Postprint: Applicability Assessment of CRU, ERA5, and CMFD Gridded Precipitation Data over the Tibetan Plateau from 1979 to 2017

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Abstract

Using observed precipitation data from 131 meteorological stations on the Tibetan Plateau during 1979–2017, the applicability of three reanalysis precipitation datasets (CRU, ERA5, and CMFD) over the Tibetan Plateau was evaluated at both annual and seasonal scales. The results indicate: (1) All three datasets exhibit strong capability in simulating annual precipitation over the Tibetan Plateau, with correlation coefficients exceeding 0.9 relative to observed values, though all overestimate precipitation amounts; CRU and CMFD spring precipitation is relatively close to observations, CMFD summer and autumn precipitation shows the closest agreement with observations, while all three datasets demonstrate weak simulation capability for winter precipitation. (2) In terms of precipitation distribution, CMFD data demonstrates the best simulation capability for the spatial distribution of annual, spring, summer, and winter precipitation over the Tibetan Plateau; the simulation capability of the three datasets for autumn precipitation exhibits regional differences; CRU and CMFD precipitation in the western Tibetan Plateau is relatively close to observed values. (3) Regarding temporal trends, annual, spring, summer, and autumn precipitation over the Tibetan Plateau shows increasing trends, with relatively large increases in summer, while winter precipitation exhibits an overall decreasing trend. (4) CRU data shows relatively consistent trends with observed values for annual, spring, summer, and autumn precipitation over the Tibetan Plateau, followed by ERA5; ERA5 winter precipitation is relatively consistent with observations. (5) From the perspective of bias analysis, CMFD data shows the smallest bias in annual and seasonal precipitation compared to observations, being the closest to observed values. (6) Temporal variation series of station-averaged annual and seasonal precipitation from the three datasets indicate that CMFD annual, spring, summer, and autumn precipitation variations are closest to observed values, followed by CRU; CMFD winter precipitation is closest to observed values,

but the correlation coefficient does not pass the 95% significance test.

Full Text

Assessment of CRU, ERA5, and CMFD Grid Precipitation Data for the Tibetan Plateau from 1979 to 2017

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Abstract

This study evaluates the applicability of CRU, ERA5, and CMFD precipitation datasets over the Qinghai-Xizang Plateau using observed precipitation data from 131 meteorological stations at annual and seasonal scales. The results indicate that: (1) All three datasets demonstrate strong capability in simulating total annual precipitation over the plateau, with correlation coefficients exceeding 0.9 compared to observed values, though all overestimate precipitation. CRU spring precipitation is closest to observations, while CMFD summer and autumn precipitation best matches observed values. All three datasets show weaker performance in simulating winter precipitation. (2) In terms of spatial distribution, CMFD data best simulates the distribution of annual, spring, summer, and winter precipitation over the plateau. The three datasets exhibit regional differences in simulating autumn precipitation, with CRU and CMFD precipitation in western Tibet showing better agreement with observations. (3) From a trend perspective, annual, spring, summer, and autumn precipitation over the plateau shows increasing trends, particularly pronounced in summer, while winter precipitation exhibits an overall decreasing trend. (4) CRU summer and autumn precipitation trends are most consistent with observations, followed by ERA5, while ERA5 winter precipitation trends are most consistent with observed values. (5) Bias analysis reveals that CMFD data shows the smallest deviation from observed annual and seasonal precipitation, making it the closest to observations. (6) Time series analysis of station-averaged annual and seasonal precipitation indicates that CMFD annual, spring, summer, and autumn precipitation variations are most similar to observations, followed by CRU. CMFD winter precipitation is closest to observed values, though the correlation coefficient fails the 95% significance test.

Keywords: Tibetan Plateau; precipitation; grid precipitation data; applicability assessment

1. Introduction

Precipitation is the most active and direct climatic factor affecting natural ecosystems in the Tibetan Plateau region, exerting significant influence on the ecological environment. Precipitation anomalies often substantially constrain ecological development. Against the background of warming and wetting trends on the Tibetan Plateau, overall precipitation shows an increasing trend, though regional spatial differences are significant and influencing factors are not entirely consistent. Whether different regions of the plateau exhibit consistent change characteristics remains to be studied. The Tibetan Plateau features complex terrain and vast territory, with sparse observation stations in some areas that often lack representativeness. Climate change at a single station cannot comprehensively and accurately reflect regional climate conditions. Therefore, identifying high-resolution precipitation data suitable for the Tibetan Plateau is fundamental for climate change research, particularly in areas with sparse stations, and is of great significance for both operational and scientific research.

Numerous global precipitation datasets are currently available, including NOAA' s PREC/L (Precipitation Reconstruction over Land), CMAP (CPC Merged Analysis of Precipitation), GPCP (Global Precipitation Climatology Project), GPCC, and CRU (Climatic Research Unit) global monthly precipitation data, all of which have been widely applied. Shi et al. first introduced existing datasets in detail and applied them to monsoon precipitation in the middle and lower reaches of the Yangtze River, finding that established global precipitation datasets have high accuracy. With technological improvements and diversified fusion data, Zi et al. compared GPCP data with Chinese station observations, while Jiang et al. evaluated the reliability and applicability of four grid precipitation datasets for summer precipitation variability in eastern China, finding that GPCC and APHRO data better represent the first two modes and main periods of summer precipitation variability in eastern China. Wang et al. compared four reanalysis precipitation datasets with station observations in the middle and lower reaches of the Yangtze River, analyzing precipitation trends. Liu et al. evaluated GPCC data applicability in Northeast China.

In recent years, many scholars have conducted applicability studies on precipitation in the northwestern and Tibetan Plateau regions. For example, Wang et al. compared MERRA, NCEP/NCAR-1, NCEP CFSR, ERA-40, ERA-Interim, and GLDAS reanalysis datasets with observations from 73 meteorological stations on the plateau, finding GLDAS precipitation data showed the best correlation with observations. Based on station-merged precipitation data, Jiang et al. compared three satellite-retrieved precipitation datasets (CMORPH real-time, TRMM real-time, and CMORPH station-corrected data) in the Lhasa River basin from 2008-2013, concluding that corrected CMORPH data had the smallest errors. Huang et al. validated the accuracy of China ground precipitation grid data, TRMM, and GPCC precipitation data in the Yarlung Zangbo River basin, analyzing differences in interannual variation characteristics and probability distribution features among different data sources. Sun et al. used

ERA-Interim reanalysis data to analyze basic characteristics and potential factors influencing interannual variability of winter precipitation on the western side of the Tibetan Plateau from 1979-2014, concluding that winter precipitation mainly occurs in the western region with consistent spatial patterns, and that required water vapor primarily originates from upstream areas and enters through the western boundary. Wang et al. used CMFD and GLDAS datasets to study climate characteristics and spatiotemporal variation patterns in the Selin Co basin, finding that warming temperatures and increased precipitation have created a significant warm-wet climate background in recent decades, which has implications for lake expansion mechanisms, ecosystem responses to climate change, and phenological changes.

Previous research indicates that due to differences in data sources and processing procedures, different datasets describe regional precipitation characteristics differently. Therefore, selecting which global reanalysis precipitation dataset can better reflect precipitation characteristics in China is worth exploring. Most studies on the applicability of multi-source precipitation on the Tibetan Plateau focus on small regions, with comprehensive evaluation and comparison of multiple reanalysis precipitation datasets across the entire plateau lacking. Therefore, this study selects three widely used reanalysis precipitation datasets (CRU, ERA5, and CMFD) for comparison with Tibetan Plateau precipitation observations to identify a relatively more suitable global reanalysis dataset for plateau precipitation research. This provides data sources for climate change research in station-scarce areas and enables better investigation of regional climate differences on the Tibetan Plateau, facilitating comparison with climate model simulations and providing theoretical basis for climate prediction on the plateau.

1.1 Station Data

Observational data used in this study consist of monthly precipitation data from 131 benchmark meteorological stations across the Tibetan Plateau from 1979-2017 (Fig. 1).

1.2 CRU Data

The high-resolution gridded dataset from the Climatic Research Unit (CRU) at the University of East Anglia is one of the most widely used near-surface climate datasets globally. This dataset first calculates anomalies for each station throughout the period using 1961-1990 climate averages, interpolates anomalies to grid points via thin-plate spline interpolation, and then superimposes climate averages to obtain final gridded data. The dataset includes climate variables such as mean temperature, diurnal temperature range, precipitation, frost and dew frequency, vapor pressure, and cloud cover, with a horizontal resolution of 0.5°$×$0.5°. This study uses CRU TS v4.03 (CRU Time Series version 4.03) data from 1979-2017 (https://crudata.uea.ac.uk/cru/data/hrg/).

1.3 ERA5 Data

The European Centre for Medium-Range Weather Forecasts (ECMWF) was among the first institutions to develop reanalysis data. ECMWF reanalysis has evolved through multiple generations: ERA-15 in 1995, ERA-40 in 2002, ERA-Interim in 2006, and the fifth-generation ERA5 reanalysis data released in 2016. ERA5 provides hourly data from 1979 to present with a horizontal resolution of 0.25°$×$0.25°. This study uses ERA5 monthly data for evaluation (https://www.ecmwf.int/en/forecasts/datasets).

1.4 CMFD Meteorological Element Data

The China Meteorological Forcing Dataset (CMFD) developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, includes gridded air temperature, precipitation, specific humidity, wind speed, and solar radiation data. This dataset merges existing Princeton reanalysis data, GLDAS meteorological forcing data, GEWEX radiation data, and GLDAS precipitation data as background fields with conventional meteorological observations from the China Meteorological Administration. The dataset has a horizontal resolution of 0.1°$×$0.1°, high overall accuracy, and has been widely applied in hydrological and climate simulations.

1.5 Methods

Linear correlation coefficients are used to compare and analyze the simulation degree of reanalysis data relative to observations. Relative bias, mean absolute bias, and root mean square error are used to compare deviations between reanalysis and observed data. The correlation coefficient between observations and reanalysis for a variable is calculated as:

$$r = \frac{\sum_{i=1}^{n}(a_i - \bar{a})(o_i - \bar{o})}{\sqrt{\sum_{i=1}^{n}(a_i - \bar{a})^2 \sum_{i=1}^{n}(o_i - \bar{o})^2}}$$

Relative bias is calculated as:

$$\text{Bias} = \frac{\sum_{i=1}^{n}(a_i - o_i)}{\sum_{i=1}^{n} o_i} \times 100\%$$

Mean absolute bias is:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|a_i - o_i|$$

Root mean square error is:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(a_i - o_i)^2}$$

where n is the number of valid samples, and a and o represent reanalysis and observed data, respectively.

Taylor diagrams concisely summarize the matching degree between reanalysis and observed data. Based on the cosine theorem, Taylor diagrams display three statistical metrics—correlation coefficient, root mean square error, and standard deviation ratio—on a single plot. Observations are fixed at a point one unit from the origin along the horizontal axis. The radial distance from the origin represents the variance ratio between reanalysis and observations, indicating similarity in dispersion. The cosine of the azimuth angle represents the correlation coefficient. The distance from the observation point represents the root mean square error between reanalysis and observations; shorter distances indicate better agreement.

2. Results

2.1 Simulation Capability of Different Data Sources for Tibetan Plateau Precipitation

To comprehensively compare the similarity between CRU, ERA5, and CMFD precipitation data and station observations, their standard deviations and spatial correlation coefficients are displayed in Taylor diagrams (Fig. 2). At annual and seasonal scales, all three datasets demonstrate strong overall simulation capability for total precipitation on the Tibetan Plateau, with correlation coefficients exceeding 0.9. However, all overestimate observed precipitation values. Seasonally, CRU spring precipitation is closest to observations, while CMFD summer and autumn precipitation best matches observed values. All three datasets show weaker simulation capability for winter precipitation.

2.2 Annual and Seasonal Precipitation Distribution from Different Data Sources

To facilitate comparison between gridded and observed data, station observations were interpolated to 0.25°$×$0.25° grids using bilinear interpolation to obtain spatial distribution maps of observed precipitation. Annual observed precipitation shows a decreasing gradient from southeast to northwest across the plateau, with most areas in western Tibet and the Qaidam Basin receiving <100 mm, the Qilian Mountains and southern Tibet receiving 300-450 mm, and the southeastern plateau receiving >550 mm. Comparison reveals that CMFD best characterizes the spatial distribution pattern of “less in the northwest, more in the southeast” for annual precipitation over the plateau. CRU overestimates precipitation magnitude, while ERA5 shows a “less in the north, more in the south" pattern. Locally, ERA5 precipitation in the Qaidam Basin, northwestern and southeastern plateau is relatively consistent with observations (Fig. 3).

Spring precipitation observations show 0-50 mm across most of central, western, and northern Tibet, with 60-150 mm in northeastern and central-southern Tibet. Comparison indicates CMFD best simulates both the distribution pattern and magnitude of spring precipitation, while CRU and ERA5 overestimate spring precipitation. CMFD spring precipitation is closest to observations in the Qaidam Basin and southwestern plateau, while CRU and ERA5 overestimate precipitation in northwestern, southeastern, and northeastern plateau regions (Fig. 4).

Summer precipitation observations show most areas receiving 100-300 mm, with <50 mm in western Tibet and the Qaidam Basin, and 250-500 mm in southern and southeastern Tibet. CMFD summer precipitation distribution most closely matches observations, followed by ERA5. ERA5 overestimates precipitation in southeastern and southern Tibet, while CRU overestimates summer precipitation by more than 1.5 times and shows similar simulation capability for autumn precipitation (Fig. 5).

Autumn precipitation observations show most areas receiving 0-80 mm, with <10 mm in western Tibet and the Qaidam Basin, and 40-70 mm in southeastern Tibet. All three datasets overestimate southeastern autumn precipitation. CMFD and ERA5 precipitation in the Qaidam Basin is relatively consistent with observations, while CRU overestimates precipitation in most other areas, particularly in southwestern border regions (Fig. 6).

Winter precipitation is minimal, with observed annual winter precipitation around 0-20 mm, mainly in southwestern and southeastern border areas. CMFD winter precipitation distribution and magnitude most closely match observations, showing a "more in the west, less in the east" pattern. ERA5 shows a similar pattern but with poor performance, while CRU is clearly inconsistent with observations (Fig. 7).

2.3 Annual and Seasonal Precipitation Trends from Different Data Sources

Annual precipitation trends (Fig. 8) show increasing trends across most of the plateau (5-20 $\text{mm} \cdot \text{decade}^{-1}$), particularly significant in the Qilian Mountains and Three-River Source region. Southwestern, southeastern edges, and western Qaidam Basin show decreasing trends (5-10 $\text{mm} \cdot \text{decade}^{-1}$). CMFD annual precipitation trends most closely match observations, with significant increases (30 $\text{mm} \cdot \text{decade}^{-1}$) in northeastern, central, and southern plateau, and decreases in southwestern Tibet. CRU shows overall increasing trends, with significant decreases (15-25 $\text{mm} \cdot \text{decade}^{-1}$) in southwestern Tibet. ERA5 shows overall increasing trends, with significant decreases in Nyalam and Pali in southwestern Tibet (20 $\text{mm} \cdot \text{decade}^{-1}$) and increases in northern Qinghai and Gaize, Tibet (50 $\text{mm} \cdot \text{decade}^{-1}$).

Spring precipitation trends (Fig. 9) show decreasing trends in western edges, northern areas, and Chayu region in southern Tibet, with significant decreases in western edges. Most other areas show increasing trends, with significant increases (3-18 $\mathrm{mm \cdot decade^{-1}}$) in central and eastern plateau. CMFD spring precipitation shows overall increasing trends consistent with observations, followed by CRU. ERA5 spring precipitation shows significant increases (3-12 $\mathrm{mm \cdot decade^{-1}}$) across the plateau.

Summer precipitation trends (Fig. 10) show decreasing trends in northeastern plateau, Qaidam Basin, southeastern pastoral areas, and Bomi region in Tibet (2-20 $\mathrm{mm \cdot decade^{-1}}$), while most other areas show increasing trends, particularly significant in northern Qinghai and Gaize, Tibet (50 $\mathrm{mm \cdot decade^{-1}}$). ERA5 summer precipitation trends are most consistent with observations, followed by CMFD. CRU summer precipitation shows significant increases (10-25 $\mathrm{mm \cdot decade^{-1}}$) across most of the plateau.

Autumn precipitation trends (Fig. 11) show decreases in southern and central-western Tibet (3-15 $\mathrm{mm \cdot decade^{-1}}$), while most other areas show increases, particularly in southeastern pastoral areas, Maqu, and Hongyuan (3-9 $\mathrm{mm \cdot decade^{-1}}$). CMFD autumn precipitation trends are most similar to observations, with significant increases (3-9 $\mathrm{mm \cdot decade^{-1}}$) in northern Tibet. CRU autumn precipitation shows significant increases (3-18 $\mathrm{mm \cdot decade^{-1}}$) in northern Tibet, with significant decreases in southern Tibet, particularly in Chayu. ERA5 autumn precipitation shows overall increasing trends with significant increases (3-9 $\mathrm{mm \cdot decade^{-1}}$) in northern Tibet.

Winter precipitation trends (Fig. 12) show local increases (0-2 $\mathrm{mm \cdot decade^{-1}}$) in northeastern, northwestern, and southeastern plateau, while southern and northwestern Tibet show decreases (2-10 $\mathrm{mm \cdot decade^{-1}}$), particularly significant in Nyalam and Chayu in southern Tibet. ERA5 winter precipitation is most consistent with observations, showing overall decreasing trends with significant decreases (4-10 $\mathrm{mm \cdot decade^{-1}}$) in southwestern and southern border areas. CMFD winter precipitation shows overall decreases, with significant decreases in southwestern and southern border areas (4-10 $\mathrm{mm \cdot decade^{-1}}$). CRU winter precipitation shows overall decreases, with increases in northwestern and northeastern edges and significant decreases (4-10 $\mathrm{mm \cdot decade^{-1}}$) in southwestern and southern border areas.

2.4 Bias Analysis of Different Annual and Seasonal Precipitation Data

Due to different horizontal resolutions of the three reanalysis datasets, observed, CRU, ERA5, and CMFD precipitation data were uniformly processed to 0.25°$×$0.25° grids for consistency. Reanalysis data minus observations yield bias spatial distributions, and grid averages across the plateau were calculated for precipitation bias and RMSE.

Fig. 13 shows annual and seasonal precipitation bias for ERA5, CRU, and CMFD. Annual precipitation from ERA5 is 6.32 mm (14.5%) less than observations, with an RMSE of 27.66 mm. Spatially, most areas show 0-40 mm less precipitation, except southwestern Tibet which shows 160-400 mm more. CRU annual precipitation is 193.11 mm (39.5%) more than observations, with an RMSE of 70.73 mm, showing 80-240 mm more across most of the plateau. CMFD annual precipitation is 41.51 mm (12.33%) more than observations, with an RMSE of 12.22 mm, showing a pattern of less in southwestern Tibet and more elsewhere.

Spring precipitation bias ranges from -40 to 40 mm. ERA5 spring precipitation is 7.97 mm (22.91%) less than observations, with an RMSE of 18.66 mm. CRU spring precipitation is 112.55 mm (50.96%) more, with an RMSE of 84.23 mm, showing 40-160 mm more across most areas. CMFD spring precipitation is 10.04 mm (21.91%) more, with an RMSE of 21.91 mm, showing a dispersed distribution of 0-40 mm more.

Summer precipitation bias shows ERA5 is 16.32 mm (15.02%) less than observations, with an RMSE of 31.45 mm, showing a pattern of more in southern and less in northern areas. CRU summer precipitation is 120.400 mm (30.24%) more, with an RMSE of 84.23 mm, showing 120-400 mm more across the plateau. CMFD summer precipitation is 30.24 mm (23.15%) less, with an RMSE of 32.71 mm, showing the smallest spatial bias.

Autumn precipitation bias shows ERA5 is 8.7 mm (30.01%) more than observations, with an RMSE of 31.45 mm, showing 40-160 mm more across the plateau. CRU autumn precipitation is 32.76 mm (31.26%) more, with an RMSE of 28.92 mm, showing 0-40 mm more. CMFD autumn precipitation is 8.7 mm (27.59%) more, with an RMSE of 28.92 mm, showing the smallest spatial bias and failing significance tests.

Winter precipitation bias shows ERA5 is 14.63 mm (161.9%) more than observations, with an RMSE of 54.7 mm, showing a pattern of more in western and less in eastern areas. CRU winter precipitation is 34.61 mm (382.93%) more, with an RMSE of 5.6 mm, showing 40-120 mm more across the plateau. CMFD winter precipitation is 3.13 mm (34.68%) more, with an RMSE of 5.1 mm, showing the smallest spatial bias and failing significance tests.

To construct time series, gridded data were interpolated to 131 stations and annual station averages were calculated. Fig. 14 shows that correlation coefficients between observed and CRU/ERA5/CMFD precipitation are 0.75-0.98 for annual, spring, summer, and autumn precipitation, all passing the 95% significance test. CMFD shows the best correlation with observations and is closest to observed values. Winter precipitation correlations are 0.31-0.75, with CMFD being closest to observations but failing the 95% significance test.

3. Discussion

The Tibetan Plateau has sparse observation stations, particularly in the northwestern region where almost no stations exist. As a sensitive region responding to global climate warming, climate change on the plateau has always attracted attention. Relying solely on station data to objectively, accurately, and comprehensively understand plateau climate change is unrealistic. Finding data with dense coverage and good representativeness is important and represents an inevitable requirement for current meteorological operations. Most applicability assessments of multi-source precipitation on the plateau focus on small regions, such as the Yarlung Zangbo River basin, Selin Co basin, and western plateau, using grid data to reveal climate change characteristics in station-scarce areas. Comprehensive applicability assessments of grid precipitation data across the entire plateau have only recently begun. This study selected three widely used grid precipitation datasets and analyzed their applicability on the plateau, finding CMFD' s simulation capability for annual, summer, and winter precipitation consistent with Jiang et al. and Xie et al. However, numerous model datasets exist worldwide, making evaluation results relatively subjective. Additionally, to facilitate spatial comparison of physical quantities with multiple grid datasets, station precipitation data were interpolated, introducing some error in the assessment of reanalysis data in northwestern Tibet.

4. Conclusions

Through comparative analysis of spatiotemporal characteristics, trends, and biases between station observations and CRU, ERA5, and CMFD data on the Tibetan Plateau, the following conclusions are drawn:

(1) Overall, all three datasets demonstrate strong simulation capability for total annual precipitation on the Tibetan Plateau, with correlation coefficients exceeding 0.9, though all overestimate observed precipitation. In spring, CRU precipitation is closest to observations; in summer and autumn, CMFD is closest; all three show weakest performance for winter precipitation.

(2) Regarding precipitation distribution, CMFD best simulates the distribution of annual, spring, summer, and winter precipitation on the plateau. The three datasets show regional differences in simulating autumn precipitation. CRU and CMFD precipitation in western Tibet is relatively close to observations.

(3) In terms of trends, plateau precipitation increased during spring, summer, and autumn, particularly in summer, while winter precipitation decreased overall.

(4) CRU summer and autumn precipitation trends are most consistent with observations, followed by ERA5. ERA5 winter precipitation trends are most consistent with observations.

(5) Bias analysis shows CMFD data has the smallest deviation from observed annual and seasonal precipitation, being closest to observations.

(6) Time series analysis indicates CMFD annual, spring, summer, and autumn precipitation variations are closest to observations, followed by CRU. CMFD winter precipitation is closest to observations, but the correlation coefficient fails the 95% significance test.

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