean, which may be explained as a result of the SST anomalies in the southeast Indian Ocean and maritime continent, differ considerably with the simulated results by Sutton and Hodson [2006], who forced the atmospheric component of the coupled model with a warm North Atlantic pattern similar to our prescribed SST anomalies. For instance, their results do not show significant precipitation anomalies over south Asia, east Asia and eastern Indian Ocean. The difference in results between the coupled and uncoupled experiments suggests that coupled atmosphere-ocean feedbacks play an important role in these regions.

The above-mentioned results suggest that the positive surface temperature anomalies in the eastern Indian Ocean and maritime continent, which are a response to the AMO through atmosphere-ocean interactions, may play a crucial role in extending the AMO’s influences to the Asian
monsoon. A question arises naturally: what is the reason for the positive surface temperature anomalies in the eastern Indian Ocean and maritime continent?

Illustrated in Figure 3 is the surface ocean temperature tendency due to surface total heat flux changes and due to Ekman current changes associated with wind stress anomalies. Flux tendency (Figure 3a) is positive in the eastern Indian Ocean and maritime continent, and Ekman tendency (Figure 3b) contribute to the positive SST anomalies in the Southeast Indian Ocean, the Bay of Bengal, and south part of South China Sea. In the tropical western and central Pacific, changes due to surface heat flux and Ekman current counteract each other, and their total effects induce the SST anomalies in distribution similar to the tendency caused by the latter because the latter are greater than the former.

The climate changes simulated by the model due to the imposed AMO are, in large scale, in agreement with the station observations in China. Surface air temperature is warmer by 0.2–0.6 °C in the central and northern China (Figure 4a), and precipitation is heavier (increase by 0.3–0.6 mm day⁻¹) in the most areas of eastern China (Figure 4b) during the warm AMO phase relative to the cold phase. These observed differences resemble the simulated results shown in Figure 1, suggesting that the AMO may play a role in influencing the interdecadal variation of east Asian summer monsoon.

Goswami et al. [2006] suggested that the warm AMO enhances the Indian monsoon rainfall by setting up a positive tropospheric temperature anomaly in late summer/autumn and resultant delayed withdrawal of monsoon. Although the precipitation difference in India is not strong in JJA (Figure 1b), it is significantly positive in SON (Figure 5a) with anomalies about 0.3–0.6 mm day⁻¹. The
enhanced rainfall in September and October suggests a late withdrawal of the Indian summer monsoon (Figure 5b). Figure 5c indicates that there is a strong positive anomaly of tropospheric temperature over the southern Eurasian in SON. This is in contrast with a weak anomaly in JJA (not shown) and implies that changes in the upper tropospheric temperature over Eurasia play a more important role in SON. The spatial pattern of Figure 5c enhances the meridional gradient of tropospheric temperature, which is defined as the difference between a north box (30–100°E, 10–35°N) and a south box (30–100°E, 15°S–10°N) by Goswami et al. [2006], and therefore leads to a delayed withdrawal of the Indian summer monsoon. The enhanced Indian monsoon in SON is also evident in lower tropospheric circulation anomalies that indicate a stronger Somali jet (not shown). These results suggest that the AMO affects the Indian rainfall through the mechanism proposed by Goswami et al. [2006].

4. Summary

[15] A coupled atmosphere-ocean model, HadCM3, is utilized to investigate the Asian summer monsoon responses to the AMO forcing. Relative to the cold AMO phase, the warm AMO induces strong Southeast and East Asian summer monsoons. These responses are found to be a result of coupled atmosphere-ocean feedback in the western Pacific and Indian Ocean. The model results suggest that, the warm AMO leads to positive SST anomalies in the eastern Indian Ocean and maritime continent through coupled feedbacks, and induces more local precipitations. This atmospheric heating leads to an anticyclonic anomaly at low troposphere over the western North Pacific and resultant more rainfall in Southeast Asia and east Asia.

[16] On the other hand, the warm AMO appears to cause a late withdrawal of the Indian monsoon through strengthening the meridional gradient of tropospheric temperature in autumn, a mechanism proposed by Goswami et al. [2006] through observational analyses. This study suggests a non-local mechanism for the Asian summer monsoon variability and provides an alternative view to understanding the observed link between the North Atlantic and the Asian summer monsoon in some paleoclimate evidences [e.g., Gupta et al., 2003]. However, the response to Atlantic SST anomalies might be model dependent and the response in the Asian monsoon region seen in HadCM3 may be too weak. The simulated monsoon precipitation anomaly in response to the imposed AMO forcing is about half of that observed. Thus, it implies that about a quarter of interdecadal variation in monsoon precipitations may be explained by the AMO forcing, given the fact that the magnitude of imposed SST anomalies in model experiments is doubled relative to that observed. The relatively weak response may imply that others factors might also play a role in the multidecadal variability in the Asian summer monsoon. It is worth to investigate whether the Atlantic impact found in HadCM3 is also found in other coupled models and what is the amplitude of the response.

[17] Acknowledgments. This work was supported by the National Natural Science Foundation of China (grant 40523001). Buwen Dong was supported by the EU Framework 6 programme under contract 003903-GOCE (DYNAMITE) and the simulations were performed in the Hadley Centre for Climate Prediction and Research.

References


Huang, R. H. (2001), Decadal variability of the summer monsoon rainfall in east Asia and its association with the SST anomalies in the tropical Pacific, CLIVAR Esch., 6(2), 7–8.


H. Ding and R. Lu, Center for Monsoon Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, P.O. Box 9804, Beijing 100029, China. (lr@lasg.iap.ac.cn)

B. Dong, National Centre for Atmospheric Science-Climate, Department of Meteorology, University of Reading, Reading RG6 6BB, UK.