GIS-based Evaluation of Climate Comfort for Red Tourism in the Shaanxi-Gansu-Ningxia Region (Postprint)

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Date: 2025-07-14T11:39:32+00:00

Abstract

Evaluation of climate comfort in the Shaanxi-Gansu-Ningxia region holds significant importance for the development of regional red tourism resources and the promotion of ecological civilization construction. Based on a comprehensive climate comfort evaluation model, this study systematically assessed the spatiotemporal distribution characteristics of climate comfort using daily mean temperature, wind speed, relative humidity, and other meteorological element data from 1953 to 2020, employing GIS spatial interpolation and comprehensive zoning methods. The results indicate that, temporally, the climate in the Shaanxi-Gansu-Ningxia region is generally comfortable from May to September and generally uncomfortable from December to February of the following year. Spatially, northern Shaanxi exhibits relatively comfortable climate conditions, whereas the Xihaigu area in the southwestern region is relatively uncomfortable. Against the backdrop of global warming, the annual number of comfortable days demonstrates an increasing trend, with the annual average number of uncomfortable climate days declining significantly after 2000. From a comprehensive zoning perspective, the southwestern and central high-altitude regions have relatively uncomfortable climates, while other areas are relatively comfortable. A 1-unit change in the climate comfort index corresponds to a 0.593% change in the red tourism passenger flow index. Yan'an's attractiveness index far surpasses that of other regions due to its abundant red tourism resources and suitable climate. Future efforts should dynamically optimize red tourism planning to adapt to climate change and tourist demands. This study provides references for regional tourism development and red tourism activities.

Full Text

Abstract

Assessing climate comfort in the Shaanxi-Gansu-Ningxia region is essential for the development of red tourism resources and the promotion of ecological civilization construction. Using daily meteorological data from 1953 to 2020, including average temperature, wind speed, and relative humidity, this study applies a comprehensive climate comfort evaluation model integrated with GIS-based spatial interpolation and zoning methods to systematically evaluate the spatiotemporal distribution characteristics of climate comfort in the region. The results show that, temporally, the climate is generally comfortable from May to September, while discomfort prevails from December to February. Spatially, northern Shaanxi exhibits relatively favorable climatic conditions, whereas the southwestern Xihaigu region is less comfortable. Under global warming, the annual average number of comfortable days shows an increasing trend, with uncomfortable days declining significantly after 2000. Comprehensive zoning reveals that southwestern and central high-altitude areas experience lower comfort levels, while other regions remain relatively favorable. Each unit change in the climate comfort index corresponds to a 0.593% change in red tourism visitor flow. Notably, Yan'an, due to its abundant red tourism resources and suitable climate, has an attractiveness index far exceeding other regions. Future red tourism planning should be dynamically optimized to adapt to climate change and evolving tourist demands. This study provides a scientific reference for regional tourism development and the sustainable advancement of red tourism activities.

Keywords: climate comfort degree; red tourism; Shaanxi-Gansu-Ningxia Region; comprehensive zoning; gravity model

1 Introduction

Climate conditions are closely related to human comfort. Climate comfort degree is a biometeorological index that evaluates human comfort levels under different climatic conditions based on meteorological elements such as temperature, humidity, and wind speed. In recent years, climate comfort evaluation has received increasing attention due to global warming and has become an important reference for measuring regional suitability for living and tourism. Numerous studies have conducted climate comfort evaluations at national, provincial, and typical tourist site scales, providing scientific foundations for residential settlement, travel, and tourism decision-making. However, research on climate comfort for tourism in the Shaanxi-Gansu-Ningxia region remains in its infancy.

The Shaanxi-Gansu-Ningxia region, located in the hilly and gully area of the central Loess Plateau, faces severe soil erosion and water loss, with an arid and unstable climate and extremely fragile ecological environments. As a typical ecologically vulnerable area in northwest China that is sensitive to climate

change, global warming will alter regional climate comfort and consequently affect tourism activities. The region is also a crucial political and cultural project for promoting red culture and inheriting revolutionary heritage, with abundant red tourism resources. Statistics show that the Shaanxi-Gansu-Ningxia region contains numerous red tourism resources, with visitor numbers showing rapid growth. Taking Yan'an as an example, tourist numbers increased from 10.243 million in 2000 to 73.083 million in 2019, with comprehensive tourism revenue rising from 5.388 billion to 49.531 billion yuan, accounting for 34.3% of the tertiary industry value-added. Red tourism has become an important pathway for economic and social development in the region.

Based on this context, this study selects the Shaanxi-Gansu-Ningxia region as the research area. Using long-term meteorological data and the ArcGIS platform, we conduct a refined assessment of regional climate comfort based on a comprehensive climate comfort evaluation model. We further construct regression models to quantitatively analyze the impact of climate comfort on red tourism visitor numbers and introduce a gravity model to rank the climate comfort attractiveness of different locations. The aim is to provide scientific theoretical support for sustainable socioeconomic development and effectively promote red tourism development in the Shaanxi-Gansu-Ningxia region.

1.1 Study Area Overview

The Shaanxi-Gansu-Ningxia region is located at the junction of Shaanxi, Gansu, and Ningxia provinces, covering a total area of 100,400 km^2 with a population of approximately 13.8 million. The study area includes 25 counties under the jurisdiction of Yan'an and Yulin cities in Shaanxi Province, 8 counties in Qingyang City of Gansu Province, and 9 counties in southern Ningxia Hui Autonomous Region [Figure 1: see original paper]. Situated in the hilly and gully area of the central Loess Plateau, this region represents a core area for ecological protection and management in the middle and upper reaches of the Yellow River, as well as one of the most severely affected areas by soil erosion globally. The regional climate is arid and unstable, transitioning from East Asian monsoon climate to typical continental climate, belonging to arid and semi-arid climate zones. The ecological environment is extremely fragile, with forest coverage of only about 17%. Precipitation is concentrated in summer and autumn, with significant interannual variability, primarily in the form of strong convective rainstorms with high intensity and short duration, which easily induce soil erosion and flood disasters.

Currently, the Shaanxi-Gansu-Ningxia region is relatively economically underdeveloped, constrained by natural and historical factors. The "Shaanxi-Gansu-Ningxia Red Tourism Area" is one of China's 12 key red tourism regions. As an important strategic rear area during the Chinese People's War of Resistance Against Japanese Aggression and the Liberation War, the region preserves a large number of diverse red tourism resources with glorious revolutionary traditions and abundant revolutionary heritage sites. Red tourism has become an

important tourism brand in the region. In recent years, the state has attached great importance to the development of red cultural tourism, introducing multiple supportive policies. Represented by Yan'an in Shaanxi, Huachi County in Gansu, and Yuanzhou District in Ningxia, the Shaanxi-Gansu-Ningxia region boasts abundant red tourism resources with great development potential. Driven by policy guidance and resource integration, red tourism has developed rapidly, injecting momentum into local poverty alleviation and bringing new opportunities for ecological civilization construction.

1.2 Data Sources

Meteorological data were downloaded from the China Meteorological Data Network (http://data.cma.cn), including daily average temperature, daily average wind speed, and daily average relative humidity from 1953 to 2020. During meteorological station selection, we followed the principles of extensive regional coverage and relatively uniform spatial distribution, prioritizing stations with complete meteorological records [Figure 1: see original paper]. Elevation data were derived from SRTM data jointly measured by NASA and NIMA, with a resolution of 90 m × 90 m. Tourism data were obtained from the "Domestic Tourism Situation" section of the Yan'an Statistical Yearbook (2000–2019) on the official website of Yan'an Municipal Bureau of Statistics.

1.3 Methods

1.3.1 Construction of Climate Comfort Index Given China's large span of latitude and longitude, diverse climate types, and significant topographic variations, comfortable periods differ across regions. Considering the climatic characteristics, cultural customs, and environmental hygiene indicators of the Shaanxi-Gansu-Ningxia region, we established 24.0°C for average temperature, 2 $m \cdot s^{-1}$ for average wind speed, and 70% for relative humidity as the most comfortable microclimate conditions. The comprehensive climate comfort index model was constructed as follows:

$$CCI = 0.68 \times |T - 24.0| + 0.5 \times |V - 2.0| + 0.07 \times |Hu - 70|$$

where CCI is the climate comfort index; T is temperature (°C); V is wind speed ($m \cdot s^{-1}$); and Hu is relative humidity (%).

Based on the probability distribution of climate comfort in the Shaanxi-Gansu-Ningxia region and referencing the World Meteorological Organization's recommended percentile method for extreme climate event calculation, we sorted the CCI values and used the 5th and 95th percentiles as thresholds to divide the index into five levels . Using the constructed comprehensive comfort model, we calculated the multi-year average monthly comfort index for the region [Figure 2: see original paper]. The results show that the comfort index values from May to September are relatively small, ranging from 3.60 to 7.95, indicating relatively

comfortable climate suitable for tourism activities. Among them, August has the lowest comfort index at 3.60, making it the most suitable month for tourism. Winter months (December–February) have comfort indices of 20.68–23.05, indicating "relatively uncomfortable" conditions. January reaches 23.05, the only month exceeding the "least comfortable" threshold of 22.52, representing the most unfavorable period for tourism. Overall, the Shaanxi-Gansu-Ningxia region has comfortable climate from May to September suitable for tourism, while winter months are less comfortable and unsuitable for outdoor activities.

1.3.2 Climate Comfort Zoning and Evaluation Elevation significantly impacts meteorological conditions. During comprehensive climate comfort zoning, we utilized GIS spatial analysis technology to integrate temperature, relative humidity, wind speed with DEM data, achieving gridded comfort zoning for more precise evaluation.

(1) Temperature gridding. Since the 42 meteorological stations are discretely distributed, we first performed planar interpolation of station temperature data. Considering that temperature decreases with altitude (0.65°C per 100 m elevation increase), we used DEM data to vertically correct the interpolation results. Through horizontal interpolation and vertical correction, we obtained the spatial distribution of average temperature in the study area.

(2) Relative humidity gridding. Since air relative humidity is closely related to temperature and elevation, the relative humidity at a certain elevation was calculated as:

$$RH_z = RH_0 \times 10^{[7.5\times T_0/(237.3+T_0)-7.5\times T_z/(237.3+T_z)]}$$

where RH_z is air relative humidity at elevation z (%), RH_0 is surface observed relative humidity (%), T_0 is surface temperature (°C), T_z is temperature at elevation z (°C), and β_z is a constant (hPa). The relative humidity spatial distribution layer for the region can be obtained through horizontal interpolation and vertical fitting using the above formula.

(3) Wind speed gridding. Since terrain effects on wind speed are complex, this study did not consider elevation factors in wind speed spatial distribution analysis. GIS technology was directly used to interpolate wind speed data and generate the average wind speed spatial distribution layer for the study area.

2 Results

2.1 Spatiotemporal Distribution Characteristics of Climate Comfort

Based on the calculated annual average comfortable days, normal days, and uncomfortable days in the Shaanxi-Gansu-Ningxia region from 1953 to 2020, we mapped their spatial distribution [Figure 3: see original paper]. The results indicate that northern Shaanxi has the most annual comfortable days, with

most areas exceeding 122 days, including Suide County reaching 133 days, and Luochuan and Hengshan districts approximately 124 and 122 days, respectively. Overall, annual comfortable days gradually decrease from east to west as terrain rises, continental climate intensifies, and aridity increases. The Xihaigu region in southern Ningxia (e.g., Xiji, Haiyuan, and Guyuan) has significantly fewer comfortable days at only 76–87 days, with Xiji County having the fewest at about 76 days, and Haiyuan and Guyuan at approximately 87 days. Annual normal days are higher in southern regions at 157–166 days, while northern Shaanxi areas like Hengshan and Suide have relatively fewer at about 127–128 days. The spatial distribution of annual uncomfortable days shows the opposite pattern, with Xihaigu region having the most at approximately 120 days, and northern Shaanxi concentrated at 90–100 days, with slightly fewer in southern areas like Luochuan at about 85 days. In summary, northern Shaanxi has relatively comfortable climate suitable for tourism, while the southwestern Xihaigu region has the lowest comfort and most uncomfortable days, making it the area with the worst tourism climate conditions.

2.2 Interannual Variation of Climate Comfort Index

The interannual variation of climate comfort index reflects long-term evolution of regional climate comfort conditions. Figure 4 shows the spatial distribution of linear tendency rates for annual comfortable days, normal days, and uncomfortable days. All regions show positive linear tendency rates for annual comfortable days, indicating an overall increasing trend. The most significant increases occur in Jingbian County and Xifeng District, with rates of 5.07–5.89 days per decade, while Suide and Hengshan in northern Shaanxi have the smallest increases at only 1.54–2.21 days per decade; other regions range between 2.97–3.86 days per decade. Annual normal days show small linear tendency rates, with most areas having slight increases of 0.33–1.39 days per decade, while a few areas like Huanxian, Wuqi, and Xiji show slight decreasing trends of -0.66 to -0.34 days per decade. Annual uncomfortable days show decreasing trends across all regions.

Mann-Kendall mutation test was applied to annual comfortable days, normal days, and uncomfortable days series [Figure 5: see original paper]. Before the 1990s, the UF statistic curve for comfortable days showed minor changes and remained below the 0 axis, indicating insignificant variation. After the 1990s, the UF curve gradually rose above 0, and after 2000, it exceeded the confidence limit, showing a continuous upward trend, indicating comfortable days began to increase significantly. The UF and UB curves intersected within the $±$1.96 confidence interval around 2000, indicating a significant mutation. For normal days, the UF curve remained within the confidence interval and crossed the UB curve multiple times, indicating no significant change or obvious mutation. For uncomfortable days, the UF curve has been declining since the 1990s and remained below the 0 axis after 2000, indicating a decreasing trend. The UF and UB curves intersected within the confidence interval around 2005, indi-

cating a mutation occurred after approximately 2005. Overall, since the 21st century, uncomfortable days have significantly decreased, and climate comfort has improved.

2.3 Comprehensive Climate Comfort Zoning

Located in the transitional zone of temperate monsoon climate, the Shaanxi-Gansu-Ningxia region features loess plateau hills and gullies. As shown in [Figure 6: see original paper], climate comfort is mainly distributed across three levels: "relatively comfortable," "normal," and "relatively uncomfortable," with no extreme "most comfortable" or "least comfortable" zones. Southwestern and central areas have higher elevations with lower average temperatures year-round, especially in winter. For example, Xiji County's winter average temperature is only -8.7°C, far below the optimal 24°C. Meanwhile, the region is dry, with Xiji's average relative humidity at only 55%, below comfortable levels. Average wind speeds exceed 2.5 $m \cdot s^{-1}$. Combined, these factors result in "relatively uncomfortable" climate comfort ratings. "Relatively comfortable" zones are mainly distributed in eastern northern Shaanxi, Xifeng area of Gansu's Qingyang, and some low-altitude areas in southern Ningxia (like Tongxin County). Central regions mostly belong to "normal" climate zones with moderate meteorological conditions. Eastern areas have lower elevations where temperature, humidity, and wind conditions are closer to optimal ranges, thus dominated by "relatively comfortable" ratings.

3 Discussion

3.1 Spatiotemporal Characteristics of Climate Comfort and Their Impact on Tourism Development

Climate comfort significantly influences tourism development and tourists' willingness to engage in outdoor activities. Analysis of climate comfort evaluation results for the Shaanxi-Gansu-Ningxia region reveals that, on an intra-annual scale, the region's climate comfort index is lower from May to September, indicating generally comfortable conditions and optimal tourism season, while December to February shows higher indices, indicating uncomfortable conditions unsuitable for outdoor tourism. Spatially, northern Shaanxi has the most annual comfortable days, while Xihaigu region has the fewest, showing a gradual decrease from east to west. Tourism activities should be scheduled during locally comfortable periods, avoiding unfavorable winter conditions. Interannually, comfortable days have increased while uncomfortable days have decreased over the past 70 years, especially after 2000, indicating climate conditions are becoming more favorable for tourism. Under climate warming, the increase in comfortable days helps extend suitable tourism periods, positively impacting sustainable tourism development. Comprehensive zoning shows no extremely unfavorable climate conditions in most areas, providing a favorable climatic background for red tourism development.

3.2 Relationship Model Between Tourist Flow Index and Climate Comfort

To quantitatively analyze the impact of climate comfort on red tourism, we selected Yan'an, the city with the most red tourism resources in the region. Yan'an has 175 red tourism resources, accounting for 51.2% of the region's total. According to Yan'an Statistical Yearbook data, tourist numbers reached 73.08 million in 2019. Climate comfort significantly impacts Yan'an tourism: visitor numbers surge to annual peaks during the National Day holiday in October, reaching 10.25 million (14.0% of annual total). Red tourism attractions account for 83.4% of total visitors. Seasonal changes in climate significantly affect tourist travel choices and seasonal distribution of tourism flow, with comfortable periods corresponding to reception peaks and harsh winters being off-seasons.

Least squares regression analysis of monthly red tourism visitors and climate comfort index in Yan'an (with October's National Day holiday as a dummy variable) yields:

$$Q = -0.593CCI + 0.065 + 0.128T$$

where Q represents visitor flow, CCI is the climate comfort index, and T is the National Day holiday dummy factor (1 for October, 0 otherwise). The model's correlation coefficient r is 0.82, indicating significant correlation. According to the regression coefficient, when the climate comfort index increases by 1 unit (i.e., comfort decreases), red tourism visitor flow index decreases by approximately 0.593%. This quantitatively proves that climate comfort changes substantially impact red tourism flow—good conditions attract more visitors, while uncomfortable conditions like severe cold significantly inhibit travel.

3.3 Regional Ranking of Climate Comfort Attractiveness and Future Optimization Paths

Spatial differences in climate comfort create varying potential attractiveness to tourists across the region. Using tourism gravity model principles, "attractiveness" can be considered a comprehensive function of red tourism resource abundance and climate comfort for regional ranking. The tourism gravity model is generally expressed as:

$$A_i = k \times \frac{R_i^{\alpha} \times C_i^{\beta}}{D_i^{\gamma}}$$

where A_i represents tourism attractiveness of location i, k is a constant coefficient determined through regression, R_i is red tourism resource abundance (number of attractions or total scenic area rating score), C_i is annual comfortable days, D_i is spatial distance or travel time to the regional tourism center

node (e.g., Yan'an), and α, β, γ are weight coefficients for resource abundance, climate comfort, and distance impacts, respectively.

According to the gravity model, considering both resource quantity (Yan'an has numerous red attractions) and climate comfort "quality," northern Shaanxi undoubtedly has stronger tourist attraction and becomes the preferred region for future red tourism development. Areas with poor climate conditions have limited potential to attract tourists despite rich red resources. Eastern northern Shaanxi areas like Suide are comfortable for nearly 124 days annually, far exceeding Xihaigu's less than 87 days. This comfort difference means tourists prefer climatically pleasant regions. Using Yan'an as the standard node (assuming $D_{Yan'an} = 1$), with parameters set as $\alpha = 0.6$ (resource weight), $\beta = 0.4$ (climate weight), and $k = 1$, calculations show: $A_{Yan'an} \approx 152.5$ and $A_{Xiji} \approx 33.1$. Thus, under equivalent conditions, Yan'an's attractiveness is about 33 times that of Xihaigu.

For red tourism route optimization, two approaches are recommended: First, construct a cross-regional red tourism route network connecting Yan'an with revolutionary sites in Gansu and Ningxia, forming a Shaanxi-Gansu-Ningxia red tourism loop. Second, optimize itinerary timing according to comfortable periods—schedule summer visits to Yan'an and surrounding outdoor sites when it's cool and pleasant, then shift to southern Ningxia and eastern Gansu in early autumn before high-altitude or arid areas become too cold. This creates a rational, seasonally complementary red tourism activity map promoting coordinated development of all red scenic areas. As regional climate improves under global warming, with comfortable days increasing (most significantly in Jingbian and Xifeng at 5.07–5.89 days per decade), this gap is narrowing. Future assessments must dynamically adjust to reflect the latest climate and tourism supply-demand conditions.

4 Conclusions

Using daily meteorological data from 1953 to 2020 and DEM data for the Shaanxi-Gansu-Ningxia region, this study classified climate comfort index levels based on a comprehensive evaluation model, analyzed its variation patterns and spatiotemporal distribution characteristics, and conducted comprehensive zoning through weighted overlay of seasonal layers. Additionally, regression and gravity models were established to explore climate comfort's impact on red tourism visitor flow. The main conclusions are:

(1) **Spatiotemporal distribution:** The multi-year average climate comfort index shows smaller monthly values from May to September, indicating generally comfortable conditions suitable for tourism, while December to February are unsuitable. Northern Shaanxi has the most comfortable days, Xihaigu the fewest, with an overall east-to-west decreasing pattern.

(2) **Interannual trends:** Linear tendency analysis shows increasing comfortable days across all areas, most significantly in Jingbian County and

Xifeng District (5.07–5.89 days per decade). Normal days show minimal linear tendency rates with slight decreases in some areas. Uncomfortable days show decreasing trends. Mutation tests indicate that after the 1990s, annual comfortable days increased significantly, with a mutation occurring around 2000. Normal days show non-significant increases after 2000, while uncomfortable days show significant decreases after 2005.

(3) **Comprehensive zoning:** The region's overall comfort levels are mainly "relatively comfortable," "normal," and "relatively uncomfortable," with southwestern and central high-altitude areas being less comfortable and other areas relatively comfortable.

(4) **Tourism impact:** Regression analysis shows that each 1-unit change in climate comfort index changes visitor flow index by 0.593%, demonstrating substantial impact. Based on the gravity model, Yan'an ranks highest in attractiveness due to abundant resources and suitable climate, while high-altitude, cold, and arid areas in southern Ningxia rank lowest, with central high-altitude areas in between. As regional climate comfort improves under global warming, this gap is narrowing. Future red tourism planning requires dynamic optimization to adapt to climate change and tourist demands, promoting sustainable regional tourism development.

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