

## Spatio-temporal Evolution Analysis of Tourism Climate Comfort in Xinjiang, China and the Five Central Asian Countries under the Context of Climate Change (Postprint)

**Authors:** Guan Jingyun, Sun Zhiyang, Xu Xiaoliang, Cheng Yifeng, Song Beibei, Ruiying Fang

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### Abstract

Xinjiang, China, and the five Central Asian countries represent typical arid regions and the Silk Road tourism cultural belt; however, the spatiotemporal variations and future risks of their tourism climate comfort require urgent systematic assessment. Based on high-resolution gridded meteorological data and CMIP6 multi-model simulation results, this study systematically analyzed the spatiotemporal evolution of the Holiday Climate Index (HCI) from 1960 to 2100. The results indicate that: (1) The HCI generally shows an upward trend with significant regional and seasonal differences; the increase is larger in mountainous areas, while some arid basins show a slight decrease. Under the SSP585 scenario, both the future HCI increase and its uncertainty are higher than those under the SSP245 scenario. (2) The intra-annual variation of HCI exhibits two patterns: “unimodal” and “bimodal.” Future climate warming will lead to a decline in summer comfort in some regions. Under the high-emission scenario, the summer HCI in the long term (2071-2100) may even be lower than that of the historical baseline period (1985-2014), resulting in a narrowing of the suitable tourism window. (3) The spatial distribution of HCI shows clear latitudinal zonality and vertical differentiation, with high-value areas concentrated in low-altitude and low-latitude regions. In the future, the range of high-value areas will expand further, but the high-comfort zones in summer ( $HCI > 90$ ) will shrink due to the impact of extreme high temperatures. (4) The tourism climate comfort period will extend significantly, with a larger increase but enhanced fluctuations under the high-emission scenario. Spatially, the pattern shows longer comfort periods in low-latitude and low-altitude areas and shorter periods in high-latitude and high-altitude areas, with significant long-term increases in high-altitude mountainous regions. The research results provide a

scientific basis for climate adaptation and sustainable development of the regional tourism industry.

## Full Text

## Preamble

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GEOGRAPHY

# Spatiotemporal Evolution of Tourism Climate Comfort in Xinjiang, China, and the Five Central Asian Countries under the Context of Climate Change

**Guan Jingyun, Sun Zhiyang, Xu Xiaoliang, Cheng Yifeng, Song Beibei, Fang Ruiying** (*School of Tourism, Xinjiang University of Finance and Economics, Urumqi, Xinjiang 830012, China*)

## Abstract

Climate change has become a critical factor influencing the sustainable development of regional tourism. This study analyzes the spatiotemporal evolution of tourism climate comfort across Xinjiang, China, and the five Central Asian countries, providing a scientific basis for regional tourism planning and climate adaptation strategies. By integrating multi-source meteorological data and employing standardized climate indices, we examine the shifts in comfort levels over recent decades. The findings indicate a significant trend of warming and shifting precipitation patterns, which have collectively altered the traditional peak tourism seasons. Spatially, the results reveal a northward expansion of comfortable zones, while certain southern regions face increasing heat stress during summer months. These results offer valuable insights for policymakers to optimize tourism resource allocation and enhance the resilience of the tourism industry in the face of global environmental shifts.

## 1. Introduction

Climate is one of the most fundamental components of the tourism environment and serves as a primary driver for the seasonal and spatial distribution of tourism activities. In the context of global warming, the frequency and intensity of extreme weather events have increased, significantly impacting the attractiveness and safety of tourism destinations. Xinjiang, China, and the five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) share similar geographical characteristics and are interconnected through the Silk Road Economic Belt. This region, characterized by its arid and semi-arid climates, is particularly sensitive to climate change.

Understanding the spatiotemporal evolution of tourism climate comfort in this transboundary region is essential for several reasons. First, it helps in identifying the changing “window of opportunity” for tourism activities. Second, it assists in the development of cross-border tourism products that are resilient to climatic shifts. Finally, it provides a theoretical framework for regional cooperation in environmental management and tourism marketing. Despite its importance, comprehensive studies covering both Xinjiang and the broader Central Asian region remain limited. This paper aims to bridge this gap by utilizing long-term meteorological datasets to evaluate the dynamics of tourism climate comfort.

## 2. Data and Methods

**2.1 Study Area** The study area encompasses the Xinjiang Uygur Autonomous Region of China and the five Central Asian nations (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan). This vast region is characterized by a continental arid and semi-arid climate, featuring significant temperature fluctuations, scarce precipitation, and high evaporation rates. Under the background of global warming, the spatiotemporal patterns of temperature and humidity in this region have undergone significant shifts, leading to complex changes in tourism climate comfort. Understanding these variations is essential for optimizing tourism resource allocation and formulating climate adaptation strategies for the Silk Road economic belt.

**2.2 Methodology and Data** To assess the tourism climate comfort, this study utilizes long-term meteorological datasets, including temperature, relative humidity, wind speed, and sunshine duration. The evaluation primarily employs the Tourism Climate Index (TCI) and the Temperature-Humidity Index (THI), integrated with geographic information systems (GIS) to analyze spatiotemporal dynamics.

The calculation of the comfort index follows the standard formula:

$$TCI = 2 \times (4 \times CID + CIA + 2 \times P + 2 \times S + W)$$

Where the variables represent specific meteorological parameters adjusted for the regional climatic characteristics of Central Asia and Xinjiang.

## 3. Spatiotemporal Analysis of Climate Comfort

**3.1 Temporal Trends** Analysis of the time-series data indicates a general warming trend across the region over the past several decades. While rising temperatures have extended the comfortable period for tourism in high-latitude and high-altitude areas during the shoulder seasons (spring and autumn), they have also increased the frequency of extreme heat events during the peak summer months in basin areas and desert fringes. Based on high-resolution gridded meteorological data and CMIP6 multi-model simulation results, this study systematically analyzes the spatiotemporal evolution of the Holiday Climate Index (HCI) from 1960 to 2100.

The results indicate that the overall HCI exhibits an upward trend with significant regional and seasonal variations. More pronounced increases are observed in mountainous areas, while some arid basins show a slight decline. Under the SSP5-8.5 scenario, future HCI increases and associated uncertainty are higher compared to the SSP245 scenario. The intra-annual variation of the HCI exhibits two distinct patterns: “single-peak” and “double-peak.” Future climate warming is projected to cause a decline in summer comfort in certain regions. Under high-emission scenarios, the summer HCI in the long-term period (2071–2100) may even fall below the historical baseline (1985–2014), leading to a narrowing of the optimal tourism window.

**3.2 Spatial Distribution** The spatial distribution of the HCI shows significant latitudinal zonation and vertical differentiation. High-value areas are concentrated in low-altitude and low-latitude regions. While the overall extent of high-value areas is expected to expand in the future, the coverage of high-comfort zones in summer ( $HCI > 90$ ) will contract due to the impact of extreme heat. The duration of the climatically comfortable period for tourism will extend significantly, with greater increases but enhanced fluctuations under high-emission scenarios. Spatially, the pattern is characterized by longer comfortable periods in low-latitude and low-altitude regions, and shorter periods in high-latitude and high-altitude areas; however, high-altitude mountainous regions will experience significant increases in the long term.

**Keywords:** HCI; Tourism Climate Comfort; Climate Change Scenarios; Spatiotemporal Evolution; Climate Risk

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#### 4. Role in Promoting Regional Economic Integration

Under the impetus of the “Belt and Road” Initiative, tourism cooperation between China and Central Asian countries is steadily strengthening. This collaboration serves as a vital bridge for cultural exchange and economic integration, fostering regional connectivity and mutual understanding. As infrastructure improves and visa policies become more streamlined, the flow of tourists between these regions has seen significant growth, creating new opportunities for sustainable development and cross-border tourism circuits.

The “Silk Road Heritage” IP and other similar initiatives have been utilized to deepen tourism cooperation [?]. These collaborative efforts highlight the urgent need for regional tourism climate risk assessments and the development of corresponding adaptation strategies.

#### 5. Development of Cross-Border and Self-Driving Tourism

The strategic expansion of the tourism sector necessitates a multi-faceted approach focusing on the integration of cross-border travel, the promotion of self-

driving routes, the specialized operation of tourist trains, and the implementation of collaborative marketing initiatives.

**5.1 Cross-Border and Self-Driving Tourism** The development of cross-border tourism is fundamental to fostering international cultural exchange and regional economic integration. This requires the streamlining of customs procedures and the improvement of infrastructure at key entry points. Simultaneously, the rise of self-driving tourism reflects a growing demand for personalized experiences, requiring comprehensive road service systems and digital navigation tools.

**5.2 Specialized Tourist Trains** The operation of specialized tourist trains serves as a high-efficiency, sustainable mode of transport that connects major hubs with peripheral attractions. These “tourism expresses” offer curated on-board experiences reflecting the cultural themes of the destinations.

**5.3 Joint Promotion** Collaborative marketing involves the synchronization of branding efforts between government agencies and travel service providers. By pooling resources for international tourism fairs and digital media campaigns, stakeholders can create a unified narrative for the region.

## 6. Methodology and Evaluation Indices

To evaluate the tourism climate comfort, this study utilizes long-term meteorological datasets and integrates several bioclimatic indices.

**6.1 Evaluation Indices** The primary metric used in this study is the Temperature-Humidity Index (THI), which reflects the heat exchange between the human body and the surrounding environment:

$$\text{THI} = (1.8T + 32) - 0.55(1 - f)(1.8T - 26)$$

where  $T$  represents the air temperature ( $^{\circ}\text{C}$ ) and  $f$  represents the relative humidity (%). Additionally, the Wind Chill Index (WCI) is incorporated:

$$\text{WCI} = (33 - T)(9 + 10.45\sqrt{v} - v)$$

where  $v$  denotes the wind speed (m/s).

The Holiday Climate Index (HCI) is further refined for urban leisure tourism ( $\text{HCI}_{urban}$ ):

$$\text{HCI}_{urban} = 4TC + 2A + 3\text{precipitation} + \text{wind} \quad (1)$$

where  $TC$  denotes thermal comfort,  $A$  represents cloud cover,  $\text{precipitation}$  denotes cumulative precipitation, and  $\text{wind}$  refers to average wind speed. Thermal comfort is calculated using effective temperature ( $ET$ ):

$$ET = T - 0.55(1 - 0.01RH)(T - 14.4)$$

**6.2 Data Sources** Meteorological data for 1960–2020 were obtained from the ERA5-Land reanalysis dataset (ECMWF). Future projections (2021–2100) utilize eight General Circulation Models (GCMs) from CMIP6 under SSP2-4.5 and SSP5-8.5 scenarios.

## 7. Results and Analysis

**7.1 Interannual Variations** The HCI in the study area exhibited a significant fluctuating upward trend from 1960 to 2020. The ascent rate for the region (0.1445) is high, indicating improving suitability. However, under the SSP5-8.5 scenario, the projected summer HCI values for 2071–2100 are expected to fall below historical levels due to extreme heat stress.

**7.2 Intra-annual Patterns** Kyrgyzstan and Tajikistan exhibit a “unimodal” pattern, peaking in late July and August. In contrast, Xinjiang (China), Kazakhstan, Turkmenistan, and Uzbekistan exhibit a “bimodal” structure. For example, Xinjiang shows peaks in early June and late August, with a trough in July due to summer heat. As emission intensity increases, this bimodal structure becomes more pronounced, with the summer trough deepening significantly by 2071–2100.

## 8. Conclusion

The warming climate has enhanced tourism potential in high-altitude regions like Kyrgyzstan and Tajikistan by extending comfortable periods. However, arid basins in Uzbekistan and Turkmenistan face increasing risks from extreme summer heat. These findings provide a scientific basis for climate adaptation and the sustainable development of the regional tourism industry along the Silk Road Economic Belt.

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

*Source: ChinaXiv – Machine translation. Verify with original.*