Cluster Analysis of Precipitation Distribution in the Qilian Mountains and Surrounding Areas and Evaluation of Precipitation Enhancement Effects in Typical Watersheds: Postprint

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Abstract

The Qilian Mountains and surrounding areas feature complex terrain with extremely uneven precipitation distribution, and scientifically dividing this region into zones and types is of great significance for understanding the precipitation distribution characteristics of the study area. Using precipitation data from 31 national basic stations in the region for May–September from 1961 to 2020, Principal Component Analysis (PCA) was employed to analyze the regional precipitation, followed by Cluster Analysis (CAST) to conduct significance testing on the results, and finally the zoning and typing results were applied to evaluate the effects of artificial precipitation enhancement operations. The results show that: (1) The Qilian Mountains and surrounding areas can be divided into 7 zones (Z1–Z7), with a cumulative variance contribution rate exceeding 78%; (2) These seven zones are centered at Ledu, Haiyan, Yeniugou, Wuwei, Gaotai, Linze, and Gangcha, respectively, and the zoning results are significantly correlated with precipitation, geographical terrain, and altitude; (3) Based on the regional historical regression statistical method to evaluate the effects of artificial precipitation enhancement operations, it was found that for the Shiyang River Basin from May to September during 1992–2020, the absolute precipitation increase and relative precipitation enhancement rate were 8.91 mm and 6.51%, respectively, with July showing the highest values (6.30 mm and 21.86%), followed by August (5.44 mm and 16.11%). Evaluation of operation effects based on surface precipitation is often influenced by the selection of control areas, and the cluster testing method not only facilitates zoning studies of precipitation in complex terrain but also provides an objective basis for scientifically selecting control areas.

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Full Text

Cluster Analysis with Statistical Test of Precipitation Distribution in Qilian Mountains and Its Surrounding Areas and Evaluation of Artificial Precipitation Enhancement in Typical Watersheds

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Abstract

The Qilian Mountains and surrounding regions feature complex topography and highly uneven precipitation distribution, making scientific zoning and classification essential for understanding regional precipitation characteristics. Using monthly precipitation data from 31 national base stations (May–September, 1961–2020), we analyzed precipitation patterns through principal component analysis (PCA) and validated the results via cluster analysis with statistical test (CAST). The zoning outcomes were then applied to evaluate artificial precipitation enhancement operations. The results demonstrate that: (1) Seven distinct zones (Z1–Z7) can effectively represent precipitation distribution in the study area, with a cumulative variance contribution rate exceeding 78%; (2) These zones are centered at Ledu, Haiyan, Yeniugou, Wuwei, Gaotai, Linze, and Gangcha stations, with classification results significantly correlated with precipitation amount, geographic terrain, and altitude; (3) Based on regional historical regression statistics, the absolute precipitation enhancement and relative enhancement rate during May–September were 8.91 mm and 6.51%, respectively. Evaluation of precipitation enhancement effects based on ground measurements is heavily influenced by the selection of comparison areas. The cluster analysis method not only facilitates precipitation zoning research in complex terrain but also provides an objective basis for scientifically selecting comparison zones.

Keywords: cluster analysis with statistical test (CAST); principal component analysis (PCA); division and classification; evaluation of precipitation enhancement effects

1. Introduction

The Qilian Mountains, located at the intersection of the Qinghai-Tibet, Mongolian-Xinjiang, and Loess Plateaus, form the interior hinterland of China's arid and semi-arid regions, spanning northeastern Qinghai and western Gansu. This folded fault-block mountain range extends sequentially from northwest to southeast as Daxueshan, Tuolaishan, Tuolainanshan, Yemananshan, Shulenanshan, Danghenanshan, Tuergendaban, Qaidamshan, and Zongwulongshan, with an average elevation above 4000 m, a length of approximately 1000 km, and a width of about 300 km. The complex terrain produces pronounced regional precipitation distribution patterns. As a critical moisture corridor in northwest China, the Qilian Mountains serve as the headwaters for numerous rivers and water systems and act as a protective barrier for surrounding regions. The northern slopes feed the Shiyang, Heihe, and Shule River basins—the foundation of the Hexi Corridor oasis—while the southern slopes nourish the Datong and Huangshui River basins, the lifeline of the Hehuang Valley. In recent years, rising snowlines, shrinking glaciers, and severe water shortages have emerged as critical constraints on sustainable socioeconomic and ecological development, attracting widespread academic attention. With climate warming, extreme weather events have become more frequent, making research on precipitation distribution and variation patterns in the Qilian Mountains region urgently relevant.

Artificial precipitation enhancement represents an effective means of exploiting atmospheric water resources and alleviating water scarcity in the Qilian Mountains, with its effectiveness and scientific basis increasingly recognized by researchers. Evaluating operational effectiveness constitutes a technically complex and critical challenge in artificial precipitation enhancement research. Due to high natural precipitation variability, the evaluation object itself contains inherent uncertainties, with multiple confounding factors making it difficult to establish clear boundaries. Key issues include identifying the artificially enhanced component within natural precipitation, eliminating "false effects" to achieve precise evaluation, and developing conceptual models. Regional historical regression statistical testing serves as the fundamental method for evaluating enhancement effects, yet it is often constrained by zoning methods and the design of impact and comparison areas. Clearly, different comparison areas yield different evaluation results. Whether employing statistical, physical, or numerical simulation tests, selecting an appropriate comparison area remains challenging. Precise zoning is crucial for scientific evaluation of precipitation enhancement effects, and cluster analysis provides a quantitative method for comparison area selection, offering a scientific basis for objective and quantitative assessment of enhancement effects.

For years, climate zoning boundaries have been questioned due to subjective human factors in geographic classification methods. While principal component analysis (PCA) partially overcomes these limitations, critical value determination for loadings remains problematic, preventing truly scientific numerical classification in some respects. Cluster analysis, also known as group analysis, is a multivariate method that classifies events based on similarity characteristics. In analysis, distance coefficients, similarity coefficients, correlation coefficients, and related distance coefficients are commonly used for similarity measurement. However, many scholars consider this method lacking in statistical foundation. The cluster analysis with statistical test (CAST) method proposed by Yao Zhensheng effectively addresses the significant deficiency of significance testing in zoning and classification processes, demonstrating broad applicability in central cluster evaluation.

Following the fundamental approach of cluster analysis with statistical testing, this study thoroughly examines the rationality of precipitation zoning and classification in the Qilian Mountains and surrounding areas. The findings will facilitate analysis of spatial variation characteristics across different precipitation zones under complex terrain, providing a scientific basis for accurately understanding precipitation variation patterns in the Qilian Mountains.

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2. Data and Methods

2.1 Data Sources Data were obtained from the National Meteorological Information Center of China Meteorological Administration, comprising monthly precipitation records from 31 national base stations in the Qilian Mountains and surrounding areas (May-September, 1961-2020). All data series underwent strict quality control. Missing values in individual periods were corrected using the Vilfert comprehensive correction method with neighboring stations, and missing values were interpolated after passing appropriateness criteria. Figure 1 [Figure 1: see original paper] shows elevation changes and meteorological station distribution in the study area. The Qilian Mountains exhibit higher elevations in the west and lower in the east, with a maximum elevation difference of 2084 m. To eliminate geographic influences on mean values and variability, data were standardized before analysis to create a spatial precipitation dataset for the Qilian Mountains. Multiple statistical methods were employed, with Matlab and ArcGIS software used to implement precipitation zoning research.

2.2 Methodology

2.2.1 Principal Component Analysis Eigenvalues represent the importance of principal components, indicating how much source data information is explained by introducing each component. Generally, eigenvalues >1 serve as the criterion for component selection. Variance contribution rate (or cumulative contribution rate) determines the weight of principal components—larger values indicate greater information content from source data. Loading values reflect the closeness between principal components and individual variables. Under standardized variables, any principal component' s loading value is essentially the correlation coefficient with the original variable, with larger values indicating greater influence on the current variable.

Principal component analysis can be summarized in four steps: (1) Standardize precipitation data to eliminate systematic errors from geographic factors; (2) Calculate the correlation coefficient matrix of standardized samples; (3) Extract factor numbers based on eigenvalues and variance contribution rates to obtain principal components within threshold ranges; (4) Analyze principal components for interpretability, rotating factors if necessary to seek better explanations through loading values.

2.2.2 Cluster Analysis with Statistical Test Cluster analysis divides samples into different groups, with results that are comprehensive, objective, and scientific, finding wide application across fields. Zoning theory research has demonstrated the relationship between statistical cluster testing and principal component analysis, considering cluster testing as the theoretical foundation for applying PCA to zoning, with multiple methods confirming this relationship' s validity. Cluster analysis commonly uses distances to measure relationships among data, such as Minkowski distance, Manhattan distance, Euclidean distance, and Chebyshev distance.

The distance between variables is represented as Cij, which is consistent with correlation coefficients while possessing normal distribution properties. Through ^{2} distribution function construction, significance testing of the clustering process can be achieved.

Assuming a meteorological element comprises a variable field X with time series length n and p stations, the distance between stations Xi and Xj can be expressed using correlation coefficient rij. Based on Yao Zhensheng' s theory, define a ^{2} distribution statistic with degrees of freedom :

$$\chi^2 = \frac{(c_{ij} - \hat{c}_{ij})^2}{\omega_{ij}}$$

where ωij = 1 - cij^2, $\hat{c}_{ij} = \sum_i c_{ij}/q$, q represents the number of variables of the same type (for meteorological variable field X, q is the number of stations in the same zoning result), cij is the distance coefficient, and ωij is the distance weight.

The testing procedure involves: (1) Calculating ^{2} statistics for corresponding stations; (2) Using $^2(\alpha)$ as the critical value at given confidence level α; (3) If $^2 < {}^2(\alpha)$, the station can be classified in the same region; (4) Taking the region's maximum loading value as the cluster center, with all qualifying stations defining the category' s scope.

2.2.3 Regional Historical Regression Testing Regional historical regression testing is a ground precipitation-based evaluation method that establishes a univariate linear regression equation using least squares method based on correlation analysis between comparison and impact area precipitation. It predicts natural precipitation in the impact area and derives absolute precipitation enhancement and relative enhancement rate through comparison between estimated and measured precipitation. This method is detailed in the Artificial Precipitation Enhancement Operation Effect Testing Technical Guidelines and referenced literature, so it will not be elaborated here.

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3. Results and Analysis

3.1 Basic Characteristics of Precipitation Distribution Precipitation distribution in the Qilian Mountains and surrounding areas aligns with mountain range orientation. Taking July as an example, eastern sections receive over 350 mm while western sections receive only about 100 mm, demonstrating extreme heterogeneity. Annual precipitation distribution is uneven, with a multi-year average of 343.7 mm (maximum 441.8 mm in 1967, minimum 240.2 mm in 1972) and precipitation variability of 81.2 mm, with high-value areas predominantly in the Qilian Mountains. Precipitation exhibits strong seasonality, concentrated in summer and scarce in winter, with over 70% occurring in summer. Spatial distribution is extremely uneven; for example, Zhangye' s precipitation is less than one-third of Gangcha' s. Precipitation correlates significantly with geographic location, showing negative correlation with latitude and positive correlation with altitude—higher latitudes receive less precipitation, while higher altitudes receive more. This pattern creates an east-west and north-south precipitation gradient, with maximum precipitation bands distributed in the 2500–3500 m zone, indicating that southwestern warm-moist airflow and summer monsoons critically influence regional precipitation formation.

3.2 Cluster Analysis of Precipitation Using the 31-station ground precipitation original matrix for May–September 1961–2020, we performed PCA on the standardized correlation matrix, then used high loading values from each principal component as cluster centers. Based on the partitioning test criteria at given confidence levels, we analyzed and evaluated the zoning results.

First, PCA was conducted on the precipitation correlation matrix (Table 1). Seven principal components were selected based on eigenvalues and variance contribution rates. The cumulative variance contribution rate reached 78.135%. After rotation, the variance contribution rates of principal components C3–C7 generally improved, indicating clearer interpretation. These seven components effectively represent most information and main trends from the original field. Compared with the first two components, others show relatively small variance contribution rates, indicating pronounced topographic influence characteristics in the Qilian Mountains and surrounding areas.

Using high loading values from PCA as center points, we evaluated each station through cluster testing. When results passed the 0.05 significance level test, the classification was considered reasonable. Table 2 shows the criteria and results. Through cluster testing, the study area formed seven relatively independent zones centered at Ledu, Haiyan, Yeniugou, Wuwei, Gaotai, Linze, and Gangcha stations (Z1-Z7), with each zone representing one type.

3.3 Characteristic Analysis of Clustering Results Based on cluster testing results, we examined distribution characteristics of each precipitation zone (Figure 2 [Figure 2: see original paper]). The findings show:

Zone 1 is located in the southeastern study area, comprising Wushaoling, Tianzhu, Yongdeng, Ledu, Ping' an, Minhe, Hualong, and Xunhua stations (25.8% of total stations). Centered at Ledu with average loading of 0.73 and annual precipitation of 296.3 mm at 1800-3000 m elevation, this zone represents the monsoon climate response area and serves as the ecological gateway and key agriculture-pasture development region.

Zone 2 lies in the south-central Qilian Mountains, including Menyuan, Haiyan, Huangyuan, Datong, Huzhu, Xining, and Huangzhong stations (22.6% of total). Centered at Haiyan with loading of 0.71 and annual precipitation of 398.5 mm at 2500-3000 m, this is a crucial water conservation area and grassland-pasture base.

Zone 3 spans the central Qilian Mountains, comprising Shandan, Minle, Sunan, Tuole, Yeniugou, and Qilian stations (19.3% of total). Centered at Yeniugou with loading of 0.70 and annual precipitation of 285.0 mm at 1700-3400 m, this represents an important ecological protection and vegetation restoration area.

Zone 4 is located at the eastern end of the northern Qilian Mountains foothills—the Shiyang River Basin—comprising Wuwei, Gulang, and Jingtai stations (9.7% of total). Centered at Wuwei with loading of 0.68 and annual precipitation of 1300-2000 mm at 1470 m, this is a critical oasis watershed with typical irrigated agriculture.

Zone 5 represents the northernmost Shule River Basin, comprising Yumen and Dunhuang stations (6.5% of total). Centered at Gaotai with loading of 0.67 and annual precipitation of only 100.4 mm, this oasis area between Tuolainanshan and Shulenanshan relies on irrigated agriculture.

Zone 6 is situated in the Heihe River Basin, originating from the central Qilian Mountains glacier zone, comprising Zhangye, Linze, and Gaotai stations (12.9% of total). Centered at Linze with loading of 0.66 and annual precipitation of 170.6 mm, this represents irrigated agriculture.

Zone 7 is the highest altitude region, comprising Tianjun and Gangcha stations (3.2% of total). Centered at Gangcha with loading of 0.65 and annual precipitation of 341.3 mm, this area on the Datongshan section is the source of multiple Qilian Mountain rivers.

The zoning results show significant correlation with precipitation, geographic terrain, and altitude. Each zone is independent with clear differences, while stations within the same zone share similar characteristics, forming a unique spatial precipitation pattern in the Qilian Mountains. This seven-zone classification aligns with research findings showing that under combined influences of westerlies, subtropical systems, and Tibetan Plateau circulation—especially mountain thermal and dynamic effects—the Qilian Mountains region readily forms cyclonic circulation. Enhanced subtropical high pressure and strengthened southwestern warm-moist airflow extend the summer monsoon northward. When cold and warm air masses meet, intense precipitation zones easily form in the Qilian Mountains. Northwest airflow patterns, eastward-moving troughs, and east-west oriented patterns all favor heavy precipitation, with local circulation and boundary layer structures effectively promoting topographic positive feedback that significantly increases precipitation, decreasing from southeast to northwest.

3.4 Evaluation of Artificial Precipitation Enhancement Effects

3.4.1 Background of Enhancement Effect Evaluation Statistical testing evaluates ground precipitation by comparing natural precipitation in comparison areas with measured precipitation in impact areas during the same period to quantify enhancement effects. However, after determining the operational impact area, different comparison areas yield different enhancement results. Cluster testing zoning results can serve as the basic criterion for comparison area selection—statistical testing is only credible when impact and comparison areas belong to the same zone.

The Shiyang River Basin serves as the empirical case study. This basin features dense population, scarce water resources, and extremely fragile ecological environment, making artificial precipitation enhancement crucial for drought relief and ecological management. The basin has established 54 operational sites (24 rocket, 17 artillery, 11 fixed flares, 2 projectile), covering over 6000 km^2. Operations began in 1975, with more than 5000 operations conducted, launching over 10,000 artillery shells and 3000 rockets, providing adequate conditions for selecting comparison and impact areas.

Prevailing winds at 500-700 hPa are northwesterly. As long as the comparison area is located upwind or crosswind of the impact area, it remains unaffected by seeding operations and maintains relative independence. The region' s inland location features arid climate, low precipitation, high evaporation, and consistent topography, climate background, vegetation characteristics, and weather systems, with significantly correlated ground precipitation. Figure 3 [Figure 3: see original paper] shows the basin' s geographic distribution and operational layout.

We selected 1992-2005 as the historical precipitation sequence period and 2006-2020 as the operational impact period, with roughly equivalent sample sizes.

Before applying regional historical regression testing, we verified normal distribution of statistical variables. To ensure regression model comparability, both comparison and impact areas must exhibit normality across both periods, tested using the Kolmogorov-Smirnov (KS) nonparametric test. Test results and analysis are shown in Table 3 .

Using comparison area precipitation as the independent variable and impact area precipitation as the dependent variable, we applied regional historical regression statistical testing to analyze precipitation across periods. Regression equations passed the 0.05 significance level test, indicating the fitted equations could represent precipitation characteristics (Table 3).

3.4.2 Enhancement Effect Evaluation and Testing For ground operations in the Shiyang River Basin, we selected Minqin as the comparison area and Liangzhou as the impact area (crosswind location). Substituting comparison area precipitation into regression equations yielded impact area precipitation estimates, enabling analysis of operational effects across periods.

May–September absolute precipitation enhancement was 8.91 mm with a relative enhancement rate of 6.51%. July showed the most pronounced effect (6.30 mm, 21.86%), followed by August (5.44 mm, 16.11%). However, monthly effects varied significantly (Table 3): May–July showed positive effects, while September showed negative effects. This pattern correlates closely with the basin' s climate background and synoptic system evolution.

May–July represents late spring to early summer—the critical "bottleneck"period. This period receives less than 20% of annual precipitation, with poor moisture conditions, low enhancement efficiency, and weak operational effects. Operational timing should be carefully selected to minimize negative effects. July-August represents the active plateau precipitation cloud system stage, especially August, with frequent convective precipitation, good moisture conditions, high enhancement efficiency, and pronounced effects. Increasing operational frequency and intensity can significantly enhance precipitation and improve overall effectiveness.

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4. Discussion

Evaluating operational effects remains a technical challenge constraining weather modification development. The Qilian Mountains' complex topography and vast area have prompted preliminary research on regional precipitation characteristics. When using statistical testing for enhancement evaluation, comparison area selection presents numerous issues, leading to uncertain results. As is well known, comparison between impact and comparison area precipitation forms the basic statistical testing approach. Numerous facts demonstrate that different comparison areas produce different enhancement effects after the operational impact area is determined. Unfortunately, no objective, accurate method or theoretical basis for comparison area selection has been established, leaving ground operation evaluation and artificial precipitation services in a difficult position.

Cluster testing zoning results provide the fundamental criterion for comparison area selection. Statistical testing is only reliable when impact and comparison areas belong to the same zone. This study employs PCA for zoning and CAST for validation, largely ensuring zoning accuracy. Applying these results to comparison and impact area selection solves the blind selection problem in enhancement evaluation—a key constraint on ground precipitation enhancement assessment. While commonly used for climate zoning, this method is rarely applied to regional precipitation research and even more uncommon in comparison area selection for artificial precipitation enhancement evaluation. Given the Qilian Mountains' complex terrain and extremely uneven precipitation distribution, establishing a scientific and accurate zoning method is crucial for understanding regional precipitation characteristics.

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5. Conclusions

Based on the consistency between PCA and cluster analysis, this study thoroughly investigated zoning methods and validated their rationality. Analysis divided Qilian Mountains precipitation distribution into seven zones. Evaluating these zones individually, we selected the Shiyang River Basin as a case study, designing comparison and impact areas and applying regional historical regression statistics to assess enhancement effects across periods. Results show absolute enhancement of 8.91 mm and relative enhancement rate of 6.51% during May–September, with July showing maximum effect (6.30 mm, 21.86%) followed by August (5.44 mm, 16.11%). These findings demonstrate that artificial precipitation enhancement effects vary by period. Timely and scientific operations can improve comprehensive effectiveness and maximize drought resistance, water storage, and ecological restoration capabilities.

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