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High-resolution precipitation simulation with WRF for the Three-River Headwaters region in China

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Abstract. The Three-River Headwater Region (TRHR), also known as China “Water Tower”. It is a sensitive region to climate change and plays a critical role in the hydrology circulation and ecological conservation of the Tibet Plateau. Climate change are greatly impacting the climate of this region. However, there exists large biases in the precipitation simulation for this region. In this study, we explored the impact of resolution and physical schemes on precipitation simulation over the TRHR. The results show that a high resolution is necessary for the precipitation modelling over the TRHR with a complex terrain. The precipitation modelling over the TRHR are sensitive to microphysics schemes and cumulus schemes. The microphysics scheme mainly determines the magnitude of simulated precipitation over the TRHR. The cumulus schemes largely influence the spatial distribution of simulated precipitation over the TRHR. Based on the sensitivity tests, we proposed an optimized combination of parameterization schemes that can remarkably improve the accuracy of simulated precipitation over the TRHR. This study is helpful to understand the mechanism of precipitation formation over the TRHR.

1. Introduction

The Three-River Headwaters Region (TRHR) is the source of the Yangtze River, Yellow River and Lancang River, located at the Tibet Plateau, which is known as China “Water Tower”. As a sensitive area affected by global climate change, the TRHR has undergone substantial changes in its ecological environment in recent years, which poses a threat to the river source safety and ecological sustainable development of this region. However, it is difficult to assess the impact caused by climate change, because the complex topography and lack of observation from meteorological stations in the TRHR. Climate model provides a useful way to conduct research associated with climate change in the TRHR.

Climate model, including General Circulation Model (GCM) and Regional Climate Model (RCM), is a key tool to explore the environmental effect induced by climate change. The coarse resolution in GCM could not detailly describe characteristics of underlying surface, which limits its capacity of



studying regional climate. This limitation of GCM can be largely resolved by downscaling technique [1]. The downscaling technique uses output from GCM as input to obtain high resolution climate information [2]. The downscaling technique includes statistical downscaling and dynamical downscaling. Statistical downscaling approach downscales GCM output to a specific observation station based on the historical statistics, without massive computation, and is comparatively simple. However, the historic period used to establish the statistical relationship could not fully characterize the unprecedented cases [3]. In contrast to statistical downscaling approach, dynamical downscaling approach is built on RCM with boundary conditions from GCM. That is, climate information with high resolution is generated through numerical integration in RCM. Thus, dynamical downscaling with mathematical and physical foundation is more physical than statistical downscaling [1].

The ultimate goal of this study is to assess the impact of climate change on regional hydrological processes. It is reasonable to utilize dynamical downscaling to conduct research in the TRHR. Previous studies have shown that the Weather Research Forecasting model (WRF) is capable to simulate climate processes in Tibet Plateau [4-6]. Moreover, this model provides sufficient physical schemes. In a word, it is better to choose WRF model as dynamical downscaling to perform this study.

Precipitation is the main meteorological factor that characterizes climate change impact. Understanding the mechanism of evolution of precipitation is of great importance to address the climate change crisis and other related hazards of the TRHR. However, there are large biases in the precipitation simulation over the TRHR to date [6-7]. In particular, it is not clear which factors restrain the accuracy of precipitation modelling. Therefore, it is necessary to evaluate the performance of physical schemes in WRF to simulate the regional climate over the TRHR.

This study aims to improve the ability of WRF to simulate climate over the TRHR, especially for precipitation. The scientific questions to address include: (1) Does an increase in model resolution improve the simulation of precipitation over the TRHR? (2) How sensitive is precipitation simulation over the TRHR to different physical schemes? Given these questions, this paper is organized as follows. In section 2, we introduce the study area and metrics to evaluate the simulations. Section 3 lists the experiment design and model configuration. Section 4 describes the influence of the resolution and physical schemes on precipitation simulations over the TRHR. Conclusions are included in section 5.

2. Materials and Methods

2.1. Materials

2.1.1. Study area. The study area, named Guoluo, is located at the eastern part of the TRHR and has an area of 76442 km² (96°58' E~101°50' E, 32°31' N~35°40' N), in which the Yellow River flows 760 km (Figure 1). This region has a typical Plateau continental climate. The annual mean temperature is -4.0 °C, and the mean temperature of the coldest month (December) is -12.1 °C. The annual rainfall is 400~700 mm with uneven spatial distribution. The northwest part of Guoluo is dry and cold with the annual rainfall of 395.2~435.8 mm, while the annual rainfall in the southeast is 655.8~759.8 mm. These statistics were calculated based on station observations from 1980 to 2020. The mean altitude of Guoluo is 4500 m, and the area with an altitude of 4000~5000 m accounts for about 80% of the entire Guoluo. The topography relief of northwest is with an elevation difference of 500~1000 m, while in southeast the altitude is between 3500~4000 m.

2.1.2. Simulation data. In this study, the ERA5 hourly reanalysis dataset was used to provide initial and boundary conditions for the WRF model. This dataset includes hourly data from 1979 to present [8-9]. Hourly data on pressure levels is divided into 37 layers in the vertical direction from 10-1000 hPa, with a horizontal resolution of 0.25° × 0.25°. These 3-dimensional variables include temperature, geopotential height, relative humidity, specific humidity and wind field. The 2-dimensional surface variables include 2m dewpoint temperature, 2m temperature, mean sea level pressure, sea surface

temperature, skin temperature, surface temperature, 10m wind field, 4 layers of soil temperature and volumetric soil water, land-sea mask and sea-ice cover, a total of 12 physical quantities [8-9].

We applied the China Meteorological Forcing Dataset (CMFD) to evaluate the quality of simulation. CMFD is a high spatial-temporal resolution gridded meteorological dataset [10]. The dataset was made through fusion of remote sensing products, reanalysis dataset and *in-situ* observation at national meteorological stations. It spans from January 1979 and keeps extending (currently up to December 2018) with a temporal resolution of 3 hours and a spatial resolution of $0.1^\circ \times 0.1^\circ$ [11]. For its high quality, this dataset has been widely used to assess the hydrometeorological modelling results across China [12-16].

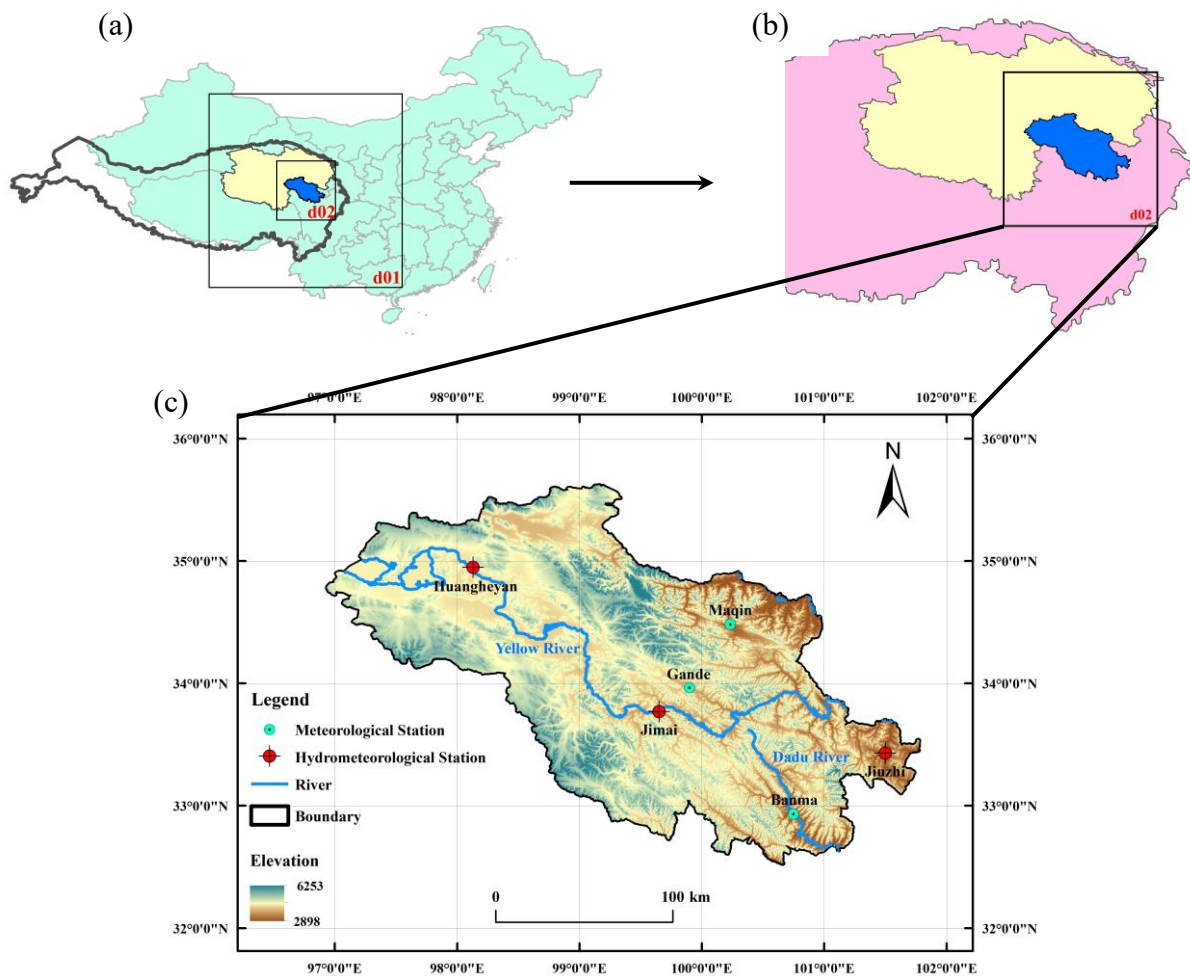


Figure 1. The location and domains of study area: (a) the location of Guoluo (blue) and Qinghai Province (yellow) in China, the boundary of domain 1 (d01) and domain 2 (d02) and Tibet Plateau (grey line); (b) the location of Guoluo in Tibet Plateau (pink); (c) the channels and hydrological/meteorological stations in Guoluo.

2.2. Methods

2.2.1. WRF model. The WRF model is a fully compressible non-static pattern and uses terrain following mass coordinates in the vertical direction, Arakawa-C grid points in the horizontal direction, and a Runge-Kutta algorithm for time integration. The Advanced Research WRF (ARW) modeling system is

designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms, which is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers. The ARW has been in development for the past few years, the current release is Version 3, available since April 2008. This study uses the Version 3.9.1.

2.2.2. Analysis and assessment methods. The pattern correlation coefficient (PCC) and root-mean-square error (RMSE) are used as metrics for model evaluation. The equations to calculate these two metrics are listed as follows:

$$\text{PCC} = \frac{\sum_{i=1}^n (s_i - \bar{s})(o_i - \bar{o})}{\sqrt{\frac{1}{n} \sum_{i=1}^n (s_i - \bar{s})^2} \sqrt{\frac{1}{n} \sum_{i=1}^n (o_i - \bar{o})^2}} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (s_i - o_i)^2} \quad (2)$$

where s_i is the simulated results for each step i , o_i is the observed value, n is the total number of time series. PCC quantifies the degree-of-fit of spatial distribution between simulation and observation, and RMSE measures the errors of simulated results apart from observation.

3. Experiment design and WRF configuration

3.1. Experiment design

To explore the effect of different horizontal resolutions on WRF simulation, we first conducted a group of simulations with 5 different resolution (i.e. 10 km, 15 km, 20 km, 25 km, 30 km). During this step, we would explicitly demonstrate and compare the results from different resolution. Then we determined a best resolution for precipitation simulation over the TRHR. Secondly, three series of tests were performed to clarify the sensitivity of WRF simulated precipitation to different kinds of parameterization schemes. We mainly focus on microphysics schemes, planetary boundary layer schemes, and cumulus schemes. Through these two steps, we attempted to find an optimized scheme setting of WRF that can largely improve the model performance over the TRHR.

3.2. WRF configuration

A non-nested simulation has been designed to determine the appropriate horizontal resolution. The domain used for this non-nested simulation is shown in Figure as d02. With Lambert Conformal projection, this domain centers at 34.0° N, 99.5° E. In addition, the projection center is 34.0° N, 99.5° E, the vertical direction adopts the mass terrain following coordinate system, the vertical layer is divided into 37 layers, and the pressure value of the top layer boundary is 50 hPa. The simulation period covers from August 1st, 2015 to the August 31th, 2015 and the time resolution of output is 1 h. The model setting of this non-nested simulation refers to that retrieved from previous study over the Tibet Plateau [12].

As the same basic configuration as non-nested simulation, we conducted a nested simulation to validate whether the accuracy improved. The nested domains are shown in Figure 1 (a). The domain center is at 34.0° N, 99.5° E. The outer domain has a horizontal resolution of 30km, with the parent grid ratio of 3 to the d02 (10 km). The grid points are 86 × 86 of d01, and 76 × 82 of d02. Additionally, the vertical layer is divided into 37 layers, and the pressure of the top layer boundary is 50 hPa. The simulation period covers from August 1st, 2015 to the August 31th, 2015.

We also conducted nested simulations to realize the sensitivity tests as mentioned in section 3.1. The domains for this nested simulation are shown in Figure 1 (a). The basic configuration of the sensitivity tests is same as nested simulation.

4. Results and discussions

4.1. The impact of horizontal resolution on the WRF precipitation simulation

In this study, we first investigated how the horizontal resolution affects precipitation simulation over the TRHR. Five resolutions (i.e., 10 km, 15 km, 20 km, 25 km, and 30 km) were selected to conduct WRF simulation. Finally, we found that the WRF with 10 km resolution shown the best simulation among these 5 resolutions. The comparison between 10 km simulation and CMFD observation is shown in Figure 2a and 2b, and the performance of others did not show here. This finding is consistent with previous studies [7] and indicates that a high resolution can describe the complex terrain in the Tibet Plateau. Although the spatial distribution of precipitation was adequately captured by the WRF with a PCC of 0.85, the model systematically overestimated the precipitation with a RMSE of 169 mm/month. This large bias is also shown by Figure 2c. As we can see, the main reason for this undesirable result attributes to the strong disturbance from the boundary. To reduce the disturbance, it is necessary to run the WRF model with nested domain.

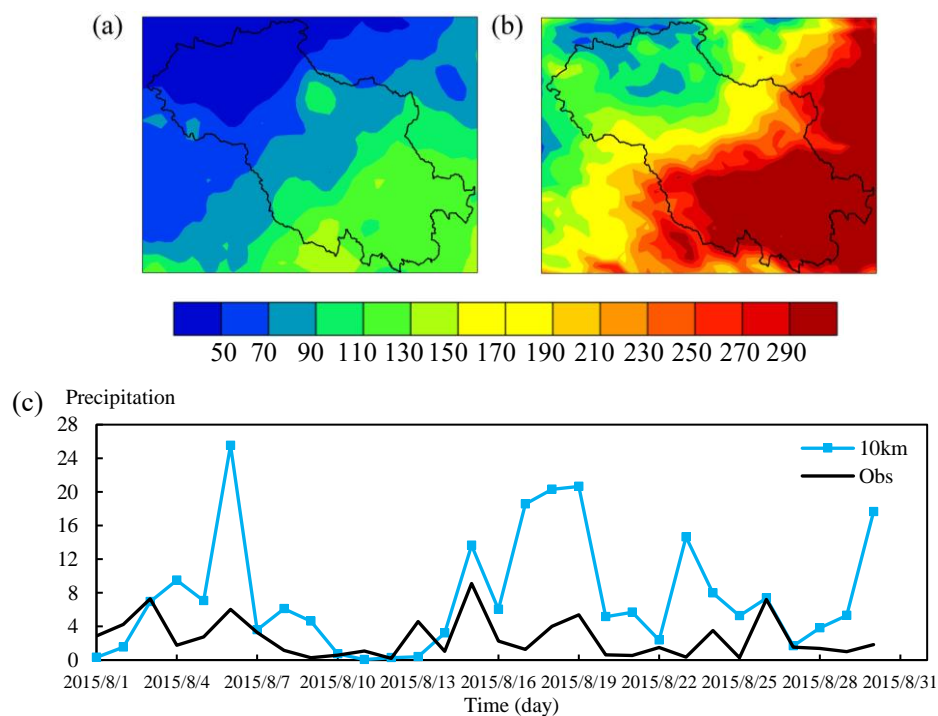


Figure 2. Comparison of precipitation WRF simulation and CMFD observation: (a) the spatial distribution simulation of CMFD; (b) the spatial distribution simulation of 10 km horizontal resolution; (c) the comparison of precipitation temporal variation (Unit: mm).

4.2. Precipitation modeling with nested domain

Considering the large bias from the single domain, we then set up a nested domain to conduct the simulation. More details about the configuration have been mentioned in Section 3.2. The result of nested domain was shown in Figure 3c. Compared to the single domain (Figure 3b), the nested domain remarkably improved the accuracy of precipitation simulation with a PCC of 0.88 and a RMSE of 75 mm/month. That is, the nested simulation efficiently prevents the propagation of boundary disturbances into the study area. Our finding highlights the importance of nested simulation for area within the Tibet Plateau. Nevertheless, there still exists large bias in the precipitation simulation as shown in the Figure 3d. In order to make further improvement in precipitation simulation over the TRHR, we need to understand the sensitivity of simulated precipitation to different physical schemes in the WRF model.

4.3. The sensitivity of precipitation modelling to WRF physical schemes

With the aim to get an optimized combination to represent the precipitation over the TRHR, we continued to investigate the influence of different physical schemes on precipitation simulation. The microphysics schemes, planetary boundary layer schemes, and cumulus schemes are three kinds of parameterizations that can affect the precipitation simulation [5, 7, 17-18]. Thus, our sensitivity tests focus on these three categories. On the basis of model setting mentioned in section 3.2, we conducted three groups of tests. These groups consist of 5 microphysics schemes (mp_physics), 5 planetary boundary layer schemes (pbl_physics), and 5 cumulus convection schemes (cu_physics) as listed in Table 1.

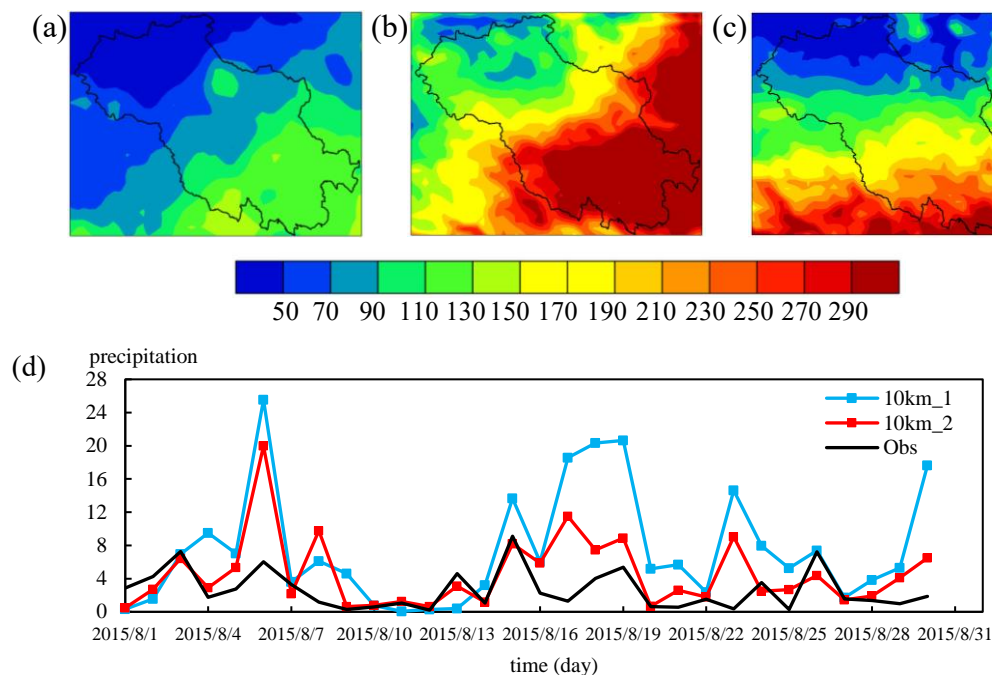


Figure 3. The comparison of nested and non-nested precipitation simulation: (a) the CMFD observation; (b) the simulation result of non-nested precipitation spatial distribution (10km_1); (c) the simulation result of nested precipitation spatial distribution (10km_2); (d) the comparison of temporal variation (Unit: mm).

Table 1. Parameters sensitivity calibration trial scheme.

Group 1	mp_physics	Kessler	Lin	WSM 5	CAM 5.1	SBU_YLin
Group 2	pbl_physics	YSU	Eta	MYNN 2.5	Pleim	UW
Group 3	cu_physics	KF	BMJ	GF	G3	Zhang-McFarlane

We first tested the WRF sensitivity to microphysics. The simulations of the 5 mp_physics are shown in Figure 4, the PCC and RMSE are shown in Table 2. It is obvious that the magnitude of precipitation is sensitive to microphysics, as the RMSE ranges from 27.62 mm/month to 78.71 mm/month. Among these microphysic schemes, the WSM 5 had the best performance (Figure 4b), whereas the Kessler brought the worst simulation that the simulated precipitation is nearly zero (Figure 4c and 4g). In a word, the microphysic scheme plays important role to determine the amount of simulated precipitation over the TRHR.

We followed tests about the WRF sensitivity to pbl_physics schemes. However, there is just slight difference among the 5 selected pbl_physics schemes (Figures not shown). Therefore, we concluded that the selection of pbl_physics schemes could not affect the ability of WRF to represent precipitation over the TRHR.

Table 2. PCC and RMSE of 5 different mp_physics simulations.

mp_physics	WSM 5	Kessler	Lin	CAM 2.5	SBU_YLin
PCC	0.93	0.54	0.92	0.88	0.91
RMSE	27.62	78.71	57.93	55.75	73.25

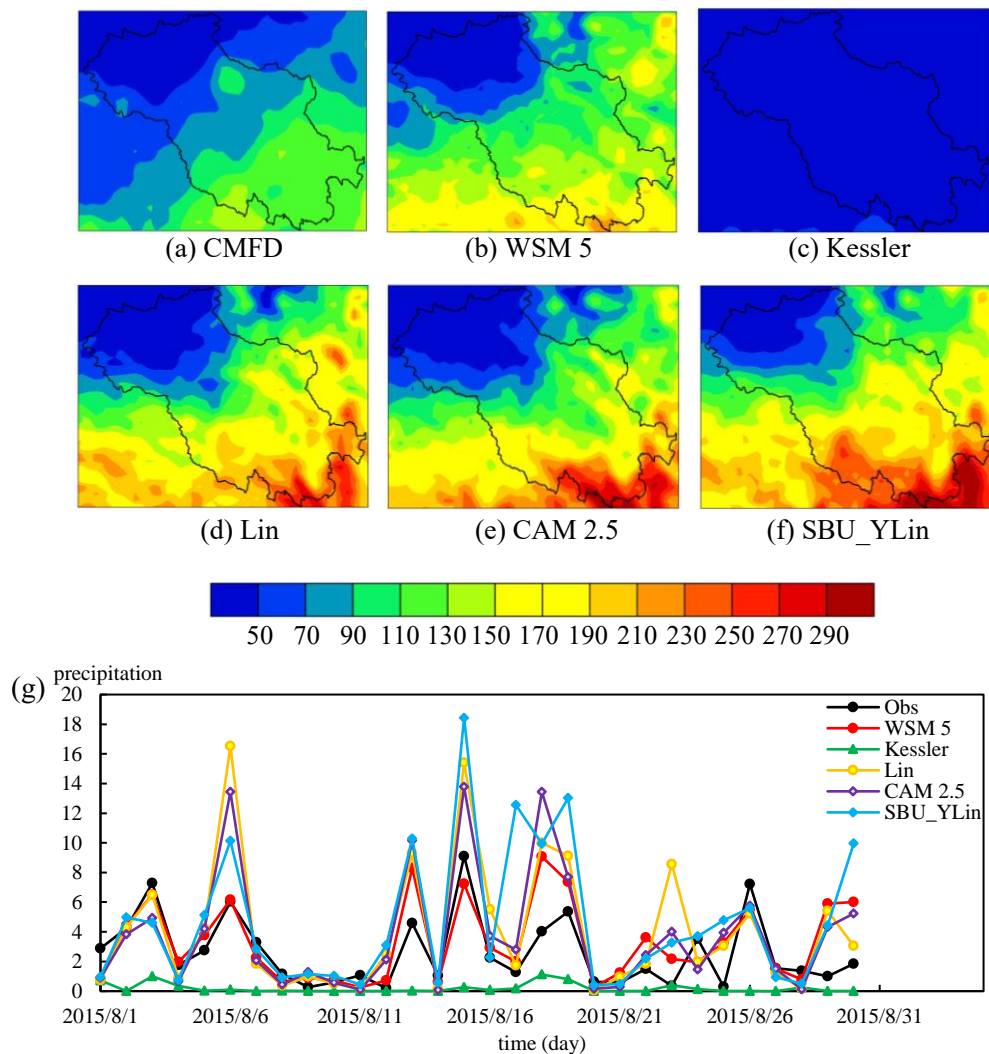
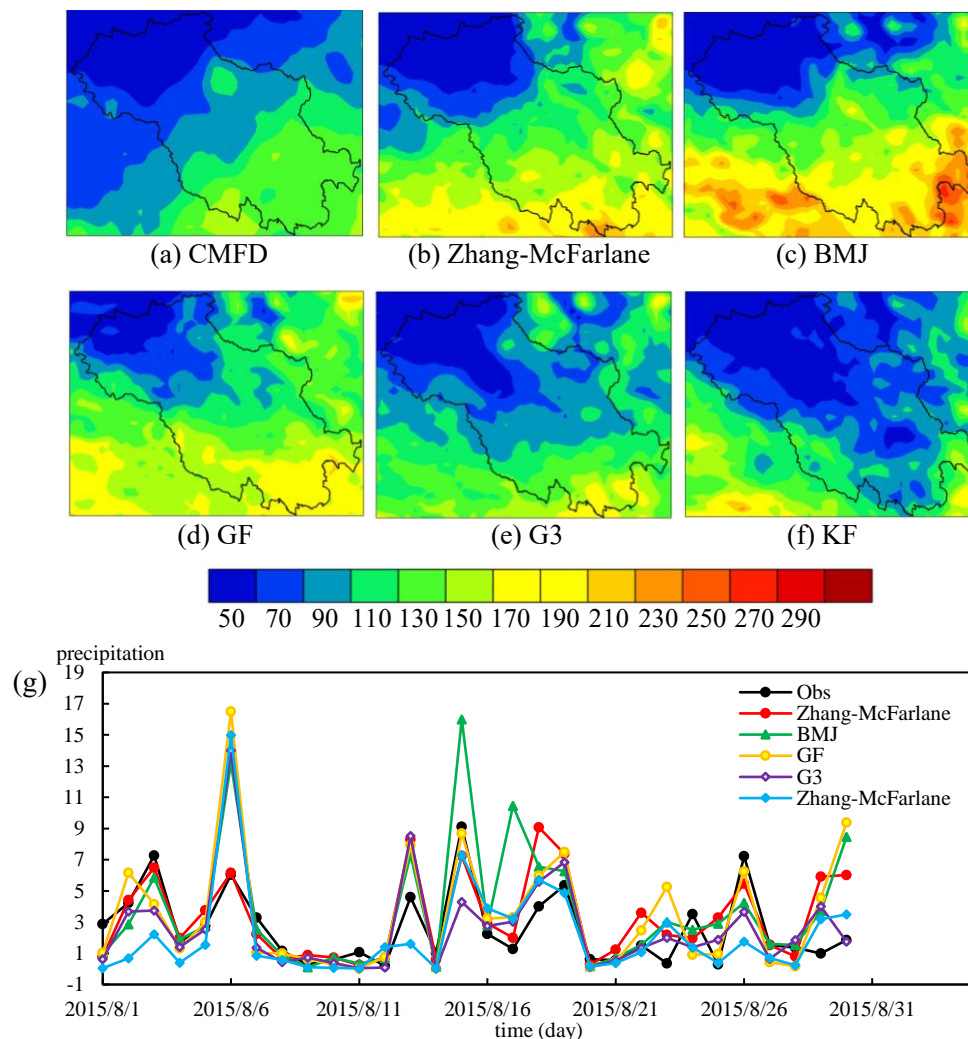


Figure 4. Comparison of 5 different mp_physics precipitation simulations: (a) ~ (f) the comparison of spatial distribution; (g) the comparison of 5 different mp_physics precipitation temporal variation simulations (Unit: mm).

We lastly assessed the sensitivity of WRF precipitation to cumulus schemes. The results of 5 cumulus schemes are shown in Figure 5, and the PCC and RMSE are shown in Table 3. It is apparent that simulated precipitation is sensitive to cumulus schemes. It should be noted that these cumulus schemes have similar RMSE around 20 mm/month. This finding indicates the selection of cumulus schemes have slight impact of the magnitude of simulated precipitation over the TRHR. Moreover, these cumulus schemes brought different spatial patterns of precipitation, and the PCC ranges from 0.72 to 0.93. The Zhang-McFarlane scheme has the best performance, whereas the KF scheme shows the worst. In summary, the cumulus schemes can significantly affect the spatial pattern of simulated precipitation over the TRHR.

Table 3. PCC and RMSE of 5 different cu_physics simulations.

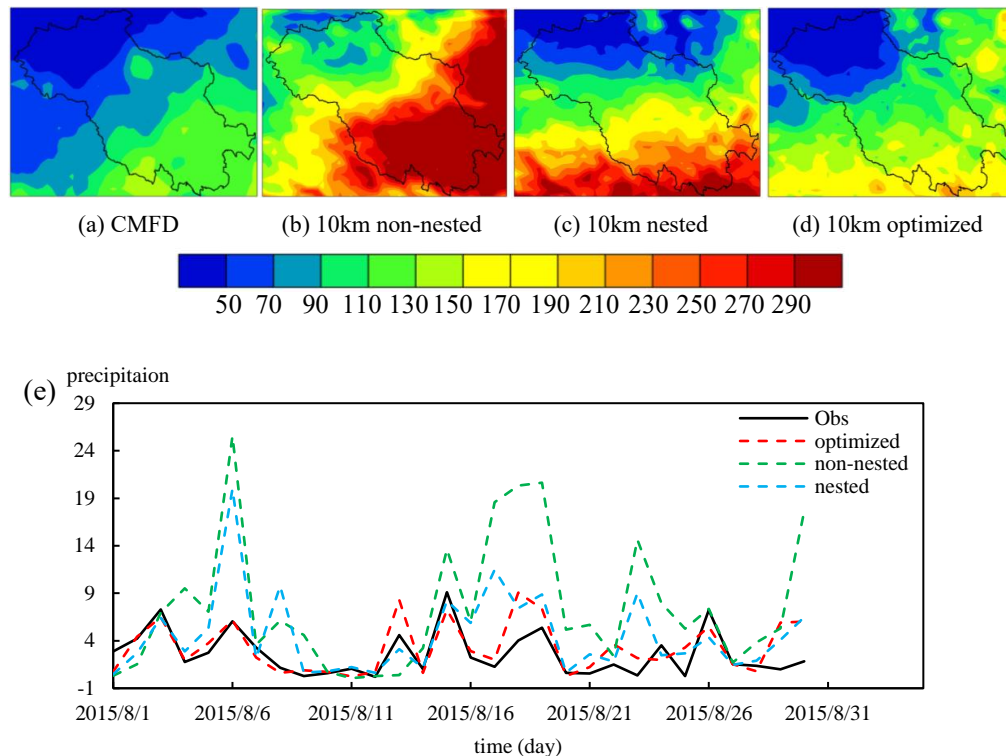
cu_physics	Zhang-McFarlane	BMJ	GF	G3	KF
PCC	0.93	0.91	0.89	0.84	0.72
RMSE	27.63	28.51	29.63	17.77	25.89

**Figure 5.** Comparison of 5 different cu_physics precipitation simulations: (a) ~ (f) the comparison of spatial distribution; (g) the comparison of 5 different cu_physics precipitation temporal variation simulations (Unit: mm).

Based on these sensitivity tests, we recommended an optimized combination of WRF parameterization schemes that can remarkably improve the accuracy of simulated precipitation over the TRHR. This optimized combination includes: RRTM longwave radiation scheme, Dudhia shortwave radiation scheme, WSM 5 microphysics scheme, MYJ planetary boundary layer scheme, Zhang-McFarlane cumulus scheme, COM land surface scheme. As we can see in the Figure 6, the spatial distribution of simulated precipitation has achieved substantial improvement, and the PCC was enhanced from 0.85 of non-nested to 0.93 of nested simulation with the optimized combination. In addition, the biases were reduced from RMSE of 169.49 mm/month to RMSE of 27.62 mm/month (Table 4).

Table 4. The improvement of PCC and RMSE.

	non-nested	nested	optimized
PCC	0.85	0.88	0.93
RMSE	169.49	74.93	27.62

**Figure 6.** The improvement of spatial distribution ((a)~ (d)) and time variation (e) of precipitation simulation (Unit: mm).

5. Conclusion

In this study, we investigated the impact of resolution and physical schemes on the precipitation simulation over the TRHR within the Tibet Plateau. We found that a high resolution of WRF modelling is necessary for the precipitation modelling over the TRHR with a complex terrain. The WRF with a 10 km resolution has a good performance, and a nested domain can largely reduce the disturbance from boundary.

Our study concluded that the precipitation simulation over the TRHR are more sensitive to microphysics schemes and cumulus schemes than planetary boundary layer schemes. In particular, the microphysics scheme plays important role to determine the magnitude of simulated precipitation over the TRHR. On the other hand, the cumulus schemes can significantly affect the spatial pattern of simulated precipitation over the TRHR. On the basis of sensitivity tests, we proposed an optimized combination of parameterization schemes that can remarkably improve the accuracy of simulated precipitation over the TRHR. This combination includes: longwave radiation scheme RRTM, shortwave radiation scheme Dudhia, microphysics scheme WSM 5, planetary boundary layer scheme MYJ, cumulus convection scheme Zhang-McFarlane, land surface scheme CLM. This study could help to deepen the understanding of the mechanism of the precipitation formation over the Tibet Plateau, and make a solid foundation for the future precipitation prediction over the Tibet Plateau.

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