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NUMERICAL SIMULATIONS OF EXTREME PRECIPITATION IN EASTERN CHINA UNDER A1B SCENARIO

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Abstract: The regional climate model (RegCM3), developed by the Abdus Salam International Centre for Theoretical Physics and nested in one-way mode within the latest version of Community Climate System Model from the National Center for Atmospheric Research, is used to conduct a set of experiments to examine its capability of climate simulation for the past 50 years and to explore possible changes in extreme precipitation (EP) in the next 100 years under the A1B scenario. Compared with the observation from the Climate Research Unit at the University of East Anglia and CPC Merged Analysis of Precipitation, RegCM3 reasonably reproduces the spatiotemporal distributions of precipitation and EP in eastern China. Based on the present-day analysis, this study examines the changes in monsoonal precipitation over eastern China in mid- and late-21st century relative to the reference period of 1970-1999. It is found that the precipitation will increase over the middle and lower reaches of the Yangtze River and areas to its north, and decrease over coastal areas to its south, especially in late-21st century. The various indices reflecting extreme events showed that the EP will enhance 10%-15% over the middle and lower reaches of the Yangtze River and areas to its north, and weaken over the areas to its south. The summer monsoon will strengthen and shift northwards under SERS A1B, bringing more water vapor and energy from the Indian Ocean and South China Sea for precipitation and eventually more precipitation over northern China.

Key words: global warming; climate prediction; East China; extreme precipitation; numerical simulation

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1 INTRODUCTION

The current and ongoing global warming trend is likely one of the biggest threats faced by mankind and is a worldwide environmental problem that profoundly affects the environment, human health, and sustainable development of the global economy. Many previous studies[1-4] have claimed that global warming during the 20th century was unprecedented in the past millennium and that the most recent 30 years were likely the warmest in the past millennium. Moreover, this warming is expected to persist.

Precipitation levels in East Asia are expected to significantly increase in the future along with global warming. The assessment report from the Intergovernmental Panel on Climate Change (IPCC)[5] noted that the average temperature and precipitation in East Asia would increase by 2.3−3.3°C and 5%−7%, respectively, until 2050. A study by Hulme et al.[6] indicated that all seasonal precipitation in East Asia would increase in response to doubled CO_2 levels. An analysis by Hu et al.[7], which was about the output from 16 models in Phase 2 of the Coupled Model Inter-Comparison Project (CMIP2), indicated that precipitation would increase in China during the summer season in response to doubled CO_2 levels. Studies based on the global atmospheric circulation model also indicated that precipitation would increase during the East Asian monsoon season[8]. Jiang et al.[9] reported an analysis of simulation results from 13 climate models that were used in the 4th IPCC Assessment Report (IPCC-AR4) under different emission scenarios; the analysis indicated that the climate in China would become significantly warmer and wetter during the 21st century and that the annual precipitation would increase by 1.5%−20%. Sun and Ding[10] published an analysis of output obtained from the A1B scenario in the Special Report on Emission Scenarios (SRES), which was based on the 19 climate models of IPCC-AR4, and indicated that precipitation

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rates would increase significantly (~9%) after the late 2040s and that the eastern part of China would experience a full rainy period; however, large deviations remain between the different models. An analysis by Li et al.[11], which incorporated the nested regional climate model of the global ocean-atmosphere coupled model, indicated that summer droughts in northern China would likely be alleviated during the next three decades and that humidity levels would increase at middle and high latitudes and decrease at relatively low latitudes. The East Asian summer monsoon would be enhanced, and the warm and wet air would likely be transported northward. Studies of future climate change in the Tibetan Plateau under the A1B scenario have also indicated that in the next 3−5 decades, most seasonal precipitation would likely increase throughout the year in most areas of the plateau[12]. Analyses of different regional climate models have also indicated that the number of rainy days would increase in southern China in response to doubled CO_2 levels[13-14].

As global warming has intensified in recent decades, extreme climate variations have attracted broad domestic and international attention. Studies conducted by Frich et al.[15] found that along with global warming, the range of increased precipitation had expanded at middle and high altitudes in the Northern Hemisphere, and there had been more heavy and extreme precipitation events. Kharin et al.[16] analyzed simulation results from the global coupled model (Canadian Global Climate Model, CGCM2) of the Canadian Climate Modeling and Analysis Center under different emission scenarios and found that the trend toward increased extreme precipitation events was significantly higher than that of average precipitation; furthermore, at the end of the 21st century, the occurrence frequency of these extreme precipitation events will be twice that in the early 21st century. Since the 1980s, the economic losses in China that were caused by major climate and weather disasters (such as large-scale droughts and floods) have increased to 100−200 billion RMB, a figure that accounts for approximately 3%−6% of the Gross Domestic Production (GDP)[17]. An analysis of observational data[18] indicated that the frequency of global extreme precipitation events had significantly changed between the early and late 20th century, and the frequency of heavy precipitation events also tended to increase. The variation of extreme precipitation in China is essentially consistent with the observation on a global scale, despite regional and local characteristics[19, 20]. However, the overall feature is that the total precipitation amount either does not change or increases with reduced event frequency and enhanced precipitation intensity, with subsequent increases in the variability of floods and droughts[21]. Studies published by Zhai et al.[22] indicated that in China, both the average intensity and value of extreme precipitation tend to increase. In particular, the ratio of extremely heavy precipitation showed an increasing trend in the 1990s. The ratio of extreme precipitation, relative to the annual precipitation, increased slightly in North China. In the past century, the rates of both abnormal precipitation events and flood disasters showed an increasing trend in eastern China[23]. In China, assessments of future climate change have been performed in recent years. For example, Gao et al.[24] suggested that in the future, precipitation levels would significantly increase in northern China and the number of days of heavy precipitation would significantly increase in southern China. Zhang et al.[25] analyzed the maximum precipitation rate over five consecutive days and a simple index of precipitation intensity, and the results of this study indicated that in the future, the frequency of extreme precipitation would increase in most areas of China.

Studies have suggested that in East Asia, only numerical models with relatively high resolutions can accurately simulate the distribution of large-scale monsoon precipitation and Meiyu periods[26, 27]. Eastern China is one of the most economically developed areas in China and has a high population density; this region is located in the monsoon zone and thus is vulnerable to the effects of flood disasters. To meet the needs for assessments of climate impact in China, it is urgent to provide high-resolution information on climate change. Based on previous studies, this study further applied the one-way nested technique (CCSM3-RegCM3) and the regional climate model (RegCM3), which was developed by the Abdus Salam International Centre for Theoretical Physics (ICTP) and nested in one-way mode within the latest version of Community Climate System Model (CCSM3) from the National Center for Atmospheric Research (NCAR), to analyze the characteristics of precipitation variation under the A1B scenario during the next century in eastern China. We have focused our discussion on extreme precipitation variations and possible causes. We give a general introduction to the one-way nested model (CCSM3-RegCM3) and the definitions of the indices of extreme precipitation in section 2. Section 3 introduces the capability of CCSM3-RegCM3 to precipitation in eastern China. The numerical simulation results and the dynamical mechanisms are presented in sections 4 and 5, followed by a summary in section 6.

2 MODEL AND METHODS

CCSM3 is the third version of the Community Climate System Model that was released by NCAR in

June of 2004. Composed of four separate models simultaneously simulating the earth's atmosphere, ocean, land surface and sea-ice, and one central coupler component, the CCSM allows researchers to conduct fundamental research into the earth's past, present and future climate states[28]. In the atmosphere and land surface components (CAM3) of CCSM3, the previous approach toward aerosol as a single background boundary layer that did not change was replaced, and the uniform optical properties are used worldwide[29]. The future forecast results from CCSM3 under different scenarios played a significant role in the fourth assessment report of the IPCC (IPCC AR4). This paper uses the CCSM3-RegCM3 to analyze the characteristics of the precipitation in eastern China in the next century under A1B scenario.

The regional climate model used in this study is the newest version of the RegCM3, which was developed by the Italian Centre of Theoretical Physics in 2003−2004[30]; this model uses the CCM3[31] radiation transfer package, improves the parameterization scheme of large-scale clouds and precipitation, and adds new sea-surface fluxes and more convection parameterization schemes (such as Betts-Miller and Emanuel). Moreover, RegCM3 used the global land coverage features from the United States Geological Survey (USGS) and multiple global elevation data from 2′−60′ to form the terrain in the model, which permitted a more accurate reflection of the status of the underlying surface and improved the data input of the model.

Forecasts of extreme precipitation events under a background of global warming have always been important in studies of global change. Regular global climate models with coarse resolutions can only give monthly (or quarterly and annual) average climate conditions on a global scale, and thus, fine climate characteristics on a regional scale as well as forecasts of extreme climate scenarios must be obtained through a variety of downscaling techniques. This study employed the currently popular one-way nested technique. Specifically, CCSM3 can be used to provide the initial fields and boundary conditions required for the RegCM3 simulation, and the computation results of RegCM3 do not feed back to CCSM3. The specific operation is that based on greenhouse gas and aerosol concentrations determined from the current and future A1B scenarios provided by IPCC AR4, this study used CCSM3 with a horizontal resolution of T42_gx1v3 (128×64 Gaussian grids in the horizontal direction on a global scale for the atmosphere and land surface model and 26 layers in the vertical direction; 320×384 grids in the horizontal direction for oceans and sea ice and 40 layers in the vertical direction) to simulate the climatic element field, including horizontal wind vector, temperature, surface pressure, and water vapor mixing ratio, at 6-h intervals in the present (1950−1999) and future (2000−2099), and to perform further simulations of the RegCM3 model. In this study, the center of the RegCM3 model is located at (100°E, 33°N) with a horizontal resolution of 60 km, and the region is divided into 110×78 grids; there are 18 layers in vertical direction, and the integration time step is 100 s. The selected physical parameterization schemes include the explicit humidity scheme, the Grell parameterization scheme of convective precipitation, the non-local planetary boundary layer scheme, the Zeng parameterization scheme of ocean flux, and the CCM3 parameterization scheme of radiation transfer. The land surface process uses the BATS scheme, and the model employs the Lambert map projection. To validate the feasibility of using the simulation outputs of CCSM3 as the initial fields and boundary conditions for RegCM3, this study used high-resolution (0.5°×0.5°) land precipitation grid data from the Climate Research Unit (CRU) of the University of East Anglia and interpolated the regional model of RegCM3 with the same resolution as the numerical experiment in this study to validate the simulation performance of the regional climate model on precipitation distribution in China. We also used grid reanalysis data of global land and oceanic precipitation (2.5°×2.5° resolution) that were provided by the Physical Sciences Division (PSD) and the CPC Merged Analysis of Precipitation (CMAP) from the National Oceanic & Atmospheric Administration (NOAA) to validate the capability of the model in simulations of daily precipitation variations.

The following five sets of numerical experiments were performed: the integral of CCSM3 simulation for the contemporary era of 1950−1999 (20C-CCSM for short), a high-resolution numerical experiment with the output data from the 20C-CCSM model in the initial fields to run a RegCM3 simulation of the contemporary era (1950−1999; 20C-RegCM), a high-resolution numerical experiment using the National Centers for Environmental Protection Reanalysis 1 project (NCEP1) as the boundary conditions for a RegCM3 simulation of the contemporary era (1950−1999; 20CR-RegCM), a numerical experiment of the integral of CCSM3 simulation under the A1B scenario for 2000−2099 (21C-CCSM), and a high-resolution numerical experiment using the output of 21C-CCSM as the boundary conditions for the integrated RegCM3 simulation of the next 100 years (2000−2099; 21C-RegCM). This study primarily analyzed the output results from the RegCM3 simulation (i.e., 20C-RegCM, 20CR-RegCM, and 21C-RegCM), and the analysis excluded the integration results for the first 10 years to avoid early instability issues in the model integration.

To analyze the characteristics of future extreme precipitation variations in eastern China under the A1B scenario, this study used the five extreme precipitation indices that were proposed by Frich et al.[32]: the daily precipitation intensity index (SDII), the index of maximum sustained without precipitation period (CDD), the index of number of days with heavy precipitation (R10), the index of maximum precipitation over five consecutive days (R5d), and the extreme precipitation contribution index (R95). The definitions and units for these indices are given in Table 1. In the fourth IPCC assessment report and the multi-model ensemble, Jiang et al.[33] examined the simulation capability for the five extreme precipitation indices under the modern climate scenario with seven general circulation models.

Table 1. Definitions of the indices of extreme precipitation.

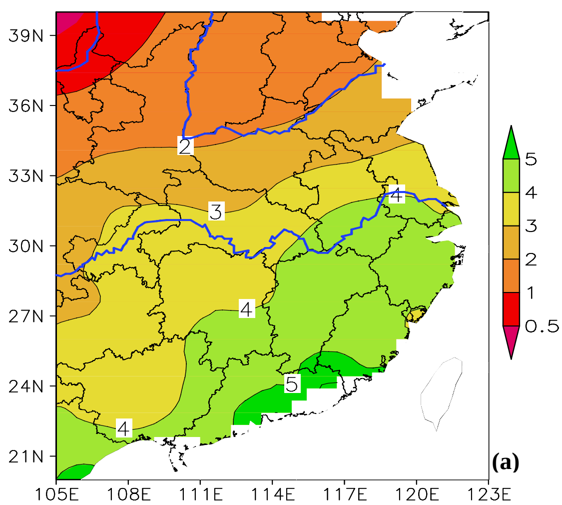
Index	Description	Definition	Unit
SDII	Average daily precipitation intensity	Total annual precipitation/days of precipitation (≥1 mm)	mm/d
CDD	Longest no-precipitation period	The maximum duration without precipitation (with daily precipitation below 1 mm)	d
R10	Days of heavy precipitation	Number of days with daily precipitation >10 mm in one year	d
R5d	Maximum precipitation in 5 consecutive days	The maximum sum of precipitation in 5 consecutive days in one year	mm
R95	Contribution rate of extreme precipitation	The percentage of summed extreme precipitation (daily precipitation ≥the 95% percentile in 1970-1999) relative to the annual total precipitation	%

3 CAPABILITY VALIDATION FOR THE CCSM3-REGCM3 SIMULATIONS OF PRECIPITATION IN EASTERN CHINA

3.1 *Validation of the capability of the regional precipitation simulation*

Successful simulations for precipitation play a significant role in evaluations of model performance. To evaluate the capability of the one-way nested CCSM3-RegCM3 technique in a climate change simulation for eastern China (20°N−40°N, 105°E−123°E), we compared the simulation results from 20C-RegCM with the observational data from CRU (monthly precipitation data) and CMAP (daily precipitation data) to verify the simulation performance of this model on monthly precipitation distribution and daily precipitation variation, respectively, in eastern China.

We applied the CRU monthly precipitation data from the RegCM3 interpolation to the same resolution as the 20C-RegCM experiment and analyzed the distribution of average precipitation in eastern China over a 30-year period (1970−1999). Fig. 1 shows that the 20C-RegCM experiment considerably simulated the distribution of precipitation magnitude in eastern China, and the average precipitation over the 30-year period exhibited the overall distribution pattern of higher and lower precipitation in the southeast/south and the northwest/north, respectively. The difference in the 30-year averages between the 20C-RegCM and CRU indicates that the overall precipitation data in eastern China are comparable to the observation data and that the simulation results are significantly lower than the observations only in the southeastern coastal areas (including the Guangdong, Fujian, and Zhejiang provinces). This is likely due to a deviation of the ocean-atmosphere coupled model CCSM3 simulation. To maintain consistency with the forecast results from the fourth IPCC assessment report for the next century, this study did not correct the model. Instead, we objectively analyzed the characteristics of future extreme precipitation variations that were simulated by the one-way nested numerical 21C-RegCM. The statistical correlation analysis indicated that the seasonal correlation coefficients between the 20C-RegCM and CRU models of 30-year average precipitation distributions in eastern China (589 grid points) were 0.860 for spring, 0.859 for summer, −0.145 for fall, and 0.787 for winter. With the exception of the fall season, for which the simulation was relatively poor, the simulation results of seasonal precipitation distributions were generally consistent with the observational data.



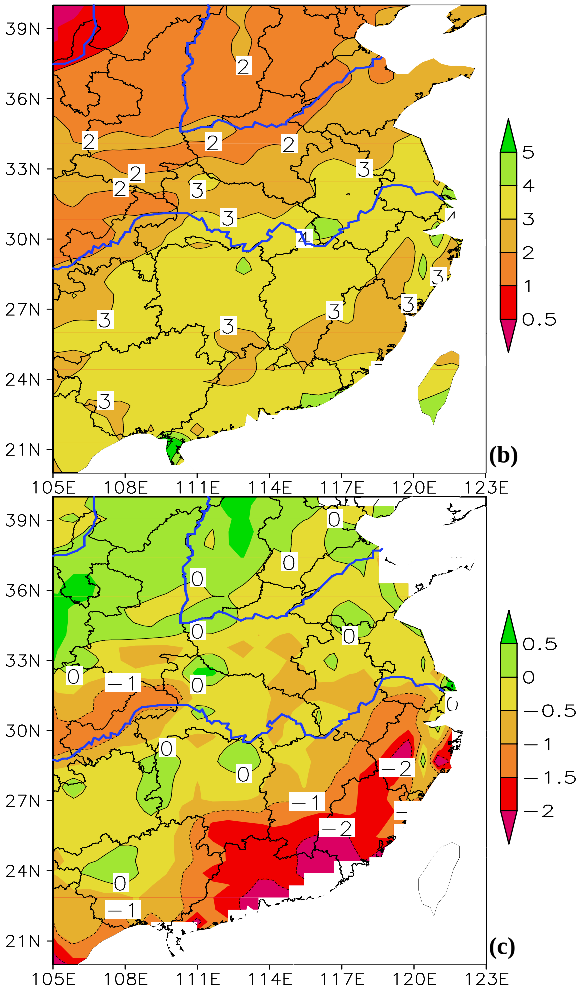


Figure 1. Distribution of precipitation (mm/d) during the past 30 years according to CRU (a), 20C-RegCM (b) and the difference between 20C-RegCM and CRU (c).

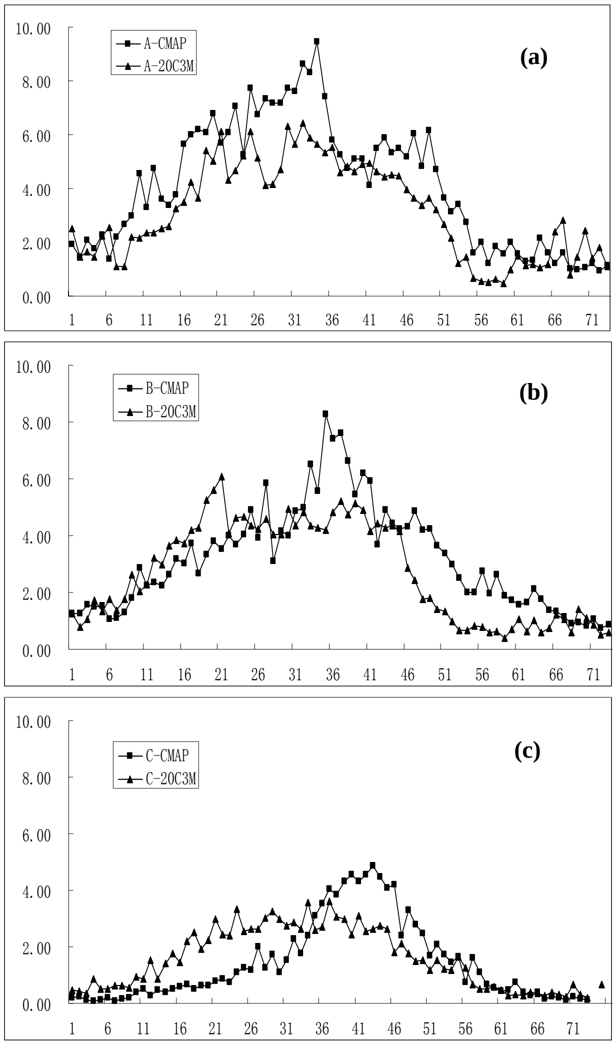


Figure 2. Series of precipitation (mm/d) in regions A (a), B (b), and C (c) during the past 30 years.

We applied the CMAP precipitation data to further verify the simulation capability of 20C-RegCM for daily precipitation variations. Fig. 2 shows the characteristics of the average precipitation variations over a 30-year period in 3 sub-regions of eastern China (region A: 22.5°N−27.5°N, 110°E−120°E; region B: 27.5°N−35°N, 110°E−120°E; region C: 35°N−40°N, 110°E−120°E). We observed that the simulated precipitation variations had the same distribution pattern as the actual precipitation variations. The annual variation showed a single peak, and the annual precipitation in eastern China is generally highest from April to October. The maximum precipitation in regions A and B occurs in June, and the maximum precipitation in region C occurs in July. The correlation analysis of 20C-RegCM and CMAP (with 73 sample points) indicated that the coefficients of direct correlation were 0.891 for region A, 0.754 for region B, and 0.654 for region C. We observed that the simulation results were generally consistent with the observational data and reproduced the characteristics of daily precipitation variation in eastern China.

3.2 *Performance validation for the simulation of the extreme precipitation index*

Generally speaking, during global warming, the variability of extreme climate events is larger than that of the average climate, and related disasters are more significant. Next, we comparatively analyzed the 20C-RegCM and 20CR-RegCM simulation results with regard to the extreme precipitation index from the contemporary era and validated the simulation capabilities of the ocean-atmosphere coupled model and the one-way nested technique of high-resolution regional climate model with regard to the extreme precipitation index.

The average daily precipitation intensity index (SDII) reflects the annual precipitation intensity, which is the ratio of the total annual precipitation and the number of days with precipitation ≥ 1 mm. Presuming that the total annual precipitation does not change, the average daily precipitation intensity index will decrease (increase) if the number of days with precipitation increases (decreases). Fig. 3 (a and f) shows the SDIIs in eastern China over a 30-year baseline period from the 20C-RegCM and 20CR-RegCM experiments, respectively. The SDIIs gradually decreased from the southeast to northwest regions, and the maximum SDII (approximately 8−10 mm/d) was located in the middle and lower reaches of the Yangtze River and the southern coastal areas. The maximum SDII was approximately 6−8 mm/d in the area north of the Yangtze River, and the one-way nested simulation from the 20C-RegCM experiment was generally consistent with the simulation results obtained from the NCEP1 data. The SDII values from the 20C-RegCM experiment were approximately 1 mm/d higher than those from the 20CR-RegCM experiment in both the middle and lower reaches of the Yangtze River and the areas to its north, and were systematically lower (approximately 1 mm/d) in the southern coastal areas; this finding is likely due to simulation errors of the ocean-atmospheric coupled models in this area.

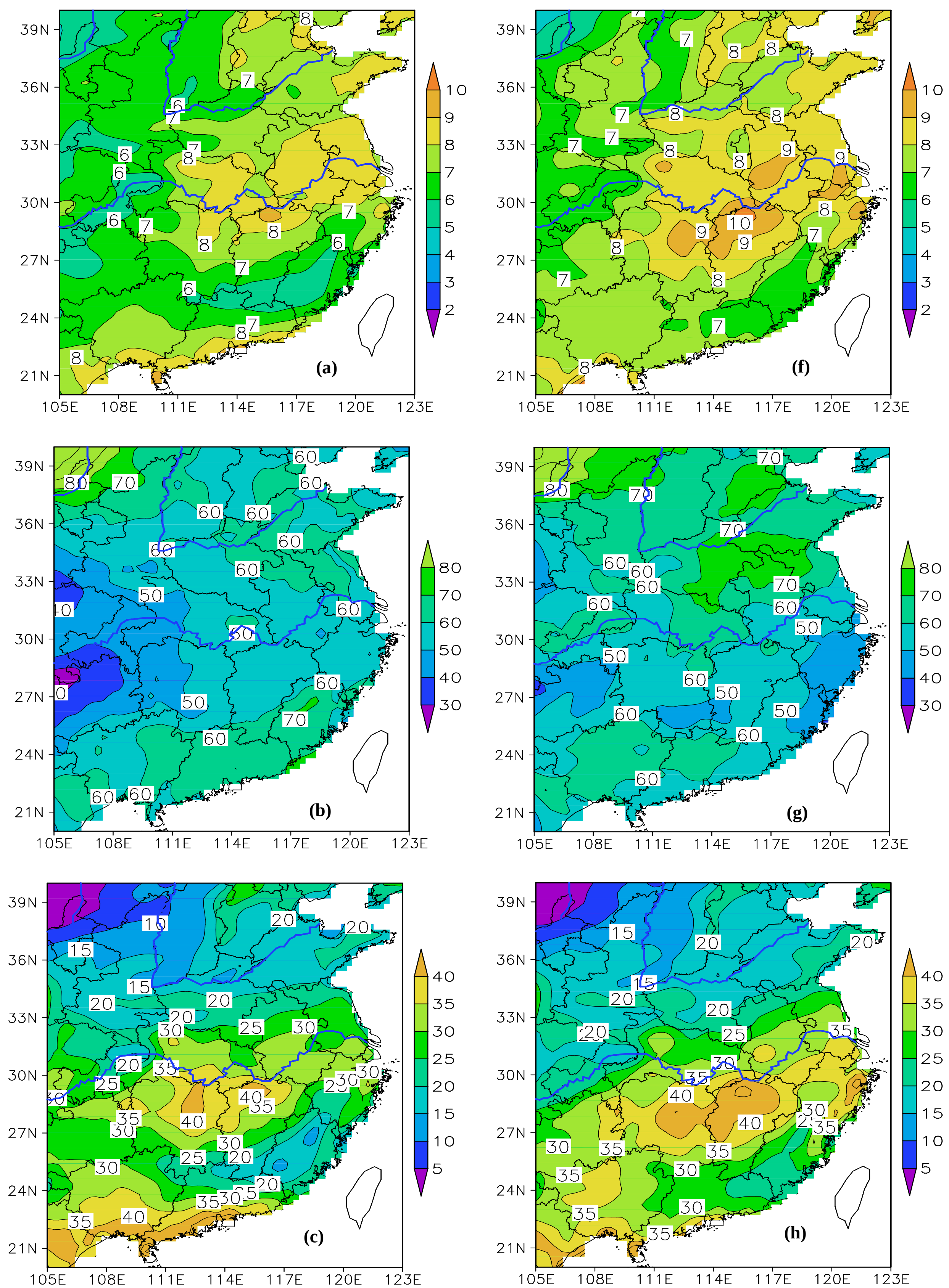
The longest sustained period without precipitation (CDD) is defined as the largest number of consecutive days in one year with daily precipitation ≤ 1 mm and reflects the magnitude of maximum regional drought in one year. A comparison of Fig. 3b and Fig. 3g indicates that the 20C-RegCM model simulates the spatial distribution characteristics for the CDD, which gradually decreases from northwest to southeast. The maximum CDD is approximately 70−80 days in Northwest China; the sustained duration is relatively short (approximately 40−50 days) in the middle and lower reaches of the Yangtze River, and is < 30 days in the Sichuan Basin. The 20C-RegCM and 20CR-RegCM results are very consistent with regard to the horizontal distributions and values. The CDD and SDII spatial distributions are generally opposite, which reflects the reasonable nature of the simulation results.

The number of days with heavy precipitation (R10) is the total number of days in one year with daily precipitation > 10 mm and reflects the frequency of heavy precipitation in one year. The model considerably (Fig. 3c, 3h) simulates the overall distribution of R10 such that there are more days with heavy precipitation in the middle and lower reaches of the Yangtze River and the southern coast and fewer days in northern China. In particular, the R10 is approximately 40 days in the middle and lower reaches of the Yangtze River and approximately 20 days in northern China. With regard to precipitation distribution and SDII, a comparison between Fig. 3c and Fig. 3h indicate that the simulation results from the 20C-RegCM and 20CR-RegCM experiments are similar.

The maximum precipitation over five consecutive days (R5d) is the maximum summed precipitation over five consecutive days in one year and reflects the variation in the maximum precipitation over five consecutive days within one year. R5d was observed to gradually decrease from the southeast to the northwest. The R5d was approximately 120−140 mm in the southern coastal region and approximately 60 mm in the north and northwest regions. A comparison of Fig. 3d with Fig. 3j indicates that the values from the 20C-RegCM and 20CR-RegCM models are generally consistent, which proves the authenticity of the CCSM3-RegCM3 simulation results.

The contribution rate of extreme precipitation (R95) is the percentage of the sum of extreme precipitation (daily precipitation ≥ 95% percentiles for the period 1970−1999) relative to the total annual precipitation and reflects the proportion of extreme precipitation in the total annual precipitation. The R95 was approximately 50% in North China, which indicates that the annual precipitation is dominated by extreme precipitation. The R95 was relatively low (approximately 30%) in the middle and lower reaches of the Yangtze River and South China, and the distribution of precipitation was relatively uniform within a 1-year period. A comparison of Fig. 3e and Fig. 3k indicates that the average spatial distribution over the 30-year period was generally consistent between the two results.

In summary, although the 20C-RegCM simulation results had certain deviations in the southeast coastal area due to systematic errors of the ocean-atmosphere coupled models, the results were generally consistent with those from the 20CR-RegCM and reflected the basic characteristics of the spatial extreme precipitation distribution in eastern China. Moreover, regular climate models are significantly superior in simulations of temperature change rather than precipitation, as demonstrated by the results of the numerical experiment in this study, and the simulation results are very similar to the observational data (not shown). The above-described results validate the reliability of CCSM3 when used for the initial fields and boundary conditions of regional climate models that simulate extreme precipitation in eastern China. Therefore, the following analysis will primarily discuss the results for the next 100 years. We will discuss the characteristics of extreme precipitation variations in eastern China under the A1B scenario and present a preliminary causal analysis drawn mainly from two representative 30-year periods during the middle (2020−2049) and late (2070−2099) 21st century.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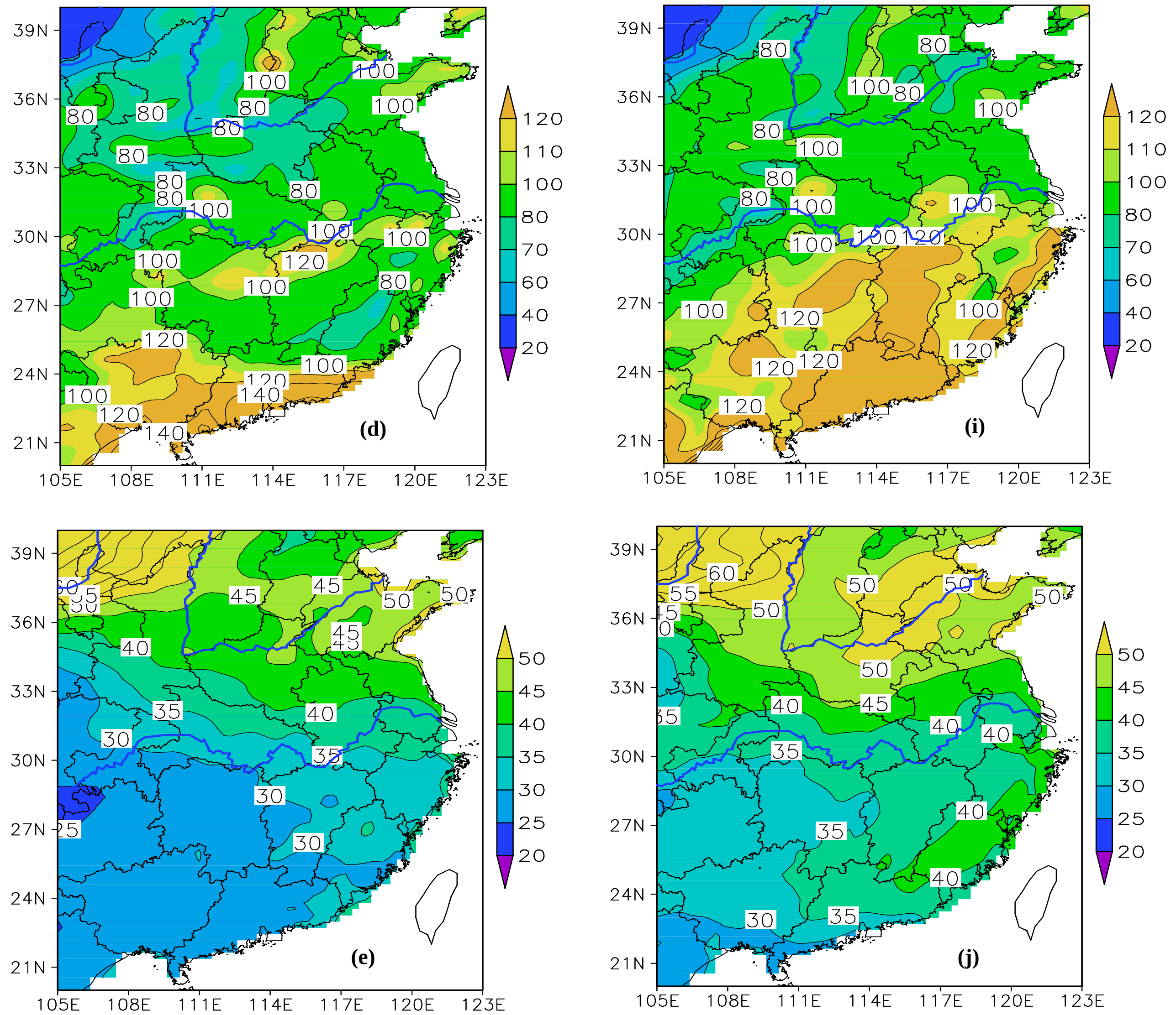


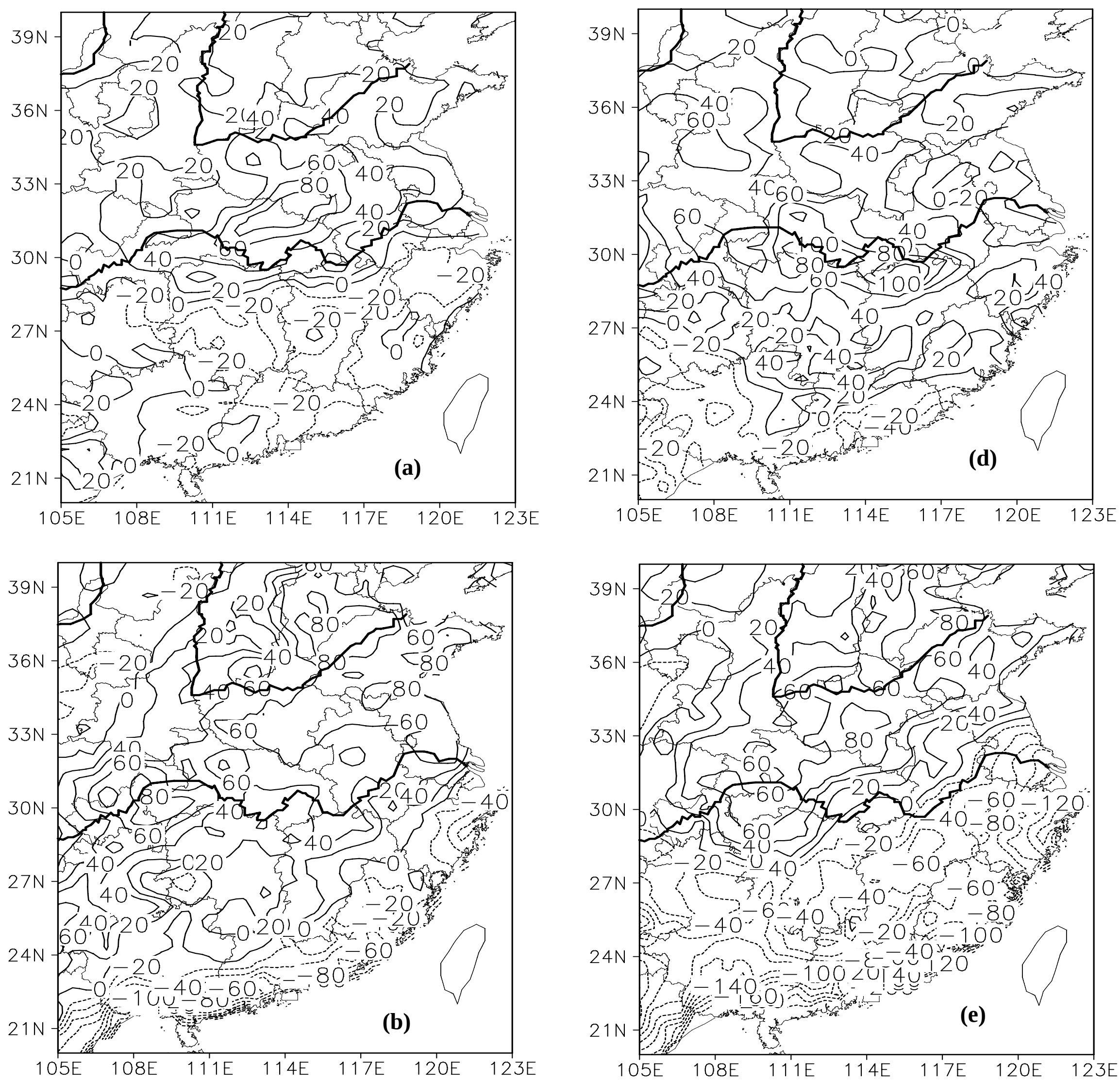
Figure 3. Distribution of extreme precipitation indices SDII, CDD, R10, R5d, and R95 in eastern China for 1970-1999. The left column is for 20CR-RegCM (a, b, c, d, e), and the right column is for 20C-RegCM (f, g, h, i, j).

4 PRECIPITATION VARIATIONS UNDER THE A1B SCENARIO DURING THE MIDDLE AND LATE 21ST CENTURY

4.1 *Average annual precipitation variation*

Figure 4 shows the spring, summer, and annual average precipitation variations during the middle and late 21st century, relative to the contemporary era (1970−1999), under the A1B scenario; data are not shown for the fall and winter seasons. Under the A1B scenario, there were generally significant increases or decreases in average precipitation during the two future 30-year baseline periods. Precipitation decreased in the south and increased in the north with respect to a dividing line generated at the middle and lower reaches of the Yangtze River. In particular, the spring and summer variations contributed most of the annual precipitation variation, as the fall and winter precipitation variations were relatively small. A comparison of precipitation variations during the middle and late 21st century, relative to the contemporary period, indicated that the magnitude of precipitation increases or decreases will be larger in the late versus the mid-21st century, especially for the spring, summer, and annual precipitation distributions. The maximum increase in spring precipitation will be located in the middle and lower reaches of the Yangtze River; the relative increase was forecast to be near 80 mm in the middle of the 21st century and near 100 mm in the late 21st century, and the summer precipitation in southern coastal areas was forecast to decrease by approximately 20 mm. The maximum increase in summer precipitation will be located in the middle and lower reaches of the Yangtze River and the areas to its north, where the forecast maximum increase in average precipitation was > 60 mm for both of the future 30-year periods. Precipitation was forecast to decrease significantly in the southern areas of China, with relative decreases in average summer precipitation near 100 mm in Guangxi, Guangdong, and Fujian during the middle of the 21st century;

these decreases will be significant in the late 21st century when the precipitation levels decrease south of the middle and lower reaches of the Yangtze River and the maximum precipitation decreases in Guangxi and Guangdong reach 160 mm. Because precipitation levels in the spring and summer seasons will significantly increase or decrease, the annual precipitation rates will also exhibit similar variations with increases in the north and decreases in the south. The magnitude of variation in the late 21st century will be larger than in the middle of the 21st century. The maximum increases in annual precipitation will occur in the Hubei, Hunan, and Chongqing, and the relative increases during both 30-year periods will be > 150 mm. The maximum decreases in annual precipitation will occur in Guangxi, Guangdong, and Fujian; the relative decrease in annual precipitation during the middle of the 21st century will reach 150 mm, and the relative decrease in the late 21st century will reach 180 mm.



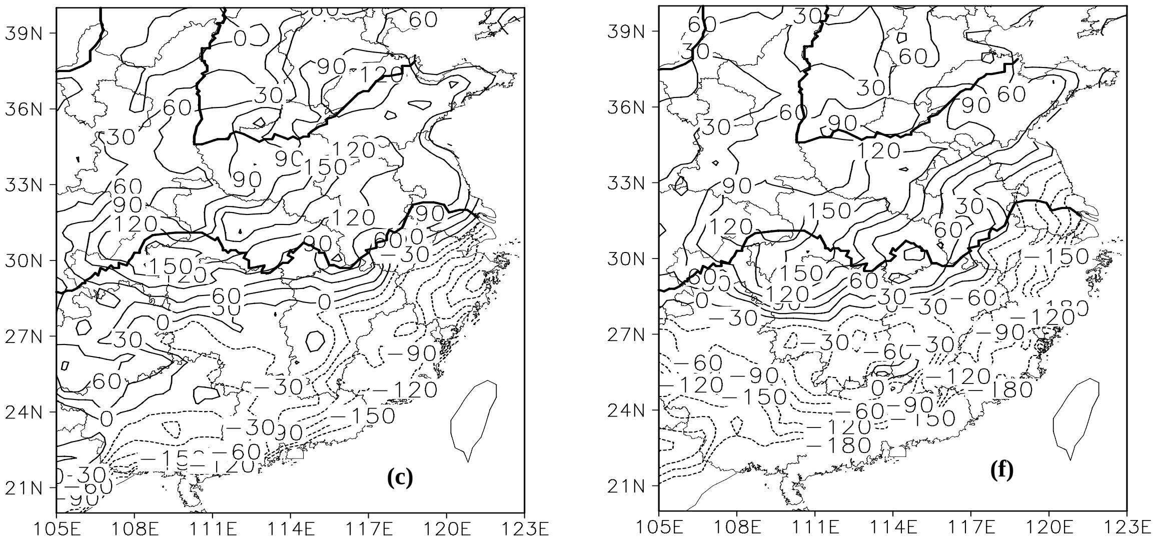


Figure 4. Differences of precipitation in spring, summer, and annual in the middle (a, b, c) and late (d, e, f) 21st century relative to the reference period of 1970-1999.

4.2 *Variation in the extreme precipitation index*

In recent years, forecasts of extreme precipitation under future climate scenarios have become a topic of interest. This study mainly analyzed the characteristics of relative variations in the five extreme precipitation indexes during the middle and late 21st century under the A1B scenario and also forecast variations in future extreme precipitation. Fig. 5 shows the percentages of respective variations in the average SDII, CDD, R10, R5d, and R95 during the middle and late 21st century, relative to the contemporary era.

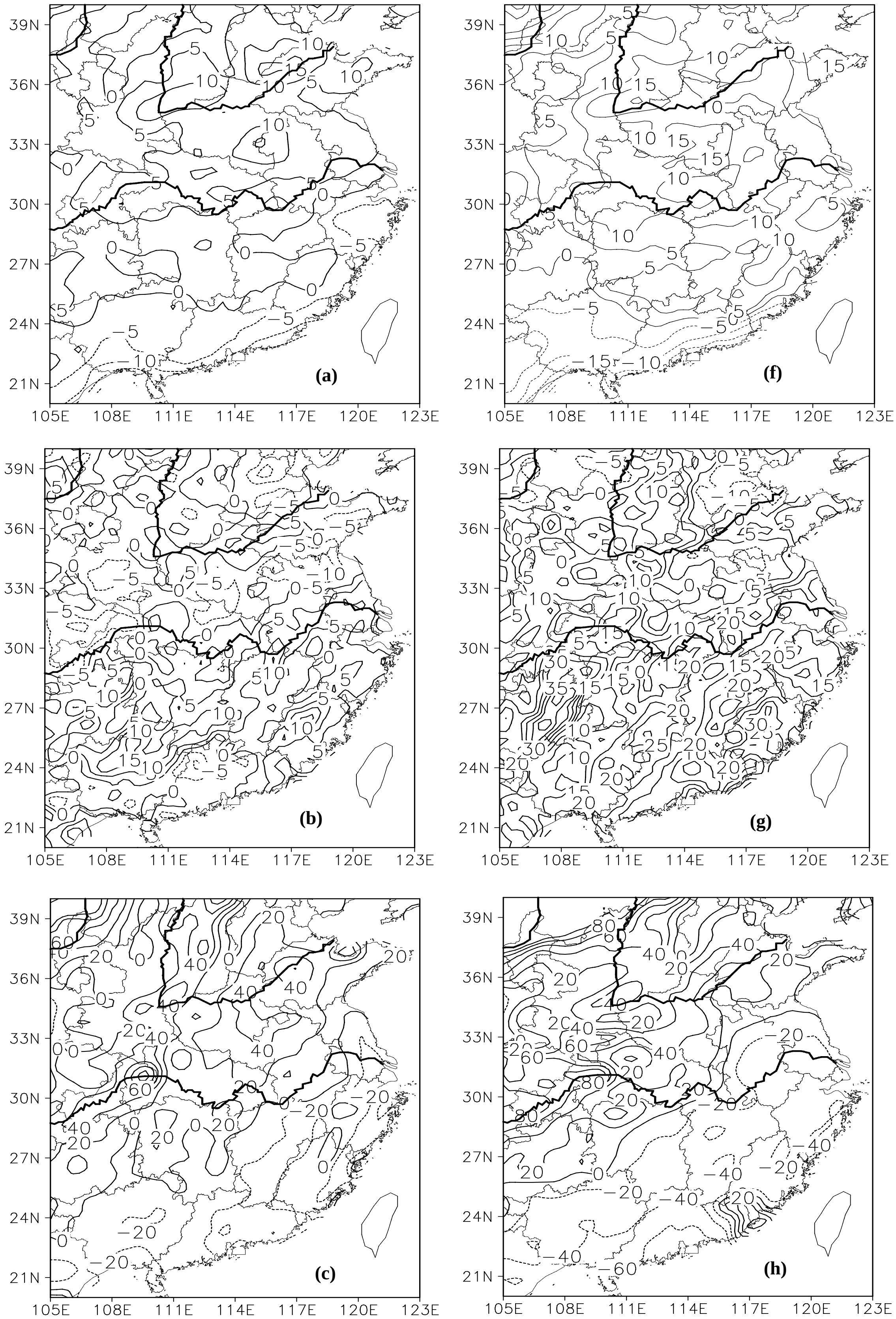
In Fig. 5a and Fig. 5f, the SDII variations indicate that, except for a small area of the southern coast, the large-area precipitation in eastern China will be enhanced during both of the future 30-year periods, and this enhancement will be more significant near the end of the 21st century. At the end of the 21st century, the SDII variation is relatively enhanced (10%) in the middle and lower reaches of the Yangtze River, and the magnitude of enhancement is most distinct (15%) in northern China, which likely indicates that the precipitation rates in northern China, especially heavy precipitation events, will increase significantly in the future.

In Fig. 5b and 5g, the CDD variations indicate that future droughts in northern China will not change significantly from the present and might even become wet. The droughts will decrease by a maximum of 10% and the CDD will increase in the middle and lower reaches of the Yangtze River and southern China. In particular, the maximum magnitude of CDD enhancement in the area to the south of the Yangtze River will approach 30% at the end of the 21st century, which indicates that the sustained drought in northern China will be reduced in the future and will be enhanced in southern China.

Figure 5c and 5h show the R10 variation characteristics. The R10 enhancement was most significant in the Shaanxi, Hubei, and Henan provinces, where the increases will reach 60% in the middle of the 21st century and might approach 80% in the late 21st century. The R10 will increase in the entire northern China, with an average R10 above 30%. The R10 variation was not significant in the middle and lower reaches of the Yangtze River and might even decrease, which indicates that the R10 in northern China will increase significantly in the future.

The R5d is the most commonly used extreme precipitation index[34-35], and the R5d magnitude directly reflects the weather events in a certain area by the most serious flood disaster in one year. Fig. 5d and Fig. 5j indicate that in the middle and late 21st century the R5d will increase in China, and this increase will be relatively obvious in the middle and lower reaches of the Yangtze River and the areas to its north. The relative increase will reach 10% in the middle of the 21st century and 20% in the late 21st century. However, the forecast relative increase is not significant in the southern coastal areas, and the R5d might decrease in some areas.

The R95 (Fig. 5e and 5k) is expected to increase by 10%−15% in most areas during the middle of the 21st century, except for relative decreases (5%−10%) in Zhejiang, Jiangxi, and a small area of the southern coast; these increases should be relatively significant in the middle and lower reaches of the Yangtze River and the areas to its north. In the late 21st century, the R95 was forecast to increase in all of eastern China, especially in the areas of Zhejiang and Jiangxi; however, a decreased R95 is expected in a small area of the southern coast. R95 will increase by 20% in the middle and lower reaches of the Yangtze River and by >10% in the area south of the middle and lower reaches of the Yangtze River (relatively insignificant in the mid-21st century).



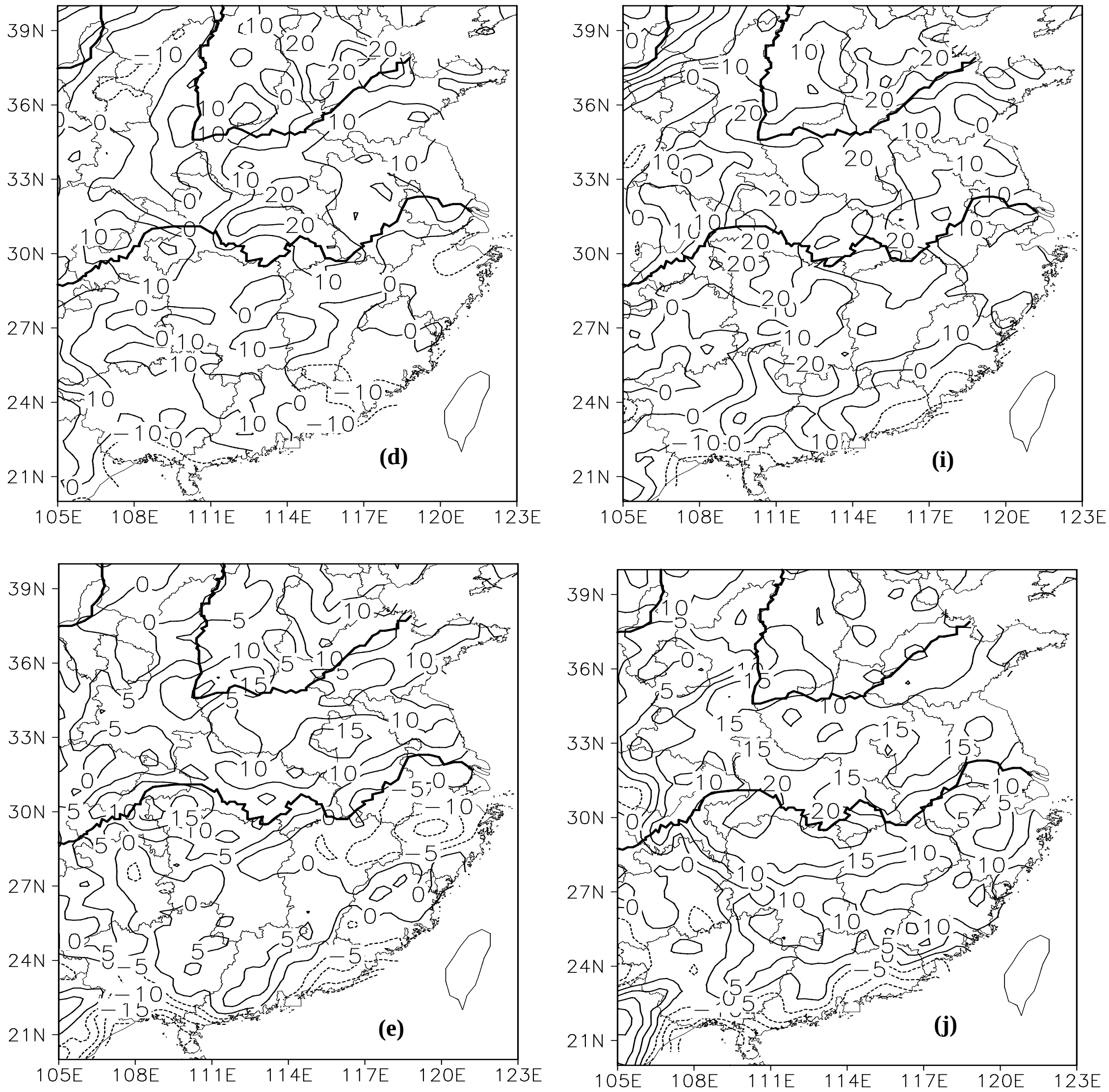


Figure 5. Percentages of relative change in SDII, CDD, R10, R5d, and R95 in the middle (a, b, c, d, e) and late (f, g, h, i, j) 21st century relative to the reference period of 1970-1999.

In summary, extreme precipitation rates in eastern China are likely to change systematically along with global warming, with expected relative increases in the middle and lower reaches of the Yangtze River and decreases in small areas of the southern coast. These changes will be more significant in the late 21st century relative to the middle of the 21st century.

5 CHARACTERISTICS OF EAST ASIAN MONSOON UNDER THE AIB SCENARIO

In China, seasonal distributions of atmospheric precipitation are very uneven (Fig. 2). Precipitation is concentrated mainly in the summer (June−August), which accounts for >50% of the total annual precipitation and the majority of the extreme precipitation events. Eastern China is located within the East Asian monsoon region, and the characteristics of precipitation variation are closely related to summer monsoon activity[36]. Next, we analyzed the characteristics of future summer monsoon in the middle and late 21st century, relative to the contemporary era, under the A1B scenario. Fig. 6 shows the variation in an average 850-hPa wind field in the middle and late 21st century, relative to the contemporary climate. We observed that under the scenario of global warming, East Asian summer monsoons will be significantly enhanced and form a meridional wind anomaly from the Yunnan-Guizhou Plateau to the middle and lower reaches of the Yangtze River up to northern China. As a result, the water vapor from the Indian Ocean and the South China Sea will be directly transported to the middle and lower reaches of the Yangtze River and the areas to its north, whereas the variations in the wind field over the southern coastal areas will not be distinct. The distribution of this wind field anomaly was very similar to the distribution of precipitation. We found that the future precipitation rates in the middle and lower reaches of the Yangtze River and the areas to its north were closely related to the summer monsoon anomaly in East Asia and that the enhancement and northward push were the main reasons for the increased precipitation. The causes of precipitation in East Asia are very complicated, and the relevant future changes in atmospheric circulation and subsequent influences on precipitation in eastern China will require in-depth studies.

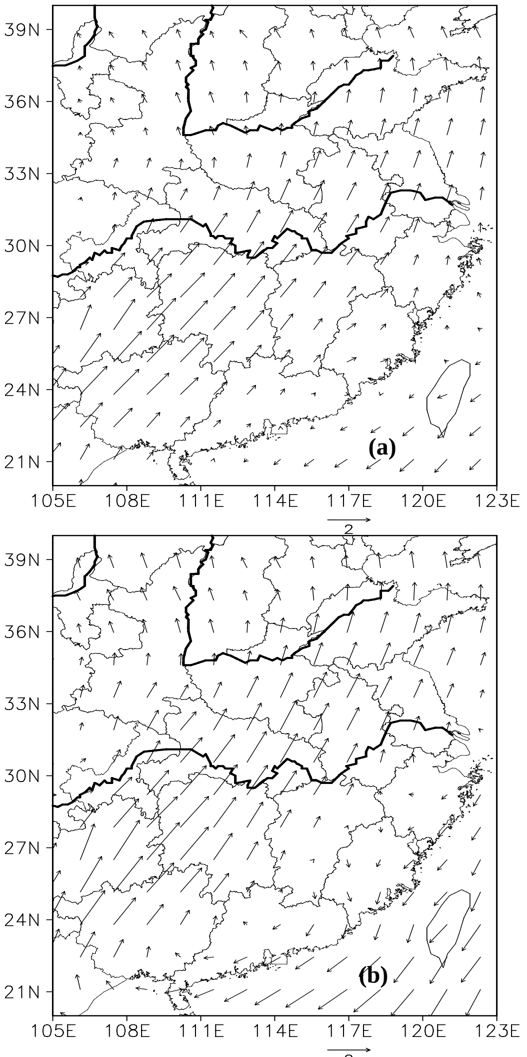


Figure 6. Differences of 850-hPa wind fields in the middle (a) and late (b) 21st century relative to the reference period of 1970-1999.

6 SUMMARY AND DISCUSSION

This study applied a one-way nested simulation to CCSM3-RegCM3 to analyze the characteristics of precipitation in eastern China in both current and future A1B scenarios. The main conclusions are as follows:

(1) We comparatively analyzed the simulation results from the 20C-RegCM model with regard to the average precipitation in the past 30 years, diurnal variations of precipitation, and the extreme precipitation index from CRU, CMAP, and 20CR-RegCM. The results revealed that CCSM3-RegCM3 considerably reflected the current spatial and temporal distributions of precipitation in eastern China and were essentially consistent with observational data. Meanwhile, the results also reproduced variations in the extreme precipitation indices and validated the reliability of the CCSM3 simulation results when used as the initial and boundary conditions of regional climate models to predict future climate change.

(2) Precipitation in eastern China underwent significant changes under the A1B scenario and generally increased in the middle and lower reaches of the Yangtze River and the areas to its north. Precipitation increased mainly in the spring and summer seasons and decreased relatively in the southern coastal areas. Precipitation variations were more distinct in the late rather than the middle 21st century, a finding that was consistent with the results of previous studies.

(3) Eastern China experienced systemic variations in extreme precipitation under the A1B scenario. The SDII, R10, R5d, and R95 all showed increasing trends in the future that were most distinct in the middle and lower reaches of the Yangtze River and areas to its north and were insignificant or decreased in the southern areas. Correspondingly, the longest period of time without precipitation decreased in the north and increased in the south. We found that under the A1B scenario, the extreme precipitation events in eastern China would increase over large areas in the middle and lower reaches of the Yangtze River and the areas to its north and relatively decrease in the southern areas; these changes were especially dramatic at the end of the 21st century.

(4) The analysis of relative variations in the average summer 850-hPa wind field in the middle and late 21st century under the A1B scenario indicated that, as the climate becomes warmer, the East Asian summer monsoon will be enhanced and advance toward northern China. In particular, the southwesterly air stream will increase significantly and carry abundant water vapor into the middle and lower reaches of the Yangtze River and the areas to its north, causing the precipitation levels to increase significantly.

The current popular approach is to use the ensemble average of multiple atmospheric circulation models to predict future climate change; however, this approach remains inadequate in some aspects. First, the error of single models might affect the overall result; second, the ensemble average of multiple models might smooth out certain extreme climate events. This study only used a one-way nested simulation with the Community Climate System Model (CCSM3) and Regional Climate Model (RegCM3) and analyzed the characteristics of future precipitation in eastern China under the A1B scenario. There were still significant errors in the simulation results. On one hand, in future studies the selection and validation of global atmospheric circulation models should be strengthened to improve the ability to simulate large-scale climate change; on the other hand, it remains necessary to improve the accuracy of climate change simulations in China with RegCM3. Meanwhile, it is desirable to compare observational data with other simulation results in order to understand the uncertainty in simulations of precipitation variation in China.

REFERENCES:

[1] MANN M E, BRADLEY R S, HUGHES M K. Northern hemisphere temperatures during past millennium: Inferences, uncertainties and limitations [J]. Geophys. Res. Letts., 1999, 26: 759-762.

[2] BRADLEY R. 1000 years of climate change [J]. Science, 2000, 288: 1353-1354.

[3] JONES P D, OSBORN T J, BRIFFA K R. The evolution of climate over the last Millennium [J]. Science, 2001, 292: 662-667.

[4] WANG Shao-wu, XIE Zhi-hui, CAI Jing-ning, et al. Study on the changes of average global temperature during the last millenary [J]. Prog. Nat. Sci., 2002, 12 (11): 1145-1149.

[5] IPCC, Summary for Policymakers [M]// Climate 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, SOLOMON S D, QIN M. MANNING Z, et al., Cambridge; Cambridge University Press, 2007.

[6] HULME M, ZHAO Z C, JIANG T. Recent and future climate change in East Asia [J]. Int. J. Climatol., 1994, 14: 637-658.

[7] HU Z Z, YANG S, WU R. Long-term climate variations in China and global warming signals [J]. J. Geophys Res., 2003, 108 (D19): 4614, doi:10.1029/2003JD003651.

[8] JIANG Da-bang, WANG Hui-jun, LANG Xian-mei. East Asian climate change trend under global warming background [J]. Chin. J. Geophysics, 2004: 47 (4): 580-596.

[9] JIANG Zhi-hong, ZHANG Xia, WANG Ji. Projection of climate change in China in the 21st century by IPCC-AR4 Models [J]. Geogr. Res., 2008 , 27(4): 787-799.

[10] SUN Ying, DING Yi-hui. Research on the East Asian summer monsoon precipitation and forecast the next hundred years [J]. Sci. China (D), 2009, 39 (11): 1487-1504.

[11] LI Qiao-ping, DING Yi-hui, DONG Wei-jie. Summer precipitation change over eastern China in future 30 years under SRES A2 scenario [J]. J. Appl. Meteor. Sci., 2008, 19(6): 770-780.

[12] LIU Xiao-dong, CHENG Zhi-gang, ZHANG Ran. The A1B scenario projection for climate change over the Tibetan Plateau in the next 30～50 years [J]. Plateau Meteor., 2009, 28(3): 475-484.

[13] KATO H, NISHIZAWA K, HIRAKUCHI H, et al. Performance of RegCM2.5/NCAR-CSM nested system for the simulation of climate change in East Asia caused by global warming [J]. J. Meteor. Soc. Japan, 2001, 79: 99-121.

[14] GAO Xue-jie, ZHAO Zong-ci, DING Yi-hui, et al. Climate change due to greenhouse effects in China as simulated by a regional climate model part II: climate change [J]. Acta Meteor. Sinica, 2003: 61(1): 29-38.

[15] FRICH P, ALEXANDER L V, DELLA-MARTA P, et al. Observed coherent changes in climatic extremes during the second half of the twentieth century [J]. Clim. Res., 2002, 19: 193-212.

[16] KHARIN V V, FRANCIS W Z. Estimating extremes in transient climate change simulations [J]. J. Climate, 2005, 18: 1156-1173.

[17] HUANG Rong-hui. Progresses in research on the formation mechanism and prediction theory of severe climatic disasters in China [J]. Adv. Earth Sci., 2006, 21 (6): 564-575.

[18] ALEXANDER L V, ZHANG X, PETERSON T C, et al. Global observed changes in daily climate extremes of temperature and precipitation [J]. J. Geophys. Res., 2006, 111 (d5): D05109.

[19] XIE Zhi-qing, JIANG Ai-jun, DING Yu-guo, et al. Spatial-temporal features of annual extremes of heavy precipitation processes in the Yangtze River Delta [J]. J. Nanjing Inst. Meteor., 2005, 28 (2): 267-274.

[20] MIAO Juan, LIN Zhen-shan. Study on the characteristics of the precipitation of nine regions in China and their physical causes II—The relations between the precipitation and physical l causes [J]. J. Trop. Meteor., 2004, 20(1): 64-72.

[21] JIANG Zhi-hong, YANG Jin-hu, ZHANG Qiang. Influence study on spring Indian ocean SSTA to summer extreme precipitation events over the eastern part of Northwest China [J]. J. Trop. Meteor., 2009, 25 (6): 641-648.

[22] ZHAI Pan-mao, ZHANG Xue-bin, WAN Hui, et al. Trends in total precipitation and frequency of daily precipitation extremes over China [J]. J. Climate, 2005, 18:1096-1108.

[23] HE Li, WU Yi-jin, DAN Chang-jun, et al. Impacts of global temperature changes in last century on drought and flood disasters in Yangtze River basin [J]. Chin. J. Agrometeor., 2007, 28 (4): 364-366.

[24] GAO Xue-jie, ZHAO Zong-ci, FILIPPO Giorgi. Changes of extreme events in regional climate simulations over East Asia [J]. Adv. Atmos. Sci., 2002, 19: 927-942.

[25] ZHANG Yong, XU Yin-long, DONG Wen-jie, et al. A future climate scenario of regional changes in extreme climate events over China using the PRECIS climate model [J]. Geophys. Res. Letts., 2006, 33, L24702, doi: 10.1029/2006GL027229.

[26] GAO Xue-jie, XU Ying, ZHAO Zong-ci, et al. Impacts of horizontal resolution and topography on the numerical simulation of East Asian precipitation [J]. Chin. J. Atmos. Sci., 2006, 30(2): 185-192.

[27] KUSUNOKI S, YOSHIMURA J, YOSHIMURA H, et al. Change of Baiu rain band in global warming projection by an atmospheric general circulation model with a 20-km grid size [J]. J. Meteor. Soc. Japan, 2006, 84: 581-611.

[28] MARIANA V, TONY C, TOM H, et al. CCSM3.0 User's Guide [M]. Boulder: National Center for Atmospheric Research, 2004.

[29] KIEHL J, TRENBERTH K. Earth's annual global mean energy budget [J]. Bull. Amer. Meteor. Soc., 1997, 78: 197-206.

[30] PAL J S, GIORGI F, BI X Q, et al. The ICTP RegCM3 and RegCNET. Regional climate modeling for the developing world [J]. Bull. Amer. Meteor. Soc., 2007, 88(9): 1395-1409.

[31] KIEHL J, HACK J, BONAN G, et al. Description of the ncar community climate model (ccm3) [R]. Technical Report, Boulder: National Center for Atmospheric Research (USA), 1996.

[32] FRICH P, ALEXANDER L V, DELLA-MARTA P, et al. Observed coherent changes in climatic extremes during the second half of the twentieth century [J]. Climate Res., 2002, 19: 193-212.

[33] JIANG Zhi-hong, CHEN Wei-lin, SONG Jie, et al. Projection and evaluation of the precipitation extremes indices over China based on seven IPCC AR4 coupled climate models [J]. Chin. J. Atmos. Sci., 2009, 33(1): 109-120.

[34] ZHANG Tian-yu, WANG Yong, CHENG Bing-yan, et al. Projection of maximum consecutive 5-day precipitation amount in Chongqing for the 21st century [J]. Adv. Climate Change Res., 2009, 5(3): 139-144.

[35] ZHANG Tian-yu, FAN Li, CHENG Bing-yan, et al. Variation of extreme precipitation index (maximum consecutive 5-day precipitation totals) in the three gorges during 1961-2007 and scenario projections [J]. Chin. J. Agrometeor., 2010, 31(2): 176-182.

[36] LI Xin-zhou, MA Zhu-guo, LIU Xiao-dong. Inter-decadal characteristics of aridification over northern China in association with variations of the atmospheric circulation during the last fifty years [J]. Chin. J. Atmos. Sci., 2006, 30(2): 277-284.

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