Analysis of Precipitation Characteristics over the Pamir Plateau in 2017 Based on WRF Simulation (Postprint)

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Abstract

The Pamir Plateau is a critical water source in Central Asia, yet precipitation data are extremely scarce due to its high elevation, which limits understanding of atmospheric precipitation and hydrological processes in the region. To characterize the spatial distribution of precipitation over the Pamir Plateau, the WRF (Weather Research and Forecasting) model was employed to simulate the spatiotemporal distribution of atmospheric precipitation from December 2016 to November 2017 at a high resolution of 6 km. Simulation results reveal that the extensive topography of the Pamir Plateau exerts a blocking effect on water vapor transport, resulting in seasonal precipitation being primarily distributed on windward slopes. During winter and spring, precipitation occurs predominantly on the western windward slopes of the Pamir Plateau, generally increasing with altitude. Precipitation zones are concentrated at altitudes of 3000-5000 m, with precipitation in high-altitude areas exceeding plain-area precipitation by several-fold. In summer, precipitation is primarily observed on the southern foothills of the Pamir Plateau. Due to this topographic barrier, the summer monsoon cannot penetrate into the interior of the plateau, resulting in precipitation of less than 100 mm at the plateau top during summer.

Full Text

Characteristics of Precipitation in the Pamir Plateau in 2017 Based on WRF Simulation

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Abstract

The Pamir Plateau is the most important water source in Central Asia, but its high altitude results in extremely scarce precipitation data, limiting understanding of atmospheric precipitation and hydrological processes in the region. To characterize the spatial distribution of precipitation in the Pamir Plateau, this study employs the Weather Research and Forecasting (WRF) model to simulate the temporal and spatial distribution of precipitation from December 2016 to November 2017 at a high resolution of 6 km. The simulation results reveal the blocking effect of the Pamir Plateau' s massive topography on water vapor transport, causing seasonal precipitation to be concentrated primarily on windward slopes. In winter and spring, precipitation occurs mainly on the windward slopes of the western Pamir Plateau, increasing overall with altitude and concentrating at elevations of 3000–5000 m, where precipitation amounts are several times higher than in plain areas. Summer precipitation appears predominantly on the southern foothills of the Pamir Plateau; due to the plateau' s obstruction, the summer monsoon cannot penetrate deep into the interior, resulting in less than 100 mm of precipitation at the plateau summit during summer.

Keywords: precipitation; WRF; high altitude; Pamir Plateau

1. Data and Methods

1.1 Data

Given the sparse distribution of meteorological stations and their general location in low-altitude valley areas that poorly match plateau topography, this study utilizes the European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) dataset and Climate Prediction Center (CPC) interpolated daily precipitation grid data at 0.5°$×0.5°*resolutiontovalidateWRFsimulationresults.TheERA5dataoffershighstationdensity, withquality* and temporal interval of 6 hours. The study domain spans approximately 32°–42°N, 67°–80°E, with all subsequent discussions referring to this region.

[Figure 1: see original paper]

1.2 Methods

The Weather Research and Forecasting (WRF) model, developed by the National Center for Atmospheric Research (NCAR), is a new-generation mesoscale numerical weather prediction system that overcomes the coarse resolution limitations of reanalysis data and effectively captures precipitation patterns in complex terrain, serving as an important tool for weather and climate research [21]. This study employs WRF version 3.8.1 at a high resolution of 6 km to simulate precipitation across the Pamir Plateau. The simulation period runs from December 1, 2016, to November 30, 2017, with December 2016 output treated as a spin-up period and excluded from analysis. Only atmospheric precipitation variations from January to November 2017 are discussed to compensate for insufficient surface observations and establish a scientific foundation for comprehensive understanding of precipitation and water resource changes in the Pamir Plateau.

Parameterization schemes include the WSM6 microphysics scheme, Kain-Fritsch cumulus parameterization, Noah land surface model, and Lambert conformal projection. This combination has demonstrated good applicability in precipitation simulation studies of the Tianshan region, showing stability across all four seasons [26]. The simulation employs dual-grid nesting centered at (37°N, 73.5°E), with horizontal grid spacings of 18 km (Grid 1) and 6 km (Grid 2), and 50 vertical levels.

2. Results

2.1 Simulation Validation

The CPC dataset is used to validate WRF simulation results. Using bilinear interpolation, WRF outputs are interpolated to 0.5°$×$0.5° resolution for spatial correlation analysis with CPC data. The correlation results for monthly precipitation from January to November 2017 are shown in [Figure 2: see original paper]. The WRF simulation results exhibit high consistency with the spatial distribution of observed precipitation, though correlation is lower in the Tarim Basin on the eastern side of the plateau and around Kongur Mountain. This may occur because the Tarim Basin receives little precipitation year-round with weak variability, while Kongur Mountain peaks exceed 7000 m, where low-resolution data cannot reflect local extreme high-altitude precipitation characteristics. The coarse resolution of CPC data smooths out spatial precipitation differences, and since its grid data are primarily interpolated from stations distributed in plain areas, significant errors exist in high-altitude regions, leading to underestimation of precipitation, particularly in winter [14]. In contrast, ERA5 data shows values closer to simulated precipitation but still fails to capture precipitation differences caused by dramatic topographic variations.

[Figure 2: see original paper]

2.2 Spatial Distribution Characteristics of Precipitation in the Pamir Plateau

To examine seasonal precipitation distribution characteristics, precipitation data are analyzed by season according to the 3000 m contour line: winter (January-February), spring (March-May), summer (June-August), and autumn (September-November). [Figure 3: see original paper] shows the spatial distribution of simulated precipitation across seasons. All three datasets reveal consistent spatial patterns, with precipitation in high-altitude areas substantially greater than in low-altitude areas, though resolution differences create significant detail variations. Compared to the 25 km resolution ERA5 data, the 6 km WRF simulation provides more detailed spatial precipitation changes, fully reflecting precipitation variability caused by dramatic terrain fluctuations.

All three datasets indicate two precipitation centers in winter: a southern center (southwestern edge of the Himalayas) and a northern center (western side of the Pamir Plateau), spanning approximately 5° of latitude on both sides of the 38°N parallel. Overall, precipitation centers concentrate in northwestern windward slope areas, with the southern center extending east-west along mountain ranges. Mountain precipitation is closely related to atmospheric circulation but also constrained by multiple factors including mountain orientation, elevation, slope aspect, gradient, moisture content, and atmospheric stability, creating complex precipitation processes and spatial variations. For complex terrain like the Pamir Plateau, high-resolution precipitation data are needed to reveal spatial changes. The high-resolution WRF simulation in [Figure 3: see original paper] better captures fine-scale precipitation structures, showing that Pamir precipitation centers consist of individual small precipitation centers at each mountain peak rather than being uniformly distributed across windward foothills. This pattern better reflects topographic forcing on precipitation distribution.

In spring, precipitation centers show no significant movement but their extent and maximum values decrease compared to winter, remaining mainly on southwestern windward slopes. In summer, the southern precipitation center shifts noticeably southward and extends toward western plains under monsoon influence, while no unified precipitation center appears in the north, with only partial precipitation points emerging in the Tianshan Mountains east of the Tarim Basin. Autumn is the dry season in Central Asia with little precipitation, and no distinct precipitation zones appear in the Pamir region.

All three datasets show spatial differences in seasonal precipitation proportions. The western and eastern Pamir Plateau exhibit low and high proportions of winter precipitation, respectively. Summer precipitation peaks appear only at the southwestern edge of the Himalayas, with significantly reduced precipitation elsewhere compared to winter and spring. In autumn, overall precipitation is far less than in other seasons, showing dry characteristics.

Central Asia is controlled by the prevailing westerlies, with the main circulation systems affecting moisture distribution being the South Asian monsoon and mid-latitude westerlies [17]. Moisture in Central Asian mountains primarily depends on mid-high latitude westerlies [18], while Himalayan precipitation is mainly influenced by South Asian monsoon [19]. The Pamir Plateau is under the control of Northern Hemisphere mid-latitude westerlies, which split into north and south branches due to obstruction by the Tibetan Plateau topography. The north-southwest airflow transports moisture from the Black Sea, Caspian Sea, and Mediterranean Sea to the Pamir region, providing conditions for winter precipitation. In summer, the Caspian Sea surface acts as a cold source, forming a seasonal anticyclone that cuts off westerly transport, leaving the Pamir Plateau under the influence of dry continental airflow east of the anticyclone and resulting in persistent low precipitation.

[Figure 3: see original paper]

[Figure 4: see original paper]

2.3 Precipitation Variation with Altitude in the Pamir Plateau

High mountain ranges significantly block moisture transport, affecting spatial precipitation distribution patterns, with elevation being a crucial topographic factor influencing precipitation differences. To reveal precipitation variation characteristics with terrain, [Figure 5: see original paper] and [Figure 6: see original paper] show latitudinal sections along 38.3°N and longitudinal sections along 72.5°E, respectively. Terrain data are derived from the surface data input within the WRF model.

The latitudinal section shows similar precipitation distribution patterns with terrain across all three datasets, but with substantial detail differences. The high-resolution WRF simulation provides finer precipitation data that captures subtle variations with elevation. In winter, WRF-simulated precipitation peaks and valleys correspond closely with mountain peaks and valleys. Precipitation increases with altitude on the western windward slopes, where precipitation is far greater than on the eastern side. Two high precipitation zones appear on the western windward slopes: a secondary maximum at 71.4°E (3000–5000 m) and a primary maximum at 75.3°E (4400 m), where winter precipitation reaches 1200–1500 mm. In contrast, precipitation decreases rapidly over the plateau surface, with the eastern Tarim Basin receiving less than 20 mm in winter. Compared to WRF, CPC data shows a winter precipitation peak at 2000 m with a maximum of 300 mm, while ERA5 shows a peak at 3000 m with a maximum of 600 mm. As resolution decreases, maximum precipitation values decrease rapidly due to spatial smoothing.

Spring precipitation patterns are similar to winter but with reduced overall amounts. In summer, northward shift of the westerlies brings continental dry airflow to northern Pamir regions, preventing significant precipitation formation on windward slopes. However, a precipitation peak appears on the eastern plateau (75°–76°E) due to a local circulation over the Tarim Basin that lifts airflow along mountain slopes, favoring precipitation formation. In autumn, enhanced westerlies produce precipitation mainly at 3000 m on windward slopes, with local maxima at mountain peaks such as Muztagh Ata, though autumn precipitation is much weaker than in winter and spring.

The longitudinal section along 72.5°E shows two precipitation centers at 38.5°N and 39.5°N in winter, with maximum precipitation of 1300 mm at 38.5°N. Spring patterns are similar but with reduced amounts. In summer, weakened westerlies and enhanced monsoon moisture primarily affect the southwestern Himalayas, increasing precipitation on windward slopes with a peak at 4200 m. The Pamir plateau interior receives significantly less summer precipitation than in winter and spring. Autumn precipitation occurs mainly in high-altitude areas with much smaller amounts than in winter and spring.

[Figure 5: see original paper]

[Figure 6: see original paper]

3. Discussion

The Pamir Plateau' s massive topography significantly influences moisture transport and precipitation. Gridded precipitation data and reanalysis products underestimate topographic precipitation in this region, while the WRF model can finely represent precipitation spatial distribution under complex terrain conditions. The simulation not only restores the spatial distribution of Pamir precipitation and identifies two precipitation centers but also reveals the increasing precipitation pattern with altitude, confirming the importance of data resolution for investigating precipitation in complex terrain.

Comparative analysis of the three datasets shows that WRF performs well in simulating plateau mountain precipitation [23], with results consistent in magnitude with existing research. However, compared to observed gridded data and reanalysis products, WRF simulations exhibit locally overestimated precipitation values. The Pamir Plateau features steep terrain with dramatic elevation changes; during WRF simulation, rapid topographic lifting causes moisture to condense quickly, producing locally high simulated precipitation values. Additionally, WRF may overdescribe mesoscale topographic lifting effects [27], enhancing terrain-forced moisture uplift and resulting in high precipitation values at mountain peaks. Furthermore, mountain meteorological stations are extremely unevenly distributed, mostly located in flat valley areas, and the representativeness of their observations for surrounding regions requires further evaluation [28].

Overall, mountain precipitation shows clear variation patterns with altitude, with major Central Asian mountain ranges following the pattern of increasing precipitation with elevation [31]. The Pamir Plateau conforms to this pattern, with prevailing westerlies transporting moisture from the Atlantic Ocean, Mediterranean Sea, Caspian Sea, and Black Sea that is intercepted by mountains and forced to ascend and condense, forming relatively abundant precipitation on the western windward slopes of the Pamir Plateau. In glacier regions of the Pamir Plateau, annual precipitation can reach 2000 mm, while the upper Amu Darya basin originating from the Pamir can receive 3000 mm annually [32], consistent with our findings.

Although WRF successfully simulates the temporal and spatial distribution of Pamir Plateau precipitation, long-term studies of precipitation variability and mechanism exploration are still lacking. Future work should strengthen precipitation simulation efforts in the Pamir region. As Chinese scientific expeditions advance, meteorological observation networks in the Pamir and Tibetan Plateau regions will become more complete with richer data, enabling deeper investigation of these issues.

4. Conclusions

This study reveals three key findings about precipitation in the Pamir Plateau: (1) Spring and winter precipitation contribute most to annual totals, representing the main precipitation seasons. In winter and spring, precipitation occurs primarily on the windward slopes of the western Pamir Plateau. (2) Precipitation generally increases with altitude, concentrating at elevations of 3–5 km, where amounts are several times higher than in low-altitude areas. (3) Summer precipitation appears mainly on the southern slopes of the Pamir Plateau; due to plateau obstruction, the summer monsoon cannot penetrate the interior, resulting in less than 100 mm of precipitation at the plateau summit.

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