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SIMULATION OF SUMMER MONSOON CLIMATE OVER EASTERN CHINA USING A REGIONAL SPECTRAL MODEL

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Abstract: In this paper, we evaluate the characteristics of the surface air temperature and the precipitation of summer monsoon, using the National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) for 20 years (1984-2003). The RSM model was designated over the eastern China with a horizontal grid spacing of approximately 30 km. The model is driven by the NCEP/NCAR reanalysis data and runs from May 21 to September 1 for each of the 20 years. The distribution and variation patterns of the 20-year summer mean surface air temperature and precipitation are reproduced by the RSM and the differences between the simulation and observation are small. However, the model overestimates the interannual variability of summer precipitation in eastern China. The correlation coefficients of the 20-year averaging summer precipitation over the whole region and the sub-domains are above 0.8. The simulated probability distributions of daily maximum and minimum temperatures are similar to the observations. Days of different precipitation intensities in the simulations are generally consistent with the observations: the simulated days of light rain, moderate rain, heavy rain and torrential rain closely resemble the observations, but the simulated maximum centers of the distribution are north of the observed ones.

Key words: Regional Spectral Model, eastern China, summer monsoon climate
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1 INTRODUCTION

The eastern China is one of the areas with the highest seasonal, inner-annual, and inter-decadal climate variability caused by its special location, vegetation and monsoon climate (Fu and Zeng[1]). Therefore, it is difficult for models to reproduce its climate. Many numerical models, including General Circulation Models (GCMs), were used to investigate the climate over the eastern China by many domestic scholars (Zhou and Li[2]; Gao et al.[3, 4]; Wang and Xiong[5]; Jiang et al. [6]; Zhou and Yu[7]). However, many current GCMs run with a relatively coarse horizontal resolution about 200-400 km. With this resolution, the mesoscale features driven by regional-scale climate forcing cannot be represented precisely. Therefore, the GCMs simulation results always show vast biases compared to the observations (Grotch and MacCracken[8]).

To circumvent the spatial resolution limitations, many "offline" methods have been developed to produce the local climatological dataset. These methods can be classified into statistical downscaling method and regional climate modeling method using a limited-area model. Goyette and Laprise[9] gave an extensive survey of techniques for the regionally downscale output from GCMs. Among those techniques mentioned above, embedding a regional model in the global atmospheric model is a common method. This method is based on physics and is able to produce nonlinearities relating mesoscale processes to large-scale flows, which is impossible to achieve by using statistical methods. It allows the users to apply high resolutions to the area of interest with reasonable computation costs. Many RCMs (Regional Climate Model) have been developed based on this method such as the RegCM3 (RCM version 3), WRF (Weather Research and Forcasting model) and the NCEP RSM (National Centers for Environmental Prediction Regional Spectral Model). The RCMs have been used to perform simulation studies in East Asia and have achieved remarkably encouraging results.

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For example, Liu et al.[10] used RegCM3 to conduct a simulation from May to August in 1998, and concluded that RegCM3 can be applied to study the summer monsoon precipitation in East China. Zhang et al. [11] conducted the 15-year (1987-2001) RegCM3 simulation, and the results showed that RegCM3 has the capability to reproduce the average circulation over East Asia, the characteristics of precipitation in China, the distribution and the seasonal variation of surface air temperature, and the interannual variability of temperature and precipitation. Zong and Wang[12] found that the RegCM3 can reproduce the summer rainfall amount and distribution over the Huaihe River Basin located in the center of East China. Gao et al.[13] also concluded that the RegCM3 had the capability to reproduce the climatology spatial distribution of surface air temperature and precipitation over China in a high resolution. Yu et al.[14] compared three different cumulus convective parameterization schemes in the WRF model, and found that all the schemes had the capability to reproduce the spatial and temporal distributions of summer monsoon precipitation and the corresponding background circulation over China. Wang and Yu[15] used the WRF model to simulate the precipitation climate of China during the rainy season of 1981–2000, and successfully reproduced the observed distribution of rainy season precipitation.

Elaborate efforts have been done to evaluate the performance of the RegCM3 and WRF to simulate the regional climate details over East China. However, the RSM is rarely used to simulate and predict the climate at a high resolution in China. The largest difference between the RSM and the other existing regional models is that the RSM is a regional spectral model. The RSM was developed by Juang and Kanamitsu[16] involving the spectral method. Previous publications on the NCEP RSM proved that the RSM had the capability to reproduce the regional climatology characteristics over the East Asia, the America and some other places. For instance, Hong and Pan[17] evaluated the RSM as a means of enhancing the depiction of regional climate details based on the lower-resolution global models over the United States, and concluded that the RSM is a very useful tool for regional climate studies. Li et al.[18] developed a fully coupled regional downscaling system based on the RSM for atmosphere and the Regional Ocean Modeling System (ROMS) for the ocean, and found that the performance of the coupled downscaling is reasonable over California. Hong and Juang[19] also examined the performance of the RSM over East Asia with the center in Korea. The model results were satisfactory in terms of the simulated large-scale features for the different years, but systematic errors still exist. Yhang and Hong[20] used the RSM to test the sensitivity of the evolution of the East Asia summer monsoon to physical parameterizations. It is found that some parameters could be improved to simulate temperature, geopotential height and precipitation patterns. Although the RSM is used widely in climate simulation and prediction, the systematic bias still exists and the performance is unstable. Therefore, it is an interesting topic to assess whether the RSM is a useful tool to investigate the climate details over the eastern China or not.

In this paper, we evaluate the capability of the RSM to provide summer monsoon climate driven by the reanalysis data over the eastern China. The model performance and systematic errors of simulated temperature and precipitation are examined. The NCEP/NCAR 40-reanalysis data are used to provide large-scale forcing for the RSM configuration. The resolution of the RSM is approximately 30 km grid over eastern China centered on the Yangtze-Huaihe Rivers basin. A brief review of the RSM, the experimental design and the statistical methods are given in the section 2. Analysis of climatology and variability of both surface air temperature and precipitation is in section 3. Section 4 examines the capacity of the RSM to simulating the extreme events. Concluding remarks follow in the section 5.

2 MODEL AND METHOD

2.1 *Model description*

The RSM model is a spectral regional climate model by using a spectral method in two dimensions: with sine and cosine series (Juang and Kanamitsu[16]). This model has been widely used in regional climate simulation and short-term forecasting. The spectral nudging method nudges the model values to large-scale forcing fields, both inside the model and over the lateral boundary zone. The model interior nudging is achieved by drawing forcing elements into the spectral field, while the lateral boundary nudging is done by bringing buffer zone. The forcing elements in the model work at mid- and high-level to ensure large-scale circulation nudged efficiently to the large-scale forcing field, while the meso- and micro-scale can develop freely. Therefore, the spectral nudging method increases the accuracy of simulated large-scale circulation and the meso- and micro-scale systems.

In this study, The RSM employs the version of the MRF-physics package documented in Hong and Pan[21]. The RSM equations include a thermodynamic equation, a momentum equation, a moisture equation and a mass conservation equation. In addition, the RSM consists of cloud-radiation interaction, long- and short- wave radiation, deep and enhanced topography, planetary boundary layer processes, shallow convection, gravity wave drag, large-scale condensation, vertical and horizontal diffusion and a simple hydrology model (Hong and Pan[21]). The physical schemes we use for different physical processes are given in section 2.2.

2.2 *Experiments setup*

We locate the model domain over the eastern China with a nominal horizontal resolution of 30km (shown in Fig.1). The number of grid points in Cartesian coordinates is 109 degree (west to east) by 98 degree (north to south). The analysis zone excludes the outer grids as a buffer zone and covers the area from 20°N to 40°N and 105°E to 130°E. The physical parameterization schemes used in this study are: the Chou radiation scheme, the Kain-Fritsch cumulus convective parameterization, the CLD3 cloud water scheme developed by Hong (Hong and Pan[17]) and the NOAH land surface model. The RSM model is driven by the NCEP/NCAR reanalysis data. The simulation period is from May 21 to September 1 in each year of the 20 years. The integration step is 180 s and the spin-up time is the first 11 days.

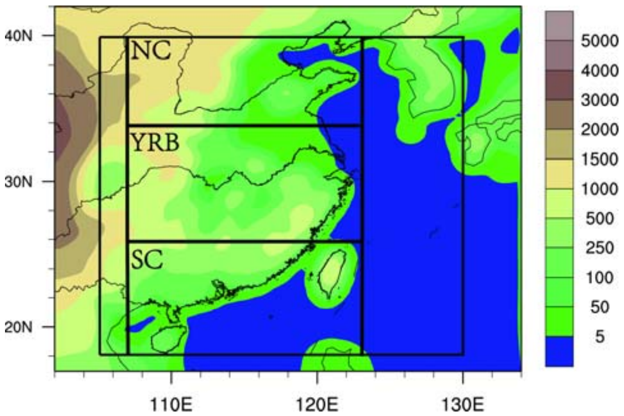

Figure 1. RSM simulation domain and topography (unit: m). The thick solid line represents the analysis zone for computing statistical skill scores in the following tables and figures.

In order to further investigate the capability of the RSM simulation over different regions, we divides the analysis zone into 3 sub-regions (shown in Fig.1): the North China (34°–40°N, 107°–123°E), the Yangtze-Huaihe Rivers basin (26°–34°N, 107°–123°E) and the South China (18°–26°N, 107°–123°E). The simulation data is integrated into the observation grids in the statistics calculation and analysis section.

2.3 *Statistical method and observation data*

In order to evaluate the overall capability of the RSM in reproducing the surface air temperature and precipitation, the distribution of basic statistics are calculated over the analysis region (Fig.1). The statistics include difference, root mean square error (RMSE) and correlation coefficient (CC) between the observation analysis and simulation results.

The observation data used to verify the simulation results are the APHRODITE (Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources) daily precipitation data at 0.25° resolution and the CMA (China Meteorological Administration) daily temperature data at 0.5° resolution.

3 ANALYSIS ON SIMULATION RESULTS

3.1 *Climatology*

3.1.1 TEMPERATURE

To investigate the model’s systematic errors in regional climate simulation, we analyze the difference of surface air temperature between the RSM simulation and the observation. Fig.2 shows the spatial distribution of the 20-year summer (June, July and August) mean temperature obtained from the RSM simulation in the left panel and the CMA observation data in the right panel. Generally, the RSM model reproduces the temperature pattern as observed: a lower temperature in the northwest and a higher temperature in the southeast. The observation shows a warm center appearing in the south of the Yangtze River, and the model agrees. The RSM simulation shows a large warm area over 29 degree in Hebei and Henan provinces, but the temperature in the observation is less than 27 degree. Also, there is a relatively cold region in the northwest China from the observation data, while the RSM model fails to reproduce it.

The temporal correlation of the temperature between the RSM simulation and the observation is also calculated. The correlations and standardized deviations are shown in a Taylor diagram of Fig.3. In this figure, all of the correlation values pass the 95% level of Fisher’s exact significant test. It shows that the correlation coefficients and standardized deviations in summer are better than the ones calculated for June, July and August respectively. Generally, the highest correlation and lowest standardized deviations among the three months are in June. Overall, the correlation in July is close to that in August, while the standardized deviations in July are lower than those in August. In contrast to the temporal correlations and standardized deviations, the simulated spatial distribution of temperature shows a lower correlation and a larger variance. The temporal variance from the simulation is closer to the observed value compared to the spatial temperature, although the values of correlation coefficient are close. We conclude that the RSM has the capacity to simulate the spatial pattern of summer mean temperature and the simulated temporal variation is realistic.

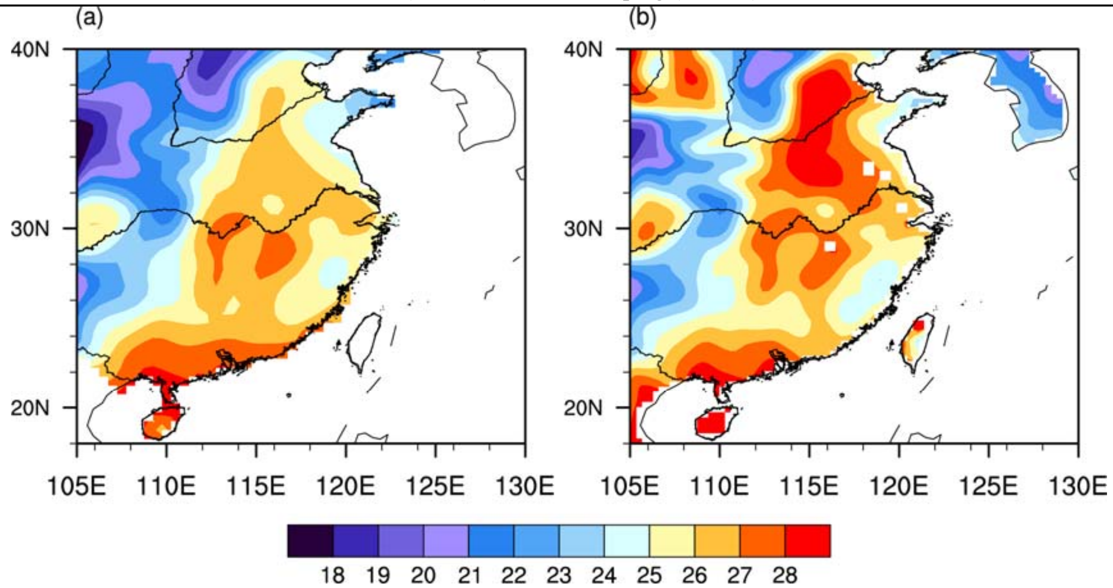

Figure 2. Spatial distribution of the summer temperature obtained from (a) the CMA observation data and (b) the RSM simulation result during the 20 years.

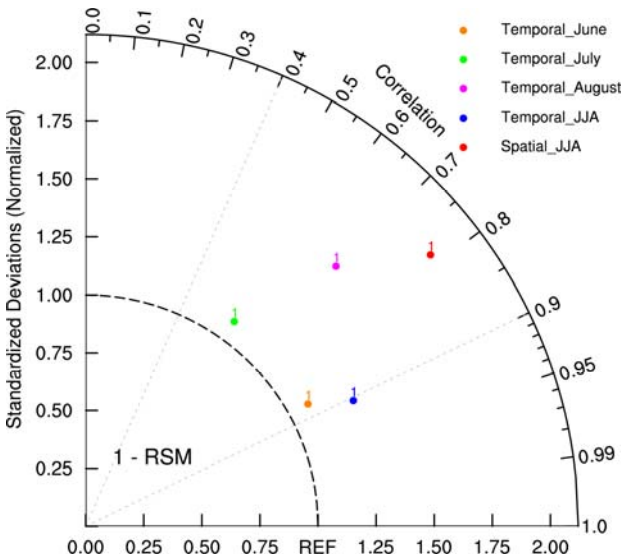

Figure 3. Taylor diagram of RSM simulation result against the CMA temperature in June, July, August, and in summer (JJA) of temporal and spatial series, respectively.

The simulated 20-year regional-averaged summer mean surface air temperature (Table 1) shows a systematic bias of around +2.1°C over the North China, and a negative bias of -2.8°C over the South China. The Yangtze-Huaihe Rivers basin has the lowest bias (+0.4°C) among the three sub-regions. The RSM is able to accurately simulate the summer mean temperature in the eastern China, especially in the Yangtze-Huaihe Rivers basin.

Table 1. Observation and simulated regional average surface air temperature (uint: °C) in the summer during the 20 years.

	North China	Yangtze-Huaihe Rivers basin	South China
OBS	22.4	25.2	27.3
RSM-OBS	2.1	0.4	-2.8

3.1.2 PRECIPITATION

We conduct an experiment in the RSM to examine the capacity to forecast the precipitation. Fig.4 shows the spatial distributions of the summer precipitation obtained from the observation and RSM experiment respectively. The major changes in the East Asian summer monsoon (EASM) include a weakening of the EASM and a shifting in precipitation patterns at the end of 1970, an increasing in South China precipitation after 1992–1993, a decreasing in precipitation in the middle-and-lower reaches of the Yangtze River and an increasing in precipitation in the Huaihe River basin after 1999 (Wang and Fan[22]). We select 1994 (Fig.4c, 4d) and 1985 (Fig.4e, 4f), which correspond to a flood and drought year, respectively. We analyze the precipitation distribution in the wet and dry years. In summer, rainfall becomes a highly localized phenomenon, mostly associated with convection. The summers of some years shows the characteristics of extreme flooding and extreme drought over the eastern China. Therefore, the 20-year summer mean precipitation do not have a vital belt. The observed 20-year mean precipitation (Fig.4a) shows two rainfall belts: one is around the Yangtze River, with a maximum about 9 mm/day over the South China; and another one is in the south region of South China, with a maximum about 12 mm/day. In contrast to the RSM experiment, the simulated precipitation distribution (Fig.4b) is similar with the observation for reproducing the two belts. However, the RSM simulation overestimates the precipitation, especially in southwest China.

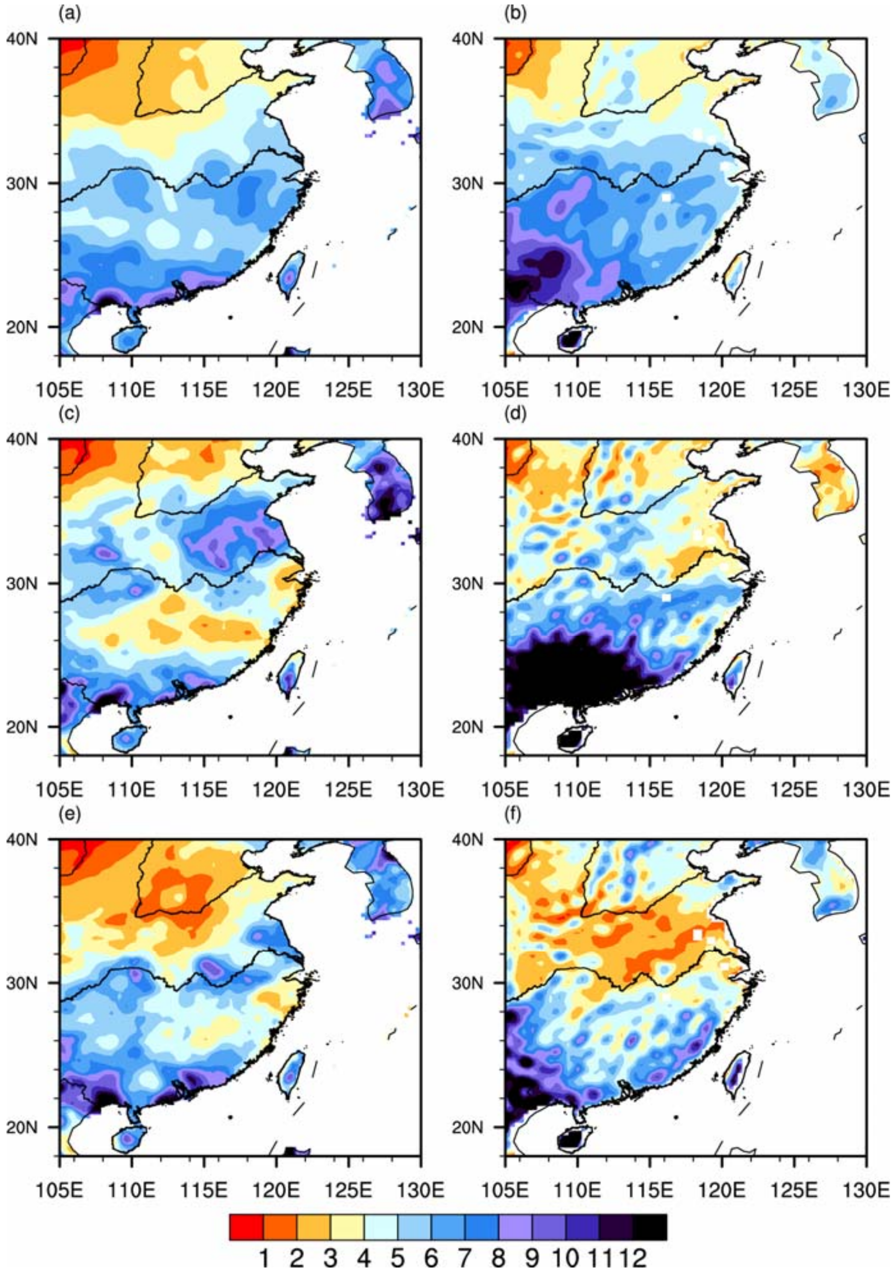

Figure 4. Spatial distribution of the summer precipitation of a) the 20 year average, c) the year of 1994, e) the year of 1985 obtained from the APHRODITE daily precipitation data, and b) the 20 year average, d) the year of 1994, f) the year of 1985 obtained from the RSM simulated result.

In 1994 (Fig.4c), the wet year, the summer rain is concentrated on the South China, with the maximum values more than 12 mm/day. The simulated rainfall in 1994 (Fig.4d) agrees well with the observation. The simulated result also shows flood regions over the South China, where precipitation value is larger than 12 mm/day. In the drought case in 1985 (Fig.4e), the precipitation is concentrated on the south region of the

South China with the values around 8–9 mm/day. The simulated precipitation in 1985 (Fig.4f) is similar to the observation. However, the simulated precipitation center is westward, and the areas are large with higher values. The RSM captures the intense and location of precipitation in the both flood and drought cases. Although the RSM tends to overestimate the intense of precipitation in the both flood and drought case, the simulated precipitation result is definitely acceptable. Note that the systematic bias is one possibility causing the differences between the modeled precipitation distribution and the observed ones. Therefore, we conclude that the RSM performs fairly well in reproducing precipitation spatial distribution and temporal tendency.

Table 2 lists the observed regional-averaged summer precipitation in three sub-regions from the simulation and the observation. Similar with the surface air temperature, the lowest precipitation bias (+0.25 mm/day), which account for 4.7% of the measured climate average, is over the Yangtze-Huaihe Rivers basin. The systematic biases over North and South China are 0.94 mm/day and -2.26 mm/day respectively.

Table 2. Observed and simulated regional average precipitation (unit: mm/day) in the summer during the 20 years.

	North China	Yangtze-Huaihe Rivers basin	South China
OBS	3.09	5.37	7.88
RSM-OBS	0.94	0.25	-2.26

We also calculate the precipitation spatial anomalies in each grid over the whole region (shown in Fig.5). In general, both the observation and the simulation show the spatial precipitation pattern with a southern flood and a northern drought. The maximum observation anomaly is around 4, while the simulated maximum value is higher and covers a larger area. Two center areas of the positive anomalies are identified. One is in the South China shown in both the RSM and the observation. The other one is in the south region of the Yangtze-Huaihe Rivers basin shown in the observation but not in the RSM. Therefore, the RSM may underestimate precipitation in the summer over the Yangtze-Huaihe Rivers basin. However, the RSM capture the precipitation anomalies of the eastern China, especially over South China.

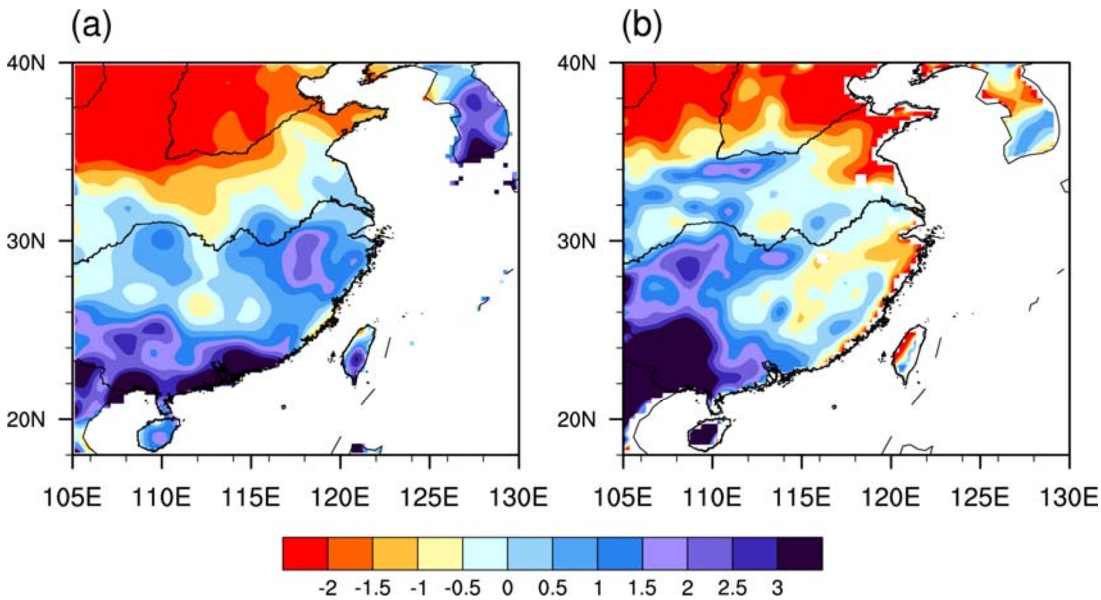

Figure 5. The anomalies of a) the APHRODITE, b) the RSM simulated summer precipitation, respectively.

3.2 *Interannual variability of surface air temperature and precipitation*

In this section, we analyze the interannual variability of the RSM simulated surface air temperature and precipitation over the eastern China.

The standard deviation distributions of observed and simulated summer mean surface air temperature are shown in Fig.6. The RSM generally captures the main distribution features of the summer mean surface air temperature interannual variability, but it still has some systematical bias over the Yangtze and Huanghe Rivers basin. The simulated surface air temperature variability locations are similar with the observation, but with higher values.

The interannual variability of the summer precipitation is also calculated (Fig 7). Fig.7a shows that the interannual variability of observed summer precipitation tends to increase from northwest to southeast in China, and it has two main large variability center located at the Yangtze River basin and South China. The simulated precipitation variability distributions (Fig.7b) are similar with the observation, but the high value center is stronger and vaster, indicating larger amplitude. The model overestimates the interannual precipitation variability in central China and southwest China.

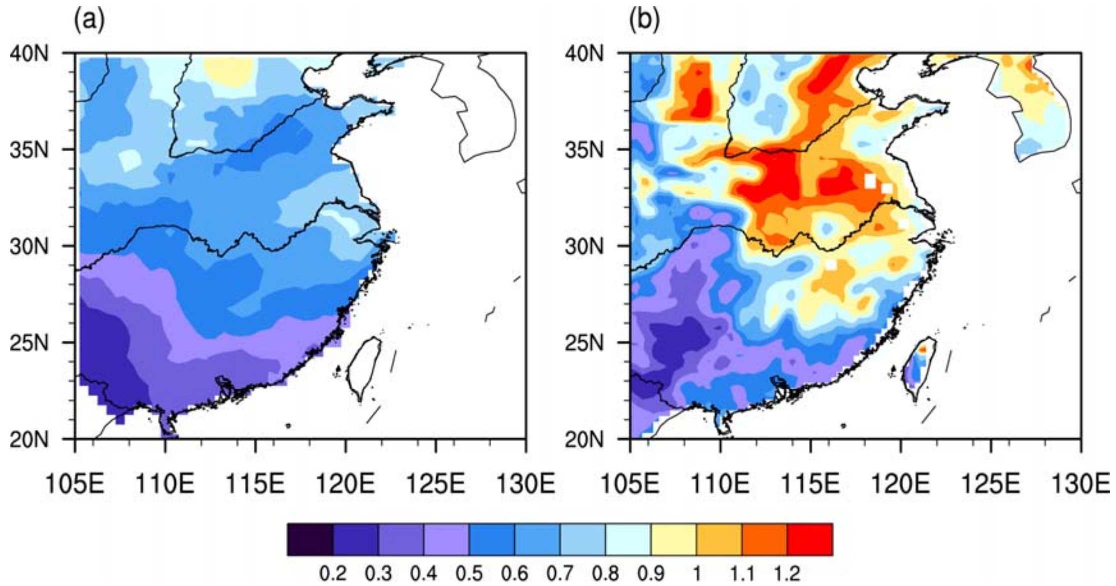

Figure 6. Variability of a) the CMA, b) the RSM simulated temporal surface air temperature in the summer from 1984 to 2003.

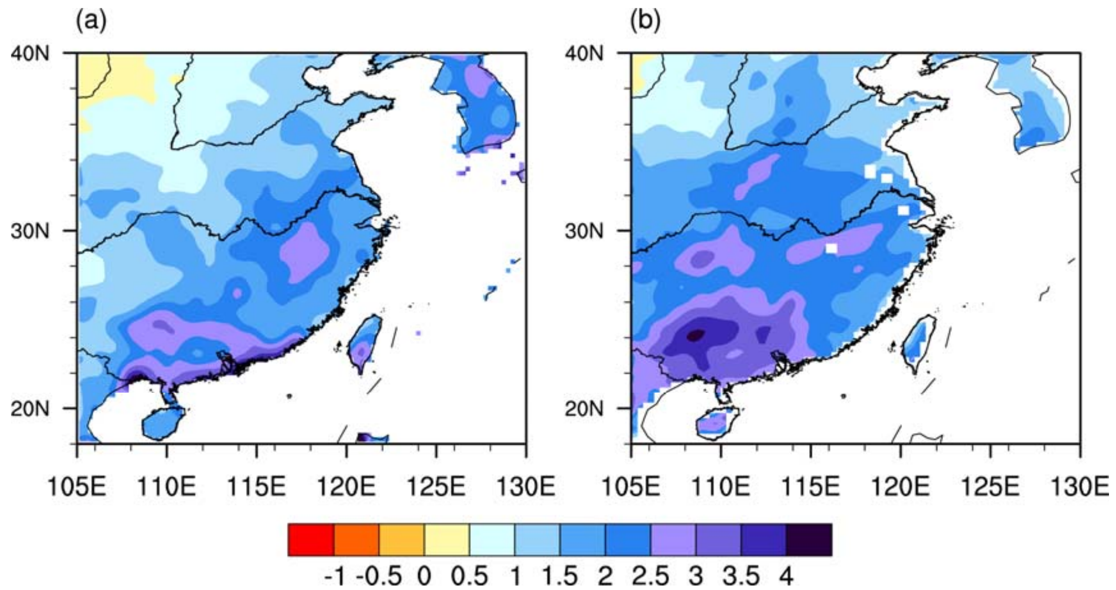

Figure 7. Variability of a) the APHRODITE, b) the RSM simulated summer precipitation.

Generally, the RSM model well reproduces the interannual variability of summer mean surface air temperature and precipitation in the eastern China.

Figure 8 represents the anomalies of regional mean summer precipitation over the whole region and the three sub-regions obtained from the observation and model simulations. In order to avoid the effect from the ocean, we only use the precipitation data over the China mainland. The anomaly values in the observation and the simulated results show a low interannual variability, except for the South China. The correlation coefficients of the whole region, North China, Yangtze-Huaihe Rivers basin, and South China are 0.82, 0.91, 0.84, and 0.88, respectively. These correlation coefficients are quit high in the summer precipitation simulation. The highest correlation is found in the North China, where also shows significant interannual variations during the 20 years. The years of 1994 and 1985 show the characteristics of wet and dry respectively. These features are well reproduced by the simulation. The RSM experiment reproduces interannual variation reasonably for the eastern China regions.

3.3 *Extreme events*

3.3.1 DAILY MAXIMUM AND MINIMUM TEMPERATURE

Figure 9 shows the probability distributions of daily maximum and minimum temperature. The single-peaked structure consists with the observation probability distribution of daily maximum and minimum temperature. The RSM captured the single-peaked structure and the peak values as observed. The RSM simulated probability of daily minimum temperature deviates to the warm area (the right panel in Fig.9), but the difference of the maximum value of probability between the model and the observation are smaller than 0.5%. That means the RSM model tends to overestimate the surface minimum temperature.

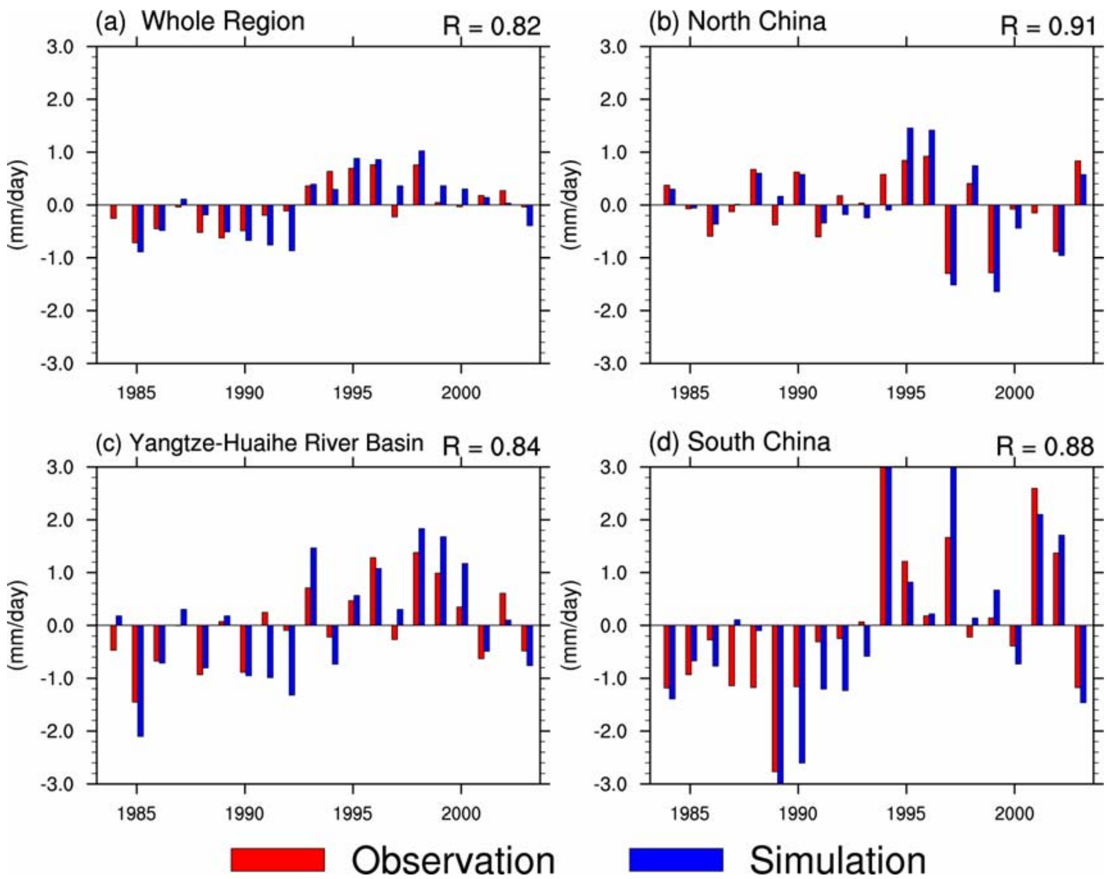

Figure 8. Variability and the correlation coefficient of temporal precipitation in the summer from 1984 to 2003 over a) the whole region, b) the North China, c) the Yangtze-Huaihe Rivers basin, d) the South China.

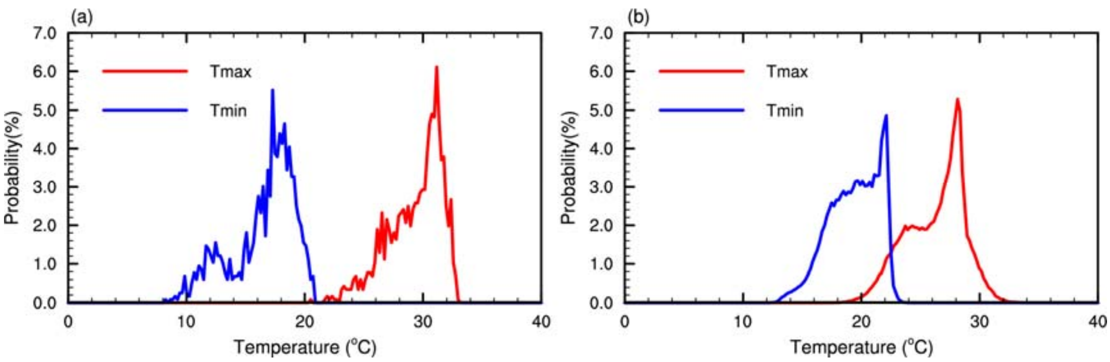

Figure 9. Probability distribution of a) the CMA, and b) the simulated daily maximum and minimum temperature.

3.3.2 DAYS OF DIFFERENT PRECIPITATION INTENSITIES

We divide the precipitation into different precipitation intensities as follows: light rain (>1, ≤10 mm/day), moderate rain (>10, ≤25 mm/day), heavy rain (>25, ≤50 mm/day) and torrential rain (>50 mm/day). Days of different precipitation intensities derived from both observations and simulations are shown in Fig.10.

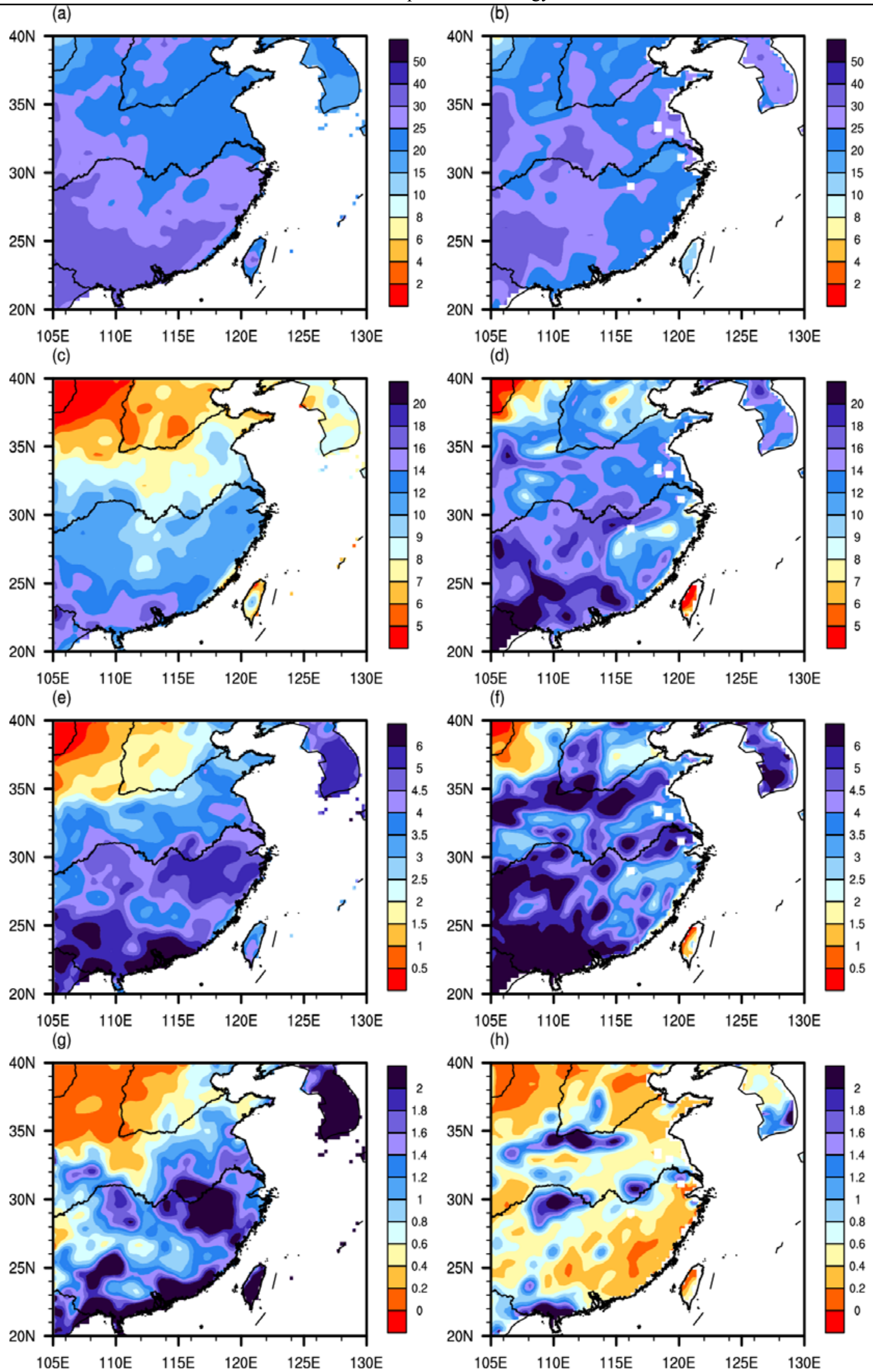

Figure 10. Days of different precipitation intensities: light rain (a, b), moderate rain (c, d), heavy rain (e, f), torrential rain (g, h) derived from the APHRODITE (a, c, e, g), and the simulation (b, d, f, h).

The observation results show that the light rain is the most common phenomenon (with about 30–40 days in the summer) in all of the four precipitation intensities scenarios. The second one is the moderate rain days with about 10–14 days in the south area of the Yangtze River and 5–8 days in the north area of the Yangtze River. The third one is the heavy rain days: 4–6 days in the south area of the Yangtze River, 3–4.5 days in the area along the Yangtze River and 0.5–2 days in the north area of the Yangtze River. The torrential rain days are the least common during the summer: 1–2 days along the Yangtze River and the South China. Obviously, the Yangtze River is a boundary to separate the wet and dry areas: the southern side of the river is wetter than the north. Compared with the observations, the RSM simulated distributions of different rain days reproduce those characteristics mentioned above. The simulated moderate rain days are the best in all the four cases regarding to the values and the distributions. However, the RSM tends to under-predict the light rain days and over-predict the days of heavy and torrential rain. For instance, in the case of the torrential rain, two maximum centers in the South China are shown in the observation, while the simulated result combines them as one belt shape.

4 CONCLUSIONS AND DISCUSSIONS

In this paper, the RSM has been used to simulate the summer monsoon climate over the eastern China. The RSM integration period is from May 21 to September 1 for each year from 1984 to 2003. The simulations are driven by the NCEP/NCAR 40-reanalysis data. And the horizontal resolution is approximately 30 km.

In summary, the results from the model are very satisfactory in terms of the surface air temperature and precipitation distribution simulation for these summers. The RSM has the capacity of reproducing the surface air temperature and precipitation pattern and the variations. This model also captures the tendency of flood and drought in some specific years. The distribution of the surface air temperature and the precipitation simulated by the RSM experiment for the 20 summers generally agree the observations. For example, it is obvious that the simulated surface air temperature spatial distribution and temporal trend are close to the observation. Besides, the RSM evidently improves the skill in simulating regional features such as precipitation. The temporal correlation coefficients between the observed and simulated yearly precipitation over the whole and the three sub-regions are rather high, with the minimum value of 0.8 (the 95% level of Fisher's exact significant test value is 0.25). Furthermore, the anomalies in each year are acceptable. It is concluded that the RSM has the capability to capture the precipitation anomalies and temporal tendency of the eastern China.

Evaluation of the RSM simulated extreme events generally agrees with the results obtained from previous studies. For instance, the simulated probability distributions of daily maximum and minimum temperature are similar with the observation result. Although the RSM tends to under-predict the light rain days and over-predict the days of heavy and torrential rain, it reproduce the spatial distribution patterns of all the four precipitation intensities.

Based on the evaluations and analysis conducted in this study, we conclude that the RSM is suitable for regional climate studies. The results also indicate the necessity for further improvements, especially in the parameterization schemes. It is necessary to find out which factors can improve the RSM precipitation simulation in high resolutions. We will conduct test simulations with the regional climate model coupled with a global model to investigate these problems.

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