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Simulation and Projection of Monso on Rainfall and Rain Patterns over Eastern China under Global Warming by RegCM3

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Abstract The authors investigate possible changes of monsoon rainfall and associated seasonal (June-July-August) anomaly patterns over eastern China in the late 21st century under the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 emission scenario as simulated by a high-resolution regional climate model (RegCM3) nested in a general circulation model (FvGCM/CCM3). Two sets of multi-decadal simulations are performed at 20-km grid spacing for present day and future climate conditions. Results show that the RegCM3 reproduces the mean rainfall distribution; however the evolution of the monsoon rain belt from South China to North China is not well simulated. Concerning the rain pattern classifications, RegCM3 overestimates the occurrence of Pattern 1 (excessive rainfall in northern China) and underestimates that of Pattern 2 (increased rainfall over the Huai River basin). Under future climate conditions, RegCM3 projects less occurrence of Pattern 1, more of Pattern 2, and little change of Pattern 3 (rainfall increase along the Yangtze River). These results indicate that there might be increased rainfall over the Huai-Yellow River area and reduced rainfall over North China in the future, while rainfall over the lower reaches of the Yangtze River basin is not modified significantly. Uncertainties exist in the present study are also discussed.

Keywords: climate change, seasonal forecast, monsoon rain patterns, regional climate model, eastern China

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1 Introduction

Precipitation in China is largely affected by the East Asian monsoon. The monsoon rainfall in June-July-August (JJA) over eastern China is of special concern because of the large number of inhabitants there and because this region is a major agriculture production area in the country. Prediction of the monsoon rainfall over eastern China is thus one of the most important issues in operational seasonal forecast by the National Climate Center (NCC) of China.

Significant climatic changes have been observed over the globe, which can largely be attributed to anthropogenic emission of the greenhouse gases (GHGs) (IPCC, 2007). For monsoon rainfall over eastern China, the change is characterized by the so called ‘‘South Flood and North Drought’’. Increased precipitation over southern China along the middle and lower reaches of the Yangtze River basin has resulted in more frequent and severe flood events, while decreased precipitation over northern China has caused drought and water shortages (e.g., Wang, 2001; Zhai et al., 2005; Yu and Zhou, 2007). Although to date there is still no commonly accepted attribution of this change (Zhou et al., 2008), the GHGs forcing may have played, and will likely further play, an important role in these changes.

Coupled atmosphere/ocean general circulation models (AOGCMs) are the primary tools used today to produce climate change projections. However, due to their coarse resolution, they usually have a poor performance in simulating the present climate over East Asia, in particular the distribution and evolution of the monsoon rainfall. Previous studies have shown that high-resolution models are needed to better reproduce the present and project the future climate over the region (e.g., Gao et al., 2001, 2006).

In this paper, changes of monsoon rainfall and rainfall patterns in JJA over eastern China are reported based on a multi-decadal high-resolution nested regional climate model (RCM) simulation. Studies on this issue are important for the assessment of climate change impacts and corresponding adaptation measures. In addition, the results can provide background information on future climate conditions, which may be useful in improving real-time seasonal forecasting.

2 Model and methodology

The RCM employed in the present study is the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model, namely RegCM3. RegCM3 is based on the model of Giorgi et al. (1993a, b) and includes the upgrades described by Pal et al. (2007). The RegCM3 domain for this study covers China and surrounding areas with a grid spacing of 20 km. The model uses its standard vertical configuration with 18 sigma layers. It is one-way nested within corresponding simulations conducted with the National Aeronautics and Space

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Administration/the National Center for Atmospheric Research (NASA/NCAR) global atmospheric model FvGCM/CCM3 (Coppola and Giorgi, 2005).

Two 30-year long simulations are carried out, a Reference Run (thereafter RF) for the period 1961–90 under observed GHGs concentrations and an the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 Scenario (IPCC, 2000) Run (thereafter A2) for the end of the 21st century, 2071–2100. More detailed information on the model settings and some preliminary results can be found in Gao et al. (2008, 2009). In the present study we focus our analysis on the monsoon rainfall and the corresponding rain patterns over eastern China in RF and their future changes as measured by the difference between A2 and RF simulations. The 0.5°×0.5° latitude-longitude gridded data by Xie et al. (2007) is employed as observations to validate the precipitation simulation in RF. The observed data are interpolated to the model grid to facilitate comparison.

The spatial distribution of rainfall over eastern China can be classified to three patterns based on its departure from climatology and the associated 500 hPa circulation as proposed by Liao et al. (1981) and Liao and Zhao (1992). Researches have shown that the three patterns correspond to the first three leading eigenvectors of EOF analysis. To be more specific, EOF 1 corresponds to Pattern 3, EOF 2 to Pattern 2, while EOF 3 to Pattern 1. The three eigenvectors explain about half of the variance (Wei and Zhang, 1988). Several new classification schemes have been proposed by different authors based on different statistical analysis (e.g., Wang et al., 1998; Sun et al., 2005; Ren et al., 2006). Here we follow the traditional three-pattern classification, which has been employed in the operational seasonal forecast at the NCC for the last decades.

Figure 1 shows a composite of five typical years for each pattern during 1961–90 based on the observation data. The typical years are 1966, 1967, 1973, 1976, and 1978 for Pattern 1; 1963, 1965, 1972, 1982, and 1989 for Pattern 2; and 1969, 1980, 1983, 1986, and 1987 for Pattern 3, respectively.

As indicated in Fig. 1, Pattern 1 is characterized by excessive rainfall in the north of the Yellow River basin, as well as in the Hua'nan area (southern most of China). Reduced rainfall is found over the Yangtze-Huai River area in Pattern 1. For Pattern 2, increased rainfall is found over the area between the Yangtze and Yellow River area (approximately along the Huai River basin) while decreased rainfall is found south of the Yangtze River and north of the Yellow River. In Pattern 3, rainfall increases along the Yangtze River and a major dry area is located north of the Huai River. The "South Flood and North Drought" pattern observed in the last decades corresponds to increased occurrence of Pattern 3 and decreased occurrence of Patterns 1 and 2.

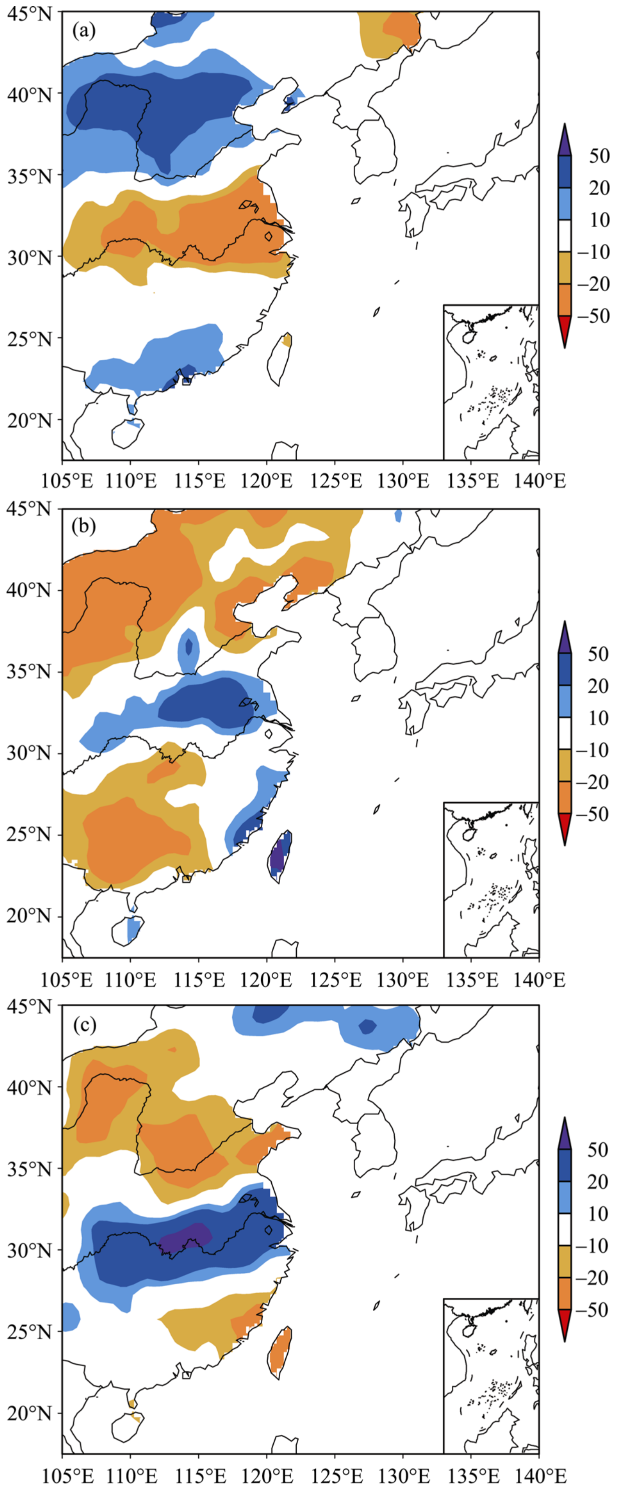

Figure 1 Typical (JJA) monsoon rainfall patterns over eastern China. The patterns are based on the departure (%) of rainfall from the climatology.

3 Results

3.1 Validation of the model performance

The simulation of mean precipitation in JJA for 1961–90 by RegCM3 is first compared with observations. As shown in Figs. 2a–b, both the pattern and amount of the observed precipitation are well captured by the model. The main discrepancy is found in the lower reaches of the Yellow River basin where the model underestimates rainfall by about 100–200 mm. The spatial correlation coefficient between the observation and RegCM3 simulation over the region is 0.42 while that for the FvGCM is 0.34 (not shown).

Although RegCM3 captures the spatial distribution of mean precipitation well at the seasonal scale, its performance at the monthly scale is not as good. To be more specific, the values of the correlation coefficient between simulation and observations in June, July, and August are 0.23, 0.12, and 0.15, respectively. It is well known that the observed monsoon rain-belt in June and early July (namely the mei-yu) is located over the Yangtze to Huai River area. Then the rain belt moves to the north reaching North China in August (Tao and Chen, 1987). The lower values of the correlation coefficient for July and August are largely caused by a poor performance in reproducing this temporal evolution of the monsoon rainfall. For example, the observed rainfall amount over the Huai-Yellow River area reaches its maximum value of 100–150 mm in August (Fig. 2c), while the simulated maximum is only in the range of 50–75 mm (Fig. 2d). A similar underestimation can be found in July (not shown).

Standard deviation (SD) is calculated for both observations and simulation to measure model's capability in simulating interannual variability (IAV). As can be seen in Figs. 3a–b, in JJA the model underestimates the variability over the Hua'nan and Yangtze River basin, and overestimates it over portions of northern China. The correlation coefficient between simulated and observed SD for JJA is 0.14. For the individual months, the coefficients are 0.09, 0.07, and 0.08 for June, July, and August, respectively. Again low correlations are found in June, July, and August, indicating a low performance of the model in simulating IAV at the monthly time scale.

The observed and simulated numbers of occurrence for the three different patterns are shown in rows 2–4 of Table 1. To classify the pattern for a certain year in the observations (simulation), the rainfall anomaly relative to the observed (modeled) 30-year-mean climatology is first calculated. Then the correlation coefficient between the anomalies with each of the three patterns (Fig. 1) is calculated. Finally the pattern of the years is defined as the pattern with the greatest value of the coefficient.

As shown in Table 1, for the 30-year period, the occurrence of Pattern 1 is the same as that for Pattern 2, with a value of 11. Pattern 3 occurs only eight times. The model overestimates the occurrence of Pattern 1 and underestimates that of Pattern 2 while it reproduces the frequency

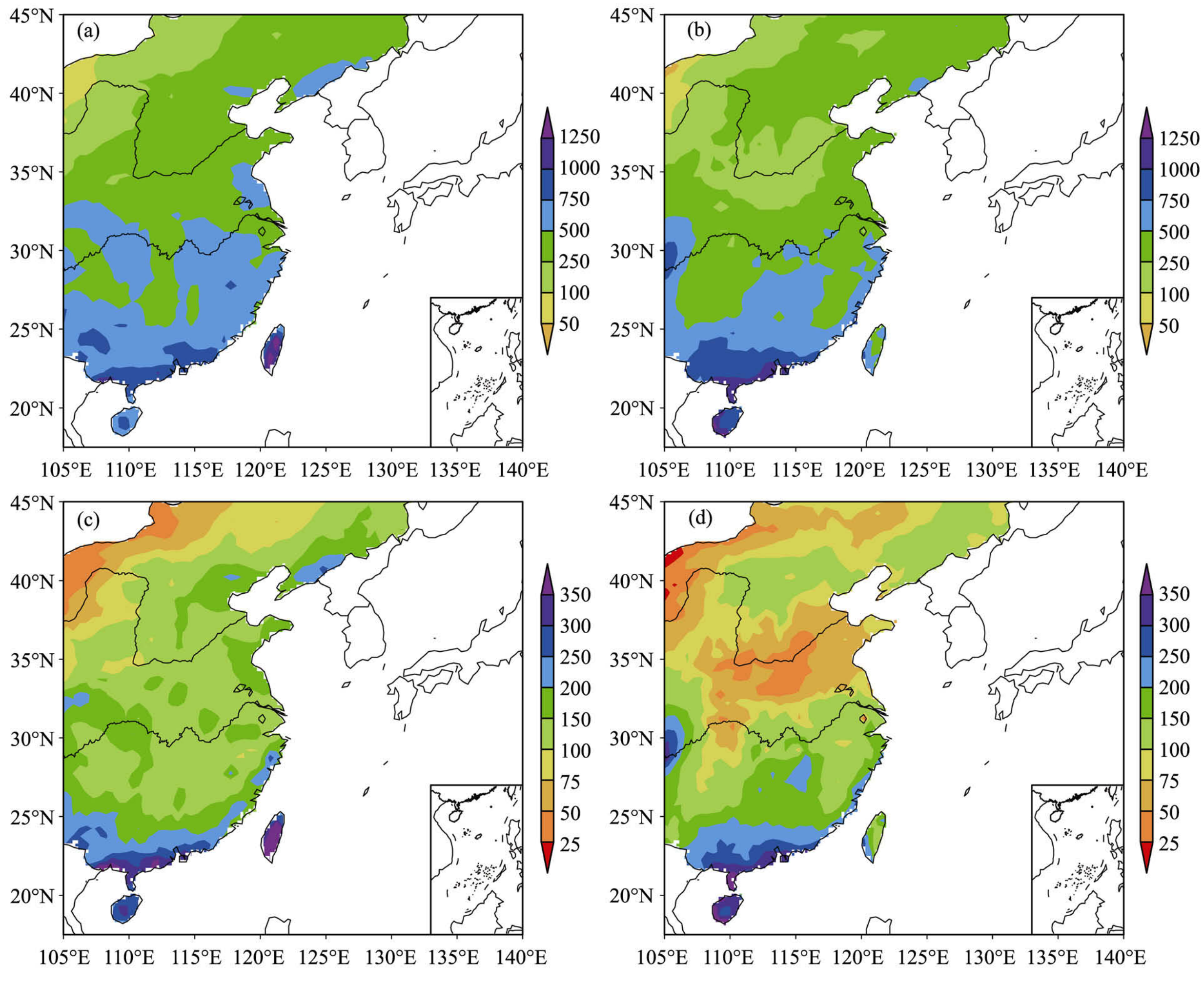

Figure 2 Mean rainfall (mm) of 1961–90 over eastern China. (a) observation in JJA, (b) simulation in JJA by RegCM3, (c) observation in August, and (d) simulation in August by RegCM3.

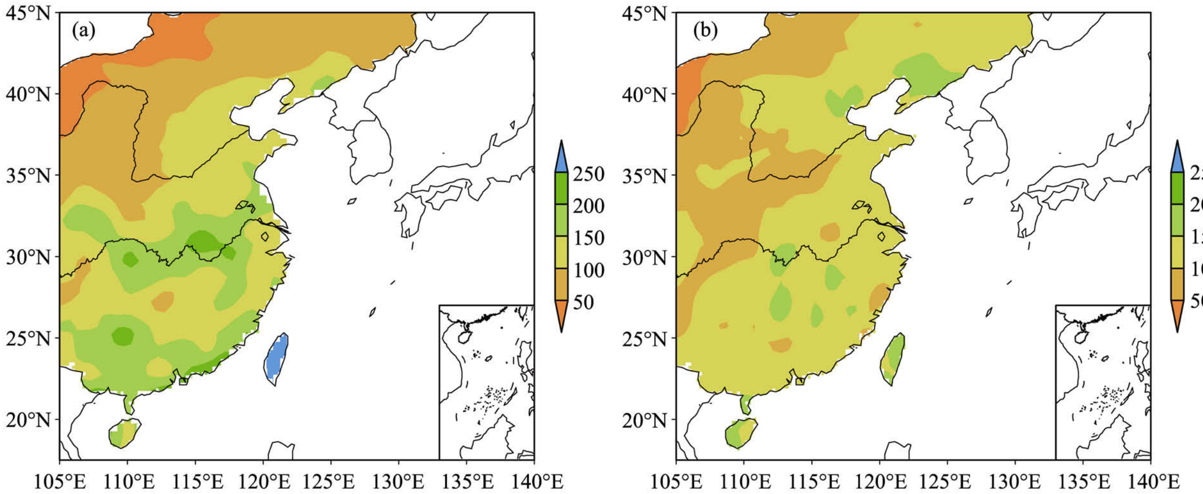

Figure 3 Interannual variability (measured by standard deviation; mm) of rainfall in 1961–90 over eastern China in JJA. (a) observation, (b) simulation by RegCM3.

Table 1 Occurrence of the rain patterns in observation, the simulation for present (RF), future (A2), and the change in the future.

	Pattern 1	Pattern 2	Pattern 3
Observation	11	11	8
RF	14	8	8
A2	11	12	7
Change (%)	–21%	50%	–13%

of occurrence for Pattern 3.

3.2 Future changes

Figure 4a presents the simulated future changes of JJA rainfall over eastern China. While a general reduction of monsoon rainfall is found over the region, a substantial precipitation increase occurs in the Huai-Yellow River area. This pattern of change is significantly different from simulations by most coarse-resolution AOGCMs, including the driving FvGCM. A prevailing increase of monsoon rainfall was simulated by many AOGCMs (IPCC, 2007; Xu et al., 2009), indicating a wetter future for northern China under global warming conditions.

As reported by Gao et al. (2008), the differences between the RegCM3 and the driving FvGCM simulations are largely due to the stronger topographic forcing and the resulting circulation changes in RegCM3. Previous studies have shown that the Asian monsoon flows often weaken in global warming simulations. In the mean time, greater warming at high latitudes leads to the weakening of the westerlies (Christensen et al., 2007). Under these conditions, northern China may be increasingly influenced by the weather and climate systems traveling from the east (Gao et al., 2008). These systems originate over the ocean and bring extra moisture, leading to increased precipitation over northern China. In the coarse-resolution model simulations, e.g., by the FvGCM, a widespread increase of rainfall is found over the region (not shown). However with much stronger topographic forcing in RegCM3, the increase of rainfall is limited to a much narrower band in the Huai-Yellow River area (Fig. 4a).

Increased IAV is simulated by the model as shown in Fig. 4b. The increase is usually greater than 25% and can

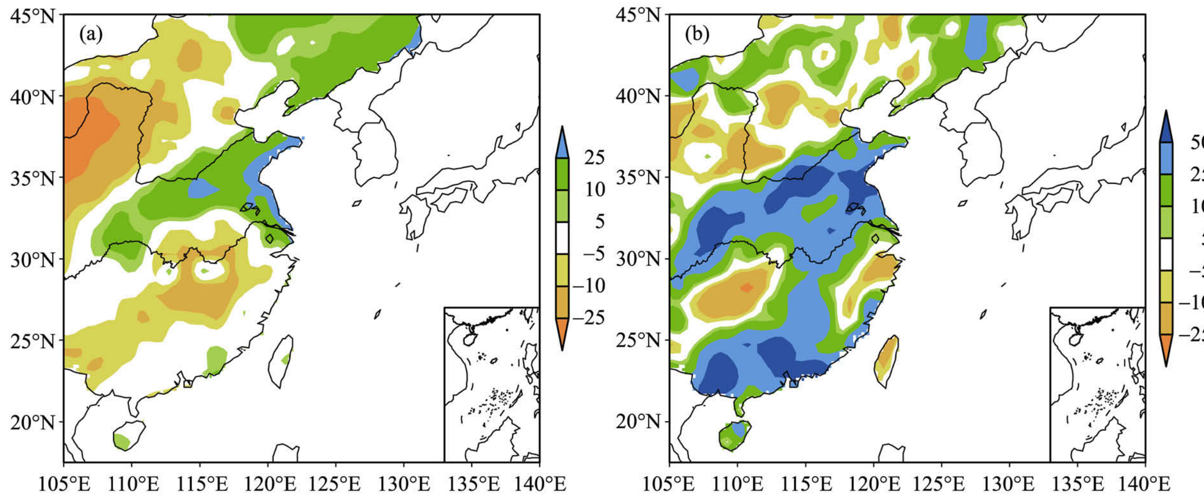

Figure 4 (a) Change (%) of rainfall and (b) IAV in 2071–2100 relative to 1961–90 in JJA as simulated by RegCM3 over eastern China.

reach 50% in Hua'nan and the area between the Yangtze and Yellow River basins. The change is not very pronounced in northern China, where a 10%–25% decrease is found. Decreased IAV is also found over several areas south of the Yangtze River basin. The general increase of the IAV over eastern China indicates that besides the rain pattern changes (see below), the contrast between wet and dry conditions for different years may become more pronounced in the future.

The changes of rain patterns are shown in rows 4 and 5 of Table 1. As can be expected, an increased frequency of occurrence of Pattern 2 and decreased frequency of Patterns 1 and 3 are found in the future. As indicated in Table 1, the occurrence of Pattern 2 may increase by 50% while the occurrence of Pattern 1 and Pattern 3 would decrease by 21% and 13%, respectively.

4 Conclusion and discussions

Future changes of monsoon rainfall and rain patterns in eastern China as classified by NCC in the operational forecast are analyzed based on a high-resolution RCM simulation over East Asia. Results show that the RCM can capture the basic summer rainfall patterns over eastern China in the present day simulation. The simulated rainfall patterns also generally agree with observations, although with an overestimation of Pattern 1 and underestimation of Pattern 2.

The projection of future monsoon rainfall changes does not support a wetter thus more favorable climate over North China in the future, in contrast to results simulated by many coarse-resolution AOGCMs. Greater occurrence of Pattern 2 and lower occurrences of Patterns 1 and 3 are simulated by the model under increased GHGs forcing.

It is noted that in the observation more Pattern-3 rainfall, i.e., more rainfall over the Yangtze River basin, occurred in the late 1990s. Of the 10 years of the 1990s (1991–2000), three occurrences of Pattern 1 (1992, 1994, and 1995), two of Pattern 2 (1991 and 2000), and five of Pattern 3 (1993, 1996, 1997, 1998, and 1999) are observed. However, during the period 2001–08, Pattern 1 occurred only once (2004), Pattern 2 four times, and Pattern 3 three times, respectively. This is in a better agreement with our projection of increased occurrence of Pattern 2 under the global warming.

Large uncertainties still exist in the projection of future changes in monsoon rainfall and the associated patterns. One of the main uncertainties is that, although the RCM employed in this study greatly improves the rainfall simulation at the seasonal scale compared to the driving GCM, it fails to reproduce the evolution of the monsoon rain belt, as well as the IAV, at the monthly scale. The bias in simulating present frequency of the patterns and the natural variability adds to this uncertainty. Ensemble simulations by an improved version of the model for the entire 21st century are needed to reduce these uncertainties and to better understand the future changes in the monsoon rain and associated patterns over eastern China.

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