Precipitation Simulation from the Cumulus Convection Parameterization Schemes Based on the WRF Model in the Weihe River Basin, China

Yinge Liu1,2,*, Aifang Cheng 1,2, Haonan Hu2
1 Key Laboratory of Disaster Monitoring and Mechanism Simulating in Shaanxi Province, College of Geography and Environment, Baoji 721013, China
2 Baoji University of Arts and Sciences, Baoji 721013, China
*Correspondence: Yingeliu@163.com

Abstract. Two cumulus convection parameterization schemes, i.e., Kain-Fritsch (K-F) and Grell-3 based on the V4.1.2 Weather Research and Forecasting (WRF) model, were used to simulate the summer precipitation in the Weihe River Basin using hourly precipitation data at the resolution of 5 km and 2 km. The precipitation experiment results at different resolution were compared and analyzed. The root square error and correlation coefficient were used to verify and evaluate the simulation results. The results show that in K-F and Grell-3, the two cumulus model simulations with a resolution of 5 km can explain the spatial distribution pattern of precipitation and the diurnal variation process, and the experimental simulation results are consistent with the actual observations. The summer precipitation simulation in June, July, and August is highly sensitive to the two cumulus parameter schemes of K-F and Grell-3. The simulated precipitation value is higher than the actual value, and the root mean square errors (RMSEs) of K-F and Grell-3 schemes are 5.49-13.29 and 5.69-10.88, respectively. In terms of precipitation simulation, Grell-3 scheme is better than K-F scheme, especially in areas with heavy rainfall. When the resolution is increased to 2 km, the regions with heavy precipitation can be displayed more finely. The influence of water vapor flux and vertical velocity changes on precipitation in the Weihe River is analyzed from two aspects, i.e., water conditions and atmospheric instability. From the simulation results by the K-F scheme, the vertical velocity fluctuations are unstable and strong in the convective area, and the convective rainfall is relatively high. From the simulation results by Grell-3, the vertical velocity is large and increased rapidly, which is conducive to the generation of large-scale heavy precipitation. Both schemes are very sensitive to the simulation of water vapor transport and vertical velocity. This study provides a basis for the research on the adaptability of regional precipitation simulation.

1. Introduction
Changes in summer temperature and precipitation have a major impact on regional agricultural production and people's lives. With global warming, human activities have intensified, and meteorological disasters caused by strong summer rainfall and high temperatures have increased. Regional precipitation and temperature changes have become a hot spot for scholars[1-2]. With the development and application of mesoscale numerical models, numerical model simulation has become an important tool and method for studying changes in the weather and climate system. Among the regional climate models, the WRF model has a complete dynamics framework and multi-source parameterization scheme, including different cumulus convection and microphysical processes. The
choice of parameterization scheme is the key to the numerical simulation of precipitation and temperature[3-4]. For different regions, the simulation with different parameter schemes leads to quite different results[5,6]. Therefore, many scholars in China and other countries have been discussing the simulation effect and adaptability of the WRF model under different regional conditions. For example, Kryza et al. [7], and Hamill et al.[8] use the WRF model to simulate the regional rainfall process in southeastern Australia, Poland and the United States, respectively. In addition, they have compared the simulated results in the precipitation process under different schemes and explored the differences in the simulation results. Pour et al. [9] and Dong et al. [10] use the coupling of WRF model and channel confluence model to analyze and explore the source of error in the model simulation results. In China, scholars use different combinations of cumulus convection and microphysical solutions to conduct simulation experiments on regional precipitation, typhoon path and intensity, precipitation in the eastern monsoon region, and extreme climate events and the impact of climate change and human activities on precipitation and temperature[11-13]. The simulation accuracy of regional precipitation for different cumulus parameter schemes is discussed in the coastal waters [14-17]. The researchers consider that the combination of different parameters in the model and the chemical schemes has certain adaptability and differences to specific areas.

However, the above research has certain limitations, and the research on the parameterization of small area simulation is still under continuous exploration. The Weihe River is the largest tributary of the Yellow River, and the prediction of precipitation change in the Weihe River Basin has an important impact on the environmental management and construction of the Yellow River Basin. The precipitation and temperature in the Weihe River Basin have seasonal variation and uneven spatial distribution. With the impact of climate warming and human activities, droughts and floods frequently occur in the region, and water resources and ecological environment security are threatened. In this paper, the summer precipitation in the Weihe River Basin is simulated at the resolution of 5 km and 2 km by combining different cumulus convection parameter schemes. In addition, the precipitation experiment results in various resolution that are compared and analyzed, and the spatial characteristics and adaptability of different scheme combinations to the simulation of precipitation are explored. The results in this paper provide a basis for exploring water resources and ecological environment management in the river basin.

2. Method and data

2.1. Introduction to the model scheme

Weather Research and Forecasting (WRF) model is a non-statically balanced, high-resolution (about 1-10 km), small and medium-scale, and fully compressible non-static model, which can be used for the simulation and forecasting of regional geosciences, air quality, weather and climate. There are different cumulus convection schemes in the WRF model. This study use the Kain-Fritsch (K-F) scheme and Grell-3 cumulus convection parameterization scheme, as well as other microphysical parameterization schemes, including RRTM longwave radiation, Dudhia shortwave radiation scheme, Noah land surface process program, Yonsei University YSU boundary layer program, and Lin microphysical process program, to simulate and evaluate the precipitation in the Weihe River.

The K-F scheme uses Lagrangian gas block correlation methods to determine whether convective instability will occur and whether it will cause cloud growth. A simple cloud model is accompanied by the rise and fall of water vapor, and the influence of updraft entrainment and downward entrainment in the cloud, as well as relatively rough microphysical processes is considered[18-19]. Using the K-F scheme, both the forecast of land stations and the simulation of the temporal and spatial distribution of precipitation have good results[20-21]. The Grell-3 scheme is a new convective parameterization framework[22], in which a large number of hypothesis sets are used. Grell-3 scheme uses precipitation data to train parameterization, and ensemble and data assimilation techniques to determine the three-dimensional parameters. The optimal value of the model’s feedback has a higher resolution, and the sinking effect can affect other surrounding grids. The simulation is more suitable for areas with a resolution of less than 10 km.
2.2. Data and experimental design
The data for the model came from the National Meteorological Information Center (http://data.cma.cn). The FNL reanalysis data from the National Environmental Forecast Center of the United States are used as the model input data (the time interval is 6 hours, and the horizontal resolution is 1°×1°). The hourly precipitation grid dataset (version 1.0) from the China National Meteorological Information Center, which is a fusion of China's automatic stations and CMORPH precipitation products, is used as the verification data. The daily precipitation grid data set (V2.0) with the horizontal resolution of 0.5°×0.5° established by the spatial interpolation of the basic meteorological element data from the national ground weather station of the National Meteorological Center in China is selected as the verification data to evaluate the simulated precipitation spatial distribution results (http://data.cma.cn).

The WRF mode (V4.1.2) is selected, and the double-layer nesting and Runge-Kutta time integration with third-order accuracy is adopted in the simulation area. The latitude and longitude of the center of the area were 107.5°E, 35.5°N, respectively. The number of grid points in the first layer (d01) and second layer (d02) re-grid area are 80×60 and 161×101, respectively, and the horizontal grid distance is 25 km and 5 km, respectively. The vertical direction is divided into 45 layers, and the top pressure of the layer is 50 hpa. The MODIS data is used to determine the land use of the underlying surface. The NCEP reanalysis data is selected as the initial field and boundary field of the model starting from 0:00 on May 1, 2018 to 0:00 on September 1, 2018 in the Weihe River Basin and surrounding areas (107°~118°E, 26.5°~34.5°N). In the simulation of precipitation, the first 30 days (May) is the starting period of the model, the step length was 60 s, the continuous integrated precipitation is 24 h, and the data was output once every 3 h. The characteristics and adaptability of WRF model simulation is tested at the horizontal resolutions of 5 km and 2 km. The distribution of the simulation areas is shown in Figure 1. The root mean square error (RMSE) and correlation coefficient between the simulated value and the observed value are used to test the simulation results, and evaluate the simulation effect of the model on the Weihe River under different schemes. By simulating the vertical velocity of atmosphere, the influence mechanism of precipitation in the Weihe River Basin is analyzed.

Figure 1 Distribution of simulated areas and weather stations.

3. Results

3.1. Precipitation simulation at 5 km resolution
Figure 2 shows the simulation results of a cumulus parameterization scheme at a resolution of 5 km. It can be seen that the summer rainfall is distributed along the Qinling and Weihe Rivers in K-F and Grell-3 parameterization scheme. The southern part has more precipitation than the northern part. The heavy rainfall is observed in the Wushu Mountains and Qinling Mountains at the source of the Weihe River. The valley area has less precipitation, and the spatial distribution of simulated precipitation is consistent with the measured spatial distribution. From the simulation, the main precipitation belts are roughly distributed along the river and Qinling Mountains, showing an east-west trend. A large northwest-southeast rain belt appeared in the southern part of the simulation area, and a small northeast-southwest
rain belt appears in the west, with heavy rainfall. The main precipitation belts in the simulation results in August are relatively scattered and the precipitation decreases. In summer, the precipitation in most areas is below 8 mm, while the areas with precipitation above 8 mm are less, mainly concentrated in the southeast of 34°N. The simulated precipitation with the K-F scheme is generally higher than the measured precipitation. In the simulation with the Grell-3 scheme, the precipitation distribution pattern affected by the terrain is simulated in detail, the heavy precipitation area is expanded, and the high precipitation areas in the northern and southern Qinling Mountains are also clearly depicted.

3.2. Precipitation simulation at 2 km resolution

In order to further test the effect of different resolution on the simulation results of WRF model with cumulus convection scheme, the resolution of the two schemes is increased to 2 km. The precipitation simulation results are shown in Figure 3. From the figure, the heavy precipitation area is in the south and the precipitation area is expanded. The simulated spatial distribution of precipitation in June, July, and August is more refined, clearly showing precipitation of 5 mm and above 10 mm, and some areas with precipitation higher than 20 mm are also observed in the southeast. Compared with the K-F cumulus solution, the Grell-3 cumulus solution can simulate high-value centers with precipitation of more than 50 mm. Due to the improvement of resolution, some precipitation centers and precipitation belts that cannot be simulated at low resolution are displayed. Especially, the regional pattern of precipitation is clearly displayed. The spatial distribution of precipitation is related to the regional water vapor source and environment to some extent. The results show that under high resolution, choosing a reasonable parameterization scheme can effectively avoid the excessive terrain forcing effect of the model and improve the accuracy of the precipitation simulation. The daily precipitation changes in June, July, and August in the selected 4 typical sites are shown in Figure 4. From the figure, in both cumulus convection parameterization schemes, the simulated value of daily precipitation has the same trend as the measured value, and the daily extreme precipitation can be successfully observed in the simulation results. For precipitation below 20 mm, the simulated value is higher than the measured value. In contrast, for the precipitation greater than 20 mm, the simulated value is basically the same as the measured value. It should be noted that the simulated value of extreme precipitation is 24 hours earlier than the measured precipitation.

![Figure 2](image_url)

Figure 2 Precipitation simulation with K-F and Grell-3 parameterization scheme at 5 km resolution. (a), (b) and (c) show simulated value of Jun, July and August in K-F scheme, and (d), (e) and (f) show simulated value of Jun, July and August in Grell-3 scheme, respectively.
Figure 3 Precipitation simulation with K-F and Grell-3 parameterization scheme at 2 km resolution. (A), (B) and (C) show simulated value of Jun, July and August in K-F scheme, and (D), (E) and (F) show simulated value of Jun, July and August in Grell-3 scheme, respectively.

Figure 4 Measured precipitation and simulated precipitation in June, July and August. a1-a3 show the precipitation in June, July, and August in Xiji, respectively; and b1-b3 show the precipitation in June,
July, and August in Tianshui, respectively.

Figure 5 Measured precipitation and simulated precipitation in June, July and August. A1-A3 show the precipitation in June, July, and August in Luochuan respectively; and B1-B3 show the precipitation in June, July, and August in Fengxiang, respectively.

3.3. Outcome evaluation

We conduct root mean square error test and correlation coefficient test using SPSS, and calculate the correlation between the simulated value and the measured precipitation. The correlation coefficient and root mean square error are shown in Table 1. In the K-F scheme, the correlation coefficient(r) in August is the smallest, which is 0.346, and the correlation coefficients in all the stations in July are greater than 0.729, which has passed the 95% reliability test. The minimum value of RMSE (5.49) is observed in July and the maximum value (13.29) is observed in August. In the Grell-3 scheme, the correlation coefficient is small in June and the highest in July. The root mean square error is large in August, and has the maximum value of 10.88. Overall, the Grell-3 scheme is better than the K-F scheme, and the simulated precipitation is greater than the measured precipitation, showing obvious humidity deviation.

| Precipitation (mm) | Day | Precipitation (mm) | Day | Precipitation (mm) | Day |
|--------------------|-----|--------------------|-----|--------------------|-----|
| Measured value     | (A1) | K-F simulated       | (A2) | K-F simulated       | (A3) |
| Measured value     | (B1) | K-F simulated       | (B2) | K-F simulated       | (B3) |

Table 1 Correlation coefficient and root mean square error in K-F scheme

|                   | Tianshui | Fengxiang | Xifengzhen | Huashan |
|-------------------|----------|-----------|------------|---------|
| June (r)          | 0.561    | 0.875     | 0.716      | 0.757   |
| July (r)          | 0.836    | 0.810     | 0.729      | 0.865   |
| August (r)        | 0.894    | 0.810     | 0.373      | 0.343   |
| June (RMSE)       | 6.793    | 13.290    | 8.097      | 10.648  |
| July (RMSE)       | 5.490    | 6.393     | 7.092      | 7.229   |
| August (RMSE)     | 12.448   | 6.913     | 4.296      | 11.068  |

Table 2 Correlation coefficient and root mean square error in Grell-3 scheme

|                   | Tianshui | Fengxiang | Xifengzhen | Huashan |
|-------------------|----------|-----------|------------|---------|
| June (r)          | 0.470    | 0.660     | 0.251      | 0.744   |
| July (r)          | 0.806    | 0.858     | 0.789      | 0.616   |
| August (r)        | 0.882    | 0.817     | 0.508      | 0.507   |
| June (RMSE)       | 5.382    | 10.249    | 6.476      | 8.761   |
| July (RMSE)       | 7.564    | 6.890     | 6.009      | 7.243   |
| August (RMSE)     | 7.135    | 10.880    | 10.221     |         |
4. Discussion
The formation of precipitation is closely related to the atmospheric moisture and the atmospheric instability. Therefore, the water vapor flux and vertical velocity changes under different schemes are analyzed from these two aspects. There are two sources of water vapor for summer precipitation in the Weihe River Basin. The water vapor from the southern part of the Western Pacific Subtropical High is transported to the Weihe River Basin through easterly wind and southerly wind. The confluence of the west wind and cold air flow provides conditions for the formation of precipitation. The area with the largest water vapor flux is mainly located in the south, while the north has relatively less water vapor. The larger area of water vapor flux is basically the same as the larger area of precipitation in the simulation.

Atmospheric instability is a necessary condition for the formation of convective precipitation in summer, and the vertical updraft velocity can reflect the instability of the atmosphere. The simulated vertical velocity profiles with both Grell-3 and K-F schemes are shown in Figure 11. It can be seen that using these two schemes, the simulation of the vertical velocity is more sensitive. In the K-F scheme, the low-level velocity at 800 hpa is only 0.003 m/s, while the upper-level maximum vertical velocity is 0.006 m/s. At different levels, the vertical velocity fluctuated, the atmosphere is unstable, and the simulated value of convective precipitation is too high. In the Grell-3 program simulation, the warm and humid air currents are relatively strong, and the instability of the atmosphere is shown as grid-scale precipitation. In the Grell-3 program, the vertical ascent speed increased linearly from 0.001 m/s in the low-level height (800 hpa) to 0.015m/s in the height of 200 hpa. Using Grell-3 scheme, the obtained vertical velocity was obviously greater than that using K-F scheme. Therefore, in the simulation under the Grell-3 scheme, there is more large-scale precipitation. These simulation results are basically consistent with those in the literature[23-24]. The analysis also shows that the finer grid resolution can improve the accuracy of cumulus convective parameterized simulation results, and has a good simulation effect on summer convective precipitation. However, the fine resolution is not as good as coarse resolution in the simulation of large-scale precipitation.

5. Conclusion
The summer precipitation simulation in June, July and August in the Weihe River exhibits high sensitivity and adaptability to the K-F and Grell-3 cumulus parameter schemes. The daily precipitation simulation values of each month are consistent with the actual values. Especially, the strong precipitation can be better simulated. The simulated precipitation with both schemes is slightly higher than the actual measured values, and the simulation errors of both schemes are 13%-39% and 10%-25%, respectively. Grell-3 scheme has better effect on precipitation simulation, especially for the areas with heavy precipitation distribution. Precipitation is mainly affected by the transportation of water vapor by the southwest airflow and the atmospheric instability. In the simulation with the K-F scheme, the obtained vertical velocity has a great change, the convection is unstable and strong, and the convective precipitation is stronger. In the simulation with the Grell-3 scheme, the vertical velocity is higher and
rapidly increased with height, which is conducive to the generation of large-scale heavy rainfall. Thus, the Grell-3 scheme is more suitable for the simulation and prediction of large-scale precipitation.

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