Spatiotemporal Distribution of Short-duration Heavy Rainfall in Xinjiang and Its Correlation with Geographic and Meteorological Factors (Postprint)

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Date: 2026-03-24T18:53:18+00:00

Abstract

Based on hourly meteorological observation data in Xinjiang from May to September between 2016 and 2024, this study analyzes the spatiotemporal distribution characteristics of short-duration heavy rainfall. Using the Multi-Scale Geographically Weighted Regression (MGWR) model, it explores the spatial heterogeneity between short-duration heavy rainfall intensity and various geographical and meteorological factors, including altitude, slope, Normalized Difference Vegetation Index (NDVI), Precipitable Water Enhancement Index (PWEI), and average temperature.

The results indicate that short-duration heavy rainfall exhibits distinct interannual and intermonthly variation characteristics, with the peak period of diurnal variation concentrated between 10:00 and 12:00. In terms of spatial distribution, high-value areas of short-duration heavy rainfall are primarily distributed in the Tianshan Mountains and their surrounding regions, while frequencies are significantly lower in plains and basins. Comparative analysis reveals that the explanatory power and goodness-of-fit of the MGWR model are significantly superior to those of the Ordinary Least Squares (OLS) and Geographically Weighted Regression (GWR) models.

By analyzing the standardized regression coefficients of each factor in the MGWR model, it is found that altitude has the most significant impact on short-duration heavy rainfall intensity, particularly in mid-altitude regions between 1000 and 2000 m. Slopes in the range of 0° to 10° exhibit high sensitivity to short-duration heavy rainfall, and NDVI also shows a strong response in high-value areas, whereas the influences of PWEI and average temperature are relatively weak. Among all stations, altitude accounts for the highest proportion as the dominant factor at 73.43%, followed by slope and

NDVI, while the dominant proportions of PWEI and average temperature are only 1.62% and 0.43%, respectively.

Full Text

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Vol. 43 No. 3 March 2026 ARID ZONE RESEARCH DOI: 10.13866/j.azr.2026.03.03 CSTR: 32277.14.AZR.20260303

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Abstract

Short-duration heavy rainfall (SDHR) is a primary meteorological disaster in Xinjiang, often triggering flash floods, landslides, and significant economic losses. Based on hourly meteorological observation data from May to September between 2016 and 2024, this study analyzes the spatiotemporal distribution characteristics of SDHR. Utilizing the Multiscale Geographically Weighted Regression (MGWR) model, we explore the spatial heterogeneity between SDHR and various geo-meteorological factors (elevation, slope, NDVI, PWEI, and mean temperature). The results indicate that SDHR exhibits significant spatial variability across the study area. Compared to OLS and GWR models, the MGWR model demonstrates superior explanatory power and goodness-of-fit. Analysis of standardized regression coefficients reveals that elevation is the most dominant factor, accounting for 73.43% of the influence, particularly in mid-altitude regions (1,000–2,000 m). Slope and NDVI also show significant contributions, while the impacts of the Prevailing Wind-direction Effect Index (PWEI) and mean temperature are relatively weak. These findings provide a scientific basis for improving heavy rainfall forecasting and disaster mitigation in arid regions.

Keywords: Short-Duration Heavy Rainfall; Spatiotemporal Distribution; Geographical and Meteorological Factors; Multiscale Geographically Weighted Regression; Xinjiang

1 Introduction

Xinjiang, located in the hinterland of the Eurasian continent, is characterized by complex topography and an arid to semi-arid climate. Despite low annual precipitation, SDHR events are frequent and highly localized, often triggered by convective systems interacting with dramatic relief. Understanding these patterns is crucial for regional water resource management.

Current research indicates that rising global temperatures enhance the atmosphere' s water-holding capacity, following the Clausius-Clapeyron relationship (approximately 7% moisture increase per degree of warming). This trend has intensified extreme precipitation events globally. In Xinjiang, approximately 73% of local floods are triggered by heavy rainfall, posing a serious threat to life and property. Previous studies [**?**, **?**] have shown that precipitation is highly uneven, influenced by Central Asian low-pressure systems and the Tianshan Mountains. However, traditional global models like Ordinary Least Squares (OLS) assume spatial homogeneity, which fails to capture local nuances. While Geographically Weighted Regression (GWR) addresses spatial non-stationarity, it uses a single global bandwidth. This study employs the MGWR model to allow for varying bandwidths across different environmental variables, providing a more nuanced multi-scale analysis.

2 Data and Methods

2.1 Data Sources

1. **Meteorological Data:** Hourly precipitation, temperature, and wind data were obtained from the "Tianqing" platform of the China Meteorological Administration. After excluding stations with >5% missing data, 926 stations were selected from an initial 2,795. SDHR is defined as hourly intensity $\geq$ 10 mm [**?**].
2. **Topographic Data:** ASTER GDEM V3 (30m resolution) provided elevation, slope, and aspect data.
3. **Vegetation Data:** NASA' s MOD13A3 monthly product provided the Normalized Difference Vegetation Index (NDVI).

2.2 Research Methods

To improve fitting accuracy, average elevation, slope, and NDVI values within a 4 km radius of each station were extracted.

2.2.1 Ordinary Least Squares (OLS) The global linear relationship is defined as:

$$y_i = \beta_0 + \sum_{k=1}^{p} \beta_k x_{ik} + \epsilon_i$$

where y_i is the dependent variable, β_k are regression coefficients, and ϵ_i is the error term. Multicollinearity was tested using the Variance Inflation Factor (VIF).

2.2.2 Geographically Weighted Regression (GWR) GWR incorporates spatial coordinates (u_i, v_i) to allow coefficients to vary:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i) x_{ik} + \epsilon_i$$

2.2.3 Multiscale Geographically Weighted Regression (MGWR) MGWR allows for variable-specific bandwidths (bwk):

$$y_i = \beta_{bw0}(u_i, v_i) + \sum_{k=1}^{p} \beta_{bwk}(u_i, v_i) x_{ik} + \epsilon_i$$

This study used R (v4.2.2) and the Golden Section Search algorithm to optimize bandwidths based on the Corrected Akaike Information Criterion (AICc).

2.2.4 Prevailing Wind-direction Effect Index (PWEI) The PWEI [?] quantifies the angle between slope aspect (α) and prevailing wind direction (β):

$$PWEI = \cos\left[\frac{\pi(\alpha - \beta + 360)}{180}\right] + 1, \qquad 0 \le \alpha < \beta$$

$$PWEI = \cos\left[\frac{\pi(\alpha - \beta)}{180}\right] + 1, \qquad \beta \le \alpha < 360$$

Values range from 0–1 (leeward) to 1–2 (windward).

3 Results and Analysis

3.1 Temporal Distribution Characteristics

Annual Variation: SDHR frequency in Xinjiang exhibits significant interannual fluctuation, peaking in 2016 and reaching a low in 2023. These patterns correlate with El Niño/La Niña cycles; for instance, 2016 marked the end of an extreme El Niño, while 2024 (a decaying moderate El Niño year) showed a recovery in precipitation frequency.

Monthly Variation: Distribution follows a unimodal pattern peaking in July (30.63% of occurrences), followed by June and August [Figure 3: see original paper]. September has the lowest frequency due to weakened moisture transport by the westerlies.

Diurnal Variation: A distinct unimodal characteristic is observed [Figure 4: see original paper]. Frequency increases from 06:00, peaking between 10:00 and 12:00. This is driven by solar radiation intensifying surface temperatures and atmospheric instability.

3.2 Spatial Distribution Characteristics

High-value areas are concentrated in western Bortala Prefecture, southern Ili, and northern Hutubi County (Tianshan Mountains) [Figure 5: see original paper]. Wenquan County recorded the highest frequency (59 occurrences at Motuo Village). The pattern follows a "higher along mountain ranges, lower in plains and basins" trend. Orographic lifting and thermal gradients between valleys and slopes are the primary drivers.

3.3 Model Comparison and Factor Analysis

Model Performance: - OLS: $R^2 = 0.10$, AICc = 6842.87 (Poor fit). **- GWR:** $R^2 = 0.56$, AICc = 2191.88. **- MGWR:** $R^2 = 0.68$, AICc = 2065.15 (Best fit). The MGWR model effectively captures spatial heterogeneity by optimizing bandwidths for each factor.

Influence of Geo-meteorological Factors: 1. **Elevation:** The core driver (standardized coefficients: -0.62 to 1.75). Its impact is most significant at 1,000–2,000 m, where forced lifting is strongest [Figure 6a: see original paper]. 2. **Slope:** Significant influence between 0° and 10°. In windward regions, it promotes condensation; in leeward regions, it may inhibit precipitation via Foehn effects. 3. **NDVI:** Coefficients range from -0.44 to 0.78. High vegetation (NDVI 0.60–0.87) promotes moisture through transpiration, particularly in the central Tianshan and Kashgar regions. 4. **PWEI and Temperature:** These factors show relatively weak direct influence (dominant in only 1.62% and 0.43% of stations, respectively). Temperature effects are inconsistent, though precipitation is more likely between 10–20°C in moisture-abundant areas.

4 Conclusion

1. SDHR in Xinjiang is highly seasonal (peaking in July) and diurnal (peaking at midday).
2. Spatial distribution is dominated by topography, with high-frequency clusters along the Tianshan Mountains.
3. The MGWR model provides the most accurate framework for analyzing SDHR, identifying elevation as the primary determinant (73.43% dominance).
4. These results emphasize the necessity of considering multi-factor synergies and spatial non-stationarity in meteorological risk assessments for arid regions.

[Figure 1: see original paper] [Figure 2: see original paper] [Figure 3: see original paper] [Figure 4: see original paper] [Figure 5: see original paper] [Figure 6: see original paper] [Figure 7: see original paper]

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