Comprehensive Evaluation of Atmospheric Environmental Parameters for Short-Duration Heavy Rainfall in the Hedong Region of Gansu Using Fuzzy Mathematics (Postprint)

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Abstract

To improve short-duration heavy rainfall forecast equations and enhance prediction accuracy, a comprehensive evaluation of the influence weights of multiple atmospheric environmental parameters on short-duration heavy rainfall forecasting in Hedong, Gansu is essential. This study utilizes precipitation data from the flood seasons in Hedong, Gansu during 2013–2018, employs the percentile method to calculate the short-duration heavy rainfall threshold for June–August in this region, selects 92 short-duration heavy rainfall cases based on this threshold, and analyzes atmospheric environmental parameters using ECMWF 0.25°$×$0.25° reanalysis data. The analysis reveals that parameters such as K-index, 700 hPa relative humidity, and precipitable water vapor exhibit good predictive significance for short-duration heavy rainfall in Hedong, Gansu. Based on fuzzy mathematics methodology and considering both significance and appropriateness, a comprehensive evaluation scheme for 28 atmospheric environmental parameters is constructed to derive parameter weights for different time periods. Comprehensive analysis demonstrates that when short-duration heavy rainfall occurs during the flood season in Hedong, Gansu, the weight ranking of atmospheric environmental parameters varies across different periods. Therefore, forecasting short-duration heavy rainfall requires consideration of the weights of atmospheric environmental parameters for the specific climate period in question, with priority given to parameters ranked higher in the weighting scheme.

Comprehensive Evaluation of Atmospheric Environmental Parameters for Short-Duration Rainstorms in the Hedong Region of Gansu Province Based on Fuzzy Mathematics

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Abstract

To improve short-duration rainstorm forecast equations and enhance forecast accuracy, it is essential to comprehensively evaluate the influence weights of various atmospheric environmental parameters on short-duration rainstorm forecasting in the Hedong region of Gansu Province. Using hourly precipitation data from the 2013–2018 flood seasons in Hedong, Gansu, this study employs the percentile method to calculate monthly thresholds for short-duration rainstorms from June to August. Based on these thresholds, 92 short-duration rainstorm cases were selected. Using ECMWF 0.25°$×$0.25° reanalysis data, the analysis reveals that parameters such as the K index, 700 hPa relative humidity, and atmospheric precipitable water exhibit good indicative significance for short-duration rainstorms in the region. A comprehensive evaluation scheme for 28 atmospheric environmental parameters was constructed based on fuzzy mathematics methods, considering both significance and moderation. The results demonstrate that the weight ranking of atmospheric environmental parameters varies across different periods during the flood season in Hedong, Gansu. When forecasting short-duration rainstorms, it is necessary to consider the weights of parameters specific to the climate period, with particular attention given to those ranked highest.

Keywords: Hedong region of Gansu Province; short-duration rainstorm; fuzzy mathematics; atmospheric environmental parameters; ECMWF fine-mesh model

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1. Introduction

Short-duration rainstorms are a common disastrous weather phenomenon in summer, characterized by short duration, high intensity, scattered distribution, and severe hazards, often triggering urban flooding, landslides, and debris flows. The Hedong region of Gansu, influenced by westerly belt weather systems, plateau weather systems, and the East Asian summer monsoon, represents a sensitive area for climate change. With complex terrain, loose soil, and large elevation differences, the region experiences frequent secondary geological disasters such as landslides and debris flows. Recent years have witnessed multiple flood disasters caused by short-duration rainstorms, resulting in significant economic losses and casualties. Research indicates that economic losses from flash floods in Gansu Province show an increasing trend. For instance, on July 8, 2010, a short-duration rainstorm in Huanxian County, Qingyang, triggered a sudden mountain flood; on August 7, 2010, multiple short-duration rainstorms in Dongxiang County, Linxia Prefecture, caused casualties; and on August 21, 2018, a short-duration rainstorm in Yuzhong County, Lanzhou, resulted in injuries. These events demonstrate the particularly strong disaster-causing potential of short-duration rainstorms in Hedong, Gansu, attracting widespread scholarly attention.

Most previous studies on short-duration rainstorms have analyzed observed data, radar, and satellite imagery. Some researchers have examined rainstorm characteristics in specific regions, while others have established conceptual models based on weather types or radar echo features. Although numerical weather prediction has developed rapidly and provides significant guidance for daily forecasting, applications reveal certain errors in precipitation forecasts. For example, studies have found that the GRAPES model tends to forecast the location of rainstorms on the northeastern side of the Tibetan Plateau as too far west and north compared to observations. To reduce forecast errors, some meteorologists have used statistical methods to correct quantitative precipitation forecasts, which improved light to moderate rain predictions but proved unsatisfactory for heavy precipitation. With the widespread application of multi-source data, scholars have obtained parameter characteristics with local forecasting significance through case analysis, but these studies typically focused on single aspects such as radar, satellite imagery, or dynamic parameters without comprehensively evaluating multiple parameters. Moreover, research shows that short-duration rainstorms in different regions and seasons exhibit varying sensitivity to atmospheric environmental parameters, with each parameter playing a different role. Consequently, a single parameter threshold cannot fully characterize the environmental conditions for severe convective weather. Therefore, comprehensive evaluation of multiple environmental parameters has been applied in severe convective weather forecasting, with some scholars using fuzzy logic methods to establish lightning forecasting techniques and others applying fuzzy comprehensive evaluation methods to assess typhoon disaster impacts and geological hazard risks, achieving good results.

This study, based on fuzzy mathematics theory and using significance and moderation as evaluation indicators, addresses the errors in numerical weather prediction for short-duration rainstorms in Hedong, Gansu. By employing ECMWF fine-mesh reanalysis data and historical cases, multiple parameters are optimized to determine the weights of atmospheric environmental parameters and forecast equations for different periods, providing scientific reference for short-duration rainstorm forecasting.

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2. Study Area and Data Sources

2.1 Study Area The Hedong region of Gansu covers an area of 1.78$×10^{5}$ km^2 between 32.52°–37.70°N and 100.73°–108.73°E, primarily including Lanzhou, Dingxi, Baiyin, Linxia, Longnan, Tianshui, Pingliang, and Qingyang. Located at the intersection of the Tibetan Plateau, Inner Mongolia Plateau, and Loess Plateau, it forms a boundary zone between China' s northwest arid region, eastern monsoon region, and Tibetan Plateau alpine region. Elevation gradually decreases from southwest to northeast. The region features complex terrain, loose soil, large elevation differences, fragile ecological environment, frequent heavy precipitation events, and secondary geological disasters.

2.2 Data Sources Precipitation data were obtained from 1,752 regional automatic weather stations in Hedong, Gansu, covering June–August 2013–2018. Atmospheric environmental parameters were derived from ECMWF 0.25°$×$0.25° reanalysis data with 6-hour intervals and spatial resolution of 0.25°, covering the domain 32.25°–37.75°N, 100°–109°E.

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3. Methods

3.1 Short-Duration Rainstorm Threshold No unified standard exists for short-duration rainstorms. Some scholars define them using orange or red rainstorm warning signals, while others use 1-hour cumulative precipitation $ 50mm.Givenvaryinggroundvegetationcoverageanddifferentimpactsofprecipitationintensityonsurfaceru
durationrainstormsbysortinghourlyprecipitationfromsmallesttolargestforeachmonthandusingthe95thperc
June : 16.6mm · h^{-1}, July : 19.1mm · h{-1}, August : 23.1mm · h^{-1}$.

3.2 Case Selection Using hourly precipitation data from Hedong, Gansu (2013–2018) and the above thresholds, 92 short-duration rainstorm processes were selected, totaling 1,752 station occurrences. These cases served as the research objects.

3.3 Spatial Distribution Characteristics Short-duration rainstorm frequency distribution (Figure 1) shows uneven spatial patterns, with more frequent events in the east and south, and fewer in the north. High-frequency zones appear in the Minshan Mountains at the border between Diebu and Zhouqu (28 station occurrences), followed by the southeastern Longnan area bordering Shaanxi' s Hanzhong Basin (24 station occurrences). Pingliang, Qingyang, and Gannan Prefecture experienced 10–20 station occurrences, while other cities had fewer than 10.

3.4 Temporal Distribution Characteristics The ten-day frequency distribution (Figure 2) shows a "single-peak" pattern, gradually increasing from early June, peaking in late July, then decreasing from early August. Late July to early August represents the most frequent period, consistent with the "late July to early August" peak for heavy precipitation in eastern Northwest China. Based on climate patterns and subtropical high pressure movements, the flood season is divided into three periods: northward shift period (June–mid July), stagnation period (mid July–late July), and southward retreat period (mid August–late August), hereafter referred to as "northward shift," "stagnation," and "southward retreat" periods.

4. Atmospheric Environmental Parameter Analysis

4.1 Climatological Mean Characteristics Numerous atmospheric environmental parameters represent severe convective weather, each with different physical meanings. No single parameter can fully characterize short-duration rainstorm potential. This study selected 28 parameters representing thermal, dynamic, instability, and moisture conditions from ECMWF reanalysis data. Calculating grid values for each flood season period and averaging regionally yields climatological means (Table 1). Analysis shows that severe weather index and deep convection index peak during the stagnation period, while total index and 500–850 hPa vertical wind shear peak during the northward shift period due to frequent interactions between the subtropical high and northern cold air, creating unstable stratification and active convection. Other parameters peak during the southward retreat period, associated with southerly warm, moist airflow control and high-energy, high-moisture environmental conditions.

4.2 Near-Occurrence Parameter Characteristics Using bilinear interpolation, station values were interpolated to 0.25° grids. Parameter values at grid points near each station at the time of short-duration rainstorm occurrence were selected and averaged by period and region, yielding near-occurrence parameter averages (Table 2). Analysis indicates that during northward shift and southward retreat periods, 500–850 hPa vertical wind shear and lifted index are smaller than climatological means, showing poor indication. In contrast, 700 hPa relative humidity and atmospheric precipitable water are significantly larger than climatological means, demonstrating good indicative significance.

5. Fuzzy Mathematics-Based Comprehensive Evaluation Scheme

5.1 Parameter Selection Given the complex terrain and large elevation differences in Hedong, Gansu, single parameters cannot adequately characterize short-duration rainstorms. Initially, 28 parameters were selected. After data optimization, parameters showing unclear characteristics during rainstorms were removed, and one representative parameter was selected from groups with similar meanings, resulting in 15 parameters for evaluation (Table 3).

5.2 Evaluation Indicators Under different surface characteristics and climate backgrounds, atmospheric environmental parameters play varying roles in short-duration rainstorms. To identify key parameters, two evaluation indicators are considered:

1. **Significance**: The difference between near-occurrence parameter values and corresponding period climatological means.
2. **Moderation**: The difference between near-occurrence parameter values and average values during rainstorm occurrence.

5.3 Parameter Matrix Construction Evaluating the 15 selected parameters (X) using the two indicators (Y) yields a parameter-evaluation matrix A, where each element a represents the average deviation and standard deviation for all station occurrences of parameter i under indicator j:

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ \vdots & \vdots \\ a_{n1} & a_{n2} \end{pmatrix}$$

where n = 15 (parameters), j = 1 (significance), j = 2 (moderation).

5.4 Dimensionless Normalization Due to different units and dimensions, parameters are normalized using the extremum method. Parameters with larger deviations from climatological values (high significance) and smaller standard deviations (good moderation) are considered more effective, yielding normalized matrix R:

Significance normalization:

$$r_{ij} = \frac{|a_{ij} - \max(a_{ij})|}{\max(a_{ij}) - \min(a_{ij})}$$

Moderation normalization:

$$r_{ij} = 1 - \frac{|a_{ij} - \min(a_{ij})|}{\max(a_{ij}) - \min(a_{ij})}$$

5.5 Evaluation Indicator Weights Standard deviation coefficient method determines indicator weights (V). Indicators that better distinguish parameters carry more information and receive higher weights:

$$\sigma_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_{ij} - \bar{r}_j)^2}, \quad V_j = \frac{\sigma_j}{\sum_{j=1}^{m}\sigma_j}$$

where m = 2 (indicators). Results (Table 4) show moderation weights exceed significance weights during all periods, indicating moderation carries richer information.

5.6 Parameter Weight Determination Technical scheme evaluation calculates comprehensive scores:

$$F_i = \sum_{j=1}^{m} V_j r_{ij}$$

Parameters are ranked by F values, and the top h parameters are selected as the basis for weight calculation. Final parameter weights are determined by:

$$W_{C_i} = \frac{F_i}{\sum_{i=1}^{h} F_i}$$

5.7 Probability Forecast Equation Applying the derived weights to probability forecasting yields the equation:

$$P_m = \sum_{i=1}^{h} W_{C_i} \cdot F_{C_i}$$

where P is the probability of short-duration rainstorm occurrence at a grid point, F_{C_i} is the historical probability characteristic value of parameter i, and W_{C_i} is its weight.

Parameter weight analysis (Table 5) reveals distinct rankings across periods: During northward shift, 700-500 hPa pseudo-equivalent potential temperature difference and 850 hPa water vapor flux rank highest; during stagnation, thermal parameter total index, dynamic parameter 700 hPa relative vorticity, and moisture parameter 700 hPa dewpoint temperature rank highest; during southward retreat, dynamic parameter 500 hPa vertical velocity, moisture parameter atmospheric precipitable water, and thermal parameter K index rank highest. Notably, 700-500 hPa pseudo-equivalent potential temperature difference ranks high in both northward shift and stagnation periods, while 500-850 hPa vertical wind shear ranks high in northward shift and southward retreat periods. Other parameters show substantial ranking differences across periods, demonstrating that different parameters must be considered for different climate periods.

6. Product Generation and Application Testing

Using ECMWF 0.25°$×$0.25° operational forecast products and calculated parameters at 08:00 and 20:00, the probability forecast equation generates hourly grid probability forecasts. Testing during the heavy precipitation event on August 4, 2020 (Figure 3), shows probabilities $ $0.6 indicating short-duration rainstorm potential. The 23:00 forecast indicated main risk areas in central Dingxi and northeastern Qingyang. Compared with observations, the forecast accurately predicted the rainstorm location in Qingyang but was slightly north of observed location in Dingxi, demonstrating reference value for Hedong short-duration rainstorm forecasting.

7. Conclusions

Using June–August hourly precipitation data from 2013–2018 in Hedong, Gansu, this study determined monthly short-duration rainstorm thresholds via the percentile method and selected 92 cases. Analysis of ECMWF reanalysis data and case characteristics yields the following conclusions:

1. Short-duration rainstorm frequency in Hedong, Gansu shows uneven spatial distribution, with more events in the east and south, and fewer in the north. The ten-day frequency distribution exhibits a "single-peak" pattern, with late July to early August being the most frequent period.
2. Analysis of climatological means and near-occurrence values of atmospheric environmental parameters reveals significant differences across periods. Parameters such as 700 hPa relative humidity and atmospheric precipitable water show good indicative significance.
3. Using relative deviation fuzzy matrix methods to comprehensively evaluate parameter weights and establish probability forecast equations demonstrates that parameter weights differ across climate periods. Forecasting must consider period-specific parameter weights.
4. Based on fuzzy mathematics theory and significance-moderation evaluation indicators, a comprehensive evaluation scheme for multiple atmospheric environmental parameters was constructed, and a probability forecast equation was established, providing scientific reference for short-duration rainstorm forecasting in the region.

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