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Prediction of summer precipitation change in the middle 21st century (2021-2050) of Qinghai-Tibet Plateau based on the MPI-ESM-MR/RegCM4 Model

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Abstract. The Regional Climate Model RegCM4.5 driven by the MPI-ESM-MR was used to predict the summer precipitation over the Qinghai-Tibet Plateau in the middle of the 21st century (2021-2050) under the RCP4.5 and RCP8.5 scenarios. Results showed that under the RCP4.5 and RCP8.5 scenarios, the average annual summer precipitation in the southeastern Qinghai-Tibet Plateau and the Qilian Mountains increased significantly, while the western Qinghai-Tibet Plateau decreased significantly, and the interannual variation trend of the summer precipitation was not significant. In the future, the summer precipitation over the Qinghai-Tibet Plateau has significant diurnal variation patterns and spatial differences between east and west regions. Specifically, summer precipitation decreases during daytime, while it increases slightly during night, especially in the eastern Qinghai-Tibet Plateau. At the same time, the increase in the probability of precipitation intensity above 10mm/day in the eastern of the Qinghai-Tibet Plateau means that the probability of extreme precipitation in the future may increase, while the precipitation intensity below 10mm/day is slightly reduced.

1. Introduction

It is well known that global and regional climates are constantly changing under the influence of complex natural and human factors. As one of the most sensitive areas of global climate change, the Qinghai-Tibet Plateau has experienced significant climate warming since the mid-1950s (Liu and Chen, 2000; Wang et al, 2008; Guo and Wang, 2012), and the warming trend ratio was much stronger than the northern hemisphere and other regions of the same latitude (Liu and Chen, 2000). Most of Asia's river systems, such as the Yangtze River, the Yellow River, the Yarlung Zangbo River, the Indus River, the



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Lancang-Mekong River and the Ganges River, all have their sources supporting the water use of 20% of the world's population (Xu et al., 2008). The Qinghai-Tibet Plateau plays an important role in the Asian water cycle and is often referred to as the “Asian Water Tower” (Xu et al. 2008; Wu et al., 2012; Xu et al., 2013). Therefore, research on the changes of the water cycle process on the Qinghai-Tibet Plateau has received extensive attention.

As one of the most important components of the energy and water cycle on the Qinghai-Tibet Plateau, precipitation plays an important role in the regulation of the climate system. Atmospheric precipitation determines the dry and wet conditions directly on the land surface, which in turn affects the thermal state and the Asian monsoon (Wu and Qian, 2003). Also, as the most critical atmospheric input to land surface hydrological systems, precipitation has a large impact on the hydrological processes of land surface models (Decharme and Douville, 2006; Tong et al., 2014). Therefore, the scientific understanding of the temporal and spatial variation characteristics of precipitation and the prediction of future changes in precipitation are urgent needs for research and management of water resources in Asia, and also for the study of land surface ecosystems and hydrological processes.

However, the precipitation on the Tibetan Plateau is mainly concentrated in summer and is caused by various precipitation mechanisms. Therefore, it is challenging to accurately estimate and predict the precipitation variation on the Qinghai-Tibet Plateau (Giorgi and Mariucci, 1996; Feng and Fu, 2006; Nan et al., 2009; Yao et al., 2013). At the same time, the observation data on the Qinghai-Tibet Plateau is limited and the spatial distribution of the meteorology station is uneven, it is very difficult to study the precipitation variation on the Qinghai-Tibet Plateau using observation data. Compared with GCMs, the regional climate models can better describe the mesoscale processes and complex topographies, have been widely used as effective tools for analyzing regional climate change characteristics and their mechanisms (Caya and Biner, 2004; Gao et al., 2011; Giorgi et al., 2012; Matthes et al., 2012; Wang et al., 2013). Many researchers have used GCMs and RCMs to estimate the future precipitation of the Qinghai-Tibet Plateau under RCPs, also the characteristics of future precipitation variation were analyzed (Liu et al., 2009; Wang et al. 2013; Yang et al., 2013; Hu et al. 2015; Zhang et al., 2015; Yang et al., 2017). However, these studies were focused primarily on the quantitative assessment and prediction of seasonal and monthly precipitation over the Qinghai-Tibet Plateau. The annual scale analysis can obtain the hydrological effects of climate change in different periods, while the seasonal and monthly scale analysis is of great significance for the rational distribution of water resources during the year. More importantly, the effective management of water resources and the prevention of disasters (e.g., urban waterlogging, dam breaks, droughts, floods) require further understanding and estimation of precipitation characteristics on the scales of hourly, daily, monthly and seasonal, especially small-scale features.

To this end, this paper uses the regional climate model (RegCM4) to study the seasonal and daily precipitation type's variation in the middle of this century (2021-2050) on the Qinghai-Tibet Plateau in the two RCP scenarios, hoping to provide reference for scientific assessment of the environment change on the Qinghai-Tibet Plateau.

2. Model, materials and methods

2.1. Model and experimental design

RegCM4 is a regional climate model developed and improved by the International Center for Theoretical Physics from RegCM3, which is widely used in regional climate simulation and prediction studies (Giorgi et al., 2012; Giorgi and Anyah, 2012). The simulation domain is consistent with CORDEX-EA (The East Asia domain in phase II of the International Coordinated Regional Climate Downscaling Experiment) (Giorgi et al., 2009) with a horizontal resolution of 50 km and 18 layers in the vertical direction. The parameter configuration used in the experimental includes the radiation package from the NCAR Community Climate Model CCM3 (Kiehl et al., 1996), the Biosphere-Atmosphere Transfer Scheme (BATs, Dickinson et al., 1993), and the Zeng ocean flux parameterization (Zeng et al, 1998), the Holtslag planetary boundary layer scheme (Holtslag et al, 1990) and the Grell convection scheme

based on the Arakawa-Schubert closure assumption (Grell, 1993). The initial and boundary condition for the experiment were derived from the test results of historical test and the prediction experiments in RCP4.5 and RCP8.5 scenario, which was submitted by the Max Planck Institute of MPI-ESM-MR in Germany to CMIP5 (Marsland et al., 2003; Raddatz et al., 2007). The buffer was 20 grid points, and the integration time step is 60 seconds. The RegCM4 was used for analysis from 1971 to 2000 (current) and 2021 to 2050 (future) under the RCP4.5 and RCP8.5 scenarios. In order to eliminate the systematic error of the model simulation in future variation prediction, the prediction results were compared with the current results to obtain future climate change. Figure 1 the study area and topography.

2.2. Materials and methods

The CN05 data was prepared by Wu Jia et al. (2013) based on the observation data from more than 2,000 meteorological stations in China, and the dataset has been widely used in simulation performance evaluation of regional climate models for China and analysis of other climate change characteristics (Gao et al., 2017; Shi et al., 2018; Wang et al., 2018). The CRU data was compiled by the Climate Research Institute of the University of East Anglia based on data from several meteorological observation databases with a resolution of $0.5^{\circ} \times 0.5^{\circ}$ (Mitchell and Jones, 2005). In this analysis, the output of RegCM4 and CRU data were interpolated to $0.5^{\circ} \times 0.5^{\circ}$ grid the same as CN05 for subsequent comparative analysis. The non-parametric Mann-Kendall method (Mann, 1945; Kendall, 1975) was used to analyze the temporal variation trend of hydro meteorological parameters, and the statistical significance of the trends was detected according to the Mann-Kendall test with a 95% confidence level. This method is considered to be a simple and effective method in climate change analysis, which is widely used in the analysis of time series data of hydrological.

3. Results

3.1. Historical experimental results test

Figure 1 shows the spatial patterns of summer precipitation (Fig.1a, c and d) and corresponding percentage biases (Fig.1c, e) from observation data (CN05 and CRU) and RG_MPI for the period of 1971-2000. According to CN05 (Fig. 1b), the summer precipitation on the Tibetan Plateau decreased gradually from southeast to northwest, and the precipitation center was concentrated in the southeast. There was a significant difference between CRU and CN05 in the spatial pattern of precipitation, for example, the precipitation center in the southern part of the Qinghai-Tibet Plateau observed in the CRU does not exist in CN05 (Fig. 1d). As shown in Figure 1a, The RG_MPI has a certain simulation ability for the actual spatial distribution of precipitation and can capture its key spatial features. According to the simulation results of RG_MPI, the eastern and southern part of the Qinghai-Tibet Plateau had abundant precipitation, while the Qaidam Basin and other regions had rare precipitation, which is consistent with the two observations. However, compared with the two observations, RG_MPI overestimated summer precipitation significantly. Figure 1c and Figure 1e showed the precipitation biases between RG_MPI and the two groups of observations. It can be found that precipitation overestimation mainly occurred in the northern Qinghai-Tibet plateau, and there was an underestimation of summer precipitation in the southern Qinghai-Tibet plateau. Overestimation in North and underestimation in South of precipitation are consistent with Wang's (Wang et al. 2013; Wang et al. 2015) simulation results under RegCM in the Qinghai-Tibet Plateau.

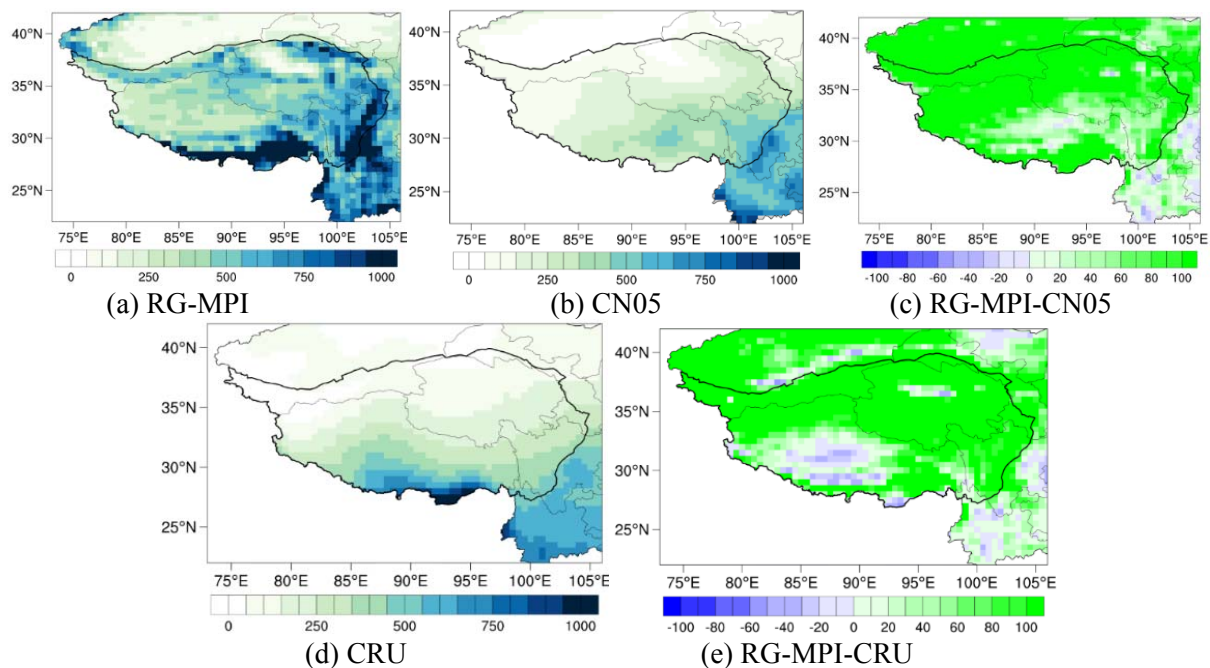


Figure 1. Spatial distribution of observed and simulated summer total precipitation (unit: mm/day) during 1971-2000 over the Qinghai-Tibetan Plateau along with the corresponding percentage biases [unit: %; defined as (simulation - observation) $\times$ 100/observation] (a RG_MPI; b CN05; d CRU; c biases between RG_MPI and CN05, e biases between RG_MPI and CRU).

3.2. Summer precipitation forecasting of Qinghai-Tibet Plateau under two RCPs scenarios

3.2.1. Climate mean state and Trend forecasting. Figure 2 shows the multi-year average variation and corresponding percentage change of the future (2021-2050) summer precipitation in the Qinghai-Tibet Plateau under the RCP4.5 and RCP8.5 scenarios compared with the current period (1971-2000). In the RCP4.5 and RCP8.5 scenarios, the multi-year average summer precipitation in the southeastern of the Qinghai-Tibet had increased, while it decreased in the northwestern of Qinghai-Tibet Plateau (Fig. 2a, 2b). The center of areas with increased precipitation located in the northwest corner of Sichuan Province, with an average increase of 1.5mm/day. The precipitation in eastern Tibet and the Qilian Mountains also increased by 1mm/day. Areas with reduced precipitation mainly located in the central and western Tibet and areas along the Kunlun Mountains, with a reduction of 0.5~1mm/day.

The precipitation variations on the Qinghai-Tibet Plateau showed obviously east-west and north-south differences (Fig. 2a, b), and the changes in precipitation in most of the central regions under RCP4.5 and RCP8.5 scenarios did not pass the significant test. In the RCP4.5 scenario, areas where precipitation changed significantly (positive or negative), were usually near the edge of the Qinghai-Tibet Plateau (Fig. 2a). In the RCP8.5 scenario, areas where precipitation changed significantly had increased, especially shown as the decrease in the western Qinghai-Tibet Plateau and the increase in the southeast Qinghai-Tibet Plateau (Figure 2b). Compared with the current period (1971-2000), the precipitation variation range was most between -30% and 30%, and the precipitation variation range in the RCP8.5 scenario was slightly larger than that in the RCP4.5 scenario (Fig. 2a, b).

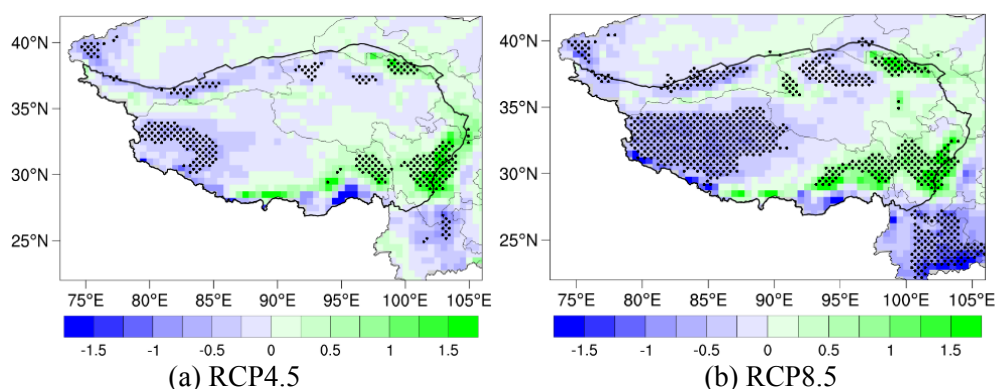


Figure 2. Average annual variation (unit: mm/day) of summer precipitation in the Qinghai-Tibet Plateau under the RCP4.5 and RCP8.5 scenarios compared with the current period (1971-2000). The black dots denote differences which are statistically significant at a significance level of 95% of student's t-test value.

Figure 3 shows the variation trends of summer precipitation in the RCP4.5 and RCP8.5 scenarios on the Qinghai-Tibet Plateau. Among them, the spatial pattern of summer precipitation variation trend (Fig. 3a) under the RCP4.5 scenario was similar to the summer precipitation variation (Fig. 2a). That is, in the eastern areas, the summer precipitation increased. Also the precipitation variation trend was mostly increased (0.1~0.15mm/year). On the contrary, in the western areas where precipitation was reduced, the precipitation variation trend was mostly reduced (-0.05~0.1mm/year). In the RCP8.5 scenario, we can also find that in the area with increasing average summer precipitation over the Qilian Mountains (Fig. 2b), the precipitation trend was also increased (Fig. 3b). The precipitation variability in the southern margin of the Qinghai-Tibet Plateau exceeded -0.2 mm/day, but none of them passed the statistical significance test. In summary, the variation trends of summer precipitation under the RCP4.5 and RCP8.5 scenarios passed a significant test only in a few regions, and the precipitation variability was all small.

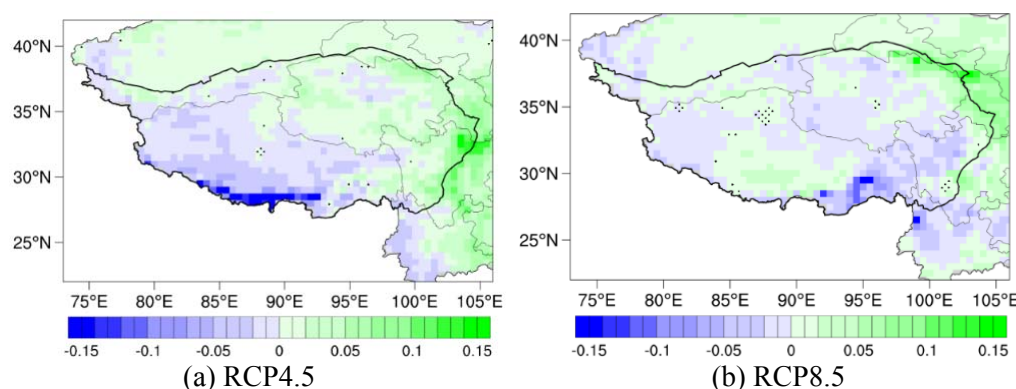


Figure 3. Interannual trend of summer precipitation (unit: mm/year) during 2021-2050 over the Qinghai-Tibetan Plateau projected by RegCM4 model with different RCPs. The black dots denote trend which are statistically significant at a significance level of 95%.

3.2.2. Estimation of hourly precipitation changes. Due to the obvious spatial difference of precipitation changes on the Qinghai-Tibet Plateau, we divided the Qinghai-Tibet Plateau into three areas to further analyse the hourly variation characteristics of precipitation in different areas, which were the eastern areas (96°E~105°E; 30°N ~34°N), the middle areas (92°E ~ 101°E; 33.5°N ~ 38°N) and the west areas(85°E ~ 95°E; 29°N ~ 33.5°N). Among them, the eastern areas (eastern Tibet and northwestern

Sichuan) and the western areas (western central Tibet) were areas where precipitation increases and decreases, respectively.

Figure 4 shows the multi-year average hourly variation (Figure 4a-c) in the eastern, central and western areas of the Tibetan Plateau between 1971 to 2000 and 2021 to 2050 (RCP 4.5, RCP 8.5). The hourly precipitation processes in the central and western parts of the Qinghai-Tibet Plateau were more consistent, while the simulated precipitation in night of the eastern areas was 0.5 mm/day higher than that in the central and western areas. In the future precipitation changes under RCP4.5 and RCP8.5 scenarios, we can see that the variation of the future precipitation in the eastern (Fig. 4a) was significantly different from that in the middle areas (Fig. 4b) and the western areas (Fig. 4c).

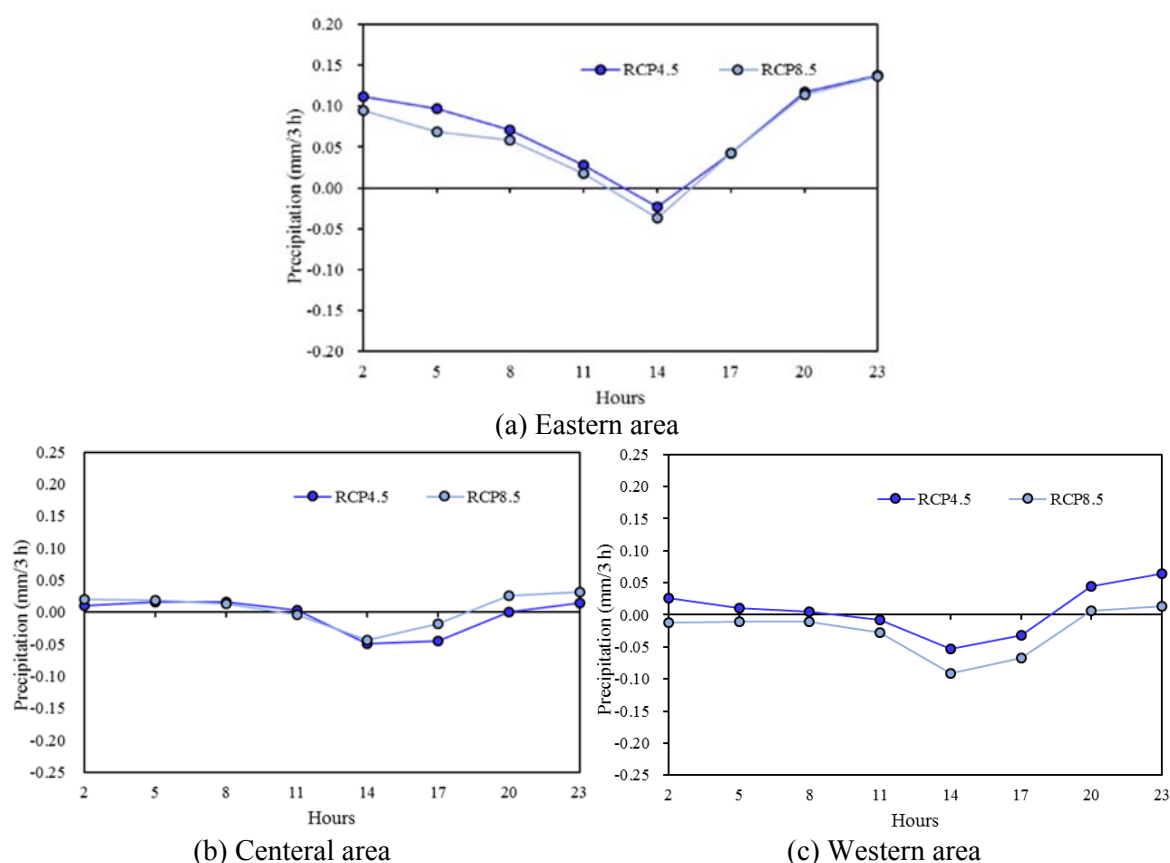


Figure 4. Domain-averaged diurnal cycle change over the period 2021-2050 for summer total precipitation (an eastern area, b central area, c western area; unit: mm/3h) under the two RCP scenarios, compared with 1971-2000.

For hourly precipitation in the eastern areas, besides a slightly decrease in 14:00, it increased during the rest period, with the maximum rate of 0.14mm/3h (23:00 at night). A similar situation existed in the central areas, but the variation degree was much smaller than that in the eastern areas. The maximum increase rate of precipitation in the central areas was only 0.02mm/3h, and the reduction rate was only 0.05mm/3h. In the western areas of the Qinghai-Tibet Plateau, hourly precipitation was mainly presented as the reduction during daytime, especially in the RCP8.5 scenario, with a maximum reduction of 0.12 mm/3 h (14:00).

Figure 5 shows the probability density distribution of average summer precipitation intensity in the eastern, central and western regions of the Qinghai-Tibet Plateau. According to Figure 5, the probability distributions of precipitation intensity in the eastern, central and western parts of the Qinghai-Tibet Plateau from 1971 to 2000 were quite different. Especially in the eastern region, about 30% of

precipitation comes from precipitation above 10mm/day, while less than 10% in the central and western regions. The precipitation intensity with the highest probability of occurrence in the eastern Qinghai-Tibet Plateau was 4~7mm/day. The precipitation with the highest probability of occurrence in the central and western regions is 2~4mm/day, accounting for 25%~40% of the total precipitation, showed strong concentration characteristics.

Under the RCP4.5 and RCP8.5 scenarios, the probability of precipitation intensity below 10 mm/day in the east was slightly reduced, while the probability of precipitation intensity above 10 mm/day was increased. Similar changes were not evident in the central and western parts of the Tibetan Plateau. The increase in precipitation intensity above 10 mm/day in the eastern part of the Qinghai-Tibet Plateau also means that the probability of extreme precipitation may increase in the future.

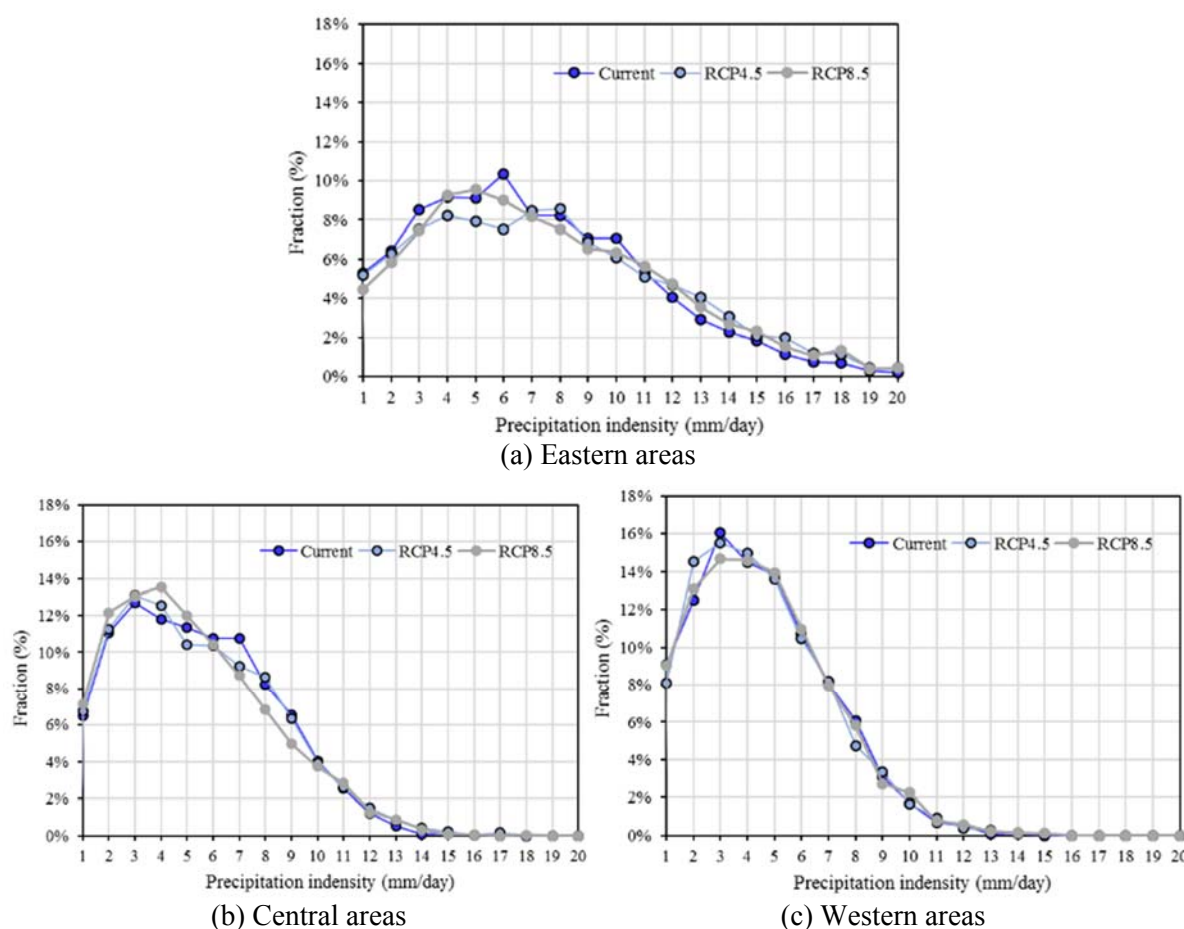


Figure 5. The probability density function (PDF) distribution of daily summer precipitation over the eastern Qinghai-Tibetan Plateau (a), central Qinghai-Tibetan Plateau (b) and western Qinghai-Tibetan Plateau (c) during 1971-2000 and 2021-2050 simulated by RegCM4 model.

4. Conclusion

This paper used the RegCM4 model to dynamically downscale the prediction results of the MPI-ESM-MR global model under the RCP4.5 and RCP8.5 scenarios, characteristics of summer precipitation changes of Qinghai-Tibet Plateau region in the 21st century (2021-2050) relative to 1971-2000 were analyzed. The main conclusions are summarized as follows:

(1) The results of RegCM4 historical test showed that the RegCM4 can simulate the spatial distribution pattern and the characteristics of the annual circulation of the main precipitation over the Qinghai-Tibet Plateau, which is helpful for analyzing the spatial variation pattern of future precipitation.

However, there are significant deviations in the simulation of precipitation, especially in the north, where precipitation was overestimated, while in the south was underestimated.

(2) The simulation results of the RCPs showed that there was a large spatial difference in the future summer precipitation changes over the Qinghai-Tibet Plateau, and this spatial change was more pronounced in the RCP8.5 scenario. There was a significant increase in the total amount of summer precipitation in the eastern part of the Qinghai-Tibet Plateau, including the north-western corner of Sichuan and eastern Tibet. In the western Tibet, the total precipitation in the Kunlun Mountains and the Qaidam Basin decreased significantly, with the rate of $-0.1\text{mm/year} \sim 0.1\text{mm/year}$.

(3) The simulation results of the RCPs showed that there were obvious diurnal variations and spatial differences in the future hourly precipitation, shown as the night-time precipitation was mainly increased, and daytime precipitation was mainly reduced. The increase of daytime precipitation in the eastern part of the Qinghai-Tibet Plateau was higher than that in the central and western regions, and the precipitation with intensity above 10mm/day was obviously increased, which means the risk of extreme precipitation in the future is increasing.

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