

Performance Evaluation of ERA5 Reanalysis Precipitation Data in Inner Mongolia

Authors: Niu Yiyang

Date: 2023-09-27T00:00:00+00:00

Abstract

ERA5 is a new-generation reanalysis product released by the European Centre for Medium-Range Weather Forecasts (ECMWF), which can provide a new source of precipitation data for areas with sparse ground observation stations. Based on daily precipitation data from 45 ground stations in Inner Mongolia from 2008 to 2017, multiple evaluation metrics were used to assess the accuracy of ERA5 reanalysis precipitation data across multiple temporal and spatial scales. Combined with 13 extreme precipitation indices and a comprehensive weighted model, the Sen's slope method and Mann-Kendall trend test were employed to analyze the spatiotemporal variation patterns of extreme precipitation and its hazard in the region from 1981 to 2021. The results show that: (1) ERA5 can well reproduce precipitation processes, exhibiting extremely strong correlation with observation data at monthly and seasonal scales (correlation coefficient $CC > 0.85$), and strong correlation at daily scale ($CC = 0.68$); at the spatial scale, ERA5 data demonstrates better detection accuracy at eastern stations than western stations. (2) Except for simple daily intensity index (SDII), total precipitation from very wet days (R95pTOT), and consecutive dry days (CDD), all other extreme precipitation indices in Inner Mongolia show a decreasing trend, with total precipitation on wet days (PRCPTOT) decreasing the fastest at $-15.74 \text{ mm} \cdot (10\text{a})^{-1}$. (3) Extreme precipitation indices show obvious regional differentiation patterns in space: extreme precipitation in western Inner Mongolia shows increased intensity, in central Inner Mongolia shows decreased frequency, intensity, and duration, and in eastern Inner Mongolia shows increased intensity but decreased frequency and duration. (4) The extreme precipitation hazard index has high-value centers in Ordos City, Hulunbuir City, Bayannur City, and Hinggan League—cities (leagues) with relatively dense populations and rapid economic development—showing a significant upward trend that warrants focused attention.

Full Text

Performance Evaluation of ERA5 Reanalysis Precipitation Data and Spatiotemporal Characteristics of Extreme Precipitation in Inner Mongolia

NIU Yiyi^{1,2,3}, LI Chunlan⁴, WANG Jun^{1,2,3}, XU Hanqing^{1,2,3,5}, LIU Qing^{1,2,3}

¹Key Laboratory of Geographic Information Science, Ministry of Education, East China Normal University, Shanghai 200241, China

²School of Geographic Science, East China Normal University, Shanghai 200241, China

³Research Center for Urban Public Security, East China Normal University, Shanghai 200241, China

⁴School of Urban and Regional Science, East China Normal University, Shanghai 200241, China

⁵Institute of Eco-Chongming, East China Normal University, Shanghai 202162, China

Abstract

ERA5 is a new-generation reanalysis product launched by the European Centre for Medium-Range Weather Forecasts (ECMWF) that provides a novel precipitation data source for regions with sparse ground observation stations. Based on daily precipitation data from 45 ground stations in Inner Mongolia from 2008 to 2017, this study evaluated the accuracy of ERA5 reanalysis precipitation data across multiple temporal and spatial scales using multiple evaluation metrics. We constructed an extreme precipitation danger index by integrating 13 extreme precipitation indices through a comprehensive weighting model and analyzed the spatiotemporal variations of extreme precipitation and its associated hazards in the region from 1981 to 2021. The results demonstrate that: (1) ERA5 can effectively reproduce precipitation processes, showing stronger correlation with observations at monthly and seasonal scales (correlation coefficient > 0.85) than at daily scales (correlation coefficient = 0.68). The detection accuracy of ERA5 data is superior for eastern stations compared to western stations. (2) Except for daily wet precipitation intensity, total heavy precipitation, and continuous dry days, all extreme precipitation indices exhibited decreasing trends in Inner Mongolia, with annual total wet-day precipitation (PRCPTOT) declining most rapidly at a rate of $-15.74 \text{ mm} \cdot (10\text{a})^{-1}$. (3) Extreme precipitation indices display distinct regional spatial differentiation: western Inner Mongolia shows increased intensity, central regions exhibit decreases in frequency, intensity, and duration, while eastern areas show increased intensity but decreased frequency and duration. (4) The extreme precipitation danger index shows high-value centers with significant upward trends in Ordos City, Hulunbuir City, Bayannur City, and Hinggan League—regions with relatively dense populations and rapid economic development that warrant particular attention. These findings

facilitate the identification of optimal datasets for analyzing climatic factors in Inner Mongolia and provide a theoretical basis for formulating climate change adaptation strategies and future climate projections.

Keywords: ERA5; precipitation; accuracy evaluation; extreme precipitation index; Inner Mongolia

1 Introduction

Reliable precipitation estimation is crucial for climate change impact assessment, hydrological modeling, and disaster risk management. As global warming intensifies, improving the monitoring accuracy of precipitation—particularly extreme precipitation events—has become essential for enhancing climate research capabilities and disaster response effectiveness. Inner Mongolia Autonomous Region (hereafter “Inner Mongolia”) is located in an arid and semi-arid monsoon climate zone characterized by vast territory but sparse and unevenly distributed meteorological stations, which significantly constrains research on precipitation spatiotemporal patterns. Consequently, identifying high-resolution gridded precipitation datasets suitable for Inner Mongolia is critical for advancing climate change research and disaster risk management in the region.

Previous studies have employed various data sources to investigate extreme precipitation, including ground station observations and satellite-based precipitation products. Station data, while accurate, suffer from limited temporal coverage and cannot capture continuous spatial distributions. Satellite products such as the Tropical Rainfall Measuring Mission (TRMM), Climate Prediction Center Morphing Technique (CMORPH), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), and corrected products from the Climate Prediction Center offer direct spatial representation but require validation against ground observations due to inherent retrieval algorithm limitations. Reanalysis datasets like ERA5 integrate advantages from both ground stations and remote sensing, representing a widely adopted data type in recent years. This study systematically evaluates ERA5 precipitation data performance across multiple spatiotemporal scales in Inner Mongolia and analyzes extreme precipitation characteristics to provide a robust foundation for regional climate research and disaster prevention.

2 Data and Methods

2.1 Data Description

ERA5 reanalysis precipitation data were obtained from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/>) covering the period from January 1, 2008 to December 31, 2017, with hourly temporal resolution and 0.25° spatial resolution. Monthly and seasonal scale data were aggregated from hourly values, with daily precipitation data pre-corrected for temporal alignment. Ground observation data from 45 meteorological stations in Inner Mon-

golia were used as reference data for evaluation.

2.2 ERA5 Reanalysis Precipitation Data Evaluation Methods

2.2.1 Evaluation Approaches Two primary evaluation methods exist for precipitation data: “grid-to-point” assessment, which interpolates gridded data to station locations for comparison with ground observations, and “grid-to-grid” assessment, which spatializes station data through methods like kriging or bilinear interpolation before comparison. This study employed the grid-to-point approach using bilinear interpolation to extract ERA5 data at station locations for direct comparison with observed precipitation data across annual, seasonal, monthly, and daily scales. Seasonal divisions followed conventional meteorological classifications: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

2.2.2 Evaluation Metrics We selected six statistical metrics encompassing error evaluation and categorical statistics (Table 1). The correlation coefficient (CC) measures linear association between observed and ERA5 data, with optimal value of 1. Relative bias (RB) quantifies systematic deviation, with optimal value of 0. Root mean square error (RMSE) measures dispersion, with optimal value of 0. For categorical metrics, probability of detection (POD) reflects the ability to accurately capture precipitation events (optimal value = 1), false alarm ratio (FAR) indicates false positive rates (optimal value = 0), and critical success index (CSI) comprehensively evaluates detection capability (optimal value = 1).

2.2.3 Extreme Precipitation Indices To characterize extreme precipitation from frequency, intensity, and duration dimensions, we adopted 13 extreme precipitation indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Table 2). These indices include: PRCPTOT (annual total wet-day precipitation), R95pTOT (very wet days), Rx1day (maximum 1-day precipitation), Rx5day (maximum 5-day precipitation), Rx7day (maximum 7-day precipitation), and others measuring heavy precipitation events, consecutive wet/dry days, and precipitation intensity.

2.2.4 Extreme Precipitation Danger Index We constructed a comprehensive extreme precipitation danger index (R) by integrating the 13 extreme precipitation indices using principal component analysis to determine weights:

$$R = \sum_{i=1}^{13} w_i X_i$$

where w_i represents the weight of the i th extreme precipitation index and X_i denotes the i th index value. This index enables quantitative assessment of rainstorm and flood disaster hazards across Inner Mongolia.

2.2.5 Temporal Trend Analysis Temporal trends were analyzed using Sen's slope method, a robust non-parametric statistical approach insensitive to measurement errors and outliers, suitable for long-term time series analysis. Positive slopes indicate increasing trends, while negative slopes indicate decreasing trends. The Mann-Kendall (M-K) trend test was employed to assess trend significance, with significance level $\alpha = 0.05$. When the test statistic $|Z| > Z_{\alpha/2} = 1.96$, the trend is considered statistically significant. The M-K test also identifies temporal mutation points where trend behavior changes abruptly.

3 Results

3.1 Accuracy Assessment of ERA5 Precipitation Data

3.1.1 Multi-Scale Temporal Accuracy Comparison of spatial distributions reveals that ERA5 effectively captures the spatial pattern of multi-year average annual precipitation in Inner Mongolia (Figure 2 [Figure 2: see original paper]). Both ERA5 and station observations show precipitation increasing from southwest to northeast, with Hulunbuir City in the east receiving the most abundant precipitation (exceeding 550 mm annually) and western Alxa League receiving the least (below 100 mm). The precipitation grade boundaries derived from ERA5 data essentially coincide with those from station data, demonstrating consistent spatial distribution characteristics.

Scatter density plots between ERA5 and station precipitation data at different temporal scales (Figure 3 [Figure 3: see original paper]) show that ERA5 exhibits strong correlation with observations at daily scales ($CC = 0.68$), though this is lower than at monthly scales ($CC = 0.88$). ERA5 data show overestimation across all temporal scales, with RB values of 8.59 mm at daily scale and 59.36 mm at monthly scale. Seasonal-scale analysis indicates highest correlation in summer and lowest in winter, likely related to greater precipitation amounts in summer and smaller amounts in winter. Monthly average precipitation comparisons (Figure 4 [Figure 4: see original paper]) demonstrate that ERA5 captures monthly variation trends well but underestimates maximum monthly precipitation, particularly in summer, possibly due to algorithmic errors in the reanalysis system.

3.1.2 Site-Scale Accuracy Assessment Site-scale evaluation using a $0.1 \text{ mm} \cdot \text{d}^{-1}$ precipitation threshold reveals that ERA5 performs better in eastern stations than western stations (Figure 5 [Figure 6: see original paper]). Error metrics show that stations with larger precipitation amounts tend to exhibit higher RB values, with most stations showing overestimation $> 0.1 \text{ mm} \cdot \text{d}^{-1}$. CC values range from 0.70 to 0.80, displaying a southwest-to-northeast increasing trend. RMSE values range from 1-2 mm in western regions to 3-5 mm in eastern regions. Categorical statistics show POD values of 0.80-0.90 in the east versus 0.40-0.50 in the west, while FAR shows the opposite pattern, consistent

with uneven precipitation distribution across the region. CSI values range from 0.40 to 0.60, indicating moderate detection capability.

3.1.3 Detection Accuracy Across Precipitation Intensities Evaluation of detection performance across different precipitation intensity thresholds (Figure 6 [Figure 6: see original paper]) shows that all three categorical statistics (POD, FAR, CSI) decrease as precipitation thresholds increase from 0.1 to 15 $\text{mm} \cdot \text{d}^{-1}$. POD decreases most significantly, from capturing over 75.6% of precipitation events at 0.1 $\text{mm} \cdot \text{d}^{-1}$ to less than 48.9% at 15 $\text{mm} \cdot \text{d}^{-1}$. FAR decreases slightly with increasing threshold, while CSI shows a small upward trend. The 0.1 $\text{mm} \cdot \text{d}^{-1}$ threshold is commonly used to distinguish precipitation occurrence, and these results demonstrate that ERA5 detection capability declines with increasing precipitation intensity.

3.2 Spatiotemporal Characteristics of Extreme Precipitation Indices

3.2.1 Spatial Patterns The 13 extreme precipitation indices exhibit distinct southwest-to-northeast spatial gradients (Figure 7 [Figure 7: see original paper]). Frequency indices (PRCPTOT, R95pTOT) decrease from west to east, with the largest precipitation differences across Hulunbuir City spanning 25–200 d. Intensity indices (Rx1day, Rx5day, Rx7day) show high values across most regions except Alxa League, with values ranging 7–8 $\text{mm} \cdot \text{d}^{-1}$. Duration indices (CWD, CDD) vary from 25–200 d across the region, with 100 d differences over east-west spans.

Spatial trend analysis (Figure 8 [Figure 9: see original paper]) reveals that frequency indices show significant decreasing trends in Hohhot City, Chifeng City, Tongliao City, Xilingol League, and Hulunbuir City, with maximum slopes of $-1.667 \text{ mm} \cdot (10\text{a})^{-1}$, particularly pronounced in densely populated areas. Intensity indices show decreasing trends only in Hohhot City, while Rx5day and Rx7day show increasing trends in western Alxa League, Ordos City, and eastern Hulunbuir City, but decreasing trends in central Hohhot, Xilingol, Chifeng, and Tongliao regions. Duration indices show opposite patterns to frequency indices.

3.2.2 Interannual Variations Interannual trend analysis (Figure 9 [Figure 9: see original paper]) indicates that PRCPTOT decreased significantly across most of Inner Mongolia at a rate of $-17.36 \text{ mm} \cdot (10\text{a})^{-1}$, with mutation points occurring around 1998. Frequency indices (R95pTOT) show non-significant decreasing trends. Intensity indices (Rx1day, Rx5day, Rx7day) exhibit increasing trends in western Alxa League, Ordos City, central Xilingol League, and eastern Chifeng, Tongliao, Hinggan League, and Hulunbuir City, but decreasing trends in Hohhot and Chifeng. Duration indices (CWD, CDD) show increasing trends with slopes of $4.924 \text{ d} \cdot (10\text{a})^{-1}$ and $-0.150 \text{ d} \cdot (10\text{a})^{-1}$, respectively, with mutation points around 1998, indicating this year as a critical turning point for climate regime shifts in Inner Mongolia.

3.3 Spatiotemporal Evolution of Extreme Precipitation Danger

The extreme precipitation danger index shows an overall decreasing trend across Inner Mongolia from 1981 to 2021 at a rate of $-0.041 \cdot (10a)^{-1}$, with a significant mutation occurring around 1998 when the trend shifted from decreasing to increasing (Figure 10 [Figure 10: see original paper]). Spatially, 19.3% of the region exhibits increasing danger index trends, with 1.93% showing statistically significant increases. High-value centers with significant upward trends are located in Ordos City, Hulunbuir City, Bayannur City, and Hinggan League—areas with relatively dense populations and rapid economic development. Low-value centers appear in Xilingol League and Ulanqab City. These patterns highlight the need for enhanced monitoring and early warning systems in high-risk regions.

4 Discussion

Reliable precipitation estimation is fundamental for climate change impact studies and disaster monitoring. Our multi-metric evaluation demonstrates that ERA5 reanalysis precipitation data exhibit high reliability in Inner Mongolia and can serve as a valuable new data source for regional precipitation research. The lower correlation at daily scales compared to monthly scales may result from error cancellation effects during temporal aggregation, consistent with findings from studies in East Asia, the Tibetan Plateau, and the Yangtze River Delta. The observed overestimation in ERA5 data may be attributed to evaporation of precipitation before detection by ground stations and inaccurate estimation of solid precipitation, as well as deficiencies in grid-scale convective parameterization schemes within the reanalysis system. However, overall errors remain within acceptable ranges.

Extreme precipitation changes can trigger urban drought and flood disasters, threatening urban safety and socioeconomic development. Our introduction of the extreme precipitation danger index establishes a direct link between extreme precipitation and hazard potential, revealing spatiotemporal patterns consistent with previous studies by Bai Meilan and You Li. Although extreme precipitation frequency shows an overall decreasing trend in Inner Mongolia, local areas exhibit significantly increasing intensity. The increasing danger index in densely populated and economically developed regions such as Ordos, Hulunbuir, Bayannur, and Hinggan League necessitates enhanced forecasting, early warning, and emergency response capabilities for flood disasters. Conversely, significant decreases in danger indices in grassland areas like Xilingol League align with drought risk assessments by Jin Ling et al., suggesting that decreasing precipitation may impact grassland biodiversity and ecological barrier functions, thereby affecting regional ecological security. These areas require improved climate projection monitoring and ecological risk early warning systems.

5 Conclusions

This study evaluated ERA5 reanalysis precipitation data performance and analyzed extreme precipitation spatiotemporal characteristics in Inner Mongolia, yielding four main conclusions:

- (1) ERA5 effectively reproduces precipitation processes in Inner Mongolia but shows overall overestimation compared to station observations. Monthly-scale data ($CC = 0.88$) outperform daily-scale data ($CC = 0.68$) due to error cancellation effects. Seasonal correlation is highest in summer and lowest in winter, likely related to precipitation amount differences. Spatially, ERA5 performs better in eastern stations than western stations, and detection capability decreases with increasing precipitation intensity.
- (2) Interannual analysis reveals that annual total wet-day precipitation (PRCPTOT) decreased most rapidly at $-17.36 \text{ mm} \cdot (10\text{a})^{-1}$ from 1981 to 2021. Most extreme precipitation indices show decreasing trends except for intensity indices (Rx1day, Rx5day, Rx7day) and total heavy precipitation (R95pTOT). Mutation points around 1998 indicate a critical climate regime shift in Inner Mongolia.
- (3) Spatially, extreme precipitation exhibits a distinct southwest-northeast gradient, increasing from southwest to northeast. Western Inner Mongolia shows increasing intensity indices but no clear trends in other indices. Central regions exhibit significant decreases in most indices (PRCPTOT, R95pTOT, Rx1day, Rx5day, Rx7day). Eastern areas show increases in intensity indices (Rx1day, Rx5day, Rx7day) but decreases in frequency and duration indices.
- (4) Although extreme precipitation frequency is decreasing overall, local areas show significantly increasing intensity. The integrated extreme precipitation danger index identifies high-value centers with significant upward trends in Ordos, Hulunbuir, Bayannur, and Hinggan League—regions with dense populations and rapid economic development (trend slope up to $0.177 \cdot (10\text{a})^{-1}$). These areas require focused attention on extreme precipitation monitoring, early warning, and emergency response. Meanwhile, decreasing precipitation in grassland regions may threaten ecological security, necessitating enhanced climate monitoring and ecological risk assessment.

References

- [1] Yong B, Chen B, Gourley J J, et al. Intercomparison of the Version-6 and Version-7 TMPA precipitation products over high and low latitudes basins with independent gauge networks: Is the newer version better in both real time and post real-time analysis for water resources and hydrologic extremes?[J]. *Journal of Hydrology*, 2014, 508: 77-87.
- [2] Tang Guoqiang, Wan Wei, Zeng Ziyue, et al. An overview of the global pre-

- precipitation measurement (GPM) Mission and its latest development[J]. *Remote Sensing Technology and Application*, 2015, 30(4): 607-615.
- [3] Huang Yizhi, Zhang Xingnan, Fang Yuanhao. Evaluation of CMORPH satellite rainfall data and its application in hydrologic process simulation[J]. *Water Resources and Power*, 2020, 38(9): 1-4.
- [4] Haile A T, Yan F, Habib E. Accuracy of the CMORPH satellite rainfall product over Lake Tana Basin in eastern Africa[J]. *Atmospheric Research*, 2015, 163: 177-187.
- [5] Ma Q, Li Y, Feng H, et al. Performance evaluation and correction of precipitation data using the 20-year IMERG and TMPA precipitation products in diverse subregions of China[J]. *Atmospheric Research*, 2021, 249: 105304.
- [6] Mantas V M, Liu Z, Caro C, et al. Validation of TRMM multi-satellite precipitation analysis (TMPA) products in the Peruvian Andes[J]. *Atmospheric Research*, 2015, 163: 132-145.
- [7] Bai Meilan, Hao Runquan, Gao Jianfeng, et al. Distribution character of extreme climatic events and evaluation of its influence on agriculture in Inner Mongolia[J]. *Agricultural Research in the Arid Areas*, 2009, 27(2): 21-27.
- [8] You Li, Dai Xingang, Zhang Yu. Extreme precipitation events in Inner Mongolia in 1961–2008[J]. *Climate Change Research*, 2010, 6(6): 411-416.
- [9] Liu Hongzhi, Xiao Changlai, Zhang Yanxiang, et al. Analysis on temporal characteristics and trend of precipitation over the past 50 years in Inner Mongolia[J]. *Research of Soil and Water Conservation*, 2015, 22(2): 74-78.
- [10] Tan M L, Santo H. Comparison of GPM IMERG, TMPA 3B42 and PERSIANN-CDR satellite precipitation products over Malaysia[J]. *Atmospheric Research*, 2018, 202: 63-76.
- [11] Yue Shuping, Yan Yechao, Zhang Shuwen, et al. Spatiotemporal variations of soil freeze-thaw state in northeast China based on the ERA5-LAND dataset[J]. *Acta Geographica Sinica*, 2021, 76(11): 2765-2779.
- [12] Jiao D L, Xu N N, Yang F, et al. Evaluation of spatial-temporal variation performance of ERA5 precipitation data in China[J]. *Scientific Reports*, 2021, 11(1): 17956.
- [13] Chen G X, Iwasaki T, Qin H L, et al. Evaluation of the warm season diurnal variability over East Asia in recent reanalyses JRA-55, ERA-Interim, NCEP-CFSR, and NASA-MERRA[J]. *Journal of Climate*, 2014, 27(14): 5517-5537.
- [14] Gabriela C R, Tereza C. Trends of daily extreme and non-extreme rainfall indices and intercomparison with different gridded datasets over Mexico and the southern United States[J]. *International Journal of Climatology*, 2021, 41(11): 5406-5430.

- [15] Wen Tingting, Guo Yingxiang, Dong Shaorui, et al. Assessment of CRU, ERA5, CMFD grid precipitation data for the Tibetan Plateau from 1979 to 2017[J]. *Arid Zone Research*, 2022, 39(3): 684-697.
- [16] Amjad M, Yilmaz M T, Yucel I, et al. Performance evaluation of satellite and model-based precipitation products over varying climate and complex topography[J]. *Journal of Hydrology*, 2020, 584: 124707.
- [17] Sharifi E, Eitzinger J, Dorigo W. Performance of the state-of-the-art gridded precipitation products over mountainous terrain: A regional study over Austria[J]. *Remote Sensing*, 2019, 11(17): 2018.
- [18] Jiang Q, Li W Y, Wen J H, et al. Evaluation of satellite-based products for extreme rainfall estimations in the eastern coastal areas of China[J]. *Journal of Integrative Environmental Sciences*, 2019, 16: 1-16.
- [19] Wang Rui, Yu Zhongbo, Yang Chuanguo, et al. Accuracy evaluation of TRMM/GPM satellite precipitation products on daily and hourly scales in upper reaches of Huaihe River Basin[J]. *Journal of Water Resources and Water Engineering*, 2018, 29(5): 109-115.
- [20] Yin Hong, Sun Ying. Characteristics of extreme temperature and precipitation in China in 2017 based on ETCCDI indices[J]. *Climate Change Research*, 2019, 15(4): 363-373.
- [21] Ma Aihua, Yue Dapeng, Zhao Jingbo, et al. Spatiotemporal variation and effect of extreme precipitation in Inner Mongolia in recent 60 years[J]. *Arid Zone Research*, 2020, 37(1): 74-85.
- [22] Xu Xinyi, Li Jianzhu, Feng Ping. Applicability of different precipitation products to runoff simulations of Luanhe River Basin[J]. *Journal of Hydroelectric Engineering*, 2021, 40(12): 25-39.
- [23] Xu Yuxia. Assessment and regionalization of flood disaster risk in Shaanxi Province based on GIS[J]. *Journal of Catastrophology*, 2017, 32(2): 103-108.
- [24] Li Sihui. Risk assessment and zonation of rainstorm and flood disasters in the southeast region of Inner Mongolia: A case study of Tongliao[J]. *Meteorology Journal of Inner Mongolia*, 2019(1): 23-28.
- [25] Huang Xiaoyuan, Li Xiehui. Future projection of rainstorm and flood disaster risk in southwest China based on CMIP6 models[J]. *Journal of Applied Meteorological Science*, 2022, 33(2): 231-243.
- [26] Li Yanni, Huang Chang, Pang Guowei. Accuracy assessment of GSMaP and IMERG satellite precipitation products in Shaanxi Province[J]. *Arid Land Geography*, 2022, 45(1): 80-90.
- [27] Sen P K. Estimates of the regression coefficient based on Kendall' s Tau[J]. *Journal of the American Statistical Association*, 1968, 63(324): 1379-1389.

- [28] Zhou C G, Gao W, Hu J, et al. Capability of IMERG V6 early, late, and final precipitation products for monitoring extreme precipitation events[J]. Remote Sensing, 2021, 13(4): 689.
- [29] Yong B, Ren L L, Hong Y, et al. Hydrologic evaluation of multi-satellite precipitation analysis standard precipitation products in basins beyond its inclined latitude band: A case study in Laohahe Basin, China[J]. Water Resources Research, 2010, 46(7): 759-768.
- [30] Zhou Qi, Zhang Haining, Ren Yuanxin. Extreme precipitation events in the Weihe River Basin from 1961 to 2016[J]. Scientia Geographica Sinica, 2020, 40(5): 833-841.
- [31] Gan Fuwan, Li Yanjie, Ni Qian, et al. Comprehensive accuracy evaluation of five satellite precipitation products in the coastal basin at multiple spatio-temporal scales[J]. China Rural Water and Hydropower, 2022(4): 72-79.
- [32] Ren Yingjie, Yong Bin, Lu Ling, et al. Evaluation of the integrated multi-satellite retrievals for global precipitation measurement (GPM) mission over the mainland China at multiple scales[J]. Journal of Lake Sciences, 2019, 31(2): 560-572.
- [33] Jin Dekai, et al. Evaluation of drought hazards in Inner Mongolia based on SPEIbase v.2.6 dataset[J]. Arid Land Geography, 2022, 45(3): 695-705.
- [34] Xiao Yang, Zhou Xu, Luo Xue, et al. Spatiotemporal characteristics of potential evapotranspiration and identification of leading factors in central Guizhou in recent 60 years[J]. Research of Soil and Water Conservation, 2021, 28(6): 190-198.
- [35] Fan Lei, Lü Aifeng, Zhang Wenxiang. Temporal-spatial variation characteristics of drought and its relationship with atmospheric circulation in Qinghai Province[J]. Journal of Arid Land Resources and Environment, 2021, 35(12): 60-65.
- [36] Ma Zice, Sun Peng, Yao Rui, et al. Temporal and spatial variation of drought and its impact on vegetation in Inner Mongolia[J]. Journal of Soil and Water Conservation, 2022, 36(6): 231-240.
- [37] Jiang Q, Li W Y, Fan Z D, et al. Evaluation of ERA5 reanalysis precipitation dataset over Chinese Mainland[J]. Journal of Hydrology, 2021, 595: 125660.
- [38] Yao Fei, Yang Xiuqin, Liu Mujia, et al. Performance evaluation of ERA5 reanalysis precipitation data in the Yangtze River Delta[J]. Journal of Soil and Water Conservation, 2022, 36(4): 178-189.

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

Source: ChinaXiv – Machine translation. Verify with original.