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A Numerical Study on Cloud Structure of Typical Summer Precipitation Process over Liupan Mountain Area

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Abstract: ***Using Weather Research and Forecasting model (WRF), four microphysical schemes (Lin, Goddard, WSM6 and Thompson) were applied for precipitation simulations over southern Ningxia on July 21st, 2024. The simulated results are used to analyze the impact of different microphysical schemes on summertime precipitation processes. The sensitivity experiments show the precipitation process simulated by WSM6 and Thompson schemes are closer to observed precipitation than Lin and Goddard schemes in Southern Ningxia mountainous areas. The evolution characteristics of the dynamic field, water vapor field, and microphysical structures of cloud structures are analyzed. In vertical direction, the cloud system in mountainous areas generally displays a structure of "catalysis-supply". The structure of water condensation in each layer of cloud is different, leading to differences in the contribution of various microphysical processes to precipitation. The super-cooled cloud water is the main source for rain water production. When cloud system grows upward, the abundant cloud water layer simultaneously enhances the microphysical processes within clouds. On the windward slope (eastern part) of the mountain, deep warm cloud layer will contribute to the development of warm cloud precipitation process, which leads to enhanced precipitation under the combined action of cold and warm clouds.***

1. Introduction

Recently, numerical simulation is becoming a significant method for studying cloud and precipitation processes since the observation data is inadequate in many cases. As a new generation of small-scale numerical models The WRF model is applied in scientific research and operation frequently. The effects of microphysical schemes on precipitation simulation vary greatly within WRF model. Therefore, conducting studies on precipitation simulation with different microphysical schemes in southern Ningxia is of great significance for localization application.

Liupan Mountain is a narrow mountain range in Northwest China which runs in a nearly North-South direction. It is located at the northeast edge of the Qinghai-Tibet Plateau as well as the intersection of the East Asian summer monsoon and westerly belt. The mountain is about 100 kilometers from north to south, with an average altitude of over 2500 meters. According to former research findings, the southern mountainous area of Ningxia is abundant in cloud water resources, especially in summer, with more orographic cloud cover and great potential for increasing rainfall. Most of its water vapor resources originate from the lower-level Bay of Bengal, South China Sea, and Indian Ocean. Below 750 hPa, the main water source is the southeast warm and humid air flow, which is lifted by the mountain and the water vapor rises and condense, thus forming deep cloud layers.

The interactions between various hydrometeors within clouds, as well as their microphysical effects, can affect the development of precipitation. There are dozens of commonly used microphysical schemes in WRF model, such as Morrison scheme, Thompson scheme, etc. They are usually based on some single or dual parameter distribution function to profile cloud droplet spectra. The Lin scheme (Lin et al., 1983; Rutledge and Hobbs, 1984) is a relatively mature single parameter scheme suitable for theoretical research. The WSM6 scheme (Hong and Lim, 2006) is also a single parameter scheme that adds hail forecasting and related processes based on WSM5 scheme, this scheme also includes condensation and melting processes during descent process that increases the accuracy. The Morrison scheme (Morrison and Pinto, 2005; Morrison et al., 2009) is a dual parameter scheme with 10 predictor variables that can accurately predict spectral distribution of particles. The Thompson scheme (Thompson et al., 2004, 2008) is also a dual parameter scheme with 8 forecast variables. Since most of the microphysical parameterization schemes are summarized from foreign studies, the adaptability of these schemes in Ningxia need to be tested.

In this research, the results of four simulation tests are verified using observation data. Furthermore, the microphysical structure, precipitation formation mechanisms, and the influence of mountain range on the precipitation cloud system over Liupan Mountain area is analyzed, so as to provide scientific basis for evaluation and improvement of microphysical parameterization schemes.

2. Model, Data and Methods

The WRF (Weather Research and Forecast) model is a new generation of high-resolution mesoscale forecasting models and assimilation systems which is devised and improved by National Center for Atmospheric Research (NCAR) and Center for Environmental Prediction (NCEP) in the USA. This model is commonly used for weather process forecasting from cloud scale to weather scale with a grid design resolution from 1-10km (Guo et al., 2010). The model consists of a pre-processing system (WPS), a main model system, and a post-processing system.
The data used in this research include NCEP FNL (National Center for Environmental Prediction final operation global

analysis) and CIMISS (China integrated meteorological information service system), the horizontal resolution of NCEP FNL is 1°×1°, which is used for WRF simulation, and the CIMISS precipitation data is used for verifying simulation results.

3. Design of Simulation Experiments

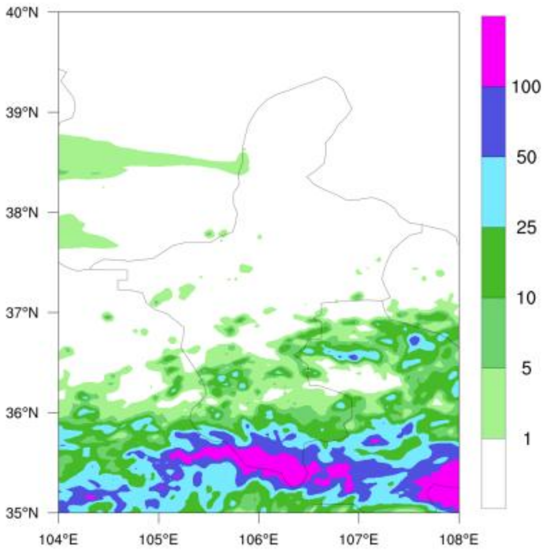
The version of WRF applied in this research is version 3.9. The details of simulation tests list in table 1. There are two nesting in each simulation test, The horizontal resolution of outside and inner nesting are 9km and 3km, respectively. The grid number of outside and inner nesting are 300×300 and 301×301, respectively. The center of simulated region is 36.2°N, 106.5°E. There are 34 vertical layers and the time step is 45s, the result output frequency is 1 hour. The settings of parameterization schemes are listed as below: The Long wave radiation uses RRTM scheme, short wave radiation is Dudhia scheme, cumulus convection adopts Kain Fritsch (innermost closure) scheme. In addition, the near surface layer scheme is the modified MM5 Monin Obukhov scheme, the land surface process scheme is the Noah scheme, and the boundary layer scheme is the YSU scheme. This study mainly uses the simulation results of the innermost layer.

Table 1: Description of simulation tests

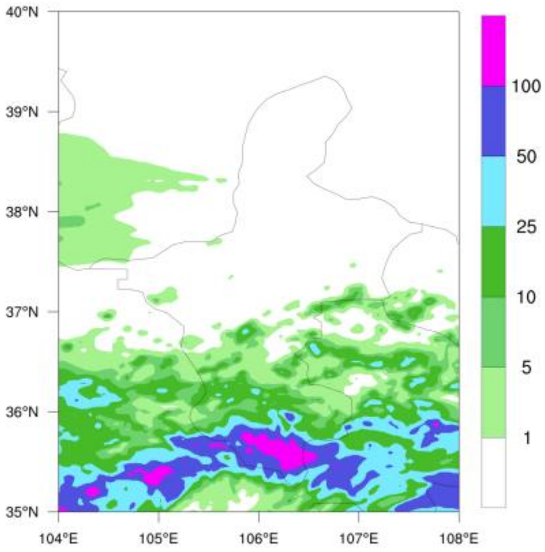
Schemes	Domain 1(d01)	Domain 1(d02)
Horizontal resolution	9km	3km
Grid number	300×300	301×301
mp_physics	Lin/WSM6/Goddard/ Thompson	Lin/WSM6/Goddard/ Thompson
ra_lw_physics	RRTM scheme	RRTM scheme
ra_sw_physics	Dudhia scheme	Dudhia scheme
cu_physics	Kain-Fritsch (new Eta) scheme	Non cumulus scheme
sf_surface_physics	Noah scheme	Noah scheme
sf_sfclay_physics	Monin-Obukhov scheme	Monin-Obukhov scheme
bl_pbl_physics	YSU scheme	YSU scheme

4. Results and Discussion

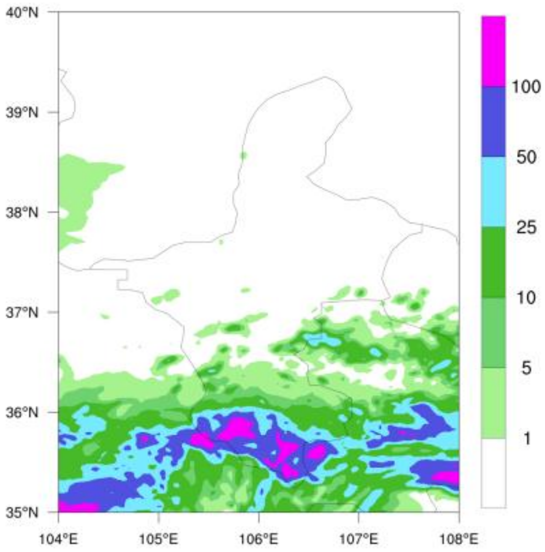
Comparing the simulated precipitation with the observed precipitation, features can be concluded that: The observed precipitation mainly occurs in southern part of Ningxia. There is an obvious rain belt that runs approximately northwest to southeast over Liupan Mountain Area. Comparing the cumulative precipitation distribution (Figure 1), it can be seen that the precipitation areas simulated by four schemes are consistent with observation precipitation areas in general, but there are certain differences. Specifically, the simulated precipitation with WSM6 (Figure 1c) and Thompson (Figure 1d) were closer to observation than the other two schemes, though the cumulative rainfall amount simulated by Thompson scheme is lightly lower than observation. The range and magnitude of heavy precipitation simulated by the Lin (Figure 1a) and Goddard (Figure 1b) schemes are larger than the observation. Therefore, WSM6 scheme is used for further analysis.



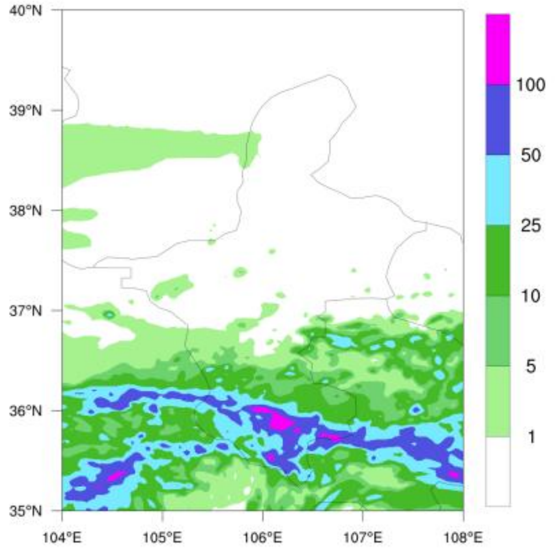
(a) Lin



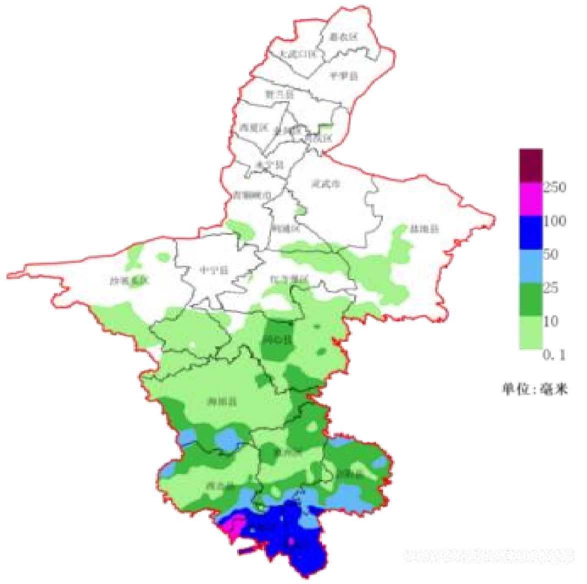
(b) Goddard



(c) WSM6



(d) Thompson

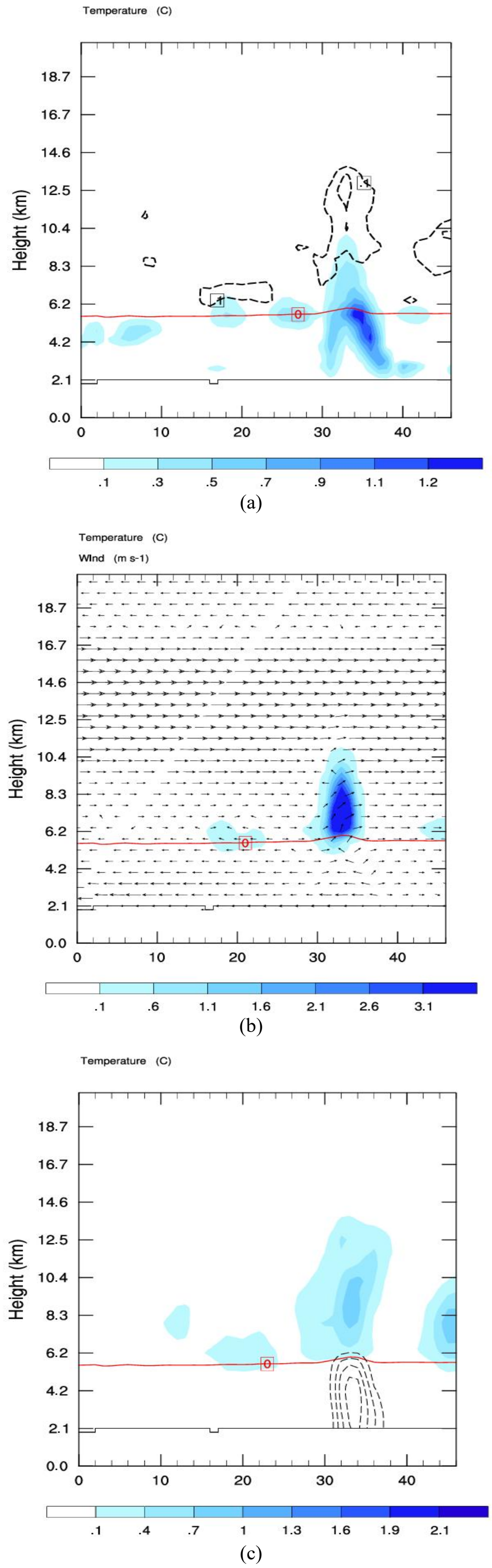


(e) Observation

Figure 1: The simulated rainfall using the scheme of (a) Lin, (b)WSM6, (c)Goddard, (d)Thompson during 08:00 July 22 to 08:00 July 23,2024, while (e) denotes observed rainfall.

The precipitation process occurred in Southern Ningxia is largely influenced by the mountainous topography, hence the latitudinal vertical profiles can be used for analysis. The specific water content of hydrometeor (cloud water, rain water, cloud ice, snow, graupel) over d02 domain (grid spacing at 3km) are drawn in Figure 2, which shows the vertical profile of specific water content of hydrometeor over Liupan Mountain Station (35.4°N).

From 5:00 to 10:00, the rainfall area is mainly concentrated over Liupan Mountain area (not shown). At 5:00, a maximum cloud water content at over 1.2 g/kg occurs over eastern slope of Liupan Mountain. the Ice crystals mainly occur at the height of 10-12km, with a relatively larger distribution range and content. There are some cloud snow crystals over mountainous areas. The maximum content of snow crystals over mountain ridges is 0.78 g/kg. The maximum content of cloud graupel (3.8 g/kg) occurs in the area which is rich in super-cooled water. The larger rainfall area corresponds to the large value areas of upper layer graupel particles and those of cloud water, indicating the precipitation in mountainous area at this time involves both cold and warm cloud processes.



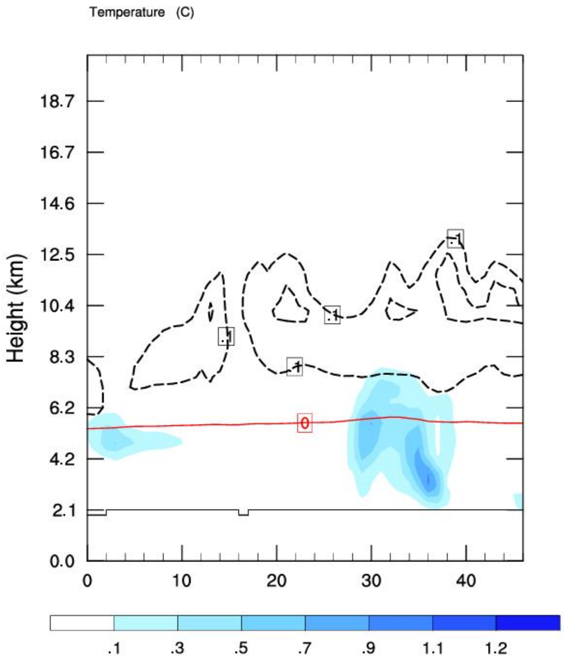
(a)

(b)

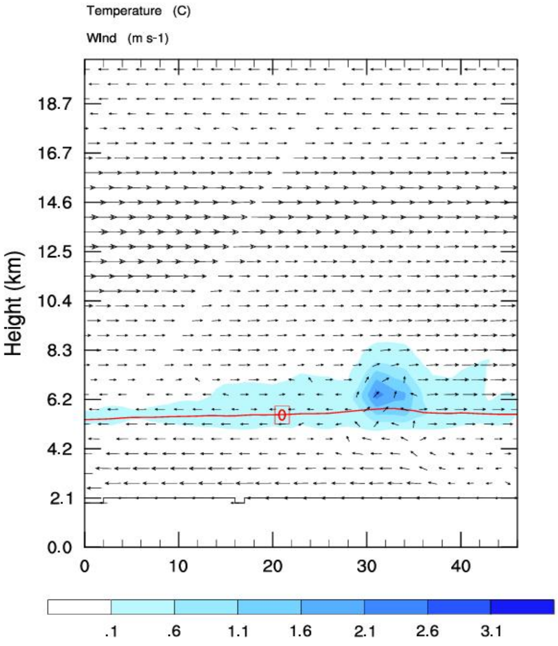
(c)

Figure 2: The latitudinal vertical profiles of (a) cloud ice crystals (dashed line) cloud water (shadow), (b) cloud graupel and wind, (c) cloud rain (dashed line) and cloud snow(shadow) with specific moisture content (unit:g/kg) are shown along Liupan Mountain Station at 05:00 on July 23rd,2024. The red line refers to temperature zero and the arrow refers to wind field (unit: m/s).

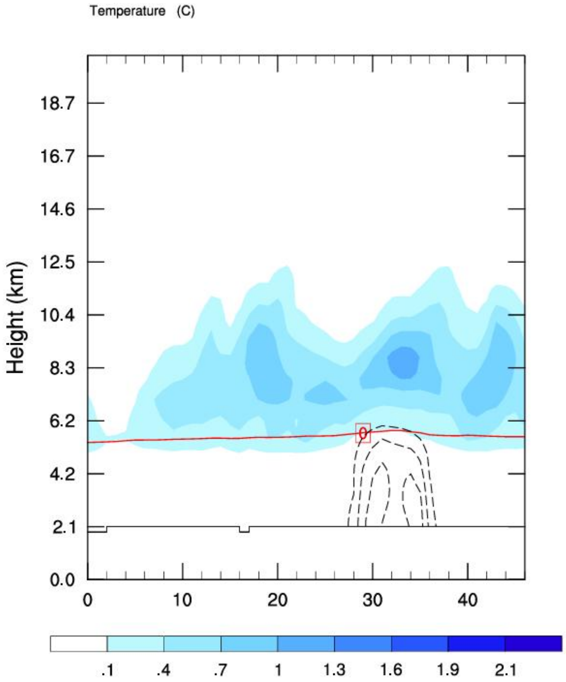
At 08:00(Figure 3), the trough at high altitude continue moving into the Liupan Mountain area, and the low-level wind in the mountain area enhanced. The vertical movement caused by the wind shear is also strengthened at the temperature layers above zero. The ice phase cloud areas (including ice crystals, graupel and cloud snow) expand obviously, while the liquid phase cloud areas (including) remain approximately the same as 05:00. The maximum cloud water content is about 0.85 g/kg. the Ice crystals mainly occur at the height of 6-12km over central and eastern slope of Liupan Mountain, with a maximum content at 0.24 g/kg. The maximum content of snow crystals over mountain ridges is 1.12 g/kg. The maximum content of cloud graupel (2.2 g/kg) occurs in the area which is rich in super-cooled water. The cloud over mountainous areas generally show a vertically "catalytic-supply" structure, there are abundant ice phase particles in upper layer, the cold cloud processes are dominant.



(a)



(b)



(c)

Figure 3: The latitudinal vertical profiles of (a) ice crystals (dashed line) cloud water (shadow), (b) cloud graupel and wind, (c)cloud snow(dashed line) and cloud rain(shadow) with specific moisture content (unit: g/kg)are shown along Liupan Mountain Station at 08:00 on July 23rd,2024.The red line refers to temperature zero and the arrow refers to wind field (unit: m/s)).

In summary, clouds over mountainous areas generally show a vertically "catalytic-supply" structure, but the microphysical structures in different parts of the cloud are different. When there are abundant ice phase particles in upper layer, the cold cloud processes are dominant, whereas when there are both ice phase particles in upper layer and abundant liquid water content in warm zone, warm and cold cloud processes will function jointly. On the windward slope (eastern part) of the mountain, deep warm cloud layer will contribute the development of warm cloud precipitation process, which leads to strong precipitation in the eastern part of the mountainous area under the combined action of cold and warm clouds.

5. Conclusions

In this article, the mesoscale numerical model WRF is applied to conduct numerical simulation experiments on a typical summer precipitation process that occurred in Liupan Mountain over southern Ningxia. Through sensitive experiments with four different cloud microphysics schemes (Lin, Goddard, WSM6, Thompson), it is found that the WSM6 and Thompson scheme are more accurate in simulating the area and magnitude of precipitation in southern Ningxia. The cloud system in mountainous areas basically reflects the "catalytic-supply" structure of clouds in vertical direction. On the windward slope (eastern part) of the mountain, deep warm cloud layer will contribute the development of warm cloud precipitation process, which leads to enhanced precipitation under the combined action of cold and warm clouds.

The conclusions are based on the simulation results of one typical summer precipitation case occurred in Liupan mountain Area. More research are needed for investigation of microphysical processes in cloud-precipitation systems, so as to deepen the understanding of summer precipitation mechanisms in Southern Ningxia, in hope that the results can be used to improve the precipitation forecasting performance of WRF in future.

Acknowledgments

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