

Comparison and Performance Evaluation of Numerical Model Heavy Rain Forecasts in Gansu Province (Postprint)

Authors: Peng Xiao, Kong Xiangwei, Chen Xiaoyan, Wu Jing, subcrystal, Li Wenxue

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Abstract

Using precipitation observation data from national meteorological stations, the precipitation forecast performance of the European Centre for Medium-Range Weather Forecasts global model (ECMWF), China Meteorological Administration Global Assimilation and Forecast System (CMA-GFS), China Meteorological Administration Mesoscale Numerical Weather Prediction System (CMA-MESO), and China Meteorological Administration Shanghai Numerical Weather Prediction Model System (CMA-SH9) during the heavy rainfall events in Gansu in the 2022 main flood season was evaluated based on the MET verification system. The results show that: (1) The accuracy rates of rain/no-rain forecasts among the four numerical models are similar, all exceeding 0.80. For the TS score of precipitation forecasts ≥ 50 mm, CMA-SH9 achieves the highest score, followed by CMA-MESO. (2) Based on the characteristics of influencing systems and circulation patterns, the heavy rainfall events in Gansu during the main flood season are classified into three types: subtropical high edge type, northwesterly flow type, and low trough type. For precipitation forecasts ≥ 50 mm, the CMA-SH9 model demonstrates the best forecast performance among the four models, particularly for low trough type heavy rainfall events, followed by the subtropical high edge type. (3) Based on MODE spatial verification, it is found that for precipitation forecasts ≥ 50 mm, the two regional models CMA-MESO and CMA-SH9 exhibit superior forecast capability compared to the two global models ECMWF and CMA-GFS; during the heavy rainfall event on July 14, the CMA-SH9 model shows relatively smaller centroid distance and axis angle deviation for the forecasted heavy rainfall, with its forecast of the location and spatial orientation of the heavy rainfall being closest to the observations.

Full Text

Preamble

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Title

Comparison and Performance Evaluation of Numerical Model Rainstorm Forecasts in Gansu Province

Authors

PENG Xiao¹, KONG Xiangwei¹, CHEN Xiaoyan², WU Jing¹, FU Jing¹, LI Wenxue¹

¹ Lanzhou Central Meteorological Observatory, Lanzhou 730020, Gansu, China

² Institute of Arid Meteorology, China Meteorological Administration, Lanzhou 730020, Gansu, China

Abstract

Using precipitation observation data from national meteorological stations and based on the Model Evaluation Tools (MET) verification system, this study evaluates the precipitation forecast performance of four numerical models during the 2022 main flood season rainstorm events in Gansu: the European Centre for Medium-Range Weather Forecasts global model (ECMWF), the China Meteorological Administration Global Assimilation Prediction System (CMA-GFS), the China Meteorological Administration Mesoscale Weather Numerical Prediction System (CMA-MESO), and the China Meteorological Administration Shanghai Numerical Prediction Model System (CMA-SH9). The results demonstrate that: (1) The four numerical models show similar accuracy in predicting precipitation occurrence, all exceeding 0.80, with CMA-SH9 achieving the highest Critical Success Index (CSI) score for \$ 50 mm precipitation forecasts, followed by CMA-MESO. (2) Based on the characteristics of influencing systems and circulation patterns, rainstorms during Gansu's main flood season can be classified into three types: subtropical high marginal type, northwest airflow type, and low trough type. Among these, CMA-SH9 demonstrates the best forecast performance for \$ 50 mm precipitation, particularly for low-trough rainstorm processes, followed by the subtropical high marginal type. (3) Spatial verification using the Method for Object-based Diagnostic Evaluation (MODE) reveals that for \$ 50 mm precipitation forecasts, the two regional models (CMA-MESO and CMA-SH9) outperform the two global models (ECMWF and CMA-GFS). The ECMWF model exhibits relatively small centroid distance and axis angle deviation for rainstorm forecasts, providing the closest match to observed rainstorm locations and spatial orientation.

Keywords: numerical model; performance evaluation; rainstorm; spatial verification; Gansu

1. Introduction

China experiences frequent rainstorm events of varying intensity annually, with occurrences observed across nearly all regions. The country's rainstorms predominantly occur during summer, characterized by a distribution pattern of "more in the south and east, less in the north and west" [?]. Compared to southern regions, Gansu Province in northwestern China experiences weaker rainstorm coverage and intensity [?]. However, due to factors such as loose soil, high susceptibility to water erosion, and underlying surface vegetation and physical properties, the destructive potential of rainstorms remains extremely severe. Therefore, accurate rainstorm forecasting in this region is crucial for mitigating disasters such as flash floods and debris flows.

Currently, numerical forecast products serve as essential references for rainstorm prediction in meteorological departments. However, limitations in model initial conditions, differences in model frameworks and parameterization schemes, and inherent model errors [?] result in deviations between model forecasts and observations during rainstorm events. Consequently, conducting verification and evaluation of numerical model rainstorm forecast performance can significantly enhance model application and improvement. Numerous studies have investigated numerical model precipitation forecast verification, revealing that different models exhibit varying forecast effectiveness across different spatiotemporal scales and precipitation magnitudes [?]. For global ensemble forecast models, their ability to capture dynamic and thermodynamic fields at mesoscales is stronger, leading to superior precipitation location and magnitude forecasts [?]. The ECMWF model demonstrates notably higher accuracy for autumn-winter and spring precipitation compared to summer [?]. In seasons with uniform precipitation characteristics, models show minimal differences for light precipitation but provide valuable references for heavy precipitation [?]. The CMA-GFS model exhibits stable performance for short-range precipitation forecasts [?], yet shows a systematic underestimation bias for regional rainstorm processes [?]. The GRAPES_{MESO} model demonstrates higher capability for continuous precipitation forecasts than for local short-duration heavy precipitation, with better performance for nowcasting of local short-duration heavy rain [?]. The East China Regional Numerical Model (now renamed SMS-WARMS), through version upgrades, has gradually improved precipitation forecasting capability, successfully predicting main rainbands with generally accurate precipitation locations [?], and showing higher skill for heavy and torrential rain forecasts in East and Southwest China.

Gansu Province is located at the intersection of the Loess Plateau, Qinghai-Tibet Plateau, and Inner Mongolia Plateau, featuring complex and diverse terrain with substantial elevation differences. During the flood season, influenced by the East Asian monsoon, the region is prone to heavy rain and short-duration

intense precipitation, increasing the difficulty of numerical model forecasting for strong precipitation processes. To better understand the forecast performance and characteristics of numerical models for Gansu rainstorms, it is necessary to conduct verification and evaluation of multiple numerical model precipitation products. This study utilizes national meteorological station precipitation observation data and the MET verification system to conduct multi-model precipitation forecast verification analysis for rainstorm events occurring in Gansu during the main flood season of 2022, and employs the MODE method for spatial verification of different rainstorm types to analyze numerical model precipitation forecast effectiveness in the Gansu region, providing guidance and reference for the localized application of numerical model forecast products.

1.1 Data

Observational precipitation data were obtained from 24-hour accumulated precipitation records at 2,053 national observation stations (Fig. [Figure 1: see original paper]) provided by the Lanzhou Central Meteorological Observatory and the National Meteorological Information Center, as well as daily 0.03° resolution multi-source merged precipitation products. Model data were selected from four commonly used operational numerical models: the European Centre for Medium-Range Weather Forecasts global model (ECMWF), the China Meteorological Administration Global Assimilation Prediction System (CMA-GFS), the China Meteorological Administration Mesoscale Weather Numerical Prediction System (CMA-MESO), and the China Meteorological Administration Shanghai Numerical Prediction Model System (CMA-SH9). The precipitation products consist of 24-hour accumulated precipitation forecasts from 08:00 BT (Beijing Time) with a maximum forecast lead time of 72 hours. The ECMWF model has a spatial resolution of $0.125^\circ \times 0.125^\circ$ with a maximum temporal resolution of 6 hours; CMA-GFS has a spatial resolution of $0.25^\circ \times 0.25^\circ$ with a temporal resolution of 3 hours; CMA-MESO has a spatial resolution of $0.03^\circ \times 0.03^\circ$ with a temporal resolution of 1 hour; and CMA-SH9 has a spatial resolution of $0.09^\circ \times 0.09^\circ$ with a temporal resolution of 3 hours.

1.2.1 Synoptic Classification

This study selected 15 rainstorm processes occurring in Gansu during the 2022 main flood season for multi-model precipitation forecast verification analysis. Referencing recent rainstorm classification methods for the Gansu region [?], the cases were categorized into three types based on influencing systems and circulation pattern characteristics: subtropical high marginal type (5 cases), northwest airflow type (4 cases), and low trough type (6 cases).

2.1 Model Rainstorm Forecast Verification

The Model Evaluation Tools (MET) is a powerful numerical weather prediction verification system developed by the Numerical Forecast Development Test Center at the National Center for Atmospheric Research (NCAR) [?]. This study conducts objective verification using the MET verification system, with verification metrics including Accuracy (ACC), Probability of Detection (POD), False Alarm Ratio (FAR), and Frequency Bias (Bias). The verification scoring formulas are presented in Table .

Quantitative verification results for the four models during the 2022 main flood season rainstorm processes (Fig. [Figure 2: see original paper]) show that all models achieve similar accuracy for precipitation occurrence forecasts, all exceeding 0.80, with CMA-SH9 showing the highest accuracy at 0.86. As precipitation magnitude increases, model CSI scores and POD gradually decrease, while corresponding FAR and missed detection rates increase. All models demonstrate good performance for \$ \$0.1 mm precipitation forecasts, with CSI scores exceeding 0.55. The ranking from highest to lowest CSI score is: CMA-SH9, CMA-MESO, ECMWF, and CMA-GFS. For \$ \$10 mm and \$ \$25 mm precipitation forecasts, CMA-SH9 maintains the highest CSI scores, with ECMWF ranking second. For \$ \$50 mm precipitation forecasts, CMA-SH9 still achieves the highest CSI score, with its missed detection rate significantly lower than other models. The two global models (ECMWF and CMA-GFS) show Bias values greater than 1.0 for \$ \$0.1 mm and \$ \$10 mm precipitation forecasts, indicating over-forecasting of precipitation events relative to observations. For \$ \$25 mm precipitation, ECMWF shows a Bias of 1.08 (slight over-forecasting), while CMA-GFS shows a Bias of 0.89 (slight under-forecasting). For \$ \$50 mm precipitation, all models exhibit Bias values less than 1.0, indicating under-forecasting of precipitation events.

2.2 Rainstorm Process Classification Verification

2.2.1 Subtropical High Marginal Type

Subtropical high marginal rainstorm processes are characterized by pronounced southerly warm-moist airflow transport, with rainstorms typically occurring during relatively stable periods following the westward extension of the subtropical high. During these periods, cold and warm airflows converge violently along the northwestern edge of the subtropical high, accompanied by strong thermal and dynamic instability. All models achieve accuracy scores above 0.80 for precipitation occurrence forecasts, with CMA-SH9 showing the highest accuracy at 0.86. CMA-SH9 also achieves the highest CSI scores for \$ \$0.1 mm, \$ \$10 mm, and \$ \$25 mm precipitation forecasts, followed by ECMWF. For \$ \$50 mm precipitation forecasts, CMA-SH9 maintains the highest CSI score and the lowest missed detection rate, significantly outperforming other models. As precipitation magnitude increases, model forecast bias also increases. The largest differences in forecast bias among models occur for \$ \$50 mm precipitation, where CMA-SH9

shows a Bias of 1.35 (over-forecasting), while ECMWF shows a Bias of 0.65 (under-forecasting).

2.2.2 Northwest Airflow Type

Northwest airflow rainstorm processes are primarily characterized by Gansu being controlled by a northwest airflow pattern ahead of a high-pressure ridge. The northwest airflow and temperature trough jointly create strong mid-to-upper level dry-cold advection, which overlays relatively warm-moist airflow or warm temperature ridges at lower levels, generating strong upward motion and intense convective activity. All models achieve accuracy scores above 0.80, slightly lower than for the subtropical high marginal type. CMA-SH9 achieves the highest CSI scores for \$ \$0.1 mm, \$ \$10 mm, and \$ \$25 mm precipitation forecasts, with ECMWF ranking second. For \$ \$50 mm precipitation forecasts, all four models achieve CSI scores of 0.0, with missed detection rates reaching 100%. Overall CSI scores and POD for northwest airflow type precipitation forecasts are lower than for the subtropical high marginal type, primarily due to higher missed detection rates. All models show Bias values less than 1.0 for \$ \$25 mm and \$ \$50 mm precipitation forecasts, indicating under-forecasting relative to observations, with more significant under-forecasting for the northwest airflow type.

2.2.3 Low Trough Type

Low trough rainstorm processes feature upper-level troughs gradually moving eastward along the westerlies over Gansu, with southwest or southerly airflow transport ahead of the 500 hPa trough and northwest airflow behind the trough. The environment exhibits high humidity, pronounced warm-moist airflow transport, and long duration. All models achieve accuracy scores above 0.85 for precipitation occurrence forecasts, significantly higher than for the subtropical high marginal and northwest airflow types. For \$ \$10 mm and \$ \$25 mm precipitation forecasts, all models show CSI scores above 0.55, with CMA-SH9 achieving the highest score of 0.65 for \$ \$25 mm precipitation, followed by the other three models. For \$ \$50 mm precipitation forecasts, the low trough type shows the highest CSI scores among the three rainstorm types, primarily due to higher POD values. All models show Bias values less than 1.0 for \$ \$25 mm and \$ \$50 mm precipitation forecasts, indicating under-forecasting relative to observations.

2.3 Spatial Verification

The Method for Object-based Diagnostic Evaluation (MODE) [?] identifies a series of “objects” in both forecast and observation fields and quantitatively calculates spatial attribute parameters of these objects in reconstructed forecast and observation fields to verify overall spatial forecast performance. Based on the MODE verification method, this study conducts spatial distribution charac-

teristic analysis for precipitation ≥ 50 mm, evaluating model performance by comparing object attributes including area, centroid distance, axis angle deviation, and intensity between forecast and observation fields.

2.3.1 Subtropical High Marginal Type

Spatial verification of the subtropical high marginal rainstorm process reveals that model forecast rainstorm areas are smaller than observed values, with centroid distances within 50 km and axis angle deviations within 30° , indicating that model forecasts are positioned slightly north of observations. For ≥ 50 mm precipitation forecasts, ECMWF and CMA-GFS failed to predict rainstorms. CMA-MESO and CMA-SH9 predicted rainstorm areas larger than observed values, with 50th percentile precipitation intensity ratios greater than 1.0, indicating stronger predicted precipitation than observed. CMA-SH9 shows smaller centroid distance and axis angle deviation, better capturing the spatial location of rainstorms.

2.3.2 Northwest Airflow Type

For northwest airflow rainstorm processes, ECMWF and CMA-GFS failed to predict ≥ 50 mm rainstorms. CMA-MESO predicted rainstorm areas significantly larger than observed values, with 50th percentile precipitation intensity slightly higher than observed, indicating stronger predicted precipitation. CMA-SH9 predicted rainstorm areas larger than observed, with 50th percentile precipitation intensity slightly higher than observed values, also indicating stronger predicted precipitation. CMA-SH9 shows smaller centroid distance and axis angle deviation, better capturing rainstorm spatial location.

2.3.3 Low Trough Type

For low trough rainstorm processes, ECMWF failed to predict ≥ 50 mm rainstorms. The other three models predicted centroid distances below 30 km and axis angle deviations below 20° , indicating more accurate position and orientation forecasts compared to the subtropical high marginal and northwest airflow types. All models predicted rainstorm areas larger than observed values, particularly CMA-MESO. The 90th percentile precipitation intensity ratios for CMA-MESO and CMA-SH9 are below 1.0, indicating weaker predicted precipitation than observed. The 50th percentile precipitation intensity ratios are close to observed values, with CMA-SH9 showing the closest match to actual conditions.

2.4 Typical Case Analysis

To further understand model forecast performance and deviation characteristics, the strongest rainstorm process during the 2022 main flood season was selected for analysis. On July 14, a subtropical high marginal rainstorm process occurred. Spatial verification identified one paired object for each model

(Fig. [Figure 6: see original paper]), with red shapes representing successfully paired rainstorm objects between each model and observations, and blue areas indicating rainstorm zones.

The CMA-SH9 model predicted rainstorm centroid distance of 4.91 km and axis angle deviation of 5.21° , with 90th percentile precipitation intensity closest to observations, demonstrating superior spatial position forecast capability. The CMA-MESO model predicted rainstorm area smaller than observed, with 90th percentile precipitation intensity below observed values, indicating weaker predicted precipitation. The ECMWF model predicted rainstorm area larger than observed, with 90th percentile precipitation intensity slightly above observed values, indicating stronger predicted precipitation. Overall, CMA-SH9 and CMA-MESO demonstrate stronger \$50 mm precipitation forecast capability than ECMWF and CMA-GFS. Compared to subtropical high marginal and northwest airflow rainstorm processes, low trough rainstorm processes show smaller centroid distances and axis angle deviations, indicating more accurate position and orientation forecasts.

3. Discussion

This study evaluated four numerical models for Gansu rainstorm forecasts and employed the MODE method for spatial verification of different rainstorm types, surpassing traditional point-to-point verification methods by quantitatively analyzing deviations in rainstorm location, intensity, and area to better meet operational forecast service requirements [?]. The analysis reveals that the two regional models (CMA-MESO and CMA-SH9) demonstrate superior \$50 mm precipitation forecast capability compared to the two global models (ECMWF and CMA-GFS), likely due to their higher resolution enabling better simulation of triggering mechanisms for mesoscale convective systems and stronger capability for forecasting intensity and coverage of locally intense precipitation or large-scale precipitation centers [?]. ECMWF's relatively small centroid distance and axis angle deviation may benefit from its better representation of Gansu's terrain, such as the Loess Plateau in eastern Gansu, enabling more accurate position and spatial orientation forecasts [?].

These results provide important reference for localized application and bias correction of numerical model products in Gansu, helping forecasters better utilize numerical model products for accurate advance prediction of rainstorm processes. However, due to limitations in time scale and rainstorm process sample size, the verification results may not fully reflect numerical model performance for Gansu rainstorms. Future work should extend the study period, collect more rainstorm samples, conduct multi-scale spatiotemporal analysis of model rainstorm forecast performance and deviation characteristics, and investigate potential causes of model forecast biases to provide greater support for localized model product application and bias correction.

4. Conclusion

Based on the MET verification system, this study conducted multi-model precipitation forecast verification analysis for 15 rainstorm processes occurring in Gansu during the main flood season of 2022, yielding the following main conclusions:

- (1) The four models show similar accuracy for precipitation occurrence forecasts, all exceeding 0.80. As precipitation magnitude increases, model CSI scores and POD gradually decrease while FAR and missed detection rates increase. For \$ 50 mm precipitation forecasts, CMA-SH9 achieves the highest CSI score, primarily due to its lower missed detection rate compared to other models and its tendency to over-forecast precipitation events relative to observations.
- (2) Based on influencing systems and circulation pattern characteristics, Gansu's main flood season rainstorms can be classified into three types: subtropical high marginal, northwest airflow, and low trough. During low trough rainstorm processes, the four models achieve accuracy scores above 0.85, significantly higher than for subtropical high marginal and northwest airflow types. CMA-SH9 demonstrates the best performance for \$ 50 mm precipitation forecasts, particularly for low trough rainstorm processes, followed by subtropical high marginal type. The two global models (ECMWF and CMA-GFS) achieve CSI scores of 0.0 for rainstorm station forecasts with missed detection rates reaching 100%.
- (3) Spatial verification analysis of model performance reveals that regional models (CMA-MESO and CMA-SH9) demonstrate superior \$ 50 mm precipitation forecast capability compared to global models (ECMWF and CMA-GFS). The ECMWF model shows relatively small centroid distance and axis angle deviation for rainstorm forecasts, providing the closest match to observed rainstorm locations and spatial orientations. In the July 14, 2022 rainstorm process, CMA-SH9 exhibited the smallest centroid distance and axis angle deviation, indicating superior spatial position forecast capability.

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