Parameter Selection and Microphysical Structure Analysis of Cloud Model Simulation for a Precipitation Event over the Qilian Mountains (Postprint)

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Abstract

Using observed data combined with a cloud model, a numerical simulation study was conducted on a typical stratocumulus precipitation process in the Qilian Mountains to investigate the influence of parameter selection on simulation results and analyze its microphysical structural characteristics. Results indicate that the optimal parameterization for the Qilian Mountains cloud model is the Thompson scheme; the distribution of various hydrometeor contents exhibits a basically unimodal pattern. At 01:00 near 4.5 km, the graupel mixing ratio and snow mixing ratio can reach values of 0.1 $\mathrm{g \cdot kg^{-1}}$ and 0.7 $\mathrm{g \cdot kg^{-1}}$, respectively, with relatively abundant supercooled water present at this height level. From the perspective of the spatial distribution and temporal correlation of the five hydrometeor types, the melting of graupel and snow makes a primary contribution to rain formation; in the vertical direction, the cloud system exhibits a "seeder-feeder" layered structure. The uppermost layer above 8 km altitude is a coexisting region of ice crystals and snow; the supercooled region above the 0 ℃ level height (4.5 km) simultaneously contains graupel particles, cloud water, and rain water. This cloud structure is conducive to precipitation formation and favorable for conducting artificial precipitation enhancement operations in the Qilian Mountains.

Full Text

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Selection of Cloud Model Simulation Parameters and Analysis of Microphysical Structure Characteristics for a Precipitation Process in the Qilian Mountains

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Abstract

Using observed data combined with a cloud model, this study conducts a numerical simulation of a typical stratocumulus precipitation process in the Qilian Mountains, investigates the influence of parameter selection on simulation results, and analyzes its microphysical structure characteristics. The results show that the optimal parameterization scheme for the Qilian Mountains cloud model is the Thompson scheme. The content distribution of various hydrometeors basically exhibits a single-peak pattern, with relatively abundant supercooled water above 4.5 km. The values of graupel mixing ratio and snow mixing ratio near 4.5 km can reach 0.1 $\mathrm{g \cdot kg^{-1}}$ and 0.7 $\mathrm{g \cdot kg^{-1}}$, respectively. Analysis of the spatial distribution and temporal correlation of the five hydrometeors indicates that the melting of graupel and snow makes a major contribution to rainwater formation. In the vertical direction, the cloud system exhibits a "seeding-feeder" layered structure: the highest layer above 8 km is the coexistence region of ice crystals and snow, while the supercooled region above the zero-degree layer (4.5 km) simultaneously contains graupel particles, cloud water, and rainwater. This cloud structure is conducive to precipitation formation and favorable for artificial precipitation enhancement operations in the Qilian Mountains.

Keywords: Qilian Mountains; cloud model; simulation parameters; microphysical structure; characteristics

Precipitation refers to the process by which water vapor in the atmosphere condenses and falls to the ground in solid or liquid form, playing an extremely important role in global water and energy cycles. Currently, global water resources are severely scarce, especially in northwestern and north-central China where precipitation is relatively low. Artificial precipitation enhancement operations to develop atmospheric cloud water resources represent an important approach to solving water shortage problems, and stratocumulus cloud systems are the main target for such operations. The dynamic and thermal structures of stratocumulus cloud systems are complex, making the study of their microphysical structure characteristics highly significant.

The Qilian Mountains are located in the hinterland of China’ s arid and semi-arid regions, with their southern foothills connecting to the Tibetan Plateau and northern foothills adjacent to the Hexi Corridor. The mountains contain numerous glaciers, with maximum annual precipitation reaching 800 mm, which is 3–4 times that of the plain areas in the Hexi Corridor, making them a veritable “high-altitude water tower.” The Qilian Mountains are rich in atmospheric cloud water resources, and combined with unique topographic conditions, they possess great potential for cloud water resource development.

In recent years, with the development of atmospheric detection technology, instruments such as satellites, aircraft, and microwave radiometers have been applied to analyze the microphysical structure characteristics of stratocumulus cloud systems. Previous studies have used aircraft observations to analyze the microphysical characteristics of stratocumulus clouds in different regions, finding that cold cloud processes near cloud tops enhance cloud water collection and facilitate precipitation formation. Other studies have analyzed artificial precipitation enhancement operations, finding that stratiform clouds are suitable cloud systems for such operations with abundant supercooled water inside. Research on the Qilian Mountains has shown that precipitation there is mainly composed of small raindrops, with more raindrops at higher altitudes, and that cloud water content is abundant with distinct differences in microphysical structure characteristics between the northern and southern slopes.

Numerical models can effectively depict cloud system development and precipitation generation, and are widely applied in cloud and precipitation process research. Parameter selection is critical in numerical simulation. Previous studies have demonstrated that both single-moment and double-moment schemes can simulate liquid water content and convective processes in stratocumulus clouds. Various studies have compared different microphysical parameterization schemes (e.g., Morrison, Kessler, Thompson) for different regions and weather events, finding that scheme performance varies by region. For instance, the Thompson scheme has shown superior performance for some heavy rain events, while the Reisner2 scheme performed slightly better for a summer precipitation process in the Qilian Mountains. These results indicate that the selection of cloud microphysical parameterization schemes varies by region and has substantial influence on precipitation simulation.

This study employs observed data obtained from the Qilian Mountain Terrain Cloud Artificial Precipitation (Snow) Enhancement Technology Research Experiment, combined with a cloud model, to conduct a numerical simulation of a typical stratocumulus precipitation process in the Qilian Mountains. The study investigates the influence of parameter selection on simulation results, identifies the optimal parameterization scheme applicable to the Qilian Mountains, and analyzes the microphysical structure characteristics of typical stratocumulus cloud systems to further clarify indicators for artificial precipitation enhancement operations in the region.

1.1 Data

Data were selected from the Qilian Mountain Terrain Cloud Artificial Precipitation (Snow) Enhancement Technology Research Experiment, covering the range of 100°-104°E, 36°-39°N. The study utilized measured hourly precipitation data from 2019-2020 across different underlying surfaces (terrain, geology, soil, and vegetation). Observation stations include national stations, regional stations, and field stations. National stations refer to surface meteorological observation stations established according to national climate analysis and weather forecasting needs; regional stations refer to surface meteorological observation stations established according to provincial (regional, municipal) administrative divisions; and field stations refer to surface meteorological observation stations established for project research needs. Additionally, the study includes NCEP/FNL (Final Operational Global Analysis) reanalysis data provided by the U.S. National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCAR).

1.2 Model Design

The numerical model employs the mesoscale Weather Research and Forecasting (WRF) model version 4.3, with three-level nested grid simulation ranges and grid resolutions as shown in Table 1. The simulation domain center is at (102°E, 37°N). The horizontal direction uses an Arakawa C grid, while the vertical direction employs a hybrid vertical coordinate. The NCEP/FNL reanalysis data with 1°$×$1° resolution serve as the initial field. Cloud microphysical processes respectively adopt the Thompson, Morrison2-mom, WDM6, and Goddard schemes. The condensate variables for the four microphysical schemes are shown in Table 2. To quantitatively evaluate the precipitation simulation results of the WRF model, this study employs three scoring metrics: Threat Score (TS), Bias Score (BIA), and Equitable Threat Score (ETS). The TS score calculates the accuracy rate of numerical model forecasts for a certain precipitation level when precipitation occurs, the BIA score assesses the frequency of forecast precipitation without considering accuracy, and the ETS score comprehensively evaluates the overall effect of precipitation classification forecasts while weakening the influence of the number of stations participating in the statistics on the TS score results. The formulas for the scores are:

$$BIA = \frac{NA + NB}{NA + NC}$$

$$ETS = \frac{NA - Nr}{(NA + NB + NC - Nr)}$$

$$TSS = \frac{NA \times ND - NB \times NC}{(NA + NC) \times (NB + ND)}$$

where NA is the number of stations with correct forecasts; NB is the number of stations with false alarms (forecasting precipitation of a certain magnitude when observed precipitation is not that magnitude); NC is the number of missed stations (observing precipitation of a certain magnitude when forecast precipitation is not that magnitude); ND is the number of stations with no precipitation in both observation and forecast; and Nr is the impact of random forecasts.

The classification of precipitation levels for statistical testing of simulated precipitation and the corresponding number of stations are shown in Table 3. Based on the maximum precipitation of this event, heavy rain and torrential rain are classified into the same category. A total of 235 stations in the third nested domain with 3 km horizontal resolution are selected as effective scoring stations (Figure 1).

2. Typical Stratocumulus Precipitation Process in the Qilian Mountains and Simulation Verification

2.1 Synoptic Situation Analysis

Figure 3 shows that the northwestern region is controlled by an upper-level westerly trough, with warm airflow ahead of the trough. The observation area is located at the intersection of cold and warm airflows behind the ridge and ahead of the trough, controlled by southwest airflow. The temperature field lags behind the height field within the trough, with strong cold air transport behind the trough. Under the combined influence of warm, moist southwest airflow ahead of the trough and cold air, precipitation weather occurs.

2.2 Parameterization Scheme Evaluation and Verification

Figure 4 shows that all four schemes can simulate the general location of the rainband and the heavy precipitation center, which is located on the southern slope of the Qilian Mountains. This precipitation process belongs to the light rain category. The simulated rainfall amount and rainband range are somewhat larger than observed, with the observed heavy precipitation center range averaging 25.32 mm, while the simulated heavy precipitation center range averaging 38.83 mm. Comparing the simulation results of the four schemes, the heavy center simulated by the Thompson scheme is slightly northward shifted compared to other schemes, while the Morrison2-mom scheme simulates precipitation in the Qilian Mountains with some displacement.

This study uses a two-dimensional linear interpolation method to interpolate the hourly precipitation data simulated by the WRF model with four parameterization schemes to the 235 selected observation stations, and calculates the three scoring results (Figure 5). The TS scores for the Thompson, Morrison2-mom, WDM6, and Goddard schemes are 0.42, 0.38, 0.35, and 0.32, respectively. Overall, the model forecasts light rain relatively well, while heavy rain forecasts are poorer. From the BIA and ETS scores, the Thompson scheme is superior to the Morrison2-mom scheme. Based on the comprehensive TS, BIA, and ETS scoring results, the Thompson parameterization scheme demonstrates better simulation performance than the Morrison2-mom scheme and is identified as the optimal parameterization scheme for the Qilian Mountains.

2.3 Comparison of Observed and Simulated Radar Echoes

Figure 6 shows the comparison of observed and simulated radar echo composite reflectivity. The observed radar echo images reveal typical stratocumulus precipitation echo characteristics for this precipitation process, with columnar convective cloud echoes embedded in a relatively uniform echo layer. Within a larger range, the echo edges appear fragmented, with stratiform precipitation echoes weaker than 25 dBZ. The echo maximum value is 45 dBZ. The precipitation system affecting the Qilian Mountains moves from southwest to northeast, and the simulated radar echo also reflects this characteristic. The locations of strong echoes are relatively close between simulation and observation, indicating that the WRF model simulates this stratocumulus precipitation process in the Qilian Mountains with considerable accuracy. Moreover, as terrain height increases, the observed and simulated radar echo changes are basically consistent.

3. Microphysical Structure Characteristics of Stratocumulus Clouds in the Qilian Mountains

Based on the above analysis, the Thompson scheme simulation results are used to analyze the microphysical structure characteristics of stratocumulus clouds in the Qilian Mountains.

3.1 Temporal Variation of Hydrometeor Mixing Ratios

Figure 8 shows the temporal-height evolution of regional average values of five hydrometeors (cloud water, rainwater, ice crystals, snow, and graupel) at the heavy precipitation center during the simulation period. The results indicate that supercooled cloud water is distributed at heights of 5-7 km (-3°C to -12°C), with a maximum value of 1.6 $g \cdot kg^{-1}$. Rainwater is mainly distributed below 4.5 km (0°C layer), with a maximum value of 0.26 $g \cdot kg^{-1}$. Ice crystals are located at 10–14 km (-50°C), with a maximum value of 0.003 $g \cdot kg^{-1}$. Snow is distributed at 4-12 km, with a maximum value of 1.2 $g \cdot kg^{-1}$. Graupel is distributed at 4–6 km, with a maximum value of 0.1 $g \cdot kg^{-1}$. The content distribution of various hydrometeors basically shows a single-peak pattern. The values of graupel mixing ratio and snow mixing ratio near 4.5 km can reach 0.1 $g \cdot kg^{-1}$ and 0.7 $g \cdot kg^{-1}$, respectively. This height layer has relatively abundant supercooled water, which is extremely favorable for the growth of graupel and snow riming. The distribution and trend of rainwater are basically consistent with those of graupel and snow, indicating that the melting processes of snow and graupel are the main sources of rainwater formation.

3.2 Vertical Distribution of Hydrometeor Mixing Ratios

Figure 9 shows that the vertical microphysical structure differs in different cloud regions. At 37.0°E, 100.5°N, there is a single cloud body with a relatively thick cloud water region, rainwater content reaching 0.1 $g \cdot kg^{-1}$, but snow and graupel contents are relatively low, and ice crystals in the upper layer are below 0.01 $g \cdot kg^{-1}$, producing a small amount of precipitation on the ground, indicating that warm cloud processes contribute mainly to precipitation at this stage. At 37.3°E, 100.8°N, the cloud layer is relatively deep with multiple cells. Ice crystals are distributed at 9-14 km (-50°C). The top heights of snow and graupel ranges are consistent with ice crystals, with maximum values reaching 0.15 $g \cdot kg^{-1}$ and 1.5 $g \cdot kg^{-1}$, respectively. The distribution of rainwater is relatively consistent with snow and graupel, with large rainwater mixing ratio values located below the large-value regions of graupel and snow, indicating that the melting processes of snow and graupel make major contributions to rainwater formation.

The coexistence region of ice crystals and snow is located in the highest layer above 8 km, while cloud water, rainwater, and graupel particles simultaneously exist in the supercooled region above the 4.5 km zero-degree layer. The upper layer above 8 km is ice-phase, the supercooled region above the 4.5 km layer is a mixed ice-water phase, and the warm region below is dominated by liquid phase. This cloud structure, known as a "seeding-feeder" cloud, represents important conditions for artificial precipitation enhancement.

4. Conclusions

Based on the Thompson scheme simulation results, this study analyzes the microphysical structure characteristics of stratocumulus clouds in the Qilian Mountains. The main conclusions are:

1. The Thompson scheme can simulate the location of the rainband and the heavy precipitation center. The simulated rainfall amount and rainband range are somewhat larger than observed. Based on comprehensive TS, BIA, and ETS scores, the Thompson parameterization scheme demonstrates better simulation performance than the Morrison2-mom scheme and is identified as the optimal parameterization scheme for the Qilian Mountains.

2. The content distribution of various hydrometeors basically shows a single-peak pattern. The values of graupel mixing ratio and snow mixing ratio near 4.5 km can reach 0.1 $g \cdot kg^{-1}$ and 0.7 $g \cdot kg^{-1}$, respectively. This height layer has relatively abundant supercooled water, which is extremely favorable for graupel and snow riming. The distribution and variation of rainwater are consistent with those of graupel and snow, indicating that the melting of graupel and snow is the main source of rainwater formation.

3. The cloud system exhibits a "seeding-feeder" layered structure in the vertical direction. The coexistence region of ice crystals and snow is located

in the highest layer above 8 km, while graupel particles, cloud water, and rainwater simultaneously exist in the supercooled region above the 4.5 km zero-degree layer. This cloud structure is conducive to precipitation formation and favorable for artificial precipitation enhancement operations in the Qilian Mountains. Additionally, the vertical microphysical structure of hydrometeors differs in different parts of the cloud system, affecting their contributions to precipitation.

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Note: Figure translations are in progress. See original paper for figures.