Evaluation and Analysis of RegCM3 Simulated Summer Rainfall over the Huaihe River Basin of China*

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ABSTRACT

This study evaluates the ability of the Abdus Salam International Center for Theoretical Physics (ICTP) version 3 Regional Climate Model (RegCM3) in simulating the summer rainfall amount and distribution and large-scale circulation over the Huaihe River basin of China. We conducted the simulation for the period of 1982–2001 and the wet year of 2003 to test the ensemble simulation capacity of RegCM3. First, by comparing the simulated rainfall amount and distribution against the observations, it is found that RegCM3 can reproduce the rainfall pattern and its annual variations. In addition, the simulated spatial patterns of 850-hPa wind and specific humidity fields are close to the observations, although the wind speed and humidity values are larger. Finally, the ensemble simulation of RegCM3 for summer 2003 failed to capture the spatial distribution and underestimated the magnitude of the precipitation anomalies, and the reasons are analyzed.

Key words: regional climate model, the Huaihe River basin, precipitation, ensemble simulation

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1. Introduction

The Huaihe River, located between the Yellow River and the Yangtze River, covering the region 30°55′–36°36′N, 111°55′–121°25′E, drains a basin of more than 270000 km^2. In the Huaihe River basin, precipitation mostly happens in summer, and there are usually two to three weeks of continuous rainy weather with the largest variability during June and July.

The summer precipitation anomalies are directly related to atmospheric circulation anomalies. Strength of the East Asian summer monsoon and midlatitude westerlies determines the amount of summer rainfall in the Huaihe River basin. In the rainy years, the Indian summer monsoon over the Bay of Bengal is enhanced, the subtropical southwest monsoon to the south of 32°–35°N is strengthened, and the convergence of the warm southwest monsoon and cold north winds causes continuous rainfall in the Huaihe River basin in summer. In the dry years, the Indian summer monsoon to the north of 18°N is weakened, the subtropical southwest monsoon is weakened, and the north cold current is also weak. As a result, the Huaihe River basin is controlled by anomalous divergence, leading to less rainfall there in summer (Wang and Wang, 2002).

During the summer of 2003, a flood of the greatest scale since 1954 hit the Huaihe River basin. Seven heavy rainfall processes occured, bringing 487 mm m^{-2} precipitation cumulatively, which was 2.2 times of the normal. However, this extreme precipitation event was not predicted by the global circulation model (GCM). Zhang et al. (2004) analyzed the large-scale atmospheric circulation and the related climate system using the NCEP/NCAR reanalysis data. Their results showed that the mid-high latitude circulation (two troughs and one ridge) was steady, and the

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western Pacific subtropical high was located at 22°–25°N, while the Huaihe River basin was just in the right diagonal of the high-level jet and the left diagonal of the low-level jet. These are the important features of the heavy rainfall.

Nevertheless, the heavy rainfall in summer 2003 was not produced by the GCM mainly because the resolution of GCM is too large to capture the regional weather. In this paper, we try to use a regional climate model (RCM) that has a higher resolution to simulate this case.

Since the 1990s, RCMs have been widely used in climate simulation and prediction. Li and Ding (2004) and Tang et al. (2006) pointed out that compared with the GCM, the RCM is able to obtain the small-scale topography and underlying surface forced effects, thus it is more accurate in describing various physical processes. Besides, the RCM has many other advantages, such as its saving computing time, being able to simulate weather and climate events on different scales, and so on. Li et al. (2005) and Ding et al. (2006a, b) successfully predicted the wet case in Huaihe River basin in summer 2003 using the regional climate model (RegCM_NCC). Castro (2007) showed that, for North America, the RCM simulation results are closer to the actual situation than the global model results.

RegCM2 (RCM version 2) and RegCM3 (RCM version 3) are typical representations of regional climate models. They have been used to perform simulation studies in the United States, Europe, Africa, Australia, East Asia–western Pacific, and other regions, and have achieved remarkably encouraging results. For example, Im et al. (2006) used RegCM3 to conduct a double-nested simulation from-October 2000 to 30 September 2003 over the Korean Peninsula, and their results showed that the model is useful for South Korean regional climate simulations. Segele et al. (2009) employed RegCM to simulate the precipitation in the Horn of Africa with different convective parameterization schemes and found that the Emanuel scheme had a very good performance for the dry year of 1984, the wet year of 1996, and the average precipitation of 18 yr.

Liu et al. (1994, 1996) showed that the RegCM can successfully simulate the East Asian summer monsoon rainfall from June to August 1990 and the extreme precipitation in East Asia in 1991. Liu et al. (2005) simulated the precipitation in eastern China from May to August 1998 by using RegCM3, and investigated the model's capability in simulating rainfall and large-scale circulation systems. They concluded that RegCM3 can be applied to studing the summer monsoon precipitation in eastern China. Liu et al. (2008) simulated the summer climate in 2005 over China, and reported that RegCM3 performed well in simulating the monthly precipitation variation and distribution in China, including the entire Qinghai-Tibetan Plateau; however, its capability to simulate the summer rainfall in Southeast China needs to be improved. The 15-yr (1987–2001) RegCM3 simulation run showed that RegCM3 well reproduced the average circulation over East Asia, the characteristics of precipitation in China, the distribution and seasonal variation of surface temperature, and the interannual variability of temperature and precipitation (Zhang and Ouyang, 2007). Li and Wang (2008) used the latest version of RegCM3 with the Anthes-Kuo, MIT-Emanuel, and Grell cumulus parameterization schemes, respectively, to simulate the heavy precipitation process that occurred in the Huaihe River basin in July 2003. They found that RegCM3 produced reasonable results in simulating summer heavy precipitation in southern China, with the Anthes-Kuo scheme yielding the best simulation results.

As for the effects of domain setting and horizontal resolution, the sensitivity experiments conducted by Yang et al. (2008) showed that reducing the model integration step, increasing its horizontal resolution, and enlarging the model domain to cover the Tibetan Plateau can improve the simulated results. Ding et al. (2006a) performed sensitivity studies and experimental seasonal prediction in China by using the RegCM_NCC with a horizontal resolution of 60 km. Gao et al. (2006) concluded that the higher horizontal resolution leads to better RegCM2 simulations in East Asia.

Although RCMs are used widely in climate simulation and prediction, the agreement between simulations and observations is still very unstable. For example, RCMs often showed deficiencies in some areas or seasons, and the simulation cannot completely avoid the generation of false precipitation centers. In addition, presently, RegCM3 is mainly used in East Asia, South China, North China, and other large-scale areas, but rarely used in smaller-scale areas for simulating and predicting the climate at higher resolutions. In this paper, we conducted the simulation of the summer rainfall and large-scale circulation over the Huaihe River basin (30°55′–36°36′N, 111°55′–121°25′E) of China for the period of 1982–2001 in order to test the ability of RegCM3. In addition, one wet year of 2003 was chosen to examine the RegCM3 ensemble simulation capacity.

2. Model description

The dynamical component of the regional climate model RegCM3 is the same as that of MM5, using σ-coordinates in the vertical and staggered Arakawa B grid in the horizontal. The main physical processes of RegCM3 include the radiative scheme, land surface scheme, planetary boundary layer scheme, cumulus convective scheme, large-scale precipitation scheme, and pressure gradient scheme. There are six kinds of lateral boundary treatment options: fixed boundary, linear relaxation boundary, time-dependent boundary, time-varying inflow and outflow boundary, sponge boundary, and index relaxation boundary. The pressure gradient treatment takes the normal way or the static force balance deduction method. RegCM3 outputs include more than forty physical quantities of the atmospheric, surface, and radiative variables.

Compared with RegCM2, RegCM3 has some major improvements. First, RegCM3 used NACR CCM3 radiative transfer scheme in place of the original CCM2 scheme. Second, RegCM3 improved the physical processes of cloud and precipitation. RegCM3 brought in the sub-grid explicit moisture program (SUBEX), therefore it can deal with non-convective clouds and precipitation processes better, which helps to reduce the generation of numerical grid storm. Moreover, aside from the original Grell and Kuo schemes, cumulus convective precipitation programs feature the newly added Bette-Miller scheme. Also, some new parameterization schemes were added into the ocean surface flux parameterization. Third, RegCM3 used the US Geological Survey global land cover characteristics data and global 30′ high-resolution terrain data, so the model can describe the underlying surface conditions more accurately. Finally, the program of RegCM3 was improved for easier debuging and application.

Moreover, the latest version of RegCM3 has added an aerosol module in the model and improved the related physical processes. At the same time, implementation of parallel computing algorithms has greatly improved the model's computation efficiency.

3. Data and experimental setup

This study used the reanalysis data NNRP1 (NOAA-NCEP Reanalysis Project 1) at the 6-h interval and a 2.5°×2.5° horizontal resolution to drive the RegCM3. The NNRP1 data include air temperature, geopotential height, vertical velocity, relative humidity, meridional wind, zonal wind, and surface pressure fields, and were interpolated to the model levels as initial and boundary conditions. The sea surface temperature data were from the NCEP/NCAR weekly average data. The 2′ × 2′ global land cover characteristics (GLCC) data were used for model topography and vegetation.

The simulation domain is centered at 35°N, 105°E and the horizontal resolution is 50 km. There are 93 grid points in the north-south direction, 112 grid points in the east-west direction, and 18 layers in the vertical stratification. The atmospheric pressure on the model top is 5 hPa, and the integration time-step is 150 s. The parameterization schemes used in this study are: exponential relaxation lateral boundary treatment, Holtslag boundary layer, Emanuel convective parameterization, and CCM3 radiative parameterization scheme. For the 20-yr JJA precipitation simulation, the model is integrated from 1 January 1982 to 31 December 2001, while in the ensemble simulation of JJA 2003, 7 days (from 1 to 7 May 2003) were set as the initial dates, respectively, for RegCM3 to integrate to 1 September. Then the average of the results produced by the seven initial fields is used to produce the final simulation of JJA precipitation of 2003.

The observation data used to verify the simulated precipitation are the 2.5°×2.5° CMAP (US Climate Prediction Center Merged Analysis of Precipitation) data based on station observations and satellite measurements, and the average monthly precipitation data of 730 stations of China. The observation data used to verify the simulated large-scale circulation are the NCEP/NCAR reanalysis data with a horizontal resolution of 2.5°×2.5°.

In order to evaluate the simulation results objectively and quantitatively, the correlation coefficient (COR), root mean square error (RMSE), and bias are calculated to examine the ability of RegCM3 in simulating the synoptic-scale features. What needs to be clarified is that the statistic analysis is conducted after the simulated rainfall field is interpolated to the observation grid.

4. Results

4.1 Simulated 20-yr summer climatological characteristics

The ability of RegCM3 in simulating the summer climate characteristics over the Huaihe River basin is verified qualitatively by using the CMAP data. Figure 1 shows the simulated and observed mean precipitation in summer during 1982–2001 over the Huaihe River basin. The major rainfall zone is located in Anhui and Jiangsu provinces along the Huaihe River, and RegCM3 has successfully captured this rainfall distribution.

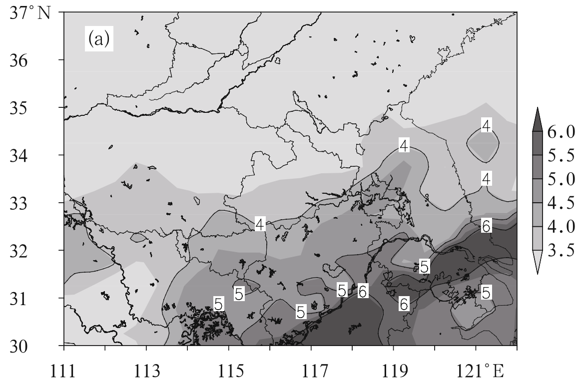
Figure 2 shows the mean 850-hPa wind vectors during 1982–2001 and the correlation coefficients between observations and simulations. A comparison between Figs. 2a and 2b shows that RegCM3 can reproduce the approximate distribution of the wind field, while the simulated wind speed was significantly larger than observations. The correlation coefficient between the simulated and observed wind speed is about 0.4, and it is larger in the southern region than in the northern region.

The mean 850-hPa specific humidity field during 1982–2001 and the correlation coefficient between observations and simulations (Fig. 3) show that RegCM3 can simulate the water vapor transport by the southwest flow. The simulated wet tongue is located very close to the observed one; particularly, the 0.0105-kg kg^{-1} wet geometric lines are almost identical to the observed ones. However, generally speaking, the simulated humidity is slightly larger than reality. The COR in the Huaihe River basin is about 0.5 or so, and in some coastal areas, the COR is up to 0.75 or above. It is noted that the NCEP data with the relatively low resolution may have resulted in the relatively high values of the simulated water vapor field.

4.2 Simulated 20-yr summer precipitation

In this part, the capability of RegCM3 in simulating the summer precipitation in the Huaihe River basin is verified in terms of both its interannual variation and spatial distribution.

Figure 4 shows observed and RegCM3 simulated mean summer precipitation in the Huaihe River basin during 1982–2001. The variability of the two time series is almost the same, and their correlation coefficient



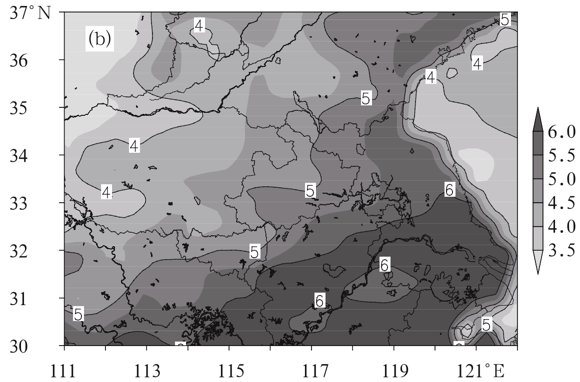


Fig. 1. Mean precipitation (mm day^{-1}) in summer for 1982–2001 over the Huaihe River basin from (a) observation and (b) RegCM3.

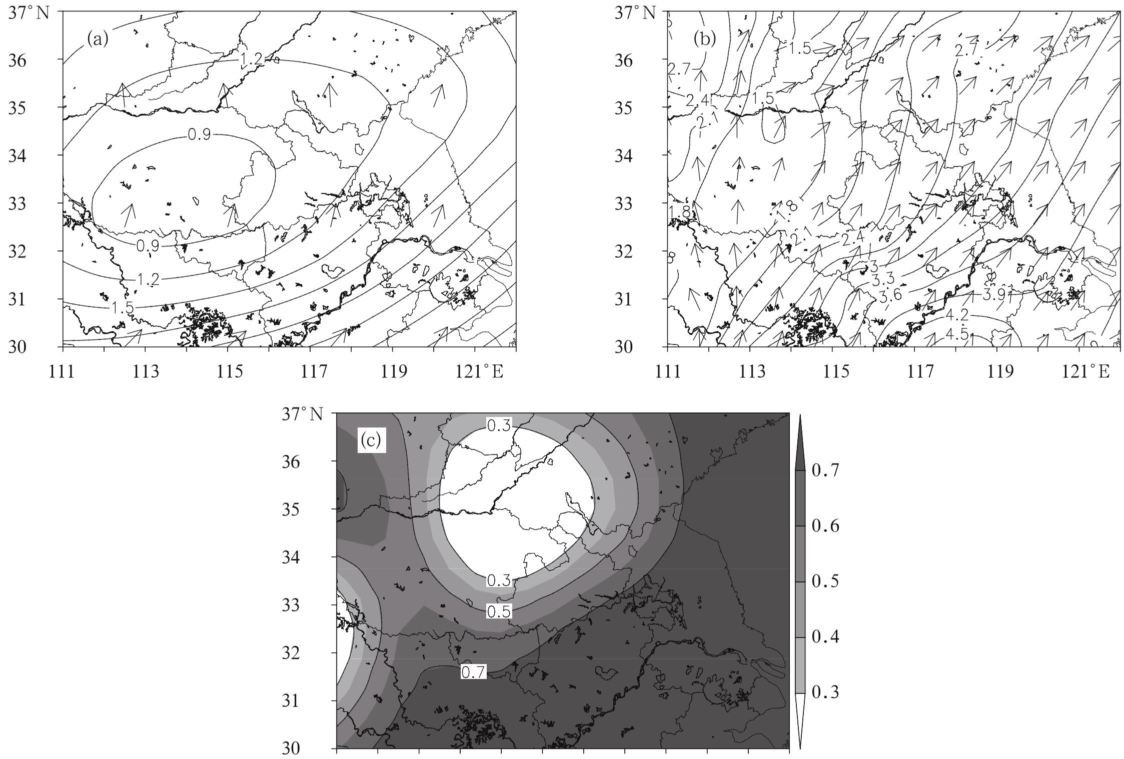


Fig. 2. Mean 850-hPa wind vectors (m s^{-1}) for 1982–2001. (a) Observation, (b) RegCM3, and (c) the COR between the observation and RegCM3. The shaded area passes the significance test.

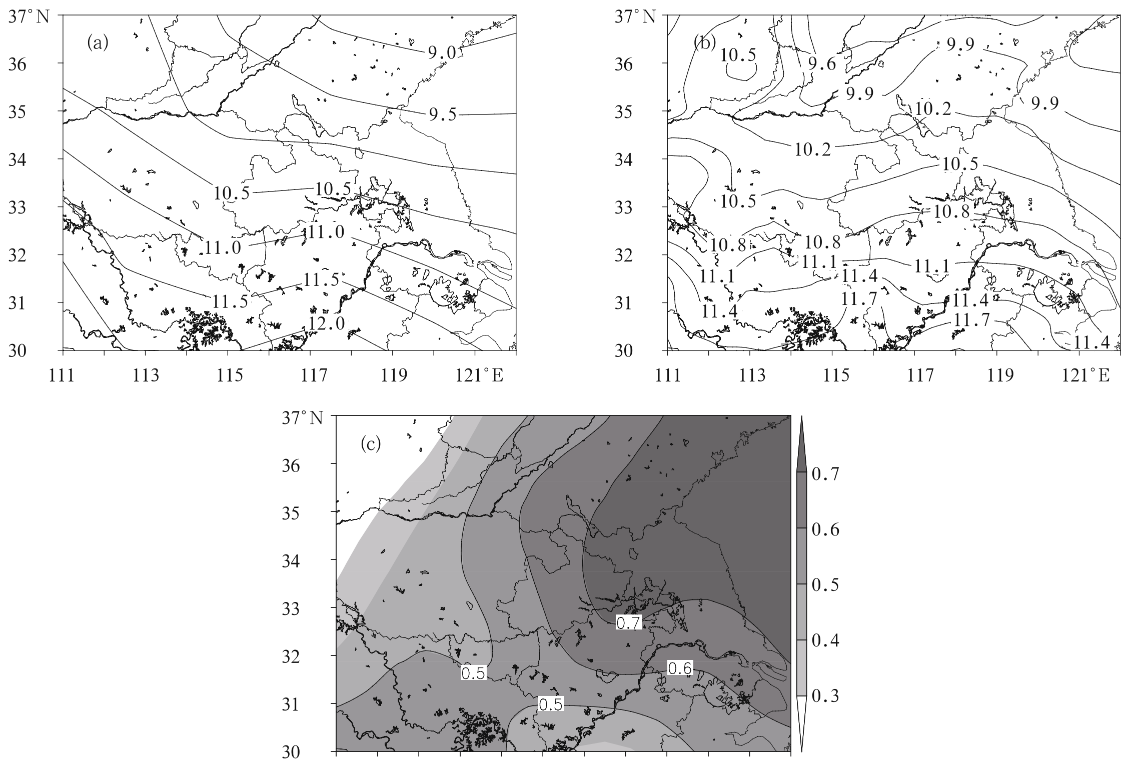


Fig. 3. Summer mean specific humidity field (g kg^{-1}) at 850 hPa during 1982–2001. (a) Observation, (b) RegCM3, and (c) the COR between the observation and RegCM3. The shaded area passes the significance test.

is 0.70, indicating that RegCM3 is capable to simulate the interannual variability of summer precipitation in the Huaihe River basin. In addition, the observation curve shows a 2–3-yr cycle, which is closely related to the severe flooding years of the Huaihe River basin.

Statistical methods are then used to quantitatively compare the simulated and observed rainfall. Figure 5 shows the spatial distribution of the COR between the summer precipitation in RegCM3 and station observation from 1982 to 2001. The higher COR, generally more than 0.4, is mostly distributed in the southern region, while the smaller COR is found in the northern region. In short, RegCM3 can simulate the interannual variability of summer precipitation in the southern portion of the Huaihe River basin.

Table 1 lists the COR, RMSE, and bias calculated from simulated and observed 20-yr precipitation series

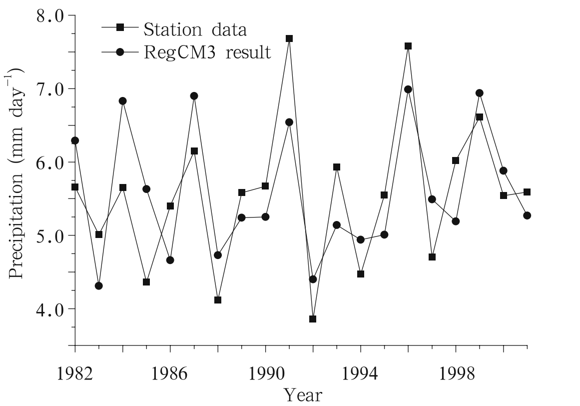


Fig. 4. Mean summer precipitation (mm day^{-1}) in the Huaihe River basin during 1982–2001.

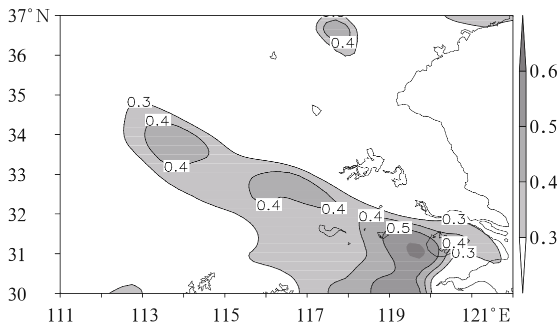


Fig. 5. Spatial distribution of the correlation coefficient between the summer precipitation in RegCM3 and station observation from 1982 to 2001. The shaded area indicates the significant correlation.

Table 1. The COR, RMSE, and bias between RegCM3 and station observation for summer-averaged precipitation over the Huaihe River basin from 1982 to 2001

COR	RMSE	bias (mm day^{-1})
0.70	0.72	0.03

over the Huaihe River basin. In Table 1, COR is up to 0.70; bias is as low as 0.03 mm day^{-1}, accounting for only 0.60% of the measured climate average. In conclusion, RegCM3 has a good capability in simulating the precipitation pattern and variability in the Huaihe River basin.

4.3 Simulated summer rainfall in 2003

In this part, the wet year of 2003 is selected as an example to evaluate the ability of RegCM3 in simulating summer precipitation in the Huaihe River basin. Here, the observed data are the monthly average precipitation at 730 stations of China. Because the observed data are rare in the region 30°–37°N, 111°–115°E, the initial longitude is set to be 115°E in Figs. 6, 7, and 8.

Figures 6, 7, and 8 are June, July, and August rainfall in 2003 over the Huaihe River basin, respectively. The comparison of simulated and measured monthly average rainfall amount and distribution shows that the ensemble simulation can generally reproduce rainfall distributions in June and August, but the simulated rainfall amount is about 1–2 mm day^{-1} less than that of observation. Besides, this ensemble simulation scheme is unable to capture the rainstorm center in July because the simulated rainfall center is located obviously more northward than the actual center. Table 2 lists the COR, RMSE, and bias calculated from simulated and measured 2003 summer precipitation series of each month over the Huaihe River basin. It is shown that RegCM3 has simulated the August precipitation very well. However, it cannot reproduce

Table 2. The COR, RMSE, and bias between RegCM3 and observation for monthly average precipitation over the Huaihe River basin in summer 2003

	COR	RMSE	bias (mm day^{-1})
June	0.17	0.15	–0.58
July	0.13	0.79	–2.88
August	0.4	0.49	–1.80

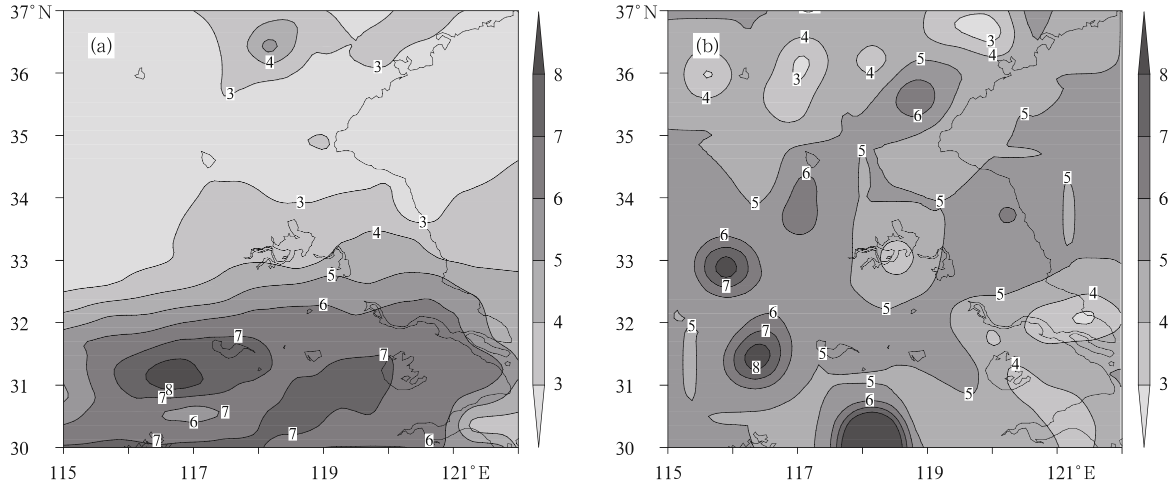


Fig. 6. June 2003 rainfall (mm day^{-1}) over the Huaihe River basin. (a) RegCM3 and (b) station observation.

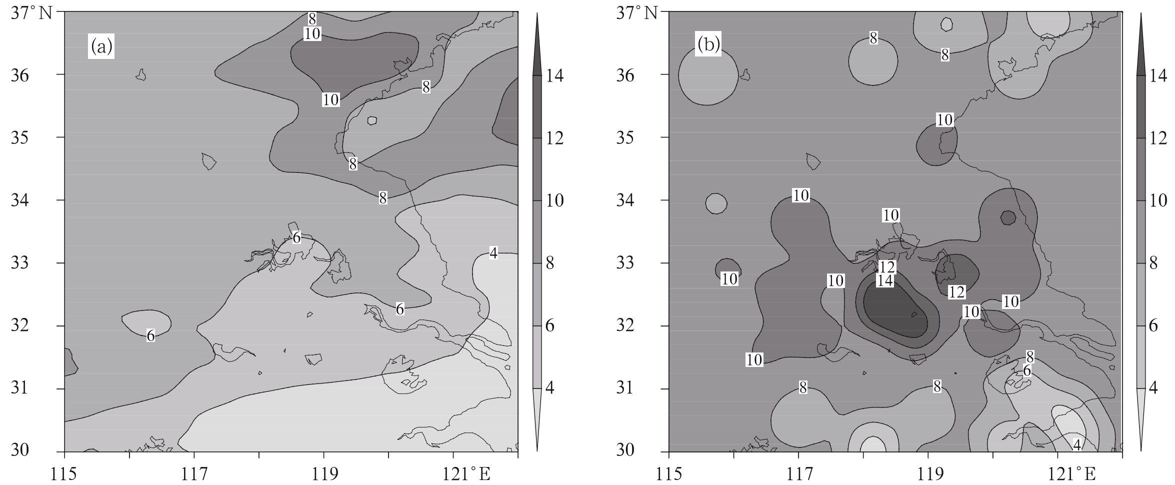


Fig. 7. As in Fig. 6, but for July 2003.

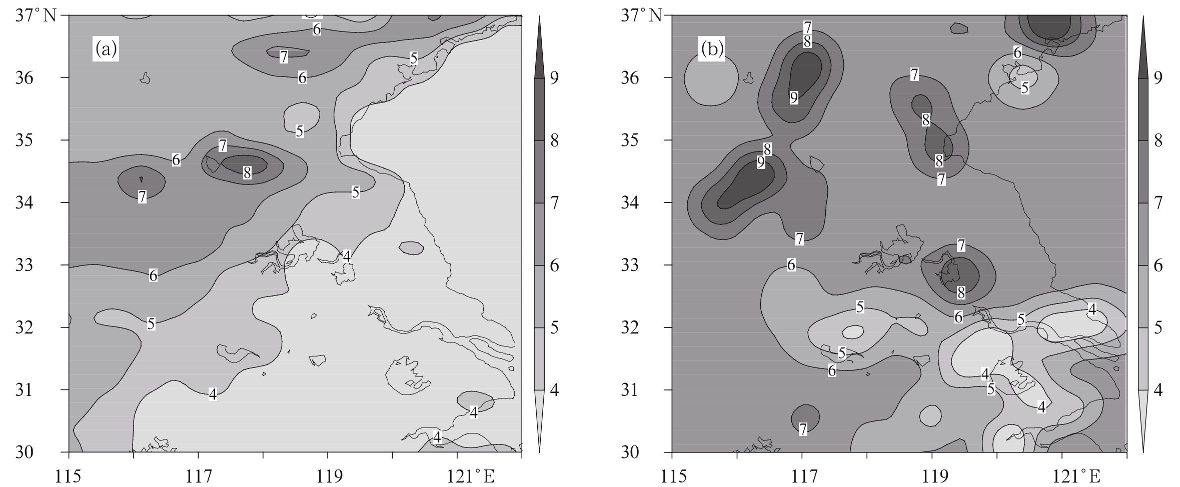


Fig. 8. As in Fig. 6, but for August 2003.

the precipitation in June and July. This may be due to the fact that the extremely heavy rainfall episodes associated with small-scale storm clouds in June and July are very difficult for RegCM3 to resolve and simulate. Therefore, the capability of RegCM3 in simulating small-scale systems needs to be improved.

5. Summary

In this paper, we simulated summer rainfall in the Huaihe River basin of China for the period of 1982–2001 and the wet year of 2003. Through comparing the simulation results with the CMAP precipitation data, the rainfall data of 730 stations of China and the NCEP/NCAR reanalysis data, the conclusions are drawn as follows.

(1) RegCM3 has the ability to simulate the rainfall distribution and its interannual variability over the Huaihe River basin. The main summer rainfall zone is located in the region of Anhui and Jiangsu provinces along the Huaihe River. There exists a 2–3-yr cycle in the summer precipitation, and this cycle corresponds closely to the severe flooding years of the Huaihe River basin.

(2) RegCM3 can simulate the general distribution characteristics of the lower 850-hPa flow and water vapor transport fields, but the simulated wind speed and humidity values are larger than observations.

(3) Statistical analysis of simulations and observations showed that RegCM3 possesses a good ability to reproduce the summer precipitation distribution in the Huaihe River basin.

(4) For the year of 2003, although RegCM3 produced more than average summer precipitation, it cannot recapitulate the extreme heavy precipitation. In addition, RegCM3 could accurately simulate the precipitation in August 2003, but failed to simulate the extreme heavy precipitation in June and July. It also failed to simulate the precipitation center. Obviously, the capability of RegCM3 in simulating small-scale systems needs to be improved.

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